

Guide to Agricultural Meteorological Practices

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CONTENTS

	Page
PREFACE	xix
List of Contributors	xxi
Acknowledgements	xxiv
CHAPTER 1. GENERAL	1-1
1.1 Scope of agricultural meteorology	1-1
1.2 Importance of agricultural meteorology	1-2
1.2.1 General importance	1-2
1.2.2 Applications	1-3
1.2.3 Conditions and requirements	1-4
1.3 Role of the Commission for Agricultural Meteorology	1-5
1.4 Tools and mechanisms in agricultural meteorology	1-7
1.4.1 Diagnostic and conceptual framework (operational link between support systems and services)	1-7
1.4.2 Agrometeorological research (basic, applied and derived operational research as tools)	1-8
1.4.3 Primary research tools (data, quantification, statistics, indices and modelling)	1-9
1.4.4 Agrometeorological monitoring and early warning (tools for warning using preparedness strategies)	1-9
1.4.5 Forecasting and prediction in agrometeorology (tools to guide preparedness with probabilities)	1-10
1.4.6 Agrometeorological aspects of crop, forest and livestock protection (direct preparedness strategies)	1-11
1.4.7 Policy matters relating to agrometeorology (initial and boundary conditions set by socio-economics and the environment)	1-12
1.4.8 Climate resources assessment for agrometeorology	1-12
1.4.9 Water resources assessment for agrometeorology	1-13
1.4.10 Soil resources assessment for agrometeorology	1-13
1.4.11 Biomass resources assessment for agrometeorology	1-14
1.4.12 Agrometeorological services	1-14
1.5 Training, education and extension in agricultural meteorology as support systems for agrometeorological services	1-15
1.5.1 General considerations	1-15
1.5.2 Training at the intermediate level	1-16
1.5.3 Challenges	1-16
1.5.4 Specialization in agricultural meteorology	1-16
1.5.5 Consequences for training, education and extension in agrometeorology	1-17
1.5.6 Syllabi for instruction and other observations on curriculum content	1-17
1.6 Challenges met and remaining in agricultural meteorology	1-18
1.6.1 A challenge met	1-18
1.6.2 Challenges remaining, from a new perspective	1-19
1.6.3 The challenges of decision support systems	1-20
ANNEX 1.A – Terms of reference of the Commission for Agricultural Meteorology	1-21
ANNEX 1.B – Needs for training/education/extension (and directly related issues) recognized as priorities in the Accra symposium	1-22
ANNEX 1.C – Outline of a recent classical basic syllabus In agrometeorology	1-23
REFERENCES	1-25

	<i>Page</i>
CHAPTER 2. AGRICULTURAL METEOROLOGICAL VARIABLES AND THEIR OBSERVATIONS	2-1
2.1 Basic aspects of agricultural meteorological observations	2-1
2.1.1 Data as a support system for agrometeorological services	2-1
2.1.2 Physical climatic variables	2-1
2.1.3 Biological variables	2-2
2.1.4 Scale of observations.	2-2
2.1.5 Extent of observations.	2-3
2.1.6 Data without metadata are unreliable	2-3
2.2 Agricultural meteorological stations	2-4
2.2.1 Classification	2-4
2.2.2 Selection and layout of a station site	2-4
2.2.2.1 Selection of a representative site location	2-4
2.2.2.2 Layout of station instruments	2-4
2.2.3 Primary handling of data.	2-5
2.2.4 Networks	2-6
2.2.5 Documentation of agricultural meteorological stations	2-7
2.2.6 Inspection and supervision of stations.	2-7
2.2.7 Fixed agrometeorological stations.	2-8
2.2.8 Mobile stations	2-8
2.2.9 Agricultural mesoclimatological surveys	2-8
2.2.10 Complementary observations to describe special mesoclimatic processes	2-9
2.2.11 Detailed physical observations of a non-routine or non-permanent character (agricultural micrometeorological research).	2-9
2.3 Observations to be carried out at agricultural meteorological stations.	2-9
2.3.1 Observations of the physical environment.	2-9
2.3.1.1 Radiation and sunshine.	2-10
2.3.1.2 Air temperature	2-11
2.3.1.3 Temperature of soil.	2-11
2.3.1.4 Atmospheric pressure	2-12
2.3.1.5 Wind	2-12
2.3.1.6 Air humidity and soil moisture (including leaf wetness).	2-12
2.3.1.7 Precipitation (clouds and hydrometeors)	2-14
2.3.1.8 Evaporation and water balance measurements	2-14
2.3.1.9 Fluxes of weather variables (derived from measured quantities)	2-15
2.3.1.10 Remote-sensing and GIS.	2-15
2.3.1.11 Recorders and integrators.	2-15
2.3.2 Observations of a biological nature	2-16
2.3.2.1 Observations of natural phenomena	2-17
2.3.2.2 Observations for agroclimatological use	2-17
2.3.2.3 Observations of direct and indirect damage owing to weather.	2-18
2.3.2.4 Detailed biological observations	2-19
2.3.2.5 Observations for operational use	2-19
2.3.2.6 Global biological observations	2-20
2.4 Instruments used at agricultural meteorological stations	2-20
2.4.1 Measurement of the physical environment	2-20
2.4.1.1 Radiation and sunshine.	2-20
2.4.1.2 Air temperature	2-22
2.4.1.3 Temperature of soil and other bodies	2-22
2.4.1.4 Atmospheric pressure	2-23
2.4.1.5 Wind	2-24
2.4.1.6 Air humidity and soil moisture (including leaf wetness).	2-24
2.4.1.7 Precipitation (clouds and hydrometeors)	2-27
2.4.1.8 Evaporation and water balance	2-28
2.4.1.9 Fluxes of weather variables (derived from measured quantities)	2-28
2.4.1.10 Remote-sensing and GIS	2-29
2.4.1.11 Calibration of recorders, integrators and automatic weather stations	2-29

2.4.2	Measurement of biological and related phenomena	2–31
2.4.2.1	Measurement of soil erosion	2–31
2.4.2.2	Measurement of runoff	2–31
2.4.2.3	Measurement of leaf area, canopy structure and photosynthesis.	2–31
REFERENCES		2–32
CHAPTER 3. AGRICULTURAL METEOROLOGICAL DATA, THEIR PRESENTATION AND STATISTICAL ANALYSIS.		3–1
3.1	Introduction	3–1
3.2	Data for agricultural meteorology	3–1
3.2.1	Nature of the data	3–1
3.2.2	Data collection	3–2
3.2.3	Recording of data	3–3
3.2.4	Scrutiny of data and acquisition of metadata.	3–3
3.2.5	Format of data	3–4
3.2.6	Catalogue of data	3–4
3.3	Distribution of data.	3–4
3.3.1	Requirements for research.	3–4
3.3.2	Special requirements for agriculturists.	3–4
3.3.3	Determining the requirements of users	3–5
3.3.4	Minimum distribution of agroclimatological documents	3–5
3.4	Database management.	3–5
3.4.1	CLICOM Database Management System.	3–6
3.4.2	Geographical Information System (GIS)	3–6
3.4.3	Weather generators (WGs)	3–7
3.5	Agrometeorological information	3–8
3.5.1	Forecast information	3–9
3.6	Statistical methods of agrometeorological data analysis	3–9
3.6.1	Series checks	3–10
3.6.2	Climatic scales.	3–10
3.6.2.1	Reference periods	3–10
3.6.2.2	The beginning of reference periods	3–10
3.6.2.3	Analysis of the effects of weather	3–10
3.6.3	Population parameters and sample statistics	3–11
3.6.4	Frequency distributions	3–11
3.6.4.1	Examples using frequency distributions	3–12
3.6.4.2	Extreme value distributions.	3–14
3.6.4.3	Probability and risk.	3–15
3.6.4.4	Distribution of sequences of consecutive days	3–15
3.6.5	Measuring central tendency	3–15
3.6.5.1	The mean.	3–15
3.6.5.2	The mode	3–16
3.6.5.3	The median	3–17
3.6.6	Fractiles.	3–17
3.6.7	Measuring dispersion	3–17
3.6.7.1	The range.	3–17
3.6.7.2	The variance and the standard deviation	3–17
3.6.7.3	Measuring skewness.	3–17
3.7	Decision-making.	3–17
3.7.1	Statistical inference and decision-making	3–17
3.7.2	Two-tailed and one-tailed tests	3–19
3.7.3	Interval estimation	3–19
3.7.4	The z-test	3–20
3.7.5	Tests for normal population means	3–20
3.7.6	The <i>t</i> -test	3–22

	<i>Page</i>
3.7.7 Estimators using pooled samples	3–23
3.7.8 The paired-comparison test and the difference-between-two-means test	3–23
3.7.9 Difference between two means	3–24
3.7.10 The <i>F</i> -Test	3–24
3.7.11 Relationship between variables	3–25
3.7.11.1 Correlation methods	3–25
3.7.11.2 Regression	3–26
3.7.11.3 Multiple regressions	3–27
3.7.11.4 Stepwise regression	3–27
3.7.11.5 Cluster analysis	3–28
3.7.11.6 Classification trees	3–28
3.7.12 Climatic periodicities and time series	3–28
3.8 Publication of results	3–29
3.8.1 General methods	3–29
3.8.2 Tables	3–29
3.8.3 Contingency tables	3–29
3.8.4 Graphs	3–29
3.8.5 Maps	3–29
3.8.6 The agrometeorological bulletin	3–29
3.8.6.1 Some examples	3–30
3.8.6.2 How costly should the agmet bulletin be?	3–32
ANNEX – Table of the normal distribution	3–33
REFERENCES	3–34
CHAPTER 4. REMOTE-SENSING AND GIS APPLICATIONS IN AGROMETEOROLOGY	4–1
4.1 Definition and role of remote-sensing	4–1
4.1.1 Reflective remote-sensing	4–2
4.1.2 Thermal remote-sensing	4–3
4.1.3 Microwave remote-sensing	4–3
4.1.4 Earth satellites	4–3
4.1.5 Weather satellites	4–3
4.1.6 Derived products	4–3
4.2 Introduction to Geographical Information Systems	4–4
4.2.1 Storing geographic data	4–4
4.2.2 Raster format	4–4
4.2.3 Vector format	4–5
4.2.4 Requirements of a GIS	4–6
4.2.5 Basic components of a GIS	4–6
4.3 Integration of remote-sensing and GIS	4–6
4.3.1 Data integration	4–7
4.3.2 Data acquisition	4–7
4.3.3 Data processing	4–7
4.3.3.1 Geometric rectification	4–7
4.3.3.2 Data conversion	4–7
4.3.3.3 Data analysis	4–8
4.3.3.4 Classification system	4–8
4.3.3.5 Data generalization	4–9
4.3.3.6 Error assessment	4–9
4.3.3.7 Sampling	4–9
4.3.3.8 Spatial autocorrelation	4–9
4.3.3.9 Location accuracy	4–9
4.3.3.10 Final product presentation error	4–10
4.3.3.11 Decision-making	4–10
4.3.3.12 Implementation	4–10
4.3.3.13 Theory of vegetation indices	4–10

4.4	Operational agrometeorological products employing GIS and remote-sensing	4-12
4.4.1	Assessment of meteorological and agronomic conditions to aid decisions on drought using remote-sensing	4-13
4.4.1.1	Precipitation	4-13
4.4.1.2	Solar radiation	4-14
4.4.1.3	Agronomic conditions	4-14
4.4.2	Operational uses of remote-sensing and GIS for irrigation scheduling	4-16
4.4.3	Operational uses of remote-sensing and GIS for soil and crop management	4-18
4.4.3.1	Evapotranspiration	4-18
4.4.3.2	Soil salinity	4-19
4.4.3.3	Remote-sensing in precision agriculture	4-19
4.4.3.4	Crop growth and intercepted radiation	4-20
4.4.3.5	Nutrient management	4-21
4.4.3.6	Pest management	4-23
4.4.3.7	Selection of growth traits	4-23
4.4.3.8	Crop yield estimation	4-24
4.4.4	Operational uses of remote-sensing and GIS for assessing environmentally sensitive areas for desertification risk	4-24
4.4.5	Aquaculture and remote-sensing	4-24
4.4.6	Operational use of remote-sensing for identification of fishing zones	4-26
4.4.7	Forest management through remote-sensing	4-26
4.5	Collaborations for resource sharing in remote-sensing and GIS	4-26
	REFERENCES	4-28
	CHAPTER 5. WEATHER AND CLIMATE FORECASTS FOR AGRICULTURE	5-1
5.1	Need and requirements for weather forecasts for agriculture	5-1
5.1.1	Climate-based strategic agronomic planning	5-1
5.1.2	Weather events	5-1
5.1.3	Usefulness of weather forecasts	5-2
5.1.4	Weather forecasts for agriculture: essential requirements	5-2
5.1.5	Some unique aspects of agricultural weather forecasts	5-2
5.2	Characteristics of weather forecasts	5-3
5.3	Considerations related to agricultural weather forecasts	5-4
5.3.1	Elements of agricultural weather forecasts	5-4
5.3.2	Format of forecasts	5-7
5.3.3	Forecasts for agricultural purposes	5-7
5.3.3.1	Sky coverage	5-9
5.3.3.2	Bright sunshine	5-9
5.3.3.3	Solar radiation	5-9
5.3.3.4	Precipitation	5-9
5.3.3.5	Temperature	5-10
5.3.3.6	Humidity	5-10
5.3.3.7	Wind speed and direction	5-10
5.3.3.8	Leaf wetness	5-11
5.3.3.9	Evapotranspiration	5-11
5.3.3.10	Water balance	5-11
5.3.3.11	Extreme events	5-11
5.4	Special agricultural weather forecasts	5-11
5.4.1	Field preparation	5-12
5.4.2	Sowing/planting	5-12
5.4.3	Application of agricultural chemicals	5-13
5.4.3.1	Foliar application	5-13
5.4.3.2	Soil application	5-14
5.4.4	Evaporation losses for irrigation	5-14
5.4.5	Weeding	5-14
5.4.6	Crop harvest and post-harvest operations (including crop curing and drying of meat and fish)	5-15

	<i>Page</i>
5.4.7	Control of plant diseases 5–15
5.4.8	Control of noxious insects 5–15
5.4.9	Transport of agricultural products 5–16
5.4.10	Operation of agricultural aviation 5–16
5.4.11	Prevention of damage due to chilling, frost and freezing 5–17
5.4.12	Forestry operations 5–17
5.4.13	Fishery operations 5–17
5.4.14	Safeguarding animal husbandry 5–19
5.4.14.1	Housing and production 5–19
5.4.14.2	Assessment of pasture productivity and grazing 5–19
5.4.14.3	Forecasting diseases 5–21
5.4.15	Protecting plants used in horticulture and arboriculture (non-forest trees) 5–22
5.5	Agricultural advisories or agrometeorological services 5–22
5.5.1	Preparation of agricultural advisories (agrometeorological services) 5–24
5.5.2	Panel of experts 5–24
5.5.3	Information requirements 5–24
5.5.4	Example of an agrometeorological advisory service of the NCMRWF in India: a preliminary impact assessment 5–25
5.6	Probability forecasts 5–25
5.6.1	The rationale for probability forecasts 5–25
5.6.2	Formulation 5–28
5.6.3	Probability forecasts at different scales 5–29
5.6.4	Probabilistic forecast formats 5–30
5.6.4.1	Probability distributions 5–30
5.6.4.2	Categorical probabilities 5–32
5.6.4.3	Time series and analogues 5–32
5.6.5	Deriving forecast distributions 5–32
5.6.5.1	From analogues 5–33
5.6.5.2	From hindcast residuals 5–33
5.6.5.3	From ensemble forecasts 5–33
5.6.6	Interpretation and attributes of probability forecasts 5–33
5.6.7	Communicating probabilistic forecasts to farmers 5–33
5.6.7.1	Keys to understanding and applying probabilistic information 5–35
5.6.7.2	Teaching probabilities to farmers 5–35
5.7	Weather forecasts for the general public 5–36
5.8	Nowcasting and very short-range forecasts 5–36
5.8.1	Definitions 5–36
5.8.2	Operational activities 5–36
5.8.3	Operational examples 5–39
5.8.4	Nowcasting and very short-range forecast of frost 5–39
5.9	Short- and medium-range forecasts 5–40
5.9.1	Definition 5–40
5.9.2	Usefulness for agriculture 5–40
5.9.3	State of technology 5–40
5.9.4	Forecasts and NWP 5–41
5.9.5	Probabilistic approach to SRF and MRF 5–41
5.9.5.1	Operational services and SRF/MRF for agriculture 5–41
5.10	Long-range forecasts 5–46
5.10.1	The basis for LRFs 5–46
5.10.2	Statistical and dynamical approaches to LRF 5–46
5.10.2.1	Statistical approach to LRF and related limits 5–46
5.10.2.2	NWP approach to LRF and related limits 5–46
5.10.3	Reliability of LRF 5–47
5.10.4	Quality control of forecasts 5–47
5.10.4.1	Quality control data 5–47
5.10.4.2	Feedback to operational services 5–48

5.11	Dissemination of weather forecasts and advisories	5–48
5.11.1	New dimensions in dissemination technology	5–48
5.11.2	Internet-based communication systems	5–49
5.11.3	“PlantelInfo” and other Internet case studies	5–49
5.11.4	Communication systems based on mobile phones	5–50
	ANNEX – Sample forecast format	5–51
	REFERENCES	5–53
	CHAPTER 6. AGROMETEOROLOGICAL FORECASTING	6–1
6.1	Overview	6–1
6.1.1	Scope of agrometeorological forecasting	6–1
6.1.2	Forecasting techniques in general	6–2
6.1.3	Areas of application of agrometeorological forecasts	6–2
6.1.3.1	Establishment of national and regional forecasting systems	6–2
6.1.3.2	Farm-level applications	6–3
6.1.3.3	Warning systems, especially for food security	6–5
6.1.3.4	Market planning and policy	6–6
6.1.3.5	Crop insurance	6–7
6.2	Variables used in agrometeorological forecasting	6–8
6.2.1	Overview	6–8
6.2.2	Technology and other trends	6–10
6.2.3	Soil water balance: moisture assessment and forecast	6–11
6.2.3.1	Presentation	6–11
6.2.3.2	Soil water balance for dryland crops	6–11
6.2.4	Actual evapotranspiration (ETA)	6–12
6.2.5	Various indices as measures of environmental variability	6–12
6.2.5.1	Various drought indices	6–12
6.2.5.2	Remotely sensed vegetation indices	6–16
6.2.5.3	El Niño–Southern Oscillation (ENSO) indices	6–17
6.2.6	Heat supply forecast	6–18
6.2.7	Potential biomass and reference yield	6–19
6.3	IMPLEMENTATION OF YIELD FORECASTS IN PRACTICE	6–19
6.3.1	Data requirements	6–19
6.3.2	Calibration and sources of error	6–20
6.4	BASIC AGROMETEOROLOGICAL FORECASTING APPROACHES	6–22
6.4.1	Empirical statistical relations	6–22
6.4.1.1	Introduction	6–22
6.4.1.2	“Golden rules” of regression forecasting and good-practice advice.	6–22
6.4.2	Crop simulation models	6–25
6.4.3	Non-parametric forecasts	6–26
6.4.4	Combination of methods	6–28
6.4.5	Extreme factors	6–30
6.4.5.1	Introduction	6–30
6.4.5.2	Analysis of factors relevant for extreme factor impact assessments	6–31
6.5	SPECIAL APPLICATIONS	6–32
6.5.1	Crop-specific methods	6–32
6.5.2	Quality of produce	6–33
6.5.3	Pests and diseases	6–33
6.5.3.1	Introduction	6–33
6.5.3.2	Plant pests and biotic diseases	6–33
6.5.4	Fire forecasting	6–36
6.5.4.1	Overview	6–36
6.5.4.2	Wildfire modelling	6–36
6.5.4.3	Forecasts for wildfire planning	6–37

	<i>Page</i>
6.5.4.4 Examples of existing models.	6–37
6.5.5 Phenology.	6–38
6.5.6 Climate change.	6–39
6.5.6.1 Introduction.	6–39
6.5.6.2 Methods.	6–39
REFERENCES	6–41
CHAPTER 7. CLIMATE AND WEATHER RISK ASSESSMENT FOR AGRICULTURAL PLANNING	7–1
7.1 Introduction	7–1
7.1.1 Understanding the climate mechanisms that contribute to climate- and weather-related risks	7–2
7.2 Climatic hazards	7–3
7.2.1 Types	7–3
7.2.1.1 Extreme events	7–3
7.2.1.2 Regional climate anomalies	7–3
7.2.2 Categories.	7–3
7.2.2.1 Drought	7–3
7.2.2.2 Heavy rainfall and floods	7–3
7.2.2.3 Strong winds: tornadoes, storms and tropical cyclones	7–4
7.2.2.4 Temperature: frost and heatwaves	7–4
7.2.2.5 Categories	7–5
7.3 Scale studies for climatic anomalies.	7–6
7.3.1 Space	7–6
7.3.2 Time	7–6
7.3.3 Space–time scales	7–6
7.4 Agrometeorological applications in the characterization of climatic hazards – modelling and data needs.	7–7
7.4.1 General circulation models	7–8
7.4.2 Regional circulation models.	7–8
7.4.3 Historical local climate data.	7–9
7.4.4 Agronomic models	7–10
7.4.4.1 Crop response	7–10
7.4.4.2 Pasture response.	7–10
7.4.5 Vegetation suitability maps	7–10
7.4.6 Remote-sensing	7–11
7.4.6.1 Vegetation indices	7–11
7.4.6.2 Soil moisture index.	7–11
7.4.6.3 Drought early warning systems	7–11
7.5 Methods of risk assessment.	7–12
7.5.1 Managing risk.	7–12
7.5.2 Analyses of long-term weather data to identify occurrence of particular risk	7–13
7.5.3 Disaster preparedness on the basis of weather forecasts	7–13
7.5.4 Anticipating risk on the basis of seasonal forecasts.	7–13
7.5.4.1 Tools	7–14
7.5.4.2 Accuracy, timeliness and value	7–15
7.6 Example of risk assessment for particular weather and climate events from literature	7–15
7.7 Extreme cases	7–17
7.8 Developing and implementing policy to reduce the risk and impact of extreme events	7–21
7.9 On-farm planning to reduce the risk and impact of extreme events	7–22
7.9.1 Crop selection and cropping sequence	7–22
7.9.2 Selection of varieties	7–22
7.9.3 Land preparation	7–23
7.9.4 Crop management	7–23
7.9.5 Pasture and livestock management	7–23
7.9.5.1 Preparing for and managing through drought	7–23
7.10 Significance of climate change	7–25

7.10.1	Climate is always changing	7–25
7.10.2	Adaptation to climate change	7–26
REFERENCES		7–27
FURTHER READING		7–33
CHAPTER 8. EFFECTS OF CLIMATE CHANGE ON AGRICULTURE		8–1
8.1	Introduction	8–1
8.2	Summary of evidence for climate change	8–2
8.3	Summary of IPCC protocol for climate change impact assessment	8–4
8.4	Sources of climate change data	8–5
8.4.1	Global climate model results	8–5
8.4.2	Regional climate models for regional and local-scale bioresource applications	8–6
8.4.3	Statistical downscaling of GCM outputs for bioresource applications	8–7
8.4.4	Reliability of extreme event prediction	8–8
8.5	Models for evaluating climate change impacts	8–9
8.5.1	Crop models	8–10
8.5.2	Animal models	8–11
8.5.3	System models	8–12
8.5.4	Forest models	8–13
8.5.5	Other bioresource models	8–13
8.6	Preparation for climate change impact assessment	8–14
8.6.1	The global context	8–14
8.6.2	Factors to consider for study design	8–14
8.6.3	Specific weather-related effects	8–15
8.6.3.1	Temperature effects	8–15
8.6.3.2	Water availability	8–15
8.6.3.3	Wind effects	8–16
8.6.3.4	Photosynthetically active radiation	8–16
8.6.3.5	Elevated CO ₂ effects	8–17
8.7	Assessing the effect of climate change on bioresource industries	8–18
8.7.1	A proposed action plan for climate change impact assessment	8–19
8.8	Closing observations	8–19
REFERENCES		8–21
CHAPTER 9. APPLICATIONS OF METEOROLOGY TO AGRICULTURE		9–1
9.1	Introduction	9–1
9.1.1	Users of agrometeorological information	9–1
9.1.2	Temporal and spatial scales of agrometeorological information and applications	9–1
9.1.3	Benefits derived from applications	9–2
9.2	Applications for governments and other large administrative bodies	9–3
9.2.1	Operational assessments	9–3
9.2.2	Agroclimatic surveys	9–4
9.2.3	Mesoscale agroclimatic surveys	9–4
9.3	Applications for farmers or groups of farmers	9–5
9.3.1	Improvements to production	9–5
9.3.1.1	Irrigation	9–5
9.3.1.2	Shelter from the wind	9–5
9.3.1.3	Shade	9–6
9.3.1.4	Greenhouses (glass and plastic)	9–6
9.3.1.5	Ground cover (mulching)	9–7
9.3.1.6	Animal housing	9–7
9.3.1.7	Storage	9–8
9.3.2	Averting dangers to production	9–8

	<i>Page</i>
9.3.2.1 Direct weather hazards	9–9
9.3.2.2 Indirect weather hazards	9–10
9.4 Other applications	9–16
REFERENCES	9–18
CHAPTER 10. AGROMETEOROLOGY OF SOME SELECTED CROPS	10–1
10.1 Agrometeorology and cotton production	10–1
10.1.1 Importance of cotton in various climates	10–1
10.1.2 Agroclimatology of cotton production	10–1
10.1.3 Other background information on cotton	10–4
10.1.4 Management aspects of cotton production	10–5
10.1.5 User requirements for agrometeorological information in cotton production	10–7
10.1.6 Agrometeorological services available for cotton production	10–8
10.2 Agrometeorology and groundnut production	10–9
10.2.1 Importance of groundnut in various climates	10–9
10.2.1.1 General	10–9
10.2.1.2 Production environments in major producing countries	10–11
10.2.2 Agroclimatology of groundnut	10–11
10.2.2.1 Rainfall or soil moisture	10–11
10.2.2.2 Growth stages and water use	10–12
10.2.2.3 Temperature	10–13
10.2.2.4 Thermal time or accumulated heat unit requirements of groundnut . .	10–16
10.2.2.5 Photoperiod or day length	10–16
10.2.2.6 Saturation deficit	10–17
10.2.3 Further background information on groundnut	10–17
10.2.3.1 Relationship between diseases and weather	10–17
10.2.3.2 Insect pests	10–20
10.2.4 Management aspects of groundnut in various environments	10–20
10.2.4.1 Protection measures	10–20
10.2.4.2 Improvement measures	10–21
10.2.5 User requirements for agrometeorological information on groundnut	10–23
10.2.6 Agrometeorological services for groundnut	10–24
10.3 Agrometeorology and maize production	10–25
10.3.1 Importance of maize in various climates	10–25
10.3.1.1 Importance of maize in the United States	10–25
10.3.1.2 Yield gap and yield potential	10–26
10.3.1.3 Maize production profile by region in the developing world	10–26
10.3.2 Agroclimatology of the crop	10–26
10.3.3 Basic management aspects of the crop in various environments	10–28
10.3.4 Other background information on the crop	10–30
10.3.4.1 Growth stage monitoring	10–30
10.3.4.2 Growth monitoring – an illustration	10–30
10.3.4.3 Biotechnology	10–30
10.3.5 Some management details	10–31
10.3.6 User requirements for climate information	10–32
10.3.6.1 Information to cope with climatic risk for maize production	10–32
10.3.7 Examples of agrometeorological services related to this crop	10–34
10.4 Agrometeorology and pearl millet production	10–36
10.4.1 Importance of pearl millet in various climates	10–36
10.4.2 The influences of agroclimatological variables on pearl millet	10–36
10.4.2.1 Rainfall	10–37
10.4.2.2 Temperature	10–37
10.4.2.3 Day length/photoperiod	10–38
10.4.2.4 Solar radiation	10–38
10.4.2.5 Wind	10–39
10.4.3 Management aspects of pearl millet in various environments	10–39

10.4.4	Other background information on pearl millet	10-42
10.4.4.1	Drought tolerance mechanisms	10-42
10.4.4.2	Diseases, pests and weeds	10-42
10.4.4.3	Insects and pests	10-43
10.4.5.	User requirements for agrometeorological information	10-44
10.4.6.	Agrometeorological services related to pearl millet in Africa and India.	10-45
10.4.6.1	Africa: Example 1	10-45
10.4.6.2	Africa: Example 2	10-46
10.4.6.3	India.	10-46
10.4.6.4	India: Example 1.	10-46
10.4.6.5	India: Example 2	10-47
10.5	Agrometeorology and potato production	10-47
10.5.1	Importance of potato in various climates.	10-47
10.5.2	Agroclimatology of potato (and some management aspects)	10-48
10.5.2.1	Air temperature, solar radiation and photoperiod	10-48
10.5.2.2	Soil temperature and soil temperature management	10-51
10.5.2.3	Atmospheric humidity, wind and wind management	10-53
10.5.2.4	Crop evapotranspiration and irrigation requirements	10-54
10.5.2.5	Soil moisture requirements and irrigation management	10-55
10.5.2.6	Irrigation scheduling.	10-56
10.5.3	Other background information on potato (yield, quality) response to irrigation management	10-56
10.5.3.1	Assuring tuber grade	10-57
10.5.3.2	Assuring internal tuber quality	10-57
10.5.4	Other management aspects of potato (irrigation and microclimate interaction with potato diseases and pests).	10-58
10.6.	Agrometeorology and rice production	10-59
10.6.1	Importance of rice in various climates	10-59
10.6.1.1	Importance of rice in tropical Asia.	10-59
10.6.2	Agroclimatology of rice.	10-61
10.6.2.1	Rice production ecosystems and main climate-related problems.	10-61
10.6.2.2	Influence of critical climate and weather variables on growth and yield	10-67
10.6.3	Other background information on rice	10-70
10.6.3.1	Climatic variability	10-70
10.6.3.2	Climate change	10-70
10.6.4	Management aspects of rice in various environments	10-73
10.6.4.1	Adaptive, protective and improvement measures	10-73
10.6.4.2	Protection measures.	10-75
10.6.5	User requirements for agrometeorological information on rice	10-77
10.6.5.1	Rice climate zones	10-78
10.6.5.2	Irrigated lowland rice	10-78
10.6.5.3	Rainfed lowland rice	10-78
10.6.5.4	Biotic risks and weather hazards	10-79
10.6.5.5	Forecast-based weather advisories for rice farming operations	10-79
10.6.5.6	Agrometeorological forecasting	10-79
10.6.5.7	Phenological forecasts	10-79
10.6.5.8	Yield forecasts.	10-80
10.6.5.9	Biometeorological models	10-81
10.6.5.10	Field-level data series	10-81
10.6.5.11	Use of forecast weather data.	10-81
10.6.6	Agrometeorological services relating to rice	10-81
10.6.6.1	Agrometeorological extension for rice farmers	10-81
10.7	Agrometeorology and sorghum production	10-82
10.7.1	Introduction	10-82
10.7.2	Agroclimatology of sorghum.	10-84
10.7.2.1	Rainfall – water management	10-84
10.7.2.2	Photoperiodism	10-85

	<i>Page</i>
10.7.2.3 Temperature	10–85
10.7.3 Other background information on sorghum	10–86
10.7.4 Management aspects of sorghum in various environments	10–87
10.7.5 User requirements for climate information	10–88
10.7.6 Examples of agrometeorological services relating to sorghum	10–89
10.8 Agrometeorology and wheat production	10–91
10.8.1 Introduction	10–91
10.8.1.1 Classification of wheat	10–91
10.8.1.2 Adaptation of wheat	10–92
10.8.2 Influences of agroclimatological variables on wheat	10–92
10.8.2.1 Temperature	10–94
10.8.2.2 Precipitation	10–95
10.8.2.3 Photoperiodism and solar radiation	10–96
10.8.2.4 Wind	10–96
10.8.3 Management aspects of wheat production in various climates	10–96
10.8.3.1 Planting date, seeding rate and plant density	10–96
10.8.3.2 Soil fertilization and plant nutrition	10–97
10.8.3.3 Tillage and residue cover management	10–97
10.8.3.4 Cropping systems	10–97
10.8.3.5 Weed, disease and pest management	10–98
10.8.4 User requirements for agrometeorological information	10–98
10.8.4.1 Use of agrometeorological data in simulation models and decision support systems	10–98
10.8.5 Examples of agrometeorological services relating to wheat	10–99
REFERENCES	10–100
CHAPTER 11. APPLICATIONS OF METEOROLOGY FOR FORESTRY AND NON-FOREST TREES . . .	11–1
11.1 Introduction	11–1
11.2 Climate and weather analysis for forestry and non-forest tree operations	11–1
11.2.1 Tree response to meteorological elements	11–1
11.2.1.1 Temperature	11–1
11.2.1.2 Radiation	11–2
11.2.1.3 Humidity and precipitation	11–3
11.2.1.4 Wind	11–5
11.2.1.5 Photoperiod	11–8
11.2.2 Pests and diseases in relation to weather	11–8
11.2.2.1 Moisture (humidity, dew, rain, snow, sleet)	11–9
11.2.2.2 Temperature	11–9
11.2.2.3 Radiation (light, day length, cloudiness, lightning)	11–10
11.2.2.4 Wind	11–10
11.2.2.5 Selected simulation models	11–10
11.2.3 Weather hazards to forest and non-forest trees	11–12
11.2.3.1 Snow and ice	11–12
11.2.3.2 Temperature extremes	11–13
11.2.3.3 Windthrow	11–13
11.2.3.4 Flooding	11–14
11.2.3.5 Other biophysical controls affecting forest growth	11–14
11.2.4 Tree nursery location and operation	11–16
11.2.4.1 Introduction	11–16
11.2.4.2 Location, design and equipment	11–16
11.2.4.3 Operations and management	11–17
11.2.5 Applications of meteorology and climatology for forestry and non-forest tree operations	11–18
11.2.6 Prescribed burning	11–20
11.2.7 Implications of climate change for forestry production	11–21
11.3 Meteorological observations for forestry applications	11–22

11.3.1	Measurement of wind and precipitation	11–22
11.3.1.1	Wind	11–22
11.3.1.2	Precipitation	11–22
11.3.2	Specialized observations for orchard pest and disease management	11–23
11.3.3	Specialized fire weather observations	11–24
11.3.3.1	Weather data for fire management	11–24
11.3.3.2	A specialized fire weather network	11–24
11.4.	Computer simulation models applied to forestry and non-forest trees.	11–24
11.4.1	Growth and production models	11–25
11.4.1.1	Canopy process models	11–25
11.4.1.2	Hydrological models.	11–26
11.4.1.3	Soil decomposition models.	11–27
11.4.1.4	Phenology models	11–28
11.4.1.5	Population models (single-tree, gap-phase dynamics).	11–28
11.4.1.6	Disturbance models	11–29
11.4.1.7	Biogeography models	11–30
11.4.1.8	Biodiversity and habitat models (including riparian systems).	11–31
11.4.1.9	Carbon budget models.	11–32
11.4.1.10	Applications to agroforestry and non-forest trees	11–32
11.4.2	Management models	11–33
11.4.2.1	Growth and yield models	11–33
11.4.2.2	Fire ecology and fuels management	11–34
11.4.2.3	Insect pest management	11–35
11.4.2.4	Storm damage control	11–35
11.4.2.5	Habitat, biodiversity management	11–35
11.4.2.6	Soil erosion assessment and control	11–35
11.4.2.7	Regeneration	11–35
11.4.2.8	Climate change impacts and adaptation.	11–35
11.4.3	Fire weather applications and models	11–36
11.4.3.1	Fire danger rating and fire behaviour prediction	11–36
11.4.3.2	An evolving fire danger rating system.	11–37
11.4.3.3	High-resolution fire danger rating.	11–37
11.4.3.4	Fire behaviour prediction	11–37
11.5	Fuel state assessment for forest, bush and grass fires.	11–38
11.5.1	Introduction	11–38
11.5.2	Weather-related elements	11–39
11.5.3	Grassland fuel state assessment	11–40
11.5.3.1	Growth of fuel	11–40
11.5.3.2	Initial measurement practices	11–42
11.5.3.3	Weighing methods.	11–42
11.5.3.4	Satellite-derived vegetation indices.	11–42
11.5.3.5	Use of fields of solar radiation.	11–43
11.5.3.6	Estimating dead fuel moisture	11–43
11.5.4	Forest fuel state assessment.	11–43
11.5.4.1	Keetch–Byram index.	11–43
11.5.4.2	Tasmanian soil dryness index	11–44
11.5.4.3	The Palmer index	11–44
11.5.4.4	Other methods.	11–44
11.5.5	Treatment of fuel state after precipitation	11–45
11.5.5.1	Grassland fuel moisture	11–45
11.5.5.2	Forest fuel moisture	11–45
11.5.6	Discussion of climate-based indices.	11–46
11.5.6.1	Historical perspective	11–47
11.5.6.2	Canadian system	11–47
11.5.6.3	United States system	11–48
11.5.6.4	Australian system	11–49
11.5.6.5	Comparison of fire danger rating systems.	11–51

	<i>Page</i>
11.5.7 Phenomena associated with fires	11–51
11.5.7.1 Curing of fuel by radiation from ongoing fires	11–51
11.5.7.2 Topography	11–51
11.5.7.3 Spotting and low-level jet streams	11–52
11.5.7.4 Fire whirlwinds	11–52
11.5.7.5 Smoke production and smoke management	11–53
11.5.8 Conclusion	11–54
REFERENCES	11–55
CHAPTER 12. WEATHER AND CLIMATE AND ANIMAL PRODUCTION	12–1
12.1 Introduction	12–1
12.1.1 Background	12–1
12.1.2 Applications of biometeorological information for rational planning, design and management	12–3
12.1.2.1 Characterization of the environment	12–3
12.1.2.2 Characterization of farm animal performance	12–4
12.1.2.3 Decision-making	12–6
12.2 Applications for farmers	12–8
12.2.1 Animal traits and physiological responses	12–8
12.2.1.1 Traits	12–8
12.2.1.2 Response to stress	12–9
12.2.2 Reducing impacts of climate on livestock production	12–9
12.2.2.1 Site selection	12–10
12.2.2.2 Windbreaks	12–10
12.2.2.3 Shades	12–10
12.2.2.4 Partially or totally enclosed shelters	12–11
12.2.2.5 Genetic improvement for adaptation	12–12
12.2.3 Environmental modification	12–12
12.2.4 Forage and pasture	12–14
12.3 Reducing impacts of livestock production on climate	12–14
REFERENCES	12–16
CHAPTER 13. APPLICATION OF AGROMETEOROLOGY TO AQUACULTURE AND FISHERIES	13–1
13.1 Introduction	13–1
13.2 Capture fisheries	13–1
13.3 Aquaculture	13–1
13.3.1 Pond culture	13–2
13.3.2 Flow-through systems	13–2
13.3.3 Open-water culture methods	13–3
13.3.4 Water-reuse systems	13–3
13.4 Climate, weather and hydrology	13–4
13.4.1 Precipitation	13–4
13.4.2 Evaporation	13–4
13.4.3 Overland flow and runoff	13–5
13.4.4 Hydroclimate	13–6
13.4.5 Water budgets	13–7
13.5 Climate, weather and water quality	13–8
13.5.1 Solar radiation	13–8
13.5.2 Water temperature	13–12
13.5.3 Winterkill	13–15
13.5.4 Thermal stratification	13–15
13.5.5 Rainfall and water quality	13–18
13.5.6 Wind	13–19
13.5.7 Barometric pressure	13–21

13.6	Research needs	13–21
13.7	Application of agrometeorology	13–21
13.8	Education needs	13–22
REFERENCES		13–23
CHAPTER 14. AGROMETEOROLOGICAL ASPECTS OF DESERTIFICATION		14–1
14.1	Introduction: desertification and WMO	14–1
14.2	A global survey of desertification and its causes	14–2
14.2.1	Drylands	14–2
14.2.2	Causes of desertification	14–4
14.2.3	Distribution of areas affected by desertification and relative importance of causes	14–5
14.3	Dryland surface climate and agrometeorological practice	14–8
14.3.1	Understanding the dryland surface climate	14–8
14.3.1.1	Water in the surface environment	14–8
14.3.1.2	Energy in the surface environment	14–9
14.3.1.3	Momentum in the surface environment	14–9
14.3.2	Application of agrometeorological practices to the surface environment	14–10
14.4	Rangeland management	14–12
14.5	Measures of desertification and related techniques	14–14
14.6	Activities relating to drought and desertification	14–16
14.6.1	International activities: the role of WMO in the UNCCD and the United Nations International Strategy for Disaster Reduction	14–16
14.6.2	Meteorological observing networks and monitoring of drought and desertification	14–17
14.6.3	Research	14–17
14.6.4	Capacity-building and transfer of knowledge and technology	14–18
14.6.5	Application of agrometeorological science and methods	14–19
14.6.6	Drought preparedness and early warning systems	14–19
14.6.6.1	Role of WMO and drought preparedness	14–20
14.6.6.2	Early warning systems.	14–20
14.6.7	WMO, desertification and the future	14–22
REFERENCES		14–23
CHAPTER 15. AEROBIOLOGY		15–1
15.1	Introduction	15–1
15.2	Types of service to be provided to users	15–2
15.3	Data and models available for use by aerobiologists	15–2
15.3.1	Remote-sensing data.	15–3
15.3.2	Vertical mixing and dispersion models.	15–4
15.3.3	Additional data required	15–5
15.4	Scales on which to consider aerobiological problems	15–6
15.4.1	Microscale transport	15–6
15.4.2	Mesoscale transport	15–7
15.4.3	Macroscale transport	15–7
15.5	Examples of aerobiological modelling – spore transport	15–8
15.5.1	Production (<i>P</i>) of spores	15–8
15.5.2	Escape (<i>E</i>) of spores from the canopy	15–9
15.5.3	Turbulent transport (<i>T</i>) and dilution	15–10
15.5.4	Survival (<i>S</i>) of spores.	15–11
15.5.5	Deposition (<i>D</i>) of spores onto plants.	15–12
15.6	Air pollution	15–12
15.7	Special considerations for flying organisms	15–13
REFERENCES		14–14

	<i>Page</i>
CHAPTER 16. APPLICATIONS OF CLIMATIC RESOURCES IN MOUNTAINOUS REGIONS	16–1
16.1 Introduction	16–1
16.2 Why is the climate different in mountainous regions?	16–1
16.3 Meteorological variables in mountainous regions	16–3
16.3.1 Incoming solar radiation	16–3
16.3.1.1 Facing the sun	16–3
16.3.1.2 Atmospheric transmissivity	16–4
16.3.1.3 Beneficial use of knowledge on incoming solar radiation in mountains	16–4
16.3.2 Temperature	16–6
16.3.2.1 Temperature versus altitude	16–6
16.3.2.2 Frost events	16–6
16.3.2.3 Daily temperature range and thermoregulating agents.	16–8
16.3.2.4 Beneficial use of knowledge on mountain temperature	16–9
16.3.3 Rainfall	16–11
16.3.3.1 Rainfall processes in mountainous regions	16–11
16.3.3.2 Rainfall, altitude and orography	16–12
16.3.3.3 Monitoring rainfall in mountainous regions	16–14
16.3.3.4 Beneficial use of knowledge of rainfall in mountainous regions.	16–16
16.3.4 Atmospheric humidity and foehn effect	16–17
16.4 Application of knowledge about spatio-temporal climate variability in mountainous regions	16–19
16.4.1 Influence of climate on soil formation: A case study	16–19
16.4.2 Soil erosion in mountains: a case study	16–22
16.5 Risk associated with mountain climatic resources	16–26
16.6 Conclusions	16–28
REFERENCES	16–29
CHAPTER 17. COMMUNICATING AGROCLIMATOLOGICAL INFORMATION, INCLUDING FORECASTS, FOR AGRICULTURAL DECISIONS.	17–1
17.1 Introduction	17–1
17.2 Use of climate information in agriculture: framing the decision problem.	17–1
17.2.1 Communication channels	17–3
17.2.2 Capacity development for effective communication	17–4
17.3 Experience from extension services: key lessons	17–5
17.3.1 The Climate Field School concept: setting the context for effective communication.	17–6
17.3.2 The necessity of training the trainers.	17–7
17.3.3 Off-farm planning and decision-making	17–8
17.3.4 Linking the decision-making calendar to the agroclimatic calendar: seasonality of climate, practices and decision-making inputs	17–8
17.4 Conclusions	17–9
ANNEX – Climate Field School programme	17–12
REFERENCES	17–13
APPENDIX I - BIBLIOGRAPHY OF LITERATURE ON AGRICULTURAL METEOROLOGY	App-I
APPENDIX II - LIST OF PERIODICALS OF INTEREST TO AGRICULTURAL METEOROLOGISTS	App-II
APPENDIX III - LIST OF INTERNATIONAL ORGANIZATIONS OF INTEREST TO AGRICULTURAL METEOROLOGISTS	App-III
APPENDIX IV - LIST OF AGRICULTURAL METEOROLOGICAL SOCIETIES	App-IV

PREFACE

The standardization of meteorological observations and the uniform publication of observations and statistics are among the functions of the World Meteorological Organization, as stated in the WMO Convention. In accordance with these objectives, the World Meteorological Congress has adopted from time to time Technical Regulations that specify meteorological practices and procedures to be followed by the Member countries of the Organization. These Technical Regulations are supplemented by a number of Guides, which describe in more detail the practices, procedures and specifications that Members are invited to follow and implement in establishing and conducting their arrangements for compliance with the Technical Regulations and in otherwise developing meteorological services in their respective countries.

In 1999, during the twelfth session of the Commission for Agricultural Meteorology (CAgM) in Accra, Ghana, the Commission endorsed the idea proposed by C.J. Stigter, then president of the Commission, calling for a complete revision of the *Guide to Agricultural Meteorological Practices*. The Commission agreed that the new Guide should be more operational than previous editions. It was decided that a special Steering Committee of Experts would be established to assist the president in revising the Guide. Its members were C.J. Stigter (the Netherlands), who served as Coordinator, A. Khamidula Abdullaev (Uzbekistan), Wolfgang Baier (Canada), Mohamed M. Eissa (Egypt), P. Kozhakhmetov (Kazakhstan), Elijah Mukhala (Zambia) and Si Giai Ngo (Vietnam).

This team approved a draft discussion paper on the revised edition prepared by the coordinator and based on the previous decisions taken in Accra. The paper was approved by the CAgM Advisory Working Group in 2001 and was revised several times. It was then used as the basis for the rewriting process. At the thirteenth session of the Commission for Agricultural Meteorology, held

in Ljubljana, Slovenia, in 2002, the Commission endorsed the approach in the discussion paper and decided on the establishment of an Expert Team on the *Guide to Agricultural Meteorological Practices*. Its members were C.J. Stigter (Lead), H.P. Das (India), Anice Garcia (Brazil), Vasiraju R.K. Murthy (India), Byong Lee (Republic of Korea) and Robert Stefanski (WMO). This Expert Team met in 2005 and aided the coordinator in finding authors and contributors for several chapters. During the next several years, the draft chapters were completed and were posted on the International Society for Agricultural Meteorology Website (www.agrometeorology.org) and on the WMO Agricultural Meteorology Programme Website (www.wmo.int/agm). These drafts were publicly available while the final editing of the complete Guide progressed.

At the 2010 meeting of the CAgM Management Group in Geneva, it was decided that the Guide would conform to the new WMO publishing standards. This meant that there would no longer be sequential editions (second, third, fourth, and so on). Each edition would instead be denoted by year of release. Therefore the revised third edition is now the 2010 edition of the Guide. This new edition is being released only on CD and online. Any developing country may request a printed version of the Guide from the WMO Secretariat. In accordance with the new WMO publishing standards, an official print edition will no longer exist as such.

It follows from the decisions of Congress that this publication is by no means a textbook on agricultural meteorology. References to such textbooks and WMO publications on agricultural meteorology are given in an appendix to this Guide. A list of journals that publish papers on agricultural meteorology is also provided, as is a list of international organizations of interest to agricultural meteorologists. The principal aim of the *Guide to Agricultural Meteorological Practices* is to provide, in a convenient form, information

regarding the practices and procedures that are of the greatest importance in agricultural meteorology.

The Organization would like to express its gratitude to all those Meteorological Services, technical commissions, expert teams and individuals who have contributed to the present publication.

It is not possible to mention them all by name, but a special word of thanks must be addressed to C.J. Stigter, lead coordinator of the revision of this Guide, for his untiring efforts in the preparation of the publication, and to the members of the Expert Teams on the *Guide to Agricultural Meteorological Practices* for their valuable contributions.

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CHAPTER 1

GENERAL

1.1 SCOPE OF AGRICULTURAL METEOROLOGY

Agricultural meteorology is concerned with the meteorological, hydrological, pedological and biological factors that affect agricultural production and with the interaction between agriculture and the environment. Its objectives are to elucidate these effects and to assist farmers in preparing themselves by applying this supportive knowledge and information in agrometeorological practices and through agrometeorological services.

Certain parts of Chapter 1 discuss the above issues and the essential literature listed in Appendix I of this Guide illustrates these issues. Agricultural meteorology of land surfaces extends from the soil layer of the deepest plant and tree roots (pedosphere), through the air layer near the ground in which crops and trees grow and animals live (which is discussed in Chapters 9–12 of this Guide), to the higher levels of the atmosphere in which processes such as the transport and dispersal of dust, seeds and pollen take place (Chapters 14 and 15). Its fields of interest range from agricultural production, including horticulture (Chapters 9 and 10), forestry (Chapter 11), animal husbandry (Chapter 12), fisheries (Chapter 13) and other forms of outdoor production (for example, Chapter 16) and indoor production (Chapter 9), agricultural planning (Chapters 5–7 and 17), processing, transport and storage (with examples in various chapters) to the agrometeorological components of food security (Chapters 6–8 and 14), poverty reduction and the sustainable development aspects of the livelihood of farmers/producers (other parts of Chapter 1, Chapter 17) and the use of their products (for example, Chapters 6 and 9). Many other chapters elaborate on these fields as they review specific subjects in more depth.

In addition to large and mesoscale climate characteristics and their variations (for example, Chapters 5 and 8), operational agricultural meteorology concerns itself with small-scale climate modifications as brought about by windbreaks, irrigation, mulching, shading, and frost and hail protection, for example (Chapters 7 and 9). Other important subjects are agroclimatic characterization (for example, Chapters 5, 9 and 14), pests

and diseases and their safe control (Chapters 7, 9 and 12), covered agriculture (Chapter 9), quality of agricultural products (Chapter 9), animal comfort aspects (Chapter 12), plant cultivation for purposes other than the production of food, such as biomass as a renewable energy resource (Chapter 10), and ecological considerations (for example, Chapters 7 and 16). Much attention is paid to the impacts of climate change and climate variability and how to prepare for them (Chapters 5–8 and 17), including phenological aspects (Chapter 6), monitoring (Chapters 4 and 14), early warning (Chapters 4–8), and estimation of changes in the risks relating to pests, diseases and extreme events such as drought, desertification and flooding (Chapters 7–9, 14 and 15).

While intensive agriculture affects the environment through the generation of air, soil and water pollutants, greenhouse gases (CO₂, methane and nitrous oxide), ammonia, and tropospheric ozone, specialized agriculture, such as monocropping over large areas, can be inimical to biodiversity. Other modes of production cause soil erosion by wind and water. Thus, agricultural meteorology has a major role to play in understanding emissions and pollution from unsustainable production systems (Chapters 7, 14, 15). Water management to ensure adequate supplies while maintaining the quality of surface sources and groundwater is a key topic (Chapters 8, 10). Applications to aquaculture and fisheries (food aspects, Chapter 13) range from site climatology, hydrodynamics of rivers and reservoirs, estimation of contamination from agricultural runoff and other ecosystem stresses, to using meteorological factors to predict the occurrence of toxic algal blooms.

Support systems for agrometeorological practices and services comprise data (and therefore quantification, details in Chapters 2–4), research (Chapters 10–16), training, education and extension (Chapters 1 and 17), and policy environments (for example, section 1.4). Mathematical models are increasingly used, especially in industrialized countries, in operational agricultural meteorology (for example, Chapters 6 and 11) in conjunction with Geographical Information Systems (GISs, Chapter 4) to provide inputs to Decision Support Systems (DSSs, also Chapter 17). These models have relied on meteorological observations (Chapters 2–4) but now also

benefit from operational numerical weather predictions and climate predictions (Chapters 5 and 8). These forecasts may be exploited to increase the utility of models for decision-makers (Chapters 5 and 6), although this remains extremely difficult in practice (Chapter 17). Remote-sensing provides access to additional biophysical parameters, such as vegetation indices and surface temperatures. Incorporation of these data into models is being undertaken (Chapters 4 and 6). The enormous potential of agrometeorological information and services (Chapter 17) underscores the great importance of training farmers and environmental managers in the use of agrometeorological practices and services (section 1.4).

In this Guide there is overlap among various chapters: this is intentional, as some subjects are considered each time from the different perspectives of the individual chapters. In contrast to the previous edition of this Guide, emphasis here is not so much on basic agrometeorological sciences, but rather on preparation for agrometeorological services and information for decision-makers (Stigter, 2007).

This Guide presents a selection of agricultural meteorological practices that lie within the scope outlined above and it is the outcome of the choices made by agrometeorological volunteers who collaborated in coordinating, writing and reviewing drafts under the guidance of the Expert Team of the Commission for Agricultural Meteorology (CAgM), whose members were charged with overseeing the present publication. Details on the scope of agrometeorology and its applications can be found in Sivakumar et al. (2000*b*) and Salinger et al. (2005).

1.2 **IMPORTANCE OF AGRICULTURAL METEOROLOGY**

There is hardly another branch of human activities that is as dependent on the weather as agriculture is. Agricultural production is still largely dependent on weather and climate, despite the impressive advances in agricultural technology over the last half a century. More than ever, agrometeorological services have become essential because of the challenges to many forms of agricultural production posed by increasing climate variability, associated extreme events and climate change. These challenges have repercussions in terms of socio-economic conditions in general, especially in developing countries.

1.2.1 **General importance**

Knowledge of available environmental resources and the interactions that occur in the area below the soil surface, the soil–air interface and the boundary layer of the atmosphere provides essential guidance for strategic agrometeorological decisions in long-range planning of agricultural systems. This applies to both favourable and unfavourable conditions – and these may vary a great deal. Typical examples are the design of irrigation and drainage schemes, decisions relating to land-use and farming patterns, and within these choices, selections of crops and animals, varieties and breeds, and farm machinery.

In modern agriculture, ecology and economy are on equal terms; through environmental issues they are even interdependent. Shortages of resources, destruction of ecological systems and other environmental issues are becoming ever more serious. The large-scale and uncontrolled use of chemical fertilizers and plant protection products is not only a burden on the environment, but quite considerably, on the farmer's budget as well.

Detailed observations/monitoring and real-time dissemination of meteorological information, quantification by remote-sensing (radar and satellites), and derived indices and operational services are important for tactical agrometeorological decisions in the short-term planning of agricultural operations at different growth stages. The well-organized, and where possible, automatic production and coordinated dissemination of this information and related advisories and services are essential. Tactical decisions include “average cost”-type decisions in sustainable agriculture with low external inputs, regarding timing of cultural practices, such as ploughing, sowing/planting, mulching, weeding, thinning, pruning and harvesting. They also include, particularly for high-input agriculture, “high cost”-type decisions, such as the application of water and extensive chemicals and the implementation of costly crop protection measures.

Regardless of the type of decision, an ever-improving understanding of the effects of weather and climate on soils, plants, animals, trees and related production in farming systems is necessary for decision-makers (farmers and managers) to ensure timely and efficient use of meteorological and climatological information and of agrometeorological services for agriculture. To these ends, choices have to be made regarding the right mixture and blending of traditional adaptation strategies,

contemporary knowledge in science and technology, and appropriate policy environments. Without policy support systems for agrometeorological services, yields with the available production means will remain below optimal (section 1.4).

1.2.2 Applications

The practical application of this knowledge is linked to the availability and accuracy of weather and climate forecasts or expected weather and climate patterns, depending on the timescale. The requirements range from accurate details of short-range weather forecasts (less than two days), to medium-range forecasts (less than 10 days) at certain critical times, to seasonal predictions of climate patterns. Development plans should not be rendered meaningless by a significant change in weather and climate behaviour. Therefore, indications of possible climatic variability and of increasingly frequent and serious extreme events in the context of global climate change are necessary within the framework of agrometeorological services, in addition to the application of other agrometeorological information.

Reliable long-term weather forecasts relevant to the agricultural community are not yet available on a routine basis all over the world. Significant services may be provided by means of agrometeorological forecasts, however, such as the dates of phenological events, the quantity and quality of crop yields, and the occurrence of animal and crop epidemics. These forecasts make use of established relationships between weather effects at an early stage of development and the final event that is expected some time after the date of issue of the forecast. This approach of “crop prediction without weather forecasting” is particularly promising for the assessment of crop conditions so that potential production anomalies may be recognized and quantitatively evaluated as early as possible. Surpluses and deficits are organized in long-term planning or occur nationally, regionally and globally. Long-term planning of global food production must therefore take into account the effects of year-to-year fluctuations in weather patterns and of potential climatic variabilities and changes on crop yields.

The global climate is influenced by a wide range of factors. Two of the most important components are CO₂ and water vapour in the atmosphere. In addition to the oceans, forests absorb CO₂ and release water vapour. Burning forests produce considerable masses of CO₂. So it is necessary to promote reforestation and to protect forests against fire and human activity, as well as against other destruction,

such as by insects, diseases and pollutants. Forest meteorology as a component of agrometeorology provides useful information and services that can be applied by forest authorities, foresters and in the event of forest fires, by fire brigades. Various reliable methods for forecasting probabilities of the start and spread of forest fires were developed around the world and are now in operational use.

Agrometeorological services in developing countries have to shoulder heavier responsibilities because of greater population pressure and changing modes of agricultural practices. In the future, more and more demands for agrometeorological information and services are expected from farming communities with regard to technologies, farming systems and patterns, water management, and weather-based pest and disease control, preferably with local innovations as starting points. Thus, future challenges will include the necessity to emphasize a bottom-up approach to ensure that forecasts, specific advisories and contingency planning reach even the small farmers, so that they are able to apply this information in their planning and day-to-day agricultural operations.

Agrometeorological services in developed countries focus on the provision of environmental data and information to national policy- and decision-makers in support of sustained food production, sustainable development, carbon sequestration in agroecosystems, and land management practices that affect the exchange processes of greenhouse gases. Because developed countries may have or develop technology to initially adapt more readily to climate change and climate variability, transfer of technology may play a certain role. Nonetheless, local innovations remain most important for application under the very different conditions found in developing countries. At present, organizations such as the WMO Commission for Agricultural Meteorology, the Food and Agriculture Organization of the United Nations (FAO) and the International Society for Agricultural Meteorology (INSAM) are playing an active role, and will have to play an increasing role, in stimulating the development and establishment of agrometeorological services and in disseminating agrometeorological information.

Advisories in drier climates include, inter alia, information at various temporal and spatial scales on the average sowing date, as well as expected sowing dates for the current season, and on operational crop protection of all kinds. In more humid climates, information on pest and disease attacks is also provided. These advisories are all based on

weather information and agrometeorological services in location-specific and user-friendly format. Other examples of important advisory fields that require attention are:

- (a) Management and modification of micro-climate;
- (b) Preparation for environmental risk and disaster mitigation to increase protection and lower vulnerabilities;
- (c) Prediction of El Niño and other rainfall variability for agricultural planning;
- (d) Information on weather-based applications of pesticides and insecticides;
- (e) Meteorological information for planning, scheduling and guiding irrigation and drainage;
- (f) Aerial transport of pollutants and knowledge regarding low-level winds for operational activities;
- (g) Work day probabilities (for instance, in planning and scheduling soil cultivation or marine and lake fishing);
- (h) Agrometeorological services for farmers at the regional level to strengthen and provide accurate forecasts and advisories for the farming community;
- (i) Communication of information in a format/language understandable to users;
- (j) Highland and mountain agriculture.

In more advanced agricultural production with a potential for technology transfer and where the capacity for adoption exists, the following may be added:

- (a) Crop weather modelling with a special emphasis on crop growth simulation models;
- (b) Development of complex data collection systems and speedy processing and interpretation of large spatial data collections;
- (c) Geographical Information Systems and their use for crop planning at scales smaller than those presently applied;
- (d) The use of remote-sensing technologies to generate information/advisories for large areas;
- (e) Quantification of carbon sequestration;
- (f) Use of audio-visual media and Internet facilities for quick dissemination of information to users.

Forecasts of significant meteorological phenomena that lead to the issuing of advisories and warnings with sufficiently long lead times are of tremendous value. Early warnings against natural disasters not only help to save crops or reduce crop damage by allowing for quick strategic planning, but they also enable farmers to advance or postpone agricultural

operations as needed. Dissemination of such warnings to the end-users on a real-time basis with the help of electronic media may become a key factor for crop production and protection.

1.2.3 Conditions and requirements

The effects of climate change on streamflow and groundwater recharge are expected to follow projected changes in precipitation. The projected climate change could further decrease the streamflow and groundwater recharge in many water-stressed countries. On the other hand, the demand for sharing of water is likely to increase in industries and municipal areas, owing to population growth and economic development. This is likely to affect irrigation withdrawals, which depend on how increases in evaporation are offset by changes in precipitation. Higher temperatures leading to higher evaporative demand would cause an increase in irrigation demand in many countries.

Crop growth simulation assessments indicate that under dryland/rainfed agriculture, the yield of some crops in tropical locations would decrease generally, even with a minimal increase in temperature. Where there is also a large decline in rainfall, the impact on tropical crop yields would be even more adverse. Some studies indicate that climate change would lower income among vulnerable populations and increase the absolute number of people at risk of hunger. Climate change, mainly through increased extremes and temporal/spatial shifts, would worsen food security in some parts of the globe.

The economic value of weather information products is steadily increasing as a result of rising public awareness over the years. Facilities for data quantity and quality control, quick processing and analysis have made this possible. While the generation of information and the issuing of products to the farming community on a real-time basis for socio-economic activities are now possible, these services need to be organized. Though much still needs to be done, various specific agrometeorological requirements are beginning to be addressed. They are as follows:

- (a) Agroclimatology for land-use planning and crop zonation;
- (b) Operational crop monitoring and agrometeorological practices based on output of crop growth simulation models;
- (c) Rainfall reliability statistics with respect to planting dates (date of sowing) and crop calendars;
- (d) Weather requirements for crops and input applications;

- (e) Forecasting and management strategies for droughts and floods;
- (f) Some pest and disease monitoring and operational crop protection using weather-based warning models;
- (g) Microclimatic management and manipulation.

Agrometeorological services in the form of technology recommendations appropriate at the field level are often required for decision-making processes of farmers. Limits imposed by the availability of production resources can be well understood by using:

- (a) Geographical Information Systems for easy information retrieval and updating purposes;
- (b) Delineation of agrometeorological zones using environmental resource information;
- (c) National-level planning with expected production outputs;
- (d) Information on crop management, such as cropping pattern, fertilizers, sowing/planting time, and so on.

Regardless of the distribution of favourable or unfavourable weather events around the globe, there remain, in the long run, insufficient food supplies to feed the world's population adequately at its present rate of increase. This can be changed only when agricultural technology is greatly improved, natural resources are more efficiently used, and national and international agencies responsible for planning and managing food supplies are provided with up-to-date information on crop conditions and potential crop failures as a basis for their decision-making.

The major role of present-day agricultural meteorology on a global scale is therefore to ensure that, under appropriate support systems, adequate and useful agrometeorological data, research tools and training are available to agrometeorologists and that relevant agrometeorological services are at the disposal of planners and decision-makers, in particular farmers, to help them cope with a variety of agricultural production problems. Local and regional organizations that are assuming their local parts in this role should find international organizations such as WMO/CAGM, FAO and INSAM ready to guide them in these matters. Recently adopted structures and new initiatives in agrometeorology are intended to make this increasingly possible.

This section was conceived and reviewed bearing in mind the long years of experience in agrometeorology of both the contributors and the reviewers. Because this Guide is not intended to serve as a

textbook, the inclusion of general or specific references did not seem warranted at this introductory stage. Readers who wish to find more general introductions to all aspects of agricultural meteorology are referred to the literature in Appendix I. An agrometeorological core library, selected relevant WMO publications and references to a didactically balanced text in agrometeorology are given in WMO (2001). Please also refer to Annex 1.C of this chapter, which outlines a basic syllabus in agrometeorology.

1.3

ROLE OF THE COMMISSION FOR AGRICULTURAL METEOROLOGY

The Commission for Agricultural Meteorology is one of the eight technical commissions of the World Meteorological Organization, a specialized agency of the United Nations. For additional background on the Commission, readers are referred to the WMO Basic Documents and the current WMO Annual Report. A short history of CAGM, which provides further insights into the workings of this body, has recently been issued (WMO, 2006a).

The definition of the role of CAGM, presented as a "Statement of Need" in a CAGM vision document of 1999, is "to promote agrometeorology and agrometeorological applications for efficient, sustainable food, fodder and fibre production for an increasing world population in fastly changing environments". CAGM encourages its Members to supply all needed agrometeorological services, such as agrometeorological advisories and relevant forecasts, to the agricultural communities to support improved planning and operational activities.

The CAGM Terms of Reference (Annex 1.A) have not been modified, in contrast to the trend in the other technical commissions of WMO. At the tenth session of the Commission in Florence (1991) and at the eleventh session in Havana (1995), it was explicitly decided to leave the Terms of Reference unchanged. In Havana it was proposed that the Commission give indications regarding their interpretation under new conditions at that session and at each future one. Subsequently, the CAGM Advisory Working Group put forward the vision document entitled "CAGM, Towards 2000 and Beyond", which was endorsed by the twelfth session of the Commission in Accra (1999) and the Thirteenth World Meteorological Congress in Geneva (1999). The Terms of Reference of the Commission were to be considered in the context of the "Statement of Need".

At each CAgM session, the actualization of these broad Terms of Reference is in the establishment of the contents of the working structure. The twelfth session of the Commission was the last meeting at which Working Groups and (joint) Rapporteurs were nominated for the various topics. A new working structure was decided on at the thirteenth session of the Commission in Ljubljana (2002) based on Open Programme Area Groups (OPAGs), Implementation/Coordination Teams and Expert Teams. Their new and comprehensive structure, contents and composition can be viewed on the CAgM Website. They were brought into operation to meet the new conditions in agrometeorology at the beginning of this new century, but still within the same guiding framework of the broad original Terms of Reference. The new structure mirrors the following continuing trends: more regional representation, strengthened links to the regional associations and increasing participation of experts from developing countries.

The responsibilities of CAgM are clearly defined in its Terms of Reference (Annex 1.A), established by the World Meteorological Congress and updated within the framework of Agrometeorology in the 21st Century – Needs and Perspectives, a 1999 WMO/CAgM international workshop in Accra. According to these terms, the Commission is responsible for the development of agrometeorological services of Members. The transfer of information to the agricultural communities should lead to the most practical use of knowledge concerning weather and climate for agricultural purposes. Use can be made of the most suitable products from what in Accra were called agrometeorological support systems in the fields of data, research, education/training/extension and policies. The trends within the Commission's role, towards more emphasis on applications of research results and on operational services to agriculture, as indicated in the previous issue of this Guide, have been increasingly strengthened over the past two decades.

To further exemplify CAgM's responsibilities, the 2002 WMO/CAgM Workshop in Ljubljana considered the topic "Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Change". Intensive discussions took place on combating and mitigating increasingly severe natural disasters, and adaptations to their occurrences. It was concluded that in many countries the present conditions of agriculture and forestry are already marginal, due to degradation of natural resources, the use of unadapted technologies and other stresses. Developed countries have the technology to adapt more readily to the projected climate changes, although shifts

in cropping patterns can be disruptive. The ability to adapt is more problematic in the tropics and subtropics and in countries in transition.

The Open Programme Area Groups were established in the new CAgM structure in response to these changing priorities in three new key areas of the WMO Agricultural Meteorological Programme:

- (a) Agrometeorological services for agricultural production;
- (b) Support systems for agrometeorological services;
- (c) Climate change/variability and natural disasters in agriculture.

The remaining priority issues of agrometeorological education, training and extension, and of support systems in policymaking for agrometeorological services, will be taken up throughout these key areas. Separate coordinators have been appointed in the CAgM Management Group for these priority issues. The use and applications of such an approach should also lead to reduced costs and greater efficiency in the consumption of water, labour, energy and other inputs.

Important challenges for the role of the Commission remain:

- (a) To raise the interest and involvement of National Meteorological and Hydrological Services (NMHSs) in agricultural meteorology;
- (b) To strengthen contacts and cooperation with relevant staff of agricultural ministries, agricultural research institutes, agricultural planning bodies, and so forth, working as teams with intermediaries between applied science and farmers whenever needed and possible;
- (c) To strengthen the orientation of agrometeorology towards clients and their needs;
- (d) To fill the gaps between the providers of agrometeorological products and the actual agrometeorological services to improve the livelihood of farmers.

In the context of these challenges, the Commission should pay attention in the very near future to policies on training and equipping extension intermediaries in agricultural meteorology in developing countries. In this way, it may be possible to avoid mistakes made in agricultural extension in a number of developing countries that tried to use provincial agrometeorologists and agricultural demonstrators who were not sufficiently trained and equipped. In this respect, the role of the Commission will primarily be to advise on policies relating to the training of such intermediaries. More generally, it will be to assist in the transfer and

adaptation of actual agrometeorological services that these intermediaries can apply to make a difference in the livelihood of the majority of farmers who have not yet been reached.

1.4 TOOLS AND MECHANISMS IN AGRICULTURAL METEOROLOGY

For the planning of programmes for agrometeorological services, and supporting the decisions and actions of producers and related training (section 1.5) and cooperation (section 1.6), it is important to recognize two basic challenges (also section 1.6). These are:

- (a) To understand the ways in which agrometeorological support systems and agrometeorological services are related (mechanisms);
- (b) To understand the wide spectrum of problems encountered and decisions to be taken in agricultural production in relation to weather and climate for which such services should be developed.

This can only be done by using the available tools as operationally as possible. To that end it must be clearly understood that agrometeorological information and services for governments and private organizations are different from those that were developed, or need to be developed, directly for and/or by various groups of farmers.

1.4.1 Diagnostic and conceptual framework (operational link between support systems and services)

A representation of the relationship expressed under (a) above was derived from the recognition of a factual separation between agrometeorological services and agrometeorological support systems (Stigter et al., 2000). This was obtained from papers presented at the 1999 WMO/CAGM Workshop in Accra on Agrometeorology in the 21st Century: Needs and Perspectives (Sivakumar et al., 2000b). Figure 1.1 depicts a simple diagnostic and conceptual framework (as named by Daniel Murdiyarso) that was developed to describe this relationship. It consists of three domains (WMO, 2004; Stigter, 2005, 2007; Stigter et al., 2005a). The first domain (A) is that of the livelihood of farmers, in which the actual services supporting actions of producers (E2 guidance) have to be operated. The second domain is that of the selection/collection and combination of knowledge (B) actually to be used to derive and establish

the agrometeorological services (E2). The third domain (C) is that of the basic agrometeorological support systems.

The separation between agrometeorological services and agrometeorological support systems was illustrated by interposition of a B-domain to further increase the operational character of applied agrometeorology (Stigter, 2003a, 2007). This B-domain was positioned between an A-domain of the livelihood of farmers, in which operational agrometeorological services have to be established, and a C-domain of agrometeorological support systems.

The B-domain contains the initial and boundary conditions for solving the problems mentioned under (b) above that exist in the A-domain. It is suggested that the B-domain should have three components:

- (a) Improved (traditional indigenous) adaptation strategies based on farmer innovations;
- (b) Functionally selected contemporary science and technology;
- (c) An understanding of prevailing policy environments.

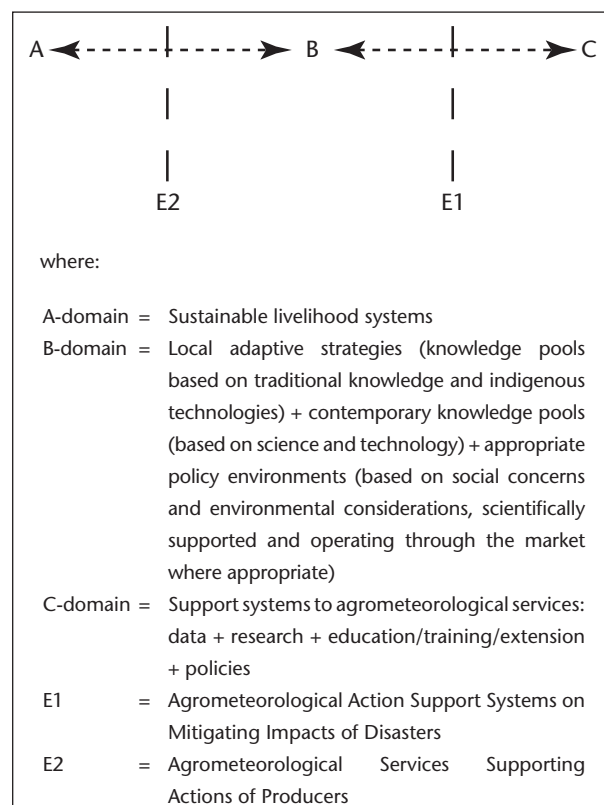


Figure 1.1. A simple diagnostic and conceptual framework picturing generation and transfer of agrometeorological information in an "end-to-end" system from basic support systems to the livelihood of famers

These components may be supposed to form the operational building blocks of agrometeorological services. If one of these components is incomplete, this will jeopardize the mechanisms of establishing operational agrometeorological services (E2) that can make a difference in the A-domain, the livelihood of farmers (Stigter, 2005).

Because farming with low external inputs in developing countries is most vulnerable, and because generally less formally educated and more marginal and poorer farmers are found there, the problems of farming systems in such regions need major attention. In addition, higher-input farming in industrialized countries constantly has to find new adaptation strategies, which require local and global support systems and policies. Such differences among various groups of farmers in industrialized, highly urbanized countries and slowly urbanizing, slowly industrializing regions call for considerable differences in approaches (Stigter, 2005). The spectra of problems encountered relating to weather and climate are very different.

Support systems to agrometeorological services (C-domain), which contain the basic support systems, embrace areas in which agricultural meteorology is best developed. From the beginning, four types of support were identified: (basic) data, research, training/education/extension and policies (Stigter et al., 2000). Utilizing their wide possibilities, an initial increase in the operational use of the support systems in applied agrometeorology provided what may be summarized as “agrometeorological action support systems on mitigating impacts of disasters” (E1). These are the early scientific/technological tools developed for problem-solving in agrometeorology. Disasters are understood here as all weather- and climate-related events that have a strong negative impact on yields (quantity and quality) and/or on the income of farmers.

Following the discussion of the mechanisms provided above, some of these important agrometeorological tools are introduced below. Some problem areas tackled by these systems to mitigate the impacts of disasters, and the operational limitations encountered in those areas, are also addressed. These will be dealt with extensively in the remainder of this Guide as well. This, however, already shows and supports the need for another increase in the operational use of tools, in the B-domain, leading to the much wider establishment of actual agrometeorological services directly supporting decisions/actions of farmers in the A-domain.

1.4.2

Agrometeorological research (basic, applied and derived operational research as tools)

Basic research in agricultural meteorology is an important part of the group of basic support systems of the C-domain. Applied agrometeorological research has played an important role in developing many of the other (E1) supportive tools that will be discussed further below. The acknowledgement of the existence of a B-domain, however, and the recognition of the realities of the A-domain, in which agrometeorological services have to be made supportive of the actions of producers (E2), mean that it is necessary to characterize another class, of “derived operational” research, as well. In the B-domain this operational research stems from the necessity to constructively bring together and use the three building blocks of agrometeorological services. In the establishment of supportive agrometeorological services in the A-domain, this research is derived from the necessity to render such services operational for the benefit of and with the farmer communities concerned, with a view to better preparing them for disasters.

Many suitable research findings or products based on such findings are not transferred at all to the farmer's field through extension (Stigter, 1999). Too many of the products of research lie idle and will never be used supportively (Sivakumar et al., 2000b). Agrometeorological research as a support system particularly needs constant regional, national and local prioritization. As long as farmers do not get their needs addressed by extension services based on research output, however, the latter remains limited to E1 support systems only (WMO, 2006b). The Accra symposium derived the following research needs (Stigter et al., 2000):

- (a) Efficiencies in the use and management of resources, including the whole production environment: climate, water, light, nutrients, space (above and below the soil surface), germplasm, biomass;
- (b) Research on agrometeorological aspects of management in agriculture at different scales for different purposes;
- (c) Validation and application of models (for example, phenology, morphological predictions, yields), limitations of models, models for specific users;
- (d) Research methods and approaches at the ecoregional level, including the assessment of socio-economic effects of weather/climate variability on food production;
- (e) Determination of the impact of climate change/variability and matters of climate forecasting and prediction in general;

- (f) Research on reducing the impact of natural disasters (including pests and diseases and anthropogenic hazards);
- (g) Consideration of ways to ensure that results of research are adopted by farmers: holistic, interdisciplinary field studies, of sufficient duration and coordination, on the operational scale;
- (h) Natural climate variability.

The present Guide aims to show how much in each of the above areas is currently being addressed and to what extent present research trends should be changed so that they are better aligned with the needs highlighted in Accra. The topics listed above also confirm the necessity of more research work in the B-domain and the A-domain. It has been suggested that a database of sound and dependable supportive (“derived”) research results should be developed by agrometeorologists in various application fields. Ongoing research programmes may have to be recast by taking a much more functional view of the problems and priorities for developing and organizing operational agrometeorological services for specific farming systems (WMO, 2006b).

1.4.3 **Primary research tools (data, quantification, statistics, indices and modelling)**

The availability of adequate and quantitative agrometeorological data is an absolute prerequisite for analysing, researching and managing production processes in agriculture, including livestock and forestry operations. The observation of meteorological conditions of importance in agricultural production encompasses physical measurements, from the upper-level recordings of radiosonde equipment to the soil surface and then some depth below it, where nutrient movements towards root systems occur. Recent advances in communication and computer technologies have allowed the establishment of measuring systems at different geographic scales, such as experimental fields, farms, cropping areas, administrative or ecoclimatic regions, and countries.

Quantification by physical methods is the basis for researching and understanding processes that explain phenomena determining growth, development and yields of important plant and animal species in agriculture. When the extent of measurements is limited, agrometeorological indices are a first attempt to relate phenomena like drought or erosion (semi-)empirically to such observations. A limited research approach to understand which factors are most involved in phenomena that are

occurring is the use of more complex statistics beyond the classical statistics of data adequately sampled in space and time.

When cause and effect relationships are better known, mechanistic modelling assembles such knowledge to provide mathematical representations of the processes involved, while still using empirical values for parameters and even empirical representations of sub-processes wherever necessary, to simulate phenomena, but error analyses are often weak (for example, Monteith, 2000). Unfortunately, even these days, statistics are still relied upon too frequently in many fields of agricultural research and the principles and advantages of the tools of the physical approach, also outside modelling, are insufficiently recognized and applied.

In many poorer countries, agrometeorological observations remain grossly inadequate and are still a major concern as well as a limiting factor for operational purposes, but improvements have been made in quantifications in general (see Chapter 2). New low-cost and reliable networks, including automatic ones, form the core of many private networks in urbanized industrialized countries, supplementing the networks supported by NMHSs. Archiving, retrieval and display systems are also rapidly improving there and provide essential links between those who collect observations and the larger communities that can understand and utilize them.

Long-term, good-quality and parallel climate and agricultural records are necessary as tools for agrometeorological research and services. Data collection and management should continuously be the focus for improving and maintaining good agrometeorological services and information. Processing, quality control, archiving and timely access are other components that add value to agrometeorological data for research and direct applications. This applies equally to classical routine data and to more specific data from within agricultural environments and specific agroecosystems.

1.4.4 **Agrometeorological monitoring and early warning (tools for warning using preparedness strategies)**

The observation and measurement of agrometeorological parameters with sufficient density in time and space have created monitoring systems that can be used as tools to follow developments and, where necessary, issue warnings. From observing the phenology of crops through to using satellite-acquired data, it may be possible

to gain adequate insights on conditions in the agricultural environment as a result of continuous monitoring. Remote-sensing (RS) techniques are playing an ever-increasing role in local and global monitoring systems. This trend is expected to continue following the launch of new satellite platforms – for example, the MeteoSat Second Generation applications, with enhanced capability in the area of environmental monitoring.

Geographical Information Systems are computer-assisted tools for the acquisition, storage, analysis and display of geographic data, including data relevant to agrometeorology. This technology is an expansion of cartographic science, enhancing the efficiency and analytic power of more traditional methodologies (Maracchi et al., 2000). The facilities offered by versatile software, such as GIS, and the Internet are rapidly transforming many of the standard functionalities of data-monitoring systems. The integration of GIS and RS data provides a platform for wider applications of agrometeorological information. The integration of thematic layers in GIS databases with a Digital Elevation Model (DEM) greatly enhances the accuracy and usefulness of the spatial distribution of such topographic information on a grid basis, which provides a three-dimensional representation of the land, started from contour lines. This is a basic information layer in agrometeorology for GIS applications, such as in comprehensive zoning for agricultural planning and the determination of climatic suitability for crops, for example in mountain areas or in locations with changing climates.

Monitoring as such becomes an agrometeorological service only if those to whom the results are made available can access, absorb and apply the results as tools for decision-making without further assistance, or when specific assistance is available to enable users to react or to teach them how to react. The same applies to early warnings based on such monitoring. More highly educated and richer farmers are therefore normally better off, while marginal and poorer farmers need either other kinds of services or extended measures as part of the agrometeorological services, to better prepare them for using early warnings as tools in operational mitigation of disaster consequences.

1.4.5 **Forecasting and prediction in agrometeorology (tools to guide preparedness with probabilities)**

Like most of the tools already mentioned, forecasting and prediction in weather and climate for

agricultural production will be extensively discussed in this Guide. Agrometeorological decision-making in agricultural operations for healthy crops or crops endangered by pests, diseases and/or other environmental disasters needs weather forecasting and climate prediction, where that is possible, to the required accuracies. Much progress has been made scientifically and successful applications in industrialized countries have increased, including, for example, heat- and cold-stress forecasting systems for poultry and sheep. Results with richer farmers in developing countries, related to predictions of sowing date, timing of irrigation and fertilizer use strategies, are slowly on the rise. The probabilistic character of forecasting remains one of its larger difficulties in wider applications, however.

It has been noted recently that multilateral agencies are calling for climate forecasts to be made available to small farmers (Blench, 1999). Disaster preparedness strategies, both of governments and non-governmental organizations (NGOs), have begun to take account of such forecasts and there is considerable interest in assigning them an economic value. Field studies of the impact of recent forecasts in Southern Africa and North-east Brazil suggest, however, that there is presently still a considerable gap between the information needed by poor, small-scale farmers and that provided by NMHSs and other governmental institutions. This was confirmed by an investigation of the role played by intermediaries (WMO, 2004).

A number of crop monitoring systems and yield forecasts are now being implemented worldwide, and upscaling to regional scales is an important trend. In these systems, commercial crops such as soybean, maize, wheat and sorghum are continuously monitored and forecast for/by government and private institutions. Crop-weather models that are mainly used for operational yield forecasting and prediction of phenological development have been generated for a large number of crops. They have different degrees of complexities. More mechanistic models are now available, but many of these models need to be further refined and tested before widespread practical application may be expected. Current research is focusing on detailed soil–water–crop relationships, determining adjusted crop genetic coefficients, bridging simulation model outputs with user needs for applications, and developing practical decision support systems. These models should, after all, address the composite problem of global climate, regional weather variability, agricultural productivity, decision-making and economic responses. They have barely been used,

however, in non-urbanized, non-industrialized countries (Meinke et al., 2001), but some adaptation and testing is taking place.

For real-time forecasts in agrometeorology, the reliability of regular, specialized information is critical. A common problem encountered in some countries is the general lack of reliability in these forecasts, which leads to a lack of trust in them (for example, Jagtap and Chan, 2000). Agriculture remains one of the few areas for which accurate short-term and extended-period forecasts can create such a material benefit. There is an important distinction between systems that supply tools leading directly to solutions/services and forecast information provided in isolation. Farmers often have difficulties in interpreting weather forecasts and in such cases, intermediaries between these products and agrometeorological services based on these products are highly valued (see 1.5).

1.4.6 **Agrometeorological aspects of crop, forest and livestock protection (direct preparedness strategies)**

Weather effects on plant, tree and animal discomfort and injury, as well as crop, forest and livestock losses, are highly complex. Protection can take the preventive form of planning crops, varieties and sites to avoid or mitigate the effects of the relevant meteorological extremes that are detrimental to plants. Another approach is to improve sites in order to reduce or avoid the impact of these extremes. Response farming is the best example of the former (Stewart, 1991). Microclimate management and manipulation is the best example of the latter (WMO, 1994). There are three main issues that have to be addressed. First, growing plants are exposed to direct weather hazards (frost, floods, drought, moving sand, and so forth). Second, the biology of many crop, forest and livestock pests and diseases is influenced by both current and past weather conditions. Finally, the harvesting and storage of crops is strongly influenced by weather conditions at the time of harvest and through to the post-harvest period.

Arguably, the key role of meteorologists in crop, forest and livestock protection is one of offering better preparedness strategies based on environmental avoidance, or mitigation through improved understanding of the processes and phenomena involved. To this end, good progress has been made worldwide in local strategic planning of the production of crops, trees and animals, as well as their varieties; in irrigation techniques and

strategies; and in crop storage design and management. General and sometimes location-specific information on the occurrence of droughts and floods, heatwaves and cold or dry spells, frost, hail or blasting sand, strong winds and other extreme events has improved as well. In all these cases, however, preparedness strategies with agrometeorological components can be drastically improved, particularly for small-scale farmers in general and marginal and poor farmers in particular. Case studies should be collected in which agrometeorology-related measures with small cost/benefit ratios have been successfully taken to reduce local damage to agricultural production as part of disaster preparedness management (Stigter et al., 2003).

Agrometeorology can also play a significant role in reducing the negative impacts caused by pests and diseases. An appropriate, preferably integrated, pest management system using meteorological and microclimatological information can reduce pre- and post-harvest losses appreciably. Agrometeorologists are now collaborating not only in the experimental stages but also during the operational stages of pest and disease control. The tactical use of weather information in the prediction of pest and disease development allows for near-optimum use and timing of pesticides and/or release of predators. Progress in the latter areas has been considerable in industrialized countries, with many examples of warning and prediction systems at the national level. Collaboration on an international scale has been less evident, however, possibly due to the empirical nature of most of the operational models. Exceptions to this would, for example, include the range of Crop Environment Resource Synthesis (CERES) crop models, in which international cooperation has been excellent. Participative integrated pest management introduction using farmer field classes has also met with some success in non-industrialized countries.

An increase in the variability of rainfall raises risks in livestock production systems, especially in drier areas. Because of this, pastoral or fully nomadic livestock systems, which are probably among the most efficient in exploiting niches of low-productivity areas in arid and semi-arid regions, are declining. This trend is expected to continue and countermeasures have already led to several serious conflicts between nomads and sedentary farmers. The availability of infrastructure such as roads and watering points is exacerbating negative environmental effects by encouraging resource use beyond the carrying capacity of the land – in some places this has already led to desertification (Onyewotu et

al., 2003). Resorting to feed supplements as a preparedness strategy may be one part of the land protection solution. On the other hand, services relating to animal disease forecasts are available only in some of the richer countries.

Major applications of meteorology and climatology to forest operations include pest and disease control, frost protection and fire prevention. In many cases, meteorological data collected by NMHSs are sufficient for use by foresters in forest management and protection operations. Specialized observations are necessary in relation to biomass moisture and combustibility, and may be made at forest fire stations. Foresters have developed forest fire rating systems, which combine and translate relevant meteorological variables and properties of combustible materials into indices that indicate the vulnerability to fires and their subsequent spread. These indices are used in the daily management of forested areas that are subject to forest fire risk. Long-term records of these indices can be used for planning purposes as well.

1.4.7 **Policy matters relating to agrometeorology (initial and boundary conditions set by socio-economics and the environment)**

All the major international conventions, to which most countries are now committed, emphasize that governments should implement policies aimed at greater sustainability (Sivakumar et al., 2000a). The various projects implemented under the WMO Agricultural Meteorology Programme have covered some of the key issues in the area of sustainable agriculture (see the Web pages of the WMO Agricultural Meteorology Programme).

Policy matters, when considered as tools, may not be explicitly referred to in the present Terms of Reference of CAgM. One of the challenges of the Commission, however, as set forth in section 1.3, is: “to fill the gaps between the producers of agrometeorological knowledge and the actual agrometeorological services in the livelihood of farmers”. The framework illustrated in Figure 1.1 was developed to show the gaps and the mechanisms that serve to fill them. In the example in Figure 1.1, policy matters appear twice, at the B- and C-domains. Under the basic support systems, basic policies should encompass any policy matters that foster the development and application of other relevant agrometeorological tools. The preceding sections of this chapter have examined these tools and their limitations as far

as farming is concerned. The optimum operational use of agrometeorological knowledge in agrometeorological services for improving the livelihood of farmers is the key function to which these tools have to contribute. Nonetheless, proper incorporation of agroclimatic considerations in the development of improved farming strategies requires a much longer time frame than has been used in the past (Sivakumar et al., 2000a).

Appropriate policy environments are given as one of the building blocks of agrometeorological services in the B-domain, in which initial and boundary conditions are determined for solving well-identified problems in the livelihood of farmers through such services. In general, these initial and boundary conditions are set by the prevailing social and economic concerns/constraints and by environmental considerations (see also the sections on resource assessments, 1.4.8 to 1.4.11). According to Norse and Tschirley (2000), technological change should no longer be driven by science, but by environmental objectives and social concerns – as farmer innovations are – while operating through the market, whenever appropriate. In this way, knowledge should be rendered most operational.

Suitable policies for the determination of the most appropriate preparedness and adaptation strategies, to improve and protect crops/forests/animals, their yields, and income generation, have to do with local, (biased) international and global markets and prices, as well as their manipulation. They also have to do with infrastructural and other facilities (such as for education/training/extension and related health services), as well as with the basic policies mentioned. Social and environmental constraints in preparedness strategies have to be addressed by special policies used as tools that can aid those farmers who would benefit most from agrometeorological services. If the initial and boundary conditions in problem-solving are not changed in this way, marginal and poor farmers will remain without proper operational services that are geared to their particular needs.

1.4.8 **Climate resources assessment for agrometeorology**

A few issues relating to resources should be dealt with separately from the point of view of agricultural meteorology. Resource assessment as a tool is basic to agrometeorology because without a proper agricultural resource base and its protection from

(further) degradation, development cannot be sustainable.

Rational use of climate information in agricultural production still requires knowledge of two types: knowledge about the specific influences of climatic factors on the growth and development of living organisms throughout their physiological cycle (or what may be called their climatic requirements), and knowledge about climatic characteristics specific to a given farming area expressed in basic statistical terms. Recent interest and concern related to increasing climate variability and climate change need to be focused on an assessment of the influence of changes in the latter type of knowledge in terms of consequences for the former kind of knowledge. Farmers and policymakers want to know whether climatic resources are changing in character or value and consequently are becoming more threatening or are easing limiting factors in agricultural production.

The following tools are current good practice in the assessment of climate resources in agrometeorology (listed in order of diminishing applications):

- (a) Determination of crop weather/climate requirements;
- (b) Classification of land into crop suitability zones, integrating both climate and soil factors;
- (c) Fitting appropriate probability distribution functions to all climatic elements (of different periods, because of climate change) for a better description of their behaviour with respect to their tendencies and variabilities;
- (d) More detailed determination of differences in the impacts of climatic events, particularly recurring events (whether or not related to El Niño–Southern Oscillation (ENSO) phenomena), such as droughts, floods and cyclones, under different preparedness strategies.

Making use of beneficial climate information in land-use planning, scheduling agricultural activities and preparing crop calendars, for example, as well as in crop, forest and livestock protection has benefited the agricultural communities of many regions, but the use of such information is still insufficient in poorer nations. Information such as (changes in) return periods, frequencies of occurrences and intensities of extreme events and assured rainfall in different growing periods is valuable in (modifying) choices for preparedness strategies. The effectiveness of such agrometeorological services depends increasingly on the ability to handle large volumes of ground and remotely sensed data and on the skills needed to generate from them timely,

useful and relevant services and information for farmer communities. The capacity to ensure that these services are actually applied is also crucial, and the use of agrometeorological intermediaries has been proposed as a way to enhance this capacity (see 1.5).

1.4.9 **Water resources assessment for agrometeorology**

Planning water use among numerous types of consumers in urban areas, industry, recreation and agriculture is currently the basis of water resources assessment. Because of the scarcity of water in many parts of the world, prudent water management and increasing water use efficiency are essential, particularly in arid and semi-arid regions. Stigter et al. (2005a) compiled a range of examples of traditional methods and farmer innovations in efficient water management.

Global and national policies and strategies are now being developed to increase awareness of water shortages, promote water conservation and water harvesting, redress mismanagement of ground-water, increase water use efficiencies (including changes in cropping patterns), promote the use of additional sources of water, and encourage recycling of water. Even in more humid areas, where dry spells have always been a widely occurring serious problem, increasing climate variability and climate change are forcing water-use planners to adopt and promote more efficient water use and water management techniques.

In many nations, substantial resources have been used to monitor floods and droughts and to design appropriate irrigation and drainage systems for agriculture. Water budget/balance calculations, including elaborate evapotranspiration calculations based on physics and plant factors, and soil moisture determinations are tools that are widely applied by policymakers involved in wastewater determinations and water-use planning in agriculture. The use of such assessments as tools in the development of agrometeorological services for farmers is appreciably less widespread, particularly in non-industrialized countries.

1.4.10 **Soil resources assessment for agrometeorology**

Climate and weather affect the chemical, physical and mechanical properties of soil, the organisms it contains and its capacity for retaining and releasing heat and moisture. Rainfall, on the one hand, adds chemical constituents to the soil but, on the other

hand, washes out soil nutrients. Weathering is an important factor in determining the nature of soil. Topsoil composition, vegetation cover with surface contact, and local weather factors largely determine the existence and extent of the problems of wind and water erosion. The state of the soil as it affects cultivation, pest control and harvesting is also greatly influenced by weather conditions. The above picture given in the previous edition of this Guide is still sufficient for a first soil resources assessment in agrometeorology. The loss of valuable agricultural land to urbanization, recreation and industrialization, also already signalled in the previous Guide, was rechallenged in Accra (Sivakumar et al., 2000b).

Soil degradation has chemical and physical components, and both are of importance in soil resources assessments. The system of soil mining and abandoning (slash and burn or shifting cultivation) is no longer extensively possible due to the lack of available land, so soils that are degrading because of insufficient content of organic matter and nutrients have to be addressed much more widely. Exposed agricultural land that is losing topsoil from the effects of wind and water must be stabilized and covered, preferably through the establishment of perennial grasslands or afforestation, which keep the soil covered in economically useful ways (see also 1.4.11). Deterioration of soil composition, threats to flora and fauna, and groundwater pollution resulting from excessive application of manures and fertilizers worries agronomists in many places.

Detailed information on the physical characteristics of different soil types in a region, such as bulk densities, field capacities, wilting points and water-holding capacities, is valuable for many operational purposes related to the efficiency and management of water use in agricultural production. The analysis and application of the above information on soil resources that is secured, geographically referenced and stored in a GIS database for agricultural areas will be enhanced if the products of that information can be absorbed and used by the farmer communities concerned, where necessary with the assistance of intermediaries (see 1.5).

1.4.11 **Biomass resources assessment for agrometeorology**

When considering the prevention of both water and soil runoff on sloping land through the use of contour hedgerows and mulching to obstruct unwanted redistribution of rainfall, the importance

of soil cover by vegetation or undergrowth with extensive surface contact cannot be overemphasized. This also applies to the rehabilitation of completely desertified areas using (a combination of) shelterbelts, scattered non-forest trees and shrubs/bushes, together with grasses, and to the suppression of wind erosion in the source areas of serious sand and dust storms through the establishment of economically useful vegetation that offers additional benefits. Keeping vegetation in this manner also prevents long-distance transport of material and nutrients. The determined implementation of strategic land-use and soil conservation policies is a crucial tool in fighting these problems.

Humankind's increasing utilization of forest lands for intensive logging, agriculture and other purposes has caused weather and climate to change locally, regionally and even globally. Forest fires are also a serious source of local and transboundary air pollution and atmospheric degradation. Correct application of meteorological and climatological information can be of considerable benefit in the protection, sustainable development and conservation of forest resources, in the greening of degraded areas through forest rehabilitation, and in afforestation and reforestation efforts. Policy matters, however, are again crucial components in this connection. Political will and political initiatives are needed to counter the misuse of biomass resources with effective and practical measures. This shows once more the importance of working in the B-domain (Figure 1.1). Remedial measures should be directed at those involved in misuse, for instance those who practise large-scale burning for clearing land, but these measures should go hand in hand with the development of alternatives (such as happened with slash-and-burn agriculture in Latin America) or the provision of compensation for the poorest groups that are affected by the changes envisaged.

1.4.12 **Agrometeorological services**

Agrometeorological services were recently defined and described for in a review of the history of the Commission for Agricultural Meteorology (WMO, 2006b). A positive influence on management operations, through the application of weather-based decision systems, would be one of the most practical contributions, through Agenda 21 principles, to sustainable development. The Ministry of Agriculture, Fisheries and Food (now the Department for Environment, Food and Rural Affairs, or DEFRA) in the United Kingdom has, for

example, promoted the protection of air, water and soil through the adoption of codes for Best Management Practices. The creation of an accessible database, consisting of an inventory of proven, practical techniques (including information and communication techniques) and effective agrometeorological services, would be very useful.

In recent years, a host of systems has been introduced, mostly in industrialized countries, to address such diverse issues as pest and disease control, livestock housing and welfare, work days for machinery planning, crop storage and drying, customized agricultural weather forecasts, and fire risk management for rangelands and forests. There is a need to assess the economic value of such agrometeorological services because policy-makers need to know whether such services are really useful. Since most policymakers are familiar with making decisions based on their economic returns and/or values, the best approach for agrometeorologists to take would be to evaluate their services in terms of success, gain and profit. This is not an easy task, and the effects need to be quantified. Nevertheless, cost/benefit analysis is a commonly used method.

Agrometeorological information, products and services need to be developed to best meet the needs of clients (Rijks and Baradas, 2000). In industrialized countries, agrometeorological information can be made easily and rapidly available to a wider spectrum of users by using modern information and communication technology. Considerable agrometeorological information is now available on the Websites of NMHSs. Some of the information is also accessible by telephone and e-mail (see Chapter 5, for example). Near-real-time data should be rapidly disseminated so that farm-level decisions can be made to avert negative effects of unfavourable weather and to benefit optimally from favourable weather (Sivakumar et al., 2000*b*). It should be repeated, however, that agrometeorological information and services for governments and private organizations are different from those that were developed, or need to be developed, directly for and/or by various groups of farmers. This has mainly to do with facilities and education, and therefore with absorption capacity for information and services. In non-industrialized countries, training of intermediaries would go a long way towards solving these problems for various groups of all but the richest and best-educated farmers (section 1.5). There is an important role here for WMO/CAGM in facilitating related policies (Stigter, 2003*a*).

1.5 **TRAINING, EDUCATION AND EXTENSION IN AGRICULTURAL METEOROLOGY AS SUPPORT SYSTEMS FOR AGRO-METEOROLOGICAL SERVICES**

1.5.1 **General considerations**

The Commission for Agricultural Meteorology continuously reviews the requirements for training, education and extension in agricultural meteorology and recommends developments in higher education programmes, in training for agrometeorological technicians, and at other vocational levels where agrometeorology is involved. This has been done only sporadically and not very explicitly at the level of end-users (for example farmers in field classes). The Commission also encourages the development of teaching materials for use in workshops and seminars and by visiting lecturers. While the scientific principles are the same in all countries, however, the potential applications and the conditions under which they are used vary greatly among countries in different climates and at different stages of development. This also applies to education, training and extension to put these applications into effect. Training programmes at all levels must therefore be adapted to national and regional needs (WMO, 2000). In terms of recent operational efforts, this includes developing extension agrometeorology around the establishment of agrometeorological services, particularly in non-industrialized countries (Stigter, 2003*b*).

A major responsibility of CAGM is to encourage training in agrometeorology and to assist in coordinating the training of agrometeorological personnel of all grades. There are requirements for training personnel at a number of levels, from carrying out well-established routines to using and developing the tools and mechanisms dealt with in 1.4. Training is directed at personnel who work mainly in NMHSs and generate the products in agricultural meteorology that are to be used by decision-makers, including governments, private organizations and farmers. These personnel also have to be able to develop new applications of agricultural meteorology in interaction with agriculturists. In non-industrialized countries, however, these personnel should not be in direct contact with the agricultural communities. That should be the task of agrometeorological intermediaries.

1.5.2 Training at the intermediate level

At the intermediate level, a proposal has been put forward to establish two separate steps in education and training for agrometeorological extension (Stigter, 2003*b*, 2005). The first class of agrometeorological intermediaries would be close to the centres where the agrometeorological information products useful for decision-makers in agricultural production are generated. Forecasts of weather and climate, monitoring and early warning products for drought, floods or other calamities, and advisories for agrometeorological services that could increase the preparedness of the population far in advance, all have to be packaged as products that can be absorbed. This needs to be done in the B-domain of Figure 1.1. Such extension intermediaries need a solid education in farmers' needs, as well as in how agrometeorology can be used in the A-domain by drawing on information from the B-domain. They should themselves work in the B-domain, guiding the establishment of agrometeorological services to support the actions of producers or their advisors (E2).

The second class of (agrometeorological) extension intermediaries should be closest to the farmers and operate exclusively in the A-domain, establishing and using agrometeorological services (E2). They should learn to articulate the needs of the farmers' communities better and seek out agrometeorological components that need attention. They should match this with what is or should become available as agrometeorological services, in close contact with the first class of intermediaries, rather than with the generators of the raw weather/climate products and general advisories (E1). In this two-step approach, meeting points for the two classes of intermediaries need to be created by the government and/or NGOs. The NMHSs should organize the first class, while the existing extension services, the government and NGOs should organize the second class of intermediaries and their contacts with the farmers.

1.5.3 Challenges

The education and in-service training (Lomas, 1999; Walker, 2005; WMO, 2006*b*) of these two classes of agrometeorological extension intermediaries is an essential part of the new, challenging approach that appears necessary in education, training and extension in agricultural meteorology. In spite of the efforts by WMO and NMHSs, local progress in agrometeorological support systems and services is often hampered by a lack of suitably trained personnel at all levels. This problem is particularly serious

in non-industrialized countries where economic development and the level of food production depend to a large extent on the assessment of their resources through surveys and on the on-farm implementation of agrometeorological services. These assessments of resources were mentioned as tools under sections 1.4.8–1.4.11. A WMO report on education and training in agrometeorology (WMO, 2000) gave three reasons for the scant use of agrometeorological services in agriculture, of which one, the absence of economic benefits, is contradicted by other information in Sivakumar et al. (2000*b*) and more recently by Salinger et al. (2005). More likely reasons are therefore:

- (a) A lack of cooperation among the institutions providing information and relevant advisories and those responsible for their transfer to the farming community;
- (b) Insufficient education and training of the user community, including the farm advisory services that provide specific agricultural advice on the basis of general weather information.

The challenge is to use the training of intermediaries as explained in 1.5.2 to address these serious problems. The usefulness of the advice to farmers, foresters and other users depends considerably on their ability to interpret, absorb and apply extension messages intelligently. There is thus a major need to provide instruction in agricultural meteorology to non-meteorologists (for example, Lomas, 1999; WMO, 2000), and to create extension agrometeorologists and intermediaries who can make the existing products more client-friendly. This training could be done at institutes where advanced agricultural education is already provided or in special training courses comprising agricultural and meteorological components. These people must then also be able to deliver the agrometeorological aspects of training for users through field classes, which appear to be a fruitful approach (WMO, 2006*b*).

The successes, failures and experiences from such extension efforts will have to be fed back into the curricula of agrometeorological personnel at NMHSs and into those of vocational schools and universities to enlighten the classical C-domain training and strengthen its usefulness.

1.5.4 Specialization in agricultural meteorology

Within agricultural meteorology education, training and extension, some need for specialization may be recognized. Annex 1.B lists recent examples of needs for training, education and extension,

along with directly related issues such as international cooperation and technology transfer, for which specialists could be useful.

Another broad classification for specialization, from the standpoint of observations and measurements, could include:

- (a) Climate monitoring and analysis leading to planning applications and early warnings of climate anomalies as agrometeorological services;
- (b) Real-time monitoring leading to the provision of operational advice in agrometeorological services, such as determining irrigation efficiency, for example;
- (c) Microclimate manipulation and prediction within crops, soils and managed environments (glasshouses, stores, and the like), leading from measurements to management options as agrometeorological services;
- (d) Special problem areas largely concerned with preparedness as agrometeorological services for agricultural hazards (including pests and diseases).

The use of the tools described in section 1.4 leads to a specialization division, from alternative points of view, that overlaps in part with the other specialization divisions mentioned above.

1.5.5 **Consequences for training, education and extension in agrometeorology**

The above approach has implications for this subject. For too long, non-industrialized countries have been tied to and have been imitating educational systems and their underlying values that originated in industrialized countries; these systems and values were alien to their rural cultures (van den Bor and Shute, 1991).

Classical, high-level training in agrometeorology (for example, WMO, 2001, and the core library proposed there) takes place in the support systems to agrometeorological services (C-domain). This also applies to books specifically written for non-industrialized countries (for example, Baldy and Stigter, 1997; Murthy, 2002). There is a large additional need to develop explicit education and training in the extension-focused B- and A-domains for the field of agrometeorological services, as outlined above. This would indeed be a new approach, with a need for feeding back results as case studies into the education of the C-domain, particularly in non-industrialized countries. In this way, the

C-domain could become better focused on supportive undertakings (E1) and on the necessary connection between E1 and E2 guidance. This adaptation in the C-domain would in turn greatly enhance the operational qualities of agricultural meteorology.

Such an approach will demand changes in the classical education and training in agrometeorology, and make agrometeorological students and trainees much more aware of application needs and actual applications of agrometeorological services that are developed with the methodologies they learn so much about. It will also demand increased attention and a shift in the focus on agrometeorology in other agricultural curricula and changes in the in-service training of purely agrometeorological personnel and agrometeorological intermediaries.

1.5.6 **Syllabi for instruction and other observations on curriculum content**

As agrometeorology covers a wide range of both temporal and spatial scales, topics throughout both ranges need to be included in highest-level basic curricula. For the temporal scale, measurements and applications go from the scale of seconds through hours, days, 5- and 10-day periods, and months to seasonal, annual and long-term data analysis. The range of spatial scales needs to go from the molecular level, organ level, plant and crop micrometeorological level through the meso-meteorological level of districts and regions to national, continental and global levels. In this way, the whole range of influences of weather and climate on agricultural production over various timescales and spatial dimensions can be studied (Walker, 2005). This is also the way dynamic modelling works, from one level to the next, both in time and space.

An example of a high-quality basic syllabus for support systems to agrometeorological services (C-domain) recently developed for WMO is illustrated in Annex 1.C (WMO, 2001). Subjects such as the national and international framework of agrometeorology, training in multidisciplinary problem-solving, and projects and seminars on specific regional problems and interests in agrometeorology should be added to deal directly with B-domain and A-domain agrometeorology. This also applies to study tours focused on case studies of agrometeorological services, such as those related to irrigation management and determination of water use efficiency, and the application of statistics

for critical evaluation of risks (and research results), for example.

Agrometeorologists are working in an applied field where the principles of meteorology interact with the practical field of agricultural production. In order for them to provide high-quality services, top-level personnel and researchers in agrometeorology need to understand the biometeorological interrelationships between weather and climate and the production of crops and livestock, including the effects on pests and diseases. The applications addressed by agrometeorologists are principally in two areas – those for planning purposes and those for operational management purposes. The climatic long-term datasets and seasonal global applications are mainly used together with the crop or livestock requirements (such as temperature and water) for crop/livestock–climate matching. This planning level is of vital importance when introducing new varieties and breeds into an area or evaluating the effects of global warming on agricultural production in a specific area, for example. For applications in agrometeorology of this type, a good understanding of the availability of long-term datasets and climate analyses, as well as of global climate models and seasonal forecasts, is needed by NMHSs and research agrometeorologists. At an operational level, the data analysis and application are usually at a more local, district or farm level during the growing season. Therefore, data analysis skills need to be applied to decision-making trees to be of practical use to farm managers, for irrigation scheduling, crop/livestock disease and pest control, and other daily/weekly farm operations (such as weeding and fertilization). For such agrometeorological services, NMHSs and research agrometeorologists need a good basis in fundamentals and applications of short-term weather forecasting, together with the crop/livestock requirements of temperature (that is, critical values), day length and water (Walker, 2005).

Syllabi for agrometeorological intermediaries will need to be drawn up on the basis of the collection and review of the experience with existing agrometeorological services in the A-domain. There is also a need to gather information from users on actually existing needs that have not or not yet been met by such services (Blench, 1999). After hands-on experience obtained in the B-domain and the A-domain in Africa, collection of such information is being attempted at various places in Asia (Stigter et al., 2005b). It is expected that better guidance (E2) will be defined for the establishment of such services from these exercises. From the same experiences, training at the level of agrometeorological

intermediaries can be developed. Several preliminary attempts in Africa and Asia to work with such intermediaries have had limited success because of the lack of appropriate training (Stigter, 2003b).

To promote widespread use and application of agrometeorological techniques and concepts, another level of training is also needed. This outreach by agrometeorologists can be at various levels of the general public and in schools. What is vital here is that the basic concepts and ideas of agrometeorology are communicated in simple, everyday language, without much technical jargon. It is also recommended that agrometeorology courses be included in all undergraduate biological and agricultural degrees. This would promote better cooperation with agricultural meteorologists, along with a better understanding of the role of agrometeorological information by agronomists and animal scientists. A further group that needs some training in the basic concepts of agrometeorology is practitioners in the media. Because they often explain and discuss messages from meteorologists and climatologists to the public at large, it is vital that they have a good basic understanding of weather and climate (Walker, 2005).

1.6 CHALLENGES MET AND REMAINING IN AGRICULTURAL METEOROLOGY

1.6.1 A challenge met

The earlier version of this Guide, published more than 25 years ago, listed “Services by meteorologists to agriculturists”, “Services by agriculturists to meteorologists” and “Joint services by meteorologists and agriculturists”. The earlier edition was aimed at “joint experts” in agricultural meteorology. The world has become much more complicated now and it is not likely that such a solution would still be feasible (see also Gommès (2003) for the approach below).

Too many areas are covered by agricultural meteorology and no one would agree on their borders. Earlier parts of this chapter highlight this as well. Irrigation, which according to WMO falls under agrometeorology and according to FAO under agricultural engineering, is one example. Desert locust outbreaks are treated as an “extreme agrometeorological event” by WMO and as a plant protection problem by the FAO. Another example can be seen in crop models, which to modellers may be part of crop ecophysiology, physiology, micrometeorology, and the like, with a big soil science component,

while a scientist or technician who wants to do crop weather modelling may assign them to agrometeorology. The list also includes pest development rates, and many other phenomena.

One may call it a policy decision, but also a challenge met. The scope of agricultural meteorology has been redefined in this Guide (1.1). This redefinition has implications for the characterization of weather/climate resources (1.4.8), climate/weather impact assessment methodologies in agricultural production (1.4.4–1.4.6), as well as for how agrometeorological knowledge will be used (1.4.1, 1.4.2 and 1.4.8). This approach makes agrometeorology much more service-oriented.

1.6.2 **Challenges remaining, from a new perspective**

The new approach is necessary because of the increased importance of agricultural meteorology that has been witnessed almost everywhere lately, although it is sometimes called by another name. This new awareness is caused by deteriorating agricultural environments due to increasing climate variability and climate change, in addition to other vagaries of weather and the encroachment of non-agricultural interests onto agricultural land. Moreover, multidisciplinary departments, teams and approaches are recognized everywhere as a basic necessity for problem-solving in agricultural production. There are still some difficulties, but in agricultural sciences and technology one can see much more collaboration among specialists in different disciplines than there was 25 years ago. At this point, at least, this is not always the situation at some government organizations providing services, however. In particular, the administrative structure of NMHSs, which at present often leaves little room for agricultural meteorology and products relating to instruments and types of data, software tools, training of officers, and so forth, should be geared much more towards the provision of generic or specialized services by intermediaries (Gommes, 2003). These are practical challenges springing from the new service orientation chosen for agrometeorology.

Another remaining challenge is the need for better quantitative estimates and better methods to derive these quantitative estimates of the actual role of weather/climate in agricultural production for various farming systems. It is necessary to arrive at a joint determination of the links between change and variability, mainly in terms of impacts, and to make sure that present needs are covered (Gommes, 2003).

The sudden change in appreciation and importance of agricultural meteorology caught professionals rather unprepared. This has a historical background. In the course of the 1980s, with increasing external inputs into changing modes of production, less importance was attached to weather and climate. This could be only partly counteracted by increasing emphasis in CAgM on “operational agrometeorology” and “economic benefits of agrometeorology”. Simultaneously, even more emphasis was given to developing countries, where attention to agrometeorology, and hence funding, remained very low and was in large part external. In advancing, industrializing developing countries, this gradually improved, but attention and funding still remain much below what is needed. In countries in transition and China, isolation especially was an insurmountable problem.

Environmental concerns due to intensification of production were already rising when climate change, and increasing climate variability in particular, struck hard. In the 1990s, agricultural meteorology tried to regroup its then relatively meagre forces and to take stock of the environmental requirements of crops, forests and livestock, particularly in low external input agriculture, and of the sustainability of the agricultural resource base everywhere, but with different emphases. Agrometeorologists appeared only partially able to cope with these demands, mainly because of the virtual non-existence of suitable agrometeorological services (Olufayo et al., 1998).

At present, the proven urgent need for better on-farm preparedness (Stigter et al., 2003) is equivalent to a revival of response farming with relevant innovations. These improved preparedness strategies, for the chronic deficiencies of weather, its microvariability in time and space, and a larger number of more serious extreme events in weather and climate, are creating an additional and growing demand for agrometeorological services (compare also with 1.5.4). This is true for industrial and non-industrial countries alike, but again with very different emphases due to the very different modes of production.

Also in agrometeorological services, a remaining challenge is to define the priority beneficiaries. In most countries, there has never been any serious market research to identify potential customers of agrometeorological services, including commercial customers (Gommes, 2003). In this regard, the United States, where a potential user can these days get a menu of choices from private services, is an exception. Elsewhere, plantations, livestock and other commercial farmers, inland and ocean

fisheries, banks, traders and the like, might also be in a position to pay for services and, indirectly, fund activities aimed at poorer customers (Weiss et al., 2000).

1.6.3 **The challenges of decision support systems**

Agricultural meteorology is concerned with how parameters influence managed and natural ecosystems. Therefore, the first challenge of a decision support system is to ensure that accurate, relevant input data are available on a timely basis. Aside from actual measurements, interpolation schemes, algorithms to predict specific meteorological parameters or remotely sensed data may be used to complete the necessary meteorological parameter dataset.

Monteith (2000) showed how emphasis has shifted between the early issues of a journal like *Agricultural and Forest Meteorology* and recent issues, from data collecting to modelling. He also confirmed that the quality of basic surface data has been constantly deteriorating over that same period. Instead, there are new sources of data, which are very useful but are no substitute for real data. Statistical or other proxies currently dominate the data landscape to a large extent. For example, deeply indirect estimates are now used in drought monitoring and flood forecasting and by the crop monitoring community throughout Africa, at the expense of observed data, with several types of risks for decision-makers. Knowing the limitations of such datasets is an absolute challenge for decision-making. In non-industrialized countries, on the other hand, automatic data collection is often very risky in terms of costs and, even more important, continuity of data (Gommes, 2003).

The next challenge of a decision support system is to go from input data to biologically meaningful results. This is often accomplished through a

simulation model that includes parameters of biological importance to the ecosystem that is being simulated. The simulation model plays a key role in changing data into useful information via a decision support system. The simulation model also helps focus research. The change from data to information should ideally be independent of location, because it should be based on the best available scientific knowledge (Weiss et al., 2000).

Many simulation models are tied together by assumptions and empiricisms (Monteith, 2000). The validity of these assumptions and the generality of these empiricisms are important research areas for the improvement of simulation modelling. Specifically, different cultivars may respond differently to the same environment and the main challenge is to quantify these differences in the modelling.

In order for a decision support system to be effective, the intended audience for this system must be carefully identified and appropriate information for this audience must be developed. This means that the information must have economic value. Introduction of such information from a decision support system as an agrometeorological service to the community should be a careful process, with appropriate feedback mechanisms, to avoid unintended negative consequences (Weiss et al., 2000).

In some cases, the end-users of the information will gain new insights into specific problems, to the point that they can continue operating independently of the initial decision support system. In other cases, specific additional training is necessary in field classes. Intermediaries with socio-economic knowledge about the farming systems concerned and an extension background should be trained to ensure that the resulting information is effectively absorbed and used (1.4.5, 1.4.12 and 1.5). This is the final challenge of each and every decision support system.

ANNEX 1.A

TERMS OF REFERENCE OF THE COMMISSION FOR AGRICULTURAL METEOROLOGY

The Commission shall be responsible for matters relating to:

- (a) Applications of meteorology to agricultural cropping systems, forestry and agricultural land use and livestock management, taking into account meteorological and agricultural developments both in the scientific and practical fields;
 - (b) Development of agricultural meteorological services of Members by transfer of knowledge and methodology and by providing advice in particular on:
 - (i) The most practical use of knowledge concerning weather and climate for agricultural purposes such as conservation of natural resources, land management, intensification of crop production, increase in the area of agricultural production, reduction of production costs, the improvement of agricultural products and the selection of improved varieties of plants and breeds of animals that are better adapted to the climatological conditions and their variability;
 - (ii) The combating of unfavourable influences of weather and climate on agriculture and animal husbandry, including weather-related pests and diseases;
 - (iii) The protection of agricultural produce in storage or in transit against damage or deterioration due to the direct and indirect influences of weather and climate;
 - (iv) The use of weather and agrometeorological forecasts and warnings for agricultural purposes;
 - (v) The interactions between air pollution and vegetation and soil;
 - (c) Methods, procedures and techniques for the provision of meteorological services to agriculture including farmers and forestry and rangeland operators;
 - (d) Formulation of data requirements for agricultural purposes;
 - (e) Introduction of effective methods for disseminating agrometeorological information, advice and warnings to agriculture by mass media;
 - (f) Meteorological aspects of desertification;
 - (g) Fisheries (food aspects only).
-

ANNEX 1.B

NEEDS FOR TRAINING/EDUCATION/EXTENSION (AND DIRECTLY RELATED ISSUES) RECOGNIZED AS PRIORITIES IN THE ACCRA SYMPOSIUM

(Sivakumar and others, 2000)

- (a) Technology transfer (in the sense of adapting proven information and services applications to the realities and needs of non-industrialized countries);
 - (b) Methods, procedures and techniques for disseminating agrometeorological information to cooperative extension services and other users who understand its value;
 - (c) Awareness and training for disaster mitigation and climate disaster prediction;
 - (d) Training assistance focused on priority services and on priority needs mentioned under data, research, policies and education;
 - (e) Methods, techniques, software packages for specific applications by the clients themselves;
 - (f) Interdisciplinary extension services for local development;
 - (g) Agrometeorological networks, including Climate Information and Prediction Services (CLIPS) products;
 - (h) Training in agrometeorology in general, with additional emphasis where agriculture is on the decline;
 - (i) International cooperation (on the needs formulated above).
-

ANNEX 1.C

OUTLINE OF A RECENT CLASSICAL BASIC SYLLABUS IN AGROMETEOROLOGY

(Based on WMO, 2001)

1. **Agricultural meteorology – its scope and aims**

Aims; range of subject matter: soil and water, plants and crop microclimate, farm animals (farm live-stock), diseases and pests of crops and animals, farm buildings, equipment and operations, artificial modification of meteorological regimes, climate change; use and provision of agrometeorological information.

2. **Radiation and the surface energy balance**

Solar energy (“short-wave” energy) from sun and sky: direct and diffuse components of solar short-wave radiation, estimation of global radiation on a horizontal surface, emission and reflection of radiation, energy in the visible spectrum – light; the energy balance and its components: the long-wave budget; surface radiation temperatures; total radiation budget and complete surface energy balance; special aspects of radiation and temperature in agriculture.

3. **The soil and its heat balance**

What is “soil”; transmission of heat in the soil; soil freezing, and the role of snow cover; diurnal and annual variations of soil; temperature and moisture; a model of soil temperature diurnal course at different depths.

4. **Water and the hydrological cycle in agriculture**

Water and vegetation; moisture characteristics of soils; determination of water loss from land surfaces: fundamentals of the evaporation process, existing methods to determine evaporation, energy balance estimation of evaporation, aerodynamic estimation of evaporation; “combination” methods of Penman and others: development of the original Penman equation, evaporation formulae of Priestley–Taylor and Penman–Monteith; special forms of precipitation: dew, snow; soil moisture budgets – irrigation need.

5. **Small-scale climate, representativity, and their dependence on topography**

Micro-, topo- and mesoclimatology; observation representativity, exposure and sampling; wind behaviour in common inhomogeneous terrain: wind around barriers of varying porosity, wind reduction by shelterbelt arrays, wind representativity at toposcale; toposcale representativity of meteorological observations; topoclimatological effects arising from landscape variations: effects of slope on incoming solar radiation, soil temperatures on slopes, effects of slopes and hills on airflow, local mesoscale circulations.

6. **Agrometeorological management at microscale and toposcale**

Introduction; soil cultivation and treatment: effects of surface colour on soil temperature, mulching, surface geometry effects on temperatures; crop management and layout: spacing of crop rows, shading, cover crops and weeding; wind shelter: effect of wind shelter on microclimate, windbreaks against damage and erosion; irrigation and drainage; frost and protection against frost damage: passive methods of protection against frost, active methods of protection against frost, short-term frost forecasting; artificial climate in glasshouses and stables.

7. **Weather hazards that adversely affect agricultural output**

Drought; artificial stimulation of precipitation; hail: distribution of hail in space and time, active suppression of hail; fire in vegetation; atmospheric transports: elementary aspects of transport over meso-scale distances, point sources, line sources, for example, sea-salt transport.

8. **Operational agrometeorology**

Alternative forms of agrometeorological decision-supporting activity; operational modelling for tactical agrometeorology; protection of crops

against pests and diseases; agroclimatological surveys: agroclimatology of the Sahel – an example of presentation, irrigation need – a climatological case study, agroclimatological analysis of a rainfed semi-arid situation; computer weather modelling for agriculture; modelling of heat stress for avocado – a case study; agrometeorological weather and climate information.

9. **Agrometeorological instruments and observation**

Basic observation rules: agrometeorological networks and documentation, dynamic responses

of meteorological instruments; agrometeorological instruments: air temperature, grass-minimum temperature and radiative surface temperature, soil temperature and soil heat flux, wind, radiation and sunshine, humidity, dew and leaf wetness, evaporation and evapotranspiration; observations of “state of the ground” and soil moisture: state of the ground, soil moisture; biological observations: observations for research and for operational use, observations of natural phenomena for agroclimatological use, specific examples of biological/phenological observations: wheat, maize, avocado; remarks on experimental procedures.

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CHAPTER 2

AGRICULTURAL METEOROLOGICAL VARIABLES AND THEIR OBSERVATIONS

2.1 BASIC ASPECTS OF AGRICULTURAL METEOROLOGICAL OBSERVATIONS

Observations of the physical and biological variables in the environment are essential in agricultural meteorology. Meteorological considerations enter into assessing the performance of plants and animals because their growth is a result of the combined effect of genetic characteristics (nature) and their response to the environment (nurture). Without quantitative data, agrometeorological planning, forecasting, research and services by agrometeorologists cannot properly assist agricultural producers to survive and to meet the ever-increasing demands for food and agricultural by-products. Such data are also needed to assess the impacts of agricultural activities and processes on the environment and climate. The following sections provide guidance on the types of observations required, their extent, organization and accuracy, as well as on the instruments needed to obtain the data, with an emphasis on those for operational and long-term stations. Older books on measurements are generally available to the public, but more recently, the number of books with components useful to agricultural meteorology has diminished. Reference can be made here, for example, to books that have become more widely used since the previous edition of this Guide was compiled, such as Fritschen and Gay (1979), Greacen (1981), Meteorological Office (1981), Woodward and Sheehy (1983), Russell et al. (1989), Percy et al. (1989), Goel and Norman (1990), Kaimal and Finnigan (1994), Smith and Mullins (2001), Strangeways (2003) and WMO (1984, 1994*b*, 2008*a*, 2008*b*). In relation to operational agrometeorology, reference can be made to certain chapters in Rosenberg et al. (1983), Griffiths (1994), Baldy and Stigter (1997), and WMO (2001*b*).

The observations required depend on the purpose for which they will be used. For the characterization of agroclimate, for climate monitoring and prediction, and for the management of natural resources, national coverage over periods of many years is required. These data also provide the background for the shorter-term decision-making involved in activities such as response farming, monitoring of, and preparedness and early warning for, natural disasters, along with forecasts for pests and diseases. For these activities, additional

observations are needed. The preparation of advisories and services on farming methods, including irrigation and microclimate management and manipulation, also requires specialized data. Finally, the needs of research call for detailed and precise data according to each research topic. There are too many specialized methods to be included in this review, but almost all research projects require information on the background climatology that may be derived from the outputs of the long-term types of stations listed below.

2.1.1 Data as a support system for agrometeorological services

In section 1.4.1 of Chapter 1, data are considered parts of support systems for agrometeorological services. This applies to assessments as well as predictions. It should be stressed that this refers to real data, that is, observed parameters, or “ground truth”. As already mentioned in Chapter 1, collection of good observations has gone out of fashion in many countries because of the illusion that computer-modelled estimates can replace them. Models can be useful only if they get real input data and if additional real observations are available to check the validity of model output.

When the data are to be related to agricultural operations, agricultural data are also essential, including the state of the crops and of animals. These complementary data are often collected by non-meteorological personnel. For all agrometeorological applications, in order to make information available to assist farmers all the time at the field level, to prepare advisories, and to allow for longer-term planning, it is necessary to combine the agricultural and the meteorological data. To make better use of the agrometeorological data in supporting agrometeorological services and to provide for effective transfer of the knowledge of agrometeorology to farmers at farm level, the science of information technology is also very useful (see also Chapter 17 of this Guide).

2.1.2 Physical climatic variables

Agricultural meteorology is concerned with every aspect of local and regional climates and the causes of their variations, which makes standard observation of climatic variables a fundamental

necessity (for instance, Hubbard, 1994). It is also concerned with any climatic modifications, which may be introduced by human management of agriculture, animal husbandry or forestry operations (for example, Stigter, 1994a). Physical variables of climate are observed to assist the management of agricultural activities. Such management includes determining the time, extent and manner of cultivation and other agricultural operations (sowing; harvesting; planting; application of biocides and herbicides; ploughing; harrowing; rolling; irrigation; suppression of evaporation; design, construction and repair of buildings for storage, animal husbandry, and so on) and different methods of conservation, industrial use and transport of agricultural products.

Indispensable climatic parameters in the development of agricultural meteorology include, more or less, all those pertaining to geographical climatology, especially those that allow interpretation of physical processes in the lowest atmosphere and upper soil layers, which are the climatic determinants for the local or regional biosphere (Monteith and Unsworth, 2007). Parameters pertaining to energy and water balance are thus very important, such as precipitation, humidity, temperature, solar radiation and air motion. Further, certain physical and chemical characteristics of the atmosphere, precipitation and soil are also important in agricultural meteorology. These characteristics can include CO₂ and SO₂; dissolved and suspended matter in precipitation; and soil temperature, moisture and salinity. Such measurements require specialized equipment, which is available only at a few selected stations. Non-routine physical (and biological, see below) observations, such as those required for research, surveys and special services (as discussed in Baldy and Stigter, 1997, for example, and Appendix II to this Guide), are usually more detailed than standard observations and thus need to be more accurate whenever processes must be studied instead of phenomena.

2.1.3 Biological variables

Besides scientific observation of the physical environment, the simultaneous evaluation of its effect on the objects of agriculture, namely, plants, animals and trees, both individually and as communities, is also a prerequisite of agricultural meteorology. The routine observations provided by climatological and agrometeorological stations should be accompanied by routine biological observations. In order to obtain the best results, these observations should be comparable with those of the physical environment in extent, standard and

accuracy. Biological observations generally are phenological or phenometric in nature or both. Phenological observations are made to evaluate possible relations between the physical environment and the development of plants and animals, while the phenometric types are made to relate the physical environment with biomass changes. The *Manual on the Global Observing System* (WMO-No. 544) and some of the WMO Technical Notes¹ include certain details about observations of this type. Literature covering this topic is given in 2.3.2 and biological measurements are provided in 2.4.2. Important observations include assessments of damage caused by weather, diseases and parasites, as well as measurements of growth and yield.

2.1.4 Scale of observations

In agricultural meteorology, observations are required on the macro-, meso- and microscales. On the larger scales it should make use of all available local observations of environmental physical parameters made by the international synoptic network of stations (see also 2.1.5). In practice, observations can be used in real time in agriculture. For parameters with very little spatial variation (such as sunshine duration), low-density observation networks normally suffice for agricultural purposes. Most of the planning activities in the agricultural realm, however, require higher-density data. These can sometimes be obtained from synoptic station observations through the use of appropriate interpolations (Wieringa, 1998; WMO, 2001b). For biometeorological research, microscale observations are often required.

New typical characteristic distances of these climatic scales are referred to in Chapter 1 of WMO (2008b). In this publication the mesoscale is defined as 3 km to 100 km, the toposcale or local scale as 100 m to 3 km and the microscale as less than 100 m (in the last case with the notation “for agricultural meteorology”). Indeed, a mesoscale of 100 km does not feel right in agricultural production and toposcale is also not the right term for a farm. In WMO (2008b), however, it is also stated in particular that applications have their own preferred time and space scales for averaging, station density and resolution of phenomena: small for agricultural meteorology and large for global long-range forecasting. With respect to agricultural meteorology

¹ Please note that the following WMO Technical Notes are listed for further reading on subjects relevant to this chapter: Nos. 11, 21, 26, 55, 56, 83, 86, 97, 101, 125, 126, 133, 161, 168, 179, 192 and 315. They can be found in Appendix I.B of this Guide.

this is discussed (differently) in WMO (2001*b*) and in Keane (2001), partly after Guyot (1998).

It follows from the above that it is desirable that use can be made of observations from agricultural meteorological stations. Such stations are equipped to perform general meteorological and biological observations and are usually located at experimental stations or research institutes of agriculture, horticulture, animal husbandry, forestry and soil sciences. Frequencies of observation, the timescale to be applied for measurements, and their averaging depend on the phenomena and processes under study, their scales, and rates of change. In WMO (2008*b*) this is discussed under “representativeness” (see also 2.2.2.1).

For research work in agricultural meteorology, standard instrumentation under standard environmental conditions is often useful, but in many cases special stations, with special equipment and non-standard exposure conditions, are required (for example, WMO, 1994*a*). For biometeorological research and for many agrometeorological problems, additional observations in confined areas, such as within crops, woods, agricultural buildings or containers for conservation or transport of produce, are often required.

2.1.5 Extent of observations

Agricultural meteorology can and should make use of all available local observations of environmental physical parameters from fixed points in the synoptic, climatological or hydrological networks, including a broad range of area and point data derived from numerical weather analysis and predictions. This includes certain upper-air data (at least in the lower layers up to 3 000 m), for instance, upper winds (aerobiology) and temperature and humidity profiles (for energy budgets). In fact, it is desirable that at selected stations additional observations of more specific interest to agriculture be made.

Climatological and hydrological stations, which are often more representative of agricultural areas than synoptic stations, provide information (daily precipitation amounts, extreme temperatures, and soon) that is useful for operational agrometeorological purposes and in the management of risks and uncertainties. Since these networks of synoptic, climatological and hydrological stations are restricted in density or in kind of observation, it is desirable that they be supplemented by agricultural meteorological stations. The complete network should include all aspects of climatic and soil variations and each type of agricultural, horticultural,

animal husbandry, hydrobiological, and forestry operations that exist in the country.

New possibilities for agricultural meteorology are offered by the availability of remote-sensing techniques (for example, Milford, 1994), which allow for the evaluation of some variables of the physical environment and the biomass over extended areas and help to guide interpolation. These types of data are useful to supplement agrometeorological information and to aid in providing forecasting and warning services to agriculture.

2.1.6 Data without metadata are unreliable

Meteorological observations do not provide reliable information about the state of the local atmosphere unless one knows how the observations were made, including the instrument, its installation height and exposure, sampling modalities and averaging times, and the way in which the measurements were processed. Specifications of all these links of the observation chain are called metadata, and their availability determines the value of measurements. Average wind speed observed at 2 m height will be about two thirds of the wind speed at 10 m height. A maximum temperature observed with a fast thermometer above dry sand can be many degrees higher than the maximum observed nearby on the same day above wet clay with a slow thermograph. To judge the content and quality of observations, it is essential to know their metadata (WMO, 2002).

Traditionally, for synoptic stations this issue was dealt with by WMO rules that specified standard instrument exposures and comparable observation procedures. The required very open terrain is not always available (even at airports), however, and many observation budgets are insufficient to meet the rules. Around 1990, climate investigations showed the great importance of knowing the actual station exposures and the like, even for officially standardized synoptic stations. For agrometeorological stations, which make varying types of observations in varying terrain, metadata have always been important, but generally were referred to as “station history”.

Therefore, it is more important than ever that records are made and kept at agrometeorological stations of the instrumentation (type, calibration, maintenance), instrument exposures (mounting, siting, surroundings at toposcale), and observation procedures (sampling, averaging, frequency of measurements, recording, archiving). Fuller specification of necessary metadata is given in 2.2.5 below.

2.2 AGRICULTURAL METEOROLOGICAL STATIONS

2.2.1 Classification

Reference should be made to Linacre (1992). According to WMO (2003b), each agricultural meteorological station belongs to one of the following categories:

- (a) A principal agricultural meteorological station provides detailed simultaneous meteorological and biological information and it is where research in agricultural meteorology is carried out. The instrumental facilities, range and frequency of observations, in both meteorological and biological fields, and the professional personnel are such that fundamental investigations into agricultural meteorological questions of interest to the countries or regions concerned can be carried out.
- (b) An ordinary agricultural meteorological station provides, on a routine basis, simultaneous meteorological and biological information and may be equipped to assist in research into specific problems; in general, the programme of biological or phenological observations for research will be related to the local climatic regime of the station and to local agriculture.
- (c) An auxiliary agricultural meteorological station provides meteorological and biological information. The meteorological information may include such items as soil temperature, soil moisture, potential evapotranspiration, duration of vegetative wetting, and detailed measurements in the very lowest layer of the atmosphere. The biological information may cover phenology, onset and spread of plant diseases, and so forth.
- (d) An agricultural meteorological station for specific purposes is a station set up temporarily or permanently for the observation of one or several variables and/or specified phenomena.

Stations corresponding to (a) are not common because of their requirements for trained professionals, technical personnel and equipment. In most countries the majority of agricultural meteorological stations belong to categories (b), (c) and (d).

2.2.2 Selection and layout of a station site

2.2.2.1 Selection of a representative site location

The accuracy of observations at a given time is a determinable fixed quality, but their representativity

varies with their application. Representativity of a measurement is the degree to which it describes reliably the value of some parameter (for instance, humidity or wind speed) at a specified space scale for a specified purpose (WMO, 2001b). Instrumentation, exposure and observation procedures must be matched to achieve useful representation – for example, local 2-minute averages for aviation, or hourly mesoscale averages for synoptic forecasts.

Therefore, when selecting a site for a station, the purpose of its observations must be decided first – should it be regionally representative, then even in a woody region an open location is preferable, because the station's observation must relate to the lower atmosphere of the region. If the purpose of establishing a station is monitoring or operational support of some local agricultural situation, then it can be representative when its location is typical for that application, maybe in a forest, in a very humid area (for disease protection purposes), or at the bottom of a valley (for studying frost protection). Even so, locations should be avoided that are on or near steeply sloping ground, or near lakes, swamps or areas with frequent sprinkling or flooding.

The site of a weather station should be fairly level and under no circumstances should it lie on concrete, asphalt, or crushed rock. Wherever the local climate and soil do not permit a grass cover, the ground should have natural cover common to the area, to the extent possible. Obstructions such as trees, shrubs and buildings should not be too close to the instruments. Sunshine and radiation measurements can be taken only in the absence of shadow during the greater part of the day; brief periods of shadows near sunrise and/or sunset may be unavoidable. Wind should not be measured at a proximity to obstructions that is less than ten times their height. Tree drip into raingauges should not be allowed to occur.

Accessibility to the weather station and the possibility of recruiting good observers locally should also be criteria for selection of a site. Finally, for major stations, the likelihood that the conditions of the location will remain the same over an extended length of time with little change in the surroundings should be investigated.

2.2.2.2 Layout of station instruments

To minimize tampering by animals and people, it is desirable to fence the weather station

enclosure. A sample layout is shown in Figure 2.1. This layout is designed to eliminate as far as possible mutual interference of instruments or shadowing of instruments by fence posts. The door of the thermometer screen must open away from the sun, to ensure that direct sunlight does not enter the screen during observations. At equatorial and tropical stations, the screen will have doors opening to both the north and the south. A larger enclosure is recommended when small plants are used for phenological observations. A rather sheltered enclosure is not a good place for measuring wind; a nearby location with better exposure may be preferable for the wind mast.

2.2.3 Primary handling of data

If the weather station is part of a network, another factor to be considered is the use of the data: whether they will be used for climatological or real-time information purposes. If the data are used for the latter, a rapid communication system is necessary for data transmission, whether by land-line, radio or satellite. The issues of using data for climatological purposes were discussed under agenda point 10.3 of the fourteenth session of the Commission for Agricultural Meteorology (CAGM), held in New Delhi, India, in 2006, on the "Expert team on database management, validation and application of models, research methods at the

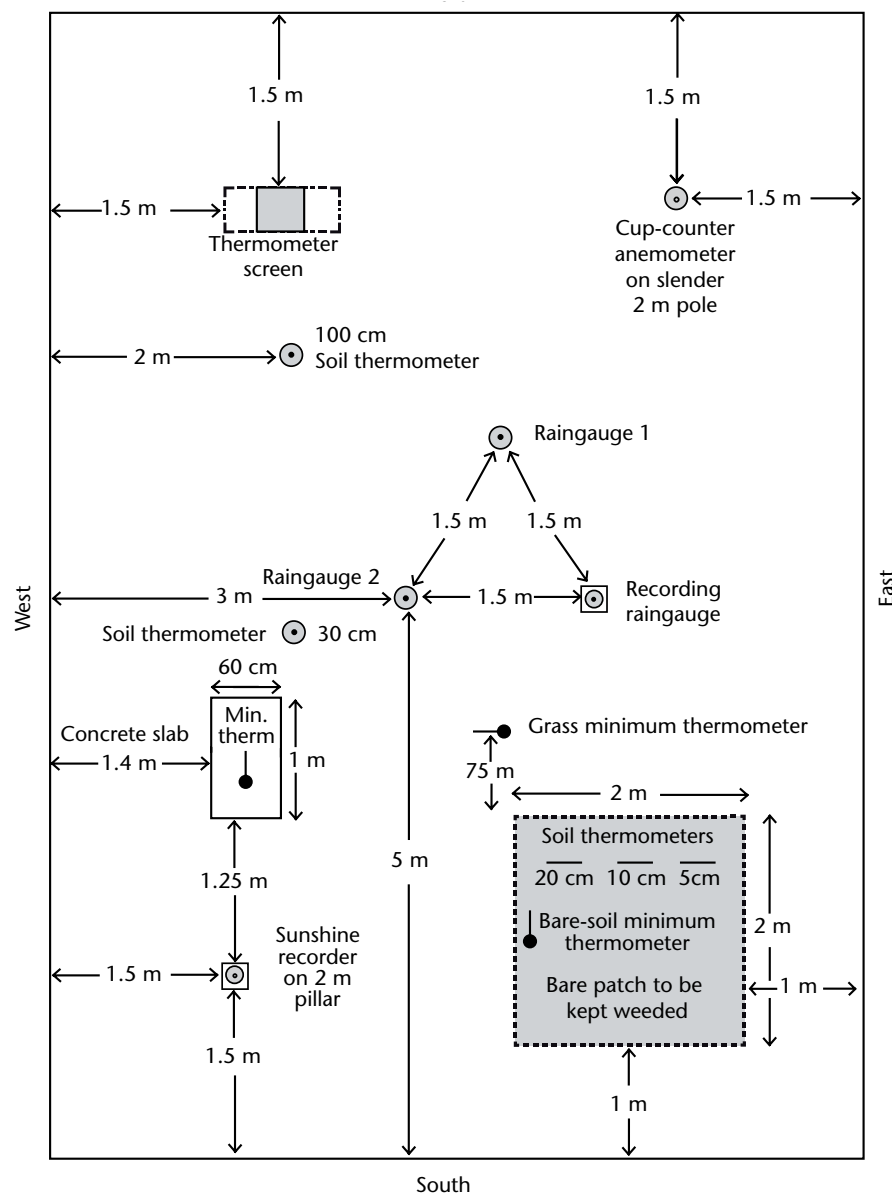


Figure 2.1. Layout of an observing station in the northern hemisphere showing minimum distances between installations (from WMO, 2000b)

eco-regional level". This discussion emphasized that data should be entered locally as they are collected (either on an hourly or daily basis) and that the data should be entered only once into a Database Management System (DBMS) and be made available to all portions of the National Meteorological and Hydrological Services (NMHSs). The DBMS system used should be capable of handling climatic and other types of data, such as ecological, hydrological, agricultural and geo-referenced data; it should also be able to easily import data from a variety of formats. Also, all data should be input directly into a DBMS and then used by various software application packages. Some quality control (QC) of the data can be conducted locally as the data are being entered. Other QC such as spatial quality checks can be undertaken at the central database. It is important that all data, both raw and those processed for the long-term archive, be backed up securely at every stage.

2.2.4 Networks

When agricultural meteorological stations are being established or reorganized, the number of stations within each region should depend on its extent, climatic types and sub-types, and the spatial variations of such factors as the natural vegetation, main crops and agricultural methods. As far as possible, each large homogeneous phyto-geographical region should be represented by at least one principal agricultural meteorological station.

Similarly, each characteristic area devoted to a particular aspect of agriculture, animal husbandry, hydrobiology or forestry should, wherever possible, be represented by an ordinary agricultural meteorological station. Sufficient auxiliary agricultural meteorological stations should be installed to ensure adequate spatial density of the observations of the meteorological and biological variables of major agrometeorological concern to the country.

From another point of view, marginal areas of agriculture and silviculture will often deserve special attention. One main object of observations made in such areas would be to determine the boundary of the region where an individual crop could be grown successfully or a specific agricultural or silvicultural procedure might be profitable; another would be to ascertain the frequency and the typical geographical distributions of the main weather hazards, with a view to reducing their adverse effects as far as possible by means of protective measures.

Areas where agricultural production is markedly exposed to losses through plant and animal diseases

are of special interest, as meteorological factors can be important in the development of these diseases. National parks and nature reserves, although usually not representative of the areas that are of major economic importance in agriculture, may provide good locations for reference stations where observations can be made over long periods under practically identical conditions.

The selection of these stations, whether principal, ordinary, auxiliary or for specific purposes, will vary from one country to another, but some general guidance may be given. The first consideration is that all agrometeorological stations should be located in regions of agricultural, silvicultural, pastoral or other forms of production. For information on representativity, see 2.2.2.1. In this connection, the following locations will often be suitable for principal (and ordinary) stations:

- (a) Experimental stations or research institutes for agriculture, horticulture, animal husbandry, forestry, hydrobiology and soil sciences;
- (b) Agricultural and allied colleges;
- (c) Areas of importance for agriculture and animal husbandry;
- (d) Forest areas;
- (e) National parks and reserves.

In the case of auxiliary stations and stations established for specific purposes, selected farms should also be considered. Experience has shown, however, that if the observations are made by alternating groups of students who may be insufficiently trained for this purpose, as in the case of observatories located at higher education institutions, very careful supervision will be needed to ensure observations of acceptable quality. In general, the observational accuracy should be a major consideration; quality must not be sacrificed for quantity.

No difficulties should normally arise in locating basic equipment in areas devoted to agriculture, horticulture and animal husbandry, since the terrain is usually relatively level and open, satisfying the general standards for locating agrometeorological and climatological stations.

Stations located in forested or silvicultural regions require special consideration. They should be representative of the general climate in the forest, and should reflect the effects of tree development within the forest. The exposure conditions and instrumental requirements of these stations are described in Chapter 11.

At the fourteenth session of CAgM it was restated that adequate density of (agrometeorological)

stations and intra- and extrapolation of routine station data to agricultural field conditions remain of great concern, particularly in developing countries. Automatic weather stations can assist in solving some of the related problems, but instrument coordination, calibration and maintenance are serious issues to be considered with great attention, and even more so with automatic weather stations, again particularly in developing countries.

Special equipment required for non-routine observations, such as that needed for experiments, research and special agrometeorological services, is generally installed outside standard enclosures, for instance, within crops, above crop canopies or in areas under cultivation.

2.2.5 Documentation of agricultural meteorological stations

The metadata information that is necessary in support of reliable observations is described at length in WMO (2003*a*) and more briefly in WMO (2008*b*). Its acquisition is summarized below.

Full information on all of the agricultural meteorological stations in the country should be available in the NMHSs. For this purpose an up-to-date directory of these stations, whether controlled by the NMHS or by other services or agencies, should be maintained. In countries where there are many regional agrometeorological services or where networks are managed by farmers and commercial enterprises, constant updating of this general directory at the national level will be needed. The directory should archive for each station:

- (a) Station identification: name, network code number(s), category of station;
- (b) Geographical location: latitude and longitude (accurate in units of a few hundred metres, for example, 0.001 degree), mapping of mesoscale region ($\approx 1:100\ 000$) with major terrain elevation changes; physical constants and profile of local soil;
- (c) Observing programme specification and history: for each parameter, the dates on which records begin and end and the dates on which instruments, observation height or site are changed. Archive of all updates of station mappings as described in (e) through (h) below. Description of observation routine procedures and basic data processing. Units in use. Routine transformations of observed parameters to archived data;
- (d) Station information contact: name of station-supervising organization or institution,

identification (name, address, telephone or fax, or e-mail) of observer(s) or other person(s) responsible for local measurements and/or their archiving.

To support and complement this national documentation, the station observer(s) at individual stations should maintain local documentation on the following metadata:

- (e) Toposcale map of surroundings (with a scale of $\approx 1:5\ 000$), as specified by the Commission for Instruments and Methods of Observation (CIMO) (WMO, 2008*b*), including location and size of obstacles, surrounding vegetation, and significant terrain features (such as hills and hollows, lakes, built-up areas, roads). This map should be updated at least yearly;
- (f) Microscale map of the station enclosure with an indication of the location of instruments and their height above the ground, updated upon changes. Description of the instrument shelter;
- (g) Photos of the enclosure and all instrument positions outside the enclosure, showing them in their surroundings (that is, from sufficient distance, 20 m or more), taken from all directions (at least six or eight, with the directions identified on the photo print), updated upon significant changes;
- (h) Regularly updated horizon mapping of solar radiation observation (see WMO, 2008*b*);
- (i) Specification of all instruments: manufacturer and model, serial number, output type and sensitivity, recording or frequency of observation, beginning and end of use;
- (j) Regularly used logbook with history of station activities: calibrations and other control activities, maintenance, all interruptions and missing observations, significant developments (for example, nearby building activities, growth of vegetation).

For some parameters, “particular” metadata requirements are mentioned in 2.4. As the above represents only a summary of the requirements, it is advisable to consult WMO (2003*a*) for a more detailed description.

2.2.6 Inspection and supervision of stations

Agricultural meteorological stations maintained by the National Meteorological Service should be inspected at least once a year to determine whether the exposure has changed significantly and to ensure that observations conform to the appropriate standards and that the instruments are

functioning correctly and are calibrated at the required times. The time interval between successive inspections of an individual station will depend upon the programme of the station and the qualifications of the local personnel responsible for the programme.

If other authorities make agricultural meteorological observations, they should enter into cooperative arrangements or special agreements with the National Meteorological Service to ensure adequate supervision and maintenance of the network, including calibration of equipment.

2.2.7 Fixed agrometeorological stations

These stations are foreseen as operating for an extended period at a fixed place, and may be:

- (a) Minimum equipment stations, consisting of a small portable screen, minimum and maximum thermometers, dry and wet bulb thermometers, totalizing anemometer at a convenient height, and raingauge. For screens that are not standard, the radiation error should be determined;
- (b) Standard equipment stations, consisting of standard screen instruments and raingauge as in (a) above, thermohygrograph, wind vane, and wind-run and sunshine recorders. These allow one to determine evaporation using empirical methods;
- (c) Semi-automatic stations with an uninterruptible power supply, which are required to provide the measurements when trained personnel are not available. There is no automatic data communication;
- (d) Automatic stations, which require less supervision, but installation, calibration and inspection must be of a high standard. An uninterruptible power supply is required and data from these stations can be used for direct computer processing. Initial and maintenance costs, as well as proper calibrations, may be limiting factors. Data should preferably also be communicated automatically.

2.2.8 Mobile stations

Mobile stations are used for surveys and research. Some mobile stations move continuously and others need equilibrium of sensors or certain periods for measurements, such as for local wind observations. When an extended but superficial survey of air temperature and humidity is required, vehicles usually carry the instruments. In these circumstances, use is made of thermocouples and

thermistors that have a rapid response (low “time constants”) and high sensitivity.

When using motor vehicles, all mechanical instruments should have anti-shock mounts and should be mounted so that the recording movement is perpendicular to the direction of the most frequent vibrations, in order to reduce the effect of these vibrations on the instruments.

2.2.9 Agricultural mesoclimatological surveys

The objective of agricultural mesoclimatological surveys is to determine meteorological variables or local special factors affecting agricultural production on a local mesoscale that are not representative of the general climate of the region. The surface relief (topoclimatology) and character (landscape), regional wind circulations, water bodies, forests, urban areas and like characteristics come under these categories. Reference may be made to *An Introduction to Agrotopoclimatology* (WMO-No. 378). These surveys are particularly useful where high measurement densities are needed and in developing countries or sparsely populated regions, where network sites are widely separated. Additional data from temporary stations that function from one to five years are useful for comparison with data from the basic network and for evaluation of interpolation of data between temporary and basic network stations. Observations with special instruments, from fixed or mobile stations, may serve to complete the general pattern.

In the older literature, mesoclimatology and topoclimatology were seen as studying the influence of the earth's actual surface on climate and of the climate on that surface. Many important factors that influence the local exchanges of energy and moisture were noted: configuration and roughness of the earth's surface; colour, density, thermal capacity, moisture content and permeability of the soil; properties of the vegetation covering it; albedo (the reflection coefficient of a surface); and so on. More recent literature still uses the same approach (for instance, Geiger et al., 1995), adding exchanges of gases other than water vapour, liquids, particles, and the like. The fourteenth session of CAgM agreed that special attention should be paid to peak values of rain, wind, and flows of water, sediment and other materials carried, because they were locally of great importance to agriculture.

The series of publications issued jointly within the framework of the FAO/UNESCO/WMO Interagency

Project on Agroclimatology between 1963 and 1982², which present agroclimatological studies in several developing regions, contain various aspects of mesoclimatological surveys. The start of a newer agroecological approach, where mesoclimatological surveys are incorporated into wider production evaluations, can be found in Bunting (1987). Modern quantitative approaches in agroclimatology at the mesoscale using remote-sensing and Geographical Information System (GIS) technologies are reviewed in the present Guide as agrometeorological services (Chapters 4 and 6). They often have to be combined with classical measurements, such as ground truth or farm-scale details (Salinger et al., 2000). These classical measurements may be from fixed or mobile, standard or automatic equipment, while complementary observations to describe the special mesoclimatic processes may sometimes be used (for instance, WMO, 2008b).

2.2.10 **Complementary observations to describe special mesoclimatic processes**

The spatial characterization, including the vertical dimension, of mesoclimatic patterns of temperature, humidity, pressure and wind in the lower troposphere for research purposes is determined as follows:

- (a) Aircraft meteorograph soundings are performed on days presenting typical air masses for each season. It may be advantageous to carry out soundings at hours of minimum and maximum surface temperatures. The soundings that are made should be selected for the problem under study, vertically spaced every 100–150 m up to 800–1 000 m, and then every 300–500 m up to 3 000 m;
- (b) Soundings up to 300–500 m are carried out with a fixed meteorograph or radiosonde suspended from an anchored balloon. To avoid wind motion, in the past balloons were usually fixed with three bracing lines; however, modern instruments compensate for the movement if required;
- (c) For the study of wind structure upto 300 m, anchored directional balloons and/or sodars pointing into the direction of the wind may be used. For greater heights,

pilot balloons with a low rate of ascent are used; their flights are followed from the ground with two theodolites. At night the balloons must be battery-illuminated. Smoke bombs may be useful to show wind direction as well as turbulence up to a limited height.

2.2.11 **Detailed physical observations of a non-routine or non-permanent character (agricultural micrometeorological research)**

Detailed accurate observations that are neither routine nor permanent are needed for fundamental research, and are usually carried out independently of conventional agroclimatological observations. Phenomena and processes concerned are, for example, listed and explained in Stigter (1994b). Such observations are made to a high degree of accuracy by skilled, scientifically trained staff and mostly include micrometeorological measurements made with specially designed instruments. For observations as highly specific as these, no general method can be formulated (see for example Woodward and Sheehy, 1983; Percy et al., 1989).

2.3 **OBSERVATIONS TO BE CARRIED OUT AT AGRICULTURAL METEOROLOGICAL STATIONS**

2.3.1 **Observations of the physical environment**

The observing programme at agricultural meteorological stations should include observations of some or all of the following variables characterizing the physical environment: solar radiation, sunshine and cloudiness, air and soil temperature, air pressure, wind speed and direction, air humidity and soil moisture, evaporation and precipitation (including observations of hail, dew and fog). The water balance, evapotranspiration and other fluxes may be deduced from these and other measurements. Minimum accuracy for the different variables is recommended in WMO (2008b) as given in Table 2.1.

These measurements refer to the programme that should be followed for permanent or routine nationwide observations. Nevertheless, the needs of agricultural meteorology frequently require additional and special information, mainly at principal and ordinary stations, such as the following:

- (a) Results of agricultural mesometeorological surveys;

2 *Une étude d'agroclimatologie dans les zones arides et semi-arides du Proche-Orient* (WMO-No. 141), *An Agroclimatology Survey of a Semi-arid Area in Africa South of the Sahara* (WMO-No. 210), *A Study of the Agroclimatology of the Highlands of Eastern Africa* (WMO-No. 339), *Estudio agroclimatológico de la zona andina* (WMO-No. 506) and *A Study of the Agroclimatology of the Humid Tropics of South-East Asia* (WMO-No. 597).

Table 2.1. Minimum accuracy recommended by WMO for some variables

Variable	Accuracy required in daily values
Temperature, including max/min, wet and dry bulb, soil	$< \pm 0.5^{\circ}\text{C}$
Rainfall	$\pm 1 \text{ mm}$
Solar radiation including sunshine	10% ($\pm 1\text{h}$)
Evaporation	$\pm 1 \text{ mm}$
Relative humidity	$\pm 5\%$
Photoperiod	10% ($\pm 1\text{h}$)
Wind speed	$\pm 0.5 \text{ ms}^{-1}$
Air pressure	$\pm 0.1 \text{ hPa}$

- (b) Data derived from remote-sensing;
- (c) Accurate physical observations on a non-routine basis (for agricultural micrometeorological research).

Some general comments concerning each of these variables or groups of variables are offered in the following publications: the *Guide to Climatological Practices* (WMO-No. 100) gives detailed guidance on climatological observations in general and considers aspects that apply equally to the observation of climatic variables for routine climatological purposes or to the programme of an agricultural meteorological station. The *Guide to Meteorological Instruments and Methods of Measurement* (WMO-No. 8) discusses extensively the instruments to be used and observing practices to be followed in meteorology. It must be stressed that the material contained in these publications and in the present Guide refer to the ultimate aims of an agricultural meteorological service. The initial steps taken by any such service can obviously be of a simpler character, but should be such that further expansion can be made along the lines indicated. Normally, only principal agricultural meteorological stations would attempt to conduct all the observations described in the present publication.

2.3.1.1 Radiation and sunshine

Reference may be made to Coulson (1975), Fritschen and Gay (1979), Iqbal (1983), WMO (1984, 2001b, 2008b), Goel and Norman (1990), Strangeways (2003), and WMO Technical Note No. 172. In addition, the duration of day length, which influences

the flowering and growth of shoots of crop plants, should be recorded or obtained at all agricultural meteorological stations. This information should be supplemented wherever possible by data obtained from radiation instruments. Principal stations should make detailed observations of radiation, including global solar radiation, photosynthetically active radiation (PAR) and net all-wave radiation. The spectral distribution of solar radiation influences the growth and development of plants and efforts should be made to include it in the observing programme. Important components are ultraviolet, PAR and near-infrared radiation.

Most commonly, a solarimeter (pyranometer) is mounted horizontally and measures the total solar irradiance on a horizontal surface. In addition, a shade ring (or occulting disk) may be used to cast a shadow on the sensitive area, eliminating the direct beam. The instrument then indicates only the diffuse (sky) radiation. The power of the direct beam may be calculated by subtracting the diffuse reading from the total radiation. Beam fraction sensors without moving parts are also now available.

Solarimeters can be used to measure the short-wave radiation reflected from a crop surface as well. An additional sensor is inverted, fitted with a shield to eliminate diffuse sky radiation, and mounted high enough over the surface so that the shadow it casts is a very small part of the surface area (crop canopy) being investigated. A pair of upward and downward facing solarimeters forms an albedometer.

Research results show that shade influences photosynthesis and temperature. At the macro level, shade occurs due to clouds, mountain slopes, and so on. At the micro level, shade varies due to the plant canopy itself, intercropping choices, surrounding trees, and the like. Photosynthesis is the major metabolic process in agriculture that depends on solar radiation. As a result, occurrences of shade and its distribution, duration and intensity influence photosynthesis and therefore the production processes. Shade and light also cause many morphological processes in plants and behavioural changes in animals. Though more shade reduces agricultural production in many field crops, it improves quality in many cases. In many fruit crops, fruit quality is improved with partial shade treatments. The effect of shade on crops can be measured using cloths that reduce insolation by a required percentage over plots of the experimental field. Tube solarimeters (made in tubular form for easy insertion horizontally under a crop canopy) are vital for measuring solar radiation and shade influence in crop growth, agroforestry and mulch

studies. For further details see 2.4.1.1, which also discusses infrared thermometers and pyrgeometers for long-wave radiation from sky and earth.

2.3.1.2 Air temperature

Reference should be made to Fritschen and Gay (1979), WMO (1984, 2001*b*, 2008*b*), Goel and Norman (1990) and Strangeways (2003). The temperature of the air should be measured in representative places, at different levels in the layer adjacent to the soil. Measurements should be made at principal agricultural meteorological stations from ground level up to about 10 m above the upper limit of the prevailing vegetation because air temperature affects leaf production, expansion and flowering. At ordinary or auxiliary stations, however, the measurements will usually be restricted to the lowest few metres above the surface, which are the most significant layers for studying climatic conditions affecting agricultural crops, their growth and development; these are also the layers with the largest gradients and most rapid fluctuations. To study the vertical distribution of temperature within the lowest two metres of the atmosphere, measurements should be made at three levels at the least, selected from the following heights: 5, 10, 20, 50, 100, 150 and 200 cm. Observations taken for special research projects vary with the needs of the problems under investigation.

In order to study the diurnal variations of temperature, recording instruments should be used at least at one level. Where a continuous record of temperature is not possible, the maximum and minimum values should be recorded at two or three levels. Such measurements should generally be made under standard conditions, namely, over a short grass cover maintained as far as possible unchanged throughout the year or, if this is impossible, over bare soil. Observations should be made, as far as possible, in the middle of a fairly large representative area (20 to 50 m in diameter) containing level ground with soil or vegetation cover. At principal agricultural meteorological stations, the measurements should be supplemented by similar ones taken in various regional crops during the growing season. These supplementary observations should be carried out at the same levels as the observations over bare soil or grass, and also at levels immediately below and above the upper limit of the vegetation.

Exposure to radiation is a serious source of error in measuring atmospheric temperature. Probably the best method of measuring air temperature is by using freely exposed electrical equipment (resistance

or thermocouple thermometers) having thin or reflective sensitive elements with a very low absorption of radiation. Where such instruments are not available, shade screens or ventilated thermometers may be used for levels at least 50 cm above bare soil or dense vegetation. Non-standard screens generally used at other meteorological stations run a risk of hampering the flow of air past the thermometers and, in bright sunshine and light winds, they may be heated to a temperature above that of the ambient air. The disadvantage is especially marked for measurements below the standard level of 1.25 to 2 m. Thermometer screens are therefore not recommended when the vertical distribution of temperature up to 2 or 3 m is desired, although small open reflective screens have been used with some success. It is necessary to protect thermometers in the open from precipitation by small roof-shaped shelters.

2.3.1.3 Temperature of soil

Reference should be made to Rosenberg et al. (1983) and WMO (1984, 2001*b*, 2008*b*). Soil temperature directly influences crop growth because the sown seeds, plant roots and micro-organisms live in the soil. The physicochemical as well as life processes in agriculture are also directly affected by the temperature of the soil. Under low soil temperature conditions, nitrification is inhibited and the intake of water by roots is reduced. Extreme soil temperatures injure plants and thereby affect growth.

The observing programme at all categories of agricultural meteorological stations should therefore also include soil temperature measurements. The levels at which soil temperatures are observed should include the following depths: 5, 10, 20, 50 and 100 cm. At the deeper levels (50 and 100 cm), where temperature changes are slow, daily readings are generally sufficient. At shallower depths the observations may comprise, in order of preference, either continuous values, daily maximum and minimum temperatures, or readings at fixed hours (preferably not more than six hours apart).

When soil temperature data are published, information should be given on the way the plot is maintained. The depths of the thermometers at 5, 10 and 20 cm should be checked periodically and maintained. Efforts should be made to ensure that good contact is maintained between the thermometer and the soil.

Regarding the surface of the plot where soil temperature is measured, two types of standard cover are used – bare soil and short grass. Wherever possible, simultaneous readings should be made under both

standards for comparison. In many places, however, it may be difficult or even impossible to maintain plots conforming to both standards. Hence the one most suited to the region should be used. Also, wherever the standard surface is not representative of the surroundings, the instruments should be placed near the centre of a large plot (for bare soil, the *Guide to Meteorological Instruments and Methods of Measurement* (WMO-No. 8) recommends 2 m × 2 m). A comparison of soil temperature observations under a standard cover and under crops shows the modifications of the temperature regime due to the principal regional crops and their cultivation, depending on soil modification, soil shading and suppression of air movement over the soil (Mungai et al., 2000).

When soil temperatures are measured in a forest, the reference level for the depths of measurement should be clearly indicated: whether the upper surface of the litter, humus or mass layer is considered to be at 0 cm; or whether the soil–litter interface is taken as zero reference. These details and any seasonal variations in them should be quoted when the data are published (for further details, see Chapter 11 of this Guide).

Whenever the ground is frozen or covered with snow, it is of special interest to know the soil temperature under the undisturbed snow, the depth of the snow and the depth of frost in the soil. Measurement of the thermal properties of the soil (such as specific heat and thermal conductivity), temperature profiles, and changes in these profiles should be included.

2.3.1.4 Atmospheric pressure

Reference should be made to Murthy (1995, 2002). The lower pressures experienced as altitude increases have important consequences for plant life at high altitude. At high altitudes and low atmospheric pressures the solubility of carbon dioxide and oxygen in water is reduced. Some plants show stunted growth at higher altitudes as concentrations of oxygen and carbon dioxide reach low levels. Plants with strong root systems and tough stems can live under increased wind speeds at low pressures in high-altitude areas. It is usually adequate to know the altitude at which an event takes place, but in some cases pressure variations have to be taken into account. Usually, a station will record pressure as part of the data for climatological work.

2.3.1.5 Wind

Reference should be made to Mazzarella (1972), Wieringa (1980), Kaimal and Finnigan (1994) and WMO (1984, 1998, 2001*b*, 2008*b*). Wind transports

heat in either sensible or latent form between lower and higher layers of the atmosphere and from lower to higher latitudes. Moderate turbulence promotes the consumption of CO₂ by crops during photosynthesis. Wind prevents frost by disrupting a temperature inversion. Wind dispersal of pollen and seeds is natural and necessary for certain agricultural crops, natural vegetation, and so on. As far as the action of wind on soil is concerned, it causes soil erosion and transport of particles and dust. Extreme winds cause mechanical damage to crops (for example, lodging or leaf damage) and forests (windthrow). Knowledge of the wind is also necessary for environmentally sensitive spray application and for the design of wind protection. For the main regional crops, it may be useful to make observations of wind profiles inside and above the crop canopies for a better understanding of exchange properties.

Agricultural meteorological stations need toposcale reference observations of both wind speed and direction, preferably at 10 m height, but at least at three times the height of any nearby vegetation (for instance, crops) and any nearby obstacles, in order to be above significant flow interference. Lower-level wind measurements are not representative at toposcale and cannot be properly corrected either, so they cannot be used as local reference or for comparison with other stations (WMO, 2001*b*). Horizontal distance to obstacles should be at least 10 times their height. When possible, the wind speed gustiness should be obtained along with average wind, for instance by recording the largest three-second gust in each averaging period.

This basic programme may be supplemented, where circumstances permit, by measurements of wind speed at one or more levels between the surface and 10 m; wind direction varies little in that layer. Except for layers rather close to the ground, this can be done by means of sensitive cup anemometers or propeller vanes, which tend to lose accuracy, however, because of the need for them to rotate into the wind (WMO, 2008*b*). Any more ambitious programme should be carried out at principal agricultural meteorological stations or operationally with mobile stations, as recently done in Africa (WMO, 2005). Wind speed and gustiness are measured at various levels right down to the ground by means of anemometers of high sensitivity, with parallel temperature measurements at those levels.

2.3.1.6 Air humidity and soil moisture (including leaf wetness)

Reference should be made to WMO (1984, 2001*b*, 2008*b*).

2.3.1.6.1 *Humidity*

Humidity is closely related to rainfall, wind and temperature. Different humidity-related parameters such as relative humidity, vapour pressure, dewpoint and other derived characteristics are explained in many textbooks. They play a significant role in crop production and strongly determine the crops grown in a region. Internal water potentials, transpiration and water requirements of plants are dependent on humidity. Extremely high humidity is harmful as it enhances the growth of some saprophytic and parasitic fungi, bacteria and pests, the growth of which causes extensive damage to crop plants. Extremely low humidity reduces the yield of crops.

Like temperature and for the same reasons, the humidity of the air should be measured in representative places, at different levels in the layer adjacent to the soil at principal agricultural meteorological and other category stations. The procedures for air temperature should also be followed for this weather variable, including taking measurements above and within vegetation.

2.3.1.6.2 *Soil moisture*

Reference may be made to Greacen (1981), Vining and Sharma (1994), Smith and Mullins (2001) and WMO (2001*b*, 2008*b*). In scheduling irrigation, the estimation of moisture content is the basic requirement. The soil water content can be determined by direct methods, such as gravimetric and volumetric determinations, and indirect methods, which may include the use of devices such as tensiometers, resistance blocks, neutron moisture meters and time domain reflectometry (see 2.4.1.6.2).

Soil moisture should be measured at all principal stations and, wherever possible, at other agricultural meteorological stations. Although rigid standardization is neither necessary nor, perhaps, even desirable, these measurements should, wherever possible, be made from the surface to depths of 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm. In deep soils, with a high rate of infiltration, measurements should be extended to greater depths. Often levels will be selected in relation to the effective rooting depths of the plants. Until it is possible to make reliable continuous recordings at some of these levels, it is recommended that observations be made at regular intervals of about 10 days; for the shallower depths, shorter intervals (seven or five days) will be necessary. In areas with snow cover, more frequent observations are required when the snow is melting.

Standard soil moisture observations should be made below a natural surface representative of the uncultivated regional environment. Simultaneous observations in areas devoted to principal regional crops and covering all cultural operations will show modifications introduced by agricultural processes. These soil moisture measurements are particularly useful in verifying soil moisture values estimated from meteorological measurements. Further discussion of soil moisture problems may be found in Technical Note Nos. 21 and 97. In operational agrometeorology, the problem of on-farm measuring density was dealt with by Ibrahim et al. (1999), who subsequently accurately determined water waste in irrigated groundnut and sorghum (Ibrahim et al., 2002). Oluwasemire et al. (2002) discussed a sampling method in intercropping conditions, while infiltration of rainwater and use of this soil moisture could be followed simply in the field by Mungai et al. (2000).

The following additional parameters will contribute to a better understanding of soil moisture conditions:

- (a) Field capacity and other hydrological constants of the soil;
- (b) Permanent wilting point;
- (c) Depth of groundwater.

2.3.1.6.3 *Leaf wetness and dew*

The weather provides liquid water not only in the form of precipitation, but also in the form of dew, which is not the same as leaf wetness but is one of its possible causes. Dew (fall) occurs in a humid atmosphere when temperature falls and wind is weak, resulting in condensation both on the vegetation and on the soil. Dew often occurs due to distillation of water from (wet) soil (dew rise). Guttation occurs on vegetation when its internal water pressure is excessive. In some very dry regions dew may well be a significant source of moisture in maintaining plant life (Acosta Baladon, 1995).

Leaf wetness can result from precipitation, from dew or from guttation. Knowledge of leaf wetness duration is vital information for the protection of crops against fungi and diseases (Technical Note No. 192), and it cannot be deduced usefully with rules of thumb such as $RH > 90$ per cent. Actual monitoring has so far been carried out only in a few countries on a routine basis with specific agrometeorological requirements in mind. Studies and recordings of leaf wetness duration (LWD) also help in developing early warning systems and plant protection, in understanding soil evaporation and in improving

leaf-surface water evaporation modelling. Calibration of sensors is also enhanced in this way.

2.3.1.7 **Precipitation (clouds and hydrometeors)**

Reference should be made to Meteorological Office (1981), Murthy (1995), Baldy and Stigter (1997), for forms in which rainwater reaches the soil, Murthy (2002) and WMO (2008*b*). WMO Technical Note No. 55 may also be useful.

At an agricultural meteorological station, visual observations and automatic instrumentation to measure total cloud coverage, that is, all sky camera observations, may be made at regular intervals to measure the total amount of cloud. In addition, cloud type and height of cloud base are required for studies of the radiation balance. Observations of hydrometeors are useful for many agricultural purposes. They include rain and drizzle (including intensity), snow (including thickness and density of snow cover, and water equivalent), hail (including water equivalent and size of hailstones), dew (amount and duration), hoar frost, rime fog, and so forth.

The amount of precipitation should be measured in the morning and evening as at synoptic stations. Additional measurements are desirable and the intensity of precipitation could be obtained by means of a recording rain gauge. Hail is the precipitation of solid ice that is formed inside cumulonimbus clouds, the thunderstorm-producing clouds. It is measured according to individual hail stone size or its liquid equivalency. Advanced techniques such as remote-sensing provide a quick and clear illustration of hailstorm patterns. Data obtained by meteorological radar can be useful in supplementing rainfall measurements and may make it possible to identify and locate hydrometeors that are particularly harmful to agriculture (hail, very heavy showers), with a view to taking appropriate action (Wieringa and Holleman, 2006).

There are still examples of volunteers who do valuable work by simply increasing rainfall measurement densities for disaster detection, and in more developed countries today they make use of the newly available means of communication (for example, Walsh, 2006). O'Driscoll (2006) described another network of this kind in which simple rainfall measurements are made in combination with the reporting of agriculturally important hail and snow. The importance of such simple rainfall data for modern farming can also be understood by viewing Websites such as <http://www.agweb.com>.

The extent and depth of snow cover should be observed regularly where appropriate; it may be desirable to give information about water equivalent and consistency of the snow cover, for instance, once or twice per week.

Especially in dry climates with large daily fluctuations in temperature, the amount of water deposited in the form of dew (or rime) may be of great importance in the water balance of the biosphere. In addition, the duration and amount of dew are important in connection with certain plant diseases (see also 2.3.1.6 above).

2.3.1.8 **Evaporation and water balance measurements**

Reference should be made to Rosenberg et al. (1983), WMO (1984, 1994*b*, 2001*b*, 2008*a*, 2008*b*) and WMO Technical Note Nos. 11, 21, 26, 83, 97 and 126. Measurement of evaporation from free water surfaces and from the soil, and of transpiration from vegetation, remains of great importance in agricultural meteorology. Potential evapotranspiration is defined as the amount of water that evaporates from the soil-air interface and from plants when the soil is at field capacity. Actual evapotranspiration is defined as the evaporation at the soil-air interface, plus the transpiration of plants, under the existing conditions of soil moisture.

Several publications explain the updated, internationally agreed energy balance calculations of crop evaporation (for example, Hough et al., 1996; FAO, 1998; Monteith and Unsworth, 2007), while their applications under on-farm tropical field conditions are now also reported (for example, Ibrahim et al., 2002). Particular attention is drawn to the difficulty of measuring potential evapotranspiration for a small wet surface within a large dry area (oasis effect). Observations of the following parameters, which contribute to knowledge of the water balance, should be made whenever possible:

- (a) Evaporation from a free water surface;
- (b) Height of the water table;
- (c) Irrigation water applied.

Generally, water is applied in fields by different irrigation methods depending upon the crop and soil condition: surface irrigation, subsurface irrigation, sprinkler irrigation and drip irrigation. Surface irrigation includes flooding, check-basin, basin, border-strip and furrow irrigation. Flooding is used exclusively for lowland rice. The check-basin method is adopted when the field is quite large and cannot easily be levelled in its entirety. The field is divided into small plots surrounded by small bunds

on all four sides. In the basin method, which is suitable for fruit crops, only the basin around the trees is irrigated. In the border-strip method the field is divided into a number of strips by bunds of around 15 cm in height. The area between two borders is the border strip. In furrow irrigation, different methods are included, such as deep-furrow, corrugation, alternate-furrow or skip irrigation, wide-spaced furrow irrigation, and within-row irrigation.

Surface irrigation methods are the most economical and are the easiest to operate. There is no requirement for additional input, but the method requires levelling of the field and entails high labour costs. It also provides for low water distribution efficiency (for example, Ibrahim et al., 2000). In the case of subsurface methods, where water gradually wets the root zone through capillary movement, weeds are less of a problem due to dry surface soil. Evaporation losses are minimized, but the maintenance of pipelines is problematic in this type of irrigation. Microirrigation, adopted where water is scarce, includes drip and sprinkler irrigation and is suitable for horticultural crops.

Because of the great importance of water resources for agriculture, detailed knowledge of the factors affecting the different terms of local soil water budgets and larger-scale water balances is highly desirable. The programme of observations for agricultural meteorology must therefore include hydrological observations, such as lake and watershed water balances and the water stages in an adjacent lake or river, which are important in connection with river floods that are significant for agriculture. Cooperation with National Meteorological and Hydrological Services is necessary in this regard (WMO, 1994b, 2008a).

2.3.1.9 Fluxes of weather variables (derived from measured quantities)

The term “flux” means the rate of flow of fluid, particles or energy through a given surface. The basis of modern micrometeorology is the “energy budget”. This may be formed over a surface (such as a lake or large crop field) or a volume (an individual tree). The key to the energy budget is the partitioning of the types or forms of energy at a surface. A surface cannot store any of the heat it receives from net radiation. Therefore, the net all-wave radiation must be partitioned into other forms of energy, which include storage of energy by the soil (ground heat flux) or body of water, energy used in evaporation or gained from condensation (latent heat flux), energy used to

heat the air or gained from cooling the air (sensible heat flux), and the energy associated with biological processes such as photosynthesis, respiration, and so on. Net radiation is the difference between total incoming and outgoing radiation of all wavelengths, and is a measure of the energy available at the surface that drives the above processes. Knowledge of the energy budget is also useful in devising frost protection methods based on an alteration of any of the fluxes (ground heat, sensible heat and latent heat). Some excellent textbooks, for example, Monteith and Unsworth (2007), give mathematical details and applications for these variables.

2.3.1.10 Remote-sensing and GIS

Reference should be made to Goel and Norman (1990), Milford (1994) and WMO (2004a, 2008b). Remote-sensing data provide in many ways an enhanced and highly feasible areal supplement to manual local observations, with a very short time delay between data collection and transmission. These data can improve information on crop conditions for an early warning system. Due to the availability of new tools, such as Geographical Information Systems, management of vast quantities of remarkably high-quality data, such as traditional digital maps, databases, models, and so forth, is now possible. GIS refers to tools used in the organization and management of geographical data, and it is a rapid means for combining various maps and satellite information sources in models that simulate the interactions of complex natural systems. Remote-sensing and GIS in combination will continue to revolutionize the inventory, monitoring and measurement of natural resources on a day-to-day basis. Likewise, these technologies are assisting in modelling and understanding biophysical processes at all scales of inquiry (Holden, 2001; WMO, 2004). Chapter 4 of this Guide provides further details and examples in this connection.

2.3.1.11 Recorders and integrators

Reference should be made to Woodward and Sheehy (1983). Recorders and integrators (for totals or period averages) are the devices that lie between the sensing of an environmental variable and the final site of computations on that variable. A variety of techniques are available for the use of transducers in this process (between sensors and display or recording). To convert transducer output into a state suitable for human vision or for recording, translation devices are useful. Electrical translators, amplifiers, and the like, belong to this category. The techniques of interfacing between the transducer

and the human eye are the most rapidly evolving. Interfacing devices are generally classified into two categories, that is, analog and digital. Analog devices provide a visual representation of transducer outputs marked on scales. Digital devices provide a numerical readout of the transducer output.

A tube is the characteristic link for devices that measure pressure (for example, the manometer, Bourdon tube, and the like). Mechanical linkages are used between temperature sensors, constructed as bimetal strips or helices, and a display, such as a meter or a chart. Hair hygrometers and barometers also rely on mechanical linkages. The problems of electrical interfaces can be virtually eliminated by replacing electrical conductors with fibre-optic links. Transmission of data from a remote location to a convenient receiving station is readily achieved by way of a radio or telemetric linkage.

Choosing the appropriate set of instruments is a complex procedure when a considerable range of instrumentation is available for displaying and recording the output from transducers. Small numbers of transducers can be efficiently interfaced with visual display and manual recording. A chart recorder is useful if automatic recording is required. Where large numbers of transducers are required, automatic recording and display are a necessity. Care should be taken to provide sufficient visual displays of current measurements to allow check-ups and control of the observation chain. If all the channels are of similar voltage, with similar response times, a complex data logger is probably not required; a data acquisition unit may suffice. When data computation is required, for example for linearization of thermocouple voltages and conversion of voltages to environmental units, then a data logger with programming steps contained in a read-only memory may be sufficient. Particular metadata for the recording of sensor signals are signal transmission data, such as cable length (for signal loss estimation), and amplification or modification of the signal.

2.3.2 **Observations of a biological nature**

Reference should be made to Slatyer and McIlroy (1961), WMO (1982), Woodward and Sheehy (1983), Russell et al. (1989), Pearcy et al. (1989), Baker and Bland (1994), and Lowry and Lowry (2001). Biological observations (physical, physiological and phenological measurements of canopies, leaves, roots, growth and yields; see Baker and Bland, 1994) are needed before relationships between weather and various aspects of agriculture

are explained. Such observations give at least a qualitative, but preferably also a quantitative measure of the response of a plant or animal to weather conditions. Biological observations assist agrometeorologists in solving the problems that arise from the relations among plants, animals and pests, on the one hand, and the connections between weather and the growth and yield of plants and animals, on the other. It should never be forgotten that such observations are made on living organisms with an inherent variability that should be taken into account in sampling methods.

As a working method for bioclimatic investigations, phenology should lay down standards for the observation of those periodic processes that are of the greatest importance for agricultural crops. In the case of annual crops, a wide variety of bioclimatic factors must be taken into consideration. They include whether the crops are winter, summer or mid-season crops, how sensitive they are to low and high air and soil temperatures, the requirement of growing degree-days and other heat units in use, irrigation, and other agronomic management. Observations of the start, climax and end of each phase are carried out: first for those crops that cover the entire ground (difficult to observe), and second for the crops planted in rows (easy to observe). In the case of perennial plants, the observations are carried out on individuals, each of which, when taken in isolation, represents a repetitive sample. Three to five fruit trees, forest trees or shrubs of the same age and planted in representative locations in an orchard, wood or plantation are sufficient to give accurate phenological averages.

In explaining the effects of the annual weather cycle on the growth and development of living organisms, it is necessary to record:

- (a) Whether the phenological process follows a pattern adjusted to the meteorological pattern; only the representative moments of phases will be observed;
- (b) Whether the phenological pattern and its phases are interrupted by weather phenomena; it is now essential to carry out simultaneous observations of the stage of development of all the visible phases of the individual plant.

Therefore, each user of biological observations must remember their limitations as to general applicability; often the best methods for recording these observations differ from country to country. As a general principle, it is essential that the

accuracy and extent of biological observations match those of the meteorological observations with which they are to be associated.

Biological observations can be conveniently divided into six broad categories:

- (a) Network observations of natural phenomena taken over a large geographical area, dealing with wild plants, animals, birds and insects;
- (b) Network observations (similar to (a)) and quantitative measurements on the periodical growth and yields of cultivated plants and farm animals. They should include observations on dates of certain events in animal and plant life, as well as cultural operations: dates of ploughing, sowing/planting, weeding, spraying, irrigation (including quantities) and harvesting (including quantities) in the case of plants; calving, milk production, and so forth, in animals. These data are required for the objective study of the relationship between environmental factors and agricultural production;
- (c) Observations of damage to cultivated crops, weeds, animals, and so forth, caused by meteorological factors; occurrence of certain pests and diseases in plants and animals, their severity and areas in which centres of infection are situated; damage caused by atmospheric events, such as hail, drought, frost, storms and their accompanying phenomena;
- (d) Detailed observations, of high accuracy or considerable complexity, required during a specific experiment at a research station or experimental site (see for example Baker and Bland, 1994);
- (e) Network observations of a less complex character than in (d) above, taken over a much greater geographical area and at a large number of sites, which are required for operational use or administrative action shortly after they are taken, that is, for immediate use;
- (f) Global biological observations for assessing the areal extent of specific biological events.

These observations are reviewed in the following paragraphs.

2.3.2.1 Observations of natural phenomena

These observations concern weather effects on wild plants and animals that are, for the most part, free from deliberate human interference. Because of this relative freedom, these data are regarded as providing a form of integration of local climate, and as such may prove suitable for use as an operational parameter. Wild flowers, trees and shrubs are suitable for these observations,

as are also migrating birds and hibernating animals.

The organization of these observations should be similar to that for cultivated plants and may often be identical in extent and procedure. Some countries make much use of volunteer non-scientific observers for this work and many countries conduct phenological investigations of the types described here.

2.3.2.2 Observations for agroclimatological use

In this category are phenological observations of cultivated crops and trees, farm animals, and general activities on the land, all of which are required to form an accurate picture of the agricultural year. They differ from those in the operational-use category in that the observations are made on a wider selection of phenomena at a permanent network of reporting stations. The observations are subsequently analysed, published or otherwise permanently recorded by a central authority, but without any degree of operational urgency.

The network can be less dense than required for operational purposes but should cover the entire country and not be confined to any smaller area of specialized agricultural production. The observations can be simpler in character than those specified in some sections of this chapter, but an agreed and fully understood standard of observation is essential. Observations normally consist of the recording of measurements of growth and yields and the dates on which certain events take place.

Each country should select its own standard programme of observations, then draw up a standard set of instructions for reporting and recording them, bearing in mind that the items contained in such a programme will serve as a basis for introducing an operational system in the future, as the need arises.

The necessity for continuity, reliability and uniformity must be impressed upon the observers, who may be volunteers with little scientific training. Each should be given a recording notebook of pocket size, which not only has space for the appropriate entries but also contains the necessary instructions and illustrations. Notebooks should be retained at the observing site; entries should be transcribed into standard forms for transmission to the central authority at convenient regular intervals.

2.3.2.3 Observations of direct and indirect damage owing to weather

2.3.2.3.1 General weather hazards

Weather hazards that may cause loss or damage to soils, plants and animals are usually snow, ice, frost, hail, heavy rain, weather conditions leading to high air pollution, unseasonable heat or cold, drought, strong winds, floods, sand- and duststorms, high- and low-level (crop-level) ozone (see WMO, 2008*b*), and the like. The secondary effects of weather likely to have adverse effects on agricultural production include forest and grass fires and the incidence of pests and diseases.

In some cases, an adequate observational system will have been included, particularly in relation to pests and diseases, forest fires, or the effects of any regularly occurring hazard, such as snow or frost. Regular systems for observing weather damage can also be incorporated into the categories described above in this chapter. Where such systems do not exist, however, special arrangements should be made to accurately assess the extent of damage.

The nature of the observations varies with the type of hazard and can be selected only by each individual country, or by a group of countries with similar climates. They must, however, be clearly specified to eliminate the risk of inaccurate assessments. Furthermore, observation systems must be devised in anticipation of damage, so that selected observers can take action immediately after the unusual weather has occurred. It is also important that good scientific information be available on the causes of the damage. A good recent example involves hail (Wieringa and Holleman, 2006).

2.3.2.3.2 Greenhouse gases

Similarly, contemporary agrometeorologists must understand that climate change due to greenhouse gases related to agricultural production indirectly causes damage to the environment and also to agriculture. Over recent decades, the earth has become warmer due to the increased presence in the atmosphere of gases such as carbon dioxide (CO₂), chlorofluorocarbons (CFCs), methane (CH₄) and nitrous oxide (N₂O). CH₄ and N₂O are the gases mainly responsible for global warming as a consequence of agriculture, while deforestation leads to less absorption of CO₂ from the atmosphere. An increase in these gases in the atmosphere enhances retention of the re-radiated heat and thus adds to the warming of the earth's

surface and lower atmosphere. Observations on these gases and the production-related processes behind their rates of release are therefore necessary to understand these processes. Research results of agronomists and soil scientists relevant to these problems proved, for example, that the soil texture has a significant role in the magnitude of CH₄ emission from rice fields. This is because percolating irrigation water removes organic acids through aeration and high percolation rates in light soils.

2.3.2.3.3 Soil erosion

Soil erosion and related phenomena are other major forms of damage caused directly or indirectly by weather. Soil erosion is the process of detachment of soil particles from the parent body and transportation of the detached soil particles by wind and water. These particles cause biological damage to crops and further problems for water provision; in operational agrometeorology observations are therefore necessary wherever this is or becomes a major problem (for instance, Mohammed et al., 1995).

The detaching agents are falling raindrops, channel flow and wind. The transporting agents are flowing water, rain splash and wind. Depending on the agents of erosion, it is called water erosion or wind or wave erosion. There are three stages of sand movement by wind, all of which usually occur simultaneously. The first one is "suspension" (the movement of fine dust particles smaller than 0.1 mm in diameter by floating in the air). Wind velocities above 3.0 km/h⁻¹ (0.8 ms⁻¹) are capable of lifting silt and very fine sand particles to heights greater than 3 to 4.5 km. Soil particles carried in suspension are deposited when the sedimentation force is greater than the force holding the particles in suspension. Suspension usually does not account for more than 15 per cent of total movement.

The second is "saltation", which is the movement of soil particles by a short series of bounces along the ground surface. It is due to the direct pressure of wind on soil particles and their collision with other particles. Particles less than 0.5 mm in diameter are usually moved by saltation. This process may account for 50–70 per cent of total movement. The third is surface creep, the rolling and sliding of soil particles along the ground surface owing to the impact of particles descending and hitting during saltation. Movement of particles by surface creep causes abrasion of the soil surface, leading to the breakdown of non-erodible soil aggregates due to the impact of moving particles.

Surface creep moves coarse particles larger than 0.5–2.0 mm in diameter. This process may account for 5–25 per cent of the total movement. Measurements of dust, saltating and creeping sand, as well as related soil and crop hazards and defence mechanisms, are essential in operational agrometeorology of affected areas (for instance, Mohammed et al., 1996; Sterk, 1997).

Soil losses by sheet and rill water erosions are most critical in sub-humid and humid areas, whereas wind erosion exacts a higher toll in semi-arid and arid areas. For both types of soil erosion, the maintenance of soil cover at or near the soil surface offers the most effective means of controlling soil and water loss and can be easily quantified (Kinama et al., 2007). Conservation tillage systems are undoubtedly among the most significant soil and water conservation practices developed in modern times but are, in some places, traditional farming practices (Reijntjes et al., 1992). Quantification of their impacts should be improved.

2.3.2.3.4 *Water runoff and soil loss*

The portion of precipitation that is not absorbed by the soil but finds its way into streams after meeting the persisting demands of evaporation, interception and other losses is termed runoff. In some humid regions, the loss may be as high as 50–60 per cent of the annual precipitation. In arid sections, it is usually lower unless the rainfall is of the torrential type. Although the loss of water itself is a negative factor, the soil erosion that accompanies it is usually more serious. The surface soil is gradually taken away and this means a loss not only of the natural fertility, but also of the nutrients that have been artificially added. Also, it is the finer portion of this soil that is always removed first, and this fraction, as already emphasized, is highest in fertility. A recent example in operational agrometeorology of measuring soil loss and water runoff from sloping agricultural land is given by Kinama et al. (2007).

2.3.2.4 *Detailed biological observations*

As in the case of physical observations mentioned above, detailed accurate biological observations are needed for fundamental research. Such observations are made by scientifically trained personnel to ensure great accuracy. The WMO Technical Regulations list the types of biological observations that may be required. It must be stressed, however, that these observations require high precision since they have been especially selected for research purposes. Because observations of this kind are neither routine nor permanent, it is impossible to

recommend general methods suitable for all purposes. This work may be carried out either under natural conditions in the field or in a laboratory environment, which may often involve the use of climate-control chambers, wind tunnels, microscopes and other experimental tools to study the reactions of both plants and animals to single or complex meteorological factors.

It is always important to measure both the physical and physiological responses of living organisms, such as the carbon dioxide intake, osmotic pressure, chemical constitution, leaf area, dry matter index, and growth rate in plants; and the basal metabolism, pulse and respiration rate, rectal temperature, blood volume and composition, blood pressure, composition of food, and so on, in animals.

Care must be taken in control-chamber experiments because the climate simulation often does not represent open-field or natural conditions quantitatively or qualitatively. In order to achieve reliable results, it may be necessary to select a sound statistical experimental design under natural conditions. In this kind of research, teamwork is highly recommended.

2.3.2.5 *Observations for operational use*

In general, the mean data provide a strong basis for comparison with current data, since departure from normal provides the most useful information for operational use. These are observations needed by regional or central authorities to assist them in taking administrative action, making functional forecasts or giving technical advice. Although they must be standard in nature, so that observations from different sources can be compared, such yardsticks as 30-year averages start to become somewhat meaningless in the light of a rapidly changing climate. Other approaches need to be developed that take time trends and increasing variability simultaneously into account.

Such observations will be needed from a large number of sites that form a national network, and will be made by skilled or semi-skilled observers who have received adequate training to meet the desired observational standards. Arrangements must be made to communicate these observations as quickly as possible to the regional or central authorities. Postal services may be adequate but more rapid means such as the Internet, fax, radio, and the like may often be needed.

The density of the network may be limited by the availability of efficient observing staff. All areas of

the country concerned with one type of operational requirement should be adequately covered. Ideally, the network density will depend on the type of problem, the crop types and distributions, the soil variations, the climate, and the population density in the region, which determine the general and repetitive sampling rates.

The authorities must strictly specify the exact nature of the biological observations in an agreed pattern, preferably accompanied by good illustrations. Observations on yield, which may concern small experimental plots or regional or national areas of production, fall under this heading. In planning these observations, the agrometeorologist should collaborate with statisticians and agricultural experts. Wherever necessary, he/she should encourage the agricultural authorities to obtain the data in a form suitable for establishing weather-yield relationships. For regional or national yields, he/she should pay attention to the accuracy of the yield measurements.

The meteorological and biological data are analysed simultaneously by regional and central authorities, which take operational decisions after proper analyses. A summary of the season's work should be prepared and either published or permanently retained for reference, so that the experience of each year is always available for subsequent consideration.

Some examples of information required for specific operational use are:

- (a) Forest fires: the state of the forest litter and its susceptibility to burning (see Chapter 8);
- (b) Diseases: the state of the plant, the presence and release of spores, the incidence and spread of infection;
- (c) Pests: the hatching of harmful insects, the build-up of insect populations, or their invasion from other territories;
- (d) Weather hazards: the state of crops and whether they are at a stage particularly susceptible to weather hazards; animals under stress due to unseasonal climate or other severe weather conditions;
- (e) Farming operations: the progress made in the farming year, in order to make weather forecasters aware of the operational implications of forthcoming weather.

2.3.2.6 Global biological observations

Besides the local observations described above, there are now modern methods for globally evaluating the distributions of biological phenomena, such as:

- (a) Aerophotogrammetry (conventional photography). This is for the mapping of relief and for determining the types of natural vegetation and crops, their phenological state, the soil type, cattle distribution, and so on. The altitude of the aircraft during observation flights must correspond to the desired photographic resolution of the phenomenon under study (through use of multispectral photography). Although this type of photography is diminishing in the developed world, in the developing world it could be still important if enough funds and hardware are available.
- (b) Aerial photography (particular wavelengths). Remote-sensing with special film, sensitized to a region of the visible spectrum, or to infrared radiation, gives valuable information on albedo, intensity and ground emission active in the energy balance. Scanners have also become available. Information can be obtained on soil moisture deficit, drought stress in vegetation, composition of the plant community and its phenological condition, and the state of crops and cattle.
- (c) Satellite observations. Satellite images are useful, especially for extended areas (Chapter 4). Estimates of rainfall and of vegetation indices are routinely available, although their accuracy varies widely depending on latitude, observing system, and the like.

2.4 INSTRUMENTS USED AT AGRICULTURAL METEOROLOGICAL STATIONS

Most of the instruments included as basic equipment at an agrometeorological station are described in WMO (2008b). Short descriptions of some agrometeorological instruments generally used for specific applications are given below. There is a clear need for frequent recalibration of all instruments.

2.4.1 Measurement of the physical environment

2.4.1.1 Radiation and sunshine

Reference may again be made to Coulson (1975), Fritschen and Gay (1979), Iqbal (1983), Goel and Norman (1990), Strangeways (2003), WMO (1984, 2001b, 2008b) and Technical Note No. 172. Some basic remarks on mounting instrumentation have been given in 2.3.1.1. Global solar radiation (direct and diffuse solar radiation) is measured with

pyranometers containing thermocouple junctions in series as sensors. The sensors are coated black to have uniform thermal response at all spectral wavelengths. With filters, non-PAR radiation can be measured, and the difference between solarimeter outputs with and without filters gives PAR data. Stigter and Musabilha (1982) did this for the first time elaborately in the tropics. Solid state sensors (photoelectric solar cells, photoemissive elements, photoresistors, and so on) may be used where radiation can be assumed to have constant spectral distribution (for example, solar radiation within limits). Different types of photometers and ultraviolet illuminometers, which are adaptations of these instruments, are used in agrometeorological research.

Light, which is indispensable for photosynthesis, is one of the major components of short-wave radiation. What is measured with a lux meter is not light intensity, but luminance, which is defined as luminous flux density intercepted per unit area. Quantum sensors that measure the PAR directly in the range between 0.4 and 0.7 micrometers are available. Ideally, crop profile measurements with quantum sensors should be taken on perfectly clear or uniformly overcast days. If this is not possible, however, the problem is partially overcome by expressing the values at each level relative to the incident radiation. These profiles are compared with leaf-area profiles when the light requirements of crops are being studied.

Tube radiometers for use in crops and agroforestry are inherently less accurate than instruments with a hemispherical dome, but can be of great use in estimating the average radiation below a crop canopy or mulch relative to the radiation above it. When mounted north to south, the sensitivity varies with the angle of the solar beam to the axis, particularly in the tropics (Mungai et al., 1997). This adds to errors that are the result of high ambient temperatures under low wind speeds, as well as condensation inside the tubes. Calibrations as a function of time and ambient conditions can largely cope with such errors, but filtered tubes for photosynthetically active radiation appeared unreliable in the tropics (Mungai et al., 1997). To measure the fractional transmission of solar radiation through a crop canopy, a number of tubes are placed beneath the canopy. Their numbers and arrangement depend on the uniformity of the crop stands (Mungai et al., 2000). A reference measure of incident solar radiation above the canopy is needed. For crop studies, the output for each tube is usually integrated over periods of a day or longer during the

growing season. Integrators or loggers are ideal for this purpose. The values of fractional interception are subsequently calculated from the integrals (for example, Mungai et al., 2000).

Surface temperature radiometers are used for measurements of infrared radiation emitted from near or remote surfaces. They are mainly used as hand-held remote sensors to measure temperatures of radiating irregular surfaces such as soil, plant cover and animal skin, and require knowledge of the emissivity coefficient of the observed surface (WMO, 2001b). Operational precautions are given by Stigter et al. (1982).

Pyrgeometers are used for the measurement of long-wave radiation from the sky (when facing upward) or from the earth (facing downward).

Net all-wave radiometers (measuring net flux of downward and upward total radiation, namely, solar, terrestrial and atmospheric radiation) contain black-coated heat-flux plate sensors, in which thermocouples are embedded to measure the temperature difference between the two sides of a thin uniform plate with well-known thermal properties. Errors due to convection and plate temperature are avoided by using forced ventilation, appropriate shields, and built-in temperature compensation circuits. Net radiometers, net pyrradiometers, net exchange radiometers or balance meters may have a standard diameter (about 6 cm) for regular use or a miniature diameter (about 1 cm) for special work on radiation exchange from plant organs or small animals.

Standard meteorological stations usually measure only sunshine duration. The traditional instrument to observe this is the Campbell-Stokes sunshine meter. WMO abolished the world standard status of this sunshine meter in 1989, as the process of evaluating the burns on its daily cards was both cumbersome and arbitrary. Instead, sunshine duration has been defined as the time during which direct radiation (on a plane perpendicular to the sun's beam) is greater than 120 W m^{-2} . This definition makes it possible now to use automatic sunshine recorders (for instance, WMO, 2001b, 2008b).

Particular metadata of radiation measurements include the wavelength transmission spectral window of a pyranometer dome, the sunshine recorder threshold radiation value, horizon mapping for each instrument measuring radiation or sunshine, and procedures or means to keep radiometer domes clean and clear.

2.4.1.2 Air temperature

Reference should again be made to Fritschen and Gay (1979), Goel and Norman (1990), Strangeways (2003) and WMO (1984, 2001*b*, 2008*b*). WMO Technical Note No. 315 is also useful. General issues were discussed in 2.3.1.2. Besides the standard instruments, several others are used in agrometeorological surveys and research.

Small and simple radiation screens, some of which are aspirated when this does not destroy temperature profiles, are useful for special fieldwork. High outside reflectivity, low heat conductivity, high inside absorption and good ventilation are desirable requirements in the construction materials and design. An idea of the radiation errors can, for example, be determined by simultaneous, replicated observations with the ventilated Assmann psychrometer at the hours of maximum and minimum temperature.

The most common thermometers for standard observations in air are those generally called differential expansion thermometers, which include liquid-in-glass, liquid-in-metal and bimetallic sensors. Because of their sizes and characteristics, many of these instruments are of limited use for other than conventional observations. Spirit-in-glass, mercury-in-glass, and bimetallic sensors, however, make useful maximum and minimum temperature measurements. When temperature observations are required in undisturbed and rather limited spaces, the most suitable sensors are electrical and electronic thermometers, which permit remote readings to be made.

Resistance thermometers are metallic annealed elements, generally of nickel or platinum, whose electrical resistance increases with temperature; readings are made with appropriately scaled meters, such as power bridges.

Thermocouples are convenient temperature sensors because they are inexpensive and easy to make. Those most frequently used in the environmental temperature range are copper–constantan thermocouples, which have a thermal electromotive force response of about $40 \mu\text{V}^\circ\text{C}^{-1}$. This relatively weak response can be increased by connecting several thermocouples in series or using stable solid state, direct current amplifiers. Thermocouples are excellent for measuring temperature differences between the two junctions, for instance, dry and wet bulb temperatures, or gradients. When they are used to measure single temperatures or spatial average temperatures (such as surface temperatures, using

thermocouples in parallel), one junction always needs to be at a known steady reference temperature.

Thermistors are temperature sensors that are seeing increasing use in agricultural and animal micro-meteorology. They are solid semiconductors with large temperature coefficients and are produced in various small shapes, such as beads, rods and flakes. Their small size, high sensitivity and rapid response are valuable characteristics, which are offset, however, by their lack of linear response (less than metallic resistances) in the resistance–temperature relationship. Additional components are therefore required to achieve linear output.

Diodes and transistors with a constant current supply that provide outputs much higher than $1 \text{ mV}^\circ\text{C}^{-1}$ have been used to construct sensitive and accurate thermometers for application in plant environments.

Infrared thermometers were discussed in 2.4.1.1. A black globe thermometer is a blackened copper sphere commonly 15 cm in diameter, with a thermometer or thermocouple inserted. When a black globe thermometer is exposed in the open or under a ventilated shelter, the effects of different radiation fluxes are integrated with convective heat (wind and air temperature) effects. Installed inside closed barns or stables, under still air conditions, this type of thermometer gives the average radiant temperature of soil, roof and walls at equilibrium.

Particular metadata for temperature measurement are the height of the sensor and a description of the screens employed (dimensions, material and ventilation).

2.4.1.3 Temperature of soil and other bodies

2.4.1.3.1 Soil

Reference should again be made to Rosenberg et al. (1983) and WMO (1984, 2001*b*, 2008*b*). All sensors mentioned in 2.4.1.2 may be used, although the thermocouple must be of a sturdy construction, provided that presence of the sensor does not affect the temperature being measured. Soil thermometers of the mercury-in-glass type are frequently used. For measurements of the soil temperature at shallow depths, these thermometers are bent at angles between 60° and 120° for convenience. At greater depths lagged thermometers are lowered into tubes. Care should be taken to prevent water from entering the tubes. Alternatively, shielded thermocouples or thermistors can be used. The temperature of

deeper soil layers can be measured with glass thermometers, thermistors, thermocouples, diodes and platinum resistance thermometers when good contact is made with the soil.

In cold and temperate climates where the soil is often deeply frozen and covered with snow, when continuous soil temperature records are not available or when many observing points are needed, different types of snow cover and soil frost depth gauges can be used. These instruments generally consist of a water-filled transparent tube, encased in a plastic cylinder that is fixed in the soil. The tube is periodically removed from its plastic casing to determine the depth to which the entrapped water is frozen. If the fixed cylinder extends sufficiently far above the soil surface, it can be used as a snow cover scale, provided that the exposed part is graduated.

For measuring the soil surface temperature, non-contact infrared thermometers are preferable, as long as emissivity is known and again, the presence of the sensor does not affect the temperature being measured by shading or otherwise influencing the natural radiation balance (Stigter et al., 1982).

Particular metadata for soil temperature profile measurements are instrument depths and regular specifications of the actual state of the surface.

2.4.1.3.2 *Other bodies*

Like the soil, plant parts such as leaves, stems, roots and fruits have mass and heat capacity. The temperature of all these organs can be measured with platinum resistance thermometers, thermistors, thermocouples, infrared thermometers, diodes, and so forth, if the instruments do not influence the energy balance of those bodies. To measure their surface temperatures and those at the outside surface of animals, one should use small contact sensors such as thermocouples and thermistors, or non-contact methods.

In animal micrometeorology special and relatively simple instruments have been used to simulate the cooling power of the air or the heat load over the homeothermic animal body. Kata thermometers are spirit-in-glass thermometers with a rather large bulb of accurately determined area. They are used to measure the time required for a fixed amount of cooling to occur after the thermometer has been warmed to a point above body temperature. Such a reading is an index that integrates the cooling effect of temperature and wind.

The heated-globe anemometer, which provides a reasonable value of the cooling power of air motions in climatic chambers and other indoor environments, is a practical thermo-anemometer. It is constructed with a chrome-plated sphere that is 15 cm in diameter and heated by a nichrome wire that can receive a variable power input. Several thermocouples in parallel with one junction fixed internally to the globe wall measure the temperature of the globe wall. The voltage of the heater is regulated to give a differential air-globe temperature of 15°C. The power needed to maintain a steady temperature is a function of the ventilation. A correction factor for thermal radiation of walls, ground and roof may be required, however, if these are significantly hotter than the air.

2.4.1.4 *Atmospheric pressure*

Reference should be made to WMO (2008*b*). Analysed pressure fields are useful in agricultural meteorology. These pressure fields must be accurately defined because all the subsequent predictions of the state of the atmosphere depend to a great extent on these fields. In mercury barometers the pressure of the atmosphere is balanced against the weight of the column of mercury, whose length is measured using a scale graduated in units of pressure. Of the several types of mercury barometers, fixed cistern and Fortin barometers are the most common. For the purpose of comparison, pressure readings may need to be corrected for ambient air temperature.

In electronic barometers, transducers transform the sensor response into a pressure-related electrical quantity in the form of either analog or digital signals. Aneroid displacement transducers, digital piezoresistive barometers and cylindrical resonator barometers fall into this category. Calibration drift is one of the key sources of error with electronic barometers. Therefore, the ongoing cost of calibration must be taken into consideration when planning to replace mercury barometers with electronic ones.

The advantage of aneroid barometers over conventional mercury barometers is that they are compact and portable. Another important pressure measuring device is the Bourdon tube barometer. It consists of a sensor element (aneroid capsule), which changes its shape under the influence of pressure, and transducers, which transform the change into a form directly usable by the observer, such as on a barograph. The display may be remote from the sensor.

2.4.1.5 Wind

Reference should again be made to Mazzarella (1972), Wieringa (1980), Kaimal and Finnigan (1994) and WMO (1984, 1998, 2001*b*, 2008*b*). Wind speed and direction measured with standard instruments under standard exposure are fundamental requirements of the science of agricultural meteorology. The most common routine observation is the wind run, providing an average over the measuring period. That period should be at least ten minutes for smoothing out typical gustiness, and at most an hour because surface wind has a very pronounced diurnal course. Different instruments are used when it is necessary to observe the more detailed structure of air motion, however, for instance, in agricultural meso- and micrometeorological studies. In such cases, wind speeds are measured with cup anemometers of high sensitivity at low velocities or with electrical thermo-anemometers or sonic anemometers.

Sensitive cup anemometers that measure all wind components and have a horizontal angle of attack of less than about 45° are the most common in routine and research use. The best have a low stalling speed (threshold of wind speed below which the anemometer does not rotate) of about 0.1 ms⁻¹, because friction loads have been minimized. The rotation produces an electrical or phototransistor signal, which is registered by a recorder or counter. Such transducers also allow separate recording of gustiness.

Sensitive propellers, if mounted on a vane, can be an alternative to cups (WMO, 2008*b*), but these days they are mainly used in research instruments (WMO, 2001*b*). Pressure tube anemometers on a vane are reliable, but so unwieldy that they are disappearing in favour of smaller instruments. A new instrument for horizontal wind speed and direction measurement is the hot-disk anemometer, which has the advantage that it has no moving parts. For steady wind direction measurement, wind vanes must have fins whose height exceeds their length.

Sonic anemometers, which sense the transport speed of sound pulses in opposite directions along a line and are thus totally linear, respond quickly enough to measure turbulence and have become useful for flux measurements in research. They cannot be used in small spaces, however, and their calibration shifts in wet weather.

For the study of wind speeds in restricted spaces, such as crop canopies and surfaces, several kinds of

thermo-anemometers are used. The hot-wire anemometer is an electrically heated wire, whose heat loss is a function of the airspeed at normal incidence to the wire. It is particularly useful for low-speed winds but very fragile, and in polluted surroundings it loses its calibration so it cannot be used operationally. Because of the dependence of wire heat transfer on wind direction, crossed-wire sensors can be used to separate the wind components in turbulent motion.

Hot-bead anemometers have heated beads, whose heat transfer is less dependent on wind direction but has a slower response. Thermocouples or thermistors sense differences in temperature between heated and non-heated beads; these differences are a function of the wind speed. Shaded Piche evaporimeters have also been used as cheap interpolating and extrapolating ancillary anemometers in agroforestry when turbulence is not too high and the temperature and humidity gradients are low (Kainkwa and Stigter, 2000; Stigter et al., 2000).

Particular metadata for wind measurement are response times of instruments; sensor height; exposure, that is, adequate description of surrounding terrain and obstacles; type of anemometer signal, its transmission and its recording; sampling and averaging procedure; and unit specification (m/s, knots, km/h, or some type of miles per hour).

2.4.1.6 Air humidity and soil moisture (including leaf wetness)

2.4.1.6.1 Humidity

Reference should again be made to Griffiths (1994), WMO (1984, 2001*b*, 2008*b*) and WMO Technical Note No. 21. The most commonly used hair hygrometers and hair hygrographs may give acceptable values only if great care is taken in their use and maintenance. The accuracy of other equipment has improved. Besides standard psychrometers equipped with mercury-in-glass thermometers, portable aspirated and shielded psychrometers and mechanical hygrometers, many instruments have been developed to measure different aspects of air humidity. Since the above-mentioned routine instruments are bulky and inadequate for remote reading, they are unsuitable for many agrometeorological observations. For observations in undisturbed and small spaces, electrical or electronic instruments are used. The best method for measuring humidity distribution in the layers near the ground is also to use thermo-electric equipment, and unventilated thermocouple psychrometers are the most suitable in vegetation

(Rosenberg et al., 1983; WMO, 2001b). Ventilated psychrometers may be used for levels at least 50 cm above bare soil or dense vegetation.

For measuring relative humidity directly, use has been made of lithium chloride or sulphonated polystyrene layers, since the electrical resistance of these electrolytes changes with relative humidity. These electrolytic sensors become affected by air contamination and high relative humidity conditions, however, and are therefore to be used with great care and frequent recalibration. For example, resistive polymer film humidity sensors are increasingly used. Instruments are usually resistant to contaminants, and common solvents, dirt, oil and other pollutants do not affect the stability or accuracy of the sensor.

Electrical dewpoint hygrometers indicate dewpoint rather than relative humidity. For example, the lithium chloride dewpoint hygrometer measures the equilibrium temperature of a heated soft fibreglass wick impregnated with a saturated solution of lithium chloride. This temperature is linearly related to atmospheric dewpoint. The response of the instrument under low relative humidity conditions is not so good, however.

More expensive and complicated, but also more accurate, instruments require that the air be sampled and delivered, without changing its water vapour content, to a measuring unit. One such instrument, an illuminated condensation mirror, is alternately cooled and heated by a circuit energized by a photocell relay, which maintains the mirror at dewpoint temperature. Infrared gas analyser hygrometers (IRGAs) rely on the fact that water vapour absorbs energy at certain wavelengths and not others. Two sampling tubes are also used to measure absolute values of water vapour concentration at two levels, while at the same time measuring the differences in these values.

Single- or double-junction Peltier psychrometers are extensively used for accurate measurement of water potential values in plant tissues and soil samples. They are generally based on the Peltier effect in chromel–constantan junctions, and the water potentials are derived from measurements of equilibrium relative humidity in representative air.

Particular metadata for any type of hygrometry are regular notes in the station logbook of maintenance activities, such as psychrometer wick replacement or cleaning of sensor surfaces. Moreover, whether or not sensors are ventilated should be recorded. Because so many different humidity parameters are in use, the metadata should specify not only the

parameters and units actually used, but they should also contain information on the way in which the archived humidity data were calculated from original observations (for example, in the form of conversion tables, graphs and small conversion programmes).

2.4.1.6.2 *Soil and grain moisture*

Reference may be made to Greacen (1981), Gardner (1986), Vining and Sharma (1994), Dirksen (1999), Smith and Mullins (2001), and WMO (2001b, 2008b). WMO Technical Note No. 97 also describes instruments used for the measurement of soil moisture. Time and space variation of soil moisture storage is the most important component of the water balance for agrometeorology. Several instruments have been constructed to measure soil moisture variations at a single point, but they avoid the variability of soils in space and depth (for example, Ibrahim et al., 1999, 2002). Gardner (1986) still described the following as a relevant indirect method of obtaining soil water content: “measurement of a property of some object placed in the soil, usually a porous absorber, which comes to water equilibrium with the soil”. Blotting paper is popular here and it may also be useful for soil potential determinations.

Subjective methods of estimating soil moisture have been used with satisfactory results in some regions where regular observations in a dense network are necessary and suitable instruments are lacking. Skilled observers, trained to appreciate the plasticity of soil samples with any simple equipment, form the only requirement for this method. Periodic observations and simultaneous determinations of soil texture at depths, by competent technicians, allow approximate charts to be constructed.

The direct methods of soil water measurement facilitate implementation of easy follow-up methods at operational levels. Gravimetric observations of soil water content have been in use for a long time in many countries. An auger to obtain a soil sample, a scale for weighing it, and an oven for drying it at 100°C–105°C are used for the purpose. Comparison of weights before and after drying permits evaluation of moisture content, which is expressed as a percentage of dry soil or, where possible, by volume (in mm) per metre depth of soil sample. Because of large sampling errors and high soil variability, the use of three or more replicates for each observational depth is recommended (see also WMO Technical Note No. 21). The volumetric method is useful for measuring the absolute amount of water

in a given soil and it has known volumes of soil sampled.

Tensiometers measure soil moisture tension, which is a useful agricultural quantity, especially for light and irrigated soils. The instrument consists of a porous cup (usually ceramic or sintered glass) filled with water, buried in the soil and attached to a pressure gauge (for instance, a mercury manometer). The water in the cup is absorbed by the soil through its pores until the pressure deficiency in the instrument is equal to the suction pressure exerted by the surrounding soil. Along with this direct measurement, an indirect measurement of soil moisture tension can be obtained from electrical resistance blocks.

Electrical resistance blocks of porous materials (such as gypsum) whose electrical resistance changes when moistened, without alteration of the chemical composition, can be calibrated as a simple measure of soil moisture content. This was operationally used successfully by Mungai et al. (2000), for example.

Among radioactive methods, the neutron probe measures the degree to which high-energy neutrons are thermalized in the soil by the hydrogen atoms in the water. It determines volumetric water content indirectly in situ at specific soil depths using a predesigned network of access tubes (Ibrahim et al., 1999). The neutron scattering and slowing method was until recently the most widely used, and it is relatively safe and simple to operate. The total neutron count per unit time is proportional to the moisture content of a sphere of soil whose diameter is larger when the soil is drier. Soil moisture is measured with the gamma radiation probe by evaluating differential attenuation of gamma rays as they pass through dry and natural soils. This method generally requires two probes introduced simultaneously into the soil a fixed distance apart, one carrying the gamma source and the other the receiver unit.

Time domain reflectometry determines the soil water content by measuring the dielectric constant of the soil, which is a function of the volumetric water content. It is obtained by measuring the propagation speed of alternating current pulses of very high frequency (>300 MHz). The pulses are reflected at inhomogeneities, either in the soil or at the probe-soil interface, and the travel time between the reflections is measured. The dielectric constant is determined on the basis of the travel time and this allows for determination of the volumetric water content of the soil. As with neutron scattering, this method can be used over a large range of

water contents in the soil. It can be used directly within the soil or in access tubes. Compared to the neutron scattering method, the spatial resolution is better, calibration requirements are less severe and the cost is lower (WMO, 2001b).

Another important measurement needed in agriculture is the moisture content of grains, which influences viability and general appearance of the seed before and after storage. It is important to know the moisture content immediately after harvest, prior to storage and shipment, after long periods of storage, and so on. The methods for measuring moisture content are generally classified as reference methods, routine methods and practical methods. The phosphorous pentoxide method (in which moisture is absorbed by the chemical) and the Karl Fisher method (in which water is extracted from seed using a reagent) are considered reference methods. The "oven-dry method" is categorized as a routine method in which the seed moisture is determined by removing the moisture from the seeds in an oven. Among the practical methods, the determination of moisture content by using samples in infrared moisture meters is easy compared to others. WMO Technical Note No. 101 deals with some of the above, but also with practical methods using electrical resistance sensors. Abdalla et al. (2001) successfully used the latter.

2.4.1.6.3 *Leaf wetness and dew*

Reference should be made to WMO (1992, 2001b). The very large number of instruments that have been developed for the measurement of dew or duration of leaf wetness (WMO Technical Note No. 55) indicates that not even a moderately reliable method has yet been found. The two main categories of leaf wetness duration (LWD) sensors being used are mechanical sensors with recorders, and electric sensors that exploit the conductivity variation as a function of wetness.

In addition to electric conductivity measurements of dew (variations on both natural and artificial surfaces), the principles of mechanical dew measurement are: modification of the length of the sensor as a function of wetness; deformation of the sensor; water weighing (dew balance recorder); and adsorption on blotting paper, with or without chemical signalling. There is also visual judgement of drop size on prepared wooden surfaces (the Duvdevani dew gauge).

Porcelain plates (Leick plates), pieces of cloth and other artificial objects can share in any dew fall or

distillation occurring on a given natural surface. Unless they are more or less flush with that surface and have similar physical properties (surface structure, heat capacity, shape, dimension, flexibility, colour and interception) they will not indicate reliably the amount of dew that the surface receives. If exposed above the general level of their surroundings, as is normal with Duvdevani blocks and usually appears to be the case with more refined “drosometer” devices, their behaviour will diverge from that of the surface below, and the observed amounts of dew may bear little relation to the dew on adjacent natural surfaces.

Weighing-type instruments, modified hygrographs with a hemp thread instead of a hair bundle, and systems with surface electrodes that connect when the surface is wet, all have their problems (WMO, 2001*b*). The surface electrode instruments are the simplest to read, but again do not measure real leaf wetness, because the sensor is a fake leaf, with, *inter alia*, a different heat capacity.

2.4.1.7 Precipitation (clouds and hydrometeors)

Reference should be made to Meteorological Office (1981) and WMO (1994*b*, 2008*b*). WMO Technical Note Nos. 21, 83 and 97 also provide information and guidance concerning instruments such as raingauges and totalizers, rain recorders (float and tipping bucket types) and snow gauges. Many of these require lower accuracy in agrometeorology than when they are used for standard climatological measurements. For some purposes no great precision in rainfall is needed, for example in classifying days as either “wet” or “dry” for insurance claims or when only rough ideas are needed concerning accumulation of rainfall over agricultural fields throughout an ongoing season for comparison with the same period in earlier years, which is a topic of interest to most farmers. The same applies to (agricultural) environmental science teaching in schools. In Mali, the National Meteorological Directorate is of the opinion that farmers need to have a means of measuring rainfall if they wish to derive the full benefit of the agrometeorological information disseminated by rural radio, and farmer raingauges are now locally manufactured (Rijks, 2003).

A few additional remarks are appropriate here on a number of instruments used for specific work and on their operation. With regard to hail measurement, observations cannot be automated, because

the only useful observation method so far is the use of a network of hail pads. As for rainfall measurement, it should be noted that wind can have an impact, along with the height and shape of the raingauge, which are by far the most important factors determining errors.

When cost is important, along with the need for high measuring densities, raingauges smaller in size than the normal standard are employed, but they are unsuitable for snow. Sometimes these are made of plastic and shaped like a wedge, other times they are just plastic receptacles. Commercially the former are often called “raingauges according to Diem” or “farmer raingauges”; the latter, if made of plastic, are known as “clear view raingauges”. Inexpensive raingauges and small-size totalizer raingauges are used for studying the small-scale distribution of precipitation, as seen with limited mesoclimates, forest or crop interception, shelterbelt effects, and so on.

In addition to the performance of routine rainfall measurements, agricultural practices call for data on the amount, duration and intensity of precipitation at the time of floods and related disasters. As the severe weather systems affecting coastal areas originate in seas and oceans, ocean-based data collection through ships and buoys is necessary. Also, the installation of automatic weather stations that meet the necessary criteria can help with monitoring and providing early warning to coastal zones about hazardous weather. In vulnerable coastal zones a dense network of stations is needed to diagnose weather-related hazards and plan measures aimed at mitigating their effects.

Radar, sometimes in parallel with satellite remote-sensing, is increasingly used to estimate both point and area rainfall by analysing the characteristics of cloud structure and water content. These data complement the surface raingauge networks in monitoring and mapping rainfall distribution, but it is essential that representative actual observations at the surface be used when taking decisions on the track of a storm for forecasting purposes. Such derived rainfall data need ongoing intensity calibration.

Particular metadata for precipitation measurement include the diameter of the raingauge rim and its height above ground; the presence of a Nipher screen or some other airflow modification feature; the presence of overflow storage; and a means, if any, to deal with solid precipitation (such as heating or a snow cross).

2.4.1.8 Evaporation and water balance

The standard instruments that are used for measuring the different components of the water balance for climatological and hydrological purposes (such as screened and open pan evaporimeters, or lysimeters) are also employed in agricultural meteorology. Reference is made to the same literature as for 2.4.1.7 and to WMO (1984, 2001*b*).

2.4.1.8.1 Evaporation

While it is possible to estimate actual or potential evapotranspiration from observed values of screen or open pan evaporimeters or from integrated sets of meteorological observations, more accurate, direct observations are often preferred. Actual evapotranspiration is measured by using soil evaporimeters or lysimeters, which are field tanks of varying types and dimensions, containing natural soil and a vegetation cover (grass, crops or small shrubs). Potential evapotranspiration (PET) can be measured by lysimeters containing soil at field capacity and a growing plant cover. A surface at almost permanent field capacity is obtained by regular irrigation or by maintaining a stable water table close to the soil surface. With lysimeters, strict control must be kept of infiltration from excess rainfall. For the observation by lysimeters to be reliable, the conditions at the surface of the instrument and below it need to be very similar to the conditions of the surrounding soil.

Among the different lysimeters, the most important for agricultural applications are the Thornthwaite lysimeters (of the drainage type), Popoff lysimeters (a combined drainage and weighing type), weighing lysimeters and hydraulic lysimeters (a more robust weighing type). Lysimeters are used to measure evaporation, transpiration, evapotranspiration (ET), effective rainfall, drainage, and chemical contents of drainage water, and to study the climatic effects of ET on the performance of crops. Lysimetry is one of the most practical and accurate methods for short-term ET measurements, but a number of factors cause a lysimeter to deviate from reality, such as changes in the hydrological boundaries, disturbance of soil during construction, conduction of heat by lateral walls, and so forth.

Atmometers or “small-surface” evaporimeters are also still in use. Of these, the inexpensive Piche evaporimeter can be utilized anywhere in meteorology and agriculture if the physics are well understood (Stigter and Uiso, 1981). Shaded Piche evaporimeters were used to replace humidity and wind speed data in the aerodynamic term of the Penman equation in Africa (WMO, 1989).

Devices for measuring net radiation, soil heat flux and sensible and advected heat are needed in energy budget methods, while continuous measurements of wind speed, temperature and water vapour profiles are needed for the aerodynamic method (see also FAO, 1998; Hough et al., 1996). When adequate instrumentation facilities and personnel are available, it is possible to compute actual evapotranspiration using energy balance or mass transfer methods. Certain semi-empirical methods that require relatively simple climatological measurements to provide estimates of PET are often of little value when evaporation is limited by water supply.

Microlysimeters are very small lysimeters that can be put into the ground and used to take soil evaporation measurements for short periods in such a manner that disturbance of the soil boundary condition does not appreciably affect evaporation from the soil. Precautions to be taken and a measuring protocol were given by Daamen et al. (1993) and operationally applied by Daamen et al. (1995) and Kinama et al. (2005).

Particular metadata for pan evaporation are the pan dimensions and rim height, and any employment of pan defence against thirsty animals (such as wire netting).

2.4.1.8.2 Irrigation

Water balance studies are incomplete without proper reference to different methods of irrigation because water of acceptable quality is becoming an increasingly scarce resource for agriculture, while this sector accounts for the largest share of water consumption. This was already dealt with in 2.3.1.8. Measurements and calculations include soil moisture conditions, water use efficiencies and water flow conditions in canals of different dimensions, including the smallest field channels (for example, Ibrahim et al., 1999, 2000, 2002).

2.4.1.9 Fluxes of weather variables (derived from measured quantities)

Reference should be made to Fritschen and Gay (1979), Kaimal and Finnigan (1994), Griffiths (1994), Murthy (1995, 2002), FAO (1998), and WMO (2001*b*).

A reliable, but complex, method to measure atmospheric fluxes is that of “eddy covariances”. In this method very fast response devices such as hot-wire, hot-film, or sonic anemometers are used to measure wind, and similarly fast response sensors are used to

measure the remaining quantities. These include the infrared gas analyser (for water vapour and CO₂) and fine-wire temperature sensors. The correlation between instantaneous departures from the mean of the wind and other variables provides an estimate of the flux. Eddy covariance systems use commercially available instruments such as a three-axis sonic anemometer and infrared gas analyser, controlled by software that also calculates and displays the surface fluxes of momentum, sensible and latent heat, and carbon dioxide. The Bowen ratio (the ratio of the sensible to latent heat fluxes) energy balance method is a reliable technique for obtaining evaporation rates and is one of the most frequently used methods for estimation of surface energy balance components and evaporation. The required observations are differences in temperature and humidity between two levels or in a profile. The Bowen ratio energy balance system provides continuous estimation of evaporative loss. This system is less complex than eddy covariances and its needs as to maintenance and power consumption are lower than for eddy covariances.

In all the studies pertaining to flux measurements, the temperature profile observations are supported with direct measurement of the soil heat flux density. Heat flux densities in the soil or in plant or animal tissues are measured close to the interface between air and soil, plant and animal with transducers or heat flux plates. Generally, these instruments are thermopiles whose output is proportional to the temperature difference between the sides of a plate crossed by the flux. Such thermopiles are usually constructed by winding a constantan spiral on a glass or plastic plate, copper-plating half of each winding in such a way that portions of the plated and non-plated constantan remain exposed in the upper and the lower sides. The conductivity of the plate material should match the heat transmission of the medium measured. For soils, the small plates are typically buried at a compromise depth of 10 cm. Burial beyond this depth makes them unrepresentative for soil heat flux at the surface, but very shallow placement leaves only a thin covering soil layer, which then may dry out or crack. The presence of plant roots also has to be considered (WMO, 2001b).

2.4.1.10 Remote-sensing and GIS

Reference should be made to Goel and Norman (1990), Milford (1994), and WMO (2008b). The remotely sensed image is typically composed of picture elements (pixels), which vary in size from a few metres to a few kilometres across. For each pixel

an associated digital number or brightness value depicts the average radiance from that pixel within a spectral band that is specified by the relevant sensor. For useful information, such as a vegetation index, to be derived from the raw data, it is usually necessary to process the data from more than one band. A geometrical correction is necessary to ensure that the location of each pixel in an image is accurately known, a process known as rectification.

Images may be transformed within a GIS, for example by principal component analysis, which creates new images from the uncorrelated values of different images. This analysis is used for spectral pattern recognition and image enhancement. Two or more different images may be combined to form a new one using a variety of different techniques. Then supervised and unsupervised classifications are taken up to find complexity of terrain. Finally, accuracy assessment is carried out to allow for the use of all these techniques in operational agricultural meteorology. In this connection, the concepts of GIS are useful for efficient planning and decision-making at farmer level, for integrating information from many sources, and for generating new information, such as the slope of a region, wind direction, possible flow of water as a result of disasters, and other risks. These aspects are discussed in further detail in Chapter 4.

2.4.1.11 Calibration of recorders, integrators and automatic weather stations

Reference should be made to Woodward and Sheehy (1983). Meteorological data can be obtained by direct reading (instantaneous) of measuring instruments and also by instruments providing a continuous record of the parameters over time, with mechanical, electrical or other analog or digital displays. All the instruments have to be calibrated to meet comparability requirements and recalibrations are essential after repairs or replacement of key parts of the instruments. The most common way to calibrate is by comparison with standard instruments that are kept at national centres and specialized laboratories and are checked from time to time against international standards.

2.4.1.11.1 Mechanical and electrical devices

Observations with instruments that do not have self-recording devices are made by individual readings at the given observation times and written into an appropriately designed observations book, in accordance with the instructions. From this basic document, data can be transferred to monthly summaries and extracted for special analysis.

In mechanical reading instruments, the changes in the length of the sensing element or sensor force are transmitted mechanically with or without amplification to a recording system that is usually based on a clock-driven paper strip of either the drum or endless belt type. The variations in the given parameter over time are displayed in graphical form or in a diagram chart. The main advantages of mechanical recorders are their relatively low cost, easy maintenance and independence from an external power supply.

In electrical recording instruments, sensors are used that produce electrical signals (voltage, differences in potential, resistance, and so on), which correspond to the parameters under consideration; or detectors are used in which initial mechanical "signals" (such as longitudinal changes and rotation) are transformed into electrical impulses by appropriate devices (such as a potentiometer and switches). Depending on the signal output of the sensor, different recorders are used, such as the null-balance potentiometric recorder, the galvanometric recorder and the Wheatstone bridge for electrical resistance measurements.

2.4.1.11.2 *Microprocessors*

With the advances in microelectronic technologies in recent years, more and more instruments using integrated circuits and microprocessors are being designed for the purpose of measuring meteorological parameters. Together with electrical sensors, the use of integrated circuit chips has allowed the construction of highly sensitive and low-weight digital readout instruments. They have the advantage of built-in "conversion" from electrical sensor outputs to technical units, including complex linearizations. The use of integrated electronic circuits and microprocessor chips has led to the construction of automatic environmental control systems and automatic weather stations (AWSs).

Electronic integrators with memory capacity for data storage that can be recalled are also available. For any particular logger memory, the duration of the record available depends on the number of sensors and frequencies of observation.

2.4.1.11.3 *Automatic weather stations*

Reference is made to WMO (2001a, 2008b). An AWS is defined as a meteorological station at which observations are made and transmitted automatically. If required, they may be interrogated either locally or from an editing

station. Most of the variables required for agricultural purposes can be measured by automatic instrumentation. As the capabilities of automatic systems expand, the ratio of purely automatic stations to observer-staffed weather stations (with or without automatic instrumentation) is increasing steadily. The guidance regarding siting and exposure, changes in instrumentation, and inspection and maintenance apply equally to automatic weather stations and to staffed weather stations. Automatic weather stations are used to satisfy several needs, ranging from a single aid to the observer at manned stations to complete replacement of observers at fully automatic stations. A general classification of these stations includes stations that provide data in real time and those that record data for offline analysis or analysis not performed in real time. It is not unusual, however, for both these functions to be discharged by the same AWS.

When planning the installation and operation of a network of AWSs, it is of utmost importance to consider the various problems associated with maintenance and calibration facilities, with their organization, and with the training and education of technical staff. In general, an AWS consists of sensors installed around a meteorological tower housed in appropriate environmental shields; a central processing system for sensor data acquisition and conversion into computer-readable format; and some peripheral equipment, such as a stabilized and uninterruptible power supply.

The agricultural meteorological demands made on sensors for use with AWSs are not very different from those made on sensors for conventional use. The siting of an agricultural AWS is a very difficult matter and much research remains to be done in this area. The general principle is that a station should provide measurements that are, and remain, representative of the surrounding area, the size of which depends on the agricultural meteorological application needed. The distance over which any station-measured parameter can be extrapolated also varies, from small for precipitation to large for incoming radiation (Wieringa, 1998). An AWS usually forms part of a network of meteorological stations and transmits its processed data or messages to a central network processing system by various data telecommunication means. The cost over a few years of servicing a network of automatic stations can greatly exceed the cost of their purchase. The sensors with electrical outputs show drifts in time and, consequently, need regular inspection and calibration.

2.4.2 Measurement of biological and related phenomena

Reference should be made to the literature mentioned in 2.3.2. While that section and Chapters 4, 6, 7 and 10 through 14 deal with biological measurements and related phenomena, there are a few additional issues that have recently received much attention and are not widely dealt with elsewhere in this Guide. These concern measurements at or near agricultural meteorological stations.

2.4.2.1 Measurement of soil erosion

A universal soil loss equation has been developed to measure/estimate water and wind erosion factors. It is discussed in Hudson (1993) and Chapter 10 of this Guide. Water erosion field measurements are dealt with in Hudson (1993) and WMO (1994b) and particle analyses are discussed in Vining and Sharma (1994), while general field measurements for wind erosion are covered by Zobeck et al. (2003). Spaan and Stigter (1991) and Mohammed et al. (1995, 1996) discuss the operational use of simple field measurements in wind erosion studies. Soil erosion (deflation) and deposition (accumulation) occur as a consequence of transport and these are scientifically quantified as height differences (for example, Mohammed et al., 1995; Sivakumar et al., 1998). When properly designed and carefully executed, erosion pins provide sound data on these changes. They are meaningful and visibly impressive to farmers and extension workers. They allow large numbers of measurements to be taken at low cost and are extremely useful to measure the changes in surface elevations of soils exposed to wind and/or water erosion (for example, Hudson, 1993).

2.4.2.2 Measurement of runoff

The equipment for measurement of runoff includes weirs and Parshall flumes, which are suitable for measuring the runoff from small watersheds, and water-recording equipment, such as water storage recorders that continuously record the water level in a stream. In studies of agriculture on sloping lands, runoff plots are successfully managed and soil loss and water runoff can be quantified (for example, Kinama et al., 2007).

2.4.2.3 Measurement of leaf area, canopy structure and photosynthesis

It is desirable to express plant growth on the basis of leaf area. The leaves are the primary photosynthetic organs of the plant. After destructive sampling (removing the leaves from the plant), the leaf area can be measured by using a leaf area meter. This instrument is portable, but expensive. It has a transparent belt conveyer to spread the leaves and has a digital display to indicate the leaf area. More simply, the leaf area can also be estimated by using the following methods: the length $\times$ width $\times$ constant method, the dry weight method, and the paper weight method. The leaf area is normally expressed in relation to ground area as the leaf area index (LAI), which is the ratio of the total leaf area of a plant to the ground area occupied by the plant. To achieve higher production, a plant should be able to utilize a maximum amount of light, for which optimum spacing should be followed. The LAI helps to derive optimum spacing to utilize the maximum sunlight for photosynthesis.

There are different optical methods for measuring LAI that are well established. Canopy structures can also be quantified in this way. Details may be found in Pearcy et al. (1989), Russell et al. (1989), Goel and Norman (1990), and Baker and Bland (1994). These references also include details on leaf, plant and stand photosynthesis measurements, and their consequences for development and growth can be found there as well. Many methods are used successfully, but they are not as accurate or rapid as IRGA systems. A sensitive technique for rapid measurements of CO₂ concentrations with attached leaves sealed in Plexiglas chambers is also used. Other related instruments include those measuring stomatal conductance, sap flow, leaf water potential, dendrometers, and the like. The literature referred to above contains details.

Measurements of crop production that include the weight of dry matter above ground, total dry matter, economic yield, and so forth are frequently taken at agricultural meteorological stations or in adjacent fields. These are useful in correlating production to climatic variables over periods that range from weeks to the entire season.

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CHAPTER 3

AGRICULTURAL METEOROLOGICAL DATA, THEIR PRESENTATION AND STATISTICAL ANALYSIS

3.1 INTRODUCTION

Agricultural meteorology is the science that applies knowledge in weather and climate to qualitative and quantitative improvement in agricultural production. Agricultural meteorology involves meteorology, hydrology, agrology and biology, and it requires a diverse, multidisciplinary array of data for operational applications and research. Basic agricultural meteorological data are largely the same as those used in general meteorology. These data need to be supplemented with more specific data relating to the biosphere, the environment of all living organisms, and biological data relating to the growth and development of these organisms. Agronomic, phenological and physiological data are necessary for dynamic modelling, operational evaluation and statistical analyses. Most data need to be processed for generating various products that affect agricultural management decisions in matters such as cropping, the scheduling of irrigation, and so forth. Additional support from other technologies, such as geographical information and remote-sensing, as well as statistics, is necessary for data processing. Geographical information and remote-sensing data, such as images of the status of vegetation and crops damaged by disasters, soil moisture, and the like, should also be included as supplementary data. Derived agrometeorological parameters, such as photosynthetically active radiation and potential evapotranspiration, are often used in agricultural meteorology for both research and operational purposes. On the other hand, many agrometeorological indices, such as the drought index, the critical point threshold of temperature and soil water for crop development, are also important for agricultural operations. Weather and climate data play a crucial role in many agricultural decisions.

Agrometeorological information includes not only every stage of growth and development of crops, floriculture, agroforestry and livestock, but also the technological factors that affect agriculture, such as irrigation, plant protection, fumigation and dust spraying. Moreover, agricultural meteorological information plays a crucial role in the decision-making process for sustainable agriculture and natural disaster reduction, with a view to preserving natural resources and improving the quality of life.

3.2 DATA FOR AGRICULTURAL METEOROLOGY

Agrometeorological data are usually provided to users in a transformed format; for example, rainfall data are presented in pentads or in monthly amounts.

3.2.1 Nature of the data

Basic agricultural meteorological data may be divided into the following six categories, which include data observed by instruments on the ground and by remote-sensing.

- (a) Data relating to the state of the atmospheric environment. These include observations of rainfall, sunshine, solar radiation, air temperature, humidity, and wind speed and direction;
- (b) Data relating to the state of the soil environment. These include observations of soil moisture, that is, the soil water reservoir for plant growth and development. The amount of water available depends on the effectiveness of precipitation or irrigation, and on the soil's physical properties and depth. The rate of water loss from the soil depends on the climate, the soil's physical properties, and the root system of the plant community. Erosion by wind and water depends on weather factors and vegetative cover;
- (c) Data relating to organism response to varying environments. These involve agricultural crops and livestock, their variety, and the state and stages of their growth and development, as well as the pathogenic elements affecting them. Biological data are associated with phenological growth stages and physiological growth functions of living organisms;
- (d) Information concerned with the agricultural practices employed. Planning brings the best available resources and applicable production technologies together into an operational farm unit. Each farm is a unique entity with combinations of climate, soils, crops, livestock and equipment to manage and operate within the farming system. The most efficient utilization of weather and climate data for the unique soils on a farm unit will help conserve natural resources, while at the same time promoting economic benefit to the farmer;

- (e) Information relating to weather disasters and their influence on agriculture;
- (f) Information relating to the distribution of weather and agricultural crops, and geographical information, including digital maps;
- (g) Metadata that describe the observation techniques and procedures used.

3.2.2 Data collection

The collection of data is very important as it lays the foundation for agricultural weather and climate data systems that are necessary to expedite the generation of products, analyses and forecasts for agricultural cropping decisions, irrigation management, fire weather management, and ecosystem conservation. The impact on crops, livestock, water and soil resources, and forestry must be evaluated from the best available spatial and temporal array of parameters. Agrometeorology is an interdisciplinary branch of science requiring the combination of general meteorological data observations and specific biological parameters. Meteorological data can be viewed as typically physical elements that may be measured with relatively high accuracy, while other types of observations (namely, biological or phenological) may be more subjective. In collecting, managing and analysing the data for agrometeorological purposes, the source of data and the methods of observation define their character and management criteria. Some useful suggestions with regard to the storage and processing of data can be offered, however:

- (a) Original data files, which may be used for reference purposes (the daily register of observations, and so on), should be stored at the observation site; this applies equally to atmospheric, biological, crop and soil data;
- (b) The most frequently used data should be collected at national or regional agrometeorological centres and reside in host servers for network accessibility. This may not always be practical, however, since stations or laboratories under the control of different authorities (meteorological services, agricultural services, universities, research institutes) often collect unique agrometeorological data. Steps should therefore be taken to ensure that possible users are aware of the existence of such data, either through some form of data library or computerized documentation, and that appropriate data exchange mechanisms are available to access and share these data;
- (c) Data resulting from special studies should be stored at the place where the research work is undertaken, but it would be advantageous to arrange for exchanges of data among centres

carrying out similar research work. At the same time, the existence of these data should be publicized at the national level and possibly at the international level, if appropriate, especially in the case of longer series of special observations;

- (d) All the usual data storage media are recommended:
 - (i) The original data records, or agrometeorological summaries, are often the most convenient format for the observing stations;
 - (ii) The format of data summaries intended for forwarding to regional or national centres, or for dissemination to the user community, should be designed so that the data may be easily transferred to a variety of media for processing. The format should also facilitate either the manual preparation or automated processing of statistical summaries (computation of means, frequencies, and the like). At the same time, access to and retrieval of data files should be simple, flexible and reproducible for assessment, modelling or research purposes;
 - (iii) Rapid advances in electronic technology facilitate effective exchange of data files, summaries and charts of recording instruments, particularly at the national and international levels;
 - (iv) Agrometeorological data should be transferred to electronic media in the same way as conventional climatological data, with an emphasis on automatic processing.

The availability of proper agricultural meteorological databases is a major prerequisite for studying and managing the processes of agricultural and forest production. The agricultural meteorology community has great interest in incorporating new information technologies into a systematic design for agrometeorological management to ensure timely and reliable data from national reporting networks for the benefit of the local farming community. While much more information has become available to the agricultural user, it is essential that appropriate standards be maintained for basic instrumentation, collection and observations, quality control, and archiving and dissemination. After they have been recorded, collected and transferred to the data centres, all agricultural meteorological data need to be standardized or technically treated so that they can be used for various purposes. The data centres need to maintain special databases. These databases should include meteorological, phenological,

edaphic and agronomic information. Database management and processing and the quality control, archiving, timely accessing and dissemination of data are all important components that render the information valuable and useful in agricultural research and operational programmes.

After they have been stored in a data centre, the data are disseminated to users. There have been major advancements in making more data products available to the user community through automation. The introduction of electronic transfer of data files via the Internet using the file transfer protocol (FTP) and the World Wide Web (WWW) has brought this information transfer process up to a new level. The Web allows users to access text, images and even sound files that can be linked together electronically. The Web's attributes include the flexibility to handle a wide range of data presentation methods and the capability to reach a large audience. Developing countries have some access to this type of electronic information, but limitations still exist in the development of their own electronically accessible databases. These limitations will diminish as the cost of technology decreases and its availability increases.

3.2.3 Recording of data

Recording of basic data is the first step for agricultural meteorological data collection. When the environmental factors and other agricultural meteorological elements are measured or observed, they must be recorded on the same media, such as agricultural meteorological registers, diskettes, and the like, manually or automatically.

- (a) The data, such as the daily register of observations and charts of recording instruments, should be carefully preserved as permanent records. They should be readily identifiable and include the place, date and time of each observation, and the units used.
- (b) These basic data should be sent to analysis centres for operational uses, such as local agricultural weather forecasts, agricultural meteorological information services, plant protection treatment and irrigation guidance. Summaries (weekly, 10-day or monthly) of these data should be made regularly from the daily register of observations according to the user demand and then distributed to interested agencies and users.
- (c) Observers need to record all measurements in compliance with rules for harmonization. This will ensure that the data are recorded in a standard format so that they can readily be transferred to data centres for automatic processing. Data can be transferred in several

ways, including by mail, telephone, telegraph, fax and Internet, and via Comsat; transmission via the Internet and Comsat is more efficient. After reaching the data centres, data should be identified and processed by means of a special program in order to facilitate their dissemination to other users.

3.2.4 Scrutiny of data and acquisition of metadata

It is very important that all agricultural meteorological data be carefully scrutinized, both at the observing station and at regional or national centres, by means of subsequent automatic computer processing. All data should be identified immediately. The code parameters should be specified, such as types, regions, missing values and possible ranges for different measurements. The quality control should be done according to Wijngaard et al. (2003), WMO-TD No. 1236 (WMO, 2004a) and the current *Guide to Climatological Practices* (WMO, 1983). Every measurement code must be checked to make certain that the measurement is reasonable. If the value is unreasonable, it should be corrected immediately. After being scrutinized, the data can be processed further for different purposes. In order to ascertain the quality of observation data and determine whether to correct or normalize them before analysis, metadata are needed. These are the details and history of local conditions, and instrumentation, operational, data-processing and other factors relevant to the observation process. Such metadata should be documented and treated with the same care as the data themselves (see WMO 2003a, 2003b). Unfortunately, observation metadata are often incomplete and poorly organized.

In Chapter 2 of this Guide, essential metadata are specified for individual parameters and the organization of their acquisition is reviewed in 2.2.5. Many kinds of metadata can be recorded as simple numbers, as is the case with observation heights, for example; but more complex aspects, such as instrument exposure, must also be recorded in a manner that is practicable for the observers and station managers. Acquiring metadata on present observations and inquiring about metadata on past observations are now a major responsibility of data managers. Omission of metadata acquisition implies that the data will have low quality for applications. The optimal set-up of a database for metadata is at present still in development, because metadata characteristics are so variable. To be manageable, the optimal database should not only be efficient for archiving, but also easily accessible for those who are recording the metadata. To allow for future

improvement and continuing accessibility, good metadata database formats are ASCII, SQL and XML, because they are independent of any presently available computing set-up.

3.2.5 **Format of data**

The basic data obtained from observing stations, whether specialized or not, are of interest to both scientists and agricultural users. A number of established formats and protocols are available for the exchange of data. A data format is a documented set of rules for the coding of data in a form for both visual and computer recognition. Its uses can be designed for either or both real-time use and historical or archival data transfer. All the critical elements for identification of data should be covered in the coding, including station identifiers, parameter descriptors, time encoding conventions, unit and scale conventions, and common fields.

Large amounts of data are typically required for processing, analysis and dissemination. It is extremely important that data are in a format that is both easily accessible and user-friendly. This is particularly pertinent as more and more data become available in electronic format. Some types of software, such as NetCDF (network common data form), process data in a common form and disseminate them to more users. NetCDF consists of software for array-oriented data access and a library that provides for implementation of the interface (Sivakumar et al., 2000). The NetCDF software was developed at the Unidata Program Center in Boulder, Colorado, United States. This is an open-source collection of tools that can be obtained by anonymous FTP from <ftp://ftp.unidata.ucar.edu/pub/netcdf/> or from other mirror sites.

The NetCDF software package supports the creation, access and sharing of scientific data. It is particularly useful at sites with a mixture of computers connected by a network. Data stored on one computer may be read directly from another without explicit conversion. The NetCDF library generalizes access to scientific data so that the methods for storing and accessing data are independent of the computer architecture and the applications being used. Standardized data access facilitates the sharing of data. Since the NetCDF package is quite general, a wide variety of analysis and display applications can use it. The NetCDF software and documentation may be obtained from the NetCDF Website at <http://www.unidata.ucar.edu/packages/netcdf/>.

3.2.6 **Catalogue of data**

Very often, considerable amounts of agrometeorological data are collected by a variety of services. These data sources are not readily publicized or accessible to potential users, which means that users often have great difficulty in discovering whether such data exist. Coordination should therefore be undertaken at the global, regional and national levels to ensure that data catalogues are prepared periodically, while giving enough background information to users. The data catalogues should include the following information:

- (a) The geographical location of each observing site;
- (b) The nature of the data obtained;
- (c) The location where the data are stored;
- (d) The file types (for instance, manuscript, charts of recording instruments, automated weather station data, punched cards, magnetic tape, scanned data, computerized digital data);
- (e) The methods of obtaining the data.

For a more extensive specification of these aspects, see Chapter 2, section 2.2.5.

3.3 **DISTRIBUTION OF DATA**

3.3.1 **Requirements for research**

In order to highlight the salient features of the influence of climatic factors on the growth and development of living things, scientists often have to process a large volume of basic data. These data might be supplied to scientists in the following forms:

- (a) Reproductions of original documents (original records, charts of recording instruments) or periodic summaries;
- (b) Datasets on a server or Website that is ready for processing into different categories, which can be read or viewed on a platform;
- (c) Various kinds of satellite digital data and imagery on different regions and different times;
- (d) Various basic databases, which can be viewed as reference for research.

3.3.2 **Special requirements for agriculturists**

Two aspects of the periodic distribution of agrometeorological data to agricultural users may be considered:

- (a) Raw or partially processed operational data supplied after only a short delay (rainfall,

potential evapotranspiration, water balance or sums of temperature). These may be distributed by means of:

- i. Periodic publications, twice weekly, weekly or at 10-day intervals;
 - ii. Telephone and note;
 - iii. Special television programmes from a regional television station;
 - iv. Regional radio broadcasts;
 - v. Release on agricultural or weather Websites.
- (b) Agrometeorological or climatic summaries published weekly, every 10 days, monthly or annually, which contain agrometeorological data (rainfall, temperatures above the ground, soil temperature and moisture content, potential evapotranspiration, sums of rainfall and temperature, abnormal rainfall and temperature, sunshine, global solar radiation, and so on).

3.3.3 **Determining the requirements of users**

The agrometeorologist has a major responsibility to ensure that effective use of this information offers an opportunity to enhance agricultural efficiency or to assist agricultural decision-making. The information must be accessible, clear and relevant. It is crucial, however, for an agrometeorological service to know who the specific users of information are. The user community ranges from global, national and provincial organizations and governments to agro-industries, farmers, agricultural consultants, and the agricultural research and technology development communities or private individuals. The variety of agrometeorological information requests emanates from this broad community. Therefore, the agrometeorological service must distribute the information that is available and appropriate at the right time.

Researchers invariably know exactly which agrometeorological data they require for specific statistical analyses, modelling or other analytical studies. Often, many agricultural users are not just unaware of the actual scope of the agrometeorological services available, but also have only a vague idea of the data they really need. Frequent contact between agrometeorologists and professional agriculturists, and enquiries through professional associations and among agriculturists themselves, or visiting professional Websites, can help enormously to improve the awareness of data needs. Sivakumar (1998) presents a broad overview of user requirements for agrometeorological services. Better applications of the type and quantity of useful agrometeorological data available and the selection

of the type of data to be systematically distributed can be established on that basis. For example, when both the climatic regions and the areas in which different crops are grown are well defined, an agrometeorological analysis can illustrate which crops are most suited to each climate zone. This type of analysis can also show which crops can be adapted to changing climatic and agronomic conditions. Agricultural users require these analyses; they can be distributed by geographic, crop or climatic region.

3.3.4 **Minimum distribution of agroclimatological documents**

Since the large number of potential users of agrometeorological information is so widely dispersed, it is not realistic to recommend a general distribution of data to all users. In fact, the requests for raw agrometeorological data are rare. Not all of the raw agrometeorological data available are essential for those persons who are directly engaged in agriculture – farmers, ranchers and foresters. Users generally require data to be processed into an understandable format to facilitate their decision-making process. But the complete datasets should be available and accessible to the technical services, agricultural administrations and professional organizations. These professionals are responsible for providing practical technical advice concerning the treatment and management of crops, preventive measures, adaptation strategies, and so forth, based on collected agrometeorological information.

Agrometeorological information should be distributed to all users, including:

- (a) Agricultural administrations;
- (b) Research institutions and laboratories;
- (c) Professional organizations;
- (d) Private crop and weather services;
- (e) Government agencies;
- (f) Farmers, ranchers and foresters.

3.4 **DATABASE MANAGEMENT**

The management of weather and climate data for agricultural applications in the electronic age has become more efficient. This section will provide an overview of agrometeorological data collection, data processing, quality control, archiving, data analysis and product generation, and product delivery. A wide variety of database choices are available to the agroclimatological user community. To accompany the agroclimatological databases that are created, agrometeorologists and software engineers develop the special software for agroclimatological database

management. Thus, a database management system for agricultural applications should be comprehensive, bearing in mind the following considerations:

- (a) Communication among climatologists, agrometeorologists and agricultural extension personnel must be improved to establish an operational database;
- (b) The outputs must be adapted for an operational database in order to support specific agrometeorological applications at a national/regional/global level;
- (c) Applications must be linked to the Climate Applications Referral System (CARS) project, spatial interpolated databases and a Geographical Information System (GIS).

Personal computers (PCs) are able to provide products formatted for easy reading and presentation, which are generated through simple processors, databases or spreadsheet applications. Some careful thought needs to be given, however, to what type of product is needed, what the product looks like and what it contains, before the database delivery design is finalized. The greatest difficulty often encountered is how to treat missing data or information (WMO, 2004a). This process is even more complicated when data from several different datasets, such as climatic and agricultural data, are combined. Some software programs for database management, especially the software for climatic database management, provide convenient tools for agrometeorological database management.

3.4.1 **CLICOM Database Management System**

CLICOM (CLimate COMputing) refers to the WMO World Climate Data Programme Project, which is aimed at coordinating and assisting the implementation, maintenance and upgrading of automated climate data management procedures and systems in WMO Member countries (that is, the National Meteorological and Hydrological Services in these countries). The goal of CLICOM is the transfer of three main components of modern technology, namely, desktop computer hardware, database management software and training in climate data management. CLICOM is a standardized, automated database management system software for use on a personal computer and it is targeted at introduction of a system in developing countries. As of May 1996, CLICOM version 3.0 was installed in 127 WMO Member countries. Now CLICOM software is available in Czech, English, French, Spanish and Russian. CLICOM Version 3.1 Release 2 became available in January 2000.

CLICOM provides tools (such as stations, observations and instruments) to describe and manage the climatological network. It offers procedures for the key entry, checking and archiving of climate data, and for computing and analysing the data. Typical standard outputs include monthly or 10-day data from daily data; statistics such as means, maximums, minimums and standard deviations; and tables and graphs. Other products requiring more elaborate data processing include water balance monitoring, estimation of missing precipitation data, calculation of the return period and preparation of the CLIMAT message.

The CLICOM software is widely used in developing countries. The installation of CLICOM as a data management system in many of these countries has successfully transferred the technology for use with PCs, but the resulting climate data management improvements have not yet been fully realized. Station network density as recommended by WMO has not been fully achieved and the collection of data in many countries remains inadequate. CLICOM systems are beginning to yield positive results, however, and there is a growing recognition of the operational applications of CLICOM.

There are a number of constraints that have been identified over time and recognized for possible improvement in future versions of the CLICOM system. Among the technical limitations, the list includes (WMO, 2000):

- (a) The lack of flexibility to implement specific applications in the agricultural field and/or at a regional/global level;
- (b) The lack of functionality in real-time operations;
- (c) Few options for file import;
- (d) The lack of transparent linkages to other applications;
- (e) The risk of overlapping of many datasets;
- (f) A non-standard georeferencing system;
- (g) Storage of climate data without the corresponding station information;
- (h) The possibility of easy modification of the data entry module, which may destroy existing data.

3.4.2 **Geographical Information System (GIS)**

A Geographical Information System (GIS) is a computer-assisted system for the acquisition, storage, analysis and display of observed data on spatial distribution. GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by mapping overlays. Maps have traditionally been used to explore the Earth and

its resources. GIS technology takes advantage of computer science technologies, enhancing the efficiency and analytical power of traditional methodologies.

GIS is becoming an essential tool in the effort to understand complex processes at different scales: local, regional and global. In GIS, the information coming from different disciplines and sources, such as traditional point sources, digital maps, databases and remote-sensing, can be combined in models that simulate the behaviour of complex systems.

The presentation of geographic elements is solved in two ways: using x, y coordinates (vectors), or representing the object as a variation of values in a geometric array (raster). The possibility of transforming the data from one format to the other allows fast interaction between different informative layers. Typical operations include overlaying different thematic maps; acquiring statistical information about the attributes; changing the legend, scale and projection of maps; and making three-dimensional perspective view plots using elevation data.

The capability to manage this diverse information, by analysing and processing the informative layers together, opens up new possibilities for the simulation of complex systems. GIS can be used to produce images – not only maps, but cartographic products, drawings, animations or interactive instruments as well. These products allow researchers to analyse their data in new ways, predicting the natural behaviour, explaining events and planning strategies.

For the agronomic and natural components in agrometeorology, these tools have taken the name Land Information Systems (LIS) (Sivakumar et al., 2000). In both GIS and LIS, the key components are the same, namely, hardware, software, data, techniques and technicians. LIS, however, requires detailed information on environmental elements, such as meteorological parameters, vegetation, soil and water. The final product of LIS is often the result of a combination of a large number of complex informative layers, whose precision is fundamental for the reliability of the whole system. Chapter 4 of this Guide contains an extensive overview of GIS.

3.4.3 Weather generators (WGs)

Weather generators are widely used to generate synthetic weather data, which can be arbitrarily long for input into impact models, such as crop models and hydrological models that are used for assessing agroclimatic long-term risk and agrometeorological analysis. Weather generators are also the tool used for

developing future climate scenarios based on global climate model (GCM) simulations or subjectively introduced climate changes for climate change impact models. Weather generators project future changes in means (averages) onto the observed historical weather series by incorporating changes in variability; these projections are widely used for agricultural impact studies. Daily climate scenarios can be used to study potential changes in agroclimatic resources. Weather generators can calculate agroclimatic indices on the basis of historical climate data and GCM outputs. Various agroclimatic indices can be used to assess crop production potentials and to rate the climatic suitability of land for crops. A methodologically more consistent approach is to use a stochastic weather generator, instead of historical data, in conjunction with a crop simulation model. The stochastic weather generator allows temporal extrapolation of observed weather data for agricultural risk assessment and provides an expanded spatial source of weather data by interpolation between the point-based parameters used to define the weather generators. Interpolation procedures can create both spatial input data and spatial output data. The density of meteorological stations is often low, especially in developing countries, and reliable and complete long-term data are scarce. Daily interpolated surfaces of meteorological variables rarely exist. More commonly, weather generators can be used to generate the weather variables in grids that cover large geographic regions and come from interpolated surfaces of weekly or monthly climate variables. On the basis of these interpolated surfaces, daily weather data for crop simulation models are generated using statistical models that attempt to reproduce series of daily data with means and a variability similar to those that would be observed at a given location.

Weather generators have the capacity to simulate statistical properties of observed weather data for agricultural applications, including a set of agroclimatic indices. They are able to simulate temperature, precipitation and related statistics. Weather generators typically calculate daily precipitation risk and use this information to guide the generation of other weather variables, such as daily solar radiation, maximum and minimum temperature, and potential evapotranspiration. They can also simulate statistical properties of daily weather series under a changing/changed climate through modifications to the weather generator parameters with optimal use of available information on climate change. For example, weather generators can simulate the frequency distributions of the wet and dry spells fairly well by modifying the four transition probabilities of the second-order Markov chain. Weather generators are generally based on the statistics. For example, to generate the amount

of precipitation on wet days, a two-parameter gamma distribution function is commonly used. The two parameters, a and b , are directly related to the average amount of precipitation per wet day. They can, therefore, be determined with the monthly means for the number of rainy days per month and the amount of precipitation per month, which are obtained either from compilations of climate normals or from interpolated surfaces.

The popular weather generators are, inter alia, WGEN (Richardson, 1984, 1985), SIMMETEO (Geng et al., 1986, 1988), and MARKSIM (Jones and Thornton, 1998, 2000). They include a first- or high-order Markov daily generator that requires long-term (at least 5 to 10 years) daily weather data or climate clusters of interpolated surfaces for estimation of their parameters. The software allows for three types of input to estimate parameters for the generator:

- (a) Latitude and longitude;
- (b) Latitude, longitude and elevation;
- (c) Latitude, longitude, elevation and long-term monthly climate normals.

3.5 AGROMETEOROLOGICAL INFORMATION

The impacts of meteorological factors on crop growth and development are consecutive, although sometimes they do not emerge over a short time. The weather and climatological information should vary according to the kind of crop, its sensitivity to environmental factors, water requirements, and so on. Certain statistics are important, such as sequences of consecutive days when maximum and minimum temperatures or the amount of precipitation exceed or are less than certain critical threshold values, and the average and extreme dates when these threshold values are reached.

The following are some of the more frequent types of information that can be derived from the basic data:

- (a) Air temperature
 - i. Temperature probabilities;
 - ii. Chilling hours;
 - iii. Degree-days;
 - iv. Hours or days above or below selected temperatures;
 - v. Interdiurnal variability;
 - vi. Maximum and minimum temperature statistics;
 - vii. Growing season statistics, that is, dates when threshold temperature values for the growth of various kinds of crops begin and end.
- (b) Precipitation
 - i. Probability of a specified amount during a period;
 - ii. Number of days with specified amounts of precipitation;
 - iii. Probabilities of thundershowers;
 - iv. Duration and amount of snow cover;
 - v. Dates on which snow cover begins and ends;
 - vi. Probability of extreme precipitation amounts.
- (c) Wind
 - i. Windrose;
 - ii. Maximum wind, average wind speed;
 - iii. Diurnal variation;
 - iv. Hours of wind less than selected speed.
- (d) Sky cover, sunshine, radiation
 - i. Per cent possible sunshine;
 - ii. Number of clear, partly cloudy, cloudy days;
 - iii. Amounts of global and net radiation.
- (e) Humidity
 - i. Probability of a specified relative humidity;
 - ii. Duration of a specified threshold of humidity.
- (f) Free water evaporation
 - i. Total amount;
 - ii. Diurnal variation of evaporation;
 - iii. Relative dryness of air;
 - iv. Evapotranspiration.
- (g) Dew
 - i. Duration and amount of dew;
 - ii. Diurnal variation of dew;
 - iii. Association of dew with vegetative wetting;
 - iv. Probability of dew formation based on the season.
- (h) Soil temperature
 - i. Mean and standard deviation at standard depth;
 - ii. Depth of frost penetration;
 - iii. Probability of occurrence of specified temperatures at standard depths;
 - iv. Dates when threshold values of temperature (germination, vegetation) are reached.
- (i) Weather hazards or extreme events
 - i. Frost;
 - ii. Cold wave;
 - iii. Hail;
 - iv. Heatwave;
 - v. Drought;
 - vi. Cyclones;
 - vii. Flood;
 - viii. Rare sunshine;
 - ix. Waterlogging.

- (j) Agrometeorological observations
 - i. Soil moisture at regular depths;
 - ii. Plant growth observations;
 - iii. Plant population;
 - iv. Phenological events;
 - v. Leaf area index;
 - vi. Above-ground biomass;
 - vii. Crop canopy temperature;
 - viii. Leaf temperature;
 - ix. Crop root length.

3.5.1 Forecast information

Operational weather information is defined as real-time data that provide conditions of past weather (over the previous few days), present weather, as well as predicted weather. It is well known, however, that the forecast product deteriorates with time, so that the longer the forecast period, the less reliable the forecast. Forecasting of agriculturally important elements is discussed in Chapters 4 and 5.

3.6 STATISTICAL METHODS OF AGROMETEOROLOGICAL DATA ANALYSIS

The remarks set out here are intended to be supplementary to WMO-No. 100, *Guide to Climatological Practices*, Chapter 5, "The use of statistics in climatology", and to WMO-No. 199, *Some Methods of Climatological Analysis* (WMO Technical Note No. 81), which contain advice generally appropriate and applicable to agricultural climatology.

Statistical analyses play an important role in agrometeorology, as they provide a means of interrelating series of data from diverse sources, namely biological data, soil and crop data, and atmospheric measurements. Because of the complexity and multiplicity of the effects of environmental factors on the growth and development of living organisms, and consequently on agricultural production, it is sometimes necessary to use rather sophisticated statistical methods to detect the interactions of these factors and their practical consequences.

It must not be forgotten that advice on long-term agricultural planning, selection of the most suitable farming enterprise, the provision of proper equipment and the introduction of protective measures against severe weather conditions all depend to some extent on the quality of the climatological analyses of the agroclimatic and related data, and hence, on the

statistical methods on which these analyses are based. Another point that needs to be stressed is that one is often obliged to compare measurements of the physical environment with biological data, which are often difficult to quantify.

Once the agrometeorological data are stored in electronic form in a file or database, they can be analysed using a public domain or commercial statistical software. Some basic statistical analyses can be performed in widely available commercial spreadsheet software. More comprehensive basic and advanced statistical analyses generally require specialized statistical software. Basic statistical analyses include simple descriptive statistics, distribution fitting, correlation analysis, multiple linear regression, non-parametrics and enhanced graphic capabilities. Advanced software includes linear/non-linear models, time series and forecasting, and multivariate exploratory techniques such as cluster analysis, factor analysis, principal components and classification analysis, classification trees, canonical analysis and discriminant analysis. Commercial statistical software for PCs would be expected to provide a user-friendly interface with self-prompting analysis selection dialogues. Many software packages include electronic manuals that provide extensive explanations of analysis options with examples and comprehensive statistical advice.

Some commercial packages are rather expensive, but some free statistical analysis software can be downloaded from the Web or made available upon request. One example of freely available software is INSTAT, which was developed with applications in agrometeorology in mind. It is a general-purpose statistics package for PCs that was developed by the Statistical Service Centre of the University of Reading in the United Kingdom. It uses a simple command language to process and analyse data. The documentation and software can be downloaded from the Web. Data for analysis can be entered into a table or copied and pasted from the clipboard. If CLICOM is used as the database management software, then INSTAT, which was designed for use with CLICOM, can readily be used to extract the data and perform statistical analyses. INSTAT can be used to calculate simple descriptive statistics, including minimum and maximum values, range, mean, standard deviation, median, lower quartile, upper quartile, skewness and kurtosis. It can be used to calculate probabilities and percentiles for standard distributions, normal scores, *t*-tests and confidence intervals, chi-square tests, and non-parametric statistics. It can be used to plot data for regression and correlation analysis and analysis of time series. INSTAT is designed to provide a range of

climate analyses. It has commands for 10-day, monthly and yearly statistics. It calculates water balance from rainfall and evaporation, start of rains, degree-days, wind direction frequencies, spell lengths, potential evapotranspiration according to Penman, and the crop performance index according to methodology used by the Food and Agriculture Organization of the United Nations (FAO). The usefulness of INSTAT for agroclimatic analysis is illustrated in Sivakumar et al. (1993): the major part of the analysis reported here was carried out using INSTAT.

3.6.1 Series checks

Before selecting a series of values for statistical treatment, the series should be carefully examined for validity. The same checks should be applied to series of agrometeorological data as to conventional climatological data; in particular, the series should be checked for homogeneity and, if necessary, gaps should be filled in. It is assumed that the individual values will have been carefully checked beforehand (for consistency and coherence) in accordance with section 4.3 of the *Guide to Climatological Practices* (WMO-No. 100).

Availability of good metadata is essential during analysis of the homogeneity of a data series. For example, a large number of temperature and precipitation series were analysed for homogeneity (WMO, 2004b). Because some metadata are archived in the country where those observations were made, the research could show that at least two thirds of the homogeneity breaks in those series were not due to climate change, but rather to instrument relocations, including changes in observation height.

3.6.2 Climatic scales

In agriculture, perhaps more than in most economic activities, all scales of climate need to be considered (see 3.2.1):

- (a) For the purpose of meeting national and regional requirements, studies on a macroclimatic scale are useful and may be based mainly on data from synoptic stations. For some atmospheric parameters with little spatial variation, for example, duration of sunshine over a week or 10-day period, such an analysis is found to be satisfactory;
- (b) In order to plan the activities of an agricultural undertaking, or group of undertakings, it is essential, however, to change over to the meso-climatic or topoclimatic scale, in other words, to take into account local geomorphological features and to use data from an observational network with a finer mesh. These complementary climatological series of data may be

for much shorter periods than those used for macroclimatic analyses, provided that they can be related to some long reference series;

- (c) For bioclimatic research, the physical environment should be studied at the level of the plant or animal, or the pathogenic colony itself. Obtaining information about radiation energy, moisture and chemical exchanges involves handling measurements on the much finer scale of microclimatology;
- (d) For research on the impacts of a changing climate, past long-term historical and future climate scenarios should be used.

3.6.2.1 Reference periods

The length of the reference period for which the statistics are defined should be selected according to its suitability for each agricultural activity. Calendar periods of a month or a year are not, in general, suitable. It is often best either to use a reduced timescale or, alternatively, to combine several months in a way that will show the overall development of an agricultural activity. The following periods are thus suggested for reference purposes:

- (a) Ten-day or weekly periods for operational statistical analyses, for instance, evapotranspiration, water balance, sums of temperature, frequency of occasions when a value exceeds or falls below a critical threshold value, and so forth. Data for the weekly period, which has the advantage of being universally adopted for all activities, are difficult to adjust for successive years, however;
- (b) For certain agricultural activities, the periods should correspond to phenological stages or to the periods when certain operations are undertaken in crop cultivation. Thus, water balance, sums of temperature, sequences of days with precipitation or temperature below certain threshold values, and the like, could be analysed for:
 - i. The mean growing season;
 - ii. Periods corresponding to particularly critical phenological stages;
 - iii. Periods during which crop cultivation, plant protection treatment or preventive measures are found to be necessary.

These suggestions, of course, imply a thorough knowledge of the normal calendar of agricultural activities in an area.

3.6.2.2 The beginning of reference periods

In agricultural meteorology, it is best to choose starting points corresponding to the biological

rhythms, since the arbitrary calendar periods (month, year) do not coincide with these. For example, in temperate zones, the starting point could be autumn (sowing of winter cereals) or spring (resumption of growth). In regions subject to monsoons or the seasonal movement of the intertropical convergence zone, it could be the onset of the rainy season. It could also be based on the evolution of a significant climatic factor considered to be representative of a biological cycle that is difficult to assess directly, for example, the summation of temperatures exceeding a threshold temperature necessary for growth.

3.6.2.3 Analysis of the effects of weather

The climatic elements do not act independently on the biological life cycle of living things: an analytical study of their individual effects is often illusory. Handling them all simultaneously, however, requires considerable data and complex statistical treatment. It is often better to try to combine several factors into single agroclimatic indices, considered as complex parameters, which can be compared more easily with biological data.

3.6.3 Population parameters and sample statistics

The two population characteristics μ and σ are called parameters of the population, while each of the sample characteristics, such as sample mean $\bar{x}$ and sample standard deviation s , is called a sample statistic.

A sample statistic used to provide an estimate of a corresponding population parameter is called a point estimator. For example, $\bar{x}$ may be used as an estimator of μ , the median may be used as an estimator of μ and s^2 may be used as an estimator of the population variance σ^2 .

Any one of the statistics mean, median, mode and mid-interquartile range would seem to be suitable for use as an estimator of the population mean μ . In order to choose the best estimator of a parameter from a set of estimators, three important desirable properties should be considered. These are unbiasedness, efficiency and consistency.

3.6.4 Frequency distributions

When dealing with a large set of measured data, it is usually necessary to arrange it into a certain number of equal groupings, or classes, and to count the number of observations that fall into each class. The number of observations falling into a given class is called the frequency for that class. The number of classes chosen depends on the number of observations. As a rough guide, the number of classes should not exceed five times the logarithm (base 10) of the number of observations. Thus, for 100 observations or more, there should be a maximum of 10 classes. It is also important that adjacent groups do not overlap. Table 3.1 serves as the basis for Table 3.2, which displays the result of this operation as a grouped frequency table.

The table has columns showing limits that define classes and another column giving lower and upper class boundaries, which in turn give rise to class widths or class intervals. Another column gives the mid-marks of the classes, and yet another column gives the totals of the tally known as the group or class frequencies.

Another column contains entries that are known as the cumulative frequencies. They are obtained from the frequency column by entering the number of observations with values less than or equal to the value of the upper class boundary of that group.

The pattern of frequencies obtained by arranging data into classes is called the frequency

Table 3.1. Climatological series of annual rainfall (mm) for Mbabane, Swaziland (1930–1979)

Year	0	1	2	3	4	5	6	7	8	9
193-	1 063	1 237	1 495	1 160	1 513	912	1 495	1 769	1 319	2 080
194-	1 350	1 033	1 707	1 570	1 480	1 067	1 635	1 627	1 168	1 336
195-	1 102	1 195	1 307	1 118	1 262	1 585	1 199	1 306	1 220	1 328
196-	1 411	1 351	1 115	1 256	1 226	1 062	1 546	1 545	1 049	1 830
197-	1 018	1 690	1 800	1 528	1 285	1 727	1 704	1 741	1 667	1 260

distribution of the sample. The probability of finding an observation in a class can be obtained by dividing the frequency for the class by the total number of observations. A frequency distribution can be represented graphically with a two-dimensional histogram, where the heights of the columns in the graph are proportional to the class frequencies.

3.6.4.1 Examples using frequency distributions

The probability of an observation's falling in class number five is $\frac{10}{50} = 0.2$ or 20 per cent. That is the same as saying that the probability of getting between 1 480 mm and 1 620 mm of rain in Mbabane is 20 per cent, or once in five years. The probability of getting less than 1 779 mm of rain in Mbabane as in class six is 0.94, which is arrived at by dividing the cumulative frequency up to this point by 50, the total number of observations or frequencies. This kind of probability is also known as relative cumulative frequency, which is given as a percentage in column seven. From column seven, one can see that the probability of getting between 1 330 mm and 1 929 mm of rain is 98 per cent minus 58 per cent, or 40 per cent. Frequency distribution groupings have the disadvantage that certain information is lost when they are used, such as the highest observation in the highest frequency class.

3.6.4.1.1 Probability based on normal distributions

A normal distribution is a highly refined frequency distribution with an infinite number of very narrow classes. The histogram from this distribution has smoothed-out tops that make a continuous smooth curve, known as a normal or bell curve. A normal curve is symmetric about its centre, having a horizontal axis that runs indefinitely both to the left and to the right, with the tails of the curve tapering off towards the axis in both directions. The vertical axis is chosen in such a way that the total area under the curve is exactly 1 (one square unit). The central point on the axis beneath the normal curve is the mean m and the set of data that produced it has a standard deviation s . Any set of data that tends to give rise to a normal curve is said to be normally distributed. The normal distribution is completely characterized by its mean and standard deviation. Sample statistics are functions of observed values that are used to infer something about the population from which the values are drawn. The sample mean $\bar{x}$ and sample variance s^2 , for instance, can be used as estimates of population mean and population variance, respectively, provided the relationship between these sample statistics and the populations from which the samples are drawn is known. In general, the sampling distribution of means is less spread out than the parent population.

Table 3.2. Frequency distribution of annual precipitation for Mbabane, Swaziland (1930–1979)

	1	2	3	5	6	7
	<i>Group boundaries</i>	<i>Group limits or class interval</i>	<i>Mid-mark xi</i>	<i>Frequency fi</i>	<i>Cumulative frequency Fi</i>	<i>Relative cumulative frequency (%)</i>
1	879.5–1 029.5	880–1 029	954.5	2	2	4
2	1 029.5–1 179.5	1 030–1 179	1 104.5	8	10	20
3	1 179.5–1 329.5	1 180–1 329	1 254.5	15	25	50
4	1 329.5–1 479.5	1 330–1 479	1 404.5	4	29	58
5	1 479.5–1 629.5	1 480–1 629	1 554.5	10	39	78
6	1 629.5–1 779.5	1 630–1 779	1 704.5	8	47	94
7	1 779.5–1 929.5	1 780–1 929	1 854.5	2	49	98
8	1 929.5–2 079.5	1 930–2 079	2 004.5	0	49	98
9	2 079.5–2 229.5	2 080–2 229	2 154.5	1	50	100
			Total:	50	–	–

This fact is embodied in the central limit theorem; it states that if random samples of size n are drawn from a large population (hypothetically infinite), which has mean m and standard deviation s , then the theoretical sampling distribution of $\bar{x}$ has mean m and standard deviation $\frac{\sigma}{\sqrt{n}}$. The theoretical sampling distribution of $\bar{x}$ can be closely approximated by the corresponding normal curve if n is large. Thus, for quite small samples, particularly if one knows that the parent population is itself approximately normal, the theorem can be confidently applied. If one is not sure that the parent population is normal, application of the theorem should, as a rule, be restricted to samples of size ≥ 30 . The standard deviation of a sampling distribution is often called the standard error of the sample statistic concerned. Thus $\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$ is the standard error of $\bar{x}$.

A comparison among different distributions with different means and different standard deviations requires that they be transformed. One way would be to centre them about the same mean by subtracting the mean from each observation in each of the populations. This will move each of the distributions along the scale until they are centred about zero, which is the mean of all transformed distributions. Each distribution will still maintain a different bell shape, however.

3.6.4.1.2 The z-score

A further transformation is done by subtracting the mean of the distribution from each observation and dividing by the standard deviation of the distribution, a procedure known as standardization. The result is a variable Z , known as a z-score and having the standard normal form:

$$Z = \frac{X - \mu}{\sigma} \quad (3.1)$$

This will give identical bell-shaped curves with normal distribution around zero mean and standard deviation equal to unit.

The z-scale is a horizontal scale set up for any given normal curve with some mean μ and some standard deviation σ . On this scale, the mean is marked 0 and the unit measure is taken to be σ , the particular standard deviation of the normal curve in question. A raw score X can be converted into a z-score by the above formula.

For instance, with $\mu = 80$ and $\sigma = 4$, in order to formally convert the X-score 85 into a z-score, the following equation is used:

$$Z = \frac{X - \mu}{\sigma} = \frac{85 - 80}{4} = \frac{5}{4} = 1.25 \quad (3.2)$$

The meaning here is that the X-score lies one standard deviation to the right of the mean. If a z-score equivalent of $X=74$ is computed, one obtains:

$$Z = \frac{X - \mu}{\sigma} = \frac{74 - 80}{4} = \frac{-6}{4} = -1.5 \quad (3.3)$$

The meaning of this negative z-score is that the original X-score of 74 lies 1.5 standard deviations (that is, six units) to the left of the mean. A z-score tells how many standard deviations removed from the mean the original x-score is, to the right (if Z is positive) or to the left (if Z is negative).

There are many different normal curves due to the different means and standard deviations. For a fixed mean μ and a fixed standard deviation σ , however, there is exactly one normal curve having that mean and that standard deviation.

Normal distributions can be used to calculate probabilities. Since a normal curve is symmetrical, having a total area of one square unit under it, the area to the right of the mean is half a square unit, and the same is true for the area to the left of the mean. The characteristics of the standard normal distribution are extremely well known, and tables of areas under specified segments of the curve are available in almost all statistical textbooks. The areas are directly expressed as probabilities. The probability of encountering a sample, by random selection from a normal population, whose measurement falls within a specified range can be found with the use of these tables. The variance of the population must, however, be known. The fundamental idea connected with the area under a normal curve is that if a measurement X is normally distributed, then the probability that X will lie in some range between a and b on any given occasion is equal to the area under the normal curve between a and b .

To find the area under a normal curve between the mean μ and some x -value, convert the x into a z-score. The number indicated is the desired area. If z turns out to be negative, just look it up as if it were positive. If the data are normally distributed, then it is probable that at least 68 per cent of data in the series will fall within $\pm 1\sigma$ of the mean, that is, $z = \pm 1$. Also, the probability is 95 per cent that all data fall within $\pm 2\sigma$ of the mean, or $z = \pm 2$, and 99 per cent within $\pm 3\sigma$ of the mean, or $z = \pm 3$.

3.6.4.1.3 Examples using the z-score

Suppose a population of pumpkins is known to have a normal distribution with a mean and

standard deviation of its length equal to 14.2 cm and 4.7 cm, respectively. What is the probability of finding, by chance, a specimen shorter than 3 m? To find the answer, 3 cm must be converted to units of standard deviation using the Standard Normal Distribution Table.

$$Z = \frac{3.0 - 14.2}{4.7} \approx -2.4 \quad (3.4)$$

These tables can be found in many statistical textbooks (Wilks, 1995; Steel and Torrie, 1980). There are, however, various types of normal tables (left-tail, right-tail) that require specific and detailed explanations of their use. In order to simply demonstrate the statistical concepts and not provide additional confusion about which type of distribution table one has available, the Excel function NORMDIST can be used to calculate the standard normal cumulative distribution.

The probability of finding a variety smaller than -2.4 standard deviations is the cumulative probability to this point. By using NORMDIST(-2.4) one obtains 0.0082, which is very small indeed. Now, what is the probability of finding one longer than 20 mm? Again, converting to standard normal form:

$$Z = \frac{20.0 - 14.2}{4.7} \approx 1.2 \quad (3.5)$$

By using NORMDIST(1.2), one obtains 0.1151, or slightly greater than one chance out of 10.

Here is a slightly more complicated example. If the heights of all the rice stalks in a farm are thought to be normally distributed with mean $\bar{X} = 38$ cm and standard deviation $s = 4.5$ cm, find the probability that the height of a stalk taken at random will be between 35 and 40 cm. To solve this problem, one must find the area under a portion of the appropriate normal curve, between $X = 35$ and $X = 40$. (See Figure 3.1). It is necessary to convert these x -values into z -scores as follows.

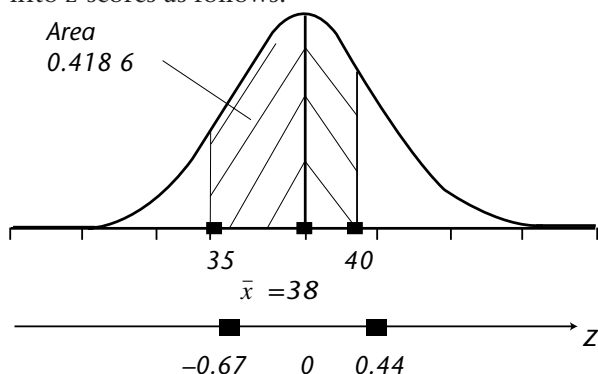


Figure 3.1. Probabilities for a normal distribution with $\bar{x} = 3.8$ and $s = 4.5$

For $X = 35$:

$$Z = \frac{X - \bar{x}}{S} = \frac{35 - 38}{4.5} = \frac{-3}{4.5} \approx -0.67 \quad (3.6)$$

For $X = 40$:

$$Z = \frac{X - \bar{x}}{S} = \frac{40 - 38}{4.5} = \frac{2}{4.5} \approx 0.44 \quad (3.7)$$

To determine the probability or area (Figure 3.1), one first needs to obtain the cumulative distribution for $Z = 0.44$, which is 0.6700. Remember that this is the cumulative distribution from Z to the left-tail. For $Z = -0.67$, the probability is 0.2514. But the probability between $Z = -0.67$ and $Z = 0.44$ needs to be determined. Therefore one subtracts probabilities, $0.6700 - 0.2514$, to obtain 0.4186. Thus, the probability that a stalk chosen at random will have height X between 35 and 40 cm is 0.4186. In other words, one would expect 41.86 per cent of the paddy field's rice stalks to have heights in that range.

Elements that are not normally distributed may easily be transformed mathematically to the normal distribution, an operation known as normalization. Among the moderate normalizing operators are the square root, the cube root and the logarithm for positively skewed data such as rainfall. The transformation reduces the higher values by proportionally greater amounts than smaller values.

3.6.4.2 Extreme value distributions

Certain crops may be exposed to lethal conditions (frost, excessive heat or cold, drought, high winds, and so on), even in areas where they are commonly grown. Extreme value analysis typically involves the collection and analysis of annual maxima of parameters that are observed daily, such as temperature, precipitation and wind speed. The process of extreme value analysis involves data gathering; the identification of a suitable probability model, such as the Gumbel distribution or generalized extreme value (GEV) distribution (Coles, 2001), to represent the distribution of the observed extremes; the estimation of model parameters; and the estimation of the return values for periods of fixed length.

The Gumbel double exponential distribution is the one most used for describing extreme values. An event that has occurred m times in a long series of n independent trials, one per year say, has an estimated probability $p = \frac{m}{n}$; conversely, the average interval between recurrences of the event during a

long period would be $\frac{m}{n}$; this is defined as the return period T where:

$$T = \frac{1}{p} \quad (3.8)$$

For example, if there is a 5 per cent chance that an event will occur in any one year, its probability of occurrence is 0.05. This can be expressed as an event having a return period of five times in 100 years or once in 20 years.

For a valid application of extreme value analysis, two conditions must be met. First, the data must be independent, that is, the occurrence of one extreme is not linked to the next. Second, the data series must be trend-free and the quantity of data must be large, usually not fewer than 15 values.

3.6.4.3 Probability and risk

Frequency distributions, which provide an indication of risk, are of particular interest in agriculture due to the existence of ecological thresholds which, when reached, may result either in a limited yield or in irreversible reactions within the living tissue. Histograms can be fitted to the most appropriate distribution function and used to make statements about probabilities or risk of critical climate conditions, such as freezing temperatures or dry spells of more than a specified number of days. Cumulative frequencies are particularly suitable and convenient for operational use in agrometeorology. Cumulative distributions can be used to prepare tables or graphs showing the frequencies of occasions when the values of certain parameters exceed (or fall below) given threshold values during a selected period. If a sufficiently long series of observations (10 to 20 years) is available, it can be assumed to be representative of the total population, so that mean durations of the periods when the values exceed (or fall below) specified thresholds can be deduced. When calculating these mean frequencies, it is often an advantage to extract information regarding the extreme values observed during the period chosen, such as the growing season, growth stage or period of particular sensitivity. Some examples are:

- (a) Threshold values of daily maximum and minimum temperatures, which can be used to estimate the risk of excessive heat or frost and the duration of this risk;
- (b) Threshold values of 10-day water deficits, taking into account the reserves in the soil. The quantity of water required for irrigation can then be estimated;
- (c) Threshold values of relative humidity from hourly or 3-hour observations.

3.6.4.4 Distribution of sequences of consecutive days

The distribution of sequences of consecutive days in which certain climatic events occur is of special interest to the agriculturist. From such data one can, for example, deduce the likelihood of being able to undertake cultural operations requiring specific weather conditions and lasting for several days (haymaking, gathering grapes, and the like). The choice of protective measures to be taken against frost or drought may likewise be based on an examination of their occurrence and the distribution of the corresponding sequences. For whatever purpose the sequences are to be used, it is important to specify clearly the periods to which they refer (also whether or not they are for overlapping periods). Markov chain probability models have frequently been used to estimate the probability of sequences of certain consecutive days, such as wet days or dry days. Under many climate conditions, the probability, for example, that a day will be dry is significantly larger if the previous day is known to have been dry. Knowledge of the persistence of weather events such as wet days or dry days can be used to estimate the distribution of consecutive days using a Markov chain. INSTAT includes algorithms to calculate Markov chain models, to simulate spell lengths and to estimate probability using climatological data.

3.6.5 Measuring central tendency

One descriptive aspect of statistical analysis is the measurement of what is called central tendency, which gives an idea of the average or middle value about which all measurements coming from the process will cluster. To this group belong the mean, the median and the mode. Their symbols are as listed below:

$\bar{x}$	–	arithmetic mean of a sample;
μ	–	population mean;
$\bar{x}_w$	–	weighted mean;
$\bar{x}_h$	–	harmonic mean.

3.6.5.1 The mean

While frequency distributions are undoubtedly useful for operational purposes, mean values of the main climatic elements (10-day, monthly or seasonal) may be used broadly to compare climatic regions. To show how the climatic elements are distributed, however, these mean values should be supplemented by other descriptive statistics, such as the standard deviation, coefficient of variation (variability), quintiles and extreme values. In

agrocimatology, series of observations that have not been made simultaneously may have to be compared. To obtain comparable means in such cases, adjustments are applied to the series so as to fill in any gaps (see *Some Methods of Climatological Analysis*, WMO-No. 199). Sivakumar et al. (1993) illustrate the application of INSTAT in calculating descriptive statistics for climate data and discuss the usefulness of the statistics for assessing agricultural potential. They produce tables of monthly mean, standard deviation, and maximum and minimum for rainfall amounts and for the number of rainy days for available stations. Descriptive statistics are also presented for maximum and minimum air temperatures.

The arithmetic mean is the most commonly used measure of central tendency, defined as:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n x_i \quad i = 1, 2, \dots, n \quad (3.9)$$

This consists of adding all data in a series and dividing their sum by the number of data. The mean of the annual precipitation series from Table 3.1 is:

$$\bar{X} = \frac{\sum x}{n} = 69\,449 / 50 = 1\,388.9 \quad (3.10)$$

The arithmetic mean may be computed using other labour-saving methods such as the grouped data technique (*Guide to Climatological Practices*, WMO-No. 100), which estimates the mean from the average of the products of class frequencies and their midpoints.

Another version of the mean is the weighted mean, which takes into account the relative importance of each variate by assigning it a weight. An example of the weighted mean can be seen in the calculation of areal averages such as yields, population densities or areal rainfall over non-uniform surfaces. The value for each subdivision of the area is multiplied by the subdivision area, and then the sum of the products is divided by the total area. The formula for the weighted mean is expressed as:

$$\bar{X}_w = \frac{\sum_{i=1}^k n_i \bar{x}_i}{\sum_{i=1}^k n_i} \quad (3.11)$$

For example, the average yield of maize for the five districts in the Ruvuma Region of Tanzania was 1.5, 2.0, 1.8, 1.3 and 1.9 tonnes per hectare (t/ha), respectively. The respective areas under maize were 3 000, 7 000, 2 000, 5 000 and 4 000 ha. If the values $n_1 = 3\,000$, $n_2 = 7\,000$, $n_3 = 2\,000$, $n_4 = 5\,000$ and $n_5 = 4\,000$ are substituted

into equation (3.11), the overall mean yield of maize for these 21 000 ha of land is as follows:

$$\begin{aligned} \bar{X}_w &= \frac{3\,000(1.5) + 7\,000(2.0) + 2\,000(1.8) + 5\,000(1.3) + 4\,000(1.9)}{3\,000 + 7\,000 + 2\,000 + 5\,000 + 4\,000} \\ &= \frac{33\,800}{21\,000} \end{aligned} \quad (3.12)$$

In operational agrometeorology, the mean is normally computed for 10 days, known as dekads, as well as for the day, month, year and longer periods. This is used in agrometeorological bulletins and for describing current weather conditions. At agrometeorological stations where the maximum and the minimum temperatures are read, a useful approximation of the daily mean temperature is given by taking the average of these two temperatures. These averages should be used with caution when comparing data from different stations, as such averages may differ systematically from each other.

Another measure of the mean is the harmonic mean, which is defined as n divided by the sum of the reciprocals or multiplicative inverses of the numbers:

$$\bar{X}_w = \frac{\sum_{i=1}^k n_i \bar{x}_i}{\sum_{i=1}^k n_i} \quad (3.13)$$

If five sprinklers can individually water a garden in 4 h, 5 h, 2 h, 6 h and 3 h, respectively, the time required for all pipes working together to water the garden is given by

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \quad (3.14)$$

= 46 minutes and 45 seconds.

Means of long-term periods are known as normals. A normal is defined as a period average computed for a uniform and relatively long period comprising at least three consecutive 10-year periods. A climatological standard normal is the average of climatological data computed for consecutive periods of 30 years as follows: 1 January 1901 to 31 December 1930, 1 January 1931 to 31 December 1960, and so on.

3.6.5.2 The mode

The mode is the most frequent value in any array. Some series have even more than one modal value. Mean annual rainfall patterns in some sub-equatorial countries have bimodal distributions, meaning they exhibit two peaks. Unlike the mean, the mode is an actual value in the series. Its use is mainly in describing the average.

3.6.5.3 The median

The median is obtained by selecting the middle value in an odd-numbered series of variates or taking the average of the two middle values of an even-numbered series. For large volumes of data it is easiest to obtain a close approximation of their median by graphical or numerical interpolation of their cumulative frequency distribution.

3.6.6 Fractiles

Fractiles such as quartiles, quintiles and deciles are obtained by first ranking the data in ascending order and then counting an appropriate fraction of the integers in the series $(n + 1)$. For quartiles, $n + 1$ is divided by four, for deciles by 10, and for percentiles by a hundred. Thus if $n = 50$, the first decile is the $\frac{1}{10}[n+1]^{\text{th}}$ or the 5.1th observation in the ascending order, and the 7th decile is the $\frac{7}{10}[n+1]^{\text{th}}$ in the rank or the 35.7th observation. Interpolation is required between observations. The median is the 50th percentile. It is also the fifth decile and the second quartile. It lies in the third quintile. In agrometeorology, the first decile means that value below which one-tenth of the data falls and above which nine-tenths lie.

3.6.7 Measuring dispersion

Other parameters give information about the spread or dispersion of the measurements about the average. These include the range, the variance and the standard deviation.

3.6.7.1 The range

This is the difference between the largest and the smallest values. For instance, the annual range of mean temperature is the difference between the mean daily temperatures of the hottest and coldest months.

3.6.7.2 The variance and the standard deviation

The variance is the mean of the squares of the deviations from the arithmetic mean. The standard deviation s is the square root of the variance and is defined as the root-mean-square of the deviations from the arithmetic mean. To obtain the standard deviation of a given sample, the mean $\bar{x}$ is computed first and then the deviations from the mean $(\bar{x}_i - \bar{x})$:

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \quad (3.15)$$

Alternatively, with only a single computation run summing data values and their squares:

$$S = \sqrt{(\sum (x_i^2) - (\sum x_i)^2/n)/(n - 1)} \quad (3.16)$$

This standard deviation has the same units as the mean; together they may be used to make precise probability statements about the occurrence of certain values of a climatological series. The influence of the actual magnitude of the mean can be easily eliminated by expressing s as a percentage of the mean to derive a dimensionless quantity called the coefficient of variation:

$$Cv = \frac{s}{\bar{x}} \times 100 \quad (3.17)$$

For comparing values of s between different places, this can be used to provide a measure of relative variability for such elements as total precipitation.

3.6.7.3 Measuring skewness

Other parameters can provide information on the skewness, or asymmetry, of a population. Skewness represents a tendency of a data distribution to show a pronounced tail to one side or another. With these populations, there is a good chance of finding an observation far from the mode, and the mean may not be representative as a measure of the central tendency.

3.7 DECISION-MAKING

3.7.1 Statistical inference and decision-making

Statistical inference is a process of inferring information about a population from the data of samples drawn from it. The purpose of statistical inference is to help a decision-maker to be right more often than not, or at least to give some idea of how much danger there is of being wrong when a particular decision is made. It is also meant to ensure that long-term costs through wrong decisions are kept to a minimum.

Two main lines of attacking the problem of statistical inference are available. One is to devise sample statistics that may be regarded as suitable estimators of corresponding population parameters. For example, the sample mean $\bar{X}$ may be used as an estimator of the population mean μ , or else the sample median may be used. Statistical estimation theory deals with the issue of selecting best estimators. The steps to be taken to arrive at a decision are as follows:

Step 1. Formulate the null and alternative hypotheses

Once the null hypothesis has been clearly defined, one can calculate what kind of samples to expect under the supposition that it is true. Then if a random sample is drawn, and if it differs markedly in some respect from what is expected, the observed difference is said to be significant and one is inclined to reject the null hypothesis and accept the alternative hypothesis. If the difference observed is not too large, one might accept the null hypothesis or call for more statistical data before coming to a decision. One can make the decision in a hypothesis test depending upon a random variable known as a test statistic, such as the z-score used in finding confidence intervals, and critical values of this test statistic can be specified that can be used to indicate not only whether a sample difference is significant, but also the strength of the significance.

For instance, in a coin experiment to determine if the coin is fair or loaded:

Null H_0 : $p = 0.5$ (namely, the coin is fair).

And alternative H_1 : $p \neq 0.5$ (namely, the coin is biased).

(Or equivalently H_1 : $p < 0.5$ or $p > 0.5$; this is called a two-sided alternative).

Step 2. Choose an appropriate level of significance

The probability of wrongly rejecting a null hypothesis is called the level of significance (α) of the test. The value for α is selected first, before any experiments are carried out; the values most commonly used by statisticians are 0.05, 0.01 and 0.001. The level of significance $\alpha = 0.5$ means that the test procedure has only 5 chances in 100 of leading one to decide that the coin is biased if in fact it is not.

Step 3. Choose the sample size n

It is fairly clear that if bias exists, a large sample will have more chance of demonstrating its existence than a small one. So one should make n as large as possible, especially if one is concerned with demonstrating a small amount of bias. Cost of experimentation, time involved in sampling, necessity of maintaining statistically constant conditions, amount of inherent random variation and possible consequences of making wrong decisions are among the considerations on which the sample sizes depend.

Step 4. Decide upon the test statistic to be used

The decision in a hypothesis test can be made depending upon a random variable known as a test statistic, such as z or t , as used in finding confidence intervals. Its sampling distribution, under the assumption that H_0 is true, must be known. It can be normal, binomial or another type of sampling distribution.

Step 5. Calculate the acceptance and rejection regions

Assuming that the null hypothesis is true, and bearing in mind the chosen values of n and α , an acceptance region of values for the test statistic is now calculated. Values outside this region form the rejection region. The acceptance region is so chosen that if a value of the test statistic, obtained from the data of a sample, fails to fall inside it, then the assumption that H_0 is true must be strongly doubted. In general, there is a test statistic X , whose sampling distribution, defined by certain parameters such as η and σ , is known. The values of the parameters are specified in the null hypothesis H_0 . From integral tables of the sampling distribution, critical values X_1 , X_2 are obtained such that

$$P [X_1 < X < X_2] = 1 - \alpha \quad (3.18)$$

These determine an acceptance region, which gives a test for the null hypothesis at the appropriate level of significance (α).

Step 6. Formulate the decision rule

The general decision rule, or test of hypothesis, may now be stated as follows:

- (a) Reject H_0 at the α significance if the sample value of X lies in the rejection region (that is, outside $[X_1, X_2]$). This is equivalent to saying that the observed sample value is significant at the $100\alpha\%$ level.

The alternative hypothesis H_1 is then to be accepted.

- (b) Accept H_0 if the sample value of X lies in the acceptance region $[X_1, X_2]$. (Sometimes, especially if the sample size is small, or if X is close to one of the critical values X_1 and X_2 , the decision to accept H_0 is deferred until more data are collected.)

Step 7. Carry out the experiment and make the test

The n trials of the experiment may now be carried out, and from the results, the value of the chosen

test statistic may be calculated. The decision rule described in Step 6 may then be applied. Note: All statistical test procedures should be carefully formulated before experiments are carried out. The test statistic, the level of significance, and whether a one- or two-tailed test is required, must be decided before any sample data are looked at. Switching tests in midstream, as it were, leads to invalid probability statements about the decisions made.

3.7.2 Two-tailed and one-tailed tests

The determination of whether one uses a two-tailed or a one-tailed test depends on how the hypothesis is characterized. If the H_1 was defined as $\mu \neq 0$, the critical region would occupy both extremes of the test distribution. This is a two-tailed test, where the values could be on either side of μ . If the H_1 was defined as $\mu > 0$ or $\mu < 0$, the critical region occurs only at high or low values of the test statistic. This is known as a one-tailed test.

With a two-tailed test, the critical region containing 5 per cent of the area of the normal distribution is split into two equal parts, each containing 2.5 per cent of the total area. If the computed value of Z falls into the left-hand region, the sample came from a population having a smaller mean than the known population. Conversely, if it falls into the right-hand region, the mean of the sample's parent population is larger than the mean of the known population. From the standardized normal distribution table found in most statistical textbooks, one can find that approximately 2.5 per cent of the area of the curve is to the left of a Z value of -1.96 and 97.5 per cent of the area of the curve is to the left of $+1.96$. An example of a normal table can be accessed from <http://www.isixsigma.com/library/content/zdistribution.asp>.

Once the null hypothesis has been clearly defined, one can calculate what kind of samples to expect under the supposition that it is true. Then, if a random sample is drawn, and if it differs markedly in some respect from what is expected, one can say that the observed difference is significant, and one is inclined to reject the null hypothesis and accept the alternative hypothesis. If the difference observed is not too large, one might accept the null hypothesis, or one might call for more statistical data before coming to a decision. The decision in a hypothesis test can be made depending upon a random variable known as a test statistic, such as z or t , as used in finding confidence intervals, and critical values of this test statistic can be specified, which can be used

to indicate not only whether a sample difference is significant but also the strength of the significance.

3.7.3 Interval estimation

Confidence interval estimation is a technique of calculating intervals for population parameters and measures of confidence placed upon them. If one has chosen an unbiased sample statistic b as the point estimator of β , the estimator will have a sampling distribution with mean $E(b) = \beta$ and standard deviation $S.D.(b) = \sigma_b$. Here the parameter β is the unknown and the purpose is to estimate it. Based on the remarkable fact that many sample statistics used in practice have a normal or approximately normal sampling distribution, from the tables of the normal integral one can obtain the probability that a particular sample will provide a value of b within a given interval $(\beta - d)$ to $(\beta + d)$.

This is indicated in the diagram below. Conversely, for a given amount of probability, one can deduce the value d . For example, for 0.95 probability, one knows from standard normal tables that $\frac{d}{\sigma_b} = 1.96$. In other words, the probability that a sample will provide a value of b in the interval $[\beta - 1.96\sigma_b, \beta + 1.96\sigma_b]$ is 0.95. This is written as $P[\beta - 1.96\sigma_b < b < \beta + 1.96\sigma_b] = 0.95$. After rearranging the inequalities inside the brackets to the equivalent form $[b - 1.96\sigma_b \leq \beta \leq b + 1.96\sigma_b]$, one obtains the 95 per cent confidence interval for β , namely the interval $[b - 1.96\sigma_b, b + 1.96\sigma_b]$. In general, confidence intervals are expressed in the form $[b - z\sigma_b, b + z\sigma_b]$, where z , the z -score, is the number obtained from tables of the sampling distribution of b . This z -score is chosen so that the desired percentage confidence may be assigned to the interval; it is now called the confidence coefficient, or sometimes the critical value. The endpoints of a confidence interval are known as the lower and upper confidence limits. The probable error of estimate is half the interval length of the 50 per cent confidence interval, namely, 0.674σ . Table 3.3 is an abbreviated table of confidence values for z .

The most commonly required point and interval estimates are for means, proportions, differences between two means, and standard deviations. Table 3.4 gives all the formulae needed for these estimates. The reader should note the standard form of $b \pm z\sigma_b$ for each of the confidence interval estimators.

For the formulae to be valid, sampling must be random and the samples must be independent. In

some cases, σ_b will be known from prior information. Then the sample estimator will not be used. In each of the confidence interval formulae, the confidence coefficient z may be found from tables of the normal integral for any desired degree of confidence. This will give exact results if the population from which the sampling is done is normal; otherwise, the errors introduced will be small if n is reasonably large ($n \geq 30$).

What should one do when samples are small? It is clear that the smaller the sample, the smaller amount of confidence one can place on a particular interval estimate. Alternatively, for a given degree of confidence, the interval quoted must be wider than for larger samples. To bring this about, one must have a confidence coefficient that depends upon n . The letter t shall be used for this coefficient and confidence interval formulae shall be provided for the population mean and for the difference of two population means.

The reader will note that these are the same as for large samples, except that t replaces z . When the sample estimators for $\sigma_{\bar{x}}$ and $\sigma_{\bar{x}_1 - \bar{x}_2}$ are used, the correct values for t are obtained from what is called the Student t -distribution. For convenience, they are related not directly to sample sizes, but to a number known as "degrees of freedom"; this shall be denoted by v . An abbreviated table of t -values is given in Table 3.5.

Table 3.4. Formulae for confidence interval estimates

	Confidence interval	Degrees of freedom (u)
1. Mean μ :	$\bar{x} \pm t \cdot \sigma_{\bar{x}}$	$n - 1$
2. Difference $\mu_1 - \mu_2$:	$(\bar{x}_1 - \bar{x}_2) \pm t \cdot \sigma(\bar{x}_1 - \bar{x}_2)$	$n_1 + n_2 - 2$

3.7.4 The z -test

The nature of the standard normal distribution allows one to test hypotheses about the origin of certain samples. The test statistic Z has a normal frequency distribution, which is a standardized normal distribution defined as:

$$Z = \frac{\bar{X} - \mu_0}{\sigma/\sqrt{n}} \quad (3.19)$$

The observations in the sample were selected randomly from a normal population whose variance is known.

3.7.5 Tests for normal population means

A random sample size n is drawn from a normal population having unknown mean μ and known standard deviation σ . The objective is to test the hypothesis $H_0: \mu = \mu'$, that is, the assumption that the population mean has value σ' .

The variate $Z = \frac{\bar{X} - \mu'}{\sigma/\sqrt{n}}$ has a standard normal distribution if H_0 is true. Z (or $\bar{X}$) may be used as the test statistic.

Example 1

Suppose that the shelf life of one-litre bottles of pasteurized milk is guaranteed to be at least 400 days, with a standard deviation of 60 days. If a sample of 25 bottles is randomly chosen from a production batch, and a sample mean shelf life of 375 is calculated after testing has been performed, should the batch be rejected as not meeting the guarantee?

Solution: Let μ be the batch mean.

Step 1. Null hypothesis $H_0: \eta = 400$.

Alternative hypothesis $H_1: \eta = 400$ (one-sided: one is only interested in whether or not the mean is up to the guaranteed minimum value).

Steps 2 and 3. $n = 25$ (given); choose $\alpha = 0.05$.

Step 4. If $\bar{X}$ is the sample mean, the quantity

$$Z = \frac{375 - 400}{60/\sqrt{25}} \quad (3.20)$$

is a standard normal variate (perhaps approximately) if H_0 is true. Z shall be used as the test statistic.

Step 5. For a one-tailed test, standard normal tables give $Z = -1.65$ as the lowest value to be allowed before H_0 must be rejected, at the 5 per cent significance level. The acceptance region is therefore $[-1.65, \text{infinite}]$.

Table 3.3. Abbreviated table of confidence values for z

Confidence level	50%	60%	80%	86.8%	90%	92%	93.4%	94.2%	95%	95.6%	96%	97.4%	98%
Confidence coefficient z	0.674	0.84	1.28	1.50	1.645	1.75	1.84	1.90	1.96	2.01	2.05	2.23	2.33

Step 6. Decision rule:

- (a) Reject the production batch if the value of Z calculated from the sample is less than -1.65 .
- (b) Accept the batch otherwise.

Step 7. Carry out the test:

From the sample data one finds that

$$Z = \frac{375 - 400}{60\sqrt{25}} = -2.083 \quad (3.21)$$

Decision: the production batch must be rejected, since $-2.083 < -1.65$. It is highly unlikely that the mean shelf life of milk bottles in the batch will be 400 days or more. The chance that this decision is wrong is smaller than 5 per cent.

Example 2

A sample of 66 seeds of a certain plant variety were planted on a plot using a randomized block design. Before planting, 30 of the seeds were subjected to a certain heat treatment. The times from planting to germination were observed. The 30 treated seeds took 52 days to germinate, while the 36 untreated seeds took 47 days. If the common standard deviation for time to germination applicable to individual seeds, calculated from several thousand seeds, may be taken as 12 days, can it be said that the heat treatment significantly speeds up a seed's germination rate?

From the data given, it is clear that the heat-treated seeds had an earlier start in growth. One may consider, however, the wider question as to whether heat-treated seeds are significantly faster germinating generally than untreated seeds.

The test is as follows:

Step 1. Let μ_A, μ_B be the germination period population means for heat-treated and untreated seeds, respectively.

Null hypothesis $H_0: \mu_A = \mu_B$ (that is, $\mu_A - \mu_B = 0$).

Alternative hypothesis $H_1: \mu_A > \mu_B$.

The specific question was whether the heat-treated seeds were faster germinating than the untreated seeds, so the one-sided alternative hypothesis is used.

Steps 2 and 3. $n_A = 30$ and $n_B = 36$ (given).

The significance level shall be $\alpha = 0.05$.

Step 4. Test statistic:

No information other than the two sample means is given. Even if the individual students' results were known, the paired comparison test could not be used – there would be no possible reason for linking the results in pairs.

The difference in means $(\bar{x}_A - \bar{x}_B)$ is approximately normally distributed, with mean $(\mu_A - \mu_B)$ and standard deviation

$$\sigma' = \sqrt{\frac{\sigma^2}{n_A} + \frac{\sigma^2}{n_B}} \quad (3.22)$$

So one may use as a test statistic the standard normal variate

$$z = \frac{(\bar{x}_A - \bar{x}_B) - (\mu_A - \mu_B)}{\sigma'} \quad (3.23)$$

And if H_0 is true, $\mu_A - \mu_B = 0$; so the test statistic reduces to

$$z = \frac{\bar{x}_A - \bar{x}_B}{\sigma'} \quad (3.24)$$

Step 5. Acceptance region:

The critical value of z at 5 per cent level of significance, for a one-tailed test, is 1.65. Therefore, the acceptance region for the null hypothesis is the set of values z less than or equal to 1.65.

Table 3.5. Abbreviated table of confidence values for t

ν	3	4	5	7	9	10	15	20	25	30
90%	2.35	2.13	2.02	1.89	1.83	1.81	1.75	1.72	1.71	1.70
95%	3.18	2.78	2.57	2.36	2.26	2.23	2.13	2.09	2.06	2.04
99%	5.84	4.60	4.03	3.50	3.25	3.17	2.95	2.85	2.79	2.75

Degrees of freedom ν

Step 6. Decision rule:

- (a) If the sample value of $z > 1.65$, conclude that heat-treated seeds germinate significantly earlier (at the 5 per cent level) than untreated seeds.
- (b) If $z \leq 1.65$, the germination rates of both heat-treated and untreated seeds may well be the same.

Step 7. Carry out the test.

The value of σ is given as 12.

Therefore

$$\sigma' = \sigma \sqrt{\frac{1}{n_A} + \frac{1}{n_B}} = 12 \sqrt{\frac{1}{30} + \frac{1}{36}} \approx 2.96 \quad (3.25)$$

And so the sample value of the test statistic is

$$z = \frac{\bar{x}_A - \bar{x}_B}{\sigma'} = \frac{52 - 47}{2.96} \approx 1.69 \quad (3.26)$$

Decision: The heat-treated seed is just significantly earlier germinating at the 5 per cent level than the untreated seed.

3.7.6 The *t*-test

The uncertainty introduced into estimates based on samples can be accounted for by using a probability distribution that has a wider spread than the normal distribution. One such distribution is the *t*-distribution, which is similar to the normal distribution, but dependent on the size of sample taken. When the number of observations in the sample is infinite, the *t*-distribution and the normal distribution are identical. Tables of the *t*-distribution and other sample-based distributions are used in exactly the same manner as tables of the cumulative standard normal distribution, except that two entries are necessary to find a probability in the table. The two entries are the desired level of significance (α) and the degrees of freedom (ν), defined as the number of observations in the sample minus the number of parameters estimated from the sample.

Then for the test statistic one uses $t = \frac{\bar{X} - \mu_0}{S/\sqrt{n}}$, which has a Student's *t*-distribution with $n - 1$ degrees of freedom.

Example using the *z*-test

A farmer was found to be selling pumpkins that looked like ordinary pumpkins except that these were very large, with an average diameter of 30.0 cm for 10 samples. The mean and standard deviation for pumpkins are 14.2 cm and 4.7 cm, respectively. The intent is to test whether the

pumpkins that the farmer is selling are ordinary pumpkins.

One can hypothesize that the mean of the population from which the farmer's pumpkins were taken is the same as the mean of the ordinary pumpkins by the null hypothesis

$$H_0 : \mu_1 = \mu_0 \quad (3.27)$$

An alternative hypothesis must also be given:

$$H_0 : \mu_1 \neq \mu_0,$$

stating that the mean of the population from which the sample was drawn does not equal the specified population mean. If the two parent populations are not the same, one must conclude that the pumpkins that the farmer was selling were not drawn from the ordinary pumpkin population, but from the population of some other genus. One needs to specify levels of probability of correctness, or level of significance, denoted by α . A probability level of 5 per cent may be applied; this means a willingness to risk rejecting the hypothesis when it is correct 5 times out of 100 trials. One must have the variance of the population against which one is checking. A formal statistical test may now be set up in the following manner:

1. The hypothesis and alternative:

$$H_0 : \mu_1 = \mu_0 \quad (3.28)$$

$$H_0 : \mu_1 \neq \mu_0 \quad (3.29)$$

2. The level of significance:

$$\alpha = 0.05 \quad (3.30)$$

3. The test statistic:

$$Z = \frac{\bar{X} - \mu_0}{\sigma/\sqrt{n}} \quad (3.31)$$

The test statistic, Z , has a frequency distribution that is a standardized normal distribution, provided that the observations in the sample were selected randomly from a normal population whose variance is known. If that has been specified, one is willing to reject the hypothesis of the equality of means when they actually are equal one time out of twenty: that is, one will accept a 5 per cent risk of being wrong. On the standardized normal distribution curve, therefore, the extreme regions that contain 5 per cent of the area of the curve need to be determined. This part of the probability curve is called the area of rejection or the critical region. If the computed value of the test statistic falls into this area, the null hypothesis will be

rejected. The hypothesis will be rejected if the test statistic is either too large or too small. The critical region, therefore, occupies the extremities of the probability distribution and each subregion contains 2.5 per cent of the total area of the curve.

Working through the pumpkin example, the outline takes the following form:

$$1. \quad H_0 : \mu \neq \mu \text{ of pumpkins} = 14.2 \text{ mm}$$

$$H_1 : \mu \text{ of pumpkins} \neq 14.2 \text{ mm}$$

$$2. \quad \alpha \text{ level} = 0.05$$

$$3. \quad z = \frac{30 - 14.2}{4.7/\sqrt{10}} = 10.6$$

The computed test value of 10.6 exceeds 1.9, so one concludes that the means of the two populations are not equal, and the plants must represent some genus other than that of ordinary pumpkins.

3.7.7 Estimators using pooled samples

Let two random samples of sizes n_1, n_2 , respectively, be drawn from a large population that has mean μ and variance σ^2 . Suppose that the samples yield unbiased estimates, $\bar{x}_1$ and $\bar{x}_2$ of μ and s_1^2, s_2^2 of σ^2 . The problem arises of combining these pairs of estimates to obtain single unbiased estimates of μ and σ^2 . The process of combining estimates from two or more samples is known as pooling. The correct ways to pool unbiased estimates of means and variances, to yield single unbiased estimates, are

$$\text{Means:} \quad \hat{\mu} = \frac{n_1\bar{x}_1 + n_2\bar{x}_2}{n_1 + n_2} \quad (3.32)$$

$$\text{Variances: } \sigma^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \quad (3.33)$$

Example:

A soil scientist made six determinations of the strength of dilute sulphuric acid. His results showed a mean strength of 9.234 with a standard deviation of 0.12. Using acid from another bottle, he made eleven determinations, which showed a mean strength of 8.86 with a standard deviation of 0.21. Obtain 95 per cent confidence limits for the difference in mean strengths of the acids in the two bottles. Could the bottles have been filled from the same source?

Working:

The difference in mean strengths of the acids is estimated by

$$\bar{x}_1 - \bar{x}_2 = 9.234 - 8.86 = 0.374 \quad (3.34)$$

The standard deviation of the sampling distribution of $\bar{x}_1 - \bar{x}_2$, written as $\sigma(\bar{x}_1 - \bar{x}_2)$, is estimated first. The data from the two samples are pooled, thus:

$$\hat{\sigma}_{\bar{x}_1 - \bar{x}_2} = s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} = s \sqrt{\frac{1}{6} + \frac{1}{11}} \quad (3.35)$$

$$\text{where } s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \quad (3.36)$$

$$= \frac{5 \times 0.0144 + 10 \times 0.0441}{6 + 11 - 2} = \frac{0.72 + 0.441}{15} = \frac{1.161}{15} = 0.0774 \quad (3.37)$$

and so $s = 0.2782$.

Therefore

$$s^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \quad (3.38)$$

With 15 degrees of freedom, the confidence coefficient is $t = 2.13$ for 95 per cent confidence. Therefore the required limits for $\mu_1 - \mu_2$ are

$$(\bar{x}_1 - \bar{x}_2) \pm t \cdot \hat{\sigma}_{\bar{x}_1 - \bar{x}_2} = 0.374 \pm 2.13 \times 0.141196 = 0.374 \pm 0.300748 \quad (3.39)$$

Thus, the 95 per cent confidence limits for the difference in mean strengths of the acids in the two bottles are 0.0733 and 0.6747. This indicates that one is 95 per cent confident that the difference in mean strengths of the acids in the two bottles lies between 0.0733 and 0.6747.

3.7.8 The paired comparison test and the difference between two means test

Example: Paired comparison test

The yields from two varieties of wheat were compared. The wheat was planted on 25 test plots. Each plot was divided into two equal parts; one part was chosen randomly and planted with the first variety and the other part was planted with the second variety of wheat. This process was repeated for all 25 plots. When the crop yields were measured, the difference in yields from each plot was recorded (second variety minus first variety). The sample mean plot yield difference was found to be 3.5 t/ha, and the variance of these differences was calculated to be 16 t/ha.

- Does the second variety produce significantly higher yields than the first variety?
- Test the hypothesis that the population mean plot yield difference is as high as 5 t/ha.
- Obtain 95 per cent confidence limits for the population mean plot yield difference.

It is clear that there is a good deal of variation in yields from plot to plot. This variation tends to

confound the main issue, which is to determine whether yields are increased by using a second variety. This confusion has been avoided by considering only the change in yields for each plot. If the second variety has no effect, the average change will be zero.

Data of this kind, in which results are combined in pairs and each pair arises from one experimental unit or has some clear reason for being linked in this way, are analysed by the paired comparison test. Each pair provides a single comparison as a measure of the effect of the treatment applied (for example, growing a different variety). Let D denote the difference in a given pair of results. D will have normal distribution with mean μ and standard deviation σ (both the parameters are unknown in this case).

Example using the t -test

Step 1.

Null hypothesis $H_0: \mu = 0$ (namely, the yield of the two wheat varieties is the same).

Alternative hypothesis $H_1: \mu > 0$ (that is, the second variety yields are higher than the first variety yields).

H_1 is one sided; a one-tailed test must be applied.

Steps 2 and 3. Twenty-five plots were used, which means that $n = 25$. A significance level of $\alpha = 0.05$ shall be used.

Step 4. The quantity $z = \frac{D - 0}{\sigma \sqrt{25}}$ is a standard normal variate and may be used as the test statistic if σ is known from previous experimentation.

The parameters of a population are rarely known. In this case, σ is not given, so it must be estimated from the sample data.

Step 5. Acceptance region: the critical level of t at the 0.05 level of significance (one-tailed test) is the same as the upper 90 per cent confidence coefficient, as provided in Table 3.5. With 24 degrees of freedom, this value is 1.71. The acceptance region is therefore all values of t from $-\infty$ to 1.71.

Step 6. Decision rule:

- If the value of t calculated from the sample is greater than 1.71, one may conclude that the second wheat variety gives higher yields than the first variety.
- If the value of t is less than 1.71, one may not reject (at the 5 per cent level) the hypothesis that the observed increases in yield in the

second wheat variety were due to chance variation in the experiment.

Step 7. Carry out the test:

From the sample data

$$t = \frac{D - 0}{S\sqrt{n}} = \frac{3.5 - 0}{6\sqrt{2}} = 2.375 \quad (3.40)$$

Decision: since $2.375 > 1.71$, one can conclude at the 5 per cent level that the second variety significantly produces higher yields than the first variety.

3.7.9 Difference between two means

A sampling result, which is frequently used in inference tests, is one concerning the distribution of the difference in means of independent samples drawn from two different populations. Let a random sample of size n_1 be drawn from a population having mean μ_1 and standard deviation σ_x ; and let an independent sample of size n_2 be drawn from another population having mean μ_Y and standard deviation σ_Y . Consider the random variable $D = \bar{X}_1 - \bar{Y}$; that is, the difference in means of the two samples. The theorem states that D has a sampling distribution with mean $\mu_D = \mu_X - \mu_Y$ and variance

$$\text{Var}(D) = \frac{\sigma_x^2}{n_1} + \frac{\sigma_Y^2}{n_2} \quad (3.41)$$

3.7.10 The F -Test

It seems reasonable that the sample variances will range more from trial to trial if the number of observations used in their calculation is small. Therefore, the shape of the F -distribution would be expected to change with changes in sample size. The degrees of freedom idea comes to mind, except in this situation the F -distribution is dependent on two values of γ , one associated with each variance in the ratio. Since the F -ratio is the ratio of two positive numbers, the F -distribution cannot be negative. If the samples are large, the average of the ratios should be close to 1.0.

Because the F -distribution describes the probabilities of obtaining specified ratios of sample variances drawn from the same population, it can be used to test the equality of variances that are obtained in statistical sampling. One may hypothesize that two samples are drawn from populations having equal variances. After computing the F -ratio, one can then ascertain the probability of obtaining, by chance, that specific value from two samples from one normal population. If it is

unlikely that such a ratio could be obtained, this can be seen to indicate that the samples come from different populations having different variances.

For any pair of variances, two ratios can be computed ($\frac{S_2^2}{S_1^2}$ and $\frac{S_1^2}{S_2^2}$). If one arbitrarily decides that the larger variance will always be placed in the numerator, the ratio will always be greater than 1.0 and the statistical tests can be simplified. Only one-tailed tests need to be utilized, and the alternative hypothesis actually is a statement that the absolute difference between the two sample variances is greater than expected if the population variances are equal. This is shown in Figure 3.2, a typical F -distribution curve in which the critical region or area of rejection has been shaded.

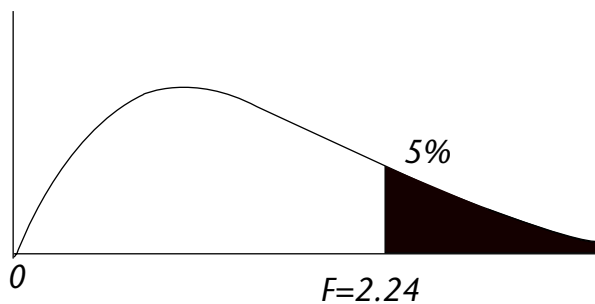


Figure 3.2. A typical F -distribution $\gamma_1 = 10$ and $\gamma_2 = 25$ degrees of freedom with the critical region (shown by shading), which contains 5 per cent of the area under the curve. The critical value of $F = 2.24$.

As an example of an elementary application of the F -distribution, consider a comparison between the two sample sets of porosity measurements on soils of two areas of a certain district. The aim is to determine if the variation in porosity is the same in the two areas. For these purposes, a level of significance of 5 per cent will be satisfactory. That is, the risk of concluding that the porosities are different, when actually they are the same one time out of every twenty trials, is acceptable.

$$F = \frac{S_1^2}{S_2^2} \quad (3.42)$$

where S_1^2 is the larger variance and S_2^2 is the smaller. Now the hypothesis

$$H_0 : \sigma_1^2 = \sigma_2^2 \quad (3.43)$$

is tested against

$$H_a : \sigma_1^2 \neq \sigma_2^2 \quad (3.44)$$

The null hypothesis states that the parent populations of the two samples have equal variances: the

alternative hypothesis states that they do not. Degrees of freedom associated with this test are $(n_2 - 1)$ for γ_1 and $(n_1 - 1)$ for γ_2 . The critical value of F with $\gamma_1 = 9$ and $\gamma_2 = 9$ degrees of freedom and a level of significance of 5 per cent ($\alpha = 0.05$).

The value of F calculated from (3.42) will fall into one of the two areas shown in Figure 3.2. If the calculated value of F exceeds 3.18, the null hypothesis is rejected and one concludes that the variation in porosity is not the same in the two groups. If the calculated value is less than 3.18, there would be no evidence for concluding that the variances are different (determine at 0.05 if variances are the same).

In most practical situations, one ordinarily has no knowledge of the parameters of the population, except for estimates made from samples. In comparing two samples, it is appropriate to first determine if their variances are statistically equivalent. If they appear to be equal and the samples have been selected without bias from a naturally occurring population, it is probably safe to proceed to additional statistical tests.

The next step in the procedure is to test equality of means. The appropriate test is:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{Sp \sqrt{(\frac{1}{n_1}) + (\frac{1}{n_2})}} \quad (3.45)$$

where the quantity Sp is the pooled estimate of the population standard deviation based on both samples. The estimate is found from the pooled estimated variance, given by:

$$Sp^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \quad (3.46)$$

where the subscripts refer, respectively, to the samples from area A and area B of the district.

3.7.11 Relationship between variables

3.7.11.1 Correlation methods

Correlation methods are used to discover objectively and quantitatively the relationship that may exist between several variables. The correlation coefficient determines the extent to which values of two variables are linearly related; that is, the correlation is high if it can be approximated by a straight line (sloped upwards or downwards). This line is called the regression line. Correlation analysis is especially valuable in agrometeorology because of the many factors that may be involved, simultaneously or successively, during the development of a crop and

also because for many of them – climatic factors in particular – it is impossible to design accurate experiments, since their occurrence cannot be controlled. There are two sets of circumstances in which, more particularly, the correlation and simple regression method can be used:

- (a) In completing climatological series that have gaps. Comparisons of data for different atmospheric elements (such as precipitation, evapotranspiration, duration of sunshine) allow estimates of the missing data to be made from the other measured elements;
- (b) In comparing climatological data and biological or agronomical data, such as yields and quality of crops (sugar content, weight of dry matter, and so on).

Care should be exercised in interpreting these correlations. Graphs and scatter plots should be used to give much more information about the nature of the relationship between variables. The discovery of a significant correlation coefficient should encourage the agrometeorologist, in most cases, to seek a physical or biological explanation for the relationship and not just be content with the statistical result.

Having discovered that there is a relationship between variables, one hopes to establish the closeness of this relationship. This closeness of agreement between two or more variables is called correlation. The closeness is expressed by a correlation coefficient whose value lies between +1 (perfect, positive correlation) and -1 (perfect, negative correlation). It is used to measure the linear relationship between two random variables that are represented by pairs of numerical values. The most commonly used formula is:

$$r = \frac{n \sum XiYi - (\sum Xi)(\sum Yi)}{\sqrt{[n \sum Xi^2 - (\sum Xi)^2][n \sum Yi^2 - (\sum Yi)^2]}} \quad (3.47)$$

If the number of pairs is small, the sample correlation coefficient between the two series is subject to large random errors, and in these cases numerically large coefficients may not be significant.

The statistical significance of the correlation may be determined by seeing whether the sample correlation r is significantly different from zero. The test statistic is:

$$t = r \sqrt{\frac{n-2}{1-r^2}} \quad (3.48)$$

and t is compared to the tabulated value of Student's t with $n-2$ degrees of freedom.

3.7.11.2 Regression

After the strength of the relationship between two or more variables has been quantified, the next logical step is to find out how to predict specific values of one variable in terms of another. This is done by using regression models. A single linear regression model is of the form:

$$Y = a + bX \quad (3.49)$$

where Y is the dependent variable;

X is the independent variable;

a is the intercept on the Y axis;

b is the slope of the regression.

The least squares criterion requires that the line be chosen to fit the data so that the sum of the squares of the vertical deviations separating the points from the line will be a minimum.

The recommended formulae for estimating the two sample coefficients for least squares are:

the slope of the line

$$b = \frac{n \sum XiYi - (\sum Xi)(\sum Yi)}{n \sum Xi^2 - (\sum Xi)^2} \quad (3.50)$$

the y-axis intercept

$$a = \frac{(\sum Yi)(\sum Xi^2) - (\sum Xi)(\sum XiYi)}{n \sum Xi^2 - (\sum Xi)^2} \quad (3.51)$$

Example

Compute a and b coefficients of the Angstrom formula.

Angstrom's formula:

$$R/RA = a + b n/N \quad (3.52)$$

is used to estimate the global radiation at surface level (R) from the radiation at the upper limit of the atmosphere (RA), the actual hours of bright sunshine (n) and the day length (N). RA and N are taken from appropriate tables or computed; n is an observational value obtained from the Campbell-Stokes sunshine recorder.

The data in Table 3.6 are sunshine normals from Lyamungu, United Republic of Tanzania (latitude 3° 14' S, longitude 27° 17' E, elevation 1 250 m).

Table 3.6. Sunshine normals from Lyamungu, United Republic of Tanzania

	n/N (X)	R/RA (Y)
Jan	0.660	0.620
Feb	0.647	0.578
Mar	0.536	0.504
Apr	0.366	0.395
May	0.251	0.368
Jun	0.319	0.399
Jul	0.310	0.395
Aug	0.409	0.442
Sept	0.448	0.515
Oct	0.542	0.537
Nov	0.514	0.503
Dec	0.602	0.582

$N = 12$, $\bar{X} = 0.467$, $\sigma_X = 0.132$, $\bar{Y} = 0.487$, $\sigma_Y = 0.081$,
 $b = 0.603$, $a = 0.205$, $r = 0.973$

The regression explains $r^2 = 95$ per cent of the variance of R/RA and is significantly below $p = 0.01$.

There are cases where a scatter diagram suggests that the relationship between variables is not linear. This can be turned into a linear regression by taking the logarithms of the relationship if it is exponential, or by turning it into a reciprocal if it is square, and so forth. For example, when the saturation vapour pressure is plotted against temperature, the curve suggests that a function like $y = p.e^{bx}$ could probably be used to describe the function. This is turned into a linear regression $\ln(y) = \ln(p) + bX$, where X is the temperature function and y is the saturation vapour pressure. An expression of the form $y = aX^2$ can be turned into a linear form by taking the reciprocal $\frac{1}{y} = \frac{X^{-2}}{a}$.

3.7.11.3 Multiple regressions

The general purpose of multiple regression is to learn more about the relationship between several independent or predictor variables and a dependent variable. A linear combination of predictor factors is used to predict the outcomes or response factor. For example, multiple regression has been successfully used to estimate crop yield as a function of weather, or to estimate soil temperatures as a function of air temperature, soil characteristic and soil cover. It has been used to perform a trend analysis of agrometeorological parameters using a polynomial expansion of time. The general linear model is a generalization of the linear regression

model, such that effects can be tested for categorical predictor variables, as well as effects for continuous predictor variables. An objective in performing multiple regression analysis is to specify a parsimonious model whose factors contribute significantly to variation in response. Statistical software such as INSTAT provides tools to select independent factors for a regression model. These programs include forward stepwise regression to individually add or delete the independent variables from the model at each step of the regression until the “best” regression model is obtained, or backward stepwise regression to remove the independent variables from the regression equation one at a time until the “best” regression model is obtained. It is generally recommended that one should have at least 10 times as many observations or cases as one has variables in a regression model.

Residual analysis is recommended as a tool to assess the multiple regression models and to identify violations of assumptions that threaten the validity of results. Residuals are the deviations of the observed values of the dependent variable from the predicted values. Most statistical software provides extensive residuals analyses, allowing one to use a variety of diagnostic tools in inspecting different residual and predicted values, and thus to examine the adequacy of the prediction model, the need for transformations of the variables in the model, and the existence of outliers in the data. Outliers (that is, extreme cases) can seriously bias the results.

3.7.11.4 Stepwise regression

This will be explained by using an example for yields. A combination of variables may work together to produce the final yield. These variables could be the annual precipitation, the temperature of a certain month, the precipitation of a certain month, the potential evapotranspiration of a certain month, or the difference between precipitation and potential evapotranspiration for a given month.

In stepwise regression, a simple linear regression for the yield is constructed on each of the variables and their coefficients of determination found. The variable that produces the largest r^2 statistic is selected. Additional variables are then brought in one by one and subjected to a multivariate regression with the best variable to see how much that variable would contribute to the model if it were to be included. This is done by calculating the F statistic for each variable. The variable with the largest F statistic that

has a significance probability greater than the specified significance level for entry is included in the multivariate regression model. Other variables are included in the model one by one. If the partial F statistic of a variable is not significant at a specified level for staying in the regression model, it is left out. Only those variables that have produced significant F statistics are included in the regression. A more in-depth explanation can be found in Draper and Smith (1981).

3.7.11.5 Cluster analysis

Cluster analysis is a technique for grouping individuals or objects into unknown groups. In biology, cluster analysis has been used for taxonomy, which is the classification of living things into arbitrary groups on the basis of their characteristics. In agrometeorology, cluster analysis can be used to analyse historical records of the spatial and temporal variations in pest populations in order to classify regions on the basis of population densities and the frequency and persistence of outbreaks. The analysis can be used to improve regional monitoring and control of pest populations.

Clustering techniques require that one define a measure of closeness or similarity between two observations. Clustering algorithms may be hierarchical or non-hierarchical. Hierarchical methods can be either agglomerative or divisive. Agglomerative methods begin by assuming that each observation is a cluster and then, through successive steps, the closest clusters are combined. Divisive methods begin with one cluster containing all the observations and successively split off cases that are the most dissimilar to the remaining ones. K-means clustering is a popular non-hierarchical clustering technique. It begins with user-specified clusters and then reassigns data on the basis of the distance from the centroid of each cluster. See von Storch and Zwiers (2001) for more detailed explanations.

3.7.11.6 Classification trees

The goal of classification trees is to predict or explain responses on a categorical dependent variable. They have much in common with discriminate analysis, cluster analysis, non-parametric statistics and non-linear estimation. They are one of the main techniques used in data mining. The ability of classification trees to perform univariate splits, examining the effects of predictors one at a time, contributes to their flexibility. Classification trees can be computed for categorical predictors, continuous predictors or any mix of the two types of

predictors when univariate splits are used. They readily lend themselves to graphical display, which makes them easier to interpret. Classification trees are used in medicine for diagnosis and in biology for classification. They have been used to predict levels of winter survival of overwintering crops using weather and categorical variables related to topography and crop cultivars.

3.7.12 Climatic periodicities and time series

Data are commonly collected as time series, namely, observations made on the same variable at repeated points in time. The INSTAT software provides facilities for descriptive analysis and display of such data. The goals of time series analysis include identifying the nature of the phenomenon represented by the sequence of observations and predicting future values of the times series. Moving averages are frequently used to “smooth” a time series so that trends and other patterns are seen more easily. Sivakumar et al. (1993) present a number of graphs showing the five-year moving averages of monthly and annual rainfall at selected sites in Niger. Most time series can be described in terms of trend and seasonality. When trends, such as seasonal or other deterministic patterns, have been identified and removed from a series, the interest focuses on the random component. Standard techniques can be used to look at its distribution. The feature of special interest, resulting from the time-series nature of the data, is the extent to which consecutive observations are related. A useful summary is provided by the sample autocorrelations at various lags, the autocorrelation at lag m being the correlation between observations m time units apart. In simple applications this is probably most useful for determining whether the assumption of independence of successive observations used in many elementary analyses is valid. The autocorrelations also give an indication of whether more advanced modelling methods are likely to be helpful. The cross-correlation function provides a summary of the relationship between two series from which all trend and seasonal patterns have been removed. The lag m cross-correlation is defined as the correlation between x and y lagged by m units.

More than any other user of climatic data, the agrometeorologist may be tempted to search for climatic periodicities that could provide a basis for the management of agricultural production. It should be noted that the *Guide to Climatological Practices* (WMO-No. 100) (section 5.3) is more than cautious with

regard to such periodicities and that, although they may be of theoretical interest, they have been found to be unreliable, having amplitudes that are too small for any practical conclusions to be drawn.

3.8 PUBLICATION OF RESULTS

3.8.1 General methods

For statistical analyses to have practical value, they must be distributed to users in a readily understandable format that does not require an advanced knowledge of statistics. Adequate details should be given in each publication to avoid any ambiguity in interpreting the numerical tables or graphs.

3.8.2 Tables

Numerical tables of frequencies, averages, distribution parameters, return periods of events, and so on, should state clearly:

- (a) The geographical location (including elevation of the observation site);
- (b) The period on which the statistical analysis is based (necessary to estimate how representative the data are);
- (c) The number of data (enabling the continuity of the series to be assessed);
- (d) The units;
- (e) The meaning of any symbols.

For frequency tables, it is better to give relative (percentage) frequencies in order to facilitate the comparison of populations consisting of different numbers of observations. In this case, it must be made quite clear whether the percentages refer to the total population or to separate classes.

3.8.3 Contingency tables

Estimates of the simultaneous occurrence of given values of several elements or events are often needed. The resulting contingency tables should be as simple as possible.

3.8.4 Graphs

Graphs are used to show in a concise format the information contained in numerical tables. They are a useful adjunct to the tables themselves and facilitate the comparison of results. Cumulative frequency curves, histograms and climograms give a better overall picture than the multiplicity of numerical data obtained by statistical analysis. The

scales used on the graph must be specified and their graduations should be shown. Publications intended for wide distribution among agricultural users should not have complicated scales (for instance, logarithmic, Gaussian, and so forth) with which the users may be unfamiliar, and which might lead to serious errors in interpreting the data. Furthermore, giving too much information on the same graph and using complicated conventional symbols should be avoided.

3.8.5 Maps

To present concisely the results of agroclimatological analysis covering an area or region, it is often better to draw isopleths or colour classification from the data plotted at specific points. The interpolation between the various locations can be used in a digital map plotted by special plotting tools such as Graph, Grids, Surfer and GIS. Many climatic parameters useful to agriculture can be shown in this way, for example:

- (a) Mean values of climatic elements (temperature, precipitation, evapotranspiration, water balance, radiation balance, and the like);
- (b) Frequencies: number of consecutive days without frost, without thawing, without rain, and so forth; return periods of atmospheric events;
- (c) Dispersion parameters: standard deviations, coefficients of variation;
- (d) Agrometeorological indices.

Depending on the scale adopted, this type of supplementary chart can be drawn more or less taking geomorphological factors into account. The users of the charts should be made aware of their generalized nature, however, and in order to interpret them usefully, users should know that corrections for local conditions must be made. This is particularly important for hilly regions.

3.8.6 The agrometeorological bulletin

Because of the diverse nature of the users, the content of an agrometeorological bulletin (agmet bulletin) cannot be standardized. But the basic objectives of all successful agmet bulletins are the same: the provision of the right agmet information to the right users at the right time. To attain this objective, the following guidelines are suggested. For a complete discussion of the matter, readers are referred to WMO (2004c).

First, it is essential to determine who the users are. One category of users may be farmers who need daily information to assist them in day-to-day activities such as sowing, spraying and irrigating. Another category may be more interested in

long-term agricultural decisions such as crop adaptation to weather patterns, marketing decisions or modelling.

Second, the users' requirements must be clearly established, so that the most appropriate information is provided. This is possible only after discussion with them. In most cases, they do not have a clear picture of the type of information that is best suited for their purpose; the role of the agrometeorologist is crucial here.

Third, the methods of dissemination of information must be decided upon after consultation with the users. Some farmers may have full access to the Internet, while others have only limited access, and others have no such access to this technology. Obviously, the presentation of data for these categories will not be the same. Furthermore, some information must be provided as quickly as possible, while other information may be provided two or three weeks later.

Fourth, it is very important to consider the cost of the agmet bulletin that is proposed to the users, especially in developing countries where the financial burden is becoming heavier.

3.8.6.1 Some examples

Some examples of the presentation of agmet information are given below to illustrate the points mentioned.

3.8.6.1.1 *Data in pentads*

Table 3.7 shows part of an agmet bulletin issued by a government service in a tropical country where agriculture is an important component of the economy. This bulletin was developed to cater for all crops, ranging from tomatoes to sugar cane. It is issued on a half-monthly basis and is sent to the users by post and is also available on the service's Website. Bearing in mind the time taken to collect the data, it would not be before the 20th day of the month at the very earliest that the bulletin would reach the users. To provide farmers (tomato growers, for example) with data relevant to their day-to-day activities, the agmet bulletin is supplemented by daily values of rainfall and maximum and minimum temperatures, which are broadcast on radio and television. Of course, data relevant to different geographical localities can be included.

Rainfall amounts (RR) and maximum temperature (MxT) are shown for a given area of a tropical country. Total rainfall amounts and the mean maximum

temperature observed during the three pentads are compared to their respective normal values.

In agmet bulletins, extreme weather events, which are masked by the averaging procedure involved in the calculation of the pentad, must be highlighted, probably in the form of a footnote, to draw the attention of users. For example, in Table 3.7 it can be seen that during the period 6–15 July, the maximum temperature was below the normal by not more than 1.8°C. But in fact, during the period 9–12 July, maximum temperature was below the normal by 2.8°C to 3.0°C; this can be of importance to both animals and plants.

The presentation of data in this format, together with the broadcast of daily values on the radio and on television, is very effective. It can be used by farmers interested in day-to-day activities and by research workers and model builders. It is suitable for all types of crops, ranging from tomatoes and lettuce to sugar cane and other deep-root crops.

3.8.6.1.2 *Data in 10-day intervals*

On the basis of the agrometeorological requirements for a Mediterranean climate with two main seasons and two transitional seasons, the main climatic parameters should be published on a year-round basis. The selection of agromet parameters/indices should be published according to the season and the agricultural situation of the crops, including data representing the various agricultural regions of the country.

The bulletin should include daily data, 10-day means or totals, and deviation or per cent from average. In parameters such as maximum and minimum temperature and maximum and minimum relative humidity, absolute values of the decade based on a long series of years are also recommended.

The list of recommended data to be published in the agrometeorological bulletin is as follows:

- (a) Daily data of maximum and minimum temperature and relative humidity;
- (b) Temperature near the ground;
- (c) Soil temperature;
- (d) Radiation and/or sunshine duration in hours;
- (e) Class A pan evaporation and/or Penman evapotranspiration;
- (f) Rainfall amount;
- (g) Accumulated rainfall from the beginning of the rainy season;
- (h) Number of rainy days;
- (i) Accumulated number of dry days since the last rainy day;

- (j) Number of hours below different temperature thresholds depending on the crop;
- (k) Number of hours temperature is below 0°C.

Examples of agrometeorological parameters or indices that should be published are:

- (a) Accumulated number of dynamic model units since the beginning of the winter as an indication of budbreak in deciduous trees;
- (b) Accumulated number of units above 13°C since the beginning of spring as an indication of citrus growth;
- (c) Physiological days – the accumulated number of units above 12°C since the beginning of spring as an indication of cotton growth.

3.8.6.1.3 Short-range weather outlook

With the availability on the Internet of short-range weather forecasts (5 to 10 days) provided by World Weather Centres (WWCs), many Agrometeorological Services are providing 5- to 10-day weather forecasts to farmers. An example is given below, showing expected rainfall (in millimetres) for two rainfed farming areas. The information was released to users through e-mail and posted on the Website.

This weather outlook, based on model output received early on Thursday 11 December from WWCs, was released in the afternoon of 11 December; it was sent by e-mail to users through farming centres and posted on the Website. This outlook was not broadcast on either radio or television. The issue of such a weather outlook is important, but it must be carefully planned. Otherwise, it can lead to financial losses, as shown below.

Little rainfall was observed during the first two pentads of December 2003 and farmers were starting to get worried. The indication that significant rain was expected on Sunday 14 December (Table 3.8) had given great hope to the farmers and, because it was a weekend, they made plans on Friday to do some fieldwork on Saturday and on Monday. Such plans are costly because they imply the booking of manpower and transport, the purchase of fertilizers, and so forth. But model output received on Friday 12 December indicated that the probability of having rain during the following five days was negligible, and in fact, it was not before 31 December that significant rainfall was observed.

Table 3.8. Example of weather outlook

<i>December 2003</i>	<i>West</i>	<i>North</i>
Friday 12	<1.0	<1.0
Saturday 13	1.1–5.0	<1.0
Sunday 14	5.1–25.0	5.1–25.0
Monday 15	1.1–5.0	1.1–5.0
Tuesday 16	<1.0	<1.0

Here, it is not the validity of the weather outlook that is questioned. The point to be noted is that no update of the outlook could reach the farmers because the farming centres were closed for the weekend. If, besides being sent by e-mail and posted on the Website, the outlook had been broadcast on radio and television, the updated version would have reached the farmers and appropriate measures could have been taken. To avoid similar incidents, it is advisable to decide on the methods for dissemination of information.

Table 3.7. Part of an agmet bulletin issued by a government service in a tropical country

<i>Agmet bulletin in pentads</i>					
<i>Rainfall data</i>			<i>Maximum temperature</i>		
<i>Dates</i>	<i>Rainfall amounts in millimetres</i>		<i>Dates</i>	<i>Maximum temperature (deg. C)</i>	
<i>November 2003</i>	<i>Observed values</i>	<i>Normal values</i>	<i>July 2003</i>	<i>Observed values</i>	<i>Normal values</i>
1–5	3.6	4.7	1–5	23.6	23.7
6–10	7.1	4.7	6–10	21.9	23.7
11–15	3.6	4.7	11–15	22.1	23.7
Total RR	24.3	14.2	Mean MxT	22.5	23.7

3.8.6.1.4 *Seasonal forecast*

An extract from a seasonal forecast issued in the first half of October 2003 for a country situated in the southern hemisphere, for summer 2003/2004 (summer in that country is from November to April), reads as follows: "The rainfall season may begin by November. The summer cumulative rainfall amount is expected to reach the long-term mean of 1 400 millimetres. Heavy rainfall is expected in January and February 2004." This seasonal forecast was published in the newspapers and read on television.

The question is: who is qualified to interpret and use this forecast? Can it be misleading to farmers? To show the problems that such a forecast can create, real data for an agricultural area covering the period October 2003 to January 2004 are presented in Table 3.9, which shows rainfall amounts recorded during the period. Out of the 35.7 mm of rainfall recorded during the second half of November, 35.0 mm fell during the period 16–25 November.

Given that October and the first half of November 2003 were relatively dry and that a significant amount of rainfall was recorded during the second half of November, and noting that the seasonal forecast opted for normal rainfall during summer and that the rainfall season may start in November, the farmers thought that the rainy season had begun. Most of them started planting their crops during the last pentad of November. Unfortunately, the rainfall during the second half of November was a false signal: December was relatively dry. The rainy season started in January 2004.

To prevent seasonal forecasts from falling into the wrong hands, it is not advisable to have them published in the newspapers; these seasonal

Table 3.9. Real data for the period October 2003 to January 2004

	<i>Rainfall amounts in millimetres (mm)</i>			
	<i>Oct. 2003</i>	<i>Nov. 2003</i>	<i>Dec. 2003</i>	<i>Jan. 2004</i>
First half	1.8	4.1	5.2	176.4
Second half	12.8	35.7	12.8	154.1

forecasts must be sent to specialists who are trained to interpret them and they should be supplemented by short-range weather forecasts.

3.8.6.2 **How costly should the agmet bulletin be?**

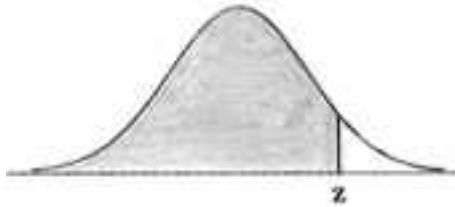
Today, agricultural systems in some small and poor countries are in great turmoil. Developed countries have dismantled the safety net, which had provided some protection to the agricultural products of these countries. It is in relation to the bleak future of agriculture in these areas that the question of the cost of issuing agmet bulletins is raised.

Sooner or later, the financial situation in these countries will not be able to sustain the issuing of costly agmet bulletins by local personnel. So agro-meteorologists must think carefully about the cost-benefit of the agmet bulletin, especially when developed countries are getting ready to offer their services for free. (And one must ask how long they will continue to be free.)

Already, shipping bulletins, cyclone warnings and aviation forecasts are being offered for free on a global scale by a few developed countries. But how long will these services be free? Sooner or later, the small and poor countries will have to pay for these services. It is very important to keep the cost of the agmet bulletin to a minimum.

ANNEX

Table of the Normal Distribution



Probability Content from $-\infty$ to Z

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990

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REMOTE-SENSING AND GIS APPLICATIONS IN AGROMETEOROLOGY

4.1 DEFINITION AND ROLE OF REMOTE-SENSING

Remote-sensing is the science and art of obtaining information about an object through the analysis of data acquired by a device that is not in contact with the object (Lillesand and Keifer, 1994). Remotely sensed data can take many forms, including variations in force distribution, acoustic wave distribution or electromagnetic energy distributions, and can be obtained from a variety of platforms, including satellites, airplanes, remotely piloted vehicles, hand-held radiometers or even bucket trucks. They may be gathered by different devices, including sensors, film cameras, digital cameras and video recorders. Instruments capable of measuring electromagnetic radiation are called sensors. Sensors can be divided into two main groups:

- (a) Passive sensors, which do not have their own source of radiation. They are sensitive only to radiation from a natural origin;
- (b) Active sensors, which have a built-in source of radiation. Examples are radar (radio detection and ranging) and lidar (light detection and ranging) systems.

Remote-sensing can be analogue (photography) or digital (multispectral scanning, thermography, radar). The elements of a digital image are called resolution cells (during the acquisition of data) or pixels (after the creation of the image). The use of remote-sensing data requires some knowledge about the technical capabilities of the various sensor systems. The technical capabilities of the sensor systems can be listed according to three kinds of resolution:

- (a) Spatial resolution, which concerns the size of the resolution cell on the ground in the direction of the flight and across. The size of the pixel determines the smallest detectable terrain feature;
- (b) Spectral resolution, which concerns the number, location in the electromagnetic spectrum, and bandwidth of the specific wavelength bands or spectral bands. This resolution differs among sensors and largely determines their potential use;
- (c) Temporal resolution, which concerns the time lapse between two successive images of the same area. This is determined primarily by

the platform used and secondarily by atmospheric conditions.

Remote-sensing provides spatial coverage through the measurement of reflected, emitted and backscattered radiation, across a wide range of wavebands, from the earth's surface and surrounding atmosphere. Remotely sensed data may be obtained from the land surface across a wide range of wavebands, from the ultraviolet, visible, near-infrared, short-wave infrared, mid-infrared, thermal infrared, and microwave regions of the electromagnetic spectrum. These bands are located in so-called "atmospheric windows": because there is a signal from the surface, total absorption (or scattering) of the light owing to atmospheric constituents does not occur.

Each waveband provides different information about the atmosphere and land surface. Clouds, rainfall, surface temperatures, temperature and humidity profiles, solar and net radiation, and the fundamental processes of photosynthesis and evaporation can affect the reflected and emitted radiation detected by satellites. The research challenge is to develop models that can be inverted to extract relevant and reliable information from remotely sensed data, providing final users near-real-time information. In general, the tools used in remote-sensing can be grouped into three main categories, namely, satellite, radar and near-to-surface instruments.

The platform for remote-sensing can be either fixed or moving, terrestrial or operating from different altitudes, and it can be either manned or unmanned. Considering the operating time, the platform can be classified as temporary, semi-permanent or virtually permanent. These aspects are important in order to understand the quality and quantity of the information available to the agrometeorological service. The distance of the instruments directly affects the resolution and the precision of the information. The resolution of observation can vary from a few square metres, with a scanner mounted on a vehicle, to continental scale, using a meteorological satellite. Due to the large volumes of data generated, an increase in temporal resolution is usually at the expense of spatial and spectral resolution. Relevant to agricultural meteorology are the earth resource satellites with high spatial resolution

and the meteorological satellites with high temporal resolution.

4.1.1 Reflective remote-sensing

The reflective portion of the electromagnetic spectrum (EMS) ranges nominally from 0.4 to 3.75 μm . Light of shorter wavelength than this is termed ultra-violet (UV). The reflective portion of the EMS can be further subdivided into the visible (VIS) (0.4–0.7 μm), near-infrared (NIR) (0.7–1.1 μm), and short-wave infrared (SWIR) (1.1–3.75 μm). Remote-sensing converts an analogue photon flux to digital images, where the number of quantization levels is a function of the number of bits used to represent the photon flux. The number of quantization levels equals two to the power of the number of bits. That is, 7-bit data provide 128 (2^7) levels of quantization, 8-bit data provide 256 (2^8), 10-bit data provide 1 024 (2^{10}) and 12-bit data provide 4 096 (2^{12}). The ability of remote-sensing measurements to distinguish different properties of the Earth's surface in the EMS is partly determined by the level of quantization. Many remote-sensing instruments have channels situated in the red and NIR wavelengths of the spectrum. These two reflective bands are often combined to produce vegetation indexes. The most common linear combinations are the simple ratio (NIR/red) and normalized difference vegetation index (NDVI); NDVI is derived from $(\text{NIR} - \text{red})/(\text{NIR} + \text{red})$. Several publications (Wiegand et al., 1991; Kaufman and Tanre, 1992; Thenkabail et al., 1994; Leprieux et al., 1996; Penuelas and Filella, 1998) provide comprehensive listings of vegetation indices.

There are positive correlations between NDVI and factors such as plant condition (Sellers, 1985); foliage presence, including leaf area index (LAI) (Curran et al., 1992; Tucker, 1979; Nemani and Running, 1989; McVicar et al., 1996a, 1996b, 1996c); and per cent foliage cover (Lu et al., 2001). Based on the relationship between LAI and NDVI, many previous studies have modelled crop yield by integrating the area under the NDVI curve (denoted $\int \text{NDVI}$) for all or part of the growing season (Rasmussen, 1998a, 1998b; McVicar et al., 2002; Honghui et al., 1999). Some researchers have used regression-based models developed from NDVI data acquired at specific times during the growing season (Maselli et al., 1992; Smith et al., 1995). The amount of green leaf is one determinant of the signal strength in the reflective portion of the EMS. There are several other important factors affecting the acquired value of the data, including both soil colour and Sun–target–sensor geometry.

The following discussion draws heavily on Roderick et al. (2000), whose work elegantly illustrates the effect of soil colour and quantization on overall reflectance and shows how change can be distinguished using remotely sensed measurements. The authors assumed a Lambertian surface (one that has no angular dependency), with no shade present and two soils, one dark (5 per cent albedo¹) and the other bright (30 per cent albedo), with green grass (10 per cent albedo) in the red portion of the EMS. On a dark soil, a 20 per cent increase in green grass results in an overall 1 per cent increase in albedo; on a bright soil it results in a 4 per cent decrease. Hence, the albedo of the elements that make up the scene and their relative proportions are important to the overall albedo. For dark soils sensed with a 7-bit instrument, a 15 per cent change in cover is needed to change the recorded digital number by 1. This falls to 0.5 per cent for a 12-bit system. At the same level of quantization, a larger relative difference between end-members requires a smaller change in the percentage of grass cover to detect change. This is because there is a greater difference in the albedo of the end-members when looking at bright soils (20 per cent difference), than when considering a dark soil (5 per cent difference).

In reality, the land surface is not a perfect Lambertian reflector (Liang and Strahler, 2000) – most surfaces in the optical (reflective and thermal) portions of the EMS are strongly anisotropic². The geometry of the Sun, target and sensor, and the size, shape and spacing of elements (for example, trees over bare ground), control the amount of shadow contributing to the signal (Hall et al., 1995). This effect, termed the bidirectional reflectance distribution function (BRDF) (Burgess and Pairman, 1997; Deering, 1989), is characteristic of vegetation structure in reflective remotely sensed images. This means that in addition to the albedo of the scene elements and their relative proportions, the spatial distribution and the pixel size of observation affect the signal measured by remote-sensing instruments (Jupp, 1989a, 1989b; Woodcock and Strahler, 1987; Walker et al., 1986; Jupp and Walker, 1996). In addition, the match between the operational scale and the resolution partly controls the strength of relationships between surface properties and remote-sensing (Friedl, 1997). Image information content is minimal when the resolution is approximately equal to the operational scale (Woodcock et al., 1988a, 1988b). Other factors

1 Albedo: the fraction of light that is reflected by a body or surface.

2 Anisotropic: having different physical properties in different directions.

affecting the reflective portion of the EMS include changes in the observed signal due to changes in the atmospheric component of the signal, such as atmospheric precipitable water (Choudhury and DiGirolamo, 1995; Hobbs, 1997) and atmospheric aerosols, and changes in the response of the sensor over time (Mitchell, 1999).

4.1.2 Thermal remote-sensing

The thermal portion of the EMS ranges nominally from 3.75 to 12.5 μm . The observed surface temperature is a function of the radiant energy emitted by the surface that is remotely sensed, be it land, ocean or cloud top. Models have been developed to allow surface temperature to be extracted from thermal remote-sensing data. Prata et al. (1995) review the algorithms and issues, including land emissivity estimation, that are involved in the calculation of land surface temperature, denoted T_s .

Thermal remote-sensing is an observation of the status of the surface energy balance (SEB) at a specific time of day. The SEB is driven by the net radiation at the surface. During the daytime, the net radiation is usually dominated by incoming short-wave radiation from the Sun, and the amount that is reflected depends on the albedo of the surface. There are also long-wave components that well up and down. At the ground surface, the net all-wave radiation is balanced among the sensible, latent and ground heat fluxes. The ground heat flux averages out over long periods; thus the SEB represents the balance between the sensible and latent heat fluxes. During the day, T_s is partially dependent on the relative magnitude of the sensible and latent heat fluxes (Quattrochi and Luvall, 1999; McVicar and Bierwirth, 2001; McVicar and Jupp, 1999, 2002).

Remotely sensed thermal data are also recorded at night. At this time, the SEB is dominated by the release from the ground of heat that was absorbed during daylight hours, which is governed by how much heat was absorbed during the day and the rate at which it is released after sunset. The environment's capacity to store heat depends on the amount of water it is storing.

4.1.3 Microwave remote-sensing

The microwave portion of the EMS ranges nominally from 0.75 to 100 cm. Radio signals have wavelengths that are included in these bands. These systems can be either active or passive. Both passive and active microwave observations have been used to determine the near-surface soil moisture for a number of experimental field sites. Radar is an

active system that consists of sending a pulse of microwave energy and then recording the strength, and sometimes polarization, of the return pulses. The way the signal is returned provides information to determine characteristics of the landscape. Radar has been used in the determination of near-surface soil moisture.

4.1.4 Earth satellites

The major earth resource satellites are LANDSAT (United States), with wavebands in VIS, NIR, SWIR and thermal infrared (TIR); SPOT (France), with wavebands in VIS and NIR; and MODIS (United States), which views the entire surface of the Earth every one to two days, acquiring data in 36 spectral bands, or groups of wavelengths. SPOT uses a push-broom linear array of charge-coupled device detectors which cover only the VIS and NIR spectral regions. In terms of agricultural meteorological applications, LANDSAT, SPOT and MODIS data are useful for characterizing the land surface.

4.1.5 Weather satellites

The remote-sensing of weather and climate by polar-orbiting and geostationary satellites is regarded as the single most significant breakthrough for monitoring the Earth's weather, climate and vegetation in the last quarter of a century. It is fortunate that when they are not viewing clouds, these satellites collect data on terrestrial vegetation and ocean temperature. Hence, they provide information on both meteorology and vegetation, the two essential inputs into agricultural meteorology. Two broad types of meteorological satellite are in common use. One is the polar-orbiting satellite of the United States National Oceanic and Atmospheric Administration (NOAA) that is placed on a low Earth orbit of 750 km. The other is the Geosynchronous Meteorological Satellite (GMS), which orbits at an altitude of some 36 000 km; GMS was launched by China, the European Space Agency, India, Japan, the United States and the Soviet Union to form a global atmospheric monitoring system. The use of air- and satellite-borne radars is expected to promote the use of remote-sensing monitoring systems for cloudy days. This aspect of remote-sensing is still in the research phase, however.

4.1.6 Derived products

All data produced by a satellite are processed for the extraction of the desired information. There are many methods, algorithms and procedures to derive

fundamental data for agrometeorological applications from remote-sensing. Among the existing indices, the most extensively used are:

- (a) The sea surface temperature (SST);
- (b) The land surface temperature (LST);
- (c) The normalized difference vegetation index (NDVI);
- (d) The optimal index of current plant cover and its variation with time.

4.2 INTRODUCTION TO GEOGRAPHICAL INFORMATION SYSTEMS

A Geographical Information System (GIS) can be defined in a broad sense as a collection of hardware, software, data, organizations and professionals for the purpose of representing and analysing geographic data. A GIS references real-world spatial data elements (also known as graphic or feature data elements) to a coordinate system. These features can usually be separated into different thematic types (for example, soils and meteorological data). A GIS can also store attribute data, which contain descriptive information pertaining to the map features. This attribute information is placed in a database that is separated from the graphics data, but linked to them. A GIS allows the examination of both spatial and attribute data at the same time. Also, a GIS lets users search the attribute data and relate them to the spatial data, and vice versa. Therefore, a GIS can combine geographic and other types of data to generate maps and reports, enabling users to collect, manage and interpret location-based information in a planned and systematic way. In short, a GIS can be defined as a computer system capable of assembling, storing, manipulating and displaying geographically referenced data.

4.2.1 Storing geographic data

A GIS provides an organized method of storing spatial data. It stores the characteristics of features (the attribute component) in a database, then links the attributes to features (the spatial component) that it displays on a map. GIS software stores the information about each feature as a record in a table and organizes the attributes into columns, and it displays the linked features, which are called a theme. Themes can be organized and displayed in a window, which is called a view. This stored information (features and attributes) can then be manipulated, retrieved and analysed using GIS methods and tools.

A GIS stores sets of features and attributes as layers. Not all of the layers it stores necessarily fit together, however. The layers may be stored in different formats, different map projections and different resolutions. In each of these cases, the datasets will not fit together or “line up”. Managing spatial data includes converting datasets into formats that can be used by the GIS, changing a map’s projection to match the projection of other maps, and most importantly, documenting the data and processes, also known as metadata.

A GIS provides several methods of retrieving information. One method is to create an attribute query. An attribute query is a set of criteria for a specific attribute. The database searches within a specified column for records that match the criteria that are set and retrieves those records. This type of query is a basic function of most databases. It takes some thought to design a query statement that retrieves (selects) only those records that are needed, leaving behind (unselected) those that are not needed. While an attribute query allows one to set criteria for a certain value or range of values for an attribute in the database, a spatial query selection allows one to retrieve records by selecting features on a map. Various tools are used to select the features on the map and through their linkage in the database, the records associated with the selected features are retrieved. Different GIS software packages have different methods of retrieval. Nonetheless, query is a very useful tool that allows the user to retrieve the information that has previously been stored.

Spatial data may be stored in either raster or vector formats with a GIS. In principle, both can be used to represent point, area and continuous spatial objects, but in practice raster formats tend to be used to represent continuous spatial objects and vector formats are used to represent point and area objects.

4.2.2 Raster format

In a raster representation, geographic space is divided into an array of cells (a matrix), as shown in Figure 4.1. All geographic representation is then expressed by assigning attributes to these cells. These cells are sometimes called pixels. The colours of cells in the figure represent different values on a nominal scale. One of the most common forms of raster data comes from remote-sensing satellites. (Pixel sizes from satellite-derived data vary from a resolution of 5 m to over 1 km, with the area of pixels ranging from 25 m² to over 1 km²).

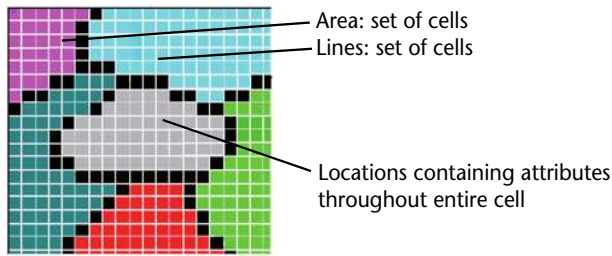


Figure 4.1. Example of raster data format in GIS

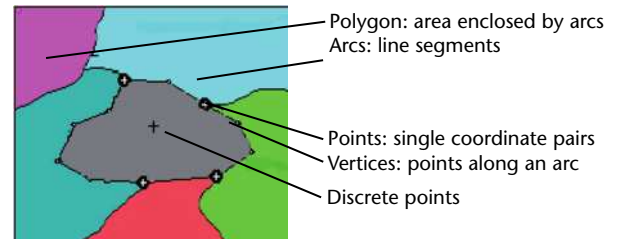


Figure 4.2. Example of vector data format in GIS

When information is represented in raster format, each component cell is assigned a single attribute value and all detail about variation within the component cell is lost. When creating raster data, several rules may be applied to specify how a cell will be coded: in most situations the attribute with the largest share of the cell's area gets the cell attribute value. In other circumstances, the rule is based on the central point of the cell and the attribute value of the central point is assigned to the cell. Although the largest share rule is almost always preferred, the central point rule is commonly used because it is quick to calculate.

4.2.3 Vector format

In a vector representation, all objects are represented as points connected by straight lines. An area is captured as a series of points or vertices connected by straight lines, as shown in Figure 4.2. The use of straight lines explains why areas in vector representations are often called polygons.

To capture an area object in vector form, one needs only to specify the locations of the points that form the vertices of the polygon area. A raster representation, on the other hand, would require a listing of all the cells that form the area. To create

a close approximation of an area in raster format, it would be necessary to resort to using very small cell sizes, and the number of cells would increase proportionally with the level of detail required. In some circumstances the precision of vector representations might be crude, since many geographic phenomena cannot be located with high accuracy. In these cases, raster representations may be a more appropriate representation of the inherent quality of the data. Also, various methods exist for compressing raster data that can greatly reduce the capacity needed to store a given dataset. Table 4.1 summarizes the features of raster and vector representations in a GIS.

Numerous thematic surveys in the form of soil survey reports, climatic maps, groundwater surveys, land cartography, and the like do exist. Integrated land and water resource information systems, based on GIS technology, will play a major role in linking multidisciplinary, geographically referenced databases of different resolutions. Digital elevation models (DEMs) play an increasingly important role in this integration and consist of topographic information on a grid basis, that is, three-dimensional representation of the land. This is a basic information layer in agrometeorology for GIS applications (Figure 4.3)

Table 4.1. Features of raster and vector representations in a GIS

<i>Factor</i>	<i>Raster</i>	<i>Vector</i>
Source	Remote-sensing	Printed maps, digitized maps
Resolution	Fixed	Variable
Volume of data	Depends on size of cells used and spatial extent of study area	Depends on level of detail
Applications	Environmental applications	Social, economic, administrative
Ease of calculation	Efficient	Relatively inefficient

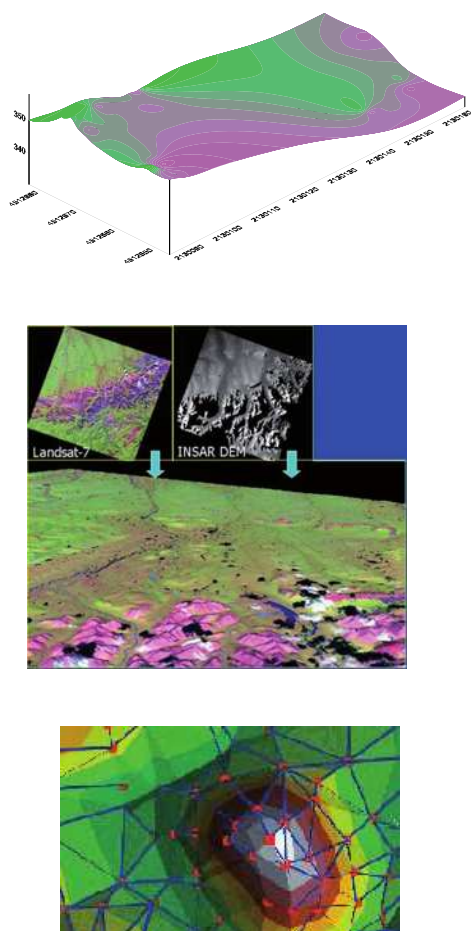


Figure 4.3. Illustrations of a digital elevation model (DEM), remotely sensed DEM and triangulated irregular network (TIN) (from top to bottom)

4.2.4 Requirements of a GIS

In a GIS, all the information can be linked and processed simultaneously, thus creating a syntactical expression of the changes induced in the system by the variation of a parameter. There are two types of archives: static and dynamic. This technology allows the contemporary updating of geographical data and their relative attributes, which leads the system to adapt rapidly to the real conditions and provides answers in near-real time.

The system requires preliminary basic information that, in the agrometeorological sector, is often furnished by the historical archives of different disciplines: geography, meteorology, climatology, agronomy, and so on. Data import requires time and attention, mainly because this information will provide the basic knowledge of the territory and the individual parameters, and it is difficult to modify once it has been obtained.

A realistic reproduction of the terrain elevation allows the use of many other parameters, such as hydrology, sunshine duration, and so forth. This layer is basic to all the others, especially for the agrometeorologist. Other elements, such as text, photographs, film, and the like, can be introduced to complete the informative layer.

4.2.5 Basic components of a GIS

The function of an information system is to improve a user's ability to make decisions in research, planning and management. An information system involves a chain of steps from the observation and collection of data, to their analysis, to deriving information and using it in some decision-making process. In this context, a GIS may be viewed as a major subsystem of an information system. A computer-based GIS may itself be viewed as having five component subsystems, including:

- (a) Data encoding and input processing;
- (b) Data management;
- (c) Data retrieval;
- (d) Data manipulation and analysis;
- (e) Data display.

4.3 INTEGRATION OF REMOTE-SENSING AND GIS

Integration with GIS is needed for remote-sensing (RS) technology to be complete. Remote-sensing represents a technology for synoptic acquisition of spatial data and the extraction of scene-specific information. Demand for remote-sensing as a data input source for spatial database development has increased tremendously during the last few years. Products derived from remote-sensing are particularly attractive for GIS database development because they can provide cost-effective, wide-area coverage in a digital format that can be directly entered into a GIS. Because remote-sensing data are typically collected in a raster data format, the data can be cost-effectively rectified or converted to a vector format for subsequent spatial data analysis or modelling applications.

A leading agrometeorological weather service, using advanced data collection and analysis tools like remote-sensing and GIS, must be equipped with sophisticated devices, but above all must have efficient and trained staff. In developing countries, there remains a risk that using limited resources (high-level agrometeorological personnel and funding) on the development of highly specialized

and complex products will not serve the needs of agricultural decision-makers. The problems and priorities of agrometeorological services need to be defined first. Methodologies come second, but will be essential if they are made available and applied properly.

Our understanding of associated data-processing errors, especially for integrating multiple spatial datasets, lags far behind. It is necessary to clearly identify the types of error that may enter into the process and understand how the error propagates throughout the processing flow. Procedures need to be developed to better quantify and report errors using standardized techniques. Performing spatial data analysis operations with data of unknown accuracy, or with incompatible error types, will produce an output product of low confidence and limited use in the decision-making process.

4.3.1 Data integration

Remote-sensing and GIS error, combined with data acquisition, processing, analysis, conversion and final product presentation, can have a significant negative impact on the confidence of decisions made using the data. The process of integrating remote-sensing data into a GIS usually includes the following analytical procedures: data acquisition, data processing, data analysis, data conversion, error assessment, and final product presentation. Error may be transferred from one data process step to the next and appear in the final product, or it may accumulate throughout the process in an additive or multiplicative fashion. Moreover, an individual process error can be overshadowed by other errors of greater magnitude.

In theory, the amount of error entering the system at each step can be estimated. In practice, however, error is typically assessed only at the conclusion of data analysis (that is, in the final product), if it is assessed at all. Usually, the decision-maker is given graphic final products, statistical data or modelling results with little or no information concerning the confidence of these materials. This limits the confidence of the implemented decision(s).

4.3.2 Data acquisition

Some data acquisition errors are common to any form of data collection and may be introduced from a number of sources. Some of these sources cannot be controlled, such as atmospheric conditions and the natural variability of the landscape, which will result in mixed pixels (depending on pixel resolution).

It is important to have an understanding of the type and amount of errors possible from all data acquisition sources and to control errors whenever possible.

The processing of multiple data layers in a GIS database is predicated upon accurate spatial registration among data layers. Therefore, it is absolutely critical that all remotely sensed data be geometrically accurate and congruent with the GIS database. Illumination geometry can affect image quality and subsequent analyses. Ideally, illumination geometry is constant or nearly constant throughout an image. In practice, however, acquisition needs dictate a relatively wide instantaneous field-of-view (IFOV), resulting in a range of illumination-measurement geometries.

4.3.3 Data processing

4.3.3.1 Geometric rectification

Simple polynomial-based algorithms have proven adequate for satellite imagery, in which geometric distortions are minimal. Adaptive or discrete techniques such as finite element programmes are required to remove the complex distortions that result from aircraft instability. If the geometry is not taken into account, this can lead to area estimation errors (Van Niel and McVicar, 2001). The geometric correction of digital remote-sensor data usually involves some type of resampling, such as nearest neighbour, bilinear or cubic convolution.

How these and other resampling algorithms affect the radiometric integrity of the data and their spatial appearance needs to be more fully understood. Techniques to better automate or fine-tune geometric processing have been developed using different methods of multiple-image spatial cross-correlation. Broader application of these useful techniques requires development of more sophisticated image-processing environments, however. Current software menu-driven or “toolkit” approaches are too primitive and tedious for routine production processing. In addition, producers of geo-corrected, remotely sensed imagery need to assess the accuracy of the outputs against independent geographical features to determine if the imagery meets positional accuracy standards (Van Niel and McVicar, 2002).

4.3.3.2 Data conversion

Processing of spatial data in image processing often involves some form of data conversion. It is possible to resample the data to such a degree that the

geometric and radiometric attributes of the resampled data have a poor relationship with the original data. A good example of resolution degradation during data conversion is when remotely sensed data are classified and then spatially filtered in order to increase classification accuracy. Once filtered, the spatial precision of resulting products may be reduced from that of the original measurements. Similarly, in the GIS analysis of slope and aspect calculated from digital elevation models, the resulting value is representative of a neighbourhood, rather than directly relatable to an individual pixel. These types of data conversions must be catalogued, studied, and their cumulative impact quantified when they are incorporated into GIS.

It is inevitable that data would need to be converted between raster and vector formats. The raster format is simply data arranged as regularly spaced, equal-sized grids. Satellite data and digital elevation models are common examples of raster data. These data are easily stored in a computer as a matrix of numbers. Vector data are more complex than raster data. Vector data maintain the true shape of a polygon using a series of arcs and nodes. Vector data are more aesthetically pleasing and are the preferred methods of data display for most GIS thematic maps that contain polygons.

Unfortunately, there can be significant error introduced by converting either from raster to vector format or from vector to raster format. The amount of this error depends on the algorithm used in the conversion process, the complexity of features, and the grid cell size and orientation used for the raster representation. Failure to consider this potential error can introduce considerable problems into any analysis.

4.3.3.3 Data analysis

In RS/GIS processing flow, data analysis involves the exploration of relationships between data variables and the subsequent inferences that may be developed. This stage of error accumulation will focus on the validity of statistical techniques. Difficulties in statistical analysis of spatially based environmental data sources involve the typical assumptions of the general linear model, compounded by the effects of spatial autocorrelation. Data analysis will also be subject to errors arising from variability in analyst expertise.

Agrometeorological data commonly violate assumptions of independence for measured parameters and error variance. The tendency of adjacent or nearly adjacent samples to have similar

values in environmental datasets, that is, spatial autocorrelation, may violate the independence of samples required in classical statistics. This may result in underestimated sample variance and inflated confidence estimates. The effects of spatial autocorrelation in remotely sensed data sources should be considered.

Flexible statistical tools need to be identified to take into account the particular difficulties of spatial environmental datasets, and then organized into a usable software environment. This would encourage adequate consideration of statistical assumptions in the development of more accurate information products.

In addition to statistical validity, the classic problem in GIS-based data analysis of misregistered polygon boundaries continues to plague those working in this field. Registration error might be seen as being somewhat distinct from the positional errors involved in the various independent data products. It is imperative that the temporal nature of remotely sensed phenomena be catalogued and judgment be made concerning the optimum period during which they are collected and their degree of longevity (Van Niel and McVicar, 2004a).

4.3.3.4 Classification system

Thematic data layers created using remote-sensing data generally require the use of some type of classification system to facilitate categorization of the data for subsequent GIS spatial data analysis. Some of the potential sources of errors induced by classification systems are: the inability of classification systems to categorize mixed pixels, transition zones or dynamic systems; poorly defined or ambiguous class definitions; human subjectivity; and the lack of compatibility among different classifications systems used with both remote-sensing and traditional data types.

Error arising from the classification system is of particular significance when dealing with natural systems. In situations involving mixed pixels and transition or dynamic processes, it is particularly important that detailed field verification data be collected to adequately describe the variation within a system, in order to minimize error related to the classification system. The problem of poorly defined or ambiguous class definitions is a common factor that often introduces an element of error. Inconsistency in classification schemes can cause serious problems, rendering certain thematic coverages unusable in combination (Van Niel et al., 2005; Van Niel and McVicar, 2004a). In addition, to optimize the information content when

classifying agricultural systems with no mixed cropping (that is, each field is planted with one crop during one growing season), GIS boundaries (considered “fine-scale” vector data) can be combined with outputs from classified remotely sensed imagery (considered “coarse-scale” raster data) to improve the overall classification accuracy (Van Niel and McVicar, 2003).

4.3.3.5 Data generalization

Data generalization is routinely performed during remote-sensing analysis for two purposes: spatial resolution and spectral or thematic data reduction. Spatial generalization involves pixel resampling prior to analysis and resampling or grouping after analysis to meet a minimum map unit. Resampling to a spatial resolution finer than the original data commonly results in substantial error. Spectral generalization may be performed by filters that either enhance certain features, such as edges, or homogenize similar pixels. Since filters alter the original pixel values, errors such as accurate location of edges or loss of spectrally similar yet unique resources may occur.

It is also common to resample a classified dataset to a minimum map unit. With the recent trend of transferring raster-based remotely sensed data into a vector-based GIS, it is important to minimize the number of polygons that must be created in the vector form. Generalization of this form may result in inaccurate boundaries and the inclusion of small resources within a larger-area resource class.

4.3.3.6 Error assessment

Ideally, an error assessment is performed after each phase of the analysis. Project funds and schedules rarely provide the opportunity to perform such a thorough error assessment, however. In remote-sensing projects, error assessments are generally performed only after completion of data analysis, and usually address only thematic and locational accuracy. Locational accuracy typically refers to how well the georeferencing algorithms correctly placed pixels into a map coordinate projection, and not the accuracy of thematic or class boundaries.

Most assessments are derived from the same data used to train the classifier. Training and testing on the same dataset results in overestimates of classification accuracy. Rigorous guidelines must be developed to ensure that these fundamental non-spatial specific error assessment problems do not continue.

4.3.3.7 Sampling

Sample size is an important consideration when assessing the accuracy of remotely sensed data that are to be used in a GIS. Each sample point collected is expensive and therefore sample size must be kept to a minimum; yet it is important to maintain a large enough sample size so that any analysis performed is statistically valid.

The sampling scheme is also an important part of an accuracy assessment. Selection of the proper scheme is critical to generating an error matrix that is representative of the entire classified image. Poor choice in sampling scheme can result in the introduction of significant biases into the error matrix, which may lead one to over- or underestimate the true accuracy. Opinions about the proper sampling scheme to use vary greatly and include everything from simple random sampling to stratified systematic unaligned sampling.

4.3.3.8 Spatial autocorrelation

Spatial autocorrelation occurs when the presence, absence or degree of a certain characteristic affects the presence, absence or degree of the same characteristic in neighbouring units. This condition is particularly important in accuracy assessment if an error in a certain location can be found to positively or negatively influence errors in surrounding locations. Surely these results should affect the sample size and especially the sampling scheme used in accuracy assessment. Therefore, additional research is required to quantify the impact of spatially autocorrelated imagery or classification products when they are subjected to error evaluation procedures.

4.3.3.9 Location accuracy

In remote-sensing, locational accuracy may be reported as the root mean square error (RMSE) resulting from the georeferencing algorithms that rectify images to map coordinates. The RMSE is the square root of the squared errors mean and reflects the proportion or number of pixels, plus or minus, in which the image control points differ from the map or reference control points. The RMSE does not truly reflect the locational accuracy of all pixels within an image, however; the RMSE only addresses the control points. The most accurate means of examining locational accuracy, which is a ground survey with a differential Global Positioning System (GPS), is too costly to implement.

4.3.3.10 Final product presentation error

The goal of most remote-sensing/GIS investigations is to produce a product that will quickly and accurately communicate important information to the scientists or decision-makers. This product may take many forms, including thematic maps and statistical tables. There used to be sources of geometric (spatial) and thematic (attribute) error in the final map products and statistical summaries.

Geometric error in the final thematic map products may be introduced through the use of base maps at different scales over a region, different national horizontal datum levels in the source materials, and different minimum mapping units, which are then resampled to a final minimum mapping unit. It is imperative that improved map legends be developed so as to include cartobibliographic information on the geometric nature of the original source materials. This is the only way a reader can judge the geometric reliability of the final thematic map products.

The highest accuracy of any GIS output product is only as accurate as the least accurate file in the data base. Thus, although the final map may look uniform in its accuracy, it is actually an assemblage of information from diverse sources. It is important for the reader to know what these sources are on the basis of a thematic reliability diagram. There is a great need to standardize the design and function of thematic reliability diagrams. Fundamental cartographic design principles must be followed, especially when constructing the class interval legends for thematic maps.

4.3.3.11 Decision-making

The decision-maker is often presented with remote-sensing/GIS-derived maps and/or statistical presentation products for use in the decision-making process. In most situations, adequate information concerning the lineage of thematic data layers and associated thematic and geometric accuracies is not provided. Ideally, in addition to the above-mentioned information, the decision-maker needs an estimate of the overall accuracy and confidence of the data product used in the process. GIS maps and statistical data are being used by decision-makers with little or no knowledge of the potential sources of error, however, and no information concerning the accuracy and confidence level of final presentation products.

It is imperative that the RS and GIS communities educate decision-makers to better understand the potential error sources associated with RS/GIS data products. As the decision-makers become more knowledgeable about the issues related to data accuracy and confidence, they will begin to demand that data concerning consumer accuracy be provided with all final presentation products. Decision-makers and data analysts can no longer work in isolation if the use of RS and GIS technologies are to become data sources on which decisions are based.

4.3.3.12 Implementation

Decisions based on data with substandard accuracy and/or inappropriate confidence levels have an increased probability of resulting in incorrect implementation actions. The obvious implications of an incorrect implementation decision are an erroneous resource management action, which can have serious consequences for the resource itself.

As remote-sensing/GIS-derived products are increasingly being utilized as a basis for implementation decisions concerning resource management and regulatory issues, there is a high potential for an explosion in the number of litigation cases in the short to medium term. A major challenge to the remote-sensing and GIS communities will be the ability to adequately defend the accuracy and reliability of (and confidence in) products used by decision-makers in implementation processes.

4.3.3.13 Theory of vegetation indices

The acronym for ratio vegetation index is RVI (Jordan, 1969; Pearson and Miller, 1972). A common practice in remote-sensing is the use of band ratios to eliminate various albedo effects. In this case, the vegetation isoline converges at the origin. The soil line has a slope of 1 and passes through the origin. The RVI ranges from 0 to infinity, and it is calculated as follows:

$$RVI = \rho_{NIR} / \rho_{red} \quad (4.1)$$

As noted above, the acronym for normalized difference vegetation index is NDVI (Kriegler, 1969; Rouse et al., 1973) and it is a common vegetation index. This index can vary between -1 and 1. In this case, vegetation isolines are considered to converge at the origin; the soil line slope is 1 and passes through the origin. It is calculated as:

$$NDVI = (\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + \rho_{red}) \quad (4.2)$$

Vegetation indices assume that external noise (soil background, atmosphere, Sun and view angle effect) is normalized, but this assumption is not always true. The relative percentage of sunlit and shaded soil and plant components is highly dependent upon the view angle. Qi et al. (1995) studied the effect of multidirectional spectral measurements on the biophysical parameter estimation using a modelling approach. When the bidirectional effect is transformed from the reflectance domain into the vegetation index domain, it can be reduced (Jackson et al., 1990; Huete et al., 1992) or increased (Kimes et al., 1985; Qi et al., 1994b), depending on the vegetation types and solar zenith angles. Qi et al. (1995) suggested that when the bidirectional effect is a major concern ($NDVI/NDVI_0 > 1$), it is better to use NIR rather than NDVI, and that the bidirectional effect on vegetation indices must be quantified before a quantitative VI-LAI relationship can be used. The green normalized vegetative index (GNDVI) is a modification of the NDVI, where the red portion is replaced by the reflectance in the green band (Gitelson et al., 1996).

DVI is the difference vegetation index (Richardson and Everitt, 1992), but appears as VI in Lillesand and Kiefer (1994). The vegetation isolines are parallel to the soil line. The soil line has an arbitrary slope and passes through the origin, while the index range is infinite.

$$DVI = \rho_{NIR} - \rho_{red} \quad (4.3)$$

PVI is the acronym for perpendicular vegetation index (Crippen, 1990) and it is sensitive to atmospheric variation. In this case, vegetation isolines are parallel to the soil line. The soil line has an arbitrary slope and passes through the origin, while the index range is between -1 and 1.

$$PVI = 1/\sqrt{a^2+1} (\rho_{NIR} - a\rho_{red} - b) \quad (4.4)$$

where a and b are the coefficients derived from the soil line: $NIR_{soil} = aRED_{soil} + b$.

WDVI is the acronym for weighted difference vegetation index (Clevers, 1988) and like the PVI, it is sensitive to atmospheric variation (Qi et al., 1994a). The vegetation isolines are parallel to the soil line. The soil line has an arbitrary slope and passes through the origin; the vegetation index range is infinite.

$$WDVI = \rho_{NIR} - a\rho_{red} \quad (4.5)$$

where a is the slope of the soil line.

Huete (1988) proposed a soil-adjusted vegetation index (SAVI) to account for the optical soil properties on the plant canopy reflectance. SAVI involves a constant L to the NDVI equation. The index range is between -1 and 1.

$$SAVI = \rho_{NIR} - \rho_{red} / (\rho_{NIR} + \rho_{red} + L) (1 + L) \quad (4.6)$$

The constant L is introduced in order to minimize soil-brightness influences and to produce vegetation isolines independent of the soil background (Baret and Guyot, 1991). This factor can vary from 0 to infinity and the range depends on the canopy density. For $L = 0$, SAVI is equal to NDVI; when L tends to infinity, SAVI is equal to PVI. For intermediate density, however, L was found to equal 0.5. Huete (1988) suggested that there may be two or three optimal adjustment factors (L), depending on the vegetation density ($L = 1$ for low vegetation; $L = 0.5$ for intermediate vegetation densities; $L = 0.25$ for higher density).

TSAVI is the acronym for transformed adjusted vegetation index (Baret et al., 1989), and it is a measure of the angle between the soil line and the vegetation isoline. The soil line has an arbitrary slope and intercept. The interception between the soil line and vegetation isoline occurs somewhere in the third quadrant. Baret and Guyot (1991) have proposed to improve the initial equation as follows:

$$TSAVI = a(\rho_{NIR} - a\rho_{red} - b) / [a\rho_{NIR} + \rho_{red} - ab + \chi(1 + a^2)] \quad (4.7)$$

where a and b are soil line parameters (slope and intercept of the soil line) and χ has been adjusted so as to minimize background effect, and its value is 0.08. TSAVI values range from 0 for bare soil and are close to 0.70 for very dense canopies, as reported in Baret and Guyot (1991).

At 40 per cent green cover, the noise level of the NDVI is four times the WDVI and almost 10 times the SAVI, corresponding to a vegetation estimation error of ± 23 per cent for the NDVI, ± 7 per cent for the WDVI, and ± 2.5 per cent for the SAVI. Therefore, the SAVI is a more representative vegetation indicator than the other VIs, but an optimization of the L factor will further increase this value (Qi et al., 1994a).

Qi et al. (1994a) developed a modified soil vegetation index (MSAVI). This index provides a variable correction factor L . Geometrically, the vegetation isolines do not converge on a fixed point as for SAVI; the soil line does not have a fixed slope and passes through the origin. The correction factor is

based on a calculation of NDVI and WdVI, as shown by relations (4.8) and (4.9):

$$\text{MSAVI} = \rho_{\text{NIR}} - \rho_{\text{red}} / (\rho_{\text{NIR}} + \rho_{\text{red}} + L) (1 + L) \quad (4.8)$$

where L is calculated as follows:

$$L = 1 - 2a * \text{NDVI} * \text{WdVI} \quad (4.9)$$

This term is computed to explain the variation of L among different types of soils. Moreover, L varies with canopy cover, and its range varies from 0 for very sparse canopy to 1 for very dense canopy. To further minimize the soil effect, Qi et al. (1994a) use an L function with boundary conditions of 0 and 1 ($L_{n=1} = \text{MSAVI}_{n-1}$) and an MSAVI equal to:

$$\text{MSAVI}_n = [(\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + \rho_{\text{red}} + 1 - \text{MSAVI}_{n-1}) * (2 - \text{MSAVI}_{n-1})] \quad (4.10)$$

The final solution for MSAVI is:

$$\text{MSAVI} = 2\rho_{\text{NIR}} + 1 - [(2\rho_{\text{NIR}} + 1)^2 - 8(\rho_{\text{NIR}} - \rho_{\text{red}})]^{0.5} / 2 \quad (4.11)$$

The acronym OSAVI stands for optimized soil adjusted vegetation index. This index has the same formulation as the SAVI family of indices, but the value L or X as referred to by Rondeaux et al. (1996) is the optimum value that minimizes the standard deviations over the full range of cover.

$$\text{OSAVI} = \rho_{\text{NIR}} - \rho_{\text{red}} / (\rho_{\text{NIR}} + \rho_{\text{red}} + 0.16) (1 + 0.16) \quad (4.12)$$

GESAVI stands for generalized soil adjusted vegetation index. This index is based on an angular distance between the soil line and the vegetation isolines. GESAVI is not normalized and varies from 0 to 1 (from bare soil to dense canopies). Vegetation isolines are neither parallel nor convergent at the origin. Vegetation isolines intercept the soil line at any point, depending on the amount of vegetation.

$$\text{GESAVI} = \rho_{\text{NIR}} - \rho_{\text{red}} b - a / \rho_{\text{red}} + Z \quad (4.13)$$

Z is the soil adjustment coefficient and it is based on the assumption that vegetation isolines intercept the soil line at any point in the third quadrant. Z decreases when vegetation cover increases (Gilabert et al., 2002). To normalize soil effects, the Z value is found at 0.35.

Indices that include the mid-infrared (MIR) band are:

The stress-related vegetation index (STVI) (Gardner, 1983):

$$\text{STVI} = \rho_{\text{MIR}} * \rho_{\text{red}} / \rho_{\text{MIR}} \quad (4.14)$$

The cubed ratio index (CRVI) (Thenkabail et al., 1994):

$$\text{CRVI} = (\rho_{\text{NIR}} / \rho_{\text{MIR}})^3 \quad (4.15)$$

The VIs that account for soil effect do not consider atmospheric conditions, sensor viewing angle, or solar illumination conditions. Kaufman and Tanré (1992) developed the atmospherically resistant vegetation index (ARVI) and the soil and atmospherically resistant vegetation index (SARVI and SARVI2), where the reflectances are corrected for molecular scattering and ozone absorption. Liu and Huete (1995) incorporated a soil adjustment and atmospheric resistance concept into a modified normalized vegetation index (MNDVI). The ARVI, SARVI and SARVI2 indices are able to remove smoke effects and cirrus clouds from images (Huete et al., 1997).

4.4

OPERATIONAL AGRO-METEOROLOGICAL PRODUCTS EMPLOYING GIS AND REMOTE-SENSING

Many public agencies, research laboratories, academic institutions, and private and public services have now established their own GISs. Due to increasing pressure on land and water resources, land-use management and forecasting (in relation to crops, weather, fire, and so forth) become more essential every day. GISs are, therefore, an irreplaceable and powerful tool at the disposal of decision-makers.

In agrometeorology, to describe a specific situation, all the relevant information available about a given territory may be used, including: water availability, soil types, land cover, climatic data, geology, population, land use, administrative boundaries and infrastructure (highways, railroads, power grids and communications systems). Each layer of information provides the operator with the possibility of considering its influence on the final result. More than just the overlapping of different themes, however, the relationship of the various layers is reproduced with models (ranging from simple "indicator formulae", such as the Universal Soil Loss Equation (USLE), to physical process-based models).

The final information is extracted using graphical representation or precise descriptive indices. Developed countries use agricultural and environmental GISs to plan the times and types of agricultural practices, territorial management activities, and population security, and to monitor devastating events and evaluate damages.

More than the classical applications of interest in agrometeorology, such as crop yield forecasting, aspects such environmental and human security are becoming increasingly important. For instance, effective forest fire prevention relies on management strategy information on an enormous scale. The analysis of data, such as the vegetation coverage with different levels of inflammability, the presence of urban agglomerations, the presence of roads and many other aspects, allows one to map the areas where risk is greater. The use of other informative layers, such as the position of the control points and resource availability (staff, vehicles, helicopters, airplanes, firefighting equipment, and so on), can help decision-makers in the management of the territorial systems. Obviously, some datasets, such as the data that underpin DEMs, are temporally invariant (or static), whereas other data sources, such as weather conditions (either near-real-time observations or short-term forecasts), are temporally dynamic.

4.4.1 **Assessment of meteorological and agronomic conditions to aid decisions on drought using remote-sensing**

This section is based on the material presented in McVicar and Jupp (1998). Precipitation and solar radiation are meteorological conditions that can be mapped and monitored by the meteorological remote-sensing community; this can be of direct assistance in the scientific process of providing advice on the occurrence of drought.

4.4.1.1 **Precipitation**

For the purpose of mapping the extent and amount of precipitation, remote-sensing provides additional information to supplement data gathered by the existing network of ground-based precipitation gauges. It is unlikely that remotely sensed data will replace the existing network of precipitation gauges. There are several remote-sensing techniques that have the potential to assist in mapping the extent of precipitation patterns. Several reviews provide background on the use of remote-sensing by satellite to estimate precipitation (Arkin and Ardanuy, 1989; Barrett and

Beaumont, 1994; Petty, 1995; Rasmussen and Arkin, 1992).

Precipitation-sized ice particles present in some clouds, higher than the freezing level, result in a lowering of the return signal from clouds in the microwave region of the EMS relative to the nominal background value (Petty, 1995). This is especially evident in the 85.5 GHz band for the special sensor microwave imager (SSM/I). It is not the liquid layer of rain overlying the surface that directly affects the signal. The tops of clouds are colder than the land surface and provide an indication of the clouds' location. For convective weather systems, cold cloud-top temperatures imply the presence of precipitation-sized ice particles that increase the likelihood of rain. Cloud-top temperatures associated with frontal activity, which also produces rain, are usually warmer than the very cold temperatures measured in convective clouds. This is the physical basis for using high-frequency, remotely sensed thermal data to map rainfall patterns.

Passive microwave remote-sensing of rainfall over land became more feasible following the 1987 launch of the SSM/I as part of the American Defense Meteorological Satellite Program (DMSP). The DMSP features a polar-orbiting Sun-synchronous (meaning a revisit time of 12.0 hours) SSM/I scanner with a swath of approximately 1 400 km. SSM/I is a four-frequency (19.35, 22.23, 37.00 and 85.50 GHz), seven-channel passive microwave radiometer (all the channels are dual polarized, except the 22.23 GHz channel, which is vertically polarized). Internationally, a large number of examples of the use of the SSM/I to estimate rainfall have been reported (Grody, 1991; Kniverton et al., 1997; Liu and Curry, 1992; Spencer et al., 1989; Wilheit et al., 1994). The accuracy of SSM/I data in estimating instantaneous precipitation over land for a 1.25-degree resolution cell is reported to be as high as 0.82 (Petty, 1995). The rainfall algorithm inter-comparison needs be conducted for longer periods over more precipitation-producing conditions, however.

International research indicates that the integration of geostationary thermal measurements with other data to make rainfall-rate estimates offers more promise than the use of remotely sensed data alone. Todd et al. (1996) used a temporally and spatially varying threshold, over small time- and space scales, to improve the identification of rainfall distribution and estimation of amount.

There are several integration techniques that may allow For improved rainfall prediction through a combination

of the thermal GMS data with other datasets (Ebert and Le Marshall, 1995). These include:

- (a) Use of pattern recognition or visible data to determine cloud type (Ebert, 1987);
- (b) Short-wave infrared (SWIR)-based inferences, which may allow one to link cloud droplet size to the presence of rainfall (Rosenfield and Gutman, 1994);
- (c) Combination of the outputs from numerical weather prediction (NWP) to include some information about current meteorological conditions (Grassotti and Garand, 1994). Herman et al. (1997) have developed an operational system for Africa using this approach to provide 10-day estimates for the entire continent.

The determination of the amount of precipitation solely from GMS data is unlikely. What appears possible is to link the “where” and “when” capabilities of remote-sensing with the “how much” from ground-based measurements. This link may be made through physically based models or through statistical methods that combine rainfall gauge data with GMS data. Whichever approach is used, complete validation of rainfall amounts derived from GMS-based estimates needs to be undertaken. Hence, GMS data are a significant information source for overcoming the large distance between rainfall measuring stations.

Using the high spatial resolution offered by remote-sensing should assist in rainfall mapping for drought events, especially in areas with a sparse rainfall measurement network. Remote-sensing, however, provides only a snapshot that may have a revisit time of at best one hour (geostationary satellites), and up to every 12 hours (polar-orbiting Sun-synchronous satellites). During that time, clouds will move and intense periods of rainfall may occur and be over before the next revisit time.

Providing accurate, precise and thoroughly validated space-time images of precipitation derived from remote-sensing is, and should continue to be, a major research area for issues such as drought, climate prediction and a thorough understanding of the global hydrologic cycle.

4.4.1.2 Solar radiation

Solar radiation is a major determinant of plant growth, via photosynthesis, which in turn affects soil moisture via transpiration from the leaves. Loss of soil moisture also occurs through direct

evaporation from the soil. Reflective measurements acquired by the GMS satellite may be used to estimate insolation over a region on a daily basis.

Weymouth and Le Marshall (1994) incorporated the following physical parameters to estimate insolation using GMS data:

- (a) Rayleigh scattering;
- (b) Absorption by water vapour;
- (c) Absorption by ozone;
- (d) Isotropic reflection and absorption by clouds;
- (e) Regularly updated surface albedo.

For clear sky and near-clear sky conditions, the average daily deviation of GMS-based estimates compared to ground-based pyranometer measurements was 4.3 per cent. This is within the error limits of well-maintained and calibrated pyrometers. Under heavy cloud conditions, the error seen in GMS-based estimates compared with ground-based pyranometer measurements increased to about 15 per cent. The relative error may appear large; however, the absolute error is small, since the amount of incoming solar radiation is low owing to the heavy cloud cover conditions.

4.4.1.3 Agronomic conditions

There are several ways in which remote-sensing can assist in mapping and monitoring agronomic conditions of direct relevance to drought. These include mapping vegetation type and monitoring vegetation condition and soil moisture.

There are a number of methods that can be used to characterize and assess vegetation condition and cover and changes in this feature over space and time using only reflective remote-sensing. There are several other promising approaches that can be used, including the relation of remotely sensed images to meteorological parameters, crop yield modelling, and inversion of plant growth models.

A number of authors, with varying degrees of integration with GIS, have analysed the difference between two years of NDVI data. Approaches vary from visual display (Hendricksen, 1986) to statistical correlations (Peters et al., 1991) to image differences between two years (Lozana-Garcia et al., 1995; Reed, 1993). The last three papers analysed drought in the context of the conditions in 1987 and 1988 in the continental United States.

The next level of complexity is to scale the NDVI response of one image to the range of responses.

The vegetation condition index proposed by Kogan (1990) is defined as:

$$VCI_j = \frac{NDVI_j - NDVI_{min}}{NDVI_{max} - NDVI_{min}} * 100\% \quad (4.16)$$

where:

VCI_j is the image of vegetation condition index values for date j ;

$NDVI_j$ is the image of NDVI values for date j ;

$NDVI_{max}$ is the image of maximum NDVI values from all images within the dataset;

$NDVI_{min}$ is the image of minimum NDVI values from all images within the dataset.

The VCI_j is a percentage of NDVI values at time j with respect to the maximum NDVI amplitude on a pixel-by-pixel basis. The VCI may be thought of as closely related to the vegetation condition in a specific region. If Advanced Very High Resolution Radiometer (AVHRR) data are recorded over a sufficient number of years in which the extremes in climate variability are sampled, the VCI may indicate potential crop yields or carrying capacities within given agricultural systems. The primary aim of developing the VCI was to assess changes in the NDVI signal over time due to weather conditions, by reducing the influence of “geographic” (Kogan, 1990) or “ecosystem” (Kogan, 1995*b*) variables, meaning climate, soils, vegetation type and topography. This provides a mechanism to compare values across different landscapes, for example between rangeland and rainforest, to determine the changes in the NDVI signal due to the prevailing weather conditions. An assumption in the calculation of the VCI is that reliable, calibrated AVHRR data be used to form the NDVI. Abrupt changes in land cover, for example woodland clearing, mean that the interpretation of this index is more problematic. Having reliable, updated baseline maps of land cover will assist in the interpretation of the VCI in such cases.

The VCI has been used to determine drought and hence, poor vegetation growth and corresponding low yields for spring wheat in Kazakhstan (Gitelson et al., 1996; Kogan, 1995*a*), cotton in China (Kogan, 1995*a*), and barley production in southern Russia (Kogan, 1995*a*).

Liu and Kogan (1996) found that the NDVI was highly correlated with water deficit and rainfall for

Cerrado (savanna grassland) and Caatinga (woodland and open woodland), which both occur in areas with distinct wet and dry seasons. For four sites, the NDVI explained 46 to 61 per cent of the variance of rainfall amount with a one-month time lag from August 1981 to July 1987. Within the time frame of the analysis there was no reporting to ensure that the land cover, and hence the response of the NDVI signal as a function of weather, had remained constant.

Liu and Kogan (1996) defined drought in four ways:

- (a) Monthly rainfall less than 50 mm;
- (b) NDVI lower than 0.18;
- (c) Monthly rainfall departure below 50 per cent of the mean (July 1985–June 1987) and 50 mm lower than the mean value (July 1987–June 1992);
- (d) VCI lower than 36 per cent.

The area of the total grain-producing region with a VCI of less than 0.36 was found to be closely related to the reduction in grain production of summer crops in Argentina and Brazil. Such analysis illustrates the potential of the VCI as an indicator of crop growth conditions. More detailed analysis, such as using a cumulative VCI of the crop production areas, may provide a predictive ability. Liu and Kogan (1996) state that the VCI provides a “better” indicator of regional drought, when compared to the other types of drought delineation, as listed under (a)–(c) above. The response of the VCI is spatially and temporally different from the other delineations, but an analytical comparison with the operational output of drought declared by governments would be a valuable addition to confirm if differences are improvements.

Moreover, water stress is only one cause of low green plant cover leading to NDVI signals. For instance, in the southern highlands of New South Wales in Australia, hydrologic drought may break in May, following autumn rains, but the pastoral drought may continue until September due to air temperature that limits plant growth. To take other environmental variables into account (for instance, air temperature, solar radiation and crop phenology), it may be best to stratify the NDVI by time. That is, the maximum and minimum NDVI for the month, or season, of interest may be used.

McVicar and Jupp (1998) suggest stratifying the NDVI response by time, and they propose that the monthly vegetation condition index (MVCI) be used. Taking January as an example, this is defined as:

$$MVCI_{j, Jan} = \frac{NDVI_{j, Jan} - NDVI_{min, Jan}}{NDVI_{max, Jan} - NDVI_{min, Jan}} \quad (4.17)$$

where:

$MVCI_{j, Jan}$ is the image of monthly vegetation condition index values for date j , which falls within the month of January;

$NDVI_{j, Jan}$ is the image of NDVI values for the j th image recorded in January;

$NDVI_{max, Jan}$ is the image of maximum NDVI values from all images acquired in January;

$NDVI_{min, Jan}$ is the image of minimum NDVI values from all images acquired in January.

This can be defined for any month, or season, within the dataset. This allows the NDVI signal from January for year j to be compared to the range of all January NDVI signals within the dataset available.

In Australia, NDVI has been used by a number of groups to make inferences about the changes in vegetation condition occurring across the Australian landscape. The analysis of AVHRR NDVI data is performed operationally and assists in the decision-making process for drought.

Cridland et al. (1995) analysed the four years of NDVI data by plotting the NDVI signal as a time series. The height, in NDVI units, from a varying baseline to the maximum peak within the growing season has to be calculated. This green “flush” is the response of the landscape to rainfall. It is defined as the maximum NDVI for a growing season subtracted from the baseline. The baseline was varied so that the influence of perennial cover in the NDVI signal was accounted for. The baseline is defined as the minimum from the previous year.

The vegetation response or “flush” recorded as the maximum for a particular year is then considered relative to the absolute maximum “flush” within the four (or more) years of data. For 1994, this would be calculated using the following relation:

$$\frac{NDVI_{max, 1994} - NDVI_{baseline' 93-94}}{\max[NDVI_{max, year} - NDVI_{baseline' year}]} \quad (4.18)$$

which can be rewritten as

$$\frac{flush_{94}}{\max[flush_{population}]} \quad (4.19)$$

One can now measure photosynthetic activity using high-resolution spectral vegetation indices, such as the physiological reflectance index (PRI) (Gamon et al., 1992). The PRI has been shown to be linked more closely to plant physiological response than the NDVI. The PRI has also been shown to be closely correlated to levels of accessory pigments called xanthophylls, which are involved in dissipation of excess photochemical energy during the plant's CO_2 assimilation process (Gamon et al., 1992). The PRI may be more sensitive to stresses, including drought, in vegetation communities that have strategies other than dropping leaves in response to dry conditions. This would be true for overstorey components of woodland and forests and may also be true of shrubs.

There are other approaches to monitoring agromonic conditions relevant to drought. These include monitoring with thermal remote-sensing, monitoring soil moisture with microwave remote-sensing, and combining thermal and reflective remote-sensing.

4.4.2

Operational uses of remote-sensing and GIS for irrigation scheduling

The canopy variables needed for calculating crop water requirements under standard conditions (including a disease-free environment and adequate fertilization) can be either extracted from tables or estimated from field and/or remote observations. Field observations are routinely used by irrigation advisory services, but their evaluation often lacks objectivity and they are difficult to carry out over extensive areas.

In this respect, the potential of remote-sensing techniques in irrigation and water resources management is now widely acknowledged. Several algorithms for retrieving biophysical parameters of vegetation, such as leaf area index, biomass density and canopy roughness, from remote-sensing data with different spatial and temporal resolutions have been successfully tried out in many different environments.

Using this as a baseline, experimental studies have assessed the direct correspondence between the spectral response of cropped surfaces and the corresponding values of evapotranspiration and the crop coefficient K_c (Bailey, 1990; Bausch, 1995; Bausch and Neale, 1987; Choudry et al., 2000; D'Urso and Menenti, 1995).

One important advantage of deriving crop coefficients from spectral measurements is that K_c values

do not depend on variables such as planting date and density, but on the effective cover. As such, the spectral K_c value includes the variability within the same crop type owing to actual farming practices.

Within the DEMETER project (D'Urso, personal communication), two different procedures for the operational estimation of crop water requirements from remotely sensed data have been developed and tested to support irrigation advisory services. The first procedure is based on the relationship between the NDVI and the value of the basal crop coefficient; the second procedure, named "K_c-analytical", is based on a direct application of the Penman–Monteith equation with canopy parameters estimated from satellite imagery, in analogy to the direct calculation proposed by the Food and Agriculture Organization. Details on both procedures are provided in the references (D'Urso et al., 2006; FAO, 1998; Moran and Jackson, 1991).

In the "K_c-NDVI", an empirical relationship between the basal crop coefficient K_{cb} and the vegetation index NDVI is derived, considering a fractional vegetation cover $f_c = 0.8$ for a canopy at full development. Experimental data have been used to derive the following linear relationship:

$$K_c = 1.25NDVI + 0.2 \quad (4.20)$$

A correction should be applied when calculating K_c for the late-season phase, because f_c remains nearly constant in that phase.

The analytical approach for mapping the crop coefficient K_c is based on the direct application of the Penman–Monteith equation, adopted in FAO Irrigation and Drainage Paper No. 56 (FAO, 1998). The vegetation parameters required in this schematization, namely the surface albedo (r), the leaf area index (LAI), and the crop height (h_c), are obtained from the processing of Earth observation (EO) data. The calculation is performed assuming that canopy resistance is at minimum value, that is, 70 s m^{-1} (potential conditions). Using ground-based meteorological data, the K_c values for each pixel are calculated.

For the estimation of r from remote-sensing data three main problems have to be solved: the directional integration of spectral radiance detected by the sensor, the spectral integration to obtain the planetary albedo, that is, at top-of-atmosphere height, and the correction of

atmospheric effects in each spectral band for deriving the surface albedo r from the planetary albedo r_p . The current sensor capabilities, such as those of the Landsat Thematic Mapper used in this study, impose several simplifications. Considering that radiance measurements are performed at different wavelengths, the spectral integration is approximated in discrete form, as expressed by the following relationship:

$$r = \pi \int_0^\infty \frac{K^\uparrow(\lambda)}{K^\downarrow(\lambda)} d\lambda \approx \pi \sum_{\lambda_i} \frac{K^\uparrow_{\lambda_i} (d^0)^2}{E_{\lambda_i}^0 \cos \theta^0} \quad (4.21)$$

In Equation (4.21) the spectral reflected radiance, $K^\uparrow_{\lambda_i} (\text{W m}^{-2})$, and the extraterrestrial solar irradiance, $E_{\lambda_i}^0 (\text{W m}^{-2})$, are integrated values over the width of each spectral band λ_i ; θ^0 and d^0 are the solar zenith angle and the Sun–Earth distance, respectively, in astronomical units. By grouping these quantities in a set of band coefficients (which are sensor-dependent), Equation 4.21 (Bausch, 1995) can be simplified in the following expression:

$$r = \sum_{\lambda} w_{\lambda} \rho_{\lambda} \quad \lambda = 1, 2, \dots, n \quad (4.22)$$

where λ represents the spectral reflectance (corrected for atmospheric effects) in the generic band.

Several authors have defined simple and feasible approaches based on empirical relationships between LAI and nadir-viewing measurements in the red and infrared bands. These methods implicitly assume that all other factors influencing the canopy spectral response, except LAI, are fixed.

In analogy with LAI, some correlation between vegetation indices and canopy roughness parameters may be found. Moran et al. (1994) tried out a purely empirical relationship linking the roughness length z_{0m} of alfalfa to the ratio of reflectance in near-infrared and red bands. Nevertheless, it should be considered that when the radiation component in the surface energy balance is dominant, which happens most frequently during the irrigation season at mid-latitude regions, the association of a mean crop height (constant) to each land-use class derived from satellite data is a satisfactory compromise in areas where the absolute accuracy of $r_{a,H}$ is of minor concern in the calculation of daily values of potential evapotranspiration (ET_p).

The application of both approaches for K_c calculation requires a pre-processing of remotely sensed data, composed of three main steps:

- (a) Inter-satellite calibration;
- (b) Atmospheric correction;
- (c) Geometric correction and image resampling.

Semi-automatic procedures have been developed in order to elaborate K_c maps from remotely sensed data in the minimum possible time. The time required for pre-processing is approximately half of what is needed for elaboration of the entire process. Once georeferenced surface reflectance has been calculated in each pixel, the algorithms for determining K_c are quite straightforward for both approaches described above.

High fragmentation of land parcels, such as in Mediterranean agriculture systems, requires high-resolution imagery to resolve the smallest plots. One of the major limiting factors is thus the inadequate repeat cycles of high-resolution satellites. It is possible, however, to obtain a revisit time of one to five days using the full set of currently available high-resolution satellites (ASTER, IKONOS, Landsat 5 TM and SPOT). The resulting average resolution of five to seven days is sufficient for the calculation of crop water requirements at both district scale and farm scale. When multiple sources of EO data are used to evaluate temporal crop evolution, factors such as sensor calibration differences among the various satellite systems, atmospheric conditions and illumination-view geometry can affect pixel value. Thus, an atmospheric correction and a scene inter-calibration have to be performed in order to reduce reflectance variation due to non-surface factors (sensor, atmospheric and geometric conditions), so that variations in

reflectance on different dates and based on different sensors can be related to actual changes in crop conditions.

An example of the derived product is shown in Figure 4.4, where K_c raster maps derived using different sensors are shown. Parcel boundaries are shown in overlay. One can see that Landsat spatial resolution is still acceptable for this study area for the smallest parcels. The six images acquired over two months during the central part of the crop phenological cycle were adequate to accurately monitor the crop development. The maximum gap between two consecutive acquisitions was ten days. That interval allows a good interpolation of the data to describe crop development. See Van Niel and McVicar (2004b) for a review of how remote-sensing can be used in irrigated rice-based agricultural systems.

4.4.3 Operational uses of remote-sensing and GIS for soil and crop management

4.4.3.1 Evapotranspiration

All objects on the Earth's surface emit radiation in the TIR part of the spectrum (approximately 8 to 14 μm). This emitted energy has proven useful in assessing crop water stress because the temperature of most plant leaves is mediated by soil water availability and its effect on crop evaporation (Jackson, 1982; Hatfield et al., 1983; Moran et al., 1989a; Pinter et al., 2003). In recent years, there has been much progress in the remote-sensing of some of the parameters that can contribute to the estimation of evapotranspiration (ET). These include surface

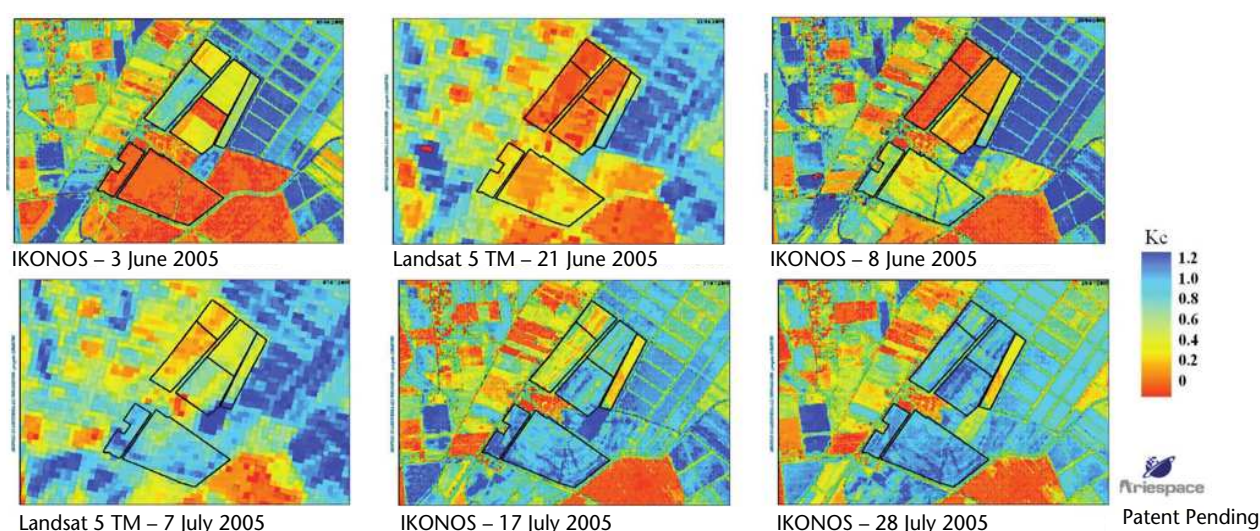


Figure 4.4. Time series of K_c raster maps from multi-sensor acquisitions (Landsat 5 and IKONOS). The planting date of the maize crop was set between 3 and 21 June.

temperature, surface soil moisture, vegetative cover and incoming solar radiation. The surface temperature can be estimated from measurements at the thermal infrared wavelengths of the emitted radiant flux, that is, 10.5 and 12.5 μm . The microwave emission and reflection or backscatter from soil, primarily for wavelengths between 5 and 21 cm, are dependent on the dielectric properties of the soil, which are strong functions of the soil moisture content. Thus, measurements of these microwave properties can be used to obtain estimates of the surface soil moisture.

Crop stress, due to water deficiency or crop diseases, is often accompanied by a decrease in the transpiration rate of the crop. Several studies have been performed with a view to estimating ET on the basis of remote-sensing data (Reginato, 1985; Jackson et al., 1987; Moran and Jackson, 1991; Moran et al., 1994, 1995; Maas, 1993*a*, 1993*b*; Carlson et al., 1995; Hunsaker et al., 2003). A combination of remote-sensing data and soil-plant-atmosphere models is commonly seen in the literature for ET estimation. The location of the “red edge” obtained with hyperspectral measurements shows potential for early detection of water stress (Shibayama et al., 1993). The “stress-degree-day” (SDD) (Idso et al., 1977*b*), “crop water stress index” (CWSI) (Idso et al., 1981; Jackson et al., 1981), “non-water-stressed baseline” (Idso et al., 1982), “thermal kinetic window” (TKW) (Mahan and Upchurch, 1988), “water deficit index” (WDI) (Moran et al., 1994) and the “normalized difference temperature index” (NDTI) (McVicar and Jupp, 1999, 2002) are indices that measure plant stress induced by water stress. These indices have been used in research on more than 40 different crop species (Gardner et al., 1992*a*, 1992*b*). Most studies have shown that the thermal infrared is more sensitive to water stress than is reflectance in visible or NIR. The reflective portion of the spectrum and VIs also respond, however, to plant water stress status when the canopy changes architecture through leaf rolling or wilting (Moran et al., 1989*b*) or alters the senescence rate (Pinter et al., 1981). Thermal plant water stress indices provide valuable information and adequate lead time to schedule irrigation and allow the onset of stress conditions to be detected more rapidly in dryland areas.

Thermal indices can overestimate water stress when canopy cover is full and the sensors view a combination of cool plant and warm soil temperatures. The WDI, which is a combination of VI and TIR (Moran et al., 1994; Clarke, 1997; Clarke et al., 2001), seems to have overcome this problem since it accounts for the amount of plant cover through the VI part of the index.

A cost-benefit study by Moran (1994) shows that irrigation scheduling with thermal infrared sensors on aircraft is both practical and affordable if growers join together to purchase the images. Hatfield (1984*c*) found that spatial variation of surface temperature in wheat changed with the degree of water availability. One alternative tool for a spatially variable irrigation can be to mount infrared sensors on irrigation booms to provide the capability to vary irrigation amounts as the unit travels across the field. VIs can then be used as surrogates for crop coefficients (K_{cb}). Crop coefficients are usually obtained from curves or tables and they lack flexibility to account for spatial and temporal crop water needs caused by uneven plant population, unusual weather patterns, non-uniform water application, nutrient stress or pest pressures (Bausch and Neale, 1987; Choudhry et al., 1994; Pinter et al., 2003).

4.4.3.2 Soil salinity

Remote-sensing can also be used to map areas of soils that have been contaminated by salt. The principle behind this application is that salt in the soil produces an unusually high surface reflectance (Leone et al., 2001). Salted areas can also be identified by detecting areas with reduced biomass or changes in spectral properties of plants growing in affected areas (Barnes et al., 2003).

Leone et al. (2001) evaluated the impact of soil salinity induced through irrigation with saline water on plant characteristics and assessed the relationships among these characteristics and spectral indices. They showed that soil salinity had a clear impact on plant characteristics and identified significant relationships among chlorophyll content, biomass, NDVI and red edge peak.

Studies have also shown an increase in canopy temperature of plants exposed to excessive salts in irrigation water (Howell et al., 1984*a*; Wang et al., 2002), suggesting the possibility of pre-visual detection of stress, which can be managed with the appropriate measure of leaching or irrigation with good-quality water.

4.4.3.3 Remote-sensing in precision agriculture

4.4.3.3.1 Direct application

Past research efforts in the area of remote-sensing have provided a rich background for potential application to site-specific management of agricultural crops. In spite of the extensive scientific knowledge, there are few examples in the literature

of direct application of remote-sensing techniques to precision agriculture. The main reasons for this are the difficulty and expense of acquiring satellite images or aerial photography in a timely fashion. With the progress in GPS and sensor technology, direct application of remotely sensed data is increasing. Now an image can be displayed on the computer screen with a real-time position superimposed on it. This allows for navigation in the field to pre-determined points of interest on the photograph. Blackmer and Schepers (1995) proposed a system for applying nitrogen to corn on the basis of photo-metric sensors mounted on the applicator machine. They showed that corn canopy reflectance changed with the rate of nitrogen within hybrids and that the yield was correlated with the reflected light. Aerial photographs were used to show areas across the field that did not have sufficient nitrogen. The machine reads canopy colours directly and applies the appropriate nitrogen rate based on the canopy colour of the control (well-fertilized) plots (Blackmer et al., 1996a, 1996b; Schepers et al., 1996).

Management zones can be extracted on a computer using VI maps and viewed with the use of a GIS over a remotely sensed image. The computer monitor displays the image along with the current position as the applicator machine moves on the field. When interfaced with variable-rate sprayer equipment, real-time canopy sensors could supply site-specific application requirements, in this way improving efficiency in the use of nutrients and minimizing ground-water contamination (Schepers and Francis, 1998).

4.4.3.3.2 *Indirect application*

The most common indirect use of remote-sensing images is as a base map on which other information is layered in a GIS. Other indirect applications include the use of remotely measured soil and plant parameters to improve soil sampling strategies; the incorporation of remotely sensed vegetation parameters into crop simulation models; and the use of these parameters to help understand the causes and identify the location of crop stress, such as weeds, insects and diseases.

In their excellent review of the possibilities and limitations of image-based remote-sensing in precision agriculture, Moran et al. (1997) classify the information required for site-specific management as information on seasonally stable conditions, information on seasonally variable conditions, and information to find the causes of yield spatial variability and to develop a management strategy. The

first class of information includes conditions that do not vary during the season (soil properties) and need to be determined only at the beginning of the season. Seasonally variable conditions, on the other hand, are those that are dynamic within the season (soil moisture, weeds or insect infestation, crop diseases) and thus need to be monitored throughout the entire season for proper management. The third category embraces the previous two to determine the causes of the variability. Remote-sensing can be useful for obtaining all three categories of information that are required for successful implementation of precision agriculture. Muller and James (1994) suggest a set of multi-temporal images to overcome the uncertainty in mapping soil texture that arises from differences in soil moisture and soil roughness. Moran et al. (1997) also suggest that multi-spectral images of bare soil could be used to map soil types across a field.

4.4.3.4 **Crop growth and intercepted radiation**

Remote-sensing techniques have also been applied to monitor seasonally variable soil and crop conditions. Knowledge of crop phenology is important for management strategies. Information on the stage of the crop could be detected with seasonal shifts in the "red edge" (Raillyan and Korobov, 1993), bidirectional reflectance measurements (Zipoli and Grifoni, 1994), and temporal analysis of NDVI (Boissard et al., 1993; Van Niel and McVicar, 2004a). Moreover, Wiegand et al. (1991) consider remote-sensing techniques as tools to measure vegetation density, LAI, biomass, photosynthetically active biomass, green leaf density, photosynthesis rate, amount of photosynthetically active tissue and photosynthetic size of canopies.

Aparicio et al. (2000) use three VIs (NDVI, simple ratio (SR) and photochemical reflectance index (PRI)) to estimate changes in biomass, green area and yield in durum wheat. Their results suggest that under adequate growing conditions, NDVI may be useful in a later crop stage, such as grain filling, where LAI values are around 2. Simple ratio, under rainfed conditions, correlated better with crop growth (total biomass or photosynthetic area) and grain yield than NDVI. This fact is supported by the nature of the relationship between these two indices and LAI. Simple ratio and LAI show a linear relationship, compared with the exponential relationship between LAI and NDVI. As suggested by the authors, however, the utility of both indices for predicting green area and grain yield is limited to environments or crop stages in which the LAI values are less than 3. They found that in rainfed

conditions, the VIs measured at any stage were positively correlated ($P < 0.05$) with LAI and yield. Under irrigation, correlations were only significant during the second half of the grain filling. The integration of NDVI, SR or PRI from heading to maturity explained 52, 59 and 39 per cent of the variability in yield within 25 genotypes in rainfed conditions and 39, 28 and 26 per cent under irrigation, respectively.

Shanahan et al. (2001) use three different kinds of VIs (NDVI, TSAVI and GNDVI) to assess canopy variation and its resultant impact on corn (*Zea mays* L.) grain yield. Their results suggest that GNDVI values acquired during grain filling were highly correlated with grain yield; correlations were 0.7 in 1997 and 0.92 in 1998. Moreover, they found that normalizing GNDVI and grain yield variability, within treatments of four hybrids and five N rates, improved the correlations in the two years of the experiment (1997 and 1998). Correlation, however, increased in 1997 at a net rate that was higher (from 0.7 to 0.82) than in 1998 (0.92 to 0.95). Therefore, the authors suggest that the use of GNDVI, especially by acquiring measurements during grain filling, is of advantage for producing relative yield maps that show the spatial variability in the field, and offers an alternative to the use of a combined yield monitor.

Raun et al. (2001) determined the capability of predicting the potential grain yield of winter wheat (*Triticum aestivum* L.) using in-season spectral measurements collected between January and March. NDVI was computed in January and March and the estimated yield was computed using the sum of the two post-dormancy NDVI measurements, divided by the cumulative growing degree-days between the first and the second readings. Significant relationships were observed between grain yield and estimated yield, with $R^2 = 0.50$ and $P > 0.0001$ over the two years of the experiment and at different (nine) locations. At some sites, the estimation of potential grain yield made in March and the grain yield measured in mid-July differed, owing to some factors that affected this yield.

The capability of VIs to estimate physiological parameters, such as the fraction of absorbed photosynthetically active radiation (fAPAR), was studied on other crops, including faba bean (*Vicia faba* L.) and semi-leafless pea (*Pisum sativum* L.), which grows under different water conditions, in an experiment followed by Ridao et al. (1998). Crops were grown under both irrigated and rainfed conditions. The authors computed several indices (RVI, NDVI, SAVI2, TSAVI, renormalized difference

vegetation index (RDVI), PVI), and linear, exponential and power relationships between VI and fAPAR were constructed to assess fAPAR on the basis of VI measurements. During the pre-LAI_{max} phase, in both species, all VIs correlated highly with fAPAR; however, R^2 at this stage did not differ significantly between indices that consider soil line (SAVI2 and TSAVI) and those that do not (NDVI, RVI, RDVI). In the post-LAI_{max} phase, the same behaviour was observed. All VIs were affected by the hour of measurement at solar angles greater than 45° . The authors concluded that simple indices, such as RVI and NDVI, could be used to accurately assess canopy development in both crops, allowing good and fast estimation of fAPAR and LAI.

4.4.3.5 Nutrient management

Appropriate management of nutrients is one of the main challenges of agricultural production, and it is also central to efforts aimed at reducing environmental impacts. Remote-sensing is able to provide valuable diagnostic methods that allow for the detection of nutrient deficiency, followed by proper application measures to remedy deficiencies that are identified.

Several studies have been carried out with the objective of using remote-sensing and vegetation indices to determine crop nutrient requirements (Schepers et al., 1992; Blackmer et al., 1993, 1996a, 1996b; Blackmer and Schepers, 1994; Daughtry et al., 2000). The results of these studies led to the conclusion that remote-sensing imagery could be a better and quicker method for managing nitrogen efficiently, compared with the traditional method.

Bausch and Duke (1996) developed an N reflectance index (NRI) from green and NIR reflectance of an irrigated corn crop. The NRI was highly correlated to an N sufficiency index calculated from SPAD chlorophyll meter data. Since the index is based on plant canopy, as opposed to the individual leaf measurements obtained with SPAD readings, it has great potential for larger-scale applications and direct input into variable-rate fertilizer application.

Ma et al. (1996) studied the possibility of evaluating whether canopy reflectance and greenness could measure changes in maize yield response to N fertility. They derived NDVI at three growing stages: pre-anthesis, anthesis and post-anthesis. NDVI is well correlated with leaf area and greenness. At pre-anthesis, NDVI showed high correlation with field greenness. At anthesis the correlation coefficient of

NDVI with the interaction between leaf area and chlorophyll content was not significant with yield. The authors concluded that reflectance measurements taken prior to anthesis predict grain yield and may provide in-season indications of N deficiency.

Gitelson et al. (1996) pointed out that under some conditions, as with the variation in leaf chlorophyll concentration, GNDVI is more sensitive than NDVI. In particular, the green band used in computing GNDVI is more sensitive than the red band used in NDVI. This change occurs when some biophysical parameters, such as LAI or leaf chlorophyll concentration, reach moderate to high values.

Fertility levels, water stress and temperature can affect the rate of senescence during maturation of crops. In particular, Adamsen et al. (1999) used three different methods to measure greenness during senescence on spring wheat (*Triticum aestivum* L.): digital camera, SPAD meter and hand-held radiometer. They derived G/R (green to red) from the digital camera and NDVI from a hand-held radiometer, while SPAD readings were obtained from randomly selected flag leaves. All three methods showed a similar temporal behaviour. The relationship between G/R and NDVI showed significant coefficient of determination and their relationship was described by a third-order polynomial equation ($R^2 = 0.96$; $P < 0.001$). The relation was linear until $G/R > 1$. When the canopy approached maturity ($G/R < 1$), NDVI was still more sensitive to the continued decline in senescence than G/R. This fact suggests that the use of the visible band is limited in such conditions. The authors found, however, that the G/R method was more sensitive than SPAD measurements.

Daughtry et al. (2000) studied the wavelengths sensitive to leaf chlorophyll concentration in maize (*Zea mays* L.). The use of VIs, such as NIR/Red, NDVI, SAVI and OSAVI, showed that LAI was the main variable, accounting for more than 98 per cent of the variation. Chlorophyll, LAI and their interaction accounted for more than 93 per cent of the variation in indices that compute the green band. The background effect accounted for less than 1 per cent of the variation of each index, except for GNDVI, for which the figure was 2.5 per cent.

Serrano et al. (2000) studied the relationship between VIs and canopy variables, namely the above-ground biomass, LAI, canopy chlorophyll A content and the fraction of intercepted

photosynthetically active radiation (fIPAR) for a wheat crop growing under different N supplies. The VI-LAI relationships varied among N treatments. The authors also showed that VIs were robust indicators of fIPAR, independently of N treatments and phenology.

Li et al. (2001) studied spectral and agronomic responses to irrigation and N fertilization on cotton (*Gossypium hirsutum* L.) to determine simple and cross-correlation among cotton reflectance, plant growth, N uptake, lint yield, site elevation, and soil water and texture. NIR reflectance was positively correlated with plant growth and N uptake. Red and middle-infrared reflectance increased with site elevation. Li et al. (2001) found that soil in depression areas contains more sand on the surface than on upslope areas. This behaviour modified reflectance patterns. As a result, a dependence on sand content was shown by NDVI with higher values in the depression areas and lower values in areas where the soil had more clay. In addition, cotton NIR reflectance, NDVI, soil water, N uptake and lint yield were significantly affected by irrigation ($P < 0.0012$). The N treatment had no effect on spectral parameters, and interaction between irrigation and N fertilizer was significant on NIR reflectance ($P < 0.0027$).

Wright (2003) investigated the spectral signatures of wheat under different N rates, and the response to a mid-season application at heading. VIs were computed (RVI, NDVI, DVI, GNDVI) and spectral data were compared with pre-anthesis tissue samples and post-harvest grain quality. The author found that imagery and tissue samples were significantly correlated with pre-anthesis tissue samples and post-harvest grain quality. The second application of N at heading improved protein only marginally. GNDVI was significantly correlated with the nitrogen content of plants. VIs used in the study, whether from satellite or aircraft, correlated well with pre-season N and plant tissue analysis, but had lower correlation with protein.

Osborne et al. (2002a, 2002b) demonstrated that hyperspectral data can be used for distinguishing differences in N and P at the leaf and canopy levels, but the relationship was not constant over all plant growth stages. Adams et al. (2000) have detected Fe, Mn, Zn and Cu deficiency in soybean using hyperspectral reflectance techniques and proposing a yellowness index that evaluated leaf chlorosis based on the shape of the reflectance spectrum between 570 nm and 670 nm.

4.4.3.6 Pest management

Remote-sensing has also shown great potential for detecting and identifying crop diseases (Hatfield and Pinter, 1993) and weeds. Visible and NIR bands can be useful for detecting infected plants as opposed to healthy plants because diseased plants react with changes in LAI or canopy structure. Malthus and Madeira (1993), using hyperspectral information in visible and NIR bands, were able to detect changes in remotely sensed reflectance before disease symptoms were visible to the human eye.

Weed management represents an important agronomic practice for growers. Weeds compete for water, nutrients and light, and often reduce crop yield and quality. Decisions concerning their control must be made early in the crop growth cycle. Inappropriate herbicide application can also have an undesirable effect on the environment and a side effect on the crop. With the advent of precision agriculture, farmers are now able to spray herbicides only when and where they are needed. This kind of approach is economically efficient and environmentally sound. Site-specific herbicide management requires spatial information on weeds, however. The discrimination between crops and weeds is usually accomplished on the basis of differences in the visible/NIR spectral signatures of crops and specific weeds (Gausman et al., 1981; Brown et al., 1994) or by acquiring images when weed colouring is particularly distinctive. Richardson et al. (1985) demonstrated that multispectral aerial video images could be used to distinguish uniform plots of Johnson grass and pigweed from sorghum, cotton and cantaloupe plots. Several other authors have utilized spectral imagery to separate crops from weeds on the basis of spectral signatures of species and bare soil (Hanks and Beck, 1998) or on the basis of leaf shape determined by machine vision technology (Franz et al., 1995; Tian et al., 1999).

Basso et al. (2004) used the CropScan hand-held radiometer to determine if a wheat field with various levels of poppy (*Papaver rhoeas*) infestation could be detected by multispectral radiometer. The study showed that the red and NIR reflectance in areas of a durum wheat field highly infested with poppy was significantly different from the red and NIR reflectance observed in areas with no infestation or with lower levels of this weed.

Remote-sensing can also be used to determine herbicide injury to a crop for insurance purposes (Hickman et al., 1991; Donald, 1998a, 1999b). To

improve the application efficiency of herbicides, Sudduth and Hummel (1993) developed a portable NIR spectrophotometer for use in estimating soil organic matter as part of the process of determining the amount of herbicide to be sprayed.

Several studies have also been carried out using remote-sensing for identifying and managing insect, mite and nematode populations. These studies have demonstrated that remote-sensing is able to detect actual changes in plant pigments caused by pest presence and damage by pests, and that it can help identify areas susceptible to infestation. Riedell and Blackmer (1999) infested wheat seedlings with aphids and measured the reflectance properties of individual leaves after three weeks. The leaves of the infected plants had lower chlorophyll concentration and displayed significant changes in reflectance spectra at certain wavelengths (500 to 525, 625 to 635 and 680 to 695 nm). In combination with other studies (Cook et al., 1999; Elliot et al., 1999; Willers et al., 1999), this study suggests the potential usefulness of canopy spectra for identifying outbreaks in actual field situations and guiding field scouts to specific areas for directed sampling. Site-specific pesticide application can reduce the impact of toxic chemicals on the environment by 40 per cent (Dupont et al., 2000).

4.4.3.7 Selection of growth traits

The use of morphological and physiological traits as indirect selection criteria for grain yield is an alternative to the breeding approach. Future wheat yield improvements may be gained by increasing total dry matter production (TDM). VIs have been proposed as an appropriate and non-destructive method to assess total dry matter and LAI. Aparacio et al. (2000, 2002) investigated whether VIs could accurately identify TDM and LAI in durum wheat and serve as indirect selection criteria in breeding programmes. They found that the best growth stages for the appraisal of growth traits were stages 65 and 75 of the Zadoks scale (Zadoks et al., 1974). VIs accurately tracked changes in LAI when data were analysed across a broad range of different growth stages, environments and genotypes. Since VIs lack predictive ability for specific combinations of environment and growth stages, their value as indirect genotype selection criteria for TDM or LAI is limited.

Ma et al. (2001) showed that canopy reflectance measured between the R4 and R5 stages in soybean adequately discriminates high- from low-yielding genotypes and provides a reliable and fast indicator

for screening and ranking soybean genotypes based on the relationship between NDVI and grain yield.

4.4.3.8 Crop yield estimation

Remote-sensing can provide valuable information on yield assessment and show spatial variation across a field. There are two approaches for yield estimation. The first is a direct method in which predictions are derived directly from remote-sensing measurements. The second is an indirect method in which remotely sensed data are incorporated into a simulation model for crop growth and development, either as intraseasonal calibration checks of model output (LAI, biomass) or in a feedback loop used to adjust model starting conditions (Maas, 1988).

The direct method for the prediction of yield using remote-sensing can be based on reflectance or on thermal parameters. Both methods have been applied successfully with various crops, such as corn, soybean, wheat and alfalfa (Tucker et al., 1979, 1981; Idso et al., 1977; Pinter et al., 1981). In his survey of 82 different varieties of wheat, Hatfield (1981) was not able to find a consistent relationship between spectral indices and yield.

Hatfield (1983) coupled frequent spectral reflectance and thermal observation in a more physiological method to predict yields in wheat and sorghum. This method requires TIR daily measurements during the grain-filling period to estimate crop stress.

Shanahan et al. (2001) demonstrated that the time of corn pollination was not a good growth stage for estimating yield because of the various factors that can cause tassel emergence dates to vary. Yang et al. (2000) found similar results, concluding that images taken at grain filling can provide good relationships between VIs and yield. The reliability of imagery for use in yield estimation decreases as the time before harvest increases because there are more opportunities for factors such as stresses to influence yield.

Aase and Siddoway (1981) cautioned that the relationships of spectral indices to yield were dependent upon normal grain-filling conditions for the crop. Similar results were found by Basso et al. (2004, personal communication, unpublished data) in which the NDVI images of a rainfed durum wheat field showed a different correlation to yield depending on the time of the image selected. In this specific case, spatial variability of soil texture and soil water uptake by plants affected by drought varied at anthesis, presenting scenarios different from the one predicted by the NDVI estimation.

4.4.4

Operational uses of remote-sensing and GIS for assessing environmentally sensitive areas for desertification risk

Soil, vegetation, climate and management are the main factors affecting environmental sensitivity to degradation, through their intrinsic characteristics or through their interaction with the landscape. Different levels of degradation risks may be observed in response to particular combinations of the aforementioned factors. For instance, a combination of inappropriate management practices and intrinsically weak soil conditions will result in environmental degradation of a severe level, while a combination of the same type of management with better soil conditions may lead to negligible degradation.

A weighted multiplicative model within a GIS has been developed in order to assess the environmental sensitivity (ES) of the Basilicata region (Italy) by taking into account the particular set of environmental and socio-economic conditions and their relationships. Furthermore, major contributing factors to degradation have been identified across this region through spatial analysis. Environmental degradation or sensitivity has been modelled as the multiplicative effect of soil, climate, vegetation and management; it is indicated in the model as quality layers.

$$ES = (Quality\ Index_1 * Quality\ Index_2 * Quality\ Index_3 * Quality\ Index_n)^{(1/n)}$$

In turn, each Quality Index (QI) represents the result of interactions among the elementary factors listed above according to the following equation:

$$QI = (Information\ Layer_1 * Information\ Layer_2 * Information\ Layer_3 * Information\ Layer_n)^{(1/n)}$$

Each layer represents a single variable and measures how such variable relates on its own to the general environmental sensitivity. The ES model is explained in detail in Basso et al. (2000). Low, high and severe risk classes were identified by grouping ES values into three classes, using a natural break classification method. As summarized in Figure 4.5, over 50 per cent of the Basilicata surface is exposed to high risk and 7 per cent to severe risk, while the remaining 37 per cent is exposed to low risk.

4.4.5

Aquaculture and remote-sensing

Mangroves form an important vegetation belt along coastal regions and their presence has considerable

influence in maintaining the proper environmental balance. Destruction of mangroves will, in the long run, have a serious impact on coastal ecosystems. Mangroves to some extent protect land from cyclones and the ill effects of cyclones on crops, cattle and human habitation.

A study by scientists at the National Remote Sensing Agency, India, using satellite remotely sensed data covering the Andhra Pradesh ecosystems to delineate many of the cultivated areas and mangroves, revealed that in 1973, the areas under prawn cultivation were almost negligible and that by 1985 and 1990, they grew by a factor of more than 5 in the Guntur district and by a factor of 10 in the Krishna district. This study showed a decrease in the area of mangrove vegetation, suggesting that the increase in prawn cultivation might have affected these mangroves. In spite of

their essential role in maintaining the ecological balance in coastal ecosystems, mangroves are being destroyed in some areas, such as in Kottapalem in Repalle Mandal in the Guntur district, for the purpose of extending the cultivation of prawns (Narayan, 1999).

Remote-sensing data may help not only in the estimation of areas under brackish water aquaculture along all of the Indian coast, but also in selecting suitable locations for prawn/shrimp farming without posing a serious threat to mangrove systems. In the Krishna district, prawn cultivation increased from 1973 to 1992, while the areas with mangroves contracted in size during the same period, as can be observed from remotely sensed satellite data gathered during this period. In terms of statistics, prawn cultivation was non-existent in the Krishna district in 1973, while the

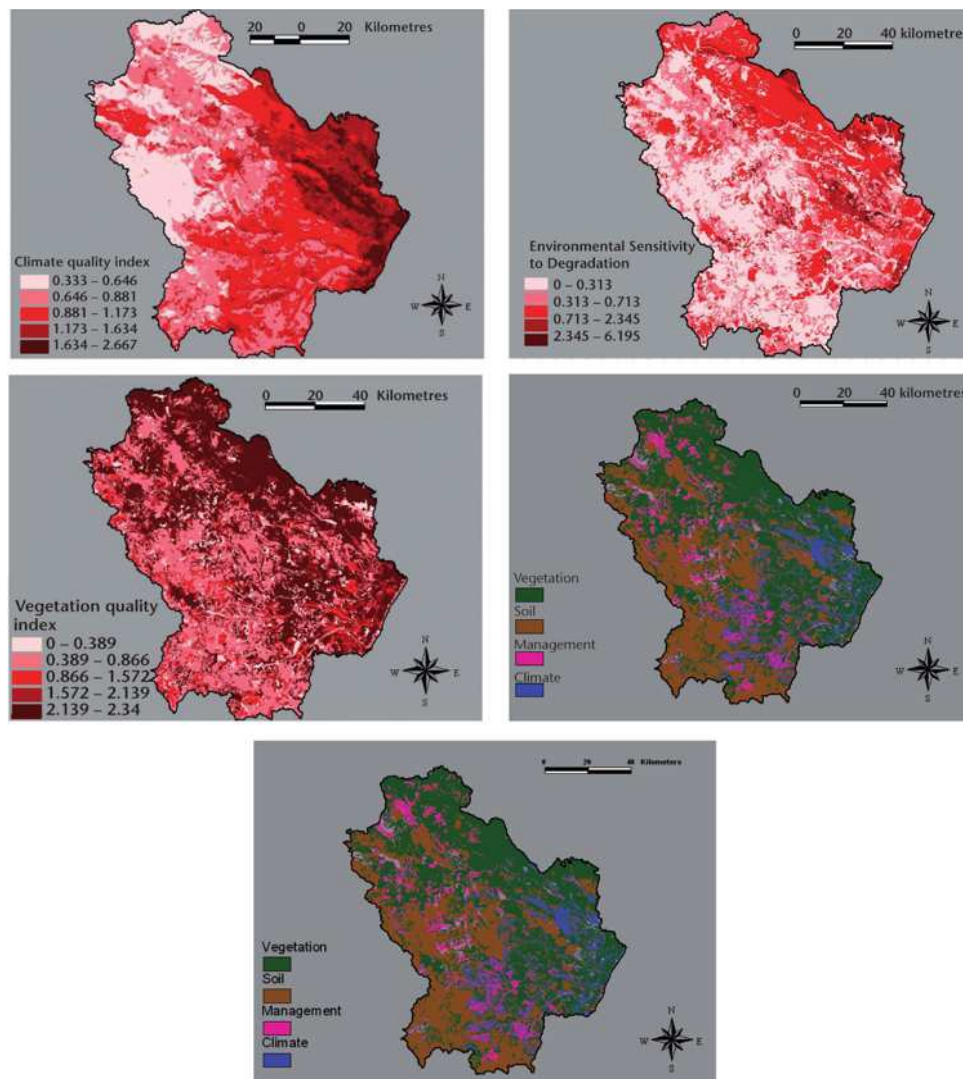


Figure 4.5. Climate quality map; vegetation quality map; environmental sensitivity; risk class and contribution factor to spatial distribution of desertification risk in the Basilicata region, southern Italy (Lat. 40°6', Long. 16°6')

mangroves extended over about 5 884 ha. In 1992, the areas under prawn cultivation increased to 6 005 ha, while the mangroves shrunk to 5 479 ha.

4.4.6 **Operational use of remote-sensing for identification of fishing zones**

With the advent of remote-sensing methods, many ocean-related applications, including fisheries, can be studied using satellite and aircraft data. One of the important parameters that can be measured with sufficient accuracy is the sea surface temperature (SST), which has been related to the concentration of fish population. Here, it has been shown how sea surface temperature can be mapped on a regular basis and how this information can be passed on to fishermen so that they can concentrate on high potential areas and improve the catch (WMO, 2004).

Sea surface temperature derived from the NOAA AVHRR satellite serves as a very useful indicator of prevailing and changing environmental conditions and is one of the important parameters behind suitable environmental conditions for fish aggregation. SST images obtained from satellite imagery over three or four days are composited and the minimum and maximum temperatures are noted. These values are processed to obtain maximum contrasts of thermal information. These are filmed to prepare relative thermal gradient images. From these images, features such as thermal boundaries, relative temperature gradients with an accuracy of 1°C, contour zones, eddies and upwelling zones are identified. These features are transferred using optical instruments to corresponding sectors of the coastal maps prepared with the help of naval hydrographic charts. Later, the location of the potential fishing zone (PFZ) with reference to a particular fishing centre is drawn by identifying the nearest point of the thermal feature to that fishing centre. The information extracted consists of distance in kilometres, depth in metres (for position fixing) and bearing in degrees with reference to the north for a particular fishing centre.

The PFZ maps thus prepared are sent through facsimile transmission (fax) to major fishermen's associations of India, unions, and governmental organizations of India, such as the Central Marine Fisheries Research Institute, Fishery Survey of India, and state fisheries departments of all maritime states of India, including the union territories of Andaman and Nicobar and Lakshadweep Islands, every Monday and Thursday. The Department of Ocean Development has already set up fax machines

at the ports of Balasore, Bhubaneswar, Thiruvananthapuram and Malpe (Karnataka State) and has plans to extend these facilities to all major fish landing centres along the Indian coast. Centres are informed periodically of PFZs by other means, whenever fax transmission is not available.

4.4.7 **Forest management through remote-sensing**

The present scenario for the use of remote-sensing in forest studies indicates that for forest cover monitoring or surveillance, the use of this technology at the national and state levels and mapping on a scale of 1:25 000 are possible. This is operationally being done by the Forest Survey of India, with a view to producing and reporting information on a biennial basis. Such information has been found to be reliable and can be generated within a short time and, if necessary, in digital format. In addition, the study of spatial distribution of forest types could also be necessary and useful, particularly to provide scientifically sound insights to forest officials as to which species need to be introduced either by replacement of natural forest or regeneration of degraded forests in the area. Preparation of forest-type maps and their distribution at the block level on a scale of 1:50 000 are now possible using satellite remote-sensing data to aid forest managers.

4.5 **COLLABORATIONS FOR RESOURCE SHARING IN REMOTE-SENSING AND GIS**

The transfer of the new techniques of processing and interpreting remote-sensing data from developed to developing countries is limited by many factors, such as the cost of receiving equipment, restrictive or very difficult access to the archives of satellite images and data, a shortage of qualified staff, and the like. The situation has improved in recent years, thanks to the availability of long series of satellite data; for example, the data archives from NOAA (United States) and Meteor (Russian Federation) contain information that goes back more than 15 years. Access to archives and the transfer of information, software and processes are becoming simpler, especially with the use of Internet tools (see, for example, Schmidt et al., 2006, and the references therein).

International organizations, and in particular WMO, are also playing an active role in the coordination of efforts involved in the reception,

processing, dissemination and use of remote-sensing data. The WMO Commission on Basic Systems has recently established a Working Group on SATellites (WGSAT) that will serve as an appropriate place for carrying out such activity. The main goal is the development of common working strategies and the improvement of regional and global management capability of satellite data.

For this reason, particular emphasis is placed on data compatibility and integration among different sources of data. WGSAT has supported a project aimed at developing receiving stations (both hardware and software) at a reasonable cost so that they can be made available to developing countries. WGSAT has discussed a possible process to improve the use of satellite data from the present global satellite observing system, and has put forward a set of recommended actions.

The WMO strategy to improve satellite system utilization consists of four components:

- (a) The strategic vision;
- (b) The long-term strategic goal;
- (c) Major strategic objectives;
- (d) The methodology to meet the objectives.

The strategic vision to improve satellite system utilization is the prospect of substantially improved transfer to communities around the world of the benefit of meteorological science and technology, via rapidly evolving global and regional communications networks. This will

allow improved access to satellite data and services and interactions between developed and developing countries.

The long-term strategic goal for the next 15 years is to achieve systematic improvements in the utilization of satellite systems by National Meteorological and Hydrological Services, with an emphasis on improving utilization in developing countries.

The major strategic objectives are:

- (a) To focus on the needs of developing countries;
- (b) To improve access to satellite data through increased effectiveness in the distribution of satellite system data and products at major hubs, in particular those maintained by the satellite operators, WMO World Meteorological Centres, Regional Specialized Meteorological Centres, and other entities as appropriate;
- (c) To improve the use of satellite data by increasing the capabilities of their applications through the direct involvement of existing WMO Member expertise.

The methodology to improve satellite system utilization is based on an iterative process to assess continuously the status of the use of satellite data and services and their impact on the various applications, and thus to identify limitations and deficiencies. The necessary steps to improve utilization will be developed and implemented through specific projects.

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WEATHER AND CLIMATE FORECASTS FOR AGRICULTURE

5.1 **NEED AND REQUIREMENTS FOR WEATHER FORECASTS FOR AGRICULTURE**

5.1.1 **Climate-based strategic agronomic planning**

Weather plays an important role in agricultural production. It has a profound influence on crop growth, development and yields; on the incidence of pests and diseases; on water needs; and on fertilizer requirements. This is due to differences in nutrient mobilization as a result of water stresses, as well as the timeliness and effectiveness of preventive measures and cultural operations with crops. Weather aberrations may cause physical damage to crops and soil erosion. The quality of crop produce during movement from field to storage and transport to market depends on weather. Bad weather may affect the quality of produce during transport, and the viability and vigour of seeds and planting material during storage.

Thus, there is no aspect of crop culture that is immune to the impact of weather. Weather factors contribute to optimal crop growth, development and yield. They also play a role in the incidence and spread of pests and diseases. Susceptibility to weather-induced stresses and affliction by pests and diseases varies among crops, among different varieties within the same crop, and among different growth stages within the same crop variety. Even on a climatological basis, weather factors show spatial variations in an area at a given time, temporal variations at a given place, and year-to-year variations for a given place and time. For cropping purposes, weather over short periods and year-to-year fluctuations at a particular place over the selected time interval have to be considered. For any given time unit, the percentage departures of extreme values from a mean or median value, called the coefficient of variability, are a measure of variability of the parameter. The shorter the time unit, the greater the degree of variability of a given weather parameter. The intensity of the above three variations differs among the range of weather factors. Over short periods, rainfall is the most variable of all parameters, both in time and space. In fact, for rainfall the short-period interannual variability is large, which means that variability needs to be expressed in terms of the percentage probability of realizing a given amount of rain, or

that the minimum assured rainfall amounts at a given level of probability need to be specified.

For optimal productivity at a given location, crops and cropping practices must be such that while their cardinal phased weather requirements match the temporal march of the relevant weather element(s), endemic periods of pests, diseases and hazardous weather are avoided. In such strategic planning of crops and cropping practices, short-period climatic data, both routine and processed (such as initial and conditional probabilities), have a vital role to play.

5.1.2 **Weather events**

Despite careful agronomic planning on a microscale to suit experience in local-climate crops, various types of weather events exist on a year-to-year basis. The effects of weather anomalies are not spectacular. Deviations from normal weather occur with higher frequencies in almost all years, areas and seasons. The most common ones are a delay in the start of the crop season due to rainfall vagaries in the case of rainfed crops (as observed in the semi-arid tropics) and temperature (as observed in the tropics, temperate zones and subtropics), or persistence of end-of-the-season rains in the case of irrigated crops. Other important phenomena are deviations from the normal features in the temporal march of various weather elements. The effects of weather events on crops build up slowly but are often widespread enough to destabilize national agricultural production.

5.1.3 **Usefulness of weather forecasts**

Occurrences of erratic weather are beyond human control. It is possible, however, to adapt to or mitigate the effects of adverse weather if a forecast of the expected weather can be obtained in time. Rural proverbs abound in rules of thumb for anticipation of local weather and timing of agricultural operations in light of expected weather. Basu (1953) found no scientific basis for anticipation of weather in many of the popular proverbs and folklore. In a recent study, Banerjee et al. (2003) arrived at conclusions similar to that of Basu (1953). The proverbs and local lore show, however, that farmers have been keen to know in advance the likely weather situations for crop operations from time immemorial. Agronomic strategies to cope with changing weather are available. For example, delays in the start of crop

season can be countered by using short-duration varieties or crops and thicker sowings. Once the crop season starts, however, the resources and technology get committed and the only option left then is to adopt crop-cultural practices to minimize the effects of mid-seasonal hazardous weather phenomena, while relying on advance notice of their occurrence. For example, resorting to irrigation or lighting trash fires can prevent the effects of frosts. Thus, medium-range weather forecasts with a validity period that enables farmers to organize and carry out appropriate cultural operations to cope with or take advantage of the forecasted weather are clearly useful. The rapid advances in information technology and its spread to rural areas provide better opportunities to meet the rising demand among farmers for timely and accurate weather forecasts.

5.1.4 **Weather forecasts for agriculture: essential requirements**

Forecasts calling for a late start to the crop season should result in departures from normal agronomic practices at the field level. High costs are associated with the organization and execution of such a strategy, and the relevant steps require a considerable amount of time. Therefore, pre-season forecasts must have a validity period of at least 10 days and not less than a week. Field measures to counter the effects of forecast hazardous weather, pests, diseases, and the like cannot be implemented instantaneously and hence mid-season forecasts should preferably be communicated five days in advance, and at the very least three days in advance. Dissemination of weather forecasts to agricultural users should be quick, with the minimum possible time lag following their formulation. Some of the measures, such as pre-season agronomic corrections, control operations against pests and diseases, supplementary irrigation, and the scheduling of early harvests, will be high-cost decisions. The weather forecasts must therefore be not only timely, but also very accurate. Weather forecasts should ideally be issued for small areas. In the case of well-organized weather systems, the desired areal delineation of forecasts can be realized. In other cases, the area(s) to which the weather forecasts will be applicable must be unambiguously stated.

5.1.5 **Some unique aspects of agricultural weather forecasts**

Some aspects of weather forecasts for agriculture are quite distinct from synoptic weather forecasts. In synoptic meteorology, the onset and withdrawal of the monsoon is related to changes in wind circulation patterns in the upper atmosphere and associated changes in precipitable water content of air in the

lower layers. Preparation of fields for sowing and the sowing of a crop with adequate availability of seed-zone soil moisture requires copious rains. Rains that do not contribute to root-zone soil moisture of standing crops are ineffective. Agriculturally significant rains, or ASRs (Venkataraman, 2001), are those that enable commencement of the cropping season and that contribute to crop water needs. For agricultural purposes, it is the start and end of ASRs that are important. ASRs may be received early as thundershowers or may be delayed. Venkataraman and Krishnan (private communication) have drawn attention to the feasibility of commencement of the cropping season far in advance of the monsoon season in Karnataka, Kerala, West Bengal and Assam in India with the help of pre-monsoon thunderstorm rains. The climatological dates of withdrawal of the monsoon and the end of ASRs in a region can also differ significantly. Both the start and end of ASRs in a province may show intraregional variations.

The use of dependable precipitation (DP) at various probability percentage levels and potential evapotranspiration (PET) have been suggested for delineation of the start and end of a crop growth period on a climatological basis (WMO, 1967, 1973; Venkataraman, 2002) and have been used in many regions. The methods differ, however, in time units employed, the probability level chosen for DP and the fraction of PET used as a measure of adequacy of crop rainfall. Based on considerations of the level of evaporative power of air (EPA), the rainfall amount required to overcome the evaporative barrier, and phased moisture needs of crop demands, Venkataraman (2001) suggested that weekly or dekadal periods be used and that the commencement and end of ASRs be taken as the point at which DP at 50 per cent probability level begins to exceed PET and becomes less than 50 per cent of PET, respectively. Monthly values of PET can be interpolated to derive short-period values. So, when rainfall probability data for weeks or dekads and the monthly values of PET are available, the commencement and end of ASRs can easily be delineated.

While clear weather is required for sowing operations, it must be preceded by seed-zone soil moisture storage. Thus, forecasts of clear weather following a wet spell are crucial. Such forecasts of dry spells following a wet spell are also required for the initiation of disease control measures. There are areas where frequent thunderstorm activity precedes the arrival of rains associated with well-defined weather systems and once started, the rains persist without any let-up. In such cases, the agronomic strategy should be to utilize pre-season rains for land

preparation and resort to dry sowings in anticipation of rain to come in the next few days. Land preparation can be done with the expectation of impending thundershowers. Dry-sown seeds will get baked out in the absence of rains, however, so it is prudent to sow when there is a forecast calling for rain in the coming days. Thus, rainy season forecasts become crucial in such areas. In temperate regions, frost can pose a severe threat to agricultural productivity. Frosts normally occur when the screen temperatures reach 0°C. The depression of the radiation minimum temperature of crops below the screen minimum will vary with places and seasons. The radiative cooling will be maximal on cold nights with clear skies and minimal on warm nights with cloudy skies. Thus, owing to night-time radiative cooling of crop canopies, crop frosts can occur even when screen temperatures are above 0°C. Similarly, dew, which influences the crop water needs and the incidence of diseases, can get deposited over crops at lower relative humidities than what is deducible from a thermohygrograph. The frictional layer near the ground is ignored by the synoptic meteorologist, but low-level winds in this layer influence the long-distance dispersal of insects (such as desert locusts) and disease spores (wheat rusts).

It is thus clear that the types of forecasts for critical farming operations would have unique features that would require further processing of certain elements of synoptic weather forecasts.

5.2 CHARACTERISTICS OF WEATHER FORECASTS

A deterministic definition states that “weather forecast describes the anticipated meteorological conditions for a specified place (or area) and period of time”; an alternative and more probabilistic definition states that “weather forecast is an expression of probability of a particular future state of the atmospheric system in a given point or territory”. In view of the above, a weather forecast may be defined as a declaration in advance of the likelihood of occurrence of future weather event(s) or condition(s) in a specified area(s) at given period(s) on the basis of a rational study of synoptic, three-dimensional and time series data of sufficient spatial coverage of weather parameters, and analyses of correlated meteorological conditions. The positive effect of weather forecasts in agriculture is maximized if weather forecasters are aware of the farmers’ requirements and farmers know how to make the most use of the forecasts that are available. Response among varieties of a

crop to a weather phenomenon is one of degree rather than of type. The type and intensity of weather phenomena that cause setbacks to crops vary among crops and among growth stages within the same crop, however. Crop weather factors mean that crops and cropping practices vary across areas, even within the same season.

In the provision of weather forecasts for agriculture, the emphasis should be on the outlook for the incidence of abnormal weather and the prevalence of aberrant crop situations. Of course, one cannot determine abnormality unless one knows what the normal picture is, with reference to both crops and weather. Thus, the first step in familiarizing weather forecasters with the weather warning requirements of farmers is the preparation of crop guides for forecasters, which should give the times of occurrence and duration of developmental phases from sowing to harvest of major crops in the regions of their forecast interest, and specify the types of weather phenomena for which weather warnings and forecasts are to be issued in the different crop phases. Such guides can be used by forecasters to prepare calendars of agricultural weather warnings with a breakdown by periods and regions. In the crop guide for forecasters, normal values of important weather elements in the crop season should also be given for the short period adopted at the national level for agrometeorological work; this guide should also be made available to the farming community so that any farmer will know immediately what the normal features of weather will be for a given crop and season at his location.

The week is the accepted time unit for agrometeorological work in India. The crop weather calendars in use in India (shown in Figure 5.1), with the week as the basic time unit, are excellent examples of the type of compiled information that can assist forecasters in framing weather warnings and forecasts directed at farmers.

Weather forecasting now has a wide range of operational products that traditionally are classified under the following groups:

- (a) Nowcasting (NC);
- (b) Very short-range forecast (VSRF);
- (c) Short-range forecast (SRF);
- (d) Medium-range forecast (MRF);
- (e) Long-range forecast (LRF).

Each weather forecast can be defined on the basis of the following criteria:

- (a) Dominant technology;
- (b) Temporal range of validity after emission;
- (c) Characteristics of input and output time and space resolution;

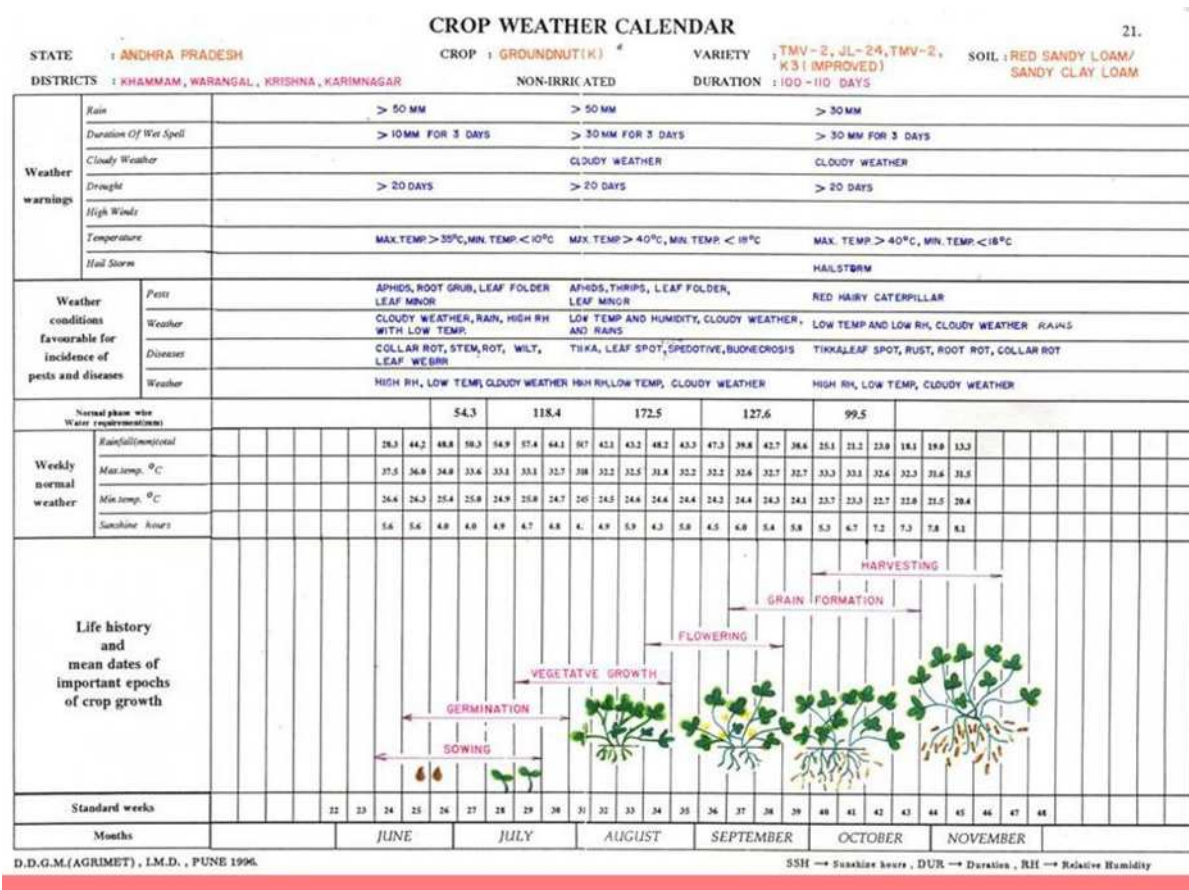


Figure 5.1. Crop weather calendar from India

- (d) Broadcasting needs;
- (e) Accuracy;
- (f) Usefulness.

Table 5.1 contains a general description of different types of weather forecasts based on criteria (a) through (e); Table 5.2 presents an almost qualitative description based on criteria (e) and (f).

5.3 CONSIDERATIONS RELATED TO AGRICULTURAL WEATHER FORECASTS

5.3.1 Elements of agricultural weather forecasts

An agricultural weather forecast should refer to all weather elements that immediately affect farm planning or operations. The elements will vary from place to place and from season to season. Normally a weather forecast includes the following parameters.

- (a) Amount and type of cloud cover;
- (b) Rainfall and snow;

- (c) Maximum, minimum and dewpoint temperatures;
- (d) Relative humidity;
- (e) Wind speed and direction;
- (f) Extreme events, such as heatwaves and cold waves, fog, frost, hail, thunderstorms, wind squalls and gales, low-pressure areas, different intensities of depressions, cyclones, and tornadoes.

An agricultural weather forecast should also contain the following information:

- (a) Bright hours of sunshine;
- (b) Solar radiation;
- (c) Dew;
- (d) Leaf wetness;
- (e) Pan evaporation;
- (f) Soil moisture stress conditions and supplementary irrigation for rainfed crops;
- (g) Advice for irrigation timing and quantity in terms of pan evaporation;
- (h) Specific information about the evolution of meteorological variables into the canopy layer in some specific cases;
- (i) Microclimate inside crops in specific cases.

Table 5.1. Definition of weather forecasts

Type of weather forecast	Acronym	Definition	Characteristics of output	Dominant technology	Other aspects	Time and space resolution of typical products
Now-casting	NC	A description of current weather variables and description of forecast weather variables for 0–2 hours	A relatively complete set of variables can be produced (air temperature and relative humidity, wind speed and direction, solar radiation, precipitation amount and type, cloud amount and type, and the like).	Analysis techniques, extrapolation of trajectories, empirical models and methods derived from forecaster experience (rules of thumb). Basic information is represented by data from networks of automatic weather stations, maps from meteorological radar, images from meteorological satellites, local and regional observations, and so on.	A fundamental prerequisite for NC is operational continuity, and the availability of an efficient broadcasting system (e.g., very intense showers affecting a given territory) must be followed with continuity in provision of information for final users.	Typical time resolution is 1 hour; typical space resolution is in the gamma mesoscale range (20–2 km).
Very short-range forecast	VSRF	Description of weather variables for up to 12 hours	A relatively complete set of variables can be produced (see nowcasting).	Analysis techniques, extrapolation of trajectories, interpretation of forecast data and maps from NWP (LAM and GM), empirical models and methods derived from forecaster experience (rules of thumb). The basic information is represented by data from networks of automatic weather stations, maps from meteorological radar, images from meteorological satellites, NWP models, local and regional observations, and so on.	A fundamental prerequisite for VSRF is the availability of an efficient broadcasting system (e.g., frost information must be broadcast to farmers who can activate irrigation facilities or fires or other systems of protection).	Typical time resolution is 1–3 hours; typical space resolution is in the beta mesoscale range (200–20 km).
Short-range weather forecast ^a	SRF	Description of weather variables for more than 12 hours and up to 72 hours	A relatively complete set of variables can be produced (see nowcasting).	Interpretation of forecast data and maps from NWP (LAM and GM), empirical models, methods derived from forecaster experience (rules of thumb). The basic information is represented by data from networks of automatic weather stations, maps from meteorological radars, images from meteorological satellites, NWP models, local and regional observations, and so on).	In SRF the attention is centred on mesoscale features of different meteorological fields. SRF can be broadcast by a wide set of media (newspapers, radio, TV, Internet, and so forth) and can represent a fundamental piece of information for farmers.	Typical time resolution is 6 hours; typical space resolution is in the alpha or beta mesoscale range (2 000–20 km).

Type of weather forecast	Acronym	Definition	Characteristics of output	Dominant technology	Other aspects	Time and space resolution of typical products
Medium-range weather forecast ^a	MRF	A relatively complete set of variables can be produced (see nowcasting).		Interpretation of forecast data and maps from NWP (GM), empirical models derived from forecaster experience (rules of thumb). NWP models represent the basic information. Techniques of “ensemble forecasting” are adopted in order to overcome the problem of depletion of skill typical of forecasts based on NWP models. Instead of using just one model run, many runs with slightly different initial conditions are made. An average, or “ensemble mean”, of the different forecasts is created. This ensemble mean will likely have more skill because it averages over the many possible initial states and essentially smoothes the chaotic nature of climate. In addition, it is possible to forecast probabilities of different conditions.	In MRF the attention is centred on synoptic features of different meteorological fields. MRF can be broadcast by a wide set of media (newspapers, radio, TV, Internet, and so on) and can represent a fundamental piece of information for farmers.	Typical time resolution is 12–24 hours; typical space resolution is in the alpha mesoscale range (2 000–200 km).
Long-range forecast	LRF	From 12–30 days up to two years	Forecast is usually restricted to some fundamental variables (temperature and precipitation); other variables, such as wind, relative humidity and soil moisture, are sometimes presented. Information can be expressed in absolute values or in terms of anomaly.	Statistical (for example, teleconnections) and NWP methods. Coupling of atmospheric models with ocean general circulation models is sometimes adopted in order to enhance the quality of long-range predictions.	An extended-range weather forecast (ERF), beyond 10 days and up to 30 days, is sometimes considered.	Typical time resolution is 1 month; typical space resolution is in the beta macroscale range (10 000–2 000 km).

^a It has been observed recently that SRF and MRF are converging towards a unique kind of forecast, because numerical weather prediction (NWP) models are the basis for both SRF and MRF. It might be more correct to distinguish between forecasts based on global models (GM) and limited area models (LAM), which range from now to $h + 72$ h, and forecasts based only on GM, which range from $h + 72$ h to $h + 7–15$ days.

Table 5.2. Accuracy, usefulness and main limitations of weather forecasts for agriculture

<i>Type of weather forecast</i>	<i>Accuracy^a</i>	<i>Usefulness</i>		<i>Main limitations</i>
		<i>Real</i>	<i>Potential</i>	
Nowcasting	Very high	Very low	Low	Unsuitability of broadcasting system; insufficient flexibility of agricultural technology
Very short-range forecast	Very high	Low	Moderate	Unsuitability of broadcasting system; insufficient flexibility of agricultural technology; farmers do not know how to make the most use of available forecasts
Short-range weather forecast	High	Moderate	High	Further adaptation of forecasts to farmers' requirements is needed; farmers do not know how to make the most use of available forecasts
Medium-range weather forecast	High or moderate until 5 days; lower thereafter	High	Very high	Further adaptation of forecasts to farmers' requirements is needed; farmers do not know how to make the most use of available forecasts
Long-range forecast	Very low	High in warning of delays in arrival of weather systems. Very low otherwise	Poor	Reliability (The reliability of LRF is higher for the tropics than for mid-latitudes. This is because tropical areas have a moderate amount of predictable signal, whereas in the mid-latitudes random weather fluctuations are usually larger than the predictable component of the weather.)

^a Subjective judgement of a weather forecaster working at mid-latitudes. The judgement refers to cloud coverage, air temperature and precipitation occurrence.

The weather requirements for each rice farming operation in the humid tropics are given in Table 5.3.

5.3.2 Format of forecasts

Formats of forecasts for agriculture vary widely in different agricultural contexts due to the high degree of variability among users, crops, agro-techniques, and so on. Specialized forecasts can be tailored for crops, animal husbandry, forestry, fisheries and horticulture. Forecasts by nature have a technical slant. Nonetheless, forecasts need to be couched in a language that is as simple as possible so that farmers are able to readily grasp their content. Therefore, "intermediaries" (employed by the National Meteorological Services and/or the extension wing of agricultural services) must be provided for, as a vital link between the forecasters (and their products) and the farmers, to explain

how forecasts are to be used as agrometeorological services for field operations.

A forecast produced for educational purposes and released weekly by the University of Milan, Italy, is presented in the Annex to this chapter. This product is composed of three main parts:

- A general evolution;
- A forecast for seven days (cloud coverage, precipitation, wind, air temperature and other phenomena, such as foehn, frost, and so forth);
- A forecast of water balance, net primary production and growing degree-days.

5.3.3 Forecasts for agricultural purposes

In order to arrive at forecasts geared toward agricultural users as detailed above, the forecasts that are initially framed need to be modified/processed. A

Table 5.3. Summary of weather requirements for each rice farming operation in the humid tropics

<i>Farming operation</i>	<i>Sky condition during farming operation</i>	<i>Soil (moisture) condition</i>	<i>Leaf wetness duration</i>	<i>Air temperature (°C)</i>	<i>Wind speed (km/h) during farming operation</i>
1. Land preparation (Hand hoeing/plowing/ harrowing/rotavating of lowland farms)	Clear or cloudy day desirable	Moist or wet	Not applicable	≤40 desired ≥15 desired	≤50 for comfort of workers
2. Seeding in seedbed or field, A ₁ dry seeds A ₂ pre-germinated	Clear or cloudy	A ₁ moist, A ₂ wet	Not applicable	<33 desired ≥15 desired	<20 desired to minimize evaporation
3. Transplanting seedlings	Clear or cloudy day	Wet	Not critical	≤40 desired ≥15 desired	0–30 for comfort of workers
4. Hand weeding/cultivating (upland farms)	Clear to partly cloudy day	Moist or dry	Not critical	≤40 desired ≥15 desired	≤50 during operation
5. Irrigation	Clear or cloudy day	Moist or dry	Not critical	Not critical ≥15 desired	Not critical
6. Spraying Pesticide or foliar fertilizer B ₁ ground application B ₂ aircraft application	Clear day desired; partly cloudy day and/ or night acceptable. (Visibility should be adequate for low-level flight of aircraft)	B ₁ Moist or dry desired for dry application in upland farms B ₂ Not critical for lowland rice farms or aircraft application	Leaves should be dry at spraying time; no rain until at least 4 h after spraying	<33 desired ≥15 desired	B ₁ 0–18 (for ground application) B ₂ 4–14 (for aircraft application)
7. Threshing/sun-drying/ cleaning grain	Clear to partly cloudy for threshing and cleaning grains; clear for sun-drying	Dry surface for operation	Not applicable	No upper limit ≥15 desired	≤25 during grain cleaning operation

more specific description of the processing of weather forecasts of single weather variables for agricultural purposes is presented below.

5.3.3.1 Sky coverage

Forecast of sky coverage can be defined by adopting some standard classes, such as sky clear (0–2 octas), partly cloudy (3–5 octas), mostly cloudy (6–7 octas) and overcast (8/8). It is also important to give information about the character of prevailing clouds. For example, high clouds produce a depletion of global solar radiation quite different from that produced by mid- or low clouds. It is important to give an idea of the expected variability of sky coverage in space and time as well. A probabilistic approach may also be adopted in order to increase the usefulness of this kind of information.

5.3.3.2 Bright sunshine

Sun shining though clouds will not affect crop performance, because in this case the reduction will be in diffuse radiation from the sunlit sky and the latter is only a fraction of total global solar radiation. So in cloud cover forecasts the fraction of cloud covering the sun should also be specified in addition to the total cloud cover.

5.3.3.3 Solar radiation

The main parameters, extraterrestrial radiation (R_a) and possible sunlight hours (N), required to derive solar radiation (R_s) from bright hours of sunshine (n) are readily available on a weekly basis for any location and period (Venkataraman, 2002). The relationship between the ratio of R_s/R_a and n/N is a straight-line type. The value of the constants, however, varies with seasons and locations but can readily be determined.

5.3.3.4 Precipitation

Snow and rainfall are probably two of the most difficult forecast variables. Quantitative forecasting of rainfall, especially of heavy downpours, is

extremely difficult and realizable only in rare instances and using highly sophisticated Doppler radars. For crop operations, however, the quantitative forecasting of rain is not half as important as the forecasting of non-occurrence of rains (dry spells) and the type of rain spell that can be expected.

Forecasts of rain can be defined by adopting some standard classes (Table 5.4) based on the climate and the agricultural context of the selected area. A probabilistic approach (Table 5.4) is quite important in order to maximize the usefulness of this forecast.

Adopting the scheme shown in Table 5.4, it is possible to produce daily information like this:

- (a) Mostly cloudy or overcast with rainfall (Class 3, high probability);
- (b) Partly cloudy with rainfall unlikely (Class 2, very low probability);
- (c) Sky clear with absence of precipitation.

Use of the same terms as in Table 5.4 to qualify the likelihood of occurrence of rainfall and rainfall amounts will confuse the public. It is better to use different terms for the two purposes. Thus, for forecasts on the chances of occurrence of rain, plain language such as “nil”, “very low”, “low”, “high” and “very high chance” should be used. If quantity can also be forecast, plain language terms such as scanty = <1 mm, moderate = 1–10 mm, heavy = 10–50 mm and very heavy = >50 mm should be used. The probability of occurrence of a given quantity of rainfall will vary with places and periods. So if probability is to be indicated for quantum of rain it should be based on climatological values of assured amounts of rainfall at various probability percentages in the area(s) and the period to which the forecast refers.

Fog can contribute significantly to crop water needs and can be measured by covering the funnel of a rain gauge with a set of fine wires. Quantitative data on fog precipitation may not be available. Nomograms for predicting the occurrence of fog at airports are available with forecasters, however, and

Table 5.4. Rainfall classes for a period of 24 hours

Quantity: Class 1: <1 mm (absent); Class 2: 1–10 mm (low); Class 3: 10–50 mm (abundant); Class 4: >50 mm (extreme)

Probability per the defined class of quantity: <1% = very low; 1–30% = low; 30–70% = moderate; >70% = high

The classes presented cover a European area (the Po Plain, northern Italy) and can be quite different for other areas.

these can be adopted for use in agricultural weather forecasts.

Dew is an important parameter influencing leaf wetness duration and it therefore plays a role in facilitating entrance of disease spores into crop tissues. Dew is beneficial in contributing to water needs of crops in winter and in helping the survival of crops during periods of soil moisture stress, as the quantum of dew collected per unit area of crop surface is many times more than that recorded with dew gauges. Dew is also desirable for using pesticides and fungicides in form of dust. The meteorological conditions required for dew formation are the same as those for fog formation, except that there needs to be an absence of air turbulence in the air layers close to the ground and the crop canopy temperature must be lower than the screen temperatures. Thus, nomograms used by forecasters for predicting fog can be used to predict dew, in the absence of low-level air turbulence, by factoring into the temperature criteria the expected depression of crop minimum temperatures below the screen minimum.

5.3.3.5 Temperature

Forecasting of air temperature is important for many agrometeorological applications. Forecasts of the temperature of soil, water, crop canopies or specific plant organs are also important in some specific cases. Crop species exhibit the phenomenon of thermoperiodicity, which is the differential response of crop species to daytime, nocturnal and mean air temperatures (for example, Solanaceae to night temperatures, Papilionaceae to daytime temperatures and Graminaceae to mean air temperatures). It is possible to derive mean day and night-time temperatures from maximum and minimum temperature data.

Forecasts of temperature are generally expressed as a range of expected values (for example, 32°C–36°C for maximum and 22°C–24°C for minimum). If the forecast is directed at mountainous territories, temperature ranges could be defined for different altitudinal belts, taking into account also the effects of aspect. Special care could be reserved for temperature forecasts at particular times of the agricultural cycle, taking into account the values of cardinal and critical temperatures for reference crops.

Other thermal variables with a specific physiological meaning (for example, accumulation of thermal units or chill units) can be the subject of specific forecasts. The base temperature above which the accumulations will apply, however, varies with crop types (for example, wheat, maize and rice: 4.5°C,

10°C and 8°C, respectively). Therefore, for forecasting the dates of attainment of specific phenological stages of crops, time series data showing actually realized heat or chill accumulations by various crops up to the time that forecasts are issued have to be maintained. A probabilistic approach can then be adopted to forecast the probable dates that specific crops will reach particular phenological stages.

5.3.3.6 Humidity

For the day as a whole, dewpoint temperature is a conservative parameter and is easier to forecast, as changes in dewpoint temperatures are associated with the onset of fresh weather systems. From maximum, minimum and dewpoint temperatures, minimum, maximum and average humidities can be derived. Users tend to understand the implications of the term “relative humidity” much better than other measures of air moisture content, such as vapour pressure and precipitable water. So the ultimate forecast has to be expressed in terms of relative humidity. Forecasting of relative humidity can be important in some specific cases. Probability of critical values (very high or very low) can also be important.

5.3.3.7 Wind speed and direction

Forecasting of wind speed is important for many different agricultural activities. Wind direction can be defined as well. It is important to give an idea of the expected variability in speed and direction of wind. The monthly windrose at a station is a climatological presentation that indicates the frequency of occurrence of wind from each of the eight accepted points of the compass and frequencies of occurrence of defined wind speed ranges in each of the eight directions. Wherever possible, the windroses must be looked at before forecasts are issued.

For agricultural purposes, wind speed and direction are required at a height of 2 m. But weather forecasts of wind refer to heights greater than 2 m. Change in wind direction between 2 m and the forecast height will not occur. Wind speed at 2 m will be considerably lower than at the forecast height, however. Ready tables to convert wind speeds at any height to the speed at 2 m are available and may be used to forecast wind at a height of 2 m.

The term kilometres per hour, km/h, is much better understood by user interests than the terms Beaufort scale, metres per second, MpS or knots. So wind speeds must be forecast in km/h for a height of 2 m.

5.3.3.8 Leaf wetness

Leaf wetness is produced by rainfall, dew or fog. Duration of this phenomenon can be important in order to plan different activities, such as the application of pesticides and harvesting of crops. Leaf wetness is a parameter that is scarcely recorded. A number of empirical methods cited by Matra et al. (2005) have been used to derive leaf wetness durations from meteorological parameters. It is possible to derive the hourly march of temperatures from maximum and minimum temperatures (Venkataraman, 2002). The temperatures during night hours have to be decreased by a value equal to the depression of the radiation minimum below the screen minimum. As mentioned earlier, dewpoint temperature is a conservative parameter. Thus, the number of hours during which dewpoint temperature is above the adjusted air temperature will give leaf wetness duration. The time taken for the moisture deposited on the crop leaves to evaporate also has to be included in the leaf wetness duration. The amount of moisture deposited on the crop may be many times more than that indicated by instruments. So the estimated moisture deposition has to be multiplied by a crop factor and the product divided by the evaporative power of the morning air. As a rule of thumb, two hours after sunrise may be added to the estimated duration of leaf wetness.

5.3.3.9 Evapotranspiration

Forecast of evapotranspiration can be important to improve knowledge of the water status of crops. This kind of forecast is founded on the correct forecast of solar radiation, temperature, relative humidity and wind speed. For real-time use, forecast of evapotranspiration has to be founded on a forecast of pan evaporation, as discussed below.

The evaporative power of air (EPA) determines the peak water needs of vegetative crops and is the datum to which all measurements of evapotranspiration (ET) should relate. The Food and Agriculture Organization of the United Nations (FAO, 1998) has advocated the use of reference evapotranspiration ET_0 as a standard measure of EPA. Computation of ET_0 requires data on net radiation over a green crop canopy, low-level wind and saturation deficit of air. An empirical method to compute ET_0 from routinely available meteorological data has been proposed. ET_0 refers to turf grass. Agricultural crops have peak water needs greater than those of turf grass, while tall crops may have peak water needs that are higher than those of short crops. Data to compute ET_0 on an operational basis are neither widely nor readily available.

Evaporation from pans filled with water (EP) is subject to weather action in a manner similar to that of EPA. EP is also easily measured. Venkataraman et al. (1984) have detailed methodologies to compute ET_0 using measured values of solar and atmospheric radiation; they have also described using these values to derive ratios of ET_0 to EP at a number of stations covering typical climate regimes. The use of pan coefficients to derive ET_0 under varied surroundings and typical settings for the pans have been suggested in the literature (FAO, 1998). Data on EP and studies relating ET of crops to EP are available. The ratio of peak ET to EP, called relative evapotranspiration (RET), can vary in space and time, but is not difficult to determine.

5.3.3.10 Water balance

A quantitative forecast of the probability of water excess or stress for rainfed crops, and of the timing and amount of irrigation for irrigated crops, is highly useful. This kind of forecast for rainfed crops is based on correct forecasting of precipitation and evapotranspiration. The water balance approach to arrive at soil moisture excess or deficiency would require daily forecasts of rain in the first month of crop growth and on a short-period basis thereafter. Influence of physiological control on crop water uptake during maturity (Hattendorf et al., 1988; Venkataraman, 1995) is also important. Since irrigation water is applied ahead of crop water consumption for forecasts of irrigation scheduling, forecasts of evapotranspiration and likely rainfall amounts on a short-period basis will do.

5.3.3.11 Extreme events

The low level of predictability of extreme events acting at meso- or microscale (frost, thunderstorms, hail, tornadoes, and so forth) is an important limitation to the usefulness of forecasts for agriculture. Table 5.5, obtained from a subjective evaluation founded on state-of-the-art forecast technologies, illustrates the level of predictability of some extreme events with strong effects on agriculture. In order to give correct information to farmers, the adoption of a probabilistic approach could be important.

5.4 SPECIAL AGRICULTURAL WEATHER FORECASTS

Special agricultural weather forecasts provide the necessary meteorological information to aid farmers in making certain special "crop- and/or cost-saving"

Table 5.5. Predictability of some extreme events relevant for agriculture (data are estimated for European area)

<i>Extreme event</i>	<i>Predictability</i>			
	NC	VSRF	SRF	MRF
Frost	high	high	low	low
Thunderstorms	high	moderate	low	low
Showers	high	moderate	low	low
Hail	low	very low	un	un
Tornadoes	very low	un	un	un
Wind gales	high	high	moderate	low

very low: <1%; low: 1–30%; moderate: 30–70%; high: >70%; un = unpredictable (forecast cannot be produced with present technologies)

decisions regarding farm operations. For the same temporal distribution of weather parameters, different crops will react differently. Again, the effects of weather or weather-induced stresses and incidence of pests and diseases are critically dependent on the state and stage of crops during which these phenomena occur. The effects of anomalies of a weather element on a given crop are location-specific. Again, the crop fetches may range from large monocultural areas to small, dispersed areas of various crops. Thus, the requirement for these special forecasts will vary among and within the seasons, from place to place, from crop to crop, and with the kind of operation, namely, cultivation, post-harvest processing, and so on.

Special forecasts are normally issued once every day for a specific operation and generally cover the next 12–24 hours, with a further outlook if necessary. These special weather forecasts must be written by a trained agricultural meteorologist in consultation with farm management specialists for the current problems. They are normally issued for planting, irrigation, applying agricultural chemicals, cultivation, harvest and post-harvest processing, and they may also address other weather-related agricultural problems associated with the crop, its stage and location. Temperature bulletins for protection against freezing are also issued as special forecasts in areas where crops may suffer damage from freezing.

5.4.1 Field preparation

Field preparation for rainfed crops is weather-dependent. In any dryland areas the amount of rainfall is very meagre and farmers should take

advantage of even minimum showers. Otherwise the moisture is lost. Minimal tillage is the current agronomic mantra for conserving moisture, retaining nutrients and keeping weeds out. An optimum soil moisture profile characterized by top dry soil, sub-surface moist soil and wet soil in the seeding zone is required to carry out field preparation for dryland farming. The prediction of the exact time of occurrence of rainfall in a particular location helps to initiate field preparation. An example of this is: “Pre-monsoon showers are expected in the 37th standard week of this year and farmers are requested to initiate field preparation activities before this week”.

5.4.2 Sowing/planting

Seed germination is dependent upon proper light and moisture, as well as soil temperature. Even with no nutritional or soil moisture constraints, rot foraging capacities vary among crops in the same soil and within the same crop in different soils. Alternating temperatures assist the germination of many species of seeds and do not unfavourably affect the germination of those that do well under constant temperatures. The amplitude, which is the difference between maximum and minimum temperatures, decreases with depth and becomes negligible at a depth of 30 cm. Hence soil temperatures at 30 cm can be taken as constant. The temperature range at which soil temperatures will equal the air temperature will principally depend on the texture and structure of soil. Under a ground-shading crop, the depth of no diurnal change is pushed up compared to that seen under bare soil.

For germination and crop establishment, the soil temperature regime at a depth of 7.5 to 10.0 cm is of importance. At these depths the maximum and minimum soil temperatures tend to follow the maximum and minimum screen temperatures.

Thus, the diurnal variations in soil temperatures in the seed zone are beneficial and not harmful. Some species of seeds are light-sensitive, however, and for them the depth of sowing and adequacy of soil moisture at the desired depth are critical. In dryland agriculture, gap-filling to correct for poor germination is often not possible. Excess germination can be corrected by thinning and the dryland farmer would prefer very good germination followed by thinning, if necessary. The farmer must, therefore, know the existing soil temperature and what the changes in soil temperature and moisture will be. Of the above two parameters, soil moisture is more important. The rooting pattern also varies from crop to crop. Further, for many crop seeds, light is necessary to initiate germination. Knowledge of the likely values of these two parameters will help farmers avoid sowing under soil conditions that would lead to a poor initial crop stand, correction of which is often not possible and if possible may hinder germination and emergence, and which consequently would require the resowing of expensive seeds.

When direct planting is resorted to, the prevailing weather conditions dominate the crop stand and establishment. Agronomic measures to modify soil temperatures and conserve seed zone moisture to ensure proper germination in marginally adverse weather conditions are possible. From maximum and minimum values of surface soil temperature or air temperature it is possible to arrive at temperature amplitudes for a given depth of soil in a given type of soil. Thus, parameters that are of interest, namely temperature below and above soil surface, atmospheric humidity and soil moisture, need to be forecast.

Soil temperature forecasts are normally issued once daily prior to and during the normal planting season. They should give the present observed conditions throughout the area with a forecast of changes during the succeeding three days, since most of the crops need one life irrigation for the emerging plumule/radicle to protrude above the soil surface when seeds are sown. An example of this type of forecast is: "Bright sunshine during the next three days will cause soil temperatures to rise sharply. Soil temperatures at normal seeding depths are expected to reach and maintain levels favourable for cotton and groundnut seed germination by

early next week. Further, atmospheric temperature will be very high for the next few days, which may affect establishment of seedlings to be planted."

5.4.3 **Application of agricultural chemicals**

Use of agricultural chemicals is inevitable in crop production. Overuse of agrochemicals such as fungicides and pesticides, however, especially the systemic types and inorganic nitrogenous fertilizers, leads to contamination of food produce and soil; pollution of air, aquifers and water reservoirs; and development of chemoresistant strains of pests, diseases and weeds. Weather forecasts as detailed in the ensuing sections on control of insects, diseases and weeds can not only help minimize the volume of agrochemicals applied, but also make the applications more effective. Agrochemicals constitute a sizeable fraction of a farmer's total cash outlay in any given production system. Minimization of the use of agrochemicals will reduce a farmer's cultivation costs and help increase the acreage of assured protection and nutrition of crops, without consuming additional resources.

The critical weather elements governing judicious application for efficient utilization are atmospheric temperature, precipitation, soil moisture content during the past and succeeding 24 hours, and the speed and direction of winds, with an emphasis on any changes in speed or direction during the forecast period. Precipitation can dilute or wash off the chemicals. Agricultural chemicals that require special attention with regard to meteorological factors are herbicides, growth regulators, hormones, insecticides, fungicides and nutrients, as well as those used for soil fumigation and rodent control. Only an agricultural meteorologist well versed in current farm operations can be aware of the different chemicals in current use and their varying requirements.

5.4.3.1 **Foliar application**

Agrochemicals for application to soils have to be carefully chosen to avoid contamination of soil, leaching into groundwater aquifers, and runoff to water reservoirs. If the same effects can be achieved by aerial sprays, foliar application is to be preferred. Soil conditions often preclude application of chemicals to soils, and under these circumstances foliar application is the requisite technique. Temperatures at the time of application and immediately following are extremely important and can determine effectiveness of foliar application of nutrients and herbicides. For certain herbicides,

such as glyphosate, the effectiveness is enhanced if the atmospheric temperature is high at the time of application and the succeeding two to four hours. On the other hand, for foliar application of nutrients, atmospheric temperature should be lower in order to avoid phytotoxicity associated with soil moisture availability.

5.4.3.2 Soil application

Precipitation is the most important factor that determines the efficacy of chemicals applied through soil. Precipitation in the succeeding 24 hours is the critical parameter. Limiting the amount of treatment through the effective use of weather information also leads to minimum pollution of groundwater and runoff.

Examples of forecasts for application of agricultural chemicals are:

Wind speeds are expected to be mostly favourable for application of agricultural chemicals today and tomorrow. Wind direction will be variable and wind speed will range from 6 to 13 km/h in the forenoon and will become southerly with speeds of 13 to 24 km/h during the late afternoon. Temperatures are likely to exceed 27°C tomorrow. So caution should be exercised in applying oil-based sprays.

Heavy rain is expected in the next 24 hours, so foliar application of chemicals may be postponed.

5.4.4 Evaporation losses for irrigation

Irrigation water is costly to farmers in most agro-ecosystems today. Overuse can be both expensive and detrimental to the crop, while underuse can result in loss of crop quantity as well as quality. Estimates of daily consumptive use can be related to the free water loss from a Class A-type evaporation pan: the free water loss over the previous day for an area is obtained from the actual values recorded, while the loss for the succeeding 24 hours must be forecast based on the forecasts of rain, wind, relative humidity and bright hours of sunshine. For example, due to wetting of its surroundings by rain, the evaporation from a pan can be 20 to 30 per cent lower than with dry surroundings. Linear approximations have been derived for the estimation of solar radiation from bright hours of sunshine, potential evapotranspiration from either pan evaporation or from associated wind, and vapour pressure deficit terms. Consumptive use rate can be estimated not only from evaporation pan losses, but also from evaporation and shade temperature

measurements, or from formulae deduced from the energy balance equation. With these values, a farmer can be informed of the field water loss occurring after the last rain or irrigation and can also be advised on the timing and quantum of irrigation, taking into consideration the expected rainfall. In this connection, it is worth mentioning that Portugal was awarded the second prize in the International Society for Agricultural Meteorology (INSAM) contest of best examples of agrometeorological services (2004/2005) for assistance to farmers in arriving at a quantitative estimate of irrigation needs.

The following are examples of water-loss forecasts:

Free water loss during the past 24 hours averaged 0.6 cm. Expected free water loss is 0.6 cm today and 0.8 cm tomorrow. Rainfall probability will remain low for the remainder of the week and crops will begin to suffer from moisture stress in four days' time. Supplementary irrigation of 7 cm in two days' time is recommended.

Rain is likely to occur in the next 24 hours in most of the areas in this region and so farmers may postpone their irrigation for this period.

5.4.5 Weeding

Weeds are one of the most serious afflictions for farming and successful farming includes weed management. Because of climatic influences, the distribution of weed flora across regions and their composition within a region vary greatly. There is no broad-spectrum weedicide that is effective against all weeds and is at same time non-toxic to crop plants, which means that herbicide prescription is a specialized job. The indication is that overuse of herbicides for an extended period will lead to chemoresistance in weeds. So herbicide applications must be minimal but effective. There are two methods of weed management, that is, hand/mechanical weeding and chemical weeding. For certain herbicides, prevailing weather decides the effectiveness of the application, as in the case of non-selective herbicides. Rain immediately after chemical weeding will neutralize the operation's effects and will result in a waste of money. Rains will help in the germination of dormant weed seeds or may promote better growth expression of weeds. Thus, clear weather following rain will assist hand or mechanical weeding.

Examples of weeding forecasts are:

Rain is likely to occur in the next 24 hours in most of the areas in this region, so farmers may postpone application of chemical herbicides and hand/mechanical weeding operations.

Following the rain spell of the last three days, weather will remain dry for the rest of the week. Hand/mechanical weeding and chemical weeding in two to three days' time are recommended.

5.4.6 **Crop harvest and post-harvest operations (including crop curing and drying of meat and fish)**

The harvesting of agricultural produce and its immediate processing before storage assume vital importance, more so than any other field operations, because a few days of fickle weather at the end of the crop season can be ruinous. The forecast for such activities should be of high order to ensure that whatever yield can be saved on the field is saved and that what is gained on the field is not lost off it. While the general agricultural weather forecast should supply the meteorological information necessary for harvest operations, post-harvest operations such as curing and storage require special forecasts of certain elements. The primary weather factors for crop harvest are rainfall and atmospheric temperature, while for post-harvest operations, in addition to the above, sunshine, wind, relative humidity and dew are also important. Precipitation may increase the moisture content in the straw of rice crop, which may delay harvest operations. Low temperature may also cause a delay. Precipitation may leach the quality of forages. Basic post-harvest operations include simple drying, as in the case of medicinal plants. Light winds assist in the winnowing operations that separate grain from chaff. In the absence of wind, blowers have to be used. Low temperature in the atmosphere may delay drying of certain valuable medicinal compounds and result in their subsequent conversion into less desirable products. In crops like tobacco, this may entail complex processes involving enzymatic reactions that are influenced by humidity and temperature. It is worth mentioning here that in order to ensure high-quality end products either from crops or meat and fish, accurate weather forecasts for curing and related actions are essential.

The following is an example of a rice harvest forecast:

Rain is expected in the ensuing week. Accordingly, harvesting may be done earlier.

The following is an example of a tobacco curing forecast:

Good tobacco curing weather prevailed during the past 24 hours. Extremely dry weather today

and tomorrow will tend to cause excessively rapid drying of tobacco. Shed should be partly closed to slow the drying.

And finally, the following is an example of a meat drying forecast:

Maximum temperature is expected to be around 30°C in the next three days. Farmers should take advantage of this period for meat and fish drying.

5.4.7 **Control of plant diseases**

Most plant diseases set in under conditions of wet vegetation and develop and spread when the wet weather clears. The rate of development of a disease depends on temperature. The cardinal and optimal temperatures for development vary with the disease organisms. Therefore, effective and economical control of most diseases primarily requires a vegetative wetting forecast. This forecast will include the number of hours during which vegetation was wet from rain, fog or dew during the preceding 24 hours; the temperatures during this period; and a prediction of the hours of wetting and of the temperature and sky conditions during the succeeding 24 hours. Armed with this information, a farmer should be able to obtain maximum control with a minimum number of chemical applications.

The computer has enabled pathologists and physiologists to generate biological models that describe the development of disease pathogens in plants. By introducing meteorological data, either daily or hourly, into these models, conditions favourable to disease development and the potential severity of outbreaks can be estimated for many diseases, such as leaf blight and stalk rot of corn.

The following is an example of a root disease forecast:

Excess moisture prevailing in the root zone of vegetable crops in the past seven days may promote root diseases such as root rot and the like. Farmers are advised to carry out soil drenching with suitable fungicides to avoid heavy crop loss.

5.4.8 **Control of noxious insects**

Within broad limits, weather is one of the principal factors controlling insect occurrence and governing the general distribution and numbers of insects. Weather factors, acting in combination, can either foster or suppress insect life; for example, temperature and humidity control the time interval between successive generations of insects, as well as the

number produced in each generation. Feeding habits are also controlled by weather and climate. Large-scale, low-level wind patterns are an important factor in the migration of insect pests. With regard to insecticides used to control pests, weather controls not only the insects' susceptibility, but also the effectiveness of the pesticides.

Insect and plant biological computer modelling, using meteorological and insect light-trap data as input, is helping to determine the time and severity of economically damaging outbreaks of the corn borer and alfalfa weevil. Biometeorological models have been developed for the emergence of adult mosquitoes and the periodicities of their flight activities leading to displacement from breeding sources and infestation of urban and agricultural areas. These models demonstrate the importance and practical use of weather and climatological data to determine strategy, tactics and logistics in programmes to monitor and control pests and their vectors. The seasonal abundance and date of emergence of mosquitoes following first flooding of eggs are predicted from cumulative variation from normal of air temperature and solar radiation. Flight activity and dispersal of flies from breeding sites to infest agricultural and urban areas are predicted from 24-hour projections of temperature, humidity and wind conditions that provide optimum hygrothermal environments for energy metabolism. The projections for optimum flight periods from daily synoptic weather forecasts facilitate the detection of invasions of pest and disease vectors and also the timing of pesticide applications to intercept and eliminate pest infestations during displacement from breeding areas.

The following is an example of a mosquito control forecast:

The incessant rains and floods may act as breeding grounds for mosquitoes. The municipal authorities are advised to spray suitable chemicals in the water bodies to avoid mosquito-borne diseases. Farmers are also advised to drain water from stagnant areas.

The following is an example of a rice hopper forecast:

The low temperature prevailing for the past 15 days and incessant rains may encourage development and infestation of rice hoppers. Farmers are advised to take suitable prophylactic spray measures.

5.4.9 **Transport of agricultural products**

Most agricultural products must be transported a fairly long distance from the place of production

to the marketplace. During transport, the temperatures of many varieties of produce must be held within very narrow limits to prevent deterioration and spoilage. Therefore, the heating and cooling of containers transporting them may be required. An accurate forecast of the maximum and minimum temperatures along the normal transport route is needed to plan the type of transport equipment and its utilization. Temperature forecasts may be given for areas for which they are not normally supplied, such as high, cold mountain passes, or hot, dry desert areas. A short weather synopsis for the period would also be valuable.

Transportation and commodity-handling agencies have expressed the need for climatological and meteorological information to improve decision-making in their logistics. For example, a series of snowstorms during the period of 28 January–4 February 1977 in southern Ontario severely disrupted the provincial milk collection system. The effects of these storms were manifold; not only was the schedule of the milk collection trucks disrupted, with serious losses resulting to the milk producers, but the trucking equipment sustained serious damage and the life of one driver was lost during a blinding snowstorm in a railway-crossing accident. The system handling a perishable commodity like milk depends on intricate scheduling geared to the farmers' storage capacity, in this case 2.5 days of milk production. Therefore, the collection trucks have to come every second day. In the case of Ontario, delays of three to four days resulted and the farmers, who often obtain 450 kg per milking and have no room to store the milk, were forced to pour it out, causing a considerable loss. The transportation system incurred a setback in the form of equipment loss and damage, overtime pay for extra hours worked and even injury and the death of one driver.

The following is an example of a forecast for the transport of onions:

The low temperature prevailing in the past 7 days may lead to deterioration in the quality of harvested onion for transport through germination. Farmers are advised to make the necessary packaging arrangements to counteract the low temperature.

5.4.10 **Operation of agricultural aviation**

Aircraft are used for a wide variety of operations in agriculture and forestry. Because they operate at low altitudes, much below those of regular

transport aircraft, they require specific details not available in routine aviation forecasts, which usually include ceiling, visibilities and turbulence. For example, to achieve successful results, low-level (surface to 30 m) wind drift and stability factors are needed, while the strength of the surface inversion is extremely important if ultra-low volume sprays (where particle size may be as small as 10 μm) are to be used. Vertical motions of more than 0.5 cm s^{-1} will cause such spray droplets to rise and disperse throughout the atmosphere rather than settle on the crop.

The following is an example of a dusting and sprinkler irrigation forecast:

Heavy winds are expected at a speed of 60 km/h today. Farmers are advised to avoid dusting operations as well as operation of sprinkler irrigation systems.

5.4.11 **Prevention of damage due to chilling, frost and freezing**

The minimum temperature forecast is an integral part of farming in hilly and subtropical/humid regions. These regions need a special minimum forecast system particularly during the cropping season. This critical information will aid farmers in the judicious allocation of their resources, such as labour and other agricultural inputs, so as to avoid crop losses. The forecast should include the minimum temperature expected in the next 24 hours. This may be station-specific or for a particular region as a whole. As long a lead time as possible is extremely important for some crops, such as citrus and apple.

The following is an example of a frost damage forecast:

Ground frosting is expected in the ensuing three days in certain parts of the northern localities and may damage grain crops. Suitable precautionary measures must be taken to avoid crop damage.

An example of a special minimum temperature bulletin follows:

A strong cold front moved through the agricultural districts late yesterday and very cold and dry air now covers the entire area. Temperatures are expected to drop sharply tonight from near 10°C at sunset to below 0°C by 0100. By sunrise minimum temperatures are expected to range from -7°C to -4°C in the coldest low-lying areas and from -4°C to 2°C in the higher locations. Minimum temperatures forecast for key stations tonight are as follows:

Key station

A: -4°C

B: -6°C

C: -7°C

D: -4°C

E: -3°C

F: -4°C

G: -5°C

Growers should relate their locations to the nearest key stations. Outlook for tomorrow night: continuing very cold with minimum temperatures generally -5°C to -2°C.

5.4.12 **Forestry operations**

From the selection of sites for afforestation to planning the harvesting of forest products, weather forecasts are of major importance to foresters. In many afforestation programmes, seeds of forest trees are sown from aircraft. Under these circumstances, precipitation plays a significant role in the germination and growth of the plant stands. When saplings are planted, precipitation plays a key role in their establishment. In addition to precipitation, the prevailing microclimate also helps to determine stand establishment. A forester can easily manipulate the microclimate through artificial mulching and other methods.

Fire is one of the greatest problems of forest management. The moisture content of inflammable parts of forest trees derived from measurements of physical atmospheric parameters is used to determine when fire danger alerts should be issued in some countries. Direct relationships exist between weather and potential fire danger and fire behaviour. Day-to-day reports and forecasts of temperature, relative humidity, wind, precipitation, thunderstorms and critical moisture content of inflammable parts are needed. Fire danger forecasts determine whether logging operations should continue and whether parks and forests should remain open for recreational purposes. The special forecasts should alert forestry personnel to the danger that fires will start (as a result of either human activity or lightning) and the potential rate of spreading, once started. Fire advisories are continuously issued on site to assist in controlling and stopping fires.

5.4.13 **Fishery operations**

Weather and climate affect fisheries more than any other category of food production. Weather affects the safety and comfort of fishermen, as most of the fishing occurs when fish are sufficiently aggregated. Cyclonic storms affect the safety of the fishing vessel,

especially when the wavelength approaches the ship's length. Short-term weather forecasts can be crucial for planning fishery operations. Information on the intensity and tracks of cyclonic storms is immensely useful for the safety of fishermen operating in the oceans. Fog is another weather element affecting fishing and safety. Weather also affects fish behaviour, aggregation, dispersal and migrations. For their part, wind, currents, light and temperature, and also lunar periodicity, affect the behaviour of fish as well as other aquatic life (Cushing, 1982).

The growth of individual fish is closely linked to the temperature of the water. Temperature not only influences the distribution and movement of fish, but also subtly affects many important biological processes, such as the number of eggs laid, incubation time, survival of the young, growth rate, feeding rate, time it takes to reach maturity and a host of other physiological processes. Other climatic factors, such as the degree of insolation, are influenced by cloud cover, while climate-dependent environmental variables, such as changes in water quality and quantity, are associated with rainfall (Boyd and Tucker, 1998). These factors can act as physiological stimuli, particularly for the timing of the onset of reproduction (Lajus, 2005). For marine fisheries, slight changes in environmental variables such as temperature, salinity, wind speed and direction, ocean currents, strength of upwelling, and predators can sharply alter the abundance of the fish population (Glantz and Feingold, 1992).

Productive aquaculture sites need good water flow to remove solid and dissolved wastes and to maintain high oxygen levels in the cages. Any increase in the frequency or severity of storms as a result of climate change could be devastating for aquaculture operations (see also Chapter 13 of this Guide).

Most riverine fish populations depend on the flood plains associated with the river for feeding and breeding during the wet season. The catch of fish in the flood zones has been directly correlated with the intensity of floods in previous years: higher floods in one year result in better catches a year or two later. The response of fish to flood conditions is not only dependent on the quantity of the flood, but also on the form of the flood curve and its time.

Although some of its effects may be beneficial, El Niño may also have a strong detrimental influence on the fisheries and marine ecosystem. Increased frequency of El Niño events, which is likely in the warmer atmosphere, could lead to measurable declines in plankton biomass and fish larvae abundance in coastal waters of South and

South-East Asia. The area off western South America is one of the major upwelling regions of the world, producing 12 to 20 per cent of the world's total fish landings (IPCC, 2001). In such upwelling regions, nutrient-rich deep waters are brought to the illuminated surface layers (upwelled), where they are available to support photosynthesis and thus large fish populations (for example, Kapetsky, 2000).

With the advent of remote-sensing methods, fisheries can be studied using satellite and aircraft data. One of the important parameters that can be measured with sufficient accuracy is the sea surface temperature (SST), which has been related to the concentration of fish population. Anomalies in the water temperatures of major oceanic currents have resulted in low commercial fish catches in recent years. There have been declines, for example, in the sardine catch in the Sea of Japan associated with changing patterns of the Kuroshio Current in El Niño–Southern Oscillation (ENSO) years (Yoshino, 1998). Here it has been shown how sea surface temperature can be mapped on a regular basis and passed on to the fishermen, who could concentrate on high potential areas and improve the catch.

SST derived from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite serves as a very useful indicator of prevailing and changing environmental conditions and is one of the important parameters that determines suitable environmental conditions for fish aggregation. SST images obtained from satellite imagery over three or four days are combined and the minimum and maximum temperatures are noted. These values are processed to obtain maximum contrast of the thermal information. The process involves filming to prepare relative thermal gradient images. From these images, features such as thermal boundaries, relative temperature gradients to a level of 1°C, level contour zones, eddies and upwelling zones are identified. These features are transferred using optical instruments to corresponding sectors of the coastal maps prepared with the help of naval hydrograph charts. Later, the location of the potential fishing zone (PFZ) with reference to a particular fishing centre is drawn by identifying the nearest point of the thermal feature to that fishing centre. The information extracted consists of distance in kilometres, depth (for position fixing) in metres and bearing in degrees with reference to the north for a particular fishing centre. The PFZ maps thus prepared are sent to the fishermen for their use through facsimile transmission (fax) or by another mode of communication (WMO, 2004b).

5.4.14 **Safeguarding animal husbandry**

It is well documented that the stress of adverse environments lowers productive and reproductive efficiency in farm animals. Hot or cold weather can adversely affect the performance of livestock by exceeding their coping capabilities. The impact of hot environments can be severe, particularly for animals with high levels of productivity. Specific responses of an individual animal are influenced by many factors, both internal and external. Growth, milk, eggs, wool, reproduction, feed conversion, energetics and mortality have traditionally served as integrative performance measures of response to environmental factors.

Temperature-dependent performance response functions have been developed for growing beef cattle, swine, broilers and turkeys; for conception rate and milk production of dairy cows; and for egg production of hens (Hahn, 1994).

5.4.14.1 **Housing and production**

Behavioural responses to the environment may suggest alterations of management for animals subjected to specific conditions and may be useful in controlling the thermal environment. Other mitigating factors include physical characteristics of the surroundings (for example, flooring materials) and behaviours permitted by the production system (for example, animals huddling in cold conditions or moving to another microclimate, such as that provided by hovers).

Bruce (1981) estimated that the lower critical temperature for grouped nursery pigs on a solid concrete floor is 2°C higher than on a perforated metal floor and 5°C higher than on a straw-bedded floor. His evaluation also estimated that lower critical temperature for pigs penned singly is about 6°C higher than for grouped pigs, the difference being the huddling effect. A lower practical temperature limit of 3°C is suggested by the Comité International du Génie Rural (CIGR, 1984) for housed livestock to avoid freezing of waterlines and other management problems. Table 5.6 depicts the air temperature recommended for housing different kinds of livestock from various climate zones of the world to avoid adverse weather periods.

An instructive example is in South Africa, where du Preez and colleagues (du Preez et al., 1990a, 1990b, 1990c) have been mapping the monthly national temperature-humidity index (THI) values from 563 weather bureau stations covering the whole country as an aid to the optimum provision of livestock management. They found that the heat stress areas

expanded from August to January and contracted during the remainder of the year. There is a risk of moderate to advanced heat stress for dairy cattle during the period November to March. Their advice, based on THI values, is shown in Table 5.7. Given an adequate volume of meteorological data, the probabilities for different THI values can be calculated for the various seasons and thus their potential impact on production can be considered.

If the soil moisture deficit is being regularly monitored, it is possible to estimate pasture growth. Thus, using climatological and synoptic forecasts of probable conditions, and on the basis of weighting by dairy cow distribution, it is possible to predict milk production. The New Zealand Meteorological Service provides such a prediction to the New Zealand Dairy Board (WMO, 1988b). For many years L.P. Smith provided a nine-month forecast of winter milk production in the United Kingdom (Smith, 1968).

5.4.14.2 **Assessment of pasture productivity and grazing**

The assessment of seasonal patterns of grass growth rates given by Brereton et al. (1987) in their model was used to calculate the number of days when the growth rate exceeded a value of 40 kg dry matter per hectare per day. This was used as a gross measure of the regional differences in the length of the grazing season. The model data were also used to estimate the date in spring when yield was sufficient for grazing to begin (1 500 kg dry matter ha⁻¹). The analysis indicates that the regional and yearly variation in grass growth is sufficient to have a significant impact on the technical and economic performance of farms.

The pattern of seasonal production of pasture was studied for selected locations in mid-latitude Europe (WMO, 1996) and the pattern was found to be predictable in broad terms as a function of the changing weather from season to season within each year. Grazing systems are assembled accordingly, and the basic objective of the systems is to achieve high utilization efficiency by maintaining a balance between herbage availability and herbage demand. The balance is usually achieved by adjusting the size of the grazing area progressively during the year in line with the progressive changes in herbage growth rate. The scheme of adjustment of the proportion of land allocated to grazing or silage is based on a notional “normal” pattern of weather during the year. But even in “normal” years, when total herbage production is near the expected average, the supply of herbage can alternate between surplus and deficit several times during the year.

Table 5.6. Recommended air temperature for housing various livestock

<i>Species/classification</i>	<i>Weight (kg)</i>	<i>Ideal temperature (°C)</i>
Poultry:		
Hens	–	18 to 24
Broilers, young	–	27 to 28
Broilers, finishing	–	20 to 22
Turkeys, young	–	29
Turkeys, finishing	–	16 to 19
Swine, restricted-fed (2xM)	5	24 to 32
	20	21 to 31
	40	18 to 30
	80	14 to 28
	140	12 to 30
Veal calf	–	–5 to 20
Rabbits^a		
Fattening	0.5 to 2.5	16 (12 to 30 acceptable)
Adult	4 to 5	15 (10 to 30 acceptable)
Doe and litter	Avg.	18 (15 to 30 acceptable)

^a Target relative humidity = 75%

Table 5.7. Proposed practical and economical actions to protect dairy cattle in South Africa and Namibia in relation to THI values over 70 (from du Preez et al., 1990b)

<i>THI values^a</i>	<i>LWSI category^b</i>	<i>Proposed precautions</i>
<70.0	Normal	Natural or artificial shade
70.0 – 71.9	Alert	Shade and/or well-ventilated barns, ad libitum water at shaded troughs
72.0 – 77.9	Critical	Former, plus overhead sprinklers and large fans in holding areas adjacent to the milking parlour; alter diet; consider heat-resistant breeds; limit stressful handling of stock to cooler hours of day or night
78.0 – 81.9	Danger	Former, plus shade over feed bunks and sprinklers with fans at feed bunks
≥82.0	Emergency	Occurs only on individual days. All former precautions applicable

^a THI refers to the Temperature–Humidity Index. Various approaches to its formation are available (WHO, 1989). Du Preez used $T \text{ dry bulb} + (0.36 \times T \text{ dewpoint}) + 41.2$, with all temperatures in °C.

^b LWSI refers to the Livestock Weather Safety Index.

The efficiency of a grass-based livestock production system depends on the maintenance of a critical balance between herbage demand and supply throughout the grazing season. If the supply is

allowed to exceed demand, herbage is under-utilized, herbage quality deteriorates and subsequent animal performance suffers. Where herbage supply falls short of demand, animal performance is

reduced and overgrazing can result in thinning of the sward and a reduction in herbage growth rate. A variety of options are available to the grassland farmer to make the adjustments to the system that are necessary to maintain an optimum sward/animal balance as the supply of herbage varies. For example, where herbage exceeds requirements, part of the grazing systems can be withdrawn temporarily and the herbage saved as silage. In paddock-grazing systems, in some circumstances, the grazing cycle can be extended, effectively storing grass in the field as a standing crop. In periods of herbage deficit an obvious option is to feed saved silage. The cycle can be shortened temporarily within limits.

5.4.14.3 Forecasting diseases

A variety of livestock parasites, such as those that cause ostertagiasis and fascioliasis, and various tick and mosquito species, can now be reliably forecast using meteorological data. This was reviewed in WMO (1978) and updated in WMO (1989); the latter also reviewed metabolic and infectious diseases. See WMO (1988b) as well.

Tactical meteorological information is of obvious value in protecting livestock against the immediate dangers of (extreme) weather. It is also of value in disease control. For example, the incidence of sway-back, a congenital hypocalcaemia of sheep, can be forecast using the number of supplemental feedings and the probability of frozen ground. Timely forecasts of the need for feeding supplemental copper to pregnant ewes affect the incidence of the disease in newborn lambs if shepherds use the information. Similarly, after a period of cold spring weather there may be a sudden rise in temperature, which triggers the growth of young grass and a reduction in the absorption of magnesium; the consequent excess potassium acts as a magnesium antagonist. Clinical attacks of ovine hypomagnesaemia usually occur some five warm days after the temperature change (Smith, 1975; Hugh-Jones, 1994).

In order to benefit the livestock owners, epidemiologists have traditionally depended upon intervention programmes and preventive and control actions to confront an ongoing disease outbreak. In order to do this, a new concept of disease forecasting has emerged that seeks to forewarn farmers and forecast the devastating disease problems, with a view to the implementation of appropriate preventive measures so that the production system is not affected. Forecasting of animal diseases is a powerful tool of epidemiology that depends on reliable past information and data on the vital parameters associated with the occurrence

of diseases. Climatic conditions in an area are major parameters that facilitate induction of diseases in epidemic forms. A few examples of disease forecasting are described here (Burman et al., 2002).

- (a) Forecasting system for fascioliasis: this system was based on appraisal of rainfall recorded on each day. A day in which 1 mm or more rainfall was recorded was counted as a wet day and a positive correlation was found between the number of wet days during June and September and the incidence of fascioliasis. A minimum rainfall of 1 mm has been considered for wet days based on the lower evaporative demand on a cloudy day. The comparison of actually recorded and forecast rates in several areas of the globe confirmed the relationship between the prevalence and the number of wet days. The initial system did not take into consideration the environmental temperature during various months and hence the predicted values and the values that actually occurred were found to be at variance in certain areas. The forecasting system was modified by taking into account the mean weekly temperatures and days that were wet compared to the standard. The modified forecasting system gave an accurate forecast of incidence in all the geographic areas. A year having 12 or more wet days per month from June to September was taken as a standard year for comparison purposes;
- (b) Forecasting of foot-and-mouth diseases (FMD): the spread of FMD in various parts of the United Kingdom was predicted on the basis of the quantity of virus emission by infected animals, and meteorological conditions such as humidity, wind velocity, wind direction and rainfall. The outbreaks actually recorded at various places conformed to the predicted values. Similar predictions were also made for Newcastle disease in poultry in the United Kingdom;
- (c) Forecasting for vector-borne diseases: mosquitoes, midges, mites, flies, and the like are hot-weather insects that have fixed thresholds for survival and are prevalent mostly in tropical countries. Anopheline mosquitoes and *falciparum* malaria transmission are sustained only where the winter temperature remains above 16°C, while the variety of mosquitoes that transmit dengue, *Aedes aegypti*, is limited by the 10°C winter isotherms. Shifts in the geographic limits of equal temperature that accompany global warming may extend the areas that are capable of sustaining the transmission of these diseases.

5.4.15 **Protecting plants used in horticulture and arboriculture (non-forest trees)**

The use of past observations can become an essential ingredient in predicting future conditions and modifying the zone forecast for a farm in a form of response farming. The information collected will also allow the grower to place protection equipment in those areas where it will most likely be needed. During a radiation frost, careful records of past occurrences can help make the critical decision of whether or not to begin protection measures. This is especially critical in areas where overhead irrigation is used. Microclimate information gathered before the establishment of a crop can help the grower select the site, type and amount of protection equipment.

According to Wurr (1997), the horticulturist's objective is to supply the product at the right time, of the right quality and with the right uniformity. All of these requirements are affected by the weather, and involve aspects of crop scheduling, crop prediction and crop management. In the area of crop management, more accurate weather prediction would offer opportunities to interactively modify crop scheduling as the season progresses; develop improved prediction systems for crop maturity; predict rates of crop deterioration or loss of marketability; delay transplanting to avoid deleterious field conditions; adjust transplant-raising conditions to provide more consistent transplants; develop improved irrigation scheduling; and optimize glasshouse crop environments. For example, if solar radiation can be predicted, even hours ahead, carbon dioxide levels for tomato production can be optimized. Similarly, if temperature can be predicted days ahead, the cost of heating can be optimized, good predictions of yield can be developed and predictions of pest activity and disease incidence can be improved.

For example, in India the nation's agricultural planning is primarily dependent on the reasonably accurate prediction of the total amount of rainfall from the beginning of June to the end of September. This kind of prediction comes under the category of long-range forecast (LRF). On the basis of LRFs, various precautionary measures can be planned and adopted. For example, if an LRF indicates below-normal rainfall, then necessary products can be purchased from the international market well in advance. Also, adequate arrangements can be made for the transport, storage and distribution of such products. The government authorities can work out various plans and schemes to counter the adverse

situation well in advance and strategies can be used at various administrative levels, such as states, districts and villages.

Prediction of rainfall, its intensity and duration well in advance (in the month of May for June and July) may, for example, help guava growers who cultivate the Mrig bahar variety to obtain a better yield. Prediction in August or September of rainfall for October to February may help grape growers adjust planning for pruning and mango growers to protect plants from mango hopper and powdery mildew. Prediction of untimely rains, windstorms, and so forth will help banana, mango and grape growers to protect their plants from these hazards well in time. Prediction of a cold wave (night temperature below 6°C or 7°C) will help the banana, papaya and grape growers protect their crops well in advance so that they can take measures such as copious watering, smudging, and the like. Prediction of a heatwave (above 45°C) will help the banana, coconut and areca nut growers to take suitable measures. Timely prediction of frost may help the growers of vegetables such as peas, beans and okra to take suitable measures for protection of their crops.

In the United States, integrated pest management (IPM) in fruit orchards has been facilitated in the intermountain states through the products of the Sustainable Agriculture Research Education (SARE) project. Awareness about IPM has been increased in participating states, with many growers using weather data and prediction programmes to schedule cultivation operations in their orchards. Insect and disease control, pheromone release, irrigation, freeze prevention, maturity indices and fruit damage have benefited from weather database prediction programmes (Seeley, 2002). Table 5.8 shows some characteristics of frost/freeze protection for horticultural crops (Perry, 1994).

5.5 **AGRICULTURAL ADVISORIES OR AGROMETEOROLOGICAL SERVICES**

"Agricultural advisories" or, in the language of this Guide, agrometeorological services (see Chapter 1 and, for example, Stigter, 2007) are an act of advice by internal experts of National Meteorological and Hydrological Services (NMHSs) to crop growers/livestock producers based on possible future weather and climate conditions, regarding "what to do" or "what not to do" to maximize advantages and minimize losses in production. Weather and climate forecasts have little importance unless they are

operationally used. This section will focus on weather forecasts. Good examples of climate forecasts as agrometeorological services, in combination with other information, can be found in Abdalla et al. (2002), Harrison (2005), and Meinke and Stone (2005), for example.

So that maximum advantage can be taken of weather forecasts, agrometeorological advisories are issued in consultation with experts of other concerned disciplines and take into consideration the past, present and predicted weather and its spatial-temporal behaviour. Any appropriate forecast on weather has tremendous benefits in terms of advance management of the negative impacts of vagaries of weather. This is because the cost of weather-related risk reduction before the fact is much smaller than the post-facto management of the losses (Rathore et al., 2006). These advisories recommend implementation of certain practices or the use of special materials to help effectively prevent or minimize possible weather-related crop damage or loss, for example, spraying advice based upon past and forecast weather conditions to combat crop diseases and insects; sowing advice for better germination and plant stand; and harvesting advice to obtain optimum crop maturity, quality, and the like. They also recommend initiation of cultural

practices that are weather-sensitive. A famous example in Africa is the service that was developed in Mali (for example, WMO, 1988a; Stigter, 2006). In the operation of agrometeorological services, it has been found that extension intermediaries between products of NMHSs and farmer-oriented organizations and farmers would be extremely helpful in getting agrometeorological services established and applied (see also Chapter 1 and, for example, WMO, 2004a).

An added advantage of such services is that wherever and whenever they are in operation, they help to reduce environmental pollution through the optimal use of agricultural chemicals. Some agrometeorological advisories are being issued by almost all the developed and developing countries on various spatial and temporal scales. In actual practice, a great deal remains to be done to achieve the expectations of a decade ago (Wieringa, 1996; WMO, 2004a). Increasing needs, commercialization and competition have improved this situation, however (for example, Stigter, 2006). Geographically large countries like China, India, the Russian Federation and the United States now have national bodies or organizations that issue advisories on a county/state/agroclimatic region basis (see an example from India later in this section), while small countries like Slovenia and the Netherlands

Table 5.8. Characteristics of frost/freeze protection methods

	<i>Advantages</i>	<i>Disadvantages</i>	<i>Comments</i>
Site selection	Preventive measure; location with good cold air drainage may be chosen		Best method of frost protection; visualize air flow and/or monitor minimum temperatures
Heaters	Radiant heat helpful in freeze; installation costs lower than irrigation; allows delay; no risk if rate not adequate	Fuel oil is expensive	Free-standing or pipeline; free-standing heaters need no power source
Irrigation	Operational cost lower than heaters; can be used for other cultural purposes, such as drought prevention	Installation costs relatively high; risk damage to crop if rate inadequate; ice build-up may cause limbs to break; overwatering can waterlog soils; does not provide protection in wind above 8 km/h	Plant part protected by heat of fusion; fixed-rate design delivers more protection than generally necessary; irrigation must continue until melting begins; backup power source essential
Wind machines	Can cover an area of 4 ha if flat and round; installation cost similar to heaters	Not effective in wind above 8 km/h or advective freeze	Mixes warm air near top of inversion down to crop height; may be used with heaters; may use helicopters
Fog	Blocks outgoing radiant heat and slows cooling	Has potential but is not currently practical	Uses greenhouse effect to trap heat in crop canopy and limit radiative cooling

issue advisories on a national basis (for example, Wieringa, 1996).

Some developed countries (European countries, Russian Federation, United States) that have advanced computing and communication systems may consider catering to the small temporal scale for agriculturally related advice and frequent updating of advisories (in terms of hours), while developing countries (like India, see 5.5.4) issue advisories covering a span of 3–10 days, which enable the farmers to take ameliorative measures. For the agricultural sector, location-specific weather forecasts in the medium range are, therefore, very important. These services may contain advice on all the farming operations or some specific operations, such as pest management (for example, Dacom, 2003), irrigation scheduling (for example, Maia et al., 2005), and livestock management (for example, Rivero Vega, 2005). An example of an agricultural advisory from India is provided in 5.5.4.

5.5.1 **Preparation of agricultural advisories (agrometeorological services)**

The formation of agrometeorological services in forecasting requires close linking of various data providers and expertise from different fields. The basic requirement is that the forecast data must be for the desired period and for the specific location under consideration. For example, twice a week the National Centre for Medium Range Weather Forecasting (NCMRWF) in India, on the basis of a T-80 General Circulation Model, provides a location-specific weather forecast with a resolution of 150 km × 150 km for six parameters, namely, rainfall, cloud cover, wind direction and speed, and minimum and maximum temperature. These forecasts are further subjected to statistical and synoptic interpretation (Rathore et al., 2006).

A panel of experts then discusses the present, past and future status of weather and crop conditions and recommends the appropriate operations for better farm management based on such forecasts. Priority is given to predominant crops of the region and the most prevalent problems, keeping in view their relative economic importance. Management practices such as what, when and how to sow; when and how much to irrigate; which measures may be adopted for plant and animal protection from stresses caused by pest and disease, temperature, wind, rainfall, and so on, are suggested. Animal shelter, nutrition and health are affected by weather

to a large extent (see Chapter 12 of this Guide and 5.4.14) and hence must be considered in the services. On the basis of local agrometeorological and farming information and the weather forecasts, the specialists discuss the options and consequent effects and then decide on the advice to be given to farmers regarding the items that fall within the scope of their expertise. These elements together constitute the agricultural advisory (Singh et al., 1999).

5.5.2 **Panel of experts**

Ideally, a panel of specialists in a topic of agricultural science and animal science is constituted for the preparation of agrometeorological services. The panel may include agrometeorologists, agronomists, soil scientists, plant pathologists, entomologists, horticulturists, nematologists, sericulturists, and specialists from agricultural extension, animal husbandry and plant breeding. Experts from all the various fields have to discuss the current crop situation, animal conditions and anticipated weather conditions in order to prepare services for the farmers and user interests of a region.

5.5.3 **Information requirements**

Weather information required for services includes weather summaries of the recent past, such as the preceding week, for example, climatic normals for the advisory period and weather forecasts for the advisory period.

Required agrometeorological information includes some indices relating to agricultural production, such as the crop moisture index and drought severity index for the recent past.

Crop information for the preparation of advisories includes information on the present crop status detailing the type, state and phenological stage of crops; infestations of pests and diseases and their severity; and other crop stresses such as nutrient stress, water stress and thermal stress.

Soil information used in the preparation of advisories describes the spatial distribution of soils. Information on soil types, physicochemical properties, nutrient status, moisture status, elevation, and contour and slope of soils is also required for the compilation of advisories.

Other information on topography of the region, land cover and land use, irrigation facilities, irrigated and rainfed areas, availability of agricultural

inputs and market trends is also considered for the preparation of advisories.

5.5.4 **Example of an agrometeorological advisory service of the NCMRWF in India: a preliminary impact assessment**

The impact assessment of this agrometeorological advisory service (AAS) was guided and monitored by a national committee of experts constituted for this purpose (Rathore et al., 2006). The AAS units selected four villages for the study. In general, units selected 40 AAS and 40 non-AAS farmers for their survey. The farmers in both categories (AAS and non-AAS) chosen by all units through random sampling were generally in the middle-aged group and had medium-to-large land holdings. The data revealed that the inputs used varied quantitatively and significantly between AAS and non-AAS farmers. Significant differences were observed in human labour, fertilizer and plant protection chemicals used. The timeliness of proper agro-advisories given for various farm operations, such as irrigation and application of fertilizer and plant protection chemicals, however, saved the crops from possible moisture stress, nutritional stress and pest attack, which contributed to better growth and development of crops, both qualitatively and quantitatively. The non-AAS farmers used the same quality of inputs, but their timing of applications was different from that of the AAS farmers. This timing did not lead to the control of nutritional and water stress and pest attack with the same efficiency, and ultimately led to differences in crop yields. The season-wise preliminary results are given below in a Table 5.9. Further details may be found in Rathore et al. (2006).

In conclusion, AAS farmers received agro-advisories based on medium-range weather forecasts, including optimum use of inputs for different farm operations. Due to a judicious and timely utilization of inputs, the cost of production for the AAS farmers was reduced by between 3 and 6 per cent, approximately. At the same time, the yield levels of the AAS farmers also rose by 8 to 21 per cent. The increased yield levels and reduced cost of production led to increased net returns of 10 to 29 per cent for the AAS farmers. These are preliminary results, because inputs differed among and between farmers. Care was taken to delineate impacts of weather-based farm advisories, but it was extremely difficult to segregate them from general agronomic advice, which was also included in the bulletin. Hence, the results also reflect impacts of activities that were not weather-based.

5.6 **PROBABILITY FORECASTS**

5.6.1 **The rationale for probability forecasts**

Agricultural predictions require forecasts of meteorological variables several days, weeks and even months ahead to enable informed management decisions. It is well known, however, that the climate system is chaotic and therefore accurate weather and climate forecasting is impossible because of the uncertainty in the initial conditions (Palmer, 2005) and structural inadequacies of prediction models (Palmer et al., 2005), given the uncertainty in the present knowledge and representation of the processes involved in generating weather and climate variability. There is

Table 5.9. Economic impact of AAS of NCMRWF: preliminary results

<i>Crop</i>	<i>Station name</i>	<i>% increase/decrease in cost of production (per acre)</i>	<i>% increase/decrease in crop yield (per acre)</i>	<i>% increase/decrease in profit (per acre)</i>
Cotton	Hisar	1	14	10
	Coimbatore	-4	16	16
Rice	Ludhiana	-6	9	18
	Kalyani	-3	21	29
Wheat	Ludhiana	-6	9	17
Mustard	Hisar	-3	8	13

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A

<i>Past weather summary (1/8/05 to 3/8/05)</i>	<i>Weather Forecast</i>
SW monsoon was vigorous over north Madhya Maharashtra and active over Konkan and Vidarbha.	Moderate rain is likely to occur at many places in Konkan, Vidarbha and Madhya Maharashtra, and at a few places in Marathwada.
Rain has occurred at most places in south and north Madhya Maharashtra and at many places in Marathwada.	
<u>Chief amounts of R/F in cm:</u>	
1/08/2005: Mahabaleshwar 31, Bhira 29, Santacruz 21, Gaganbawda 19, Colaba 16, Alibag 13, Ratnagiri and Harnai 10 each, Pune and Nagpur 6 each, Kolhapur and Akola 5 each.	Warning: Heavy rain is likely to occur at isolated places in Thane and Raigad districts and in Vidarbha during next 48 hours.
2/08/2005: Mahabaleshwar 39, Bhira 27, Santacruz and Ratnagiri 15 each, Harnai 10, Colaba 9, Dahanu 7, Pune 6, Patan and Mehekar 5 each.	
3/08/2005: Mahabaleshwar 18, Dahanu 17, Ratnagiri 9, Bhira 7, Pune (Pashan) 2, Aurangabad and Akola 1 each.	<u>Outlook:-</u> Decrease in rainfall activity.

State and stage of the crops and the advisories

81% sowing of Kharif crops was completed on 22 July. Paddy crop was damaged in the districts of Raigad, Ratnagiri, Thane, Sindhudurga and Kolhapur, and in the western talukas of Pune and Satara districts due to recent heavy rainfall; crops such as soya bean, groundnut and jowar are also likely to be damaged in Kolhapur, Sangli, Satara, Nanded and Parbhani districts. As heavy rain spell is decreasing slowly, re-transplanting of paddy in Konkan, South Madhya Maharashtra and Western Pune if nursery is available, or sprouting seed sowing, may be started after current rain spell. Sunflower or castor seed may be sown as contingency crop in Madhya Maharashtra, Marathwada and Vidarbha where crop has been damaged. Late sowing or re-sowing may be started after complete current rain cessation. Vegetable crops are likely to be affected by aphids and jassids due to warm high humidity, so farmers are advised to apply plant protection measures after current rain spell.

Details of crop information and the necessary advisories are given below

<i>Crop</i>	<i>Stage</i>	<i>State</i>	<i>Agromet/Agricultural Advisories</i>
Sugarcane preseasonal (M. Mah., Marathwada, Vid.)	Active vegetative growth	Satisfactory, crop is under flood on the banks of Panchaganaga and Krishna rivers in south Madhya Maharashtra due to very heavy rain.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation. On the incidence of white woolly aphids, release 2 500 larvae of <i>Crysoperla carnea</i> or 1 000 eggs or pupa of <i>Konobathra aphidivora</i> per hectare on leaves early in the morning after current spell of rain on a non-rainy day.

<i>Crop</i>	<i>Stage</i>	<i>State</i>	<i>Agromet/Agricultural Advisories</i>
Kharif jowar (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory in Kolhapur, Sangli, Satara, western Pune, Nanded and Parbhani due to heavy rain; satisfactory in other districts.	Excess water may be drained out from the field.
Bajra (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory in Kolhapur, Sangli, Satara, western Pune, Nanded, Hingoli and Parbhani due to heavy rain; satisfactory in other districts.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation. A dose of 65 kg urea/ha may be applied after current spell of rain on a non-rainy day.
Rice (Konkan, M. Mah., Vid.)	Seedling Transplanting (Early tillering in Konkan and South Madhya Maharashtra)	Crop is in poor state in all the districts of Konkan and in Kolhapur, Sangli and western parts of Pune and Satara. Satisfactory in other districts, mild incidence of stem borer in Thane and army worm and silver shoot in Sindhudurga district.	Postpone the transplanting of seedlings in Konkan and Madhya Maharashtra and Vidarbha. For the control of stem borer use 10 G phorate 10 kg or 5 G quinalphos 15 kg/ha, or spray 850 ml endosulphan/ha in 500 litres water after current spell of rain on a non- rainy day.
Groundnut (M. Mah., Marathwada, Vid.)	Early vegetative growth	Satisfactory, crop is likely to be damaged in Kolhapur, Sangli, Nanded, Hingoli, Parbhani and western parts of Pune and Satara.	Excess water may be drained out from the field.
Soya bean (M. Mah., Marathwada, Vid.)	Early vegetative growth	Satisfactory, crop is likely to be damaged in Kolhapur, Sangli, Nanded, Parbhani and Satara. Mild incidence of leaf roller in Nagpur and Kolhapur and army worm and semi-lopper in Amraoti division.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation.
Irrigated cotton (Vidarbha)	Early vegetative growth / Active vegetative growth	Satisfactory, crop is likely to be damaged in Amraoti, Yeotmal	Excess water may be drained out from the field. A dose of 33 kg nitrogen/ha may be given by ring method after current spell of rain.
Kharif cotton (M. Mah., Marathwada, Vid.)	Early vegetative growth	Moderately satisfactory, crop is likely to be damaged in Nanded, Parbhani Amraoti, Yeotmal. Mild incidence of aphids and jassids in Nagpur and Nashik division.	Drain out excess water from the field and apply plant protection measures for standing crop after complete rain cessation.

a need to address the uncertainty problem in such a way as to distinguish between those occasions on which forecasts deteriorate rather slowly with lead time (relatively skilful forecasts) and those occasions when they deteriorate rather rapidly with lead time (relatively unskilful forecasts). The answer to this question requires addressing the feasibility of quantifying the uncertainty in forecasts in a stochastic manner.

The rationale for probability forecasts has a scientific and an economic component (Murphy, 1998). First, weather and climate forecasts must be expressed in terms of probabilities (or equivalent modes of expression) to accommodate the uncertainty inherent in the forecasting processes. As the amount of uncertainty can be situation-dependent, the level of uncertainty associated with a given forecast can be properly conveyed in a stochastic sense through the use of probabilities. In general, forecasts expressed in a non-probabilistic format are unable to accurately reflect the true state of knowledge concerning future conditions of a forecast system. Weather forecasts must be expressed in probabilistic terms to enable the end-users to make the best possible decisions, as reflected by their levels of economic and/or social welfare.

Probability forecasting is not expected to be considered only in the formulation of weather and climate forecasts for agricultural purposes, but to be extended to the agricultural predictions themselves. Probability forecasts have already been demonstrated to have superior benefits in some agricultural applications that make use of meteorological and climatological information.

In particular, crop yield prediction has benefited from a collaborative effort within the seasonal climate forecast community. Challinor et al. (2005) and Cantelaube and Terres (2005) offer examples of probability forecasts of annual crop yield and compare the benefits versus non-probabilistic forecasts.

5.6.2 Formulation

Probability forecasts differ from non-probabilistic forecasts in that, depending on the expected likelihood of occurrence of an event, a probability value between 0 and 1 is assigned to possible future states. This probability is only a component of the probability distribution function (PDF) of the variable, which gives a probability forecast value for each possible event. Within the paradigm of deterministic prediction, a signal refers to the location of the mean of the PDF and its deviation

from the climatological mean, whereas the noise is represented by the spread of the PDF. For probability predictions, a signal is represented as the entire forecast PDF and its difference from the climatological PDF. This concept allows for an interesting definition of predictability: a variable x can be considered predictable if the forecast PDF of x differs sufficiently from the climatological PDF of the same variable to influence relevant decision-makers to make better decisions than they would without forecast information.

Forecast uncertainty can be quantified by a variety of methods, including subjective, statistical and dynamical ensemble methods. Similarly, probability forecasts can be generated through different methods. By considering a wide range of forecast information, forecasters can subjectively prepare probability forecasts. Alternatively, statistical/empirical techniques can be used either on their own, based on historical observational data (for example Mason and Mimmack, 2002), or in combination with dynamical models and past verification statistics (Kruizinga and Murphy, 1983; Coelho et al., 2006). It is certainly true that not all probability forecasts produced by these methods are precise. Nevertheless, it can be stated without equivocation that probability forecasts exhibit reasonable skill (and skill considerably in excess of that achieved by the corresponding non-probabilistic forecasts) and can be produced for most if not all weather conditions of interest.

Predictions using dynamical models of the climate system may require further explanation given their present ubiquity and continuous progress. Predictions with dynamical models require a good estimate of the initial conditions of the atmosphere and the ocean. Since the initial conditions can never be measured with infinite precision, the error propagation created due to prior abstractions in initialization fundamentally limits the ability to forecast precisely (Thompson, 1957). Small perturbations of the initial conditions grow fast, leading to a rapid loss of initial information and predictability. Lorenz (1963) confirmed this sensitivity in numerical simulations of a simplification of atmospheric convection based on three equations.

Forecast models are run many times from slightly different initial conditions, all of them consistent with the error introduced to estimate the best possible initial condition. This means that the forecaster has an ensemble of forecasts available at the same time and this technique is therefore otherwise known as ensemble forecasting (Molteni et al., 1996; Toth

and Kalnay, 1997). The ensemble can be used to produce probability forecasts without relying on statistical methods based on past events (Hagedorn et al., 2005). Assuming that the forecasts are independent realizations of the same underlying random process, an estimate of the forecast probability of an event is provided by the fraction of the forecasts predicting the event among all forecasts considered. Figure 5.2 shows an example of such probability forecasts produced with the monthly ensemble forecast system of the European Centre for Medium-Range Weather Forecasts (ECMWF).

Errors in the sampling of the set of initial conditions and in the dynamical model structure, however, mean that the dispersion of an ensemble forecast at best only approximates the forecast PDF (Hansen, 2002). This may lead to overconfidence in probability assessment based on ensemble relative frequencies. Some statistical methods have been considered to correct these errors and provide sound probability forecasts based on ensemble forecasts (Wilks, 2006).

The widespread interest in the development and application of ensemble prediction is a sign that the meteorological and climatological operational communities acknowledge explicitly the uncertainty inherent in the forecasting process. An opportunity now exists to provide the full spectrum of users with reliable probabilistic information concerning the likelihood of occurrence of future conditions through probability forecasting.

Dynamical predictions of weather and climate suffer from structural model uncertainty, in addition to uncertainties in initial conditions. Model uncertainty arises mainly because of the process of parameterization, that is, the way in which subgrid-scale motions are represented in weather and climate models (Palmer et al., 2005). At present, there is no underlying theoretical formalism from which a PDF of model uncertainty can be estimated. A pragmatic approach relies on the fact that dynamical forecast models have been developed somewhat independently at different climate institutes. An ensemble comprising such quasi-independent models is referred to as a multimodel ensemble (Palmer et al., 2004a, 2004b). This is an approach that can be easily extended to the user-model component to increase the skill of the end-user predictions.

5.6.3 Probability forecasts at different scales

The features described above are applicable to the whole range of probabilistic forecast systems, from

medium-range weather, through monthly and up to decadal and longer climate timescales, which are available with a varying updating frequency, as described in Rodwell and Doblas-Reyes (2005). Users may want to employ all these systems in an integrated forecasting system, updating decisions as new probability forecasts are available. For instance, managers might have access to probability seasonal forecasts once a month. This information can somehow be merged with that provided by monthly forecasts available once a week to improve the first few weeks of the seasonal forecast information.

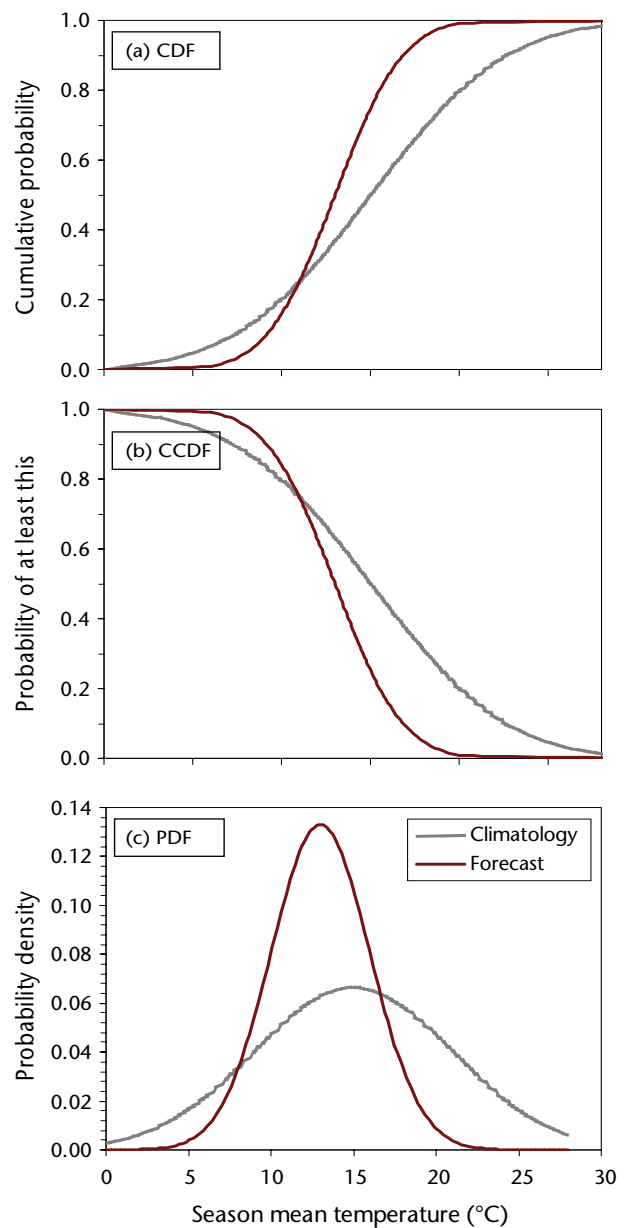


Figure 5.2. Hypothetical temperature forecast expressed as shifted cumulative distribution (a), probability of exceedence (b) and probability density (c)

Similarly, given that long-term decisions in agricultural systems are made at the interannual timescale, adaptation to ongoing climate change can be achieved by training the users to employ seasonal-to-interannual climate probability forecasts.

5.6.4 Probabilistic forecast formats

Probabilistic forecast information can be conveyed in explicit, quantitative terms in the form of probability distributions or as categorical probabilities, implicitly in the form of time series, and qualitatively as narrative. Table 5.10 summarizes the strengths and limitations of each.

5.6.4.1 Probability distributions

Forecasts of continuous quantities (such as precipitation and temperature) are appropriately interpreted, and expressed graphically as shifts from the climatological probability distribution. Probability distributions can be expressed in either cumulative or density forms (or in mass form in the

discrete case). A cumulative distribution function (CDF) expresses the probability that a random variable X takes on a value less than or equal to a given x , or $F_x = \Pr \{X \leq x\}$ (Figure 5.2a). A CDF increases smoothly for continuous variables, and in discrete jumps for discrete variables.

The probability of exceedance (also known as the complementary cumulative distribution function, or CCDF) is simply one minus the cumulative distribution function: $F_x^c(x) = \Pr \{X > x\} = 1 - F_x(x)$

(Figure 5.2b). The probability of exceeding a particular threshold (a CCDF), as in the case of rainfall, appears to be easier to understand than the probability of an outcome below a threshold (a CDF), as will be the situation with temperatures in winter.

For a continuous variable, the probability density function (PDF) is the first derivative, or slope, of the CDF. Graphically, it appears as the familiar “bell curve” for the normal distribution (Figure 5.2c), and shows the relative probability of

Table 5.10. Alternative formats for probabilistic forecasts

<i>Format</i>	<i>Use</i>	<i>Strengths</i>	<i>Weaknesses</i>
<i>Probability distribution</i>			
Histogram, Probability density (PDF)	Present entire forecast distribution of a measured quantity	Provides full distribution information Good at conveying relative probability of different outcomes, skewness, tails More likely exposed to PDF than CDF in school	Derivation of PDF difficult to explain Difficult to compare multiple distributions Interpretation might require training
Cumulative distribution (CDF)	Present forecast distribution of a measured quantity. Compare multiple distributions	Provides full distribution information Directly relates climatic thresholds and probability Straightforward to derive from, relate to, historical series Can compare multiple distributions	Interpretation usually requires some training
Probability of exceedance (CCDF)	Present forecast distribution of a measured quantity. Compare multiple distributions	Same as for CDF Belief that $\Pr \{X > x\}$ is easier to understand than $\Pr \{X \leq x\}$	Interpretation usually requires some training
Box plots	Present forecast distribution percentiles (0, 25, 50, 75, 100) of a measured quantity. Compare multiple distributions	Intermediate information between full distribution and simple range Percentiles (quartiles, median) and extremes explained as, for example, “ k out of n years” Can compare multiple distributions	Interpretation usually requires training

<i>Format</i>	<i>Use</i>	<i>Strengths</i>	<i>Weaknesses</i>
Error bars	Present a simple measure of uncertainty of a measured quantity on a deterministic (for example, time series) graph	Reduces distribution to expected value and a range	Potential ambiguity due to multiple error metrics Ignores low-probability, high-impact events
<i>Categorical probabilities</i>			
Probability of occurrence	Present probability that a discrete event will occur	Appropriate format for extreme, high-impact events	Inappropriate for continuous quantities
Probability of exceeding median (or mean)	Probabilistic representation of spatial distribution of a forecast measured quantity	Simplest probabilistic representation Lends itself to mapping Useful when relative, not absolute, outcomes are relevant	Discards distribution information Imposes artificial thresholds Tendency to confuse shift in probability with shift in direction from “normal” Tendency to anchor on most probable category Local interpretation requires climatology information
Terciles	Probabilistic representation of spatial distribution of a forecast measured quantity	“Standard” for many operational forecasting institutions Lends itself to mapping Substantial existing experience and educational material	Same as probability of exceeding median Interpretation usually requires training Potential misunderstanding of category boundaries
<i>Time series</i>			
Analogue years	Possible supplement to aid explanation of formal probability formats	Provides an intuitive explanation of forecast in terms of past years with similar forecast	Resulting distributions inconsistent with more rigorous methods No clear evidence of relative ease of understanding
Predicted and observed series	Possible supplement to aid understanding and transparency of formal probability formats	Useful for explaining basis for probabilistic forecasts in terms of past performance Provides evidence that farmers desire as complementary information Allows users to intuitively validate probabilistic forecasts	Danger of contributing to deterministic interpretation Danger of anchoring if the current forecast is included
<i>Narrative</i>			
Narrative	Text-based media (for example, radio) Supplement to formal probability formats	Text-based media (for example, rural radio) sometimes have greatest reach at lowest cost	Qualitative descriptors of probability prone to inconsistent interpretation Difficult to explain basis for forecasts or their climatology context with text alone

every outcome. A histogram is used to represent the probability distribution of a discrete variable (known as a probability mass function, or PMF), and to approximate the distribution of a continuous variable based on the number of observations within each interval.

Both CDF and PDF are of value for farming decisions. Curves and histograms associated with probability density may be more familiar even to secondary school students. Use of CDF over PDF is preferable, however, as a CDF graph relates probabilities and climatic thresholds and it is relatively easy to relate a CDF to a time series.

5.6.4.2 Categorical probabilities

Simple event probabilities are the appropriate way to express uncertainty about high-impact meteorological events when the primary concern is whether an event occurs, rather than its intensity. An example is the need to know the likely occurrence of rain, rather than its quantity, for control operations against pests and diseases. The climatological probability that a given event *E* will occur is estimated by its historical relative frequency, and it is defined as the limit as the number of observations *N* approaches infinity. A forecast provides additional information that modifies the climatological probability.

Categorical probability formats are also used routinely to express forecasts of continuous meteorological quantities of interest to agriculture. The climatological distribution is divided into categories, such as above and below median, terciles (for example, the wettest, middle and driest third of past years), or percentage probability of realization of a given value of a parameter and/or given situation. The forecast is expressed as a shift from the probabilities that define the categories. Categorical probability formats lend themselves to maps. Colour-coding represents the probability associated with a particular category (for example, above median), or the dominant category in the case of tercile forecasts. Probability shifts can be represented independently of the fine-scale spatial variability of climatological quantities.

The tercile format is being used for issuing operational forecasts and regional climate outlooks. The tercile and other categorical probability formats are not recommended as a primary means of presenting location-specific forecasts to user interests. Categorical probability formats discard potentially

useful distribution information, and impose thresholds that have no intrinsic relevance to decisions. Ambiguity about the definition of categories (O'Brien et al., 2000; Patt and Gwata, 2002), a tendency to confuse shift in probability with shift in direction from "normal" (Dalglish, personal communication) and a tendency to anchor on the most probable category make interpretation difficult in the absence of substantial training.

5.6.4.3 Time series and analogues

A time series of observations and hindcasts based on an operational forecast model may be a useful complement to forecast distribution formats. It can reduce some of the non-clarity behind probabilistic forecasts by allowing users to evaluate the forecast system's uncertainty based on past performance. Showing hindcasts as expected values, however, carries the risk of miscommunicating a deterministic interpretation, particularly if the current forecast value appears in the graph.

Time series graphs can also be used to highlight analogous years (for example, El Niño or La Niña years) when predictors (such as SSTs and the Southern Oscillation Index, or SOI) were similar to the current year. This illustrates how the current state of predictors can shift the distribution of expected outcomes, and may be a useful way to present a probabilistic forecast that is based on such categorical predictors. Although forecasts that are based on continuous or multivariate predictors could also serve as a basis for selecting years when predictors were most similar to their current values, the probability distribution of the resulting analogue years will generally not be consistent with estimates from hindcast residuals (5.6.5.2) or global circulation model (GCM) ensemble distributions (5.6.5.3).

For time series data, bar graphs appear to be easier to interpret than points or line graphs. For a visual representation of relative depth of a column of accumulated precipitation, farmers can participate in drawing rainfall depths to scale, then filling in bars and adding axes.

5.6.5 Deriving forecast distributions

This section briefly summarizes three objective methods to derive forecast probability distributions. For each method, probability distributions can be represented either empirically as illustrated, or by fitting the data to a theoretical distribution, which would typically be a gamma distribution for

precipitation amounts, and a normal one for mean temperatures. The simpler case of forecasting the probability of a discrete event is not addressed.

5.6.5.1 From analogues

Statistical forecasting based on historical analogues involves classification of predictors into a few categories, such as El Niño, neutral and La Niña based on SSTs in the equatorial Pacific, then taking the set of past years falling within the category that corresponds to current conditions as a forecast distribution. Historical analogues provide a simple, intuitive approach to deriving and explaining probabilistic forecasts.

The marked year-to-year variations in the temporal distribution of a weather parameter on a short-period basis restrict the use of the concept of analogous years to specific situations, such as late or early setting in, early withdrawal or persistence of weather systems. Spurious predictors, artificial forecast skill and systematic underestimation of forecast uncertainty – risks inherent in statistical forecasting – are particular concerns for the analogue method when the number of categories and limited record length lead to small sample sizes within each category. Use of credible predictors and independent validation and hypothesis testing are essential to limit these biases.

5.6.5.2 From hindcast residuals

Figure 5.3a shows a hypothetical time series of mean temperature observations (y) and hindcasts ($\hat{y}$), derived from sampling a multivariate normal distribution and calibrated to the observations by linear regression. The distribution around the current forecast $\hat{y}_T$ is estimated by the distribution of hindcast residuals $\epsilon_i = y_i - \hat{y}_i$, centred on $\hat{y}_T$. Subtracting predictions from observations yields a time series of hindcast residuals (ϵ) (Figure 5.3b), which are then sorted to derive a residual CDF (Figure 5.3c). The forecast distribution for 2001 is obtained by adding its expected value, $\hat{y}_{2001} = 12.^\circ\text{C}$, to each ϵ (Figure 5.3d). The method is applicable to statistical or dynamic forecast models, and accounts for the overall prediction error of the forecast system. Distributions derived from historical analogues (5.6.5.1) are a special case, which uses the subset of ϵ from years within the given predictor class.

For strongly skewed variables, the magnitude of forecast residuals, and therefore the spread of a forecast distribution, tends to increase in the

direction of skewness. Because rainfall amounts tend to be positively skewed, forecast uncertainty tends to be greater in wet than in dry years. The residual distribution will not capture this bias unless the skewness is corrected using a transformation of the predictand and/or the predictor. Raising to a power <1 (for example, $y' = y^{1/2}$, $y' = y^{1/3}$, $y' = \ln(y)$, $y' = 1/y$) can correct positive skewness. Box and Cox (1964) provide an objective procedure for selecting an optimal power transformation that can be automated in a spreadsheet. The forecast distribution is derived from the transformed series, and then the inverse transformation is applied to the entire forecast distribution.

5.6.5.3 From ensemble forecasts

Several operational climate centres derive probabilistic long-range forecasts from ensembles of multiple GCM integrations. Initializing GCMs with different atmospheric conditions gives an indication of the uncertainty associated with initial conditions. Use of several different GCMs captures uncertainty associated with model structure and assumptions. The spread of resulting predictions can be interpreted as a measure of forecast uncertainty, but must be calibrated before forecasts can be expressed as probability distributions at a local scale. There is not yet a consensus about the best calibration method (Doblas-Reyes et al., 2005; Palmer et al., 2005).

5.6.6 Interpretation and attributes of probability forecasts

Forecast probabilities can be interpreted as a relative frequency or as the forecaster's degree of belief. In the former interpretation, the uncertainty is a property of the system under consideration, whereas in the latter case the uncertainty is a property of the person issuing the forecast (Murphy, 1998). Measurement of the statistical consistency between the predicted probabilities and the actually realized frequencies is known as reliability. The ability of the probability forecast system to delineate situations in which an event occurs with lower or higher frequency than the climatological frequency is known as resolution. Measurement of the variability of the forecast PDF with reference to the climatological PDF is known as sharpness. Ideally a skilful probabilistic forecast should seek a trade-off between high reliability and resolution. In a perfectly reliable forecast system sharpness is identical to resolution. When reliability is not perfect, however, resolution and sharpness should not be confused. For a detailed discussion and

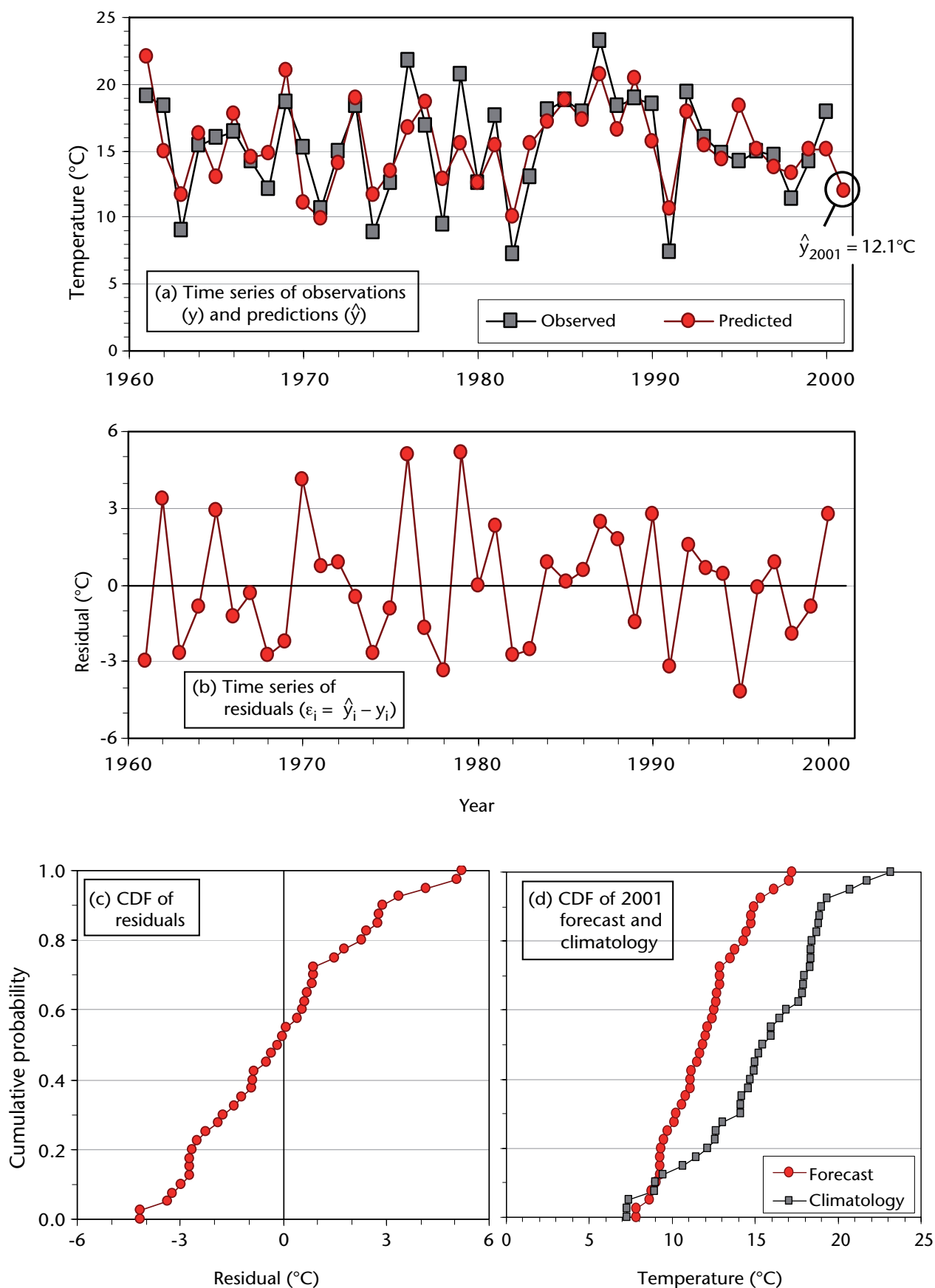


Figure 5.3. Steps in deriving the probabilistic forecast from hindcast residuals, illustrated with synthetic data

availability of tools relating to measures of reliability, sharpness and resolution, reference may be made to Jolliffe and Stephenson (2003).

5.6.7 **Communicating probabilistic forecasts to farmers**

5.6.7.1 **Keys to understanding and applying probabilistic information**

There are fundamental difficulties in understanding and applying probabilistic information for decision-making (Nicholls, 1999; Tversky and Kahneman, 1981). Agricultural meteorologists can help farmers overcome some of these difficulties, however, particularly in settings that allow direct interaction.

As an example, presenting information in the form of natural frequencies (such as “Belle Glade gets more than 160 mm of rainfall in January to March in about 10 out of every 20 years”), rather than the equivalent but more abstract notion of probability of a future outcome (“the probability of getting more than 160 mm of rainfall next January to March at Belle Glade is 50 per cent”), tends to improve interpretation of probabilistic information (Gigerenzer and Hoffrage, 1995).

Another technique is to relate information to experience. The work of Hansen et al. (2004) suggests that probabilistic information acquired from personal experience is processed and applied more effectively than information acquired from statistical descriptions. Because farmers’ livelihoods are weather-dependent and inherently probabilistic, they can be expected to understand uncertainty from their own experience, although not necessarily in formal probability language or formats. Helping farmers map probabilistic forecast information into their own experience base can therefore enhance the utility of the information.

Trust and transparency are important as well. Building up trust in the credibility of information provided takes time and deliberate, planned efforts. Communicating probabilistic information in a transparent manner, and not as a “black box”, is essential in this effort, as it allows farmers to shift their trust from the information provider to the data and the process. Presenting past performance of the forecast system against observations, and explaining (in simplified terms) the process of deriving probabilistic forecasts, contribute to transparency and therefore help to boost confidence.

5.6.7.2 **Teaching probabilities to farmers**

The logical progression of the following processes has proven to be a useful way to introduce farmers to probabilistic long-range forecasts and has been effective and well received in a workshop setting with smallholder farmers in Kenya, while a subset was used in a self-directed tutorial with farmers in Florida (United States).

Measured time series are related to farmers’ experience. For example, efforts are made to elicit farmers’ qualitative memory of climatic conditions for the past five years. Then observations from a nearby station are presented, and farmers are allowed to plot them as a time series bar graph and then validate the measured outcomes against their collective memory.

The time series are converted to relative frequency or probability. Starting with a blank graph indicating quantity (for example, seasonal rainfall) on the x-axis and frequency (for example, “years with at least this much rain”) on the y-axis, farmers are allowed to sort from lowest to highest (if using probability of exceedance) on the new graph. The points are connected, and the y-axis is changed from number of years to relative frequency or probability. The consistency between the two formats is emphasized.

Enough explanation and repetition are provided to ensure understanding. For example, rainfall associated with a given probability, probability associated with a given rainfall threshold, and the range of likely rainfall are discussed. It may be useful to draw hypothetical shifts and discuss their interpretation. One way to explain a shift in the climatological distribution to the right or left is to ask farmers to identify and discuss the climate in locations that are somewhat wetter or drier.

The procedure should be repeated, for example, for El Niño or La Niña years. Educating the rural communities about El Niño and La Niña will help convey the notion that a forecast is a shift of the climatological distribution, even if operational forecasts are more complicated or not based on the El Niño–Southern Oscillation phenomenon. By this point, farmers should be comfortable enough with the formats to allow use of prepared time series graphs with El Niño or La Niña years highlighted, and prepared shifted CDF or probability of exceedance graphs.

Forecast distributions are related to decisions. Organization of brainstorming sessions among

farmers about potential management responses to either hypothetical or actual forecasts will help to reinforce both their appropriate interpretation and their relevance for farming decisions.

Culturally relevant indigenous forecasts, gambling analogies or other analogies of decisions under uncertainty are used. This aspect of the process requires detailed understanding of local culture and language.

Accelerated experience through decision games is provided. Well-designed games that link real or imaginary payouts to decisions and sampled probabilistic outcomes allow farmers to experience, in a short time, a number of imaginary forecasts, decisions and sampled climatic outcomes, and imaginary or real payouts. Spinners and draws of colour-coded objects (for example, candies, buttons) have been used effectively to sample outcomes in proportion to prescribed forecast probabilities in educational decision games.

5.7 WEATHER FORECASTS FOR THE GENERAL PUBLIC

The provision of weather warnings and forecasts to the general public is one of the primary roles of all National Meteorological and Hydrological Services and is intended for relatively large areas where agricultural production may be diversified. These forecasts are limited to the meteorological elements and factors and should include forecasts of maximum and minimum temperatures; type, duration and amount of precipitation; cloudiness; and wind speed and direction. Agriculture, fisheries, forestry and water resource management, among many other sectors, benefit directly from the service. To be effective, forecasts and warnings obviously must reach users in a timely fashion. Moreover, they should be presented in a suitable manner and be readily understandable and usable. Since the forecasts are concerned with stating the weather probabilities of certain areas over certain time periods, the phraseology used should be in accordance with these probability aspects rather than precise, and flexible rather than rigid. The forecasts should be related to well-defined regional localities where configuration implies some degree of homogeneity of weather patterns (WMO, 2001).

The interpretation of the weather's influence on crops or agricultural operations is not mentioned in the general forecast. Only agricultural meteorologists with a thorough knowledge of current agricultural

techniques and operations must make such interpretations.

5.8 NOWCASTING AND VERY SHORT-RANGE FORECASTS

5.8.1 Definitions

Nowcasting (NC) and very short-range forecasting (VSRF) techniques were created for fields such as civil protection and transportation. Nevertheless, in the last few years their importance for agriculture has been rapidly growing due to the improvement of techniques for production and broadcasting of forecast information and the increasing flexibility of agro-techniques to cope with variability of weather conditions. A short definition and some general characteristics of NC and VSRF have been presented in Table 5.1.

NC is the extrapolation of current weather to some future time (up to 2 h), mainly based on the behaviour of existing phenomena as described by intensive observations; VSRF is the anticipation of events beyond the period during which extrapolation usually works (up to 12 h) (Schlatter, 1986). NC and VSRF focus on meso- and microscale weather events, with spatial scales below 1 000 km and timescales of several hours.

In the state-of-the-art services, NC is very close to VSRF from the point of view of applied forecast techniques and it is not easy to make a clear separation between the two techniques (Heijboer et al., 1989; Coiffier, 2004); for this reason they will be jointly discussed in this section. Some authors (for example Schlatter, 1986) say that NC could be based exclusively on extrapolation techniques and does not involve knowledge extensively applied for VSRF (physics, dynamics or the application of numerical and conceptual models).

5.8.2 Operational activities

Basic information about NC and VSRF is presented in Table 5.11. Agricultural and biological data, from ground truth or remote-sensing sources (such as local and regional observations of crop phenology, pests and diseases, agricultural practices), are important ancillary data for production of useful and reliable agrometeorological information (for example, nowcasting of precipitation or frost can be useful for a given crop only during particular phenological phases).

Usually the forecaster's work for NC and VSRF consists of producing a reference forecast based on available information and checking whether the actual behaviour of the selected phenomena agrees with the forecast one. This latter task needs real-time comparison of forecast values with real-time synoptic and/or remotely sensed data. When the actual evolution differs from the forecast one, the forecaster should be able to adjust the forecast and amend the products delivered to the end-users. This task becomes particularly critical when a severe weather event is taking place. For example, in the specific case of heavy precipitation (Horváth and Geresdi, 2003) the adjustment of the forecast over small areas with the help of the whole set of available tools, and the preparation of alarm bulletins, takes up all of the forecaster's time (Coiffier, 2004). The consequence is that it is crucial to have techniques at one's disposal to organize all the available data in a georeferenced framework, interpret the existing information, and display in real time the information for the forecaster. Automatic techniques useful for these aims are:

- (a) Geographical Information Systems (GISs);
- (b) Techniques for data assimilation and quality checks;
- (c) Techniques for analysis of spatial data;
- (d) Tools to detect differences between the forecast and the actual situation;
- (e) Numerical and conceptual models adapted to territory and operational activity.

All of the above techniques could be fault-tolerant and could also operate with reduced sets of data (Mouchart and Rombouts, 2005).

GIS is useful for the management of different kinds of basic data as georeferenced layers (Olaya, 2004).

Assimilation is the first phase of the operational chain of NC and VSRF and a fundamental aspect for the quality of numerical weather prediction (NWP) model products (Macpherson, 2001). Data quality checks are crucial to avoid the negative effect of wrong data that may not be detected by normal quality control procedures, which usually do not work in real time (for example: the effect of wrong hourly rainfall data on the quality of NC and VSRF). Real-time quality control procedures (checking of absolute and relative – spatial, temporal, intersensor and intersystem – consistency) are needed to eliminate outliers of faulty data and to highlight questionable data that need particular attention by the forecaster (Daley, 1993).

Analysis of spatial data is founded on geostatistical approaches in order to describe the spatial features of meteorological phenomena (Goovaerts, 1997) and to extrapolate their behaviour, field of motion and trajectory (Steinaker et al., 2000) from observations and remotely sensed imagery.

Automatic tools to detect differences between the forecast and the present situation are useful in order to minimize the subjective decisions of the forecaster and the possibility of error. The availability of a GIS technology is an important element for obtaining satisfying results in this case as well.

Numerical models are useful in NC and VSRF for prognostic and diagnostic purposes (Kaspar, 2003). Classical examples are given by energy balance models useful for analysis and forecasting of temperatures of vegetation (Bonan, 2002), or hydrological models useful for forecasting runoff and

Table 5.11. Nowcasting and very short-range forecast: basic information for the forecaster

	<i>Class</i>	<i>Data</i>
<i>Monitoring data</i>	Punctual atmospheric data	Local and regional observations of atmospheric phenomena (cloud coverage, present and past weather events) Data from networks of automatic weather stations
	Remotely sensed atmospheric data	Maps from systems for lightning detection Images from polar and geostationary meteorological satellites Maps from meteorological radar Sodar data
<i>Forecast data</i>	Data from numerical models	Products of NWP models (LAM and GM)
		Products from biological models (for example: phenological models)

floods due to strong rainfall (Jones, 1998; Gwangseob and Barros, 2001; Bowler and Pierce, 2004; Olaya, 2004; Grimbacher and Schmid, 2005). Availability of NWP models parameterized and validated for the reference territory and the weather phenomena for ready implementation in forecasting can be of great help. The usefulness of NWP prognoses can be evaluated on the basis of and taking into account the velocity of mesoscale development of weather phenomena. This means that time and spatial scales of NWP outputs must be defined in order to satisfy all the operational requirements for phenomena that show a very rapid mesoscale development (Heijboer et al., 1989), and that the assimilation procedure of NWP must be defined in order to receive local observational inputs with hourly or sub-hourly time steps.

Conceptual models are useful in order to provide: (i) a definition of phenomena in terms of features recognizable by observations, analyses or validated simulations; (ii) a description of the life cycle of phenomena (time of appearance, size, intensity and

accompanying weather); (iii) a statement of the controlling physical processes, which enables one to understand the factors that determine the mode and rate of evolution of the phenomena; (iv) specification of the key meteorological fields demonstrating the main processes; (v) guidance for predicting formation using the diagnostic and prognostic fields that best discriminate between development and non-development; and (vi) guidance for predicting movement, evolution, senescence and disappearance (Conway et al., 1999). Advantages offered by conceptual models to forecasters involved in NC and VSRF are summarized in Table 5.12. Some conceptual models with examples are mentioned in Table 5.13.

Further improvements in VSRF and NC could be obtained not only through the enhancement of operational and broadcast techniques, but also by means of an increase in the continuity of operations of agrometeorological services, which can also be obtained by expanding the automation of procedures.

Table 5.12. Some reasons for the usefulness of conceptual models to forecasters (Conway et al., 1999)

<i>Usefulness</i>	
1.	Help in understanding and diagnosing phenomena
2.	Synthesis of all available information
3.	Four-dimensional "mental picture" of atmosphere
4.	Basis for isolating weather processes
5.	Basis for extracting the main signals from complex patterns
6.	Tools for assisting diagnosis of numerical models
7.	Supplement to numerical models for the nowcasting scale
8.	Tools for identifying errors in the numerical forecast
9.	Fast forecast method
10.	Independent forecast method
11.	Forecast method particularly for hazardous weather
12.	Possibility of filling in data gaps

Table 5.13. Some conceptual models with some examples

<i>Conceptual model type</i>	<i>Examples</i>
Models of fronts and frontal substructures, including topographical influences	Frontal models, such as a model using conveyor belts (Browning and Mason, 1981)
Models of convective phenomena	Supercell thunderstorms (Ray, 1986) Radiation fog (Guedalia and Bergot, 1994)
Models of fog, frost and low cloudiness	Radiation or advective frost (Stull, 1997)
Models of topographically induced weather features Other models	Sea/land breezes (Atkinson, 1981) Forecasting of dust storms (Barnum et al., 2004)

Table 5.14. Examples of the use of nowcasting and very short-range forecasts for agriculture

<i>Objective</i>	<i>Principal forecast variables</i>
Manage works without producing soil compaction	Precipitation
Manage field activities during the growing period of crops	Temperature, wind and precipitation
Minimize the waste of biocides applied against weeds, pests and diseases	Temperature, wind and precipitation
Manage frost mitigation activities	Temperature of air and crop tissues
Manage harvest activities for different crops	Precipitation, relative humidity, wetness of crops
Prevent and mitigate the effects of flash floods or debris flow	Precipitation

5.8.3 Operational examples

Nowcasting and very short-range forecasting can be useful for many different agricultural activities (Table 5.14).

5.8.3.1 Nowcasting and very short-range forecast of frost

Nowcasting and very short-range forecast of frost are extremely important for the management of agricultural practices against this event (such as low-volume irrigation, ground-based fans, trash fires). In Italy some agrometeorological services have used specific NC and VSRF outputs during the period crops were exposed to risk of late frost (from February to April) or early frost (October and November).

Friuli Venezia Giulia is a region located in north-eastern Italy with a significant presence of fruit trees (apple, pear, peach and actinide). Usually frost is very frequent during winter, but during spring and fall frosts pose a significant risk for fruit-growing. For this reason, several orchards are provided with low-volume irrigation devices that are used against spring frost and, in some situations, against fall frost (for example: risk for actinide fruits).

In order to switch on the irrigation, it is important to know when the frost will take place. The Regional Environmental Protection Agency for Friuli Venezia Giulia has produced a tool called ANGELA (*Algoritmo di Nowcasting per le GELate*, or algorithm for nowcasting of frost), which works routinely during periods potentially exposed to frost risk, giving the forecast temperature evolution from sunset to sunrise.

ANGELA is fed from dusk to dawn with the following data:

- Minimum temperature subjective forecast. This is the forecast of the minimum temperature for the coming night issued by the

forecaster. It is the synthesis of NWP outputs, meteorological data from all weather stations and the forecaster's skill.

- Hourly night-time temperature measurements gathered from automatic weather stations. These data are refreshed every hour so they give an up-to-date snapshot of the ground temperature field.

The physical model implemented in ANGELA for the night-time temperature drop is that of Reuter (Pelosi, 1986). In this model, the ground temperature is a function of sunset temperature and the time passed since sunset:

$$T_n = T_s - K \cdot n^{1/2}$$

In this equation T_n is the temperature at n hours from the sunset in °C, T_s is the temperature recorded at sunset in °C, K is the temperature drop coefficient and n is the number of hours since sunset. In spite of its simplicity, the model is quite realistic if the coefficient K is updated every hour during the night. The initialization of the model is done with the forecaster's minimum temperature, the sunset temperature and the length of the night in hours, assuming that the lower temperature is reached at the end of the night. In this step two values for K are computed: one concerning the pure minimum temperature issued by the forecaster and the other concerning the forecaster's minimum temperature minus 2°C. This is done to give two extreme values for K : K_{max} and K_{min} , which define the range for the K values computed in the further steps. The starting K is the simple average of the two extremes. Every hour after sunset, for each automatic weather station, the observed temperature is used to compute the new constants K . To give more robustness to the forecasts, that is to issue temperature forecasts without too much fluctuation throughout the entire night, the applied K is constrained in the defined range by means of a linear combination of K , K_{max}

and K_{min} . Furthermore, a quality check on observed temperatures is performed in order to avoid the use of local spikes.

Once the observed temperatures are available at the Agrometeorological Service Centre (CSA) and the ANGELA temperature forecasts are computed, an automatic connection with a local television broadcasting station updates the forecast, making the information available to everybody in real time. In recent years the ANGELA system was also adopted by the Veneto Regional Environmental Protection Agency.

In Trentino the frost warning service is run by the Agricultural Institute of San Michele (IASMA) and Meteotrentino. The service is aimed at providing minimum temperature forecasts to apple growers and crop practices assistants. Frost nowcasting is disseminated via the Web, while real-time temperatures (10° updating) are available via teletext and SMS on demand. For a selected number of stations, mechanistic models have been calibrated, which yield, site by site, the best estimates of minimum temperature when suitable meteorological conditions are predicted for the following night (clear sky, very stable atmosphere and calm or very light wind). If such conditions are assessed by the local meteorological service, models are implemented and issued on the Web. The Reuter algorithm (Pelosi, 1986) is also applied in an hourly update mode, correcting the hourly temperature decrease by recorded temperature data. Another approach consists of post-processing atmospheric model outputs by machine learning techniques: a “random forest” algorithm is applied to the fields predicted by ECMWF (temperature, wind, humidity, geopotential, sky cover) at the control time of 6 a.m. on the following day. The temperature forecast is improved with respect to the raw model output, and the forecast is available about 10 hours before sunset.

5.9 SHORT- AND MEDIUM-RANGE FORECASTS

5.9.1 Definition

Short- and medium-range forecasts describe the behaviour of weather variables (precipitation, air temperature, sky coverage and solar radiation, wind velocity and direction, and so on) and weather phenomena (frontal systems, anticyclones, tropical cyclones, squall lines, and the like). The typical range is beyond 12 hours and up to 72 hours for short-range forecasts (SRFs) and beyond 3 days and up to 10 days for medium-range forecasts (MRFs). A

short definition and some general characteristics of SRFs and MRFs are presented in Tables 5.1 and 5.2.

5.9.2 Usefulness for agriculture

SRFs and MRFs are important for farmers in the planning of work such as:

- (a) Preparatory activities, including land preparation and preparation of plant material;
- (b) Planting or seeding/sowing;
- (c) Management of crops, fruit trees and vines; application of fertilizer, irrigation; thinning, topping, weeding; pest and disease control;
- (d) Management of grazing systems;
- (e) Harvesting, on-farm post-harvest processing and transport of produce;
- (f) Livestock production activities (for dairy enterprises, beef systems, lamb and other livestock systems).

Furthermore, quantitative forecasts are an important source of data for simulation models that produce information useful for farmers (simulation of crop phenology; water and nutrient cycles; crop production; weed, disease and pest cycles).

5.9.3 State of technology

Forecast technology is constantly evolving due to the expansion of scientific knowledge of atmospheric systems and advances in technologies, such as monitoring tools that use satellites, networks of automatic weather stations, radars, lightning detection systems and so on. Other evolving technologies include forecasting tools, such as NWP techniques, statistical methods, empirical models, and methods derived from forecaster experience (rules of thumb).

The activities of the weather forecaster in nowcasting and very short-range forecasting are founded on analysis and extrapolation of trajectories that refer to a relatively wide set of products (radar maps, meteorological satellite images, NWP models, local and regional observations, and so on). In short- and medium-range forecasts, the evolution of atmospheric variables is mainly derived by numerical methods (NWP). The experience of the forecaster is important in order to evaluate the accuracy of outputs of one or more models for the particular area (topography, distance from sea, soil use, and so on).

The work of forecasters has evolved significantly over the years to take advantages of both scientific and technological improvements. The skill of numerical models has improved so much that some centres have implemented automating routine forecasts to allow forecasters to focus on high-impact

weather or areas where they can add significant value. It is not easy to determine a standard way to create weather forecasts since the methods used depend on several factors (Coiffier, 2004):

- (a) The forecast range;
- (b) The size of the domain to be covered (a large portion of the globe, a regional domain, a small country, a city);
- (c) The geographical context and related climatology (mid-latitudes, tropical or equatorial areas, isolated islands);
- (d) The potential risk associated with the expected weather at various ranges;
- (e) The organization of the forecast service (multi-purpose or specialized for agriculture);
- (f) The technical environment (available external and/or internal NWP products, in situ observations, satellite and radar images, lightning detection network, infrastructure catering to the needs of the forecaster, Web access);
- (g) The know-how of forecasters (professional experience and operational experience relevant to the selected area);
- (h) The reference end-user for forecasts (for example: general-purpose services or specialized ones for fields such as agriculture, civil defence, aviation, marine operations, hydrologic and water management service and road administration);
- (i) The reliability of the current state of weather variables.

5.9.4 Forecasts and NWP

Numerical Weather Prediction provides useful information for up to approximately 6–12 days (120–240 hours) in the future. It is based on solving a complex set of hydrodynamic equations that describe the evolution of the atmosphere, subject to the initial atmospheric state and initial conditions at the Earth's surface. Since the initial state is not known perfectly, all forecasts begin with estimates. Unfortunately, the system is very sensitive to small changes in the initial conditions (it is a chaotic system) and this limits the ability to forecast the weather deterministically beyond 6–12 days.

MRFs are founded on the use of the output of one or more global NWP models. Moreover, SRF redaction is founded on local area models (LAMs). At present, the availability of LAMs until 2–3 days after their emission can be considered the limit between an SRF and an MRF.

It is important to define these forecasts and describe the principal inputs (such as NWP) and outputs, with some significant examples. Model output

statistics (MOS) are statistical methods applied to outputs of NWP in order to improve the forecast skill for local or microscale phenomena that are not correctly modelled in a mechanistic way (for example, frost, maximum temperature, rainfall quantity or probability).

5.9.5 Probabilistic approach to SRF and MRF

An important evolution in SRF and MRF is represented by the introduction of a probabilistic approach to future states of weather. The same terminology adopted by forecasters is sometimes an expression of this uncertainty (see Table 5.15).

An example of a subjective probabilistic forecast for a viticultural area of Italy is represented in Table 5.16. Probability of precipitation was needed by farmers in order to apply pesticides during the vegetative period.

Ensemble forecasts are a mathematical method that can take into consideration the inherent uncertainty in MRF and SRF. Traditional weather forecasts are founded on the output of the best models available and used until they lose their skill due to the growth of small errors in the initial conditions. In medium-range forecasts, model skill is typically lost after six days or so, depending on the season. An alternate method that produces forecasts with skill up to 15 days after the initial forecast uses what is called the “ensemble forecasting” method, which was introduced to produce improved medium-range (3–15 days) weather forecasts. Instead of using just one model run, many runs with slightly different initial conditions are made. An average, or “ensemble mean”, of the different forecasts is created. This ensemble mean is likely to be better because it averages the many possible initial states and essentially smooths the chaotic nature of climate. In addition, it is now possible to forecast probabilities of different conditions because of the large ensemble of forecasts available.

5.9.5.1 Operational services and SRF/MRF for agriculture

5.9.5.1.1 Agrometeorological forecasting and advisory service

Agrometeorological forecasting services (or agrometeorological sections of general-purpose meteorological services) are organizations that produce information specialized for agriculture, forestry and fisheries. Agrometeorological (advisory)

Table 5.15. Quantitative aspects and uncertainty of precipitation forecasts expressed by means of words used by the forecaster (from National Weather Service, n.d.)

	<i>Probability of precipitation</i>	<i>Terms used</i>
	0%	None
	10%	Slight chance – Isolated
	20%	Slight chance
	30–50%	Chance – Scattered
	60–70%	Likely – Numerous
	80–100%	Categorical (“rain this afternoon”)
<i>General rules</i>	The likelihood of occurrence of precipitation is stated as a percentage. A measurable amount is defined as 0.01” (one hundredth of an inch) or more (usually produces enough runoff for puddles to form). The measurement is of liquid precipitation or the water equivalent of frozen precipitation. The probability is for a specified time period. The probability forecast is for any given point in the forecast area.	
<i>Examples</i>	1) In a precipitation forecast, the following terms of duration imply a high probability (80–100%) of occurrence: brief, occasional, intermittent, frequent. 2) If a forecast for a given county says that there is a 40% chance of rain this afternoon, then there is a 40% chance of rain at any point in the county from noon to 6 p.m. local time. This point probability of precipitation is determined by the forecaster by multiplying two factors: forecaster certainty that precipitation will form or move into the area x areal coverage of precipitation that is expected. 3) If the forecaster is 80% certain that rain will develop but is expected to cover only 50% of the forecast area, then the forecast would read “a 40% chance of rain” for any given location. 4) If the forecaster expects a widespread area of precipitation with 100% coverage to approach, but he/she is only 40% certain that it will reach the forecast area, this would, as well, result in a “40% chance of rain” at any given location in the forecast area.	

Table 5.16. Example of probabilistic approach to precipitation forecast. ERSAL (Lombardy Regional Agency for Agricultural Development) project for rationalization of pesticide distribution on vineyards. Forecast of rainfall for viticultural areas of Franciacorta, Cellatica, Botticino, Valtenesi and Lugana. Wednesday 2 July 1997

<i>Day</i>	<i>Probability of rainfall</i>
Thursday	0
Friday	2
Saturday	1
Sunday	2

Classes of probability of rainfall: 0 = absent (0%); 1 = low probability (0–30%);
2 = Medium probability (30–70%); 3 = High probability (>70%)

services are acts by such units for operational use. Some examples are discussed below.

5.9.5.1.1.1 Forecasts of cold spells and paddy rice

Cold spells during differentiation of flower organs are a significant risk for rice crop in extreme areas of the boreal (for example, France, Italy, China) and austral hemispheres (for example, Australia).

A drop in temperatures below the critical threshold (10°C–15°C for most of the mid-latitude varieties) causes male sterility with a significant decline in production. Cold spells are frequently triggered by synoptic and mesoscale phenomena (outbreaks of Arctic air and related thunderstorms) that can be forecast relatively easily by means of SRF and MRF. Farmers who receive this information can act by raising the level of water in ponds.

5.9.5.1.1.2 Output of NWP models and agro-meteorological simulation models

The Agrometeorological Research Station at Braunschweig of the German Weather Service (Deutscher Wetterdienst, 2004) has developed the agrometeorological advisory system AMBER. In AMBER, Kalman-filtered results of local (LM) and global (GME) LAM models at hourly intervals for locations of weather stations, as well as measured data at these locations, are used as boundary conditions for agrometeorological models. These are the AMBAV and AMBETI models, which calculate agrometeorological quantities for different crops and types of soil. These, in turn, are used to run a variety of models. Through the AMBAV model, the actual evapotranspiration for a variety of crops and types of soil is calculated considering soil moisture and crop development, which are derived from the phenological observations. In the AMBETI model, Braden (1995) calculates temperatures, water transport and moisture for several depths of different soils and for several canopies, including soil chill, as well as the development and melting of a snow cover. The interception of precipitation and radiation by crops and transmission of radiation into crop canopies, in addition to leaf wetness and leaf temperatures, are modelled.

With the help of these results from agrometeorological models for individual locations, the following information is derived by means of more specific agrometeorological models:

- (a) Occurrence of specific plant diseases and pests;
- (b) Advice about the need for spraying and other agricultural management/farming activities;
- (c) Soil tractability;
- (d) Optimal time for planting, irrigating and fertilizing for different crops;
- (e) Estimation of the extent of volatilization, runoff and infiltration of fertilizers, fungicides and pesticides;
- (f) Forecast of grain humidity, yield and harvest quality;
- (g) Estimation of the optimal harvest time for different crops and of each crop for different types of soil.

From the multitude of results obtained, those of interest for different groups of clients (for example, irrigating farmers, vegetable cultivators and animal producers) are selected and presented in different tables and figures. These results are sent automatically by e-mail and by fax to clients, such as individual progressive farmers, machinery groups

and agricultural organizations for given locations and their surroundings.

5.9.5.1.1.3 Forecasts and distribution of waste or nutrients

In recent years, large animal-feeding operations in the United States have come under intense scrutiny. A rise in the number of these operations has occurred at a time of increased awareness of the effects of non-point source pollution. Regional initiatives, such as the Chesapeake Bay Program, have focused in part on the non-point pollution caused by animal-feeding operations. Environmental catastrophes, such as the North Carolina hog farm spillage in the wake of Hurricane *Floyd*, have served to focus the spotlight on large, concentrated animal-feeding operations.

National rules were defined in order to carry out operations like animal feeding or waste distribution without nutrient/pollution runoff. In particular, Natural Resources Conservation Service (NRCS) technical standards and guidelines state that wastes and/or wastewater may not be discharged on land when the soil is saturated, frozen or covered with ice or snow; during precipitation; or when significant precipitation is reasonably expected within the next 72 hours. As a result of these rules, discharge of wastes/wastewater over land is based on two forecast products of the National Weather Service (NWS):

- (a) A valid NWS forecast (Figure 5.4) as primary information;
- (b) A farmers' map (Figure 5.5) as a secondary tool that can be utilized to evaluate whether land application activities can be conducted when the forecast alone would not.

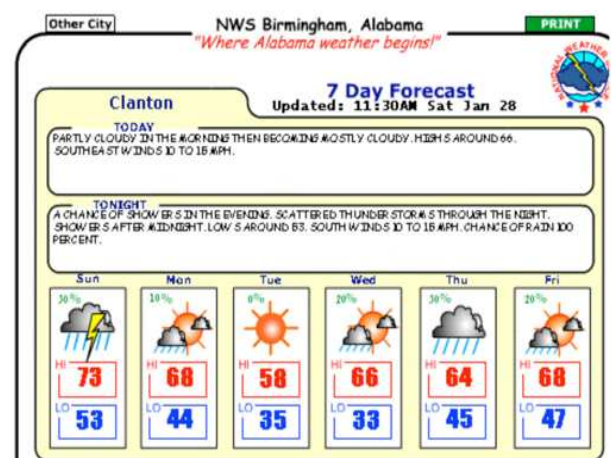


Figure 5.4. Example of NWS forecast available at http://www.srh.noaa.gov/bmx/data/forecasts/Clanton_forecast.html

Alabama Animal Waste/Nutrient Land Application Map
Issued: Jan 27, 2006 10:19 PM Based on Current 72 Hour Forecast

Valid Until: 01-28-2006 10:19AM



Areas in red are unfavorable for spreading of waste/nutrients
Areas in white are favorable for spreading of waste/nutrients

Figure 5.5. Example of NWS forecast map
available at http://www.srh.noaa.gov/bmx/data/FARMERS_MAP/farmers_map.html

Farmers can dispose of animal waste/nutrient on land if the NWS forecast predicts less than 50 per cent rain chance for each of the next 72 hours. In this case, the farmers' map is not needed. On the contrary, if NWS predicts 50 per cent or greater rain chance for each of the next 72 hours, a farmer can use land for disposal only if the farmers' map shows that the area in which the application will take place is white (not red). In other words, the farmers' map is intended to provide farmers with an additional option when the likelihood of rain is elevated, but the amount of rain predicted is low (not expected to cause runoff from the field). If farmers need to use land for disposal when the rain prediction is 50 per cent chance or greater sometime during the next 72 hours, they can view the farmers' map (available on the Internet site of the NWS), verify that their area is white (not red), print a copy for their records, and then carry out the land disposal according to the nutrient management plan prepared as part of their facility's comprehensive waste management system plan.

Use of land application for disposal is not authorized up to 72 hours prior to a significant chance or amount of rain. Use of land application for disposal may commence or resume immediately following the rain, however, provided that the weather prediction for the next 72 hours is favourable, and field conditions meet NRCS technical standards and guidelines.

5.9.5.1.1.4 Examples of operational agro-meteorological services in India

The India Meteorological Department (IMD) renders Agromet Advisory Services (AAS) to the country's farming community in the form of bulletins. These advisories are prepared jointly by the experts of IMD and agricultural specialists at respective state departments of agriculture and are tailored to the requirements of farmers in the given state. These bilingual (in the local/regional language and also in English) bulletins are disseminated on a real-time basis through All India Radio, the Doordarshan Kendra television network, newspapers and the IMD Website.

All the AAS centres of IMD actively monitor the state of crops, the occurrence of pests and diseases, and extreme weather events throughout the country. Accordingly, IMD issues warnings for pests and diseases and remedial measures against extreme weather events. These are communicated to users and to planners in time to safeguard crops, and they allow for updating of the status of agriculture at the policymaking level in the respective states. The AAS centre in the north-western part of the country also monitors the desert locust situation in north-west India and issues advisories to the state departments of agriculture concerned. Some examples of agrometeorological services in different regions of India are provided below.

For north-west India:

Severe frost conditions prevail in Himachal Pradesh and Jammu and Kashmir during second week of January. Snowfall likely to occur at a few places over Himachal Pradesh and Jammu and Kashmir divisions for the next five days. Under these circumstances, farmers in the above states are advised to take the following precautionary measures:

Irrigation should be given to protect standing crops from ground frost, as adequate soil moisture keeps the soil comparatively warm and saves it from frost.

Owing to ground frost, smoking should be conducted to protect crops.

In the morning, two men holding a rope should move across the field so that the dew formed over the leaves will drop.

Protect the young saplings of orchard trees from cold injury by covering them with polythene or paddy straw.

As morning humidity will be of the order of 85 per cent in Punjab and Haryana, the incidence of rust diseases will be likely (above the economic threshold level) on wheat. It is advised to monitor the incidence of diseases and apply Mancozeb at the rate of 2 g/l of water. Use 200 litres of water for one acre.

For east India:

Blast disease may appear in the seedbed of rice during this period due to the prevailing weather conditions in West Bengal. If noticed, spray Ediphenphos 50% @ 1 ml or Triamiphos 48% @ 1 ml or Carbenidazole 50% @ 1 ml per litre of water. A total of 75 litres of water is required to spray 25 satak of seedbed land.

Downy mildew is reported in cucurbits in Orissa and the disease intensity is expected to increase further under the prevailing weather condition. To control downy mildew, spray Redomyl/Mancozeb @ 2 g per litre of water. Use 200 litres of water for one acre.

For north-east India:

There is a likelihood of incidence of pod borer on red gram during this period in Assam under prevailing weather condition. To control pod and apion borer, spray Melathion 50EC @ 1.5 ml per litre of water or Fenitrothion 50EC @ 2 ml per litre of water on a non-rainy day.

As there was no significant rainfall in most of the districts in Assam during last few weeks and dry weather will prevail for next five days, apply required irrigation wherever crops are at pod formation stage.

For south India:

There was no rainfall for the last five weeks in all the districts of Andhra Pradesh and no significant rainfall is expected for the next five days. Under the circumstances, apply irrigation to the standing crops to bring the soil moisture to its field capacity.

*Release predators like *Dipha* sp, adopt wider spacing, inter-crop with soybean and pulses of short duration and ratoon sugarcane to control woolly aphids in Mysore, Mandya, Hassan, Bidar and Bangalore districts in Karnataka.*

Attack of red palm weevil is reported in coconut in Kerala. Fill leaf axil with Sevidol 8 G @ 25 gm mixed with fine sand 200 gm per tree, and trunk hole filling and sealing with 10 ml DDVP in 1 litre of water.

For west India:

The lowest minimum temperature of -2°C was recorded at Pilani on 09.01.06 in Rajasthan. Cold-wave conditions accompanied by ground frost likely to occur in extreme north of Jaipur and Bikaner divisions for the next five days. The following precautionary measures may be taken.

Irrigation should be given to protect standing crops from ground frost, as adequate soil moisture keeps the soil comparatively warm and saves it from frost.

Due to ground frost, smoking should be conducted to protect the crop.

In the morning two men holding rope should move across the field so that dew formed over the leaves will drop.

Protect the young saplings of orchard trees from cold injury by covering them with polythene or paddy straw.

As temperature is abruptly high, that is, 3°C – 9°C above normal in Rajasthan, maturity of barley and wheat may be advanced by about 10–12 days, which may lead to shorter reproductive phase and lower yield of crops. Apply irrigation at frequent intervals to barley, wheat, gram, cumin, beans and vegetables to supplement the high rate of transpiration from the crop as temperature is 3°C – 9°C above normal and there was no rain over the state for last few weeks and the dry weather will prevail for next five days.

For central India:

As there was no significant rain during last few weeks and dry weather is likely to prevail during next few days in Madhya Pradesh and Chattisgarh, apply irrigation to the standing crops to bring soil moisture to its field capacity.

5.9.5.1.2 General-purpose meteorological services

General-purpose services produce and broadcast forecasts for very wide categories of end-users. These services could survey the needs of farmers and provide information useful for this particular

category of users, especially when this information is crucial for quantity and quality of production.

5.10 LONG-RANGE FORECASTS

Long-range forecasts (LRFs) are forecasts for periods greater than one month. The contents of this section have been drawn mainly from the ECMWF Website (http://www.ecmwf.int/products/forecasts/seasonal/documentation/ch1_2.html).

5.10.1 The basis for LRFs

Despite the chaotic nature of the atmosphere, long-term predictions are possible to some degree thanks to a number of components that are to a certain extent predictable, although they do show variations on long timescales (seasons and years) (ECMWF, 2005). The most important of these components is the ENSO cycle, which refers to the coherent, large-scale fluctuation of ocean temperatures, rainfall, atmospheric circulation, vertical motion and air pressure across the tropical Pacific. It is a coupled ocean–atmosphere phenomenon centred over the tropical Pacific, but the scale of the fluctuations is quite vast, with the changes in sea surface temperatures often affecting not just the whole width of the Pacific but the other ocean basins too, and the changes in tropical rainfall and winds spanning a distance of more than one-half the circumference of the earth. El Niño episodes (also called Pacific warm episodes) and La Niña episodes (also called Pacific cold episodes) represent opposite extremes of the ENSO cycle. The ENSO cycle is the largest known source of year-to-year climate variability (ECMWF, 2005).

Changes in Pacific SST are not the only cause of predictable changes in the weather patterns. There are other causes of seasonal climate variability. Unusually warm or cold sea surface temperatures in the tropical Atlantic or in the Indian Ocean can cause major shifts in seasonal climate in nearby continents. For example, the sea surface temperature in the western Indian Ocean has a strong effect on the precipitation in tropical eastern Africa, and ocean conditions in the tropical Atlantic affect rainfall in north-eastern Brazil. In addition to the tropical oceans, other factors that may influence seasonal climate are snow cover and soil wetness. When snow cover is above average for a given season and region, it has a greater cooling influence on the air than usual. Soil wetness, which comes into play most strongly during warm seasons, also has a cooling influence. All these

factors affecting the atmospheric circulation constitute the basis of long-term predictions (ECMWF, 2005).

To summarize, seasonal forecasts provide a range of possible changes that are likely to occur in the season ahead. It is important to bear in mind that because of the chaotic nature of the atmospheric circulation, it is not possible to predict the daily weather variations at a specific location months in advance. It is not even possible to predict exactly the average weather, such as the average temperature for a given month (ECMWF, 2005).

5.10.2 Statistical and dynamical approaches to LRF

5.10.2.1 Statistical approach to LRF and related limits

A possible starting point for seasonal forecasting is a good knowledge of climate, that is, the range of weather that can be expected at a particular place at a particular time of year. Beyond a simple knowledge of climatology, statistical analysis of past weather and climate can be a valid basis for long-term predictions. There are some regions of the world and some seasons in which statistical predictions are quite successful: an example is the connection between the rainfall in March–May in the North-east Region of Brazil and the sea surface temperatures in the tropical Atlantic in the months before and during the rainy season (ECMWF, 2005).

Another example can be seen in the experimental forecasts of El Niño based on the study of the correlation between this phenomenon and patterns of sea surface temperature, surface pressure and wind (Adams et al., 2003). In theory, a very long and accurate record of the Earth's climate could reveal the combined (and non-linear) influences of various factors on the weather, and analysis of many past events could average out the unpredictable parts. In practice, the 50–100 year records typically available represent an incomplete estimate of the Earth's climate. In addition, seasonal predictions based on past climate cannot take full account of anthropogenic or other long-term changes in the Earth's system (ECMWF, 2005).

5.10.2.2 NWP approach to LRF and related limits

An alternative approach is to use the numerical weather prediction method by solving the complex set of hydrodynamic equations that describe the

evolution of the Earth's climate system. For an NWP-based seasonal forecast, it is important to consider both the atmospheric and oceanic components of the Earth's system. In fact, the air-sea interaction processes that describe the complicated interchange between the atmosphere and ocean are essential to represent the ENSO cycle. Just as for synoptic-range NWP forecasts, the calculation depends critically on the initial state of the climate system, particularly the tropical Pacific Ocean for ENSO. Because of the chaotic nature of the atmosphere, a large number of separate simulations are made. They will all give different answers in terms of the details of the weather, but they will allow something to be said about the range of possible outcomes and the probabilities of occurrence of different weather events (ECMWF, 2005).

If the numerical models were very realistic, and if very large ensembles of such calculations could be performed, the probability distribution of weather to be expected in the coming months would be accurately described. To the extent that predicted distribution differs from normal because of the initial conditions of the ocean, atmosphere and land surface, the ensemble calculations could predict the correct seasonal forecast "signal". Unfortunately, there are a number of problems that limit the seasonal forecast skill. Numerical models of the ocean and atmosphere are affected by errors, observations of the ocean are sparse, and techniques for estimating the extra uncertainty that this introduces are not yet well developed (ECMWF, 2005).

5.10.3 Reliability of LRF

The benefits of seasonal forecasting are likely to be most evident in forecasts for the tropics. This is because tropical areas have a moderate amount of predictable signal. This explains the use of LRF as a component of early warning systems (WMO, 2000) in order to extrapolate the potential occurrences of ENSO-related extreme weather/climate events. Models that transfer projected ENSO signals directly into agricultural stress indices have been developed for agricultural application (ECMWF, 2005). By contrast, in mid-latitudes random weather fluctuations are usually larger than the predictable component of the weather.

Much work will be needed to relate probabilities of large-scale weather patterns to detailed impacts and applications. It must be remembered, however, that there are tight limits on what is physically possible to achieve with a seasonal forecast system. It will be possible only to predict a range of likely outcomes. In many cases this range will be relatively large, and

there will always be a risk of an unexpected occurrence. In many parts of the world, most of the variability in the weather will remain unpredictable (ECMWF, 2005).

Some seasonal forecasts available today are issued with probabilities (or error bars) that have been properly calibrated against past cases. An example is the Canonical Correlation Analysis (CCA) prediction of El Niño variability, which is regularly shown in the NOAA Climate Diagnostics Bulletin. Such forecasts are probably fairly reliable, but they have very wide error bars: they may state that in six months there might be strong El Niño conditions, or fairly strong La Niña conditions, or anything in between (ECMWF, 2005).

5.10.4 Quality control of forecasts

5.10.4.1 Quality control data

The checking of forecast quality is an instrument that can be applied by services and end-users. In particular, end-users can choose better forecast products and services. Thornes and Stephenson (2001) present six attributes of a weather forecast that make up the total quality: reliability, accuracy, skill, resolution, sharpness and uncertainty.

The reliability of a forecast can be measured by calculating the bias. This will show if the forecasters are consistently over-forecasting the number of particular events (for example, frosts or snow). The percentage of correct forecasts is a very simple measure of forecast accuracy.

There are many different skill scores (for example, the Pierce Skill Score and the Odds Ratio Skill Score) that attempt to assess how much better the forecasts are than those that could be generated by climatology, persistence or chance.

Resolution is important in the forecasting of precipitation – being able to distinguish between snow, sleet, freezing rain, hail, drizzle and rain, for example. Sharpness is a measure of the spread of the forecasts away from climatology. For example, a forecast method that can predict frosts in spring as well as winter shows high sharpness, whereas a forecast method that can only predict frosts in winter has low sharpness. Uncertainty relates to the climate. For instance, some areas have comparatively fewer frosts than others.

A number of measures of forecast quality are therefore required, but in order to avoid confusion they must be easy to calculate and their

statistical significance should be testable (Thornes and Stephenson, 2001). The production and release of quality control data are important in order to guide the choice of the right weather prediction by farmers. If quality data are not available, agrometeorologists or farmers can use directly observed data (meteorological measurements of temperature, precipitation, sky coverage, weather phenomena, and so on) in order to evaluate the skill of forecasts. Statistical analysis can be carried out by means of non-parametric methods.

5.10.4.2 Feedback to operational services

The feedback of end-users is important in order to improve the forecast performance of services and single forecasters.

5.11 DISSEMINATION OF WEATHER FORECASTS AND ADVISORIES

Irrespective of its nature and importance, any information is useless until and unless it is promptly delivered to the users (for example, Vogel and O'Brien, 2006). Reliability of forecasts, expected weather-induced risks or weather-induced losses, and farmers' attitudes towards risk will affect the use of weather forecasts. Meinke et al. (2006) introduce salience, credibility and legitimacy as essential factors. All these factors can be assessed through the participation of farmers (for example, Onyewotu et al., 2003; Roncoli, 2006). A farmer's risk-bearing ability (income and assets) and individual characteristics, such as vulnerability and preparedness, will determine his or her attitude and adaptation skills with regard to risk. This, combined with expected weather-induced losses, will decide whether a farmer will be willing to use weather forecasts. Based upon a farmer's experience with traditional weather forecasts and expected losses due to adverse weather at different stages of crop growth, the extent of his or her use of forecasts may vary at different seasons and crop-growth stages. Thus, particularly in developing countries, there could be a number of categories of farmers using forecasts and other information (Rathore et al., 2006). In China the conclusion was drawn from large surveys that farmers with different income levels and rural people working in different occupations related to agriculture clearly had varying information needs, information sources and uses of information depending on their educational level as well (Ying and Stigter, unpublished results). In this connection, there may be different target

groups of users for agricultural weather forecast services and other agricultural advisories.

Weather forecasts are generally used more by highly skilled professionals such as researchers, extension workers, policymakers and progressive farmers. On the other hand, agricultural advisories are used more by farmers with less formal education for farm management purposes. There are some similarities and dissimilarities between these two target groups. The first group of users may rely more on fast electronic systems for the transfer of information, such as the Internet, CD, Very Small Aperture Terminal (VSAT) networks and e-mail. Conventional methods of communication, such as bulletins, pamphlets, posters, postal letters, newspapers, radio, television, (mobile) phone, pagers, local announcements, village meetings, local time-bound markets and personal communication are better to reach the second group of users (for example Rijks and Baradas, 2000). With the advent of computers and the Internet, emphasis is often being placed on electronic communication systems. Television and radio services are still the best ways of communicating advisories among rural people, however, because these are not only rapid methods, but they make it possible to contact large and illiterate masses as well. Broadcasting of advisories in the local language provides an edge over other means of communication (WMO, 1992; Weiss et al., 2000). With television and radio there remains the drawback that information appears only for short periods, unless taped, while much Internet-based information can be accessed for a longer time.

5.11.1 New dimensions in dissemination technology

Information technology is advancing very rapidly. There is good reason to claim that the present century will be the century of information technology. Easily available fast Internet facilities, supercomputers, high-capacity servers and efficient linking between information points have given a much-needed boost to information technology. While in the last century the communication systems were mostly one-way communications, in the present century interactive communication systems are being developed more extensively. There are some examples of interactive communication systems for the dissemination of agricultural advisories, and they are being adopted commercially by the most advanced providers and users in the United States, Japan and some European countries. The choice of technology must be made at the local level, however, and farmers have to be reached and exposed to information about the services. This

applies to developed and developing countries alike (see also Chapter 17 of this Guide).

5.11.2 **Internet-based communication systems**

The advantage of Internet-based interactive systems is that spatial variability in soil and management practices can be addressed. Farmers are advised on their farm-specific problems (for example Maia et al., 2005). Local weather conditions, type of soil, type of crop and phenological stage, as well as level and type of insect pest infestation, are considered in offering advisories for decision-making on sowing, harvesting, irrigation, nutrient management and chemical application (for example Dacom, 2003). In this system, users have the option of providing the observed field conditions or manipulating the input levels to analyse the different possible scenarios. An example from Denmark is described below to shed some light on this system. It should, however, also be realized that there is a serious risk that in many areas of the world it will not be possible to reach farmers through the Internet or other new technologies and therefore auto-referential services may end up being created.

5.11.3 **"PlanteInfo" and other Internet case studies**

The Danish Institute of Agricultural Sciences (DIAS) and the Danish Agricultural Advisory Centre (DAAC) jointly launched the Web-based online information system "PlanteInfo" (<http://www.PlanteInfo.dk>) in 1996 to provide decision support for crop production on an experimental basis. Over more than a decade, PlanteInfo has gone through many alterations and has now reached maturity in its effort to advise farmers on agricultural activities. More than 2 per cent of farmers and 50 per cent of crop advisers in Denmark are actively using the PlanteInfo system. Most of the PlanteInfo content is delivered as personalized Web pages requiring login; PlanteInfo stores information on users' geographical position and provides Web pages automatically on the basis of local weather observations and forecasts.

As an agrometeorological service, PlanteInfo provides information concerning arable crops (spring and winter wheat, spring and winter barley, oat, winter rye, triticale, spring and winter rape, peas, sugar beet and potato), fodder crops (grass and maize), vegetables (carrots, cauliflower, cabbage and onion) and fruits (strawberries and apples). A simple mechanistic simulation model runs in the background on input data generated

by PlanteInfo (Thysen and Jensen, 2004). Crop development and soil characteristics are considered for decision-making on irrigation and nutrient management. A separate module provides information on pests and diseases on the basis of weather parameters (such as aggregate temperature, aggregate soil temperature, rainy days, rainfall, humidity, and so forth) and the current state of the crop, as well as weeds, pests and diseases. Individual farmers are required to select the type of crop and cultivars and other input parameters, such as weather station and soil type, from a table on the Website. At the same time they are expected to furnish information on sowing, crop stage, amount of nitrogen applied, irrigation and previous crop (for residue management). The output is provided as a document that can be used after consideration of local conditions.

Other Web-based systems that provide agrometeorological services for crop management include SAgMIS in the Republic of Slovenia for irrigation management (Sušnik and Kurnik, 2004); IRRINET, BIDRICO and PLASMO in Italy for irrigation management (Rossi et al., 2004), irrigation and frost management (Gani et al., 2004), and grapevine downy mildew control (Orlandini et al., 2004), respectively; and ISIP (Information System for Integrated Plant Production) in Germany for plant protection (Röhrig and Sander, 2004). Paz and Batchelor (2003) developed another Web-based system for soybean crops in the United States, but forecast weather was not included and it does not deliver advice.

The Internet is also used in a non-interactive mode for the dissemination of agrometeorological services. The information is stored in text form on the Internet, and it is accessible to users from certain URLs, for example, <http://www.agmet.igau.edu.in> (Sastri et al., 2005). Advisories are also sent from the Internet to users by e-mail list servers, which require the e-mail addresses of the users.

The Advice concept (Thysen and Jensen, 2004) is aimed at bridging the information gaps and resolving the conflicting interests among information providers, information users (farmers) and intermediates (local advisers). It was observed over time that farmers are not enthusiastic to adopt the computer-based interactive advanced technology of advisory dissemination because of a reluctance to invest sufficient time in learning how to use the technology. But in recent years, agriculture has become an enterprise and a large number of professionals are engaged in the work of commercially advising farmers.

5.11.4 **Communication systems based on mobile phones**

Systems for the dissemination of services based on mobile phone networks are used in both interactive and non-interactive mode. The most advantageous feature of mobile phone systems is that farmers are able to communicate with the Web-based systems while in the field and can request advice concerning a newly discovered problem. Farmers can also update the farm database immediately after observations or application of treatments. In PlanteInfo, the Irrigation Manager has been optimized to advise on irrigation scheduling for individual fields. The Irrigation Manager needs to be set up with information on soil type, crop and emergence date. Local weather data (observed and forecast) are provided by the PlanteInfo weather database. The request is sent from the mobile phone (smartphone) to the PlanteInfo server, which is directed to the PlanteInfo Mobile homepage. Users can access the PlanteInfo system on mobile phones and generate the desired output in an interactive mode.

Mobile-based communication systems can also be used to get services and information in non-interactive mode. This mode is generally used for receiving the weather forecast or warnings of weather hazards such as frost, flash flood and forest

fire. The PlanteInfo system provides services and information related to weather and agricultural warnings in both modes of mobile communication.

A frost warning system based on Short Message Service (SMS) technology was launched in the Friuli Venezia Giulia region of north-eastern Italy in 2003. This area is prone to frost, especially in the months of March, April, May and November. The ANGELA model forecasts the night temperatures with a time resolution of one hour. A frost warning is sent to farmers through SMS twice per night, so that they can take necessary actions to protect crops (Gani et al., 2004). The probable time and region for the occurrence of frost are mentioned in the SMS. The Norwegian Meteorological Institute has been using the Varsling Innen PlanteSkadegjørere (VIPS) Web-based warning system (Folkedal and Brevig, 2004) and the Governmental Extension Services in Germany have been using the Information System for Integrated Plant Production (ISIP) (Röhrig and Sander, 2004) to provide information and services for crop protection via SMS communication since 2003. An SMS system of information and services transmission is also being tested by the Environmental Agency of the Republic of Slovenia for irrigation management (Sušnik and Kurnik, 2004).

ANNEX

Università degli Studi di Milano
Faculty of Agriculture – Department of Crop Science
CAMPUS WEATHER FORECAST

Thursday 16 June '05

authors: Luigi Mariani and Domenico Ditto

(Students that want to co-operate to this forecast may contact prof. Luigi Mariani)

Forecast produced for educational aims. The use for commercial or operational aims is explicitly denied. Servizio Meteorologico dell'Aeronautica and ARPA – Servizio Meteorologico regionale are the authorities for operational weather forecasting in Lombardia. Our data is not an alternative or substitute for the official weather forecasts.

GENERAL EVOLUTION

A ridge of the subtropical anticyclone gives conditions of stability and advects hot and humid air masses from North Africa towards Po plain. For the reference period weather will be sunny or almost sunny without significant probability of rainfall. Light winds or calm. Predictability of forecasted weather types: high until Monday, medium for Tuesday; low for the following days.

FORECAST FOR MILAN EAST – FACULTY OF AGRICULTURE

cloudiness and significant phenomena							
Thu 17/6	Fri 18/6	Sat 19/6	Sun 20/6	Mon 21/6	Tue 22/6	Wed 23/6	Thu 24/6
							
							
Detailed forecast							
Thursday 17				Friday 18			
Sunny throughout the day with a few scattered clouds. No precipitation is expected. Light winds or calm. Low Temperature 20°C; High temperature 31°C.				Sunny throughout the day with a few scattered clouds. No precipitation is expected. Light winds or calm. Low Temperature 22°C; high temperature 30°C.			
Saturday 19				Sunday 20			
Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 23°C; high temperature 30°C.				Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 24°C; high temperature 30°C.			
1.6.1 Monday 21				Tuesday 22			
Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 24°C; high temperature 31°C.				Sunny throughout the day. No precipitation is expected. Light winds or calm. Low Temperature 23°C; high temperature 29°C.			
Wednesday 23				Thursday 24			
Cloudy with low probability of rain (class 2; probability: very low). Light winds or calm. Low Temperature 23°C; high temperature 28°C.				Cloudy without rain. Light winds or calm. Low Temperature 24°C; high temperature 28°C.			

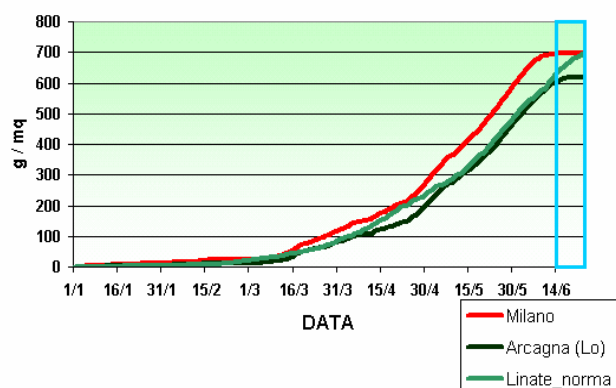
Pluviometric classes in 24 hours: Quantity: class 1: <1 mm (absent); **classe 2:** 1-10 mm (low); **classe 3:** 10-50 mm (abundant); **classe 4:** >50 mm (extreme) **probability for the reported class of quantity:** <1%=very low; 1-30%=low; 30-70%=moderate; >70%=high

NUVOLOSITA'					LEGENDA						
0/8	1-2/8	3-5/8	6-7/8	8/8	foschia	nebbia	FENOMENI		foehn	temporale	gelata
											

AGROMETEOROLOGICAL MODELS - 1 january / 23 june 2005

(cyan boxes are for simulations carried out on forecasted meteo data)

1. Net Primary Production (NPP)

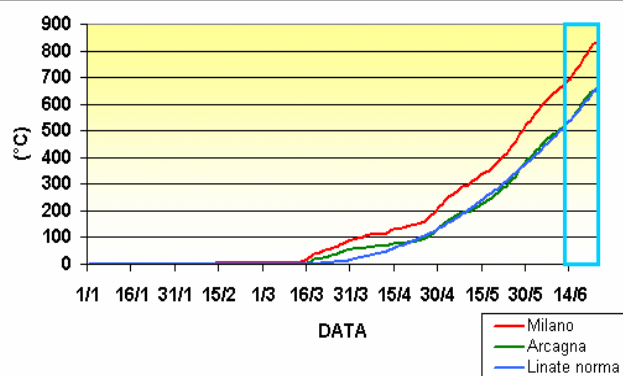


Net Primary Production (NPP) represents the organic carbon cumulated by plants. In this case NPP is referred to a meadow of C3 plants (*Arrhenatheretum*) ed is estimated by SIM_PP model (Mariani, Bocchi e Maugeri) [Carbon data = g m^{-2}]

COMMENT TO DATA

The storage of carbon was stopped due to soil water shortage. In these conditions the total storage at Milano, that in the previous period was above the normal due to the UHI effect, is reached by normal production (Milano Linate).

2. HEAT UNITS - BASE 10°C



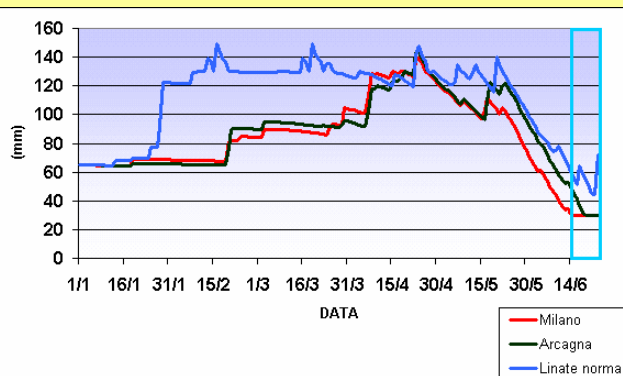
Thermal units (TU) are calculated subtracting 10°C from mean daily temperatures and cumulating only positive values.

They represent a measure of thermal resources for plants which present minimum cardinal of 10°C (summer crops, vine).

COMMENT TO DATA

Very close to normal TU calculated for Arcagna. Positive anomaly for TU cumulated at Milano, forecasted in increase also for the next week.

1.6 WATER



Soil water balance (WB) gives a quantitative evaluation of soil water useful for plants. This WB is carried out with the water balance unit of SIM_PP model (Mariani, Bocchi e Maugeri). Reserve is composed by a single reservoir with field capacity of 130 mm and wilting point of 30 mm. Water content at the beginning of balance was 50% of the AWC.

COMMENT TO DATA

The low levels of spring rainfall justify the anticipate emptying of soil water storage.

Sources of data: for the experimental farm of Arcagna we used data of meteorological station of Montanaso (www.ucea.it); for Milano Linate the reconstruction of daily data was carried out by means of a data generator to monthly climate data 1971-2000 of Servizio Meteorologico dell'Aeronautica (www.meteoam.it)

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AGROMETEOROLOGICAL FORECASTING

6.1 OVERVIEW

6.1.1 Scope of agrometeorological forecasting

Agrometeorological forecasting covers all aspects of forecasting in agricultural meteorology. Therefore, the scope of agrometeorological forecasting very largely coincides with the scope of agrometeorology itself. In addition, all on-farm and regional agrometeorological planning implies some form of impact forecasting, at least implicitly, so that decision support tools and forecasting tools largely overlap (Dingkuhn et al., 2003; Motha et al., 2006).

In the current chapter, the focus is on crops, but attention will also be given to sectors that are often neglected by the agrometeorologist, such as those occurring in plant and animal protection¹. In addition, the borders between meteorological forecasts for agriculture and agrometeorological forecasts are not always clear. Examples include the use of weather forecasts for farm operations such as spraying pesticides or deciding on the suitability of a terrain for passage in relation to adverse weather. Many forecasts issued by various national institutions (including those related to weather, but also commodity prices or flood warnings) are vital to the farming community, but they do not constitute agrometeorological forecasts. Some non-agrometeorological approaches do, however, have a marked agrometeorological component. This applies, for instance, to the airborne pollen capture method² of crop forecasting developed by Besselat and Cour (1997).

It is important to note at the very beginning of the present chapter that operational forecasting is done for different spatial scales (Gorski and Gorska,

2003). At the lowest end, the “microscale”, we have the field or the farm. Data are usually available with good accuracy at that scale. For instance, the breed or the variety is known, and so are the yield and the environmental conditions: soil type, soil depth, rate of application of inputs. The microscale is the scale of on-farm decision-making by individuals, irrigation plant managers, and so on.

The macroscale is the scale of the region, which is why forecasting for a district or province is usually referred to as “regional” forecasting. Regional forecasts are at the scale of agricultural statistics. Regional forecasts are relevant for a completely different category of users, including national food security managers, market planners and traders, and so forth. At the macroscale, many variables are not known and others are meaningless, such as soil water-holding capacity.

Needless to say, the real world covers the spectrum from macro- to microscales, but the two extremes are very well defined in terms of customers and methods³. Several applications are at an intermediate scale. They would include, for instance, certain types of crop insurance, the “livelihood analysis” that is now applied in many food security monitoring systems, fire monitoring systems, and so on.

Next, the links between forecasting and monitoring should be mentioned. Traditionally, monitoring is implemented by direct observation of the stage and condition of the organisms being monitored (type 1), or by observation of the environmental conditions that are conducive (or not) to the development of organisms (type 2)⁴. The second type applies mostly to pests and diseases. Surprisingly, type 1 monitoring is often more expensive than type 2 because of elevated labour costs. On the other hand, when data are collected to assess environmental conditions, this is relatively close to forecasting as data requirements naturally overlap between type 2 monitoring and forecasting.

¹ Plant and animal pathologists do traditionally deal with these issues, but they are not necessarily aware of the modern techniques (such as geostatistics) that are now familiar to most agrometeorologists.

² The method applies mostly to high-value and predominately wind-pollinated crops, such as grapes. Airborne pollen is sampled and calibrated against production in the surrounding area. The method is currently underdeveloped regarding the physico-physiological emission and capture of pollen by plants as a function of environmental conditions, transportation of pollens by air, trapping efficiency, including trap behaviour, and the effect of atmospheric agents, especially rain.

³ Time scales usually parallel spatial scales, with a decrease in sampling frequencies when they refer to large areas.

⁴ A reviewer rightly underlines the similarities between indirect monitoring (type 2) and nowcasting.

6.1.2 **Forecasting techniques in general**⁵

There are a variety of generic forecasting methods, most of which can somehow be applied to agrometeorological forecasting as well (Petr, 1991). According to Armstrong (2001), “judgement pervades all aspects of forecasting”. This is close to a definition that one of the authors has frequently applied to crop yield forecasting, which can be seen as “the art of identifying the factors that determine the spatial and interannual variability of crop yields” (FAO, 2003a). In fact, given the same set of input data, different experts frequently come up with rather different forecasts, some of which, however, are demonstrably better than others, hence the use of the word “art”.

There appears to be no standard classification of forecasting methods (Makridakis et al., 1998; Armstrong, 2001). Roughly speaking, forecasting methods can be divided into various categories according to the relative proportion of judgement, statistics, models and data used in the process. Armstrong identifies 11 types of methods, which can be grouped as:

- (a) Judgemental, based on stakeholders’ intentions or on the forecasters’ or other experts’ opinions or intentions. Some applications of this approach exist in agrometeorological forecasting, especially when other factors, such as economic variables, play a part (for instance, the “Delphi expert forecasting method” for coffee described by Moricochi et al., 1995);
- (b) Statistical, including univariate (or extrapolation), multivariate (statistical “models”) and theory-based methods. This is the category in which most agrometeorological forecasting belongs;
- (c) Intermediate types, which include expert systems (basically a variant of extrapolation with some admixture of expert opinion) and analogies, which Armstrong places between expert opinions and extrapolation models. This is also covered in the present chapter.

In this chapter, “parametric models” are considered to be those that attempt to interpret and quantify the causality links that exist between crop yields and environmental factors – mainly weather, farm management and technology. They include essentially crop simulation models⁶ and statistical⁷

⁵ Definitions used in the present chapter may differ from those adopted in other scientific areas.

⁶ Also known as process-oriented models or mechanistic models.

⁷ For an overview of regression methods, including their validation, refer to Palm and Dagnelie (1993) and to Palm (1997).

“models”, which empirically relate crop yield with assumed influential factors. Obviously, crop yield weather simulation belongs to Armstrong’s Theory-based Models.⁸ Non-parametric forecasting methods are those that rely more on the qualitative description of environmental conditions and do not involve any simulation as such (Armstrong’s Expert Systems and Analogies).

6.1.3 **Areas of application of agrometeorological forecasts**

6.1.3.1 **Establishment of national and regional forecasting systems**

There are a number of examples of institutionalized forecasting systems. As far as the authors are aware, they are never referred to as “agrometeorological forecasting systems”, even if many are built around some form of agrometeorological core (Glantz, 2004). Most forecasting and warning systems involving agriculture, forests, fisheries, livestock, fires, commodity prices, food safety and food security, the health of plants, animals and humans, and so forth, do have an agrometeorological component.

Some forecasting systems are operated commercially, for instance, for high-value cash crops (coffee, sugar cane, oil palm), directly by national or regional associations of producers. The majority of warning systems, however, have been established by governments or government agencies or international organizations, because of the high costs involved, the highly specific information needed for government programmes, or a lack of commercial interest (for example, in food security).

On the other hand, it is striking how few integrated warning and forecasting systems do exist. Clearly, fire forecasting, crop yield forecasting, pest forecasting and many other systems have various types of data and methods in common. Yet, they are mostly operated as parallel systems. For a general overview of the technical and institutional issues related to warning systems, refer to the above-mentioned volume by Glantz.

Good examples of pest and disease warning systems can be found in Canada, where pest warning services are primarily the responsibility of the provincial governments. In Quebec, warning services are administered under the Réseau d’avertissements phytosanitaires (RAP). The RAP was established in 1975; it includes 10 groups of experts and 125 weather stations and covers 12 types of crops. Warnings and other outputs from

⁸ Armstrong considers only econometric models.

the RAP can be obtained by e-mail, fax or the Internet (Favrin, 2000).

Warning and forecasting systems have recently undergone profound changes linked with the widespread access to the Internet. The modern systems permit both the dissemination of forecasts and the collection of data from the very target of the forecasts. Agricultural extension services usually play a crucial role in the collection of data and the dissemination of analyses of forecasting systems (FAO, 2001b, 2003a). In addition to providing inputs, users can often interrogate the warning system. Light leaf spot (*Pyrenopeziza brassicae*) is a serious disease of winter oilseed rape crops in the United Kingdom. At the start of the season, a prediction is made for each region using the average weather conditions expected for that region. Forecasts available to growers over the Internet are updated periodically to take account of deviations in actual weather from the expected values. The recent addition of active server page technology has allowed the forecast to become interactive. Growers can input three pieces of information (cultivar choice, sowing date and autumn fungicide application information), which are taken into account by the model to produce a risk assessment that is more crop- and location-specific (Evans et al., 2000).

Before they become operational, forecasting systems are often preceded by a pilot project to fine-tune outputs and consolidate the data collection systems. A good example is provided by the Pilot Agrometeorological Forecast and Advisory System (PAFAS) in the Philippines because of the number of institutional users involved. The general objectives of the proposed PAFAS were to provide meteorological information for the benefit of agricultural operations (observation and processing data) and to issue forecasts, warnings and advisories of weather conditions affecting agricultural production within the pilot area (Lomotan, 1988).

This section emphasizes that few warning systems can properly assess the damage caused by extreme agrometeorological events to the agricultural sector. Such damage may be significant; it may reach the order of magnitude of the gross national product (GNP) growth. For many disaster-prone countries, agricultural losses due to exceptional weather events are a real constraint on their overall economy. When infrastructure or slow-growing crops (such as plantations) are lost, the indirect effects of disasters on agriculture may last long after the extreme event takes place. The time needed to recover from some extreme agrometeorological events ranges from months to decades.

6.1.3.2 Farm-level applications

6.1.3.2.1 Overview

Farmers in all cultures incorporate weather and climate factors into their management processes to a significant extent. Planting and crop selection are functions of the climate and of the normal change of the seasons. Timing of cultural operations, such as cultivation, application of pesticides and fertilizers, irrigation and harvesting, is strongly affected by the weather of the past few days and in anticipation of the weather for the next few days. In countries with monsoonal climates, planting dates of crops depend on the arrival of the monsoonal rains. Operations such as haymaking and pesticide application will be suspended if rain is imminent. Cultivation and other cultural practices will be delayed if the soils are too wet. The likelihood of a frost will trigger frost-protection measures. Knowledge of imminent heavy rains or freezing rains will enable farmers to shelter livestock and to protect other farm resources. Irrigation scheduling is based on available soil moisture⁹ and crop water-use rate, both of which are functions of the weather. Farmers have always been very astute weather watchers and are quick to recognize weather that is either favourable or unfavourable to their production systems.

This traditional use of weather in farm management is significant, but it is not the only use of weather information in farm management. In addition to these well-known direct effects of weather on agricultural production, weather-wise farm management takes into account the indirect effects of weather. Temperature determines the rate of growth and development¹⁰ of insects, temperature and humidity combinations influence the rate of fungal infection, evapotranspiration rates determine water-use rates and irrigation schedules, and radiation and moisture availability are important in the rate of nutrient uptake by crops. These effects of weather on production are not directly observable and are not the basis of a “yes” or “no” or “don’t” type of decision, but they have significant economic potential when incorporated into the farm management process (McFarland and Strand, 1994).

⁹ The terms “soil moisture” and “soil water content” are used interchangeably.

¹⁰ Growth refers to the accumulation of biomass or weight by organisms. It is a quantitative phenomenon. Development, on the other hand, refers to the qualitative modifications that take place when organisms grow: formation of leaves, differentiation of flowers, successive larval stages of some insects, and so forth. While this chapter deals mainly with growth forecasting, there are applications in which development receives the most attention (see 6.5.5).

Consequently, regarding the importance of weather forecasting in farm management, the following aspects are crucial:

- (a) Current weather information (for example, forecasts) must be provided routinely to the decision-maker by an outside agency. Farmers cannot observe or develop all the necessary information;
- (b) Managers have to incorporate less-than-perfect weather information into their decision processes;
- (c) Farmers can develop and evaluate their decision processes for direct effects of weather, but must rely on outside expertise for decision support regarding indirect effects of weather.

The use of weather information in farm management in developing nations is particularly valuable when the level of production inputs is increased. Virtually all the inputs that characterize increased production are weather sensitive and most are also weather information sensitive. Irrigation, fertilization, pesticides, fungicides and mechanization are all more weather sensitive than traditional agricultural operations. In these cases, the incorporation of weather into the management process should be included when the technology involving the appropriate inputs is transferred. For example, when the use of insecticides for crop protection is implemented, the full use of weather information in pest management and the effects of weather on the application should be included in the technology transfer process.

Weather contingency planning for the farm level is not well developed. Swaminathan (1987) recommended that a "Good Weather Code" be developed, in addition to contingency plans based on drought or monsoon failure. Areas that are chronically drought-prone need measures to promote moisture retention and soil conservation.

Pest management is both weather sensitive and weather information sensitive. Weather sensitivity is primarily defined as the effects of wind, temperature and precipitation on application of the pesticide. The weather-sensitive aspects of pest management are supported by the more or less conventional weather information from the mass media. If the farmer is aware of the nature of the weather sensitivity, the existing decision processes should be sufficient. Scheduling of the times of application to avoid unfavourable winds or anticipated rains is within the farmer's traditional use of weather information. Weather information sensitivity is primarily the optimal timing of the pesticide as a function of temperature effects on

insect population dynamics and the crop growth rates. Insects are poikilothermic organisms, whose rate of growth and development is determined by the heat energy of the immediate environment. Temperature, as a measure of available heat energy, is used extensively to derive insect growth rates and development simulation models.

6.1.3.2.2 *Response farming applications*

"Response farming" is a methodology developed by Stewart (1988) and based on the idea that farmers can improve their return by closely monitoring on-farm weather and by using this information in their day-to-day management decisions. The emphasis here is on the use of quantitative current data, which are then compared with historical information and other local reference data (information on soils, and so on). This is a simple variant of the what-if approach. What about planting now if only 25 mm of rainfall has been recorded from the beginning of the season? What about using 50 kg N-fertilizer if rainfall so far has been scarce and the fertilizer will increase the crop water requirement and the risk of a water stress?

The method implies that, using the long-term weather series, decision tools (usually in tabular or flow-chart form) have been prepared in advance. They are based on the following information:

- (a) Knowledge of local environmental/agricultural conditions (reference data);¹¹
- (b) Measurement of local "decision parameters" by local extension officer or farmer;
- (c) Economic considerations.

In the latter, the decision tools must be prepared by national agrometeorological services in collaboration with agricultural extension services and subsequently disseminated to farmers. This operation will be the most difficult in practice (WMO/CTA, 1992).

A similar concept to response farming is flex cropping; it is used in the context of a crop rotation where summer fallow is a common practice, especially in dry areas, such as the Canadian prairies. Rotations are often described as 50:50 (1 year crop, 1 year fallow) or 2 in 3 (2 years crop, 1 year fallow). The term flex crop has emerged to describe a less rigid system in which a decision to re-crop (or not) is made each year based on available soil water content and the prospect of

¹¹ A simple example of this could be a threshold of air moisture or sunshine duration to decide on pest risk, or a threshold of salt content of water to decide on irrigation-salinity risk. Normally, other parameters (economic) also play an important part.

getting good moisture during the upcoming growing season (Zentner et al., 1993; P. Dzikowski and A. Bootsma, personal communication).

Weisensel et al. (1991) have modelled the relative profitability and riskiness of different crop decision models that might be used in an extensive setting. Of particular interest is the value of information added by the availability of spring soil moisture data and by dynamic optimization. The simulation has shown that flex cropping based on available soil moisture at seeding time is the most profitable cropping strategy. The authors stress the importance of accurate soil water content information.

6.1.3.2.3 *Farm management and planning (modern farming)*

Farmers have been using weather forecasts directly for a number of years to plan their operations, from planting wheat to harvesting hay and spraying fungicides. Simulation models, however, have not really entered the farm in spite of their potential. The main causes seem to be a mixture of lack of confidence and lack of data¹² (Rijks, 1997).

Basically three categories of direct applications of forecasts can be identified:

- (a) What-if experiments to optimize the economic return from farms, including real-time irrigation management. This is the only area in which models are well established, including models in some developing countries (FAO, 1992);
- (b) Optimization of resources (pesticides, fertilizer) in the light of increasing environmental concern (and pressure);
- (c) Risk assessment, including the assessment of probabilities of pest and disease outbreaks and the need to take corrective action.

Contrary to most other applications, on-farm real-time operations demand well-designed software that can be used by the non-expert, as well as a regular supply of data. In theory, some inputs could be taken automatically from recording weather stations, but specific examples are rare. A publication by Hess (1996) underlines the sensitivity of an irrigation simulation program to errors in the on-farm weather readings.

¹² For developing countries, one of the reviewers of this document adds the very basic "lack of electricity", lack of computers, lack of knowledge about the existence of models, not to mention the fact that models are rarely developed for the farming community.

Systems have been described in which some of the non-weather inputs come from direct measurement. Thomson and Ross (1996) describe a situation in which model parameters were adjusted on the basis of responses by soil water sensors to drying. An expert system determined which sensor readings were valid before they could be used to adjust parameters.

Irrigation systems have a lot to gain from using weather forecasts rather than climatological averages for future water demand. Fouss and Willis (1994) show how daily weather forecasts, including real-time data on the likelihood of rainfall from the daily National Weather Service forecasts, can assist in optimizing the operational control of soil water and scheduling agrochemical applications. The authors indicate that the computer models will be incorporated into decision support models (Expert Systems) that can be used by farmers and farm managers to operate water-fertilizer-pest management systems.

Cabelguenne et al. (1997) use forecast weather to schedule irrigation in combination with a variant of the Environmental Policy Integrated Climate model (EPIC, formerly the Erosion Productivity Impact Calculator). The approach is apparently so efficient that discrepancies between actual conditions and weather forecasts led to a difference in tactical irrigation management.

This section ends with an interesting example of risk assessment provided by Bouman (1994), who has determined the probability distribution of rice yields in the Philippines based on the probability distributions of the input weather data. The uncertainty in the simulated yield was large: there was a 90 per cent probability that simulated yield was between 0.6 and 1.65 times the simulated standard yield in average years.

6.1.3.3 *Warning systems, especially for food security*¹³

Many warning systems target both individual and institutional users, although governments are usually the main target of warnings for food security. In

¹³ Largely taken from WMO, 1997. Although pests and diseases are not the focus of this section, it is worth noting that many models developed in the general field of plant pathology can often be associated with the crop-weather models in impact assessments and warning systems. For an overview of such models, refer to Seghi et al. (1996). Most of them are typical developed-country applications, because both data availability and good communications permit their implementation in a commercial farming context.

many developing countries, farmers still practice subsistence farming, that is, they grow their own food, and depend directly on their own food production for their livelihood. Surpluses are usually small; they are mostly commercialized in urban areas (the urban population constitutes about 30 per cent of the total population in Africa). Yields tend to be low: in Sahelian countries, for instance, the yields of the main staples (millet and sorghum) are usually in the range of 600 to 700 kg/ha during good years. Interannual fluctuations are such that the national food supply can be halved in bad years or even drop to zero in some areas.

This is the general context in which food surveillance and monitoring systems were first established in 1978. Currently, about one hundred countries on all continents operate food security warning systems; the names of these systems vary, but they are generally known as (Food) Early Warning Systems (EWSs). They contribute to:

- (a) Providing national decision-makers with advance notice of the magnitude of any impending food production deficit or surplus;
- (b) Improving the planning of food trade, marketing and distribution;
- (c) Establishing coordination mechanisms among relevant government agencies;
- (d) Reducing the risks and suffering associated with the poverty spiral.

EWSs cover all aspects from food production to marketing, storage, national imports and exports, and consumption at the household level. Monitoring weather and estimating production have been essential components of the system from the outset, with the direct and active involvement of National Meteorological Services. Over the years, the methodology has kept evolving, but crop monitoring and forecasting remain central activities:

- (a) Operational forecasts are now mostly based on readily available agrometeorological or satellite data, and sometimes a combination of both. They do not depend on expensive and labour-intensive ground surveys and are easily revisable as new data become available;
- (b) Forecasts can be issued early and at regular intervals from the time of planting until harvest. As such, they constitute a more meaningful monitoring tool than the monitoring of environmental variables (rainfall monitoring, for instance);
- (c) Forecasts can often achieve a high spatial resolution, thus leading to an accurate estimation of areas and number of people affected.

Due to the large number of institutional and technical partners involved in EWSs, interfacing among disciplines has been a crucial issue. For instance, crop prices are usually provided as farm-gate or marketplace prices, food production and population statistics cover administrative units, weather data correspond to points (stations) not always representative for the agricultural areas, satellite information comes in pixels of varying sizes, and so forth. Geographical Information System (GIS) techniques, including gridding, have contributed to improving links in the “jungle” of methods and data (Gommes, 1996).

6.1.3.4 Market planning and policy

Advance knowledge of the likely volume of future harvests is a crucial factor in the market. Prices fluctuate as a function of the expected production¹⁴ (read: forecast production), with a large psychological component.

In fact, prices depend more on the production that the traders anticipate than on actual production. Accurate forecasts are, therefore, a useful planning tool. They can also often act as a mechanism to reduce speculation and the associated price fluctuations, an essential factor in the availability of food to many poor people.

Figure 6.1 shows that wheat prices increased from about US\$ 150 per tonne in 1993 to about US\$ 275 per tonne at the end of 1995. The main causes were the policy of both the United States and the European Union to reduce stocks (stocks are expensive to maintain), and the poor prospect for the 1995/1996 winter wheat in the United States and European Union. Maize, a summer crop, was affected by “contagion”. Had the forecasts been more accurate and reliable, it is clear that the prices would have remained more stable: they peaked around May 1996, and then returned to normal values.

A similar, but more dramatic situation occurred with coffee prices in 1977 when they reached an all-time high due to low stocks and frost in some of the main producing areas in Brazil (Brazil produces about 28 per cent of the world output, of which more than half comes from the states of São Paulo and Minas Gerais).

Commercial forecasts are now available by subscription. CROPCAST, for instance, provides estimates not only for yields, but also for production, areas, stocks,

¹⁴ The main factors affecting prices are world production forecasts, speculation, weather, stocks and the time of the year.

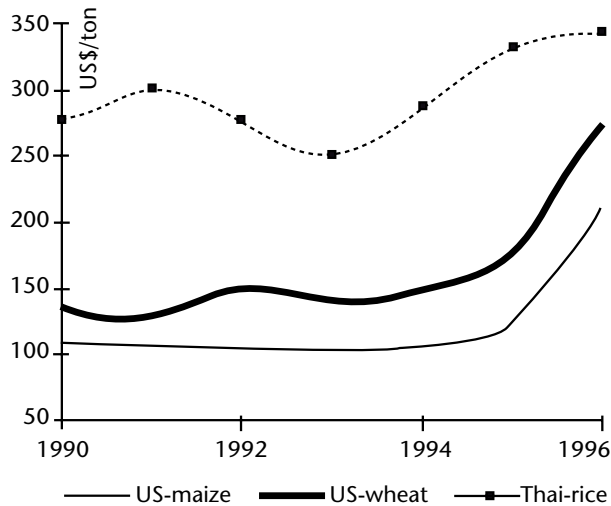


Figure 6.1. Variations in wheat, rice and maize prices between 1990 and 1996 (fixed 1996 CIF1 US\$ prices). The ticks on the X-axis represent the beginning of the respective years.

crop condition and futures prices (<http://www.mda-federal.com/mda-earthsat-weather/crop-cast-ag-services>).

On a local scale, many food-processing plants depend on production in their area, which is linked to the seasonality of production for most crops (canning of fruit and vegetables, sugar from sugar beet, cotton-fibre processing, oil from sunflowers and oil palm¹⁵, and so forth). It is important to have accurate forecasts for the volume to be processed and for the timing of operations.

6.1.3.5 Crop insurance

Crop insurance is one of the main non-structural mechanisms used to reduce risk in farming; a farmer who insures his crop is guaranteed a certain level of crop yield or income, which is equivalent, for instance, to 60 or 70 per cent of the long-term average. If, for reasons beyond the farmer's control, and in spite of adequate management decisions, the yield drops below the guarantee, the farmer is paid by the insurer a sum equivalent to his loss, at a price agreed before planting.

Crop insurance schemes can be implemented relatively easily when there is sufficient spatial

variability of an environmental stress (such as with hail), but they remain extremely difficult to implement for some of the major damaging factors, such as drought, which typically affect large areas, and sometimes entire countries.

One of the basic tools for insurance companies is risk analysis (Abbaspour, 1994; Decker, 1997). Crop forecasting models play a central part: when run with historical data, they provide insight into the variability patterns of yield. Monte Carlo methods play an important part in this context, either in isolation or in combination with process-oriented or statistical models. Almost all major models have been used in a risk assessment context, including the World Food Study, or WOFOST, model (Shisanya and Thuneman, 1993) and the Australian Sugar Cane, or AUSCANE, model (Russel and Wegener, 1990), among others (de Jager and Singels, 1990; Cox, 1990).

Many of the papers presented in July 1990 at the international symposium in Brisbane, Australia, on Climatic Risk in Crop Production: Models and Management in the Semi-arid Tropics and Subtropics, are relevant in the present context.

The use of crop insurance is not widespread in many developing countries and transition economies, although the World Bank and the World Food Programme are currently setting up schemes that should considerably facilitate food security-related operations by resorting to insurance-based emergency funds. The difficulty in implementing insurance schemes to assist smallholders is best explained by the fact that many farmers live at the subsistence level, that is, they do not really enter commercial circuits. Rustagi (1988) describes the general problem rather well. For instance, insurance companies insure a crop only if the farmer conforms to certain risk-reducing practices, such as early planting. The identification of the "best" planting dates constitutes a direct application for process-oriented crop-weather models. The paper quoted by Shisanya and Thuneman (1993) uses WOFOST to determine the effect of planting date on yields in Kenya.

An interesting example regarding both forecasting of the quality of products and insurance is given by Selirio and Brown (1997). The authors describe the methods used in Canada for the forecasting of the quality of hay: the two steps include the forecasting of grass biomass proper, and subsequent forecasting of the quality based essentially on the drying conditions. One of the reasons models have to be used is the absence of a structure that measures, stores and markets

¹⁵ Oil palm and other palms pose a series of very specific forecasting problems due to the long lag between flower initiation and harvest. This period usually covers three years or more. In addition, probably more than in other plants, qualitative factors are critical, for instance the effect of temperature on sex differentiation (only female flowers produce seeds, thus oil). See Blaak (1997) for details.

forage crops that is comparable to what is available for grain crops. In addition, field surveys are significantly more expensive to carry out than forecasts.

Crop forecasts used in crop insurance schemes must conform to several criteria that are less relevant for other applications:

- (a) Tamper-resistance: Potential beneficiaries of the insurance should not be in a position to directly or indirectly manipulate the yield estimate;
- (b) Objectivity: Once the methodology has been defined in precise terms, the forecasts can be calculated in an objective manner;
- (c) Special calibration techniques: A “poor year” is defined as a year in which conditions are bad enough to trigger the payment of claims to insurance subscribers. A “poor year” can be defined based on at least three approaches: (1) absolute yield levels (possibly the most appropriate choice for food security); (2) a percentage of the average local yield (a “fair” choice as expectations are different in high-potential and low-potential areas; and (3) probability of exceeding a specific yield (this usually gives “good” results in terms of statistical significance). Rather than the statistical strength of the correlation between yield and crop-weather index, it is the number of false positives (good year assessed to be poor) and false negatives (poor year assessed as good) that constitutes the most important criterion;
- (d) Insensitivity to missing data: The best way to circumvent the occurrence of missing spatial data is to use gridded information that is not too sensitive to individual missing stations, provided sufficient data points are available and the interpolation process takes into account topography and climatic gradients;
- (e) Publicity: Methodology has to be made available and understandable to potential subscribers of the insurance to build up mutual trust. Yield forecasts must be published regularly, for instance in national agrometeorological bulletins and through other channels, such as Websites.

6.2 **VARIABLES USED IN AGROMETEOROLOGICAL FORECASTING**

6.2.1 **Overview**

In agrometeorological forecasting, a statistic (for example, yield) that is being forecast depends very often on a number of variables belonging to different technical

areas, from the socio-economic and policy realms to soil and weather. The idea behind agrometeorological forecasting is first to understand which factors play a part in the interannual variability of the forecast parameter, and then to use the projections for those factors to estimate future yield.

A hypothetical example is shown in Figure 6.2: innovation and trend are mainly associated with technology, such as breeds and improved harvesting techniques. Policy covers essentially economic decisions (such as prices) that lead producers to increase or decrease inputs or, in general, to modify management practices in response to the socio-economic environment. Extreme factors and weather are separated here for two reasons: (1) not all extreme factors are weather related and (2) for those that are, the mechanism of their interaction with agricultural production is rather different from the mechanisms usually at play under “normal” conditions (see 6.4.5).

“Weather” is supposed to remain within the normal physiological range of variations: organisms can respond in a predictable way, following well-established and generally well-understood patterns (such as photosynthesis response to light intensity, transpiration of animals as a function of atmospheric moisture content and temperature). On the other hand, “extreme” factors exceed the normal range of physiological response.

Sections 6.2.2. to 6.2.5 below provide a list of variables that are frequently used for agrometeorological forecasting. For many years, agrometeorological forecasting has resorted to raw weather variables as the main predictors. The current tendency is to focus on value-added variables, that is, variables that have undergone some agrometeorological pre-processing using various models. Two such variables are soil moisture and actual evapotranspiration (ETA). Both are estimated using models. Soil moisture, for instance, constitutes a marked improvement over rainfall, because it assesses the amount of water that is actually available for crop growth and takes into account rainfall amount and distribution. Without entering into a discussion of indices and indicators, one can regard soil moisture as a complex derived indicator, a value-added forecasting variable.

There is no standard method to select variables used for crop forecasting, as clearly shown by the number and variety of approaches that have been developed for agrometeorological forecasting since the 1950s. The inclusion of limiting factors in the equations is characteristic of the existing methods.

These factors vary in relation to crop, cultivation technique, soil and climate conditions. For example, equations for arid regions include moisture provision indices (productive water reserves in the soil, precipitation, and so forth), whereas for rice (cultivated by flooding), atmospheric temperature and solar radiation values serve as the parameters. Data on crop conditions (number of stalks, leaf surface area, plant heights) are used in an array of methods. The majority of existing theoretical and applied yield forecast methods are based on statistical analysis of agrometeorological observation data and on correlation and regression analyses. The equations derived in these instances should refer only to specific regions and cannot be used in others.

Many mathematical models, however, in attempting to represent the complex processes of yield formation by allowing for many factors (including physiological processes, the stereometry of a crop, energetics of photosynthesis, and microflora activity in the soil), cannot be used at the present time to forecast yields in production conditions involving millions of hectares (regional forecasts). The primary reason for this is that it is not feasible to organize observations of these complex processes. Another factor is the efficiency required for synthesizing a forecast. Some forecast models are not efficient in the use of the simplest and least laborious forms of calculation, which permit the rapid retrieval of vast amounts of information even with a limited number of predictors.

Further refinement of the existing yield forecast methods requires considerable improvements of the reference data, namely, the agricultural statistics used for calibration, including improved maps of regional yield patterns. The extent of damage caused by pests and diseases, which is itself related to weather conditions, should be included as a correction factor.

Any deficiencies in the accuracy of agrometeorological forecasting depend on (a) how well the initial observations represent regional conditions; (b) how homogeneous the regional conditions (climate, soil characteristics, and so on) are; (c) how accurate the observations themselves are; and (d) how sensitive the model is to the variations in the agrometeorological variable being forecast (see 6.3.2).

Long- or medium-range weather forecasting methods have not yet reached the level of accuracy desirable for operational use, particularly in tropical countries. The temporal instability of some predictors does not allow the continued use of such models over a long time without change. The periodic revision of models also has to be viewed in the light of the possible impact of global warming and climate change on the interannual variability of meteorological parameters. In the case of medium-range weather forecasts, their accuracy level has improved potentially in extra-tropical countries (see 6.2.5.3).

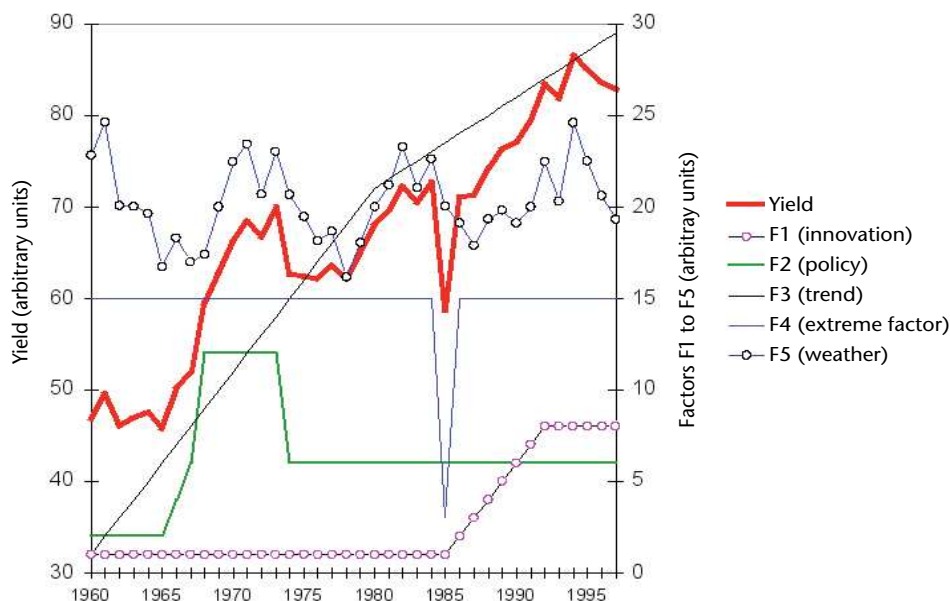


Figure 6.2. A hypothetical example showing how yield depends on various factors

6.2.2 Technology and other trends

Most agricultural systems are affected by technology trends and, sometimes, variations that are short-lived and not necessarily related to environmental conditions.¹⁶ One should stress that some biological production systems display regular variations that are endogenous or due to management practices. Some crops, for instance coffee in Kenya, display an alternating pattern of high and low yields (Ipe et al., 1989.) Another essential point is that trends may be difficult to detect in the presence of very high weather variability. Before the effect of weather conditions can be assessed, it is necessary to remove the trend (that is, to “detrend” the time series) and other non-weather factors.

The example in Figure 6.3 (Republic of Korea) shows a typical upward trend due to improved technology (varieties, management, inputs), as well as the linear and quadratic trend. The coefficients of determination

amount to 0.71 and 0.74, respectively. The coefficient achieved with the “best” trend model (a sigmoid, not shown) amounts to 0.80. Within the remaining 20 per cent, weather probably accounts for about half.

The sharp drop in 1980 was due to severe low temperatures around the heading through early ripening stage. Tong-il varieties are high-yielding hybrids that are very sensitive to abnormally cool temperatures due to the failure in pollination. In the late 1970s, the weather had been mostly favourable to rice cultivation, especially to the Tong-il type (B. L. Lee, personal communication). Threshold effects (such as the temperature effect mentioned above) are extremely difficult to forecast by most techniques. Non-parametric methods have an advantage over other approaches in this respect.

The middle curve shows the detrended yield (using the quadratic trend). This is the yield that will be used to calibrate a regional crop forecasting model. The lower curve shows the ratio between the yield of the current year and the average of the yields of the four preceding years, assuming that the trend is not significant over such a short period. The advantage of this approach is that no trend has to be

¹⁶ A fundamental assumption in model-building is that the behaviour of the agricultural production system is stationary or invariant over time. If this is not so, regression methods are generally invalid.

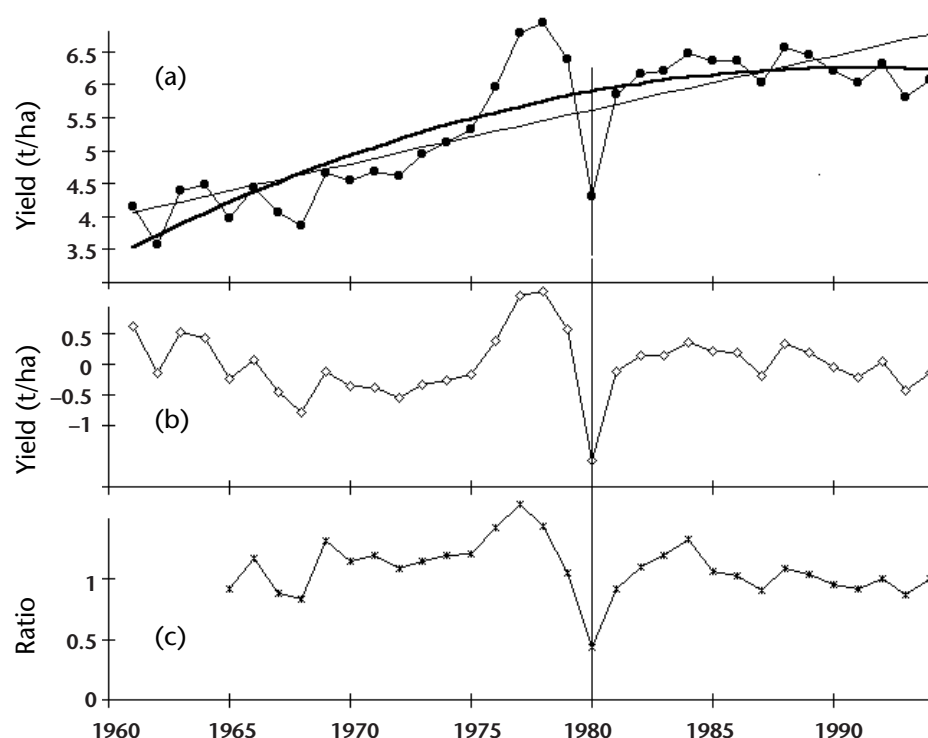


Figure 6.3. Yield of total paddy in the Republic of Korea between 1960 and 1994 (based on FAO statistics). The top curve (a) indicates the actual yields with their linear and quadratic trends; the middle curve (b) is the detrended yield, that is, the difference (residual) between actual yield and the quadratic trend; the lower curve (c) shows the ratio between the yield of year N and the average of the 4 years from N-1 to N-4.

determined, and no hypothesis has to be made about the shape of the trend. Some studies deal with the technology trend by predicting the difference between this year's yield and last year's yield (first order difference). As the method seems to ignore background climate, it is not further discussed here.

A number of methods can be used to cope with trends. The "best" approach is, of course, to include in the forecasting model some variables that contribute to the trend, whenever independent information is available about the technology component (such as the number of tractors per hectare or actual fertilizer use per hectare). One of the main factors behind trends, however, is the gradual change in the mix of varieties, which remains difficult to handle. In addition to the trend removal techniques illustrated above (largely drawn from Gommès, 1998a, 1998b), it is also possible to include time as a variable in statistical forecasts. The number of existing empirical methods developed to handle this problem is another illustration of the fact that crop forecasting relies frequently on the experience of the forecaster (it is "art", as mentioned several times).

6.2.3 Soil water balance: moisture assessment and forecast

6.2.3.1 Presentation

Soil moisture content at sowing and fruiting times is closely related to the emergence, growth and productivity of plants. In order to use irrigation efficiently, it is necessary to know the actual amount of water required to make up the depleted portion of the soil moisture at the various crop growth stages. Techniques have been developed accordingly for the forecasting – or assessment – of available moisture in a 1 m layer of soil at the beginning of the growing period. This is of great assistance to farm operators and agricultural planning agencies as a forecasting variable. This forecast is often based on climatological water balance methods or empirical regression-type equations.

An assessment of moisture conditions is based on past and present climatological data (such as precipitation, radiation, temperature, wind) with or without the use of soil moisture measurements. An extrapolation of this current estimate into the near future is possible through the use of long-term averages or other statistical values of the above meteorological data in the water balance equation. In addition, a soil water content forecast equation

is based on a statistical analysis of recorded soil water content data related to one or several other agrometeorological variables. This approach uses, sometimes on a probability basis, the occurrence of events in the past for extrapolation into the near future. Water balance methods use the following basic equation:

$$P - Q - U - E - \Delta W = 0 \quad (6.1)$$

where P is the precipitation or irrigation water supply, Q is runoff, U is deep drainage passing beyond the root soil, E is evapotranspiration and ΔW is change in soil water storage.

Each of the terms in this equation has special problems associated with its measurement or estimation. In most practical applications it is assumed that certain terms, such as Q or U , are negligible. Another assumption is that ΔW , at least over large areas and extended periods, can be set equal to zero. For short-term or seasonal applications, an approximate value of ΔW , that is, the soil water storage at the beginning and end of the period under consideration, is required. Such a value can be obtained from soil moisture measurements (WMO, 1968) but, more practically, from using climatic data in appropriate estimation techniques, such as those by Thornthwaite, Penman, Fitzpatrick, Palmer, Baier-Robertson or Budyko (WMO, 1975).

6.2.3.2 Soil water balance for dryland crops

An example of the application of the water balance approach to estimating soil moisture, as well as the stress period for dryland crops, is the cumulative water balance developed by Frère and Popov (1979), based on 10-day values of the precipitation and potential evapotranspiration. The water balance is the difference between precipitation received by the crop and the water lost by the crop and the soil through transpiration and evaporation, which is a fraction of the potential evapotranspiration. The water retrieval in the soil is also taken into account. The basic formula is as follows:

$$S_i = S_{i-1} + P_i - WR_i \quad (6.2)$$

where S_i is the water retained in the soil at the end of the 10-day period; S_{i-1} is the water retained in the soil at the onset of the 10-day period; P_i is precipitation during the 10-day period; WR_i represents the water requirement of the crop during the 10-day period.

WR_i in turn is defined as

$$WR_i = Kcr_i \times PET_i \quad (6.3)$$

in which PET_i is the potential evapotranspiration during the 10-day period and Kcr_i is the crop coefficient during the 10-day period.

Regression-type techniques for estimating soil moisture or changes in the water reserves have been developed in many countries for specific crops, soils, climates and management practices. The equations used take the following form:

$$\Delta Z = aW + bT + cP + d \quad (6.4)$$

where ΔZ is the change in soil moisture of a 1 m layer of soil over a 10-day period; W represents soil moisture reserves at the beginning of the 10-day period; T denotes mean air temperature over the 10-day period and P is the total precipitation over the 10-day period; a , b , c and d are regression coefficients.

Das and Kalra (1992) developed a multiple regression equation to estimate soil water content at greater depths from the surface layer data:

$$S = 0.22502 (d - d_0) + 50 (1 - 0.000052176 (d - d_0)^2) - 2.35186 \quad (6.5)$$

where S is the soil moisture at depth d and 50 is the soil moisture at or near the surface layer whose depth is d_0 . This equation was fitted to the moisture data under wheat grown in India under various irrigation treatments.

6.2.4 Actual evapotranspiration (ETA)

In the mid-1950s de Wit was among the first to recognize that there is a direct link between transpiration and plant productivity (van Keulen and van Laar, 1986). Transpiration can be limited due to a short supply of water in the root zone, or by the amount of energy required to vaporize the water. It can be said that plant growth (biomass accumulation) is driven by the available energy, but that plants “pay” for the energy by evaporating water. This is one of the basic “tenets” of agrometeorology.

Relative evapotranspiration is defined by the equation $Q = LE/LE_m$ and relative assimilation by $R_{ass} = F/F_m$. LE and F are evapotranspiration and assimilation, respectively. The subscript in LE_m and F_m denotes maximum values. A plot of relative assimilation R_{ass} as a function of relative transpiration Q is close to linear when Q values are relatively high (at least $Q > 0.6$). If other effects can be assumed to be constant, the relative assimilation over a day (measured as biomass accumulation) is directly

related to relative evapotranspiration (approximated by ETA):

$$\text{Daily biomass accumulation} \approx K * \text{ETA} \quad (6.6)$$

ETA is one of the best forecasting variables in absolute terms because, as indicated above, it is directly related to biomass production. But it is also useful owing to its synthetic nature (it includes radiation as one of its main driving forces). And finally, the linearity between ETA and biomass assimilation has been shown repeatedly to hold across many scales, from leaf to plant, to field and to a region.

The persistence of the relationship between ETA and biomass accumulation across spatial scales derives essentially from the fact that both CO_2 absorption and water transpiration take place through the same anatomic structure, the stomata. Maximum evapotranspiration (LE_m) and maximum assimilation (F_m) occur when the stomata are completely open, and both are close to zero when the stomata are closed. LE is the evaporative heat loss ($\text{J m}^{-2} \text{d}^{-1}$), the product of E , the rate of water loss from a surface ($\text{kg m}^{-2} \text{d}^{-1}$) and L , the latent heat of vaporization of water ($2.45 \times 10^6 \text{ J kg}^{-1}$).

It is recommended that actual ET be included as one of the variables in crop forecasting methods using multiple regression. Alternatively, variables derived from ETA are also often resorted to, for instance, the ratio between actual ET and potential ET (Allen et al., 1998). The Cuban early warning system for agricultural drought has been using this index because of its direct relation with crop yields (Rivero et al., 1996; Lapinel et al., 2006). There are other related indices, such as Riábchikov's index (Riábchikov, 1976), that can be used in climate change impact assessments. As ETA cannot be measured directly in most cases, it is best estimated using a water balance, as explained in 6.2.3.2.

6.2.5 Various indices as measures of environmental variability

6.2.5.1 Various drought indices

6.2.5.1.1 Overview

Drought indices can be quantified using a variety of relationships involving annual¹⁷ climatic values and long-term normals. The majority of the indices reflect the meteorological drought but not necessarily the shortage of water for agriculture. The problem

¹⁷ Shorter periods than annual are often considered.

of agricultural drought pertains to physical and biological aspects of plants and animals and their interactions with the environment. Since growth (biomass accumulation) is a complex soil–plant–environmental problem, agrometeorological drought indices¹⁸ must reflect these phenomena truly and accurately.

The indices can, however, provide useful variables when assessing the extent to which plants have been adversely affected by the moisture deficiency, taking into consideration supply and demand of soil water content. The soil water deficiency during the growing season may result in a partial or complete loss of crop yield. But the rainfall amount below which a reduced crop is considered drought-stricken depends on the degree to which a crop can withstand the moisture deficiency, as well as the stage and state of the crop. The time step used to derive the drought indices is crucial. A day or month may not be suitable. A pentad or weekly values are usually appropriate. These indices can also serve specific purposes, such as irrigation scheduling and drought management.

6.2.5.1.2 *Palmer drought severity index*

The Palmer drought severity index (PDSI) (Palmer, 1968) relates the drought severity to the accumulated weighted differences between actual precipitation and the precipitation requirements of evapotranspiration. The PDSI is based on the concept of a hydraulic accumulating system and is actually used to evaluate prolonged periods of abnormally wet or dry weather.

The index is a sum of the current moisture anomaly and a portion of the previous index, so as to include the effect of the duration of the drought or wet spell. The moisture anomaly is the product of a climate-weighted factor and the moisture departure. The weighted factor allows the index to have a reasonably comparable significance for different locations and time of year.

The moisture departure is the difference between water supply and demand. Supply is precipitation and stored soil moisture, and demand is the potential evapotranspiration, the amount needed to recharge the soil, and runoff needed to keep the rivers, lakes and reservoirs at a normal level. The runoff and soil recharge and loss are computed by keeping a hydrological account of moisture storage in two soil layers. The surface layer

can store 2.54 cm, while the available capacity in the underlying layer depends on the soil characteristics of the division being measured. Potential evapotranspiration is derived from Thornthwaite's method (Thornthwaite, 1948).

Note, however, that Thornthwaite's method is not recommended for all climate conditions. Variants of the PDSI using Penman–Monteith potential evapotranspiration or modified water balances have also been used (Paulo and Pereira, 2006; Pereira et al., 2007; Szalai and Szinell, 2000). The index is measured from the start of a wet or dry spell and is sometimes ambiguous until a weather spell is established. Table 6.1 contains the Palmer drought index categories. A week of normal or better rainfall is welcome, but may be only a brief respite and not the end of a drought. Once the weather spell is established (by computing a 100 per cent “probability” that the opposite spell has ended), the final value is assigned. This is not entirely satisfactory, but it does allow the index to have a value when there is a doubt that it should be positive or negative.

One aspect that should be noted is that the demand part of the computations includes three input parameters – potential evapotranspiration, recharge of soil moisture, and runoff – any one of which may produce negative values. If only enough rain fell to satisfy the expected evapotranspiration, but not enough to supply the recharge and runoff, then a negative index would result. If such an odd situation continued, agriculture would progress at a normal pace but a worsening drought would be indicated. Then if rainfall fell below the minimum needed for agriculture, crops would suffer drastic and rapid decline because there would be no reserve water in the soil.

6.2.5.1.3 *The crop moisture index*

Palmer (1968) developed the crop moisture index from moisture accounting procedures used in calculations of the drought severity index to measure the degree to which moisture requirements of growing crops were met during the previous week. The crop moisture index gives the status of purely agricultural drought or moisture surplus affecting warm-season crops and field activities and can change rapidly from week to week.

The index is the sum of the evapotranspiration anomaly, which is negative or slightly positive, and the moisture excess (either zero or positive). Both terms take into account the value of the previous week. The evapotranspiration anomaly is weighted

¹⁸ The Website of the National Drought Mitigation Center (<http://drought.unl.edu/>) has many useful definitions and data relating to drought.

Table 6.1. Palmer drought index categories

<i>Moisture category</i>	<i>PDSI</i>	<i>Moisture category</i>	<i>PDSI</i>
Extremely wet	≥ 4.00	Incipient drought	-0.50 to -0.99
Very wet	3.00 to 3.99	Mild drought	-1.00 to -1.99
Moderately wet	2.00 to 2.99	Moderate drought	-2.00 to -2.99
Slightly wet	1.00 to 1.99	Severe drought	-3.00 to -3.99
Incipient wet spell	0.50 to 0.99	Extreme drought	≤ -4.00
Near normal	0.49 to -0.49		

to make it comparable for different locations and times of the year. If the potential moisture demand exceeds available moisture supplies, the index is negative. If the moisture meets or exceeds demand, the index is positive. It is necessary to use two separate interpretations because the resulting effects are different depending on whether the moisture supply is improving or deteriorating.

General conditions are indicated and local variations caused by isolated rains are not considered. The stage of crop development and soil type should also be considered in using this index. In irrigated regions, only departures from ordinary irrigation requirements are reflected. The index may not be applicable for seed germination, for shallow-rooted crops that are unable to extract the deep or subsoil moisture from a 1.5 m profile, or for cool-season crops growing when average temperatures are below 12.5°C.

6.2.5.1.4 *The standardized precipitation index (SPI)*

The SPI was designed to be a relatively simple, year-round index applicable to all water supply conditions. Simple in comparison with other indices, the SPI is based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of timescales from one month out to several years. Any time period can be selected, and the choice is often dependent on the element of the hydrological system that is of greatest interest. This versatility means that the SPI can be used to monitor short-term water supplies, such as soil moisture that is important for agricultural production, and longer-term water resources, such as groundwater supplies, stream flow, and lake and reservoir levels.

Calculation of the SPI for any location is based on the long-term precipitation record for a desired period (three months, six months, and so forth). This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edward and McKee, 1997). A particular precipitation total is given an SPI value according to this distribution. Positive SPI values indicate precipitation above the median, while negative values indicate precipitation below the median. The magnitude of departure from zero represents a probability of occurrence so that decisions can be made based on this SPI value.

Efforts have been made to standardize the SPI computing procedure so that common temporal and spatial comparisons can be made by SPI users. A classification scale suggested by McKee et al. (1993) is given in Table 6.2.

The SPI has several limitations and unique characteristics that must be considered when it is used. Before the SPI is applied in a specific situation, a knowledge of the climatology for that region is necessary. At the shorter timescales (one, two or three months), the SPI is very similar to the representation of precipitation as a percentage of normal, which can be misleading in regions with low seasonal precipitation totals.

6.2.5.1.5 *Rainfall deciles*

Gibbs and Mather (1967) used the concept of rainfall deciles to study drought in Australia. In this method, the limits of each decile of the distribution are calculated from a cumulated frequency curve or an array of data. Thus the first decile is that rainfall

amount which is not exceeded by the lowest 10 per cent of totals, the second decile is the amount not exceeded by 20 per cent of totals, and so on. The fifth decile or median is the rainfall amount not exceeded on 50 per cent of the occasions. A similar approach was implemented in a number of countries, for instance in Cuba (Lapinel et al., 1993, 1998, 2000, 2006).

The values of the decile give a reasonably complete picture of a particular rainfall distribution, while knowledge of the decile range into which a particular total falls gives useful information on departure from normal. The first decile range (the range of values below the first decile) implies abnormally dry conditions, while the tenth decile range (above the ninth decile) implies very wet conditions. Das et al. (2003) use this concept to identify the different types of drought situations in India.

6.2.5.1.6 Aridity anomaly index

The India Meteorological Department (IMD) monitors agricultural drought on a real-time basis during the *kharif* crop season (summer crop season) for the country as a whole and during the *rabi* crop season (winter crop season) for those areas that receive rainfall during post-monsoon/winter seasons. The methodology involves computing an index known as the Aridity Index (AI) of the crop season for each week for a large number of stations, using the following formula:

$$AI = \frac{\text{Water deficit}}{\text{Water need}} = \quad (6.7)$$

$$\frac{\text{Actual evapotranspiration} - \text{Potential evapotranspiration}}{\text{Potential evapotranspiration}} \times 100$$

The departure of AI from normal is expressed as a percentage.

The following criteria are used to demarcate the area of various categories of agricultural drought. Anomalies can be plotted on a map to demarcate areas experiencing moisture stress conditions so that information is passed on to various users. These anomalies can be used for crop planning and in the early warning systems during drought situations (Table 6.3).

6.2.5.1.7 Surface water supply index

Another index that is in use is the surface water supply index (SWSI) (Shafer and Dezman, 1982). This measure was drawn up for use in mountainous areas where snowpack plays a significant role. Percentiles of seasonal (winter) precipitation, snowpack, stream flow and reservoir storage are determined separately and combined into a single weighted index, which is scaled and constrained to lie in the range -4 to $+4$, a typical range of the Palmer index. The question of how to determine the weights remains open; they need to vary during the year to account for elements such as snowpack, which disappear in summer, or for elements that have small or artificially manipulated values, such as reservoir storage. How to combine the effects of large reservoirs with small relative variability and small reservoirs with large variability in the same drainage basin is also a problem. The SWSI is most sensitive to changes in its constituent values near the centre of its range, and least sensitive near the extremes.

6.2.5.1.8 Crop water stress index

Jackson (1982) presented a theoretical method for calculating a crop water stress index (CWSI), requiring estimates of canopy temperature, air temperature, vapour pressure deficit, net radiation and wind speed. The CWSI was found to hold promise for improving the evaluation of plant water stress. The use of canopy temperature as a plant's drought indicator and stress is used by Idso et al. (1980) to calculate the stress degree-day (SDD) index. The cumulative value is related to final yields.

Table 6.2. SPI classification scale

SPI values	Drought category
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
-2.00 or less	Extreme drought

Table 6.3. Aridity anomaly index

Drought category	Anomaly value
Mild drought	up to 25 per cent
Moderate drought	26–50 per cent
Severe drought	more than 50 per cent

6.2.5.1.9 *Water satisfaction index*

Frère and Popov (1979) developed a crop-specific water satisfaction index (WSI) to indicate minimum satisfactory water supply for annual crops. At the end of the growing period, this index, which is calculated for every 10-day period, reflects cumulative water stress experienced by the crop during its growth cycle. The WSI is a weighted measure of ETA that can be correlated with crop yield.

6.2.5.1.10 *Other water-related indices*

There are a number of other water-related indices¹⁹ developed for specific applications, such as the rainfall anomaly index, or RAI (Van-Rooy, 1965; Oladipo, 1985; Barring and Hulme, 1991; McGregor, 1992; Hu and Feng, 2002). The national rainfall index proposed by Gommès and Petrassi (FAO, 1994) is spatially weighted according to the agricultural production potential. It provides a convenient bridge to studies in which national socio-economic data are considered in relation to rainfall and drought (Reddy and Minoiu, 2006).

6.2.5.2 *Remotely sensed vegetation indices*

This section focuses on the classical indices developed around the normalized difference vegetation index (NDVI), and definitions of these indices are given below. A number of other indices are used by various authors, however, such as the green leaf area index, greenness, vegetation condition index (VCI), transformed soil adjusted vegetation index, enhanced vegetation index, fraction of absorbed photosynthetically active radiation (fAPAR), and many others. In addition, the “raw” satellite variables can also be used as indices (for example, plant reflectance) and several indices known from crop ecophysiology, such as leaf area index, are now estimated on the basis of satellite observations as well.

Satellite-based vegetation indices also vary according to the satellite being used (for example, Gobron et al., 1999, for the Medium Resolution Imaging Spectrometer (MERIS) Global Vegetation Index (MGVI); and Huete et al., 2002, for indices based on Moderate Resolution Imaging Spectroradiometer (MODIS) data).

Finally, one should also stress that even if the names of the indices are similar or identical, the fact that they were obtained from different satellites using different spatial resolutions and different sensors results in variables that are not necessarily

comparable. The typical NDVI was originally obtained from Advanced Very High Resolution Radiometer (AVHRR) images taken from National Oceanic and Atmospheric Administration (NOAA) satellites starting more than 20 years ago. Currently, NDVIs are available from SPOT-VEGETATION (since 1998), EOS-MODIS (from 2000), and even from meteorological satellites, such as the METEOSAT Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) NDVI (Tucker et al., 2005).

During periods of drought conditions, physiological changes within vegetation may become apparent. Satellite sensors are capable of discerning many such changes through spectral radiance measurements and manipulation of this information into vegetation indices, which are sensitive to the rate of plant growth as well as to the amount of growth. Such indices are also sensitive to the changes in vegetation affected by moisture stress.

The visible and near-infrared (IR) bands on the satellite multispectral sensors allow monitoring of the greenness of vegetation. Stressed vegetation is less reflective in the near-IR channel than non-stressed vegetation and also absorbs less energy in the visible band. Thus the discrimination between moisture-stressed and normal crops in these wavelengths is most suitable for monitoring the impact of drought on vegetation.

Aridity anomaly reports used by IMD do not indicate arid regions. They give an indication of the moisture stress in any region on the timescale of one or two weeks, and they are useful early warning indicators of agricultural drought (Das, 2000). The NDVI is defined by them as:

$$\text{NDVI} = \frac{\text{NIR} - \text{VIS}}{\text{NIR} + \text{VIS}} \quad (6.8)$$

where NIR and VIS are measured radiation in near-infrared and visible (chlorophyll absorption) bands.

The NDVI varies with the magnitude of green foliage (green leaf area index, green biomass, or percentage green foliage ground cover) brought about by phenological changes or environmental stresses. The temporal pattern of NDVI is useful in diagnosing vegetation conditions. The index is more positive the more dense and green the plant canopy, with NDVI values typically in the range of 0.1–0.6. Rock and bare ground have an NDVI near zero, and clouds, water and snow have an NDVI of less than zero.

¹⁹ <http://drought.unl.edu/whatis/indices.htm>

Moisture stress in vegetation, resulting from prolonged rainfall deficiency, is reflected by lower NDVI values. Such a decrease could also be caused by other stresses, such as pest/disease infestation, nutrient deficiency or geochemical effects of the soil. Distinguishing moisture stress from other effects does not present a problem with coarse-resolution data over large areal units, because neither pest/disease attack nor nutrient stress is selective in terms of area or crop type.

Finally, three more indices characterizing moisture (VCI), thermal (the temperature condition index, or TCI) and vegetation health (the vegetation and temperature condition index, or VT) conditions were constructed following the principle of comparing a particular year's NDVI and brightness temperature (BT) with the entire range of variation during extreme (favourable/unfavourable) conditions. Since the NDVI and BT interpret extreme weather events in an opposite manner (for example, in case of drought, the NDVI is low and BT is high; conversely, in a year without drought, the NDVI is high, while the BT is low), the expression for TCI was modified to reflect this opposite response of vegetation to temperature.

The VCI and TCI were defined as:

$$VCI = 100 \times \frac{(NDVI - NDVI_{\min})}{(NDVI_{\max} - NDVI_{\min})} \quad (6.9)$$

$$TCI = 100 \times \frac{(BT_{\max} - BT)}{(BT_{\max} - BT_{\min})} \quad (6.10)$$

where NDVI, $NDVI_{\max}$ and $NDVI_{\min}$ are the smoothed weekly NDVI and its multi-year absolute maximum and minimum, respectively; BT, $BT_{\max}$ and $BT_{\min}$ are similar values for BT. The VCI and TCI approximate the weather component in NDVI and BT values. They change from 0 to 100, reflecting variation in vegetation conditions from extremely poor to optimal. In drought years leading to yield reduction, VCI and TCI values drop below 35 (Kogan, 1997). This level was accepted as a criterion for drought detection. The VCI and TCI were also combined in one index (VT) to express their additive approximation of vegetation stress, as shown by the following equation:

$$VT = \frac{VCI + TCI}{2} \quad (6.11)$$

With the development of the validation dataset, some weights will be assigned to the VCI and TCI indices.

6.2.5.3 El Niño–Southern Oscillation (ENSO) indices

6.2.5.3.1 Overview

In addition to the indices of agricultural drought, a number of general indices have been developed. These are really indices of the degree to which the weather has been abnormal. They do not attempt to include the biological uncertainties that arise when one tries to derive an index that relates to the specific agricultural or hydrological effects of a period of abnormally dry weather. Even so, a general drought index, properly interpreted, can be very useful for agricultural purposes (WMO, 1975).

6.2.5.3.2 ENSO indices as good predictors for future rainfall

The current state of drought-forecasting scenarios strongly suggests that some of the ENSO-based seasonal prediction methods, and methods based on other sea surface temperature (SST) anomaly patterns, can be used in several regions (Australia, East Africa and Southern Africa, for example) for skilful seasonal rainfall prediction and thus for crop forecasting. Significant efforts are required, however, to provide skilful drought predictions in a form that users can readily apply to crop forecasting.

6.2.5.3.3 Statistical forecasts of sea surface temperature

Even for regions with a strong ENSO influence, the historical record shows a less-than-perfect relationship between SST and anomalies in precipitation: precipitation anomalies typically show a consistent ENSO relationship in 75–80 per cent of the ENSO episodes during the last century. Even the best-performing statistical SST prediction schemes, however, have cross-validated correlations between observed and predicted tropical eastern Pacific SST of 0.8–0.9 for two seasons ahead in the northern summer through fall. Thus, if the anomaly correlation of the given regional precipitation with the observed SST is 0.8 in strong ENSO years, one might reasonably expect to make predictions of precipitation with anomaly correlations of 0.6–0.7 during such years – namely, in about half of all years. The average correlation over all years will be substantially less; this is consistent with experience (Barnston and Smith, 1996). At this relatively low level of overall skill, precipitation forecasts are best couched in terms of probabilities.

One of the main limitations of ENSO-based seasonal prediction schemes, however, is that ENSO is active in its warm or cold phases only about half the time. Over the past 100 years, there have been 30 warm and 19 cold episode years, according to the criterion of Ropelewski and Jones (1987), which is based on the Southern Oscillation Index (SOI). The close relationship between the SOI and the central equatorial Pacific sea surface temperature anomaly was noticed during most of the twentieth century. If precipitation were skilfully predictable during all such ENSO episodes, but not otherwise, drought prediction would be possible only about half the time. But crops must be planted and water resources managed every year. ENSO is not the only factor influencing many drought-prone regions, however.

6.2.5.3.4 *Prospects for improved forecasts: a case study for Australia*

Although the El Niño–Southern Oscillation is a major influence on Australian climate and provides a mechanism for predicting some aspects of droughts, considerable improvement would be needed for the forecasts to reach an acceptable level of skill at all times of the year, and for all of the country. As noted earlier, the ENSO effect is clearest in eastern and northern Australia. Further work is needed to provide a system that adequately forecasts rainfall in southern and western parts of the country. More crucially, the El Niño–Southern Oscillation does not provide much skill in prediction around the start of winter (February–June), when many farmers are preparing for planting. Most of Australia's crops are winter cereals, so information about winter and spring rainfall, available before planting, is crucial if farmers are to profit from insights into the ENSO phenomenon.

6.2.5.3.5 *Applying El Niño forecasts to agriculture*

Since the 1982–1983 El Niño event, the influence of this phenomenon on Australian climate has become well recognized. A computer package, “Australian RAINMAN” (RAInfall INformation for better MANagement), developed by the Queensland Department of Primary Industries and the Bureau of Meteorology, allows farmers and others to investigate the likely consequences of particular phases or trends of the SOI on rainfall at thousands of locations. When this information is combined with readily available current SOI values, users can prepare their own seasonal climate forecasts.

The availability of forecasts does not necessarily mean that they will be used to change decisions or, even if

they are, that the resulting decisions will lead to increased profit or less risk. There must be careful evaluation of how the forecasts might be used. Hammer et al. (1996) investigated the value of ENSO-based forecasting methodologies to wheat crop management in northern Australia by examining decisions on nitrogen fertilizer and cultivar maturity using simulation analyses of specific production scenarios. The average profit and risk of losses were calculated for the possible range of fixed (the same each year) and tactical (variable depending on the ENSO-based seasonal forecast) strategies. The technical (forecast-based) strategies would have led to significant increases in profit (up to 20 per cent) and/or reduction in risk of a loss (up to 35 per cent). The skill in seasonal rainfall and frost predictions, based on the El Niño–Southern Oscillation, generated the value from using tactical management. This study demonstrated that the skill obtainable in Australia was sufficient to justify, on economic grounds, the use of these forecasts in crop management. Presumably they could also be useful in drought management decision-making, for instance in determination of appropriate stocking rates on pastoral properties (McKeon et al., 1990).

6.2.6 **Heat supply forecast**

Heat supply forecast is required in the case of certain heat-loving plants to assess the most likely thermal conditions during the next growing season. Thermal conditions indicated mostly by growing degree-days (GDDs) during the growing season are useful for arriving at any strategic decision in the case of many major crops like soya bean, maize, wheat, and so forth (particularly temperate crops). This type of information is also useful in taking precautionary measures against insect pest and disease attacks on crops, for irrigation scheduling at critical growth stages, for prediction of harvesting time, for the drying of seeds to the required moisture content and for marketing fresh products. Finally, GDD is an essential variable in estimating the development stage of plants and pathogens such as fungi and insects.

In the region encompassing the subtropics and the mountainous areas of the tropics, total effective air temperatures (the temperature total over a period with mean diurnal temperatures higher than 10°C) are commonly used as agroclimatic indices for heat assurance characteristics during the growth of winter-growing crops. In order to estimate the degree of heat assurance in the region over the growing season and to compare this assurance among the different areas in the geographical cultivation range, the relationship between total effective temperature ($T_{\text{tot,eff}}$) in the 10°C–20°C

range and overall total temperature higher than 10°C ($T > 10$) can be calculated (Chirkov, 1979).

This relationship, over a total effective temperature range of 600°C–1 800°C has a non-linear nature and is expressed by means of the equation

$$T_{\text{tot,eff}} = 6.74 T > 10 + 140; R = 0.94 \quad (6.12)$$

Using this equation, it is easy to estimate effective heat resources in the geographical cultivation range.

For the purpose of estimating heat resources in the continental areas of a moderate climate region, as well as in the subtropics, a correction is introduced over the duration of the frost-free period, which is shorter in this region than the period with a temperature higher than 10°C.

6.2.7 Potential biomass and reference yield

Potential biomass is mentioned in the current context because crop forecasting methods regularly require a variable to express the local yield potential. This can be solved using several techniques. The easiest approach is to use average yield, when time series and cross-sectional data are used for calibration. Other authors prefer to use the local “yield potential”, that is, the yield that could be achieved in the absence of limiting factors. This “yield potential” is often expressed as the net primary production potential, or NPP.²⁰

There are a number of more or less empirical equations relating NPP with major limiting environmental factors such as rainfall or radiation. One of the most famous equations, developed by Monteith in the 1970s, is known as the “production ecology equation”. It applies a chain of “efficiencies” (factors) to gradually convert extra-terrestrial radiation to global radiation to photosynthetically active radiation (PAR) to radiation actually absorbed by vegetation (such as crops) and stored as chemical energy in biomass. The production ecology equation has been widely used for many applications (Binkley et al., 2004; Allen et al., 2005; Economo et al., 2005; Lindquist et al., 2005).

²⁰ A word of caution about NPP: NPP is seen in the current context as ecological production potential (net primary production potential), which differs from the net primary “agricultural” productivity. The factor that converts total dry biomass (roots, stems, leaves, grain) to grain, fibre, sugar, and so on, is known as harvest index H. H is usually in the range of 0.2 to 0.5.

An interesting equation, called the “Chikugo” model, is given by Uchijima and Seino. It is very useful for tropical areas where temperature is not limiting. It involves several terms of the water balance, that is, radiation and rainfall:

$$NPP = 6.938 \cdot 10^{-7} H \exp [-3.6 \cdot 10^{-14} (H/Prec)^2] \quad (6.13)$$

Uchijima and Seino use Budyko’s “radiative dryness index” (RDI), defined as $H/(L \cdot Prec)$, which is the ratio between H (the annual net radiation) and the product of L and Prec, L being the latent heat of vaporization of water and Prec annual precipitation. RDI expresses how many times the available energy can evaporate the rainfall. The equation shows the Chikugo model in International System of Units (SI) units²¹: NPP is the net primary productivity in g (dry matter) $m^{-2} \text{ year}^{-1}$, H in $J m^{-2}$, Prec in mm (equivalent to $kg m^{-2}$). The equation applies over the crop growing period.

6.3 IMPLEMENTATION OF YIELD FORECASTS IN PRACTICE

6.3.1 Data requirements

The data required for agrometeorological forecasting falls into two broad categories: (i) the input data that are required for each forecast, and (ii) data to calibrate and assess the model (see 6.4.2). In the case of crop forecasting, this second category of data must include yield data; it may also include other crop data such as phenology, biomass and leaf area index (LAI). Although crop yield data have already been discussed in some detail, two issues should be emphasized. First, the availability of these data is absolutely crucial if a forecasting system is to be reliable. Second, controlled-environment experiments and agricultural yield trials play an important role in understanding crop growth and the interaction between genotype and environment. The gap between yields obtained in these circumstances and those obtained in the growers’ fields is significant, however. There is a clear need for good-quality measurements of regional and local-level yields.

Input data requirements depend upon the forecasting method used. Simulation models (that is, process-based, or mechanistic, models) usually require daily inputs of temperature, radiation and rainfall as a minimum. Information on the soil type, crop variety

²¹ L, the latent heat of vaporization of water, disappears from the equation because it is a constant absorbed in the other constants. It is given explicitly in the original publication of the Japanese scientists.

and management techniques is also required, although the level of detail depends upon the model used (see 6.4). The spatial scale on which the model operates is particularly relevant here. For example, point-based models can be run using meteorological station data as long as the station is within or very close to the area where the crop is grown. At the other end of the modelling spectrum, models that simulate crop growth over larger areas require weather inputs that are representative of that area.

Satellite data are a useful source of large-area information for crop modelling. In addition to providing up-to-date rainfall estimates, they provide vegetation indices that can be used to derive LAIs. This, in turn, may be used to assess the performance of the crop model and update predictions. Meteorological forecasts must be used where projections into the future are required. These vary in character depending upon lead time and spatial scale. For example, forecasts up to approximately 10 days can be deterministic, whereas monthly and seasonal forecasts should consider chaos theory and therefore are often expressed probabilistically. Chapter 5 contains more information on weather and climate forecasting.

Simulation models and satellite data are complementary, because remote-sensing can contribute to estimating surface agrometeorological variables (FAO, 2001a). Furthermore, satellite inputs are currently used in crop modelling (Seguin, 1992; Nieuwenhuis et al., 1996; Stott, 1996; Cleever and van Leeuwen, 1997). In spite of current shortcomings of the proposed methods, there is little doubt that with improving spatial and spectral resolutions, progress will be made in the area of water balance components (soil moisture) and biomass estimations (especially the above-mentioned LAI and conversion efficiencies).

Early attempts to use satellite data in crop forecasting focused mainly on vegetation indices (VI), that is, satellite-derived indices that are related to living green biomass (see 6.2.5.2). While the qualitative use of VIs has become routine in many countries, their quantitative use in crop yield forecasting has remained disappointing, owing to well-understood factors. It is suggested that one of the largest potentials for VIs and other satellite inputs, such as cloud information, lies in their use as auxiliary variables for stratification, zoning and area averaging of point data in combination with GIS and geostatistics.

In many circumstances, particularly in many developing countries, fields tend to be small and irregular

in size and shape, and crops are often mixed, so that the sensors measure essentially a mix of crops and natural vegetation. It is then generally assumed that crops follow greenness patterns similar to vegetation. This is a reasonable assumption in areas where vegetation shows marked seasonality, for instance in semi-arid areas. Many of the difficulties listed disappear at higher spatial resolutions.

Rainfall information derived from weather radar and imagery from microwave satellites are now commonly available to the operational agrometeorologist. Microwave imagery provides estimates of superficial soil moisture. Together, the two sources have the potential to improve soil moisture estimations and, therefore, forecasts as well.

Whatever the source of data – observations, estimates, forecasts or a combination of these – it is important to recognize the associated measurement error and its impact on the agrometeorological forecast. This is the subject of 6.3.2 below.

6.3.2 Calibration and sources of error

Model calibration is the comparison of model output with reference values, usually actual yield, or some qualitative feature of an agricultural product, such as protein content of hay or tannin concentrations in wine. Errors are usually discovered during calibration and it is one of the objectives of calibration to reduce them.

The term “calibration” is used mainly²² for simulation models and it does not necessarily cover the same concept or criteria for different authors (for a more detailed discussion, see Gommès, 1998a). Accuracy, precision and sensitivity to changes in inputs are some of the criteria that are taken into consideration. The comparison of the model outputs with the real world is done for variables that are proxies in most instances; for example, simulated water uptake by roots cannot be compared with actual uptake rates, because such rates are unknown.²³ Because soil moisture can be observed, simulated soil moisture is compared with actual soil moisture. Unfortunately, actual soil moisture can depend on factors that are not taken into account by the simulation model, and in many cases, calibration, while necessary, does not ensure that the model describes the actual soil–plant–atmosphere interactions.

²² The term is also used for the calibration of sensors and instruments, the geometric correction of satellite images, and in several other areas.

²³ They can be observed, but in a very complex experimental setting.

In addition, reference data are often from experimental fields, most of which are very different from farmers' fields, where yields in particular are significantly lower than in experimental farms. For the purpose of regional crop forecasting, there used to be only one yardstick: regional yields as provided by national statistical services (NSSs). This is the reason crop forecasts are eventually calibrated against statistics and, strictly speaking, crop forecasts predict agricultural statistics. They also incorporate all errors and biases present in the statistics.

There is, however, a potential source of calibration data that, to the knowledge of the authors, has never been implemented: the original crop-cutting data that are the basis of many area and yield estimates produced by national statistical services. If NSSs could georeference the point yield measurements, they would offer a unique and unbiased source of calibration data.

The importance of using models only at the scale for which they were developed has been stressed above. This holds particularly in regional forecasting where statistical crop-weather models found their first applications. The European Community crop forecasting system is based on a version of WOFOST that is not crop-specific (Dallemand and Vossen, 1995; Vossen and Rijks, 1995; Supit, 1997); it is run with daily data interpolated to large pixels (50×50 km) and subsequently calibrated against agricultural statistics. For Europe, Vossen and Rijks list the main methodological issues as:

- (a) A change of scale;
- (b) Limited precision of input information, in particular weather data that do not necessarily represent the main cropping areas, uncertainties regarding phenology, and the like. The fact that inputs are no longer real data but spatial averages could be added here;
- (c) Some missing data, for instance, rooting depth (this factor is rarely critical in some humid climates where water supply is usually sufficient);
- (d) Insufficient spatial resolution of inputs;
- (e) Insufficient knowledge of agro-pedo-meteorological growth conditions and yield for the various regions of Europe;
- (f) Poor timeliness of some of the inputs.

It is suggested that an additional point could be mentioned, perhaps the most important one: the very long "distance" between the raw weather data and the final yield estimate at the regional scale. The "distance" would be measured in terms of pre-processing (indirect estimation of radiation, area averaging for many variables, and the like) and processing by the internal machinery of the models. It is suggested that many

process-oriented models are too complex for regional applications. Sensitivity analysis normally refers to model parameters, not to the input data, in particular the weather data, which are "given". It would nevertheless be most interesting to artificially contaminate the input data with a random factor or increasing magnitude to see what fraction of estimated detrended yield can actually be assigned to weather.

The section below discusses some sources of errors that commonly affect regional crop forecasts. They include:

- (a) Observation errors in the primary environmental and agronomic input data;
- (b) Processing errors in the input data, including transmission and transcription;
- (c) Biases introduced by processing: many models and forecasting methods are run with a mixture of actual (observed) and estimated data, that is, missing data that were estimated using models, other methods or expedients. Many inputs are now derived indirectly, with increasing frequency, from remote-sensing or weather radar. The conversion of the sensor reading to a physical environmental variable (radar rainfall, radiation) is prone to error;
- (d) Spatial "scale" errors: actual forecasts often have recourse to data with different spatial scales, such as points (stations), polygons (soil features), pixels of varying sizes (radiation, rainfall), and administrative units (agricultural statistics);
- (e) Temporal scale errors: in some cases daily-mean inputs of weather may not be enough to resolve key crop processes (see 6.5.6.1). Also weather forecasts tend to have greater error the longer the lead time;
- (f) Errors in ecophysiological crop parameters are relevant mostly for simulation models. They are also subject to scale errors: for instance, it is unlikely that the mesophyll resistance to water vapour diffusion measured in the lab can be applied to a field, let alone be used for a whole district;
- (g) Simulation model errors due to either structural model errors (incomplete or incorrect representation of the relevant processes) or accidental model errors (bugs in the computer implementation of models);
- (h) Errors due to non-simulated factors (pests, weather at harvest). There are models to assess their impact (for example, Debaeke and Chabanis, 1999), but those models are themselves subject to errors;
- (i) Errors in the agricultural statistics used for the calibration;
- (j) Calibration errors (choice of the statistical relation between crop model output and

agricultural statistics): this applies particularly when the data exhibit a trend that is not captured by the crop model. In this situation, assuming a linear or curvilinear trend may result in different forecasts;

- (k) Errors in the “future data”, that is, the weather or climate forecasts used for computing crop forecasts proper;
- (l) “Second-order errors”: assume that a correct forecast is made at the time of planting. Farmers may base their management decisions on the forecast: if they expect, for instance, that prices will drop because a large volume of production is anticipated, they may decide to use less fertilizer. As a result, although the original forecast based on historical data was correct, the use of the forecast in management has resulted in a larger-than-anticipated error (underestimate of production). Second-order errors are one of the reasons that forecasting methods have to be recalibrated annually.

Conflicts between results of different forecasting techniques do occur frequently: in most real-world situations, several forecasts are available from different sources and methods. The situation is often resolved rather empirically (final forecast is average of forecasts) or using “convergence of evidence”, that is, if two methods out of three agree, the third is discarded (refer to 6.4.4, which discusses the combination of methods).

When a forecast is made over an extended period of space and/or time, these sources of errors are manifest as errors in the mean yield (over time or space) and errors in the magnitude of variability in yield. Even when the mean and variability of yield are correctly simulated, the spatial and/or temporal distribution of yield may be incorrect. Root mean square error in yield estimation can be broken down into these three components in order to improve the understanding of the sources of errors (see, for example, Challinor et al., 2004).

6.4 BASIC AGROMETEOROLOGICAL FORECASTING APPROACHES

6.4.1 Empirical statistical relations

6.4.1.1 Introduction

Agrometeorological yield forecasting using a multiple regression always starts with a table of data containing yields and a series of agrometeorological and other variables that are thought to determine the yields. An

example of such a table is given below (Figure 6.4) with data from Malawi. Such tables are often referred to as the “calibration matrix.”

A regression equation (usually linear) is derived between crop yield and one or more agrometeorological variables, for instance:

$$\text{Yield} = 5 + 0.03\text{Rain}_{\text{March}} - 0.10T_{\text{C,June}} \quad (6.14)$$

with yield in tonnes ha⁻¹, March rainfall in mm and June temperature in °C. Beyond its simplicity, the main advantages of the equation are that calculations can be done manually, data requirements are limited, and the equation can be easily derived using standard statistical packages or a spreadsheet. An example of a statistical potato yield forecast is shown in Figure 6.5 below.

The main disadvantages of regression models are their poor performance outside the range of values for which they have been calibrated, that is, their inability to yield correct values in the event of extreme factors (see 6.5.4). This is why multiple regression “models” potentially lead to nonsensical forecasts. The equation above, for instance, suggests that low March rainfall (a negative factor) could be corrected by below-zero temperatures in June (frost), which obviously does not make sense. Another disadvantage is the need to derive a series of equations to be used in sequence as the cropping season develops.

Crop forecasting is as much art as science: with the same input data, some experts produce reliable and stable methods, while others come up with equations²⁴ that the experienced eye can discard at first glance. Nonsensical equations can be produced when the blind application of statistics prevails over common sense and agronomic knowledge.

6.4.1.2 “Golden rules” of regression forecasting and good-practice advice

The present note attempts to summarize some of the considerations that the crop forecaster should keep in mind when deriving multiple regression

²⁴ Whether multiple regression “models” are models at all is open to debate. If the explanatory variables are actual factors that influence yield (such as sunshine or soil moisture), it may be argued that the multiple regression equations qualify as models. If the equations use variables (predictors) that describe environmental conditions but do not influence yields (such as NDVI), however, the equation is not, strictly speaking, a model.

EPA-RDP	Yield (Kg/Ha)	YEAR	WRSIfin mm	DEfflow mm	DEFrip mm	ETAveg mm	WEXini mm
LINTHIPE-THIWI_LIFIDZI-1996	104	1996	86.4	0	-47.2	89.5	110.1
KABWAZI-THIWI_LIFIDZI-1996	109	1996	87.3	0	-43.1	88.7	112.9
KARONGA_CENTRAL-KARONGA-1997	110	1997	95.6	-2.4	-2.8	73.6	113.2
NAMPEYA-KAWINGA-1997	121	1997	89.1	-8.7	-14.5	86.9	129.3
MITOLE-CHIKWAWA-2005	128	2005	44.5	-227.8	-107.7	119.4	59.5
MITOLE-CHIKWAWA-1995	152	1995	33.6	-335.9	-91.0	113.7	35.9
MBEWE-CHIKWAWA-1995	160	1995	33.0	-335.9	-91.0	114.3	48.6
MIKALANGO-CHIKWAWA-2005	169	2005	42.4	-246.4	-101.2	118.6	60.9
MBWADZULU-MANOCHI-1995	184	1995	61.7	-112.0	-81.3	103.7	48.6
LIRANGWE-SHIRE_HIGHLANDS-2005	199	2005	59.5	-120.9	-91.8	106.1	50.1
NASENGA-MANGOCHI-1995	230	1995	71.7	-72.2	-62.0	96.5	34.6
NAMPEYA-KAWINGA-2005	251	2005	84.0	-43.0	-26.2	103.4	34.1
NANYUMBU-KAWINGA-1998	258	1998	84.0	-44.8	-19.5	91.6	32.1
LISUNGWI-MWANZA-1995	260	1995	47.8	-216.5	-99.6	110.9	96.8
DOLO-CHIKWAWA-2005	266	2005	48.6	-217.4	86.2	117.4	52.8
MPATSA-NSANJE-2005	271	2005	65.4	-130.2	-53.9	110.4	39.4
MULANJE_SOUTH-MULANJE-2005	272	2005	87.4	-27.9	-22.0	94.4	34.1
MAGOTI-NSANJE-1995	278	1995	52.5	-173.8	-50.8	109.0	43.5
MPINDA-PHALOMBE-2005	298	2005	74.2	-53.5	-45.9	91.3	26.0
MAKHANGA-NSANJE-2005	301	2005	50.7	-211.5	-77.8	117.0	55.5
CHIKWEO-KAWINGA-1998	302	1998	88.0	-25.0	-13.0	88.4	40.1
NASENGA-MANGOCHI-1998	305	1998	82.6	-60.2	-17.4	94.1	43.2
ULONGWE-BALAKA-1997	328	1997	76.5	-2.4	-41.3	99.0	178.9
MULANJE_WEST-MULANJE-2005	333	2005	85.5	-22.1	32.3	91.6	44.8
MAKHANGA-NSANJE-1995	345	1995	47.5	-207.7	-52.4	110.5	58.8
NTONDA-SHIRE_HIGHLANDS-2005	347	2005	49.1	-194.1	-93.2	110.0	51.5
KALAMBO-CHIKWAWA-1995	352	1995	37.5	-294.6	-107.8	114.6	99.4
PHALULA-BALAKA-2005	360	2005	70.6	-68.6	-68.4	99.1	47.5
NTUBWI-ZOMBA-2005	366	2005	68.5	-79.0	67.5	95.9	31.4
MPATSA-NSANJE-1995	368	1995	65.0	-110.5	-38.1	107.7	18.1
NANYUMBU-KAWINGA-2005	368	2005	77.3	-58.1	-46.8	99.9	34.1
MAGOTI-NSANJE-2005	374	2005	55.9	-181.3	-70.7	115.1	44.8
MPINDA-PHALOMBE-1995	376	1995	93.7	-7.4	-16.8	82.5	33.4
KALAMBO-CHIKWAWA-2005	379	2005	57.7	-140.6	-104.0	122.9	62.2
MIKALANGO-CHIKWAWA-1995	388	1995	36.6	-290.2	-71.2	112.4	23.2
KASONGO-PHALOMBE-2005	391	2005	84.0	-24.4	-31.9	88.1	16.7

Figure 6.4. Some lines from a typical calibration matrix (the actual lines amount to 1360). The data are for different RDPs ("regions") and EPAs ("districts") during the years from 1995 to 2005 in Malawi. For instance, the two first lines are for the EPAs of Linthipe and Kabwazi in 1996 (both in Thiwi Lifidzi RDP). Lines 5 and 6 are both for Mitole in Chikwawa, but for different years. The variables are: the yield of local maize ("local" stands for unimproved varieties), the year, the water satisfaction index at harvest time, water deficit at the time of flowering, water deficit at the time of ripening, actual evapotranspiration (ETA) during the vegetative phase and water excess during the initial phase (germination).

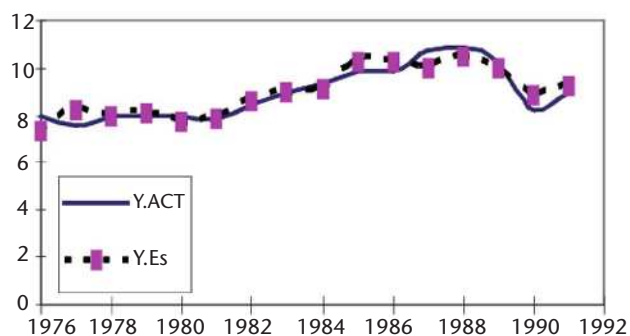


Figure 6.5. Comparison of actual yields (T/ha) of autumn potato (Y.ACT) with estimated yields (Y.Es) in Egypt (Giza area). Y.Es was obtained through a regression equation between yields (ordinate), September and October maximum temperatures, and solar radiation. (From Dawod, 1996)

equations (so-called yield functions) that will eventually be used for forecasting crop yields. The process by which the coefficients of a yield function are derived is known as calibration²⁵. The rules below are purely empirical or based on common sense:

- (a) Use only variables that are known to be meaningful for the crop under consideration. When there are good reasons to suspect that the response of crop production to a given variable is not linear, use a quadratic term in addition to the linear term.
- (b) Retain only those variables for which the coefficients are significantly different from 0. This is to say that the regression coefficients must be significantly larger (absolute values) than their standard errors. This can be tested statistically (ratio of coefficient to its error), but common sense is usually enough.
- (c) The sign of the coefficients must correspond to what is known about the response of the crop to the variable considered. This applies also to the quadratic terms.
- (d) The coefficients must be spatially coherent, which is to say that they must vary smoothly over adjacent districts.
- (e) The quality of a regression equation is given, in addition to the statistics (R , R^2 , coefficients significantly different from 0), by the average error of estimated yields.
- (f) Trends must be removed before carrying out the regression work proper. The trends need not be linear.

²⁵ Roughly, calibration of “statistical” models can be seen as the equivalent of “validation” of process-oriented models.

- (g) Be aware of the fact that there are two types of variables: continuous-quantitative ones (such as minimum temperature affecting crops through night-time respiration) and qualitative ones (such as male sterility induced by high temperatures).
- (h) Always use a variable that stands for the local yield potential.
- (i) A yield function does not have to be linear. In some cases, a multiplicative function can be more appropriate.

In addition, it is good practice to:

- (a) Compute the correlation matrix among all variables to get a better feel for the redundancy of the information;
- (b) Plot the yield against time, to get an idea of the shape of the trend and decide on which function should be used for the time trend;
- (c) Run a principal component analysis on the calibration matrix to realize how redundant your data set actually is, and to identify the most important factors. Run this analysis twice: excluding the yield as a variable, to get a feel for the variable groupings and redundancy; and with yield to identify the variables that are associated with the yield, as well as those that are irrelevant;
- (d) Pay attention to the fact that the weather variables may play a secondary role, and ignore them altogether. For coffee in Mexico, it was shown that the most important variables influencing yields included altitude above sea level, number of weeding rounds, age of the plantation and type of smallholding (Becerril-Roman and Ortega-Obregon, 1979);
- (e) Plot detrended yield against each individual variable to see the shape of the regression curve and the strength of the statistical correlation, after removing the trend. If any relation is clearly non-linear, add a quadratic term²⁶ to account for curvilinearity;
- (f) Ignore redundant variables and multicollinearity as far as possible, or use the regression through a principal component analysis. Always prefer techniques with (manual or “automatic”) addition of variables to techniques with deletion of variables;
- (g) Use techniques to ensure the stability of the coefficients (randomly or systematically eliminating up to 50 per cent of the observation points of the time series);

²⁶ For instance, if the plot of yield against W_Ex_Flor (Water Excess at the time of flowering) looks like a saturation curve (that is, yield levels off at higher W_Ex_Flor values), use both W_Ex_Flor and $W\_Ex\_Flor^2$ as a regression variable.

- (h) Use jackknifing to determine the actual accuracy of the method;
- (i) Regularly recalibrate yield functions unless conditions remain stable over time, because yield functions often become obsolete after a couple of years as a result of changing environment and farming practices.

6.4.2 Crop simulation models²⁷

Process-oriented crop simulation models are deemed to be the most accurate and the most versatile of models in that they attempt to describe a crop's behaviour (physiology, development) as a function of environmental conditions. They tend to be less sensitive to "new" situations, namely, situations that did not occur during the period used to "train" the model. Crop simulation models, however, are sometimes not suitable for operational regional crop forecasts, for a variety of reasons, in particular their complexity. A corollary of the complexity is the arbitrariness of many parameters when models are run in regional forecasting mode.

To illustrate the complexity, one should note that the current versions of leading models such as EPIC, Crop Environment Resource Synthesis (CERES) and WOFOST, use approximately 50 crop characteristics, about 25 parameters to describe soils, plus 40 or so management and miscellaneous parameters. In comparison, there are usually just five or six daily weather variables that actually drive the models (rainfall, minimum and maximum temperatures, wind speed, radiation and air moisture²⁸). The internal variables used by WOFOST amount to about 260, of which half are crop variables, 30 per cent are soil variables and 20 per cent are weather variables (including all the astronomic variables, such as day length, extraterrestrial radiation, and so forth). Output variables can, in principle, be any of the internal model variables. The EPIC manual, for instance, lists 180 input parameters and output variables. In comparison, CropSyst uses "only" 50 input parameters.

All process-oriented models more or less openly use ad hoc variables to force the models to behave in the same way as the experimental data. It is not always easy to decide which variables are ad hoc

without digging deeply into the operation of the models, and this is possible only with the models for which detailed documentation and often the source code are available. The ad hoc variables are sometimes grouped under a category of "miscellaneous" variables, or they have names like "reduction factor", "adjusted rate", "correction factor" or "coefficient of crop yield sensitivity to water stress". For example, the 1995 EPIC User's Guide (Mitchell et al., 1995) has a "factor to adjust crop canopy resistance in the Penman equation" and a "nitrogen leaching factor".

Most of the simulation models were developed as research tools: they apply at the field scale. When simulation models are used to forecast crops, they must therefore be run at the scale to which they apply, basically a "point".

To use models at the regional scale, three basic approaches are available:

- (a) Operating models with regional input data that are regional (spatial) averages of point data. Due to the heterogeneity of the input data, and the non-linear relationships between model inputs and outputs, this method is prone to aggregation error (Hansen and Jones, 2000). Beyond a certain spatial scale, which will depend upon the spatial heterogeneity of the region (climate, topography, soils), aggregation of inputs such as solar radiation and rainfall can lead to significant error (Baron et al., 2005). Indeed, some models may have inputs that are not available on the given scale (for instance, the average number of grains per spike). Relatively simple process-based models can, however, produce accurate results using spatially averaged data (for example, Challinor et al., 2004);
- (b) Many authors run crop simulation models on a grid, that is, they interpolate all model inputs to a common grid (Braga and Jones, 1999). This applies mainly to crop parameters and to weather data, since soil characteristics are usually available as maps from which model inputs (such as soil characteristics) can easily be read. This is the approach followed by the European Union's Monitoring Agriculture with Remote Sensing (MARS) programme (Genovese, 1998; Boogaard et al., 2002; Rojas et al., 2005);
- (c) Models can be run at a limited number of stations (mostly weather stations) where most required inputs are actually available. Once the station yield has been computed, it is subsequently spatialized (gridded, rasterized) so that a regional average can be computed. This

²⁷ For the sake of completeness, gene-based models should also be mentioned. In the words of White and Hoogeboom (2003), "advances in genomics suggest the possibility of using information on gene action to improve simulation models, particularly where differences among genotypes are of interest". See also Boote et al., 2003.

²⁸ Air moisture and air humidity are equivalent terms.

is the approach usually followed by the Food and Agriculture Organization of the United Nations, or FAO (Gommes et al., 1998).

Without entering into the merits of the three approaches above, it is sufficient to observe that they tend to be very prone to error when many pre-processed inputs are used (such as weather grids). In addition, they all have to be calibrated against agricultural statistics, thereby somehow losing the advantages associated with the “scientific” approach. Ideally, models should be calibrated against crop cuttings, namely, the elementary plot yield sampled in statistical surveys.

Each of these approaches to the issue of spatial scale has its own advantages and disadvantages (see Hansen and Jones, 2000; Challinor et al., 2003). An important consideration is the complexity of the crop model and how this relates to the spatial scale and complexity of model inputs (Sinclair and Seligman, 2000; Challinor et al., 2006).

One of the main advantages associated with simulation models is very practical: if weather forecast information is available, then the models can be run to the time of harvest, and the variable to be forecast (yield, pest development rate, and so on) can be calibrated against data corresponding to the time of their cycle (which corresponds with the time of harvest for crops). In other words, it is necessary to compute only one yield function, contrary to “statistical” models, which often require a different equation or set of equations for each forecasting time: one at planting, one for flowering, and one for each phenological phase.

When crop models are used with seasonal forecasts (Challinor et al., 2005a) or stochastic weather generators (Lawless and Semenov, 2005), probabilistic statements about the state of the crop at the end of the season can be made. As the season progresses, forecast information can be replaced with observations (Hansen et al., 2004), and the skill of the forecast should then increase.

6.4.3 Non-parametric forecasts

For the purposes of this chapter, non-parametric forecasts are considered to be methods that do not, at least explicitly, use any model or statistical relations. Non-parametric methods are also known as descriptive methods, and they cover the spectrum from simple descriptive thresholds to expert systems to analogies. They are particularly useful in assessing qualitative and indirect effects of weather on crops. The simplest descriptive methods are those that involve one or two thresholds.

For the simplest descriptive methods, it is sufficient to identify the environmental (agrometeorological) variables that are relevant to the organism under consideration. This is normally done with statistical clustering analysis on a combination of time series and cross-sectional data. Once the groups have been identified, it must be verified that the response of the system being forecast corresponds to various clusters that differ significantly from each other.

One of the reasons that simple descriptive methods can be very powerful is that climate variables do not vary independently: they constitute a “complex”. For instance, low cloudiness is associated with high solar radiation, low rainfall, high maximum temperatures and low minimum temperatures. Each of the variables affects crops in a specific way, but since they are correlated, there is also a typical combined effect, which the non-analytical descriptive methods can capture. The same observations are at the root of the Crop Environment Matrix (CEM) proposed in 1990 by Hackett. This simple tabular method used to summarize crop ecophysiological relationships for land evaluation projects can serve as a rapid means of recording site characteristics and coarsely predicting crop performance. The CEM approach was implemented for bananas, cashew, cassava, coconut, arabica coffee, robusta coffee, karuka (*Pandanus* sp.), mango, oil palm, pineapple and sweet potato.

Many non-parametric methods have been designed for forecasting pest and disease outbreaks. A famous example is the “Irish rules”, which spell out the criteria that may trigger an outbreak of potato late blight: more than 11 consecutive hours with relative moisture above 90 per cent and temperature above 10°C (Keane, 1998). One of the first implicit uses of a descriptive method for crop yield forecasting that the authors are aware of is the work of Krause (1992), in which it appears that crop yields are associated with NDVI profiles over time, specifically not the NDVI values, but their behaviour over time between planting and harvest.

The descriptive methods have a number of advantages: (i) no assumption is made as to the type of functional relationship between the variables and the resulting yield; (ii) the clustering²⁹ takes into account the fact that many climatological variables tend to be intercorrelated, which often creates

²⁹ Clustering is the statistical method used to identify patterns of one or more variables. Clusters are purely qualitative, even if they can be characterized by the descriptive statistics of the variables.

methodological problems, at least with the regression methods described above; (iii) confidence intervals are easy to derive; (iv) once developed, the descriptive methods require no data processing at all; and (v) their actual implementation is extremely straightforward. Figure 6.6 and Table 6.4 show examples of these methods.

Many El Niño impacts on agriculture currently being debated can be treated by descriptive methods: El Niño effects on agriculture result from a long series of effects (El Niño → Global atmospheric circulation → Local weather → Local crop yield), in which each step introduces new uncertainties. As mentioned above, this chain of interactions can also be seen as a “complex” starting with the ENSO index. In Southern Africa, for instance, warm El Niño events are associated with a premature start to the rainy season, followed by a drought at the time of flowering of maize, the main crop grown in the area.

This pattern usually results in good vegetative growth, followed by drought-induced crop losses. Cane et al. (1994) have found a good relationship between El Niño parameters (the very beginning of the causal chain) and maize yields in Zimbabwe, which constitutes a good illustration of the concepts described in the later sections of the paper. In Australia, Maia and Meinke (1999) have shown how groundnut yields can be associated with different phases of the Southern Oscillation Indices.

The literature also has some examples of combinations of non-parametric and parametric methods. Everingham et al. (2002) run a sugar cane model in which “future weather” is given by a set of analogue years based on a seasonal forecast issued by the South African weather service.

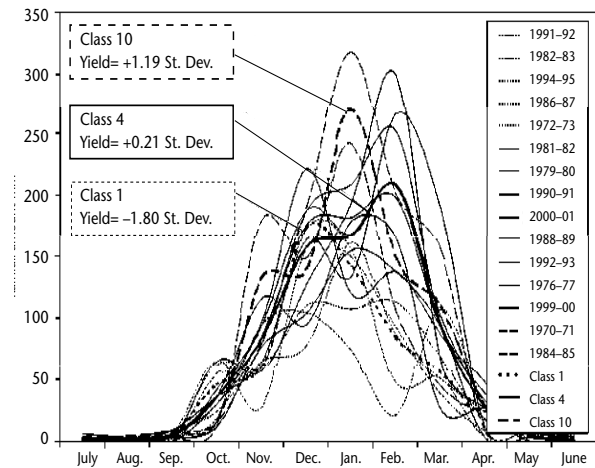


Figure 6.6. Three out of 10 typical rainfall profiles for Zimbabwe (averages and individual years). Rainfall is expressed in mm. (From Gomme, unpublished)

Expert systems are more complex (Russell and Muetzelfeldt, 1998; Russell et al., 1998). They use the techniques of artificial intelligence to infer the impact of environmental conditions on crop yield. To do so, they require a base of data, a knowledge base and an “inference engine”, which is the software that constitutes the interface between the data and the users.

A knowledge base includes all the normal database functions, but has additional functionality in terms of the way questions can be asked. For instance, a knowledge base “knows” synonyms, it knows orders of magnitude (“low yield”), it understands contexts (general information, such as properties of a group of plants, for example, grasses), and it is normally able to perceive implicit information. Implicit information is the

Table 6.4. Example of a threshold-based crop forecasting table for maize in Zimbabwe based on yields recorded during the period 1961–1962 to 2000–2001. Yields are expressed in standard deviations about the average for the period. (From Gomme, unpublished)

Criterion 1 January rainfall (mm)	Yield (average and 95% confidence interval)	Criterion 2	Threshold	
75 to 155	1.07 –1.64 to –0.50	February rainfall	<120 mm –1.74 –2.35 to –1.13	>120 mm –0.52 1.16 to 0.12
150 to 249	0.25 –0.05 to 0.55	February rainfall	<170 mm 0.07 –0.50 to 0.35	>170 mm 0.57 0.25 to 0.89
250 to 327	0.78 0.35 to 1.08	December rainfall	<190 mm 0.92 0.23 to 1.63	>190 mm 0.66 0.08 to 1.25

information generally associated with a category, such as humic gleysol (pH, drainage properties, depth, texture, and so on).

The inference engine controls the reasoning used to answer queries. Knowledge bases can use the outcome of one rule as an input for another. An example provided below is adapted from Russell (Russell and Muetzelfeldt, 1998), the author of a detailed wheat knowledge base for Europe, which at the same time illustrates the concept and shows the usefulness of knowledge bases in crop-weather modelling: “What are the consequences of high temperatures in March on wheat yield in Spain?” The expert system must first “understand” what is meant by high temperatures, next it must “know” at what phenological stage wheat will be in Spain at the given time. Finally, the programme must “understand” the concept of Mediterranean region: if no specific data are available for Spain, the system will “know” that Italy, Greece and southern France are part of the same region and that some data can be borrowed from there.

The European wheat knowledge base puts special emphasis on the identification of alarm situations, based on research and expert knowledge. As such, a knowledge base constitutes a unique monitoring tool as it is unlikely that any of the other types of models will be able to perceive the more complex environmental interactions and sequences, such as a succession of very warm days at the beginning of flowering of orchard crops, followed by a week of heavy rain, which will have several indirect effects, such as poor pollination.

Expert systems can be combined with the traditional process-oriented models (Edwards-Jones, 1993). Kamel et al. (1995) have developed a tool to support the regional management of irrigated wheat in Egypt, which captures local expertise through the integration of expert system technology and a crop simulation model (CERES). The system can improve the selection of sowing date and variety; pest monitoring, identification and remediation; and harvest management. It may also allow for better utilization of resources, especially water.

6.4.4 Combination of methods

This section focuses on yield forecasts using different methods in combination³⁰. In fact, most actual

agrometeorological forecasting systems result from the combination of several approaches. Multiple linear regression models are quite adapted to integrate several yield forecasting methods. Their precursors include “biometric forecasts”, in which some biometric measure is related with yield, for instance, the correlation between the diameter of the stem base and clean coffee yield can be used for predictions (Bustamante et al., 2004).

When a main limiting factor affects crop production, for instance rainfall in the semi-arid tropics, or solar radiation for lowland rice, models can be shown to be unnecessarily complex. For instance, Rivero (1999) has run CERES-rice with 30 years of data and found that, eventually, the yields simulated by the model are a simple linear function ($R^2 = 0.845$) of radiation during the grain filling stage: the inter-comparison of the outcomes of different methods provides useful insight into the quality of the results achieved by different techniques.

Starting in the 1990s, the MARS project put together information based on technological trends, agrometeorological models and remote-sensing thanks to a multiple regression analysis (Genovese, 1998; Boogaard et al., 2002; Rojas et al., 2005). Due to the availability of new statistical techniques, simple climatic variables are currently being used again by some practitioners because they can explain yields as well as and sometimes even better than more sophisticated variables obtained through models. The explanatory variables of the multiple regressions were either selected by experts or derived from statistical selection.

Until recently, the selection of variables was limited by the number of variables and by the statistical tools available. For instance, Gibramu (1997) uses partial regression coefficients to manually identify main variables for his coffee yield forecasts. Recently, statistical tools were proposed to help agrometeorological experts select the best explanatory variables, according to a first statistical selection confirmed or not in a second step by their own expertise. STATCAT (Curnel et al., 2004) is one of these tools, but the Actions in Support of the Enlargement of the MARS Crop Yield Forecasting System (ASEMARS) project, which has been launched for the extension and updating of the MARS project, is also producing its own statistical tool for extracting the best explanatory variables that explain the best yield estimates and predictions.

The procedure follows two steps: in a first “calibration” step, a subset of explanatory variables (containing sometimes several hundred candidate

³⁰ This is not to be confused with situations such as a forecast of yields in mixed cropping systems. A specific example (reported by Somarriba, 1990) is a model to estimate the stable timber output, basically a by-product, from shade stands of *Cordia alliodora* in coffee farms in Costa Rica.

explanatory variables) that best explain crop yields is defined using an automatic stepwise selection method.

Traditionally, stepwise regression has been widely used since it requires little computing power, and is easy to understand and implement. The probability significance thresholds for entry and retention of candidate predictors in the model are both set to = 5%. Models with high R^2 in this calibration step do not necessarily have high predictive power, however. Therefore, in a second “validation” step, the selected regression equations are tested in more depth using leave-one-out (LOO) cross-validation.

This technique ensures that results are replicable; it checks the prediction performance of a model for “new” years, which were not considered in the calibration step. In practice, for the validation of a given model (with fixed X-predictors, selected by the stepwise regression), the LOO is implemented as follows: remove one year from the database, fit the regression with the same X-predictors and the data of the remaining years, use the found equation to estimate the yield of the withdrawn year, and define that year’s error (estimated minus true yield Y).

When this procedure is repeated for all the years ($i = 1$ to n), an independent error estimate can be obtained in absolute or relative terms:

$$\text{Absolute error} = \frac{\sum_{i=1}^n |\hat{Y}_i - Y_i|}{n} \quad (\text{kg ha}^{-1})$$

$$\text{Relative error} = \frac{\sum_{i=1}^n \frac{|\hat{Y}_i - Y_i|}{Y_i}}{n} \quad (6.15)$$

where $\hat{Y}_i$ is the estimate of Y_i .

These LOO-derived criteria provide independent estimates of the predictive power of the selected models. In the same way, one can also derive an independent R_p^2 value. The p-suffix is added to distinguish R_p^2 from the less stringent R^2 value that is found in the calibration.

In addition, three more diagnostic tools are used for model evaluation: multicollinearity between explanatory variables is detected with the Variance Inflation Factor (Kutner et al., 2005); preference is given to regression models with low “shrinkage” (difference between R^2 and R_p^2); and all models are rejected if the regression line between predicted and observed

yields differed significantly from the diagonal (intercept = 0, slope = 1).

Each province, department or other sub-national level of a country has its own regression model calculated with the above approach. Outputs are then aggregated and used for the yield prediction at the country level. This approach has been successfully applied in Senegal and Morocco (Figures 6.7 and 6.8) and is presently being tested in Turkey.

The combination of methods could be used to predict yields from different points of view, when all the factors affecting crops cannot be combined in a unique model. It should be based on local experience and judgement, choosing pragmatically the best methods according to the type of the limiting factors (rainfall, temperature, diseases, pests, irrigation, technical progress, and so forth) and available databases. The combination of methods is a way of estimating the uncertainty in the prediction. As an illustration, one can assume that it is possible to assess yield using seven different models as in the example for Belgium below (Figure 6.9).

The different models used by agrometeorologists for predictions in the Belgian Agrometeorological Bulletin are:

- The technology trend: INS-Trend;
- The potential biomass calculated using an agrometeorological conceptual model: POT_BIO21;
- A remote-sensing biomass status indicator: RS(13);
- A model derived from the number of days of frost during winter: Gel2;
- A linear model combining an RS indicator with a climatic indicator (number of frozen days in winter): Gel2 + RS(13);
- A scenario analysis: Scenarios;

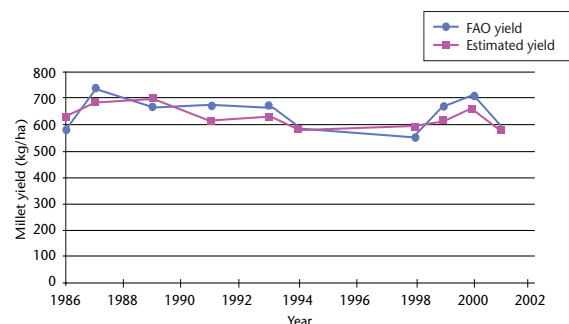


Figure 6.7. Comparison between millet estimated yield and FAOSTAT data in Senegal (Global Monitoring for Food Security project, Rosillon and Tychon, 2006)

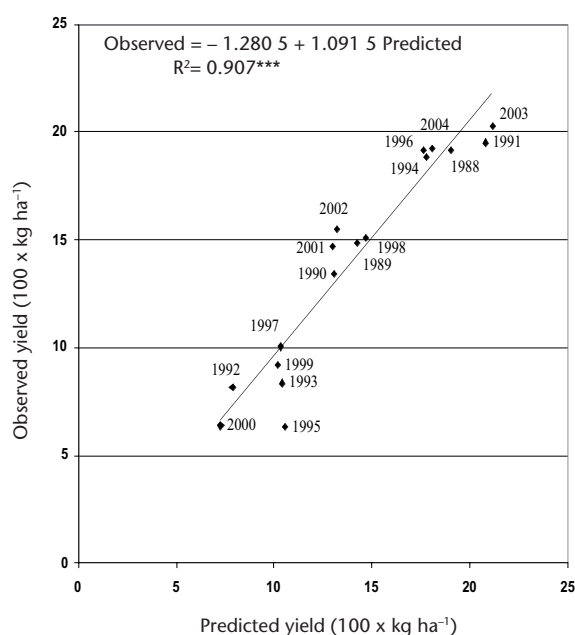


Figure 6.8. Regression at county level between mean of observed and predicted wheat grain yield using all Ordinary Least Squares models of 23 provinces of Morocco (Balaghi, 2006)

- (g) A complete model containing trend, climatic data, remote-sensing and agrometeorological data: Belgian Crop Growth Monitoring System (BCGMS).

If the models' outputs are standardized and compared to a mean value, outputs can easily be interpreted as illustrated (Figure 6.9). For example, in 1995 and 2000, all the models propose the same yield estimate. It is probable that for these two years, the prediction

uncertainty will be low and a good estimate can be expected, while for 1996, the expert will be confronted with large uncertainty in his or her forecast. At that time the expert will have to be very cautious in his or her comments and explain the complexity of the situation. This uncertainty information is absolutely crucial in yield forecasting, as models cannot take into account all the natural variability and all the environmental factors that affect yields (diseases, pests, soil types, and so on). Prediction without indication of its uncertainty remains a weak point of many present forecasting systems. Publications about models now regularly also provide information about uncertainty. See Chokmani et al. (2001) for an illustration from crop protection.

6.4.5 Extreme factors³¹

6.4.5.1 Introduction

The section begins with a word of caution about "extreme" factors. Strictly speaking, extreme factors are factors that are extreme in a statistical sense, that is, their occurrence is infrequent. Common speech often uses the word "extreme" to describe violent factors such as strong winds. These two definitions of the word "extreme" do not always overlap. In the current section, "extreme" is understood to mean "statistically rare and damaging to crops".

The effect of extreme factors on agricultural production systems is exceedingly difficult to forecast. This is

³¹ The section on extreme factors borrows mainly from WMO (1997, 2003) and Gomme (1998b).

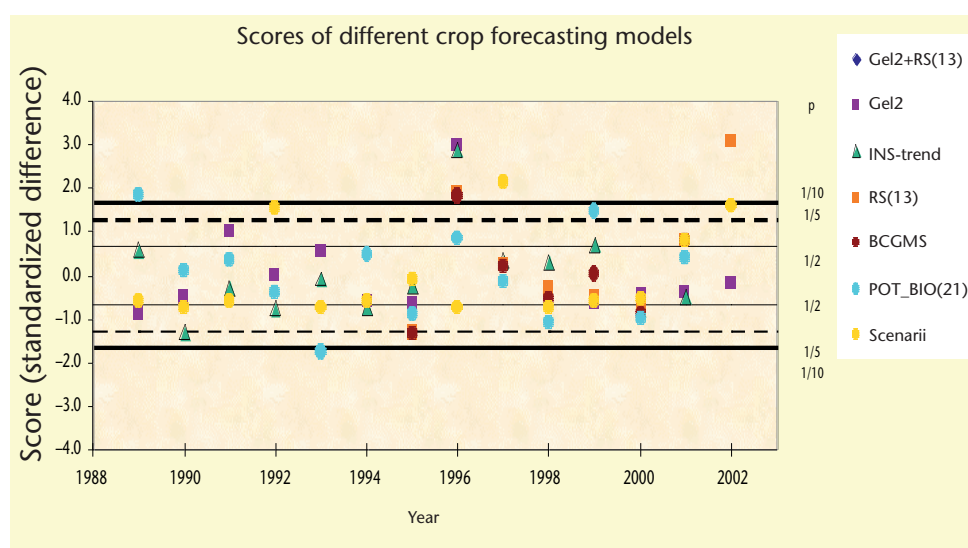


Figure 6.9. Uncertainty analysis of yield forecasting models (Curnel et al., 2004)

because many extreme factors physically damage and hurt organisms: cattle may be exposed to drowning in the event of floods, cell walls are damaged by ice crystals during freeze events, sugar canes are broken by strong winds during hurricanes. Forecasting the response of biological systems under conditions that physically damage the organisms is usually extremely difficult. One of the reasons for the lack of any standard tools is the lack of good impact databases. Losses are often due to unexpected factors: one of the major causes of crop losses after Hurricane *Juana* hit Nicaragua in 1988 was the germination of maize grains still on the cobs in the fields, but before harvest (FAO, 1988). This is not unlike the situation described below regarding the host-pest/pathogen-environment complex (6.5.3.2.2).

Finally, conditions can be extreme because of a combination of unusual conditions, resulting in rather complex interactions among factors. A typical complex interaction is the one observed during heavy rains and floods. Waters during these events have several combined destructive effects on crops, animals and the environment. Erosion and resedimentation are physical effects caused by running water, while waterlogging and root asphyxiation involve crop physiology. But floods may have positive effects as well, such as silt deposition, recharging of water reserves, and soil desalination. Of particular importance in this context are riverbed changes and major landslides, which may completely modify the agricultural landscape. Another example of this is the combined effect of tsunamis, strong winds and floods, and the “ocean spray” of seawater blown inland during storms or cyclones. Salt may take years to be washed out, thus reducing crop yields.

Agrometeorological disasters result from the interaction of a meteorological factor, or a combination of meteorological factors, with an agricultural system. The extent of the damage depends as much on the characteristics of the agricultural system as on the physical event that causes it. There are still few models that can handle processes (recovery and regrowth) after mechanical damage has occurred. A good early example is given by Moore and Osgood (1987) in their studies on yield forecasting after cyclones. Cyclones break a large proportion of the stalks in sugar cane fields. The model estimates the rate of recovery of the damaged plants in view of their age at the time of the cyclone, the extent of the damage and the classical agrometeorological parameters. The mechanical damage has to be estimated separately, however, and it constitutes one of the inputs in Moore and Osgood’s approach.

A more systematic treatment of the factors to take into account when assessing vulnerability to extreme agrometeorological events, or losses associated with these events, is presented below.

6.4.5.2 Analysis of factors relevant for extreme factor impact assessments

6.4.5.2.1 Weather factors

- (a) Mechanical versus non-mechanical factors: Mechanical factors are those that directly and physically damage plants. Continuous rains and drought fall into the category of non-mechanical disasters. The energies involved in non-mechanical disasters are usually of the same order of magnitude as the normal factors; non-mechanical disasters are more often due to abnormal duration, distribution or simultaneous occurrence rather than to unusual intensity.
- (b) Energy or intensity: as mentioned above, the energy or intensity of the weather factors linked with disasters may be vastly different from their normal range. High intensity is mostly linked with relatively short durations (hours or days). The wind speeds that accompany tornadoes and hurricanes are about one order of magnitude greater than the average. In addition, the kinetic energy (and destructive power) of winds varies with the square of wind velocity. Similar considerations apply to the size of hailstones and frost intensity.
- (c) Presence/absence: this characterizes factors, such as hail, that occur with very low absolute frequencies.
- (d) Cumulative/non-cumulative effects: Trees uprooted by violent wind gusts are unlikely to suffer further damage from the same factor. Heavy rains, however, typically have a cumulative effect on soil erosion, and both the duration and the intensity play an important part (WMO, 1983). A practical consequence is that for rainfall damage assessment, a number of different types of data are required, while for wind a single value (maximum wind speed) is usually sufficient.
- (e) Timing and succession of events: some extreme events build up gradually, quite independently of their intensity, as is the case with droughts or waterlogging. In many instances, it is not possible to assign a precise point in time for the beginning (or the end) of an extreme agrometeorological event. This is the main justification behind monitoring and warning systems. The rate of change also plays an important role for factors such

as temperatures. Organisms can adapt more easily to slow changes.

6.4.5.2.2 *Crop factors*

- (a) Thresholds and qualitative effects: these effects characterize a number of plants and animals with regard to their response to weather factors. Well-known examples are the effect of high temperatures on the sterility of many annual crops (for example, Wheeler et al., 2000) or the breaking of the stems and branches of certain rubber cultivars by wind. Another interesting example of this is given by Foong (1980, based on various authors), in which abnormal sunshine duration leads to abnormal frequency of male inflorescence in oil palm. The existence of thresholds is a major cause of non-linear response of crop yields to adverse weather factors.
- (b) Specific differences: There are numerous examples of certain crops suffering very different losses under comparable adverse conditions. According to FAO (1988), Hurricane *Juana* (21–23 October 1988) almost completely destroyed coconut palms (more than 70 per cent were broken or uprooted) in the worst-hit areas of the western coast of Nicaragua, while the most badly affected cocoa plantations lost fewer than half their trees. It is also a common observation that plantations suffer more direct and apparent damage than natural forests, because the latter constitute efficient protective barriers. It should be noted, however, that the complex natural ecosystems may take a long time to rebuild their diversity, sometimes even centuries. To cite an extreme example, it is also a common observation that root and tuber crops and creeping plants suffer very little from hurricanes, while tree crops and cereals may be badly hit. Similarly, floating rice varieties (like the B. Aman in Bangladesh) are characterized by very fast stem elongations, which can keep pace with rapidly rising waters during floods.
- (c) Phenology and size: Crop development stages are a very important qualitative factor. While still in their early stages, grasses and cereals suffer little wind damage (Sturrock, 1975); rice appears to be very sensitive to hail at the time of transplanting and harvest. Wind will affect rice most at the time of heading and reaping (Daigo, 1957), and the damage to adult trees may vary from defoliation to uprooting.

As noted above, one of the major causes of crop losses after Hurricane *Juana* hit Nicaragua in 1988 was the germination of maize still drying on the cobs in the fields (FAO, 1988). Flowering appears to be the

most sensitive stage, as any factors preventing fertilization or flower-set will result in very poor yield, independently of the crop's standing biomass.

6.5 SPECIAL APPLICATIONS

6.5.1 Crop-specific methods

Most simulation models are currently packaged as multi-crop modular tools that are made crop-specific through crop-specific parameters. A well-known example is WOFOST, a family of models³² known as the "Wageningen family" (van Diepen et al., 1989; Supit et al., 1994; Hijmans et al., 1994; van Kraalingen et al., 1991). The crop growth model is generic, but parameters are provided for wheat, grain maize, barley, rice, sugar beet, potato, field bean, soybean, oilseed rape and sunflower. The original version simulated crop behaviour under European conditions. Other versions exist for tropical regions.

Another well-known family of models (CERES³³) has variants that can simulate wheat, maize, rice, sorghum, millet, barley, sunflower, sugar cane, chickpea, tomato, pasture, groundnut and potatoes. There are models for Bambara nuts and tulips, onions and tobacco, garden crops, field crops and greenhouses, mushrooms, silkworms, and so forth.

Amid this plethora of tools, however, agrometeorological forecasting remains a difficult task whenever yields are to be forecast for decision-making at the provincial or regional level. The specific reasons for this situation have been outlined above.

One should also stress that yield is not the only variable for which there is demand in the private and public sectors. An example is pest, disease and crop phenology, especially outbreak or maturity dates. Many fruits are still harvested by hand, and the logistics of hiring the labour, storing and transporting the produce, and marketing are best planned as far as possible in advance. Some applications are costly to implement, and they are usually confined to high-value, fragile crops such as grapes (Riou,

³² Other major model families include EPIC and the Soil and Water Assessment Tools (SWAT), both by the Texas A&M University System (TAMUS). Still another is CropSyst, developed in the early 1990s by Stöckle (1994).

³³ CERES (cereals), CROPGRO (mainly legumes) and CANE-GRO (sugar cane) are now grouped under the Cropping System Model (CSM); Jones et al., 2003.

1994), vegetables³⁴ (Bazlen et al., 1996), and flowers (when they are grown outdoors).

6.5.2 Quality of produce

A new category of forecasting has been gaining importance over recent years: forecasting the quality of products. This concerns not only the very impressionistic wine market³⁵ (Desclée, 1991; Ashenfelter et al., 1995; Jayet and Mathurin, 1997; Jones et al., 2005), but also some processed cereals, in which, for instance, starch/protein ratios should ideally remain within a relatively narrow range. Descriptive methods have also been used successfully to estimate the quality of agricultural products such as wine. Given that the concept of “quality” is sometimes difficult to describe in quantitative terms, the non-parametric approach is probably the most suitable, that is, any index that describes the similarity between the current year and historical “good” years would, de facto, constitute a useful forecasting variable.

The definition of quality varies from produce to produce, and is often determined by an industrial process. For instance, the quality of milk can be defined by the concentrations of fat and casein (Bettati and Cavuto, 1994); for wheat, grain protein content, gluten content and grain hardness are used. Other variables that are often considered include concentrations of starch and water in grain crops or the water content of hay. They are part of the German agrometeorological advisory system AMBER (WMO, 1995; Löpmeier and Friesland, 1998). For forecasting grain quality, it is feasible to establish correlation equations between biochemical constituents and the canopy-reflected spectrum (Huang et al., 2004).

6.5.3 Pests and diseases

6.5.3.1 Introduction

This section covers several different forecasting-related issues. The first is the forecasting of the

presence³⁶ of pest and disease agents (pathogens) as a function of environmental variables. This was given some attention above.

“Presence” can result from the development of the pathogen in loco, or from its transport by vectors that may or may not be related to weather. The “presence” measures the exposure of vulnerable organisms to pest and disease attack risk. Whether or not there will be resulting economic loss depends on the vulnerability³⁷ of the system exposed to the pathogen. Assessing vulnerability is the second issue to be covered in forecasting potential impact. According to the context, “vulnerability” can take different forms. For white fir in California, Ferrel et al. (1994) use the term “vigour”.

It should also be noted that the emphasis is now often on the role of agrometeorological forecasting as a tool to reduce the cost of pest and disease control operations by reducing their frequency and spraying only when the risk and vulnerability are high.

Some situations may involve several pathogens and a chain of intermediate hosts, which makes forecasting particularly difficult (Malone et al., 1998), because several types of organisms and different models are concerned. This clearly affects data requirements compared with simpler situations. In addition, due to the complexity of population dynamics, it is often necessary to resort to data covering several years in order to model pest attacks, for instance for the East African armyworm (Haggis, 1996).

Strand provides a recent assessment (Strand, 2000), and Shtienberg (2000) refers to the increasing relevance of models in disease forecasting. In this connection, Bains et al. (1995) provide a good review for a developing country.

6.5.3.2 Plant pests and biotic diseases

6.5.3.2.1 Overview

The number of different pests and diseases affecting crops and forest trees is so large that a general treatment of the agrometeorological approach to these organisms is almost impossible. According to the population development, pests and diseases can be subdivided in mono- or polycyclic, respectively, if they complete a single cycle (for example, smuts and buns of cereals, and one-generation

³⁴ The paper by Bazlen also includes an example of a “biometric” forecast combined with a more classical agrometeorological approach. In biometric forecasts, some characteristic size is measured on a plant at a typical time (for example, cob length in maize) and used as a forecasting variable, alone or in combination with other factors.

³⁵ “Impressionistic” because in addition to quality proper (defined by pH, tannin content, sugar, colour, and so on), the manipulation of demand plays a prominent role, particularly during average and mediocre years (see Ashenfelter et al., 1995).

³⁶ Even if conditions are favourable, the pathogen is not necessarily present. The incidence (the impact) of the pathogen is relevant only if a pathogen is present.

³⁷ This is a variable that has to be defined operationally.

insects) or multiple cycles (for example, cereal aphids, leaf blight, leaf spot diseases, rusts and mildews) during the growing period of crop. The expected damage for monocyclic pests and diseases depends mainly on the initial level of attack (for example, seed and seedling removal); on the other hand, the damage level for polycyclic pests and diseases depends not only on the initial level of infection but also on the ability of the causal agent to develop through repetitive life cycles to a level that affects crop production (Rijsdijk, 1986).

Another criterion for classification of pests and diseases is the mode of interaction with the host: certain pests and diseases remove green tissues or whole plants without affecting the remaining parts of plants or other plants (for example, leaf beetles and various soil pests that remove whole seedlings). Many other pests and diseases not only affect tissues, but also influence the physiology of plant parts not yet infected (for example, effects on photosynthesis and leaf ageing by cereal aphids and many plant diseases).

6.5.3.2.2 *The host-pest/pathogen-environment complex*

The knowledge of meteorological variables is crucial to define the environment of pests and diseases. This fact was qualitatively well known for a long time, but quantitative evidence of it was attained after the implementation of mathematical models simulating the host-pathogen-environment complex for plant diseases and host-pest-predator/parasite-environment complex for pests (France and Thornley, 1984; Magarey et al., 2006).

The beginning and end of a pest/disease attack are determined by (i) the abundance of disease inoculum or pest population; (ii) the condition of the host; (iii) environmental relations affecting the plant-pest/disease complex and acting, for example, on the susceptibility of plants and the virulence of diseases.

The concept of environmental relations adopted in the above-mentioned scheme is very broad and includes: (i) micrometeorological variables; (ii) physical properties of the soil (temperature, air, water, and so on); (iii) microbiological conditions of the soil (including effects on cycles of macro- and microelements); and (iv) agroecosystemic interactions among different organisms, including interactions between parasites and predators or interactions between diseases and pests.

An example of environmental relations can be seen in the enhancement of the effect of diseases/pests produced by previous attacks of another disease or pest (such as the wounds produced by chewing insects) that leave openings in foliage and stems for bacteria and fungi to enter the plant. In addition, some insects (such as aphids) act as vectors for viruses. Furthermore, it is well known that plants subjected to water shortage, lack of nutrients or other stress conditions are more susceptible to pests (insects, mites, nematodes, and so on) or diseases (fungi, bacteria or viruses).

6.5.3.2.3 *Mathematical models for pests/diseases*

The approach to plant disease epidemics and their control based on mathematical models has a relatively long history (Kranz, 1974; Pietravalle et al., 2003) and at present is an integral part of current research in plant disease epidemiology; plant pest modelling has been largely the preserve of entomologists and applied ecologists.

In this context it is possible to identify two main kinds of models:

- (a) field models working at microscale (canopy layer);
- (b) territorial models working at mesoscale.

While an empirical approach is often a specific characteristic of territorial models, field models are frequently based on a semi-empirical or mechanistic approach.

Pest/disease models may represent modules of crop production models, because a quantitative evaluation of losses of production due to pests and diseases is needed in order to estimate the final production of crop. Principal end-users of pests/disease models are:

- (a) Farmers, whose main task is the raising of crops and the production of food, and whose only interest is to apply control measures where they are effective, economically warranted and environmentally sustainable;
- (b) Extension agents responsible for offering advice on pest and disease control;
- (c) Agricultural authorities responsible for rural policy, food markets and food security;
- (d) Environmental authorities responsible for protection of the environment.

A reference model can be defined for each type of end-user, as shown in Table 6.5.

In this context, agrometeorology plays some specific roles and in particular:

- (a) Support for the implementation, calibration and validation of models;
- (b) Production of meteorological data (past, present and forecast) for models;
- (c) Production of biological observations (for example, outputs of phenological networks);
- (d) Support for integration of data coming from different sources (physical and biological data, remote-sensing, weather stations, and numerical weather prediction (NWP) models).

6.5.3.2.4 *Agrometeorological data for pest and disease models*

For the end-users of pests/disease models, the final questions are: When will an epidemic develop? How will the epidemic develop? What will the final disease/pest severity be? Answers to these questions can be obtained by means of specific simulation models producing forecasts of the onset and development of pests/diseases.

It is important to know that the term “forecast” as used by pest and disease experts represents a description of the real-time development of an infection on the base of real-time monitoring of meteorological variables (Magarey et al., 2005).

The adoption of forecast meteorological data for pest/disease simulation models is significantly limited by two kind of problems: (i) the insufficient quality of deterministic forecasts; and (ii) the existing gap between the scale of development of pests and diseases (micrometeorological scale, canopy layer) and the reference scales of NWP models.

Table 6.5. Simulation models of pests/diseases for different kinds of end-users

End user	Reference models	
	Field models (microscale)	Territorial models (mesoscale)
Farmers	X	
Extension agents	X	X
Agricultural authorities		X
Environmental authorities		X

The problem of the quality of deterministic forecasts can be approached with probabilistic methods. They are useful in defining scenarios of development of pests and diseases with an associated level of probability.

The existing gap between the scale of development of pests and diseases and NWP scales can be overcome by improved on-site measurements (station density) and by means of two principal techniques of downscaling:

- (a) Physical techniques founded on micrometeorological models;
- (b) Statistical techniques based on an analysis of the relationship between NWP data and microscale data, techniques that in meteorology are known as model output statistics (MOS).

Micrometeorological models may represent mechanistically the space and time behaviour of meteorological variables in the canopy layer based on data produced by NWP models or meteorological stations outside the canopy.

MOS techniques are based on algorithms that can be adapted to specific weather types, topography aspects and canopy characteristics (for example, in mid-latitudes, anticyclonic conditions in mountain territories produce phenomena like thermal belts or cold lakes, and the dynamics of cold airmasses is influenced by the shape, dimension and orientation of canopies).

6.5.3.2.5 *Long-distance transport of pests and diseases*

Meteorological forecasts and, in particular, the study of trajectories of air masses can be useful in evaluating the risk of long-distance transport of pests and diseases. A most remarkable case of migration in a noctuid lepidopteron is that of *Agrotis ipsilon*, which travels from tropical areas towards mid-latitudes. A forecast of the arrival of adults of *Agrotis* in northern Italy can be based on:

- (a) The presence of seedlings of crops (for instance, maize, soybean);
- (b) A wet surface of soils;
- (c) A circulation pattern with advection of airmasses from North Africa. Normally a trough on the western Mediterranean with a north-south axis represents these conditions.

After their arrival, adults deposit eggs and a new generation of caterpillars will eventually damage seedlings. In reality the mechanism of migration of these insects is sometimes more complicated

because adults coming from Africa can deposit eggs in southern Italy, producing new populations that migrate towards the north in the next year.

Another example is represented by bacteria cells of the plant pathogen *Erwinia amylovora*, which are sometimes aerosolized from ocean water, transported within cloud systems, and successively deposited in precipitation at inland sites. This transport process may be implicated in the transfer of plant pathogenic bacteria from aquatic environments to susceptible plant hosts, which ultimately results in greater risk of crop loss due to disease development (Franc and DeMott, 1998).

6.5.4 Fire forecasting

6.5.4.1 Overview

Wildfires, also known as forest fires, vegetation fires, grass fires, brush fires, or bush fires, are uncontrolled fires often occurring in wildland areas, but which can also consume houses or agricultural resources (FAO, 1986). After a triggering event (sometimes represented by lightning without rainfall, or in other cases by an involuntary or voluntary human action (such as arson)) the wildfire ignites, followed by a phase of propagation and a phase of senescence that precedes the extinction.

6.5.4.2 Wildfire modelling

Mathematical models adopted in this field are useful in quantifying the risk of fire, and in describing or forecasting the propagation of wildfires. A necessary condition for the outbreak and successive propagation of wildfires is the presence of a sufficient quantity of fuel: dry plant material and litter such as leaves, needles and small twigs lying on the ground in a freshly fallen or decomposing state. In living green plants the water content is usually too high for ignition. Only if the water uptake via the roots ceases during drought, can the water content decline to a level favourable for ignition. Dead material, however, can more rapidly take up and lose moisture because there is no water-transfer control by the stomata and no water repellence on the leaves, because their waxy surface decays with time. The meteorological factors that control the moisture content and therefore enhance or reduce the wildfire risk are: wind, temperature, solar radiation, precipitation (rainfall, dew, snow), and drought (as a prolonged period of water deficiency) (Bovio et al., 2002). All of these are purely physical meteorological factors; the only exception is drought, which is a physical

and biological phenomenon that can be quantified, for example, by water balance models.

Estimating forest fire risk (which, according to FAO terminology, is the chance that a fire will start) involves identifying the potential contributing variables and integrating them into a mathematical expression, that is, an index. This index, therefore, quantifies and indicates the level of risk. A literature review of wildfire risk methods shows how different approaches are used for the evaluation of fire risk. Traditionally, forest fire risk has been computed at national or local scales using different data sources and methodologies (San Miguel-Ayaz et al., 2003).

For example, the following national models can be listed:

- (a) The United States National Fire Danger Rating System;
- (b) The Canadian Forest Fire Danger Rating System;
- (c) The Australian and New Zealand systems;
- (d) The European integrated forest fire risk index.

The behaviour of fire (in particular direction and speed of propagation) is determined by factors such as fuel availability and type, topography, temperature and humidity of airmasses, and wind speed and direction. In particular, hot, dry and gusty winds (such as foehn winds) represent a crucial factor in the propagation of wildfires. These elements are considered in deterministic or probabilistic models that analyse or forecast the behaviour of fires and can provide important support for wildfire suppression. The effect of receiving information at the fire front that is correct and timely has enabled fire teams to move to safe locations without being caught by a change in meteorological conditions (for example, wind).

Wildfire models (of risk or propagation) must be calibrated and validated locally on time series of wildfires and meteorological data of sufficient length; calibrated models can be run with past or real-time meteorological data or with forecast ones. A review of information systems for wildland fire management was presented by Albright and Meisner (1999).

After the end of a fire it is important to carry out a rational damage assessment and fire damage mitigation in order to prevent negative effects such as soil erosion or enhanced flooding. Specific models can be useful in order to produce:

- (a) A post-fire quantitative evaluation of fire severity (Scanlon and Valachovic, 2006);
- (b) A prediction of post-fire mortality of trees (Fowler et al., 2006);
- (c) A prediction of the colonization of burned area by new vegetation.

Meteorological and remotely sensed data can be important inputs for these models and GIS techniques are useful in order to obtain final products that can benefit management activities.

6.5.4.3 Forecasts for wildfire planning

Weather forecasts, used directly or as inputs for wildfire models (Table 6.6), can significantly improve decision processes for:

- (a) Planning of monitoring activities, with the choice of the appropriate level of attention;
- (b) Planning of wildfire suppression activities;
- (c) Planning of prescribed fire (controlled application of fire to existing naturally occurring fuels under specified environmental conditions, following appropriate precautionary measures, which allows the fire to be confined to a predetermined area and accomplishes the planned land management objectives).

Wildfire suppression planning is usually focused on short-term high-resolution predictions, but prescribed fire planning can require a long-range forecast horizon. Because the research to date indicates that forecast accuracy is limited beyond one or two weeks, specific measures of uncertainty are needed that are germane to fire management planning. For long-range planning, ensemble forecasts are needed to identify a range of possible scenarios with associated probability measures.

6.5.4.4 Examples of existing models

The Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992) is used to estimate the rate of spread. The FBP system is an empirical model that predicts fire behaviour conditions for 17 fuel types found in Canada. Using daily and hourly weather values and indices from the Canadian Forest Fire Weather Index (FWI) System as inputs, the FBP system predicts measurable physical parameters, including the forward rate of spread (ROS) in metres per minute (Anderson et al., 2005).

The BEHAVE Fire Behaviour Prediction and Fuel Modelling System (Andrews, 1986) incorporates Rothermel's model, based on the principle of

conservation of energy. Rothermel (1983) represents the rate of fire spread as a function of fuel density, particle size, bulk density, and rate of fuel consumption. Because an analytical solution to the problem of fire behaviour is not possible on this basis, Rothermel approximates a solution from laboratory experiments.

The European integrated forest fire risk index (Sebastian-Lopez et al., 2000) is based on the one developed for the computation of the Fire Potential Index (Burgan et al., 1998). The model requires as inputs NDVI values to calculate the relative greenness, meteorological data to estimate the dead fuel moisture content, and a fuel map to estimate the fuel loads.

The Climate Prediction Center (CPC) in the United States has been exploring an experimental research forecast capability for fire severity and danger. The current experimental fire weather forecasts are being updated to include the National Fire Danger Rating System (NFDRS) that has been used over the continental United States since 1978. In addition to fire danger indices, a drought index is also produced as part of the fire danger rating. There are three basic inputs to computing the fire danger rating:

Table 6.6. Usefulness of different kinds of forecasts for different activities

Activity	Reference models	Reference forecasts			
		NC and VSRF	SRF	MRF	LRF
Planning of monitoring activities	Risk indices		X	X	X
Decision processes for wildfire suppression	Propagation models	X	X	X	
Decision processes for prescribed fire	Propagation models	X	X	X	X
Planning of ecosystem recovery after wildfire	"After wildfire" models			X	X

NC: nowcasting; VSRF: very short-range forecast; SRF: short-range forecast; MRF: medium-range forecast; LRF: long-range forecast. Also refer to section 4.2, where additional information can be found on the time horizon of forecast models.

weather, topography and fuels. Because fire danger is a cumulative phenomenon, weather is the driver in terms of producing seasonal changes in fire danger estimates.

Topography is used to reflect the fact that fire burns faster upslope than on flat ground. Vegetation is deemed to be fuel for fire danger rating purposes. Twenty NFDRS fuel models represent the vegetation types across the United States, defining fuel characteristics such as depth, load by live and dead classes, heat content, fuel particle size, and so on. These basic inputs are converted into various fire danger indices by processing them through a modified version of the fire spread model. The fuels data for the NFDRS are defined at 25 km spatial resolution, while the weather data are at resolutions of 25, 50 and 200 km. The higher-resolution fuels data allow for the display of more fire danger variability because of the assumption that the actual weather parameter values are reasonably constant over this area.

There are still a number of research questions that need to be answered, including persistence characteristics, cross-correlations among the indices, predictability characteristics, and the relation of these indices to fire occurrence and size, as well as the accuracy of the fire danger predictions. The NFDRS module created for the severity forecasting research project by the United States Forest Service is being used to convert weather forecasts into experimental fire danger rating forecasts. NFDRS indices include forecasts of the energy release component, burning index, spread component and ignition component, derived directly from the model output; these forecasts cover daily, weekly, monthly and seasonal time periods (Roads et al., 2005)

6.5.5 Phenology³⁸

Phenology, the description of the development stages of wild plants, agricultural fruit and crops, and other organisms (for instance, insects) has several well-defined applications, in addition to its use in simulation models. Certain agricultural activities often require advanced information on the dates of specific stages of crop development.

Most European countries maintain networks that collect phenological data. For instance, the German Weather Service (Deutscher Wetterdienst, or DWD) currently runs a phenological network comprising

approximately 1 550 stations. The phenological observation programme of DWD has 167 stages of development. On selected trees, bushes and shrubs the unfolding of leaves, flowering, fruit ripeness and colouring of the leaves, for example, are observed; in the case of agricultural crops, tillage and harvest data are also collected in addition to selected phases. The observed data from the basic phenological network have been collected and archived at the end of every vegetation period since 1951.

An early forecast of the ripening dates of many crops has considerable economic advantages. It provides lead time for organizing such operations as the harvesting, packaging and transporting of produce, as well as for planning the time of harvest to coincide with market requirements (Lomas, 1970; Edey, 1977). In experimental and plant breeding work it is necessary to have a good understanding of the effect of environmental factors on crop development behaviour (Goyne et al., 1977; Brown, 1978; Clarkson and Russell, 1979). Information on the rate of development and the dates of various phenological stages is useful as input into models used for crop-weather surveillance systems and for agricultural economics analyses. Because of its importance in a number of agricultural areas of activity, it is necessary to understand the physiological process of development and how the rate of development is affected by certain environmental factors.

Phenology can be modelled based on vernalization, photoperiod, thermal response and intrinsic earliness (Cao and Moss, 1997), most of which are plant-specific. Intrinsic earliness is conditioned by the genetic features of the plant and it has constituted a main target for breeders. It is one of the mechanisms to avoid several difficulties linked with adverse factors such as drought or early fall frost. Photoperiod and vernalization are qualitative responses of seeds or young plants that require exposure to a cold period of a certain length and intensity before they can develop properly (Gommes, 1998a).

Temperature has a directly observable effect on the rate of development of plants and cold-blooded organisms. With regard to crops, the effects are significant not only in temperate countries, but in tropical countries as well (examples for rice are given by Dingkuhn (1995) and Mahmood (1997)).

The most common technique to determine the effect of temperature is the often-criticized method of temperature sums, also known as sum of degree-days

³⁸ For a more detailed treatment of this subject, including the "Q10" and other approaches to the simulation of development rates, the reader is referred to Gommes, 1998a.

(SDD) (Chang, 1974), or thermal time. The method assumes that the amount of heat (measured by temperature) required for a plant to develop from planting to stage S is a constant.

Starting from planting³⁹, the following sum is computed:

$$\text{SSDs} = \frac{\text{Day on which stage } S \text{ is reached} - T - T_b}{\text{Planting day}} \quad (6.16)$$

where

$T - T_b$ is taken as 0 when $T < T_b$

T is taken as T_u when $T > T_u$

T is average daily temperature, T_b is the base temperature below which no development takes place, and T_u is an upper threshold temperature above which it is assumed that temperatures cease to have an effect on development. For instance, the sum of temperatures from sowing to emergence could be 100°C, meaning that with a base temperature of 10°C, the plant would emerge after 10 days at an average temperature of 20°C.

The concept of growing degree-days has been rightly criticized as an oversimplification. It remains nevertheless in wide use and a number of modifications have been suggested to adapt it to specific crops, regions and other circumstances. For instance, Dawod (1996) used the equation below to compute daytime temperatures T_{DD} (average temperature from sunrise to sunset) as an input to phenological estimations for potatoes in Egypt:

$$T_{DD} = T_A + (T_X - T_N)/6.1 \quad (6.17)$$

where T_A is the mean 24-hour temperature, T_X is maximum temperature and T_N stands for minimum temperature.

6.5.6 Climate change

6.5.6.1 Introduction

This section provides a short overview of some issues relating to agrometeorological forecasting and climate change impacts. Increasing recognition of the importance of anthropogenic climate change and its impacts has led to the birth of very long-range agrometeorological forecasting. Forecasting the yield of crops for

the coming decades – even to the end of the century – is useful for both adaptation and mitigation. Hence long-range forecasts can enable long-term planning of resources, such as germplasm, which can be used to adapt to climate change. Where negative impacts are predicted, these can be used to highlight the importance of reducing emissions of greenhouse gases. Climate scientists are becoming increasingly interested in working with crop scientists in order to understand and evaluate the effects of climate change on agriculture (for example, Huntingford et al., 2005). Climate change is likely to have a significant impact on the prevalence of pests and diseases, the availability of water, the growth and development of crops, and many other agricultural processes. This section focuses on crops.

Climate change has both direct and indirect impacts on crop growth and development. Higher ambient levels of carbon dioxide have an impact on C_3 crops by increasing photosynthesis and decreasing water use. Indirect effects result from changes in weather and climate that are caused by higher levels of greenhouse gases. These changes may be within, or beyond, the current observed range of climate variability. This distinction is significant because agricultural systems will be particularly at risk when the changes in climate are unprecedented. Hence the projected increase in extremes of rainfall and temperature are critical for agriculture. Many crops are sensitive to high temperatures during flowering, for instance; and to further complicate matters, this sensitivity may occur only during a particular part of the day (Challinor et al., 2005b; Wheeler et al., 2000).

6.5.6.2 Methods

The long-range nature of climate change projections, coupled with the potential for unprecedented conditions, has three major implications. First, it is difficult to justify the use of empirical crop models, since these are calibrated under current conditions. For example, some information about the response to increased carbon dioxide is available from experimental studies (for example, Ainsworth and Long, 2005); however, this information is incomplete and one is forced to rely upon the dialogue between crop experiments and modelling to extrapolate the future impacts more precisely. Hence most climate change studies use process-based models of the kind described in 6.1.4.

A related concern exists for process-based models. If models are over-tuned for the current climate, the credibility of the model when it is run with climate change data will be in question. The risk

³⁹ The calculations can also start from some conventional date before planting if the planting date is to be determined in temperate and cold climates.

of over-tuning increases with the number of unconstrained parameters in the model, since observations may be correctly simulated without representing the processes involved (the right answer for the wrong reason). Hence a crop model should be sufficiently complex to capture the response of the crop to the environment, while minimizing the number of parameters that cannot be estimated directly. Some studies (for example, Parry et al., 2004) use predictive equations based on the statistical relationships between climate and crop model output. Even for a simple model, this can produce very different results from the direct use of the model (Challinor et al., 2006). Here again there is a risk of relying on observed relationships that may change as climate changes.

The third implication of the characteristics of climate change is the importance of quantifying uncertainty. There is a cascade of uncertainty – from levels of emissions of greenhouse gases to the response of the atmosphere and the subsequent response of the agricultural system. This makes the deterministic forecasting of climate change impacts impossible; any predictions must be made probabilistically. Uncertainty can be quantified by sampling a range of crops, locations, models or scenarios. Using a range of (crop and/or climate) models can account for structural model error (see 6.3.2). Uncertainty associated with parameter values can be quantified by varying model parameters within known uncertainty ranges (Challinor et al., 2005c).

The approaches used to quantify the impacts of climate change on food production are subject to the same issues with spatial scale as are shorter-range forecasts (see 6.5.4.3). Assessments can be made at the field scale, and then scaled up, or simulations can be carried out at the regional scale using large-scale inputs. Each of these has its own advantages and disadvantages (Challinor et al., 2003, 2006; Baron et al., 2005; Hansen and Jones, 2000).

Field-scale assessment has the advantage of potentially capturing important local-scale management and biophysical processes and their interactions. Such assessments require weather data at a much higher resolution than that provided by climate models, however. Techniques for downscaling weather information are often empirical, and hence necessarily produce location-specific results whose accuracy is contingent on the stationarity of the relationships used. Another option is crop modelling at or near the scale of the climate model. While this “large-area” method leaves the crop simulations prone to both aggregation error and the propagation of errors from the climate model, which can be significant, this method has shown promising results (for example, Challinor et al., 2006). It also permits full integration of the crop and climate model, which can account more fully for changes in land use and their potential feedbacks, such as methane emissions from rice, on the climate system (Osborne et al., 2007).

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CLIMATE AND WEATHER RISK ASSESSMENT FOR AGRICULTURAL PLANNING

7.1 INTRODUCTION

This chapter defines the assessment of climate and weather risk and its importance in agricultural planning to mitigate the impacts of climate variability and extreme events.

The term weather is used to describe day-to-day variations in our atmosphere. This includes precipitation, temperature, humidity and cloud cover, among other variables. Weather forecasts are essentially short-term, as the reliability of forecasts falls off rapidly after five days. Weather is therefore an instantaneous concept. The climate of a region is described by collating the weather statistics to obtain estimates of the daily, monthly and annual means, medians and variability of the weather data. Climate is therefore a long-term average of weather.

Agricultural planning – strategic (long-term) and tactical (<10 days) – needs to weigh climate-related and other risks to attain the producer's goals and to spell out the sort of information that farmers need to aid their planning, such as climate, technical/managerial, and market data, for example. A key aspect needed in linking climate and weather risk to agricultural planners is an appreciation of the overall management system in question from the decision-makers' viewpoint. Managers need information for both tactical and strategic decision-making.

As an example, an Australian survey of agricultural planners provided a myriad of planning horizons and key decisions (sometimes referred to as “decision points”) that could be influenced by weather and climate variability at different timescales. In addition, it has been realized that the decision system extends across the whole value chain in agricultural production that is affected by weather and climate variability. The sugar industry can serve as an example that has relevance to many agricultural planning systems: there are decisions at the farm scale (irrigation, fertilization, fallow practice, land preparation, planting, pest management) and at the transportation and milling scale (improved planning for wet season disruption, planning for season start and finish, crop size forecasts, civil works schedules). There are catchment-scale issues (land and water resource management, environmental management), as well as issues at the “marketing scale” (crop size forecasts, planning for high-premium early season supply, shipping and global supply management) and at the policy scale (water allocation planning, planning for extreme events) (Everingham et al., 2002; Stone and Meinke, 2005).

Varying timescales and key agricultural decisions are also important, especially in terms of the need to recognize how different climate and weather systems affect different farming decisions. Table 7.1 provides an example of the complexity inherent in

Table 7.1. Agricultural decisions at a range of temporal and spatial scales that could benefit from targeted climate forecasts (Meinke and Stone, 2005)

<i>Farming decision type</i>	<i>Frequency (years)</i>
Logistics (e.g., scheduling of planting/harvest operations)	Intraseasonal (>0.2)
Tactical crop management (e.g., fertilizer/pesticide use)	Intraseasonal (0.2–0.5)
Crop type (e.g., wheat or chickpeas) or herd management	Seasonal (0.5–1.0)
Crop sequence (e.g., long or short fallows) or stocking rates	Interannual (0.5–2.0)
Crop rotations (e.g., winter or summer crops)	Annual/bi-annual (1–2)
Crop industry (e.g., grain or cotton; native or improved pastures)	Decadal (~10)
Agricultural industry (e.g., crops or pastures)	Interdecadal (10–20)
Land use (e.g., agriculture or natural systems)	Multidecadal (20+)
Land use and adaptation of current systems	Climate change

matching appropriate climate forecast systems with the farming decision type (from Meinke and Stone, 2005).

7.1.1 **Understanding the climate mechanisms that contribute to climate- and weather-related risks**

Weather and climate variability can result from interactions between the climate system's various components – the atmosphere, oceans, biosphere, ice layer, land surface and anthropic action.

Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between “climate change” attributable to human activities altering the atmospheric composition and “climate variability” attributable to natural causes.

Climate disasters can be divided into extreme events and regional climate anomalies. Global climate change may produce a larger number of climatic disaster occurrences. This is based on the fact that a linear increase in the average of a climatic variable implies a non-linear increase in the occurrence probability of extreme values of such variable. Also, an increase in its variability means an incremental change in the occurrence probability of extreme values (Cunha, 2003).

A WMO study, *Agrometeorology Related to Extreme Events*, (WMO, 2003a) notes that “Although natural calamities cannot be avoided, their destructive impact, in terms of human losses and animal lives related to ecological equilibrium, could certainly be considerably minimized. Planning and management for the prevention and mitigation of extreme events are matters of vital significance for the safety and well-being of millions of people who inhabit exposed disaster areas. In addition to local and national action, international and regional cooperation should be promoted for an enhanced prevention and mitigation.”

Micro- to large-scale studies have shown anomalies for isolated climatic elements (Grimm et al., 1998; Souza et al., 2000; Garcia et al., 2002; André

et al., 1996, 2004; Krishnamurti et al., 2002; Chiang and Sobel, 2002; Su and Neelin, 2003). The vast majority of the Earth's surface is void of data, however. Moreover, databases are essential for conducting analysis, developing trends and determining anomalies in global and regional climate.

Climate data are essential in planning and reducing the risks associated with climate anomalies. Assessing and forecasting the impacts of short-term climate variability and weather risks, as well as their relationship to extreme events, could help mitigate the effects of climate variability and facilitate the scheduling of agricultural activities.

The definitions of risk, hazard and anomalies differ as follows:

- (a) Hazard is an event or process that is potentially destructive; it is the probability of occurrence of a potentially damaging phenomenon within a given time period and location of interest;
- (b) Risk is the magnitude of a potential loss (lives lost, persons injured, property damaged, and economic activity disrupted) within the area subject to hazard for a particular location and a reference period;
- (c) Anomaly is the deviation of a meteorological quantity value in a given region from the normal (mean) value for the same period.

Impacts from natural disasters on agriculture, rangeland and forestry can be positive or negative. While the impacts are predominantly negative and do affect human society significantly (Joy, 1991), there are some positive impacts or benefits that should be pointed out in any discussion of the impacts of natural disasters.

Positive impacts of natural disasters include increased rainfall to inland areas from tropical cyclones along coastal areas (Ryan, 1993), the fixing of atmospheric nitrogen by thunderstorms, the germination of many native plant species as a result of bushfires, and the maintenance of fertility of flood-plain soils due to flooding (Blong, 2002). The influx of funds into disaster-relief activities after the occurrence of natural disasters can also sometimes be positive for local communities, as was shown for the city of Mobile, Alabama, after Hurricane *Frederic* (Chang, 1984). Negative impacts will be discussed in detail in this chapter.

7.2 CLIMATIC HAZARDS

7.2.2 Categories

7.2.1 Types

7.2.2.1 Drought

7.2.1.1 Extreme events

Extreme events can vary from short-lived, violent phenomena of limited extent such as tornadoes, flash floods and severe thunderstorms, to the effects of large systems such as tropical and extra-tropical cyclones, and the effects of prolonged drought and floods. Drought and floods are responsible for more significant impacts on human life and property and can affect one area for several months to years. About 65 per cent of the estimated worldwide natural disaster damage is of meteorological origin. Meteorological factors have contributed to 87 per cent of the number of people reported affected by natural disasters and to 85 per cent of related deaths (WMO, 2004). Recent scientific studies also indicate that the number of extreme events and their intensity may increase as the global temperature continues to rise due to climate change.

Drought is a shortage of water for essential needs, which for agricultural purposes relates to plant growth. It is also a relative term, however, in that it might be considered a deficiency of water for a few weeks or months in a high rainfall area or a lack of water over several years in arid lands. It also should not be confused with desertification, which is a consequence of human activity, such as overstocking the land relative to its carrying capacity, something that is particularly common in arid lands in times of below-average rainfall. Excessive tillage is another cause of desertification.

Drought differs from other natural hazards in that its effects often accumulate slowly over time, and may linger for years after the termination of the event (Wilhite, 2000). Because of this, drought is often referred to as a creeping phenomenon (Tannehill, 1947).

7.2.1.2 Regional climate anomalies

Mesoscale storms and severe local storms fall into this category. Hail causes millions of dollars of damage to crops and property each year. Tornadoes are among the most feared natural phenomena. More tornadoes occur on the North American continent than anywhere else in the world, though they can affect (and have affected) nearly all regions of the world. Fortunately, their scale is relatively small (diameters range from about 15 m to over 2 km), so they affect a limited area.

Droughts must be viewed as an integral part of a natural climatic cycle, even though extreme droughts can have disastrous consequences. Treating drought simply as a disaster that could not be anticipated, with subsequent pleas for national or international assistance, ignores the fact that the impact of all but the most severe droughts can be mitigated through careful planning and risk management (O'Meagher et al., 1998, 2000; Botterill, 2003, 2005). It is also useful to distinguish among meteorological, hydrological and agricultural drought phenomena, in that the severity of these are only partially correlated; the severity of an agricultural drought depends on how deficiency of rainfall and soil moisture is expressed in terms of plant growth, and ultimately in terms of the health and welfare of rural communities (for example, du Pisani et al., 1998; Keating and Meinke, 1998; Stafford Smith and McKeon, 1998; White et al., 1998).

Small-scale severe weather phenomena (SCSWP) are weather events that are sparsely dispersed in space and time and may have important impacts on societies, such as loss of life and property damage. Their temporal scales range from minutes to a few days at any location and typically cover spatial scales from hundreds of metres to hundreds of kilometres. The Technical Summary of the Working Group I Report of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) describes SCSWP as follows: "Recent analyses of changes in severe local weather (e.g., tornadoes, thunderstorm days, and hail) in a few selected regions do not provide compelling evidence to suggest long-term changes. In general, trends in severe weather events are notoriously difficult to detect because of their relatively rare occurrence and large spatial variability" (IPCC, 2001).

Massive fires can be triggered during and after periods of drought, by lightning or by human actions, in almost every part of the world. These fires destroy forests, grasslands and crops. They also kill livestock and wild animals, damage or destroy settlements, and put the lives of inhabitants at risk (WMO, 2006).

7.2.2.2 Heavy rainfall and floods

According to the WMO publication *Working Together for a Safer World*, flood hazards represent about 32

per cent of all damage from natural disasters (WMO, 2004). It is estimated that extreme weather events will increase in frequency and severity during the twenty-first century as a result of changes in mean climate and/or climate variability. Changes in temperature and precipitation may lead to dramatic shortening of the return periods of floods. Flood disasters are intensified by environmental degradation, urbanization, demographic shifts and poverty, industrialization and overall economic development.

Prevention of these disasters requires the development of programmes that include the management of the water cycle as a whole, with a view to the adoption of an integrated hazard management approach. WMO and the Global Water Partnership (GWP) are promoting a new concept of Integrated Flood Management (IFM). IFM ensures disaster reduction through the prevention of flooding, mitigation of adverse impacts through appropriate adaptation strategies and preparation of the community to respond appropriately to flood forecasts and warnings.

7.2.2.3 Strong winds: tornadoes, storms and tropical cyclones

Tropical cyclones are among the most destructive of all natural hazards, causing considerable human suffering in about 70 countries around the world. They form over all tropical oceans, with the possible exception of the South Pacific east of about 140° W. In the western North Pacific, mature tropical cyclones are known as typhoons – they are also referred to as hurricanes in the western hemisphere and cyclonic storms or tropical cyclones in other areas. As described in *Agrometeorology Related to Extreme Events* (WMO, 2003b), tropical cyclones are the offspring of ocean–atmosphere interactions, powered by heat from the sea, steered by the easterly trades and mid-latitude westerlies. An average of 80 tropical cyclones form annually over the tropical oceans, with the typhoon region of the western North Pacific accounting for approximately 30 of these (Obasi, 1997). The impact of tropical cyclones is greatest over coastal areas that bear the brunt of the strong winds and flooding from rainfall. For example, while the annual average for the Bay of Bengal and the Arabian Sea is only five tropical cyclones per year, some of the most destructive tropical cyclones in history have occurred in that region, such as the severe tropical cyclone in Bangladesh in 1970, which claimed 300 000 lives.

El Niño is generally associated with worldwide changes in the patterns of precipitation and temperature, tropical cyclones and hurricane activity, the behaviour of subtropical jet streams, and many other general circulation features over various parts of the world. The magnitude of hurricanes is assessed with the Saffir–Simpson scale, which takes into account maximum sustained winds and minimum storm central pressure.

Losses to agriculture, rangelands and forests from tropical cyclones can be due to direct destruction of vegetation, crops, orchards and livestock; damage to infrastructure such as canals, wells and tanks; and long-term loss of soil fertility from saline deposits over land flooded by seawater. Typhoons can inflict severe damage on agriculture: for example, in southern Hainan on 2 October 1999, some 25 million timber and rubber trees were blown down (WMO, 1994). A typhoon that struck Thailand on 4 November 1989 destroyed some 150 000 ha of rubber, coconut and oil palm plantations and other crops (WMO, 1997).

Not all the impacts of cyclones are negative, however, and some reports cite beneficial effects of tropical cyclones. Ryan (1993) mentions some important benefits of tropical cyclones in Australia. Increased water availability in water-critical regions makes agricultural production less susceptible to the dry season. Researchers estimate that nine major hurricanes in the United States since 1932 terminated dry conditions over an area of about 622 000 km² (Sivakumar, 2005).

7.2.2.4 Temperature: frost and heatwaves

A “frost” is the occurrence of an air temperature of 0°C or lower, measured at a height of between 1.25 and 2.0 m above ground, inside an appropriate weather shelter (FAO, 2005). Most frost events occur during clear and calm nights, often preceded by relatively warm and sunny days. This type of frost originates from the reduction of downward long-wave radiation from the atmosphere owing to the absence of, or low, cloud cover, and from the stratification of the air near the ground that develops under weak wind conditions. Because cold air flows downslope, much like water, the valley floors and lower portions of the slopes are colder. This type of frost is classified, in relation to its origin, as a “radiation frost”. Another less common but relevant type of frost is the “advection” or “wind” frost, which originates from the advection of freezing cold air into a region. This type of frost is accompanied by wind and clouds and predominantly affects the higher portions of valleys.

Frost damage is the leading weather hazard, on a planetary scale, as far as agricultural and forest economic losses are concerned. Only a small fraction of the farmland is frost-free and few crops never experience frost damage. Frost reduces substantially the world's production of vegetables, ornamentals, field and row crops, pasture, forage and silage crops, fruit trees (deciduous and evergreens), vines and berries. Sometimes forest trees are also affected (FAO, 2005).

Frost damage is possible only after the onset of freezing. Thus it is probably more accurate to refer to "freeze damage". Freezing inside the protoplasts (intracellular freezing) is always lethal, and is most likely due to the disruption of the membrane systems that compartmentalize cells. Fortunately, this type of damage is rare or does not occur in nature (Levitt, 1978). Under natural cooling rates, freezing of the plant tissues starts outside the cells (extracellular freezing) in the intercellular solution, because this solution is more diluted than the solution present in the cytoplasm. As the temperature of the freezing tissue gets lower, the ice masses grow, pulling out water from the protoplast, which shrinks as a result. The driving force behind this water movement is the gradient of vapour pressure, since saturation vapour pressure over ice is lower than over water at the same temperature. The loss of water by the protoplast (that is, desiccation) may or may not affect the viability of the cells, depending on the tissue/plant hardiness. Some tissues cannot recover after any amount of ice has formed extracellularly, but, at the other extreme, there are plants/tissues that can endure freezing down to the temperature of liquid nitrogen (-196°C).

The temperature at which a given level of freeze damage is expected is called a critical temperature. Critical temperatures change with species/variety, phenological stage and a number of hardening factors. For most crops, critical temperatures have been published and compiled (FAO, 2005). Forest trees are mostly affected by frost if there is a deacclimation period and they lose their hardiness prior to a frost event. Nevertheless, there are also published critical temperatures for some forest trees (Larcher, 1982; Tibbits and Reid, 1987; Ashworth and Kieft, 1995; Ryyppö et al., 1998).

Heatwaves are most deadly for humans in mid-latitude regions, where they concentrate extremes of temperature and humidity over a period of a few days or even weeks in the warmer months. The oppressive airmass in an urban environment can result in many deaths, especially among the very young, the elderly and the infirm. In 2003, much of western Europe was affected by heatwaves during

the summer months. In France, Italy, Netherlands, Portugal, Spain and the United Kingdom, they caused some 40 000 deaths. Extremely cold spells cause hypothermia and aggravate circulatory and respiratory diseases (WMO, 2006a).

7.2.2.5 Others

Duststorms and sandstorms are ensembles of particles of dust or sand lifted to great heights by strong and turbulent wind. They occur mainly in parts of Africa, Australia, China and the United States. They threaten lives and health, especially of persons caught in the open and far from shelter. Transportation is particularly affected as visibility is reduced to only a few metres.

Precipitation in the form of large hailstones can reach diameters of over 10 cm and can fall at speeds of over 150 km/h. Worldwide losses to agriculture in a typical year are more than US\$ 200 million. Hailstorms have also caused deaths and great damage to cities around the world. In a matter of minutes, an ice storm can deposit a layer of ice heavy enough to bring down power and telephone lines and snap branches from trees. The ice covers roads, railroad tracks and runways, making driving extremely hazardous, delaying trains and closing airports.

Fog is a suspension of very small, usually microscopic, water droplets in the air. Dense fog has a serious impact on transportation when the visibility is significantly reduced. Highways, airports and ports are closed for safety. Fog can cause considerable economic losses. Smog is a combination of fog and air pollution. It has serious implications for human health.

Pollutants include particulate matter and noxious gases from industry, vehicles and human activities. Smoke and haze result from forest or wildland fires, from slash-and-burn forest or crop clearing, or from ash generated by volcanic explosions in stable air conditions. Smoke, haze and pollution have serious implications for human health – the local population may have to wear gas masks. These conditions reduce visibility, and air and road traffic can be disrupted. Smog, acid rain, the ozone hole and an adverse increase in the greenhouse effect are also caused by air pollution. Stable atmospheric conditions often lead to a concentration of pollutants.

Desert locusts inflict damage in Africa, the Middle East, Asia and southern Europe. When weather and ecological conditions favour breeding, the

insects are forced into a small area. They stop acting as individuals and start acting as a group. Within a few months, huge swarms form and fly downwind in search of food. Swarms can be dozens of kilometres long and can travel up to 200 km a day. A small part of an average swarm (or about one tonne of locusts) eats the same amount of food in one day as 10 elephants, 25 camels or 2 500 people. Swarms jeopardize the lives of millions of farmers and herders in already fragile environments. Locust plagues during or immediately after drought conditions can spell even greater disaster, as was the case in several Sahelian countries in 2005 (WMO, 2006b).

7.3 SCALE STUDIES FOR CLIMATIC ANOMALIES

When investigating climate trends, owing to different force balances, it is important to note that atmospheric motions behave with varying temporal and spatial scales and are often non-linear.

7.3.1 Space

Atmospheric circulation patterns are of critical importance in determining the climate of a location. On a global scale, atmospheric motions transport heat from the tropics towards the poles. Evaporation over the oceans supplies much of the water molecules that support precipitation over land. These circulation patterns are in large part driven by energy differences among regions of the globe. On a smaller scale, precipitation on the lee side of a mountain is typically less than on the windward side. On a still smaller scale, the amount of snow downwind of a snow fence is on average greater than the amount upwind (Ackerman and Knox, 2003). Spatial scales may be classified as follows:

- Microclimate – near the ground over a front yard, climate conditions near the surface over distances of a few metres. Large perturbations to the microclimate can rapidly affect plant life;
- Mesoclimate – climate conditions over a few square kilometres, for example, climate of a town, valley or beach. Other examples of mesoclimate features are orographic precipitation, lake effects, gravity waves and stratospheric-troposphere exchange through mixing at the top of deep cumulonimbus clouds;
- Macroclimate – climate conditions for a state or a country, over scales of approximately 1 000 km or greater;

- Global climate – this is the largest spatial scale, since it refers to climate conditions over the entire Earth. Climate change and climate variability, stratospheric dynamics, and the general circulation fit into this category. Energy input from the sun drives global climate. The solar gain is controlled by the orbit of the Earth around the sun and determines the length of seasons. The so-called climatic controls, or factors that produce the observed climate in any given place, are: latitude, distribution of land and water, ocean currents, prevailing winds, position of high- and low-pressure systems, and topography.

7.3.2 Time

Atmospheric fluctuations occur on various timescales. Long-term fluctuations in climate can be caused by changes in ocean circulation or changes in the concentration of greenhouse gases due to human activity, for example. Fluctuations on shorter timescales can be caused by changes in cloudiness and water vapour, for example. Atmospheric timescales are divided as follows:

- Microscale – seconds to hours;
- Mesoscale – hours to days;
- Macroscale – days to weeks;
- Global scale – weeks to months or years.

7.3.3 Space-time scales

Figure 7.1 illustrates the energy spectrum in all scales of motion, showing peaks in frequencies of a few days (synoptic scale) or several weeks (planetary scales). There are also peaks at one year, one day and

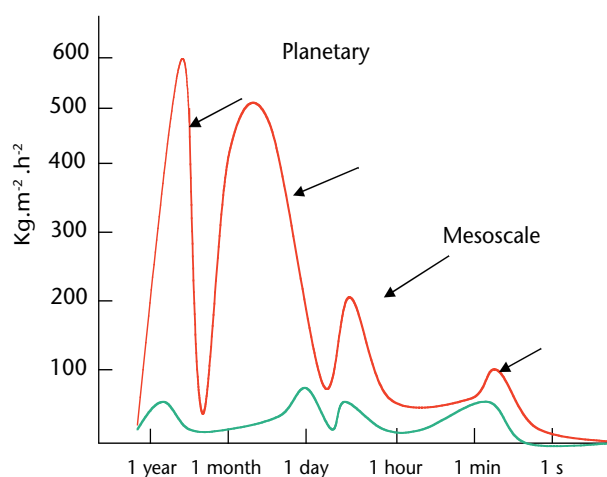


Figure 7.1. Mean kinetic energy of the westward-eastward component of the wind in the free atmosphere at 3.2 km (red line) and near the surface of earth (green line)

a few minutes. Nevertheless, the spectrum is a continuum.

Orlanski (1975) proposed a set of scales that include the micro-, meso- and macroscales. These three are further subdivided from larger to smaller into α , β and γ scales, as shown in Figure 7.2. As the scale becomes smaller, the effects of some processes become increasingly more difficult to treat explicitly or deterministically. Depending on the horizontal scale of interest, different atmospheric processes become significant. Turbulence, the gustiness superimposed on the mean wind, can be visualized as consisting of irregular swirls of motion called eddies. Eddies produce effects at the microscale. The small-scale phenomena associated with the microscale are so transient in nature that deterministic description and forecasting of individual eddies is virtually impossible.

The scales of atmospheric motions are interconnected and nearly continuous. Macroscale processes drive mesoscale and microscale processes as energy is transferred from larger to smaller

scales. Conversely, small-scale processes can organize to develop larger-scale systems, such as convective storms.

Figure 7.3 shows examples of the range and scales of natural hazards that are observed, detected, monitored and forecast by WMO networks (WMO, 2006b).

7.4

AGROMETEOROLOGICAL APPLICATIONS IN THE CHARACTERIZATION OF CLIMATIC HAZARDS – MODELLING AND DATA NEEDS

The Intergovernmental Panel on Climate Change was established in 1988 by WMO and the United Nations Environment Program (UNEP) to assess scientific, technical and socio-economic information relevant to the understanding of climate change, its potential impacts and options for adaptation and mitigation.

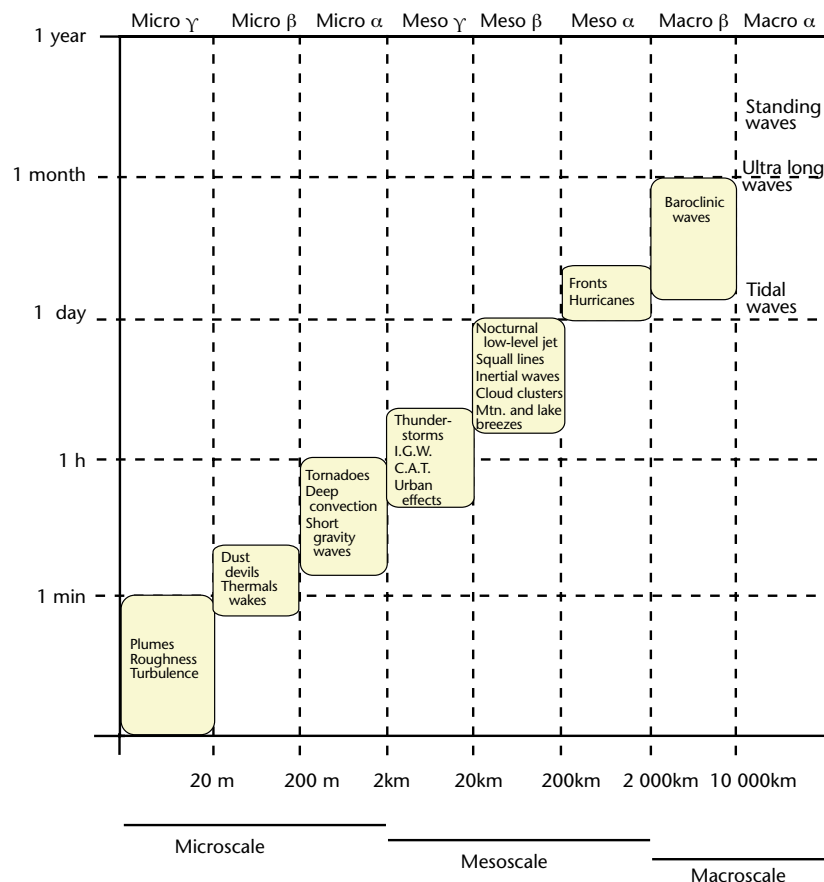


Figure 7.2. Scale definitions and different atmospheric processes with characteristic time- and horizontal scales (adapted from Orlanski, 1975). C.A.T. refers to Clear Air Turbulence and I.G.W. to Inertial Gravity Waves (OFCM, 2004).

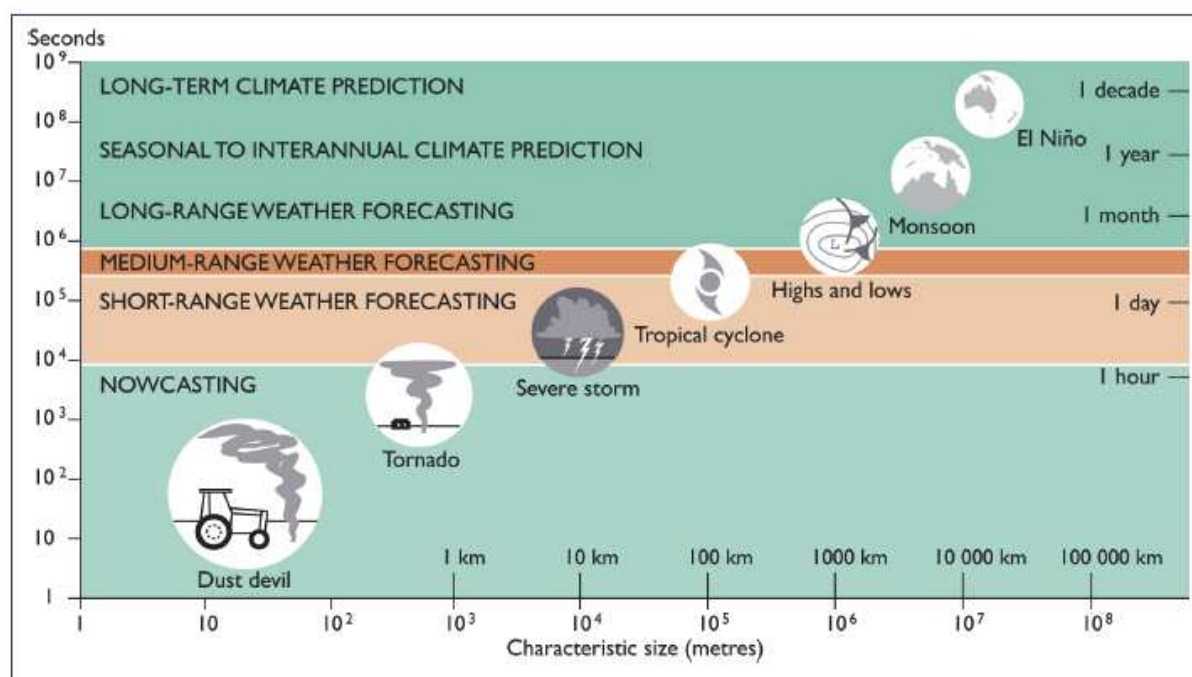


Figure 7.3. Range and scales of natural hazards that are observed, detected, monitored and forecast by WMO networks

The IPCC Third Assessment Report (IPCC, 2001), states that “the Earth’s climate system has undergone changes on both global and regional scales since the pre-industrial era”, and “there is newer and stronger evidence that the Earth’s warming observed over the last 50 years is due to human activities”. Among the hazards predicted to occur due to global change, the most threatening for mankind are an increase in the intensity and frequency of storms, floods, droughts and heat-waves, and the effects of sea level rise in coastal areas. There is, however, a great deal of uncertainty in these predictions and research that aims to improve climate model predictions is under way in many research centres around the world. A number of empirical mathematical models have also been developed and applied (Long and Drake, 1991; Long, 1991). Predicting how vegetation will respond to climate change is critical to understanding the impacts of atmospheric changes on both natural ecosystems and crop growth.

7.4.1 General circulation models

Characterization of climatic hazards for some crops has been carried out using general circulation models (GCMs) and the confidence in the ability of these models to project future climate has been increasing. The most detailed predictions are based on coupled atmosphere–ocean general circulation models that provide credible

simulations of climate, at least for sub-continental scales. Models cannot yet simulate all aspects of climate, however. For example, they still cannot account fully for the observed trend in the temperature difference between the surface and the lower atmosphere. There are also significant uncertainties regarding clouds and their interaction with radiation and aerosols (UNFCCC, 2004).

There are numerous GCMs in use and under construction in research centres around the world. For instance, some of the general circulation models that were used by the IPCC were the French ARPEGE model; the American NASA GEOS-2 and GISS models and NOAA CCM2 models; the German ECHAM model; and the Canadian MAM model, to name a few.

7.4.2 Regional circulation models

Regional Circulation Models (RCMs) are used in many parts of the world to determine specific characteristics of the weather in mesoscale. RCMs have a regional domain, over one state or country, for example, and provide more spatially detailed predictions than those obtained with GCMs. Many RCMs are being adapted and implemented in different parts of the world. The principal RCMs in use are:

- (a) RAMS – Regional Atmospheric Modelling System (Pielke et al., 1992);

- (b) ETA – RCM, with Eta Coordinate (Mesinger et al., 1988);
- (c) MM5 – Penn State Mesoscale Model, Fifth Generation (Chen and Dudhia, 2001);
- (d) ARPS – Advanced Regional Prediction System (Xue et al., 1995);
- (e) MBAR – Brazilian Model of High Resolution (INMET).

7.4.3 Historical local climate data

Climate information can benefit rural producers through the use of seasonal forecasts, and by improving the management of climate variability per se. Significant climate variability implies the likely occurrence of drought and floods.

Historical climate information is crucial to plan the production year. It influences the long-term strategies regarding which crops to grow and when to plant or sow, which for most crops is the primary determinant of when harvesting takes place. Tactical decisions on how much to sow have to be made in relation to climate and market forecasts, along with decisions on when and how much to irrigate, pest control, and crop protection.

Increased self-reliance by rural producers requires the ability to manage both crop and livestock enterprises exposed to a variable climate and to minimize the impact of drought. It also requires the ability to manage risk more effectively: production risk, environmental risk, financial risk and market risk (White, 1997). Improved seasonal outlooks are but one approach to helping farmers become more self-reliant. Ways of offsetting the risks associated with climate variability in order to create opportunities require a systems approach (Hammer and Nicholls, 1996; Hammer et al., 2000).

Climate data have long been invaluable for making farm management decisions, including in areas where seasonal forecasts have proved unreliable. Historical records of rainfall, temperature and even wind speed have been used to determine optimal times for the sowing and harvesting of crops, and for lambing and calving on grassland farms, as well as for irrigation planning.

Ancillary information that can help a producer assess a current season and decide on various tactics includes: rainfall to date (for instance, within a growing season), amount of standing herbage (or crop development), weight of livestock, amount of stored supplements and the capacity to deal with adverse seasons. Weather forecasts (<10 days) are of particular value in making tactical decisions.

A range of decision support systems (DSSs) are available for analysing historical data to determine probabilities of rain, frosts, and the beginning and end of growing seasons. In Australia, for instance, these include Australian Rainman (Clewett et al., 2003), which provides more detailed analysis of rainfall probability distributions, and the MetAccess system (Donnelly et al., 1997) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO). More complex DSSs and models are able to simulate changes in soil moisture, pasture or crop growth, liveweight change, supplementary feed requirements and cash flow. An example is the “Whopper Cropper” cropping systems DSS, in which the DSS can play a valuable role in encouraging farmers to be more tactical in their decision-making and consider planting a crop when there is adequate stored moisture, or to take a more strategic approach. It can also encourage debate on the design of planned and flexible cropping rotations.

In this respect, the development of DSSs has made it apparent that the best way to obtain an appropriate balance between demand- and supply-driven development of a DSS is via dialogue among the key participants in the decision-making. Including this dialogue in a participatory action research programme suggests that the term “decision support systems” may be better described as “discussion support systems”. Discussion support systems such as “Whopper Cropper”, which can be applied in most agricultural environments, can then provide a complementary vehicle for delivery of agricultural simulation-aided discussions. These systems can also focus on farm management advisers as key intermediary agents, who then act as facilitators in the process (Nelson et al., 2002).

Thus these DSSs, in combination with the findings of field experiments and farm surveys, are useful in determining optimal management strategies (such as long-term stocking rates and cropping rotation strategies) and short-term tactics (such as supplementary feeding, decisions about buying and selling livestock, purchasing grain futures or cheap supplies if available, sowing pastures in spring or sowing summer crops, determining areas for cutting hay for conservation or sale, whether or not to irrigate, and controlling for pests or diseases).

The use of long series of weather data has also helped in determining probabilities and risk associated with frost. The Food and Agriculture Organization of the United Nations (FAO, 2005) published personal computer programs that calculate the probabilities of having a minimum

temperature lower than a given value in a specified time period, the last spring and first autumn frost dates, length of growing season, and probabilities and risk of frost damage to a specified crop.

7.4.4 Agronomic models

Biophysical models of agricultural systems can provide useful and often necessary information to complement field experimentation and farm surveys, since if properly validated, they enable the system response to be assessed over many locations and seasons. They provide a logical link between climate information and performance of plants and livestock in the field, and can therefore be an effective means of determining the responsiveness of soil moisture, plants and livestock to changing climatic conditions. Since such models should also be realistically responsive to changes in management, the effects of both management and climate can be studied simultaneously. For example, Fouché et al. (1985) used a model to show how the frequency and duration of droughts on the South African veldt increased with stocking rate. The models are also proving to be invaluable for spatial and temporal simulations within Geographical Information Systems (GISs) in terms of drought monitoring, and as mentioned above, in estimating the value of seasonal forecasts for various locations and farming systems.

7.4.4.1 Crop response

Plant growth models need to be sufficiently mechanistic to predict plant responses to changes in the environment. Although considerable attention has been given to defining the appropriate functional forms within vegetation models (Thornley and Johnson, 1990), most models are specific to the major ecosystem in which they have been developed and have an important empirical base. This includes many of the crop models that have been developed to predict grain yield or to evaluate management strategies, such as different sowing dates, and how the efficiency of water use and the use of nitrogen and other fertilizers may be manipulated.

A number of crop models are now being used both in modelling the effects of climate variability on crop production and in determining management strategies to help identify the genotypes and approaches that allow for mitigation of the impact of below-average seasons. Examples of the use of crop models for modelling and forecasting crop production include Keating and Meinke (1998),

Stephens (1998), and Potgieter et al. (2005) in Australia, and Lourens and de Jager (1997) and de Jager et al. (1998) for the maize model in Southern Africa.

7.4.4.2 Pasture response

Models of grazing systems, such as GRASP in northern Australia (McKeon et al., 1990) and DYNAMOF (Bowman et al., 1993, 1995) and GrazPlan (Donnelly et al., 1997; Freer et al., 1997; Moore et al., 1997) in southern Australia, are of considerable value in determining appropriate long-term stocking rates, supplementary feeding and other strategies. In other words, they can be of fundamental importance in achieving sustainable grazing systems and in improving the management of climate variability per se.

Such models are of value in assessing the severity and impact of different droughts on grassland and rangelands comprising a range of vegetation types in different locations (Donnelly et al., 1998; Stafford Smith and McKeon 1998; du Pisani et al., 1998; White et al., 1998). The GRASP model has also been incorporated into a GIS-based prototype of a national drought monitoring system in Australia (Carter et al., 2000). Experimentation is under way with an alternative but simpler spatial/temporal model, GrowEst Plus, based on the original model of Fitzpatrick and Nix (1970), to develop indices that may be used to analyse specific events, such as drought, or to characterize the reliability of a growing season as an aid to managing environmental sustainability (Laughlin et al., 2007).

7.4.5 Vegetation suitability maps

Agroecological zoning systems are an example of the use of data and models for the construction of suitability maps. The main system for land resource assessment is the agroecological zoning (AEZ) methodology developed by FAO, along with supporting software packages for application at global, regional, national and sub-national levels. AEZ uses various databases, models and decision support tools, which are described below.

The AEZ concept involves the representation of land in layers of spatial information and the combination of these layers using GIS techniques. The combination/overlay of layers produces agroecological cells. In this way a land resources database is created that contains information on the AEZ cells. AEZ integrates in the database various kinds of geo-referenced datasets, which can include topography; administrative boundaries; road/

communications; towns and settlements; rivers/water bodies; geology; soil; physiography; landforms; erosion; rainfall; temperature; moisture regime; watersheds; irrigable areas; land use/land cover and forest reserves; and population. The AEZ methodology and models have been applied in developing a global digital AEZ land resources database derived from the digitized soil map of the world (DSMW). The database contains information on soil and landforms, temperature regime and length of growing period, agroecological zones, forest and protected areas, and land suitability for about 30 main crops (<http://www.fao.org/ag/agl/agll/cropsuit.asp>).

7.4.6 Remote-sensing

Remote-sensing can provide useful estimates of vegetation cover and condition, plant water status, and the spatial limits of severe droughts over large areas of land (McVicar and Jupp, 1998; McVicar et al., 2003). Such information is invaluable in monitoring changes in land use, the impact of changing seasons and years on vegetation cover and “greenness”, the beginning and end of growing seasons, the impact of livestock grazing intensity on vegetation, and the extent of erosion and other forms of land degradation. It is also a valuable source of data for validating agronomic models.

McVicar and Jupp (1998) describe four ways in which remote-sensing can assist in mapping and monitoring agronomic conditions in relation to climate variability. These include:

- (a) Vegetation condition: monitoring with reflective remote-sensing;
- (b) Environmental condition: monitoring with thermal remote-sensing;
- (c) Soil moisture: monitoring with microwave remote-sensing;
- (d) Environmental stress: combining thermal and reflective remote-sensing.

7.4.6.1 Vegetation indices

Most vegetation indices are derived by combining the red and near-infra-red (NIR) reflective bands recorded by the LANDSAT Thematic Mapper™, the NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors and other remote-sensing instruments used on satellite platforms. Vegetation indices based on satellite data include measurements of leaf area index (LAI) (Tucker, 1979) and plant condition (Sellers, 1985), as well as the simple ratio (NIR/Red) and the Normalized Difference Vegetation Index (NDVI), which is given an extensive review by McVicar and Jupp (1998).

7.4.6.2 Soil moisture index

Thermal remote-sensing is an instantaneous observation of the status of the surface energy balance. This is driven by the net radiation of the surface, which is dominated during the daytime by incoming short-wave radiation from the sun; the amount reflected depends on the albedo of the surface.

The difference between daytime and night-time soil temperatures can be used to monitor changes in superficial soil moisture. McVicar et al. (1992) and Jupp et al. (1998) jointly developed the Normalized Difference Temperature Index (NDTI) to remove seasonal trends from the analysis of daytime land surface temperatures derived from the AVHRR sensor. The NDTI, which is a very close approximation of the moisture availability, has the form:

$$\text{NDTI} = (T_{\infty} - T_s)/(T_{\infty} - T_0) \quad (7.1)$$

where T_{∞} is a modelled surface temperature if there is an infinite surface resistance, that is, evapotranspiration (ET) is zero; T_s is the surface temperature observed from the AVHRR sensor, and T_0 is a modelled surface temperature if there is zero surface temperature resistance; hence ET equals ET_p (potential evapotranspiration). As McVicar and Jupp (1998) explain, T_{∞} and T_0 can be thought of as the physically limited upper and lower temperatures, respectively, for given meteorological conditions and surface resistances. If T_0 is close to the T_{∞} value, it is an indication that conditions are “wet”, as when soil moisture in surface layers approaches “field capacity”.

7.4.6.3 Drought early warning systems

Drought early warning systems can help achieve a greater level of drought preparedness. Although some of these systems have shortcomings, such as being unreliable, poorly targeted or not user-friendly (Wilhite, 2005), others are proving invaluable at the regional and national levels for monitoring and mitigating the effects of drought.

The integration of spatial datasets, including remotely sensed data, with agronomic models is leading to the development of integrated spatial/temporal systems for both grasslands (du Pisani et al., 1998; Carter et al., 2000; Brinkley et al., 2004) and crops (Lourens and de Jager, 1997; de Jager et al., 1998; Stephens, 1998).

Drought monitoring systems are also being used in developing countries (for example, the Famine Early Warning System (FEWS), the Regional Remote Sensing

Unit of the Southern African Development Community (SADC) based in Zimbabwe, and the FAO Global Information and Early Warning System on Food and Agriculture (GIEWS)). These often appear to be used primarily to focus reactive relief efforts on “drought disasters”, however, rather than being integral to the implementation of carefully thought out policies aimed at managing for drought and improving the sustainability of agricultural production systems. Furthermore, having such systems in place will be of only limited value if the required transportation and telecommunications infrastructure and extension services are inadequate.

In arid, semi-arid and marginal areas with a probability of drought incidence of at least once in ten years, for example, it is important for those responsible for land-use planning, including agricultural programmes, to seek expert climatological advice regarding rainfall expectations. Drought is often a result of the interaction of human patterns of land use and the rainfall regimes. Thus, there is an urgent need for a detailed examination of rainfall records of these regions. In this regard, the development of methods for predicting the occurrence of rainfall many weeks or months in advance deserves high priority.

Since technological inputs quickly reach an optimum level, more emphasis should be placed on drought management policies, especially in dryland farming areas. Agricultural planning and practices need to be worked out with consideration given to the overall water requirements within an individual agroclimatic zone. Crops that need a short duration to mature and require relatively little water need to be encouraged in drought-prone areas. Irrigation, through canals and groundwater resources, needs to be monitored to ensure optimum utilization, avoiding soil salinity and excessive evaporation loss. A food reserve is needed to meet the emergency requirements of up to two consecutive droughts. A variety of policy decisions on farming, human migration, population dynamics, livestock survival, ecology, and so on must be formulated (Das, 1999).

Sustainable strategies must be developed to alleviate the impact of drought on crop productivity. In areas of recurring drought, one of the best strategies for alleviating drought is to manipulate varieties in such a way as to avoid drought, or to minimize its effects by adopting varieties that are resistant to drought at different growth stages.

If drought occurs during the middle of a growing season, corrective measures can be adopted; these vary from reducing plant population to fertilization or weed management. In high rainfall areas where

there are a series of wet and dry spells, rainfall can be harvested in either farm ponds or in village tanks and can be recycled as lifesaving irrigation during a prolonged dry spell. The remaining water can also be used to provide irrigation for a second crop with a lower water requirement, such as chickpea. No one strategy can be adopted universally, however. In fact, all such strategies are dependent upon location, time, crop, crop stage and (to some extent) socio-economic conditions. Developing such strategies for each specific factor can help make agriculture sustainable (Das, 2005).

7.5 METHODS OF RISK ASSESSMENT

7.5.1 Managing risk

Producers recognize risk management as an important activity in their decision-making process. This enables them to manage their businesses more effectively in a physical environment where drought or other extreme events are common, though unpredictable, occurrences. Risk management recognizes that producers also operate in an economic environment of less-than-perfect knowledge. There are three types of risk in agriculture: production risk, financial risk and marketing risk.

Production risk is imposed primarily by seasonal variability. This risk may be reduced by avoiding excessively high stocking rates, developing strategies for reducing stock numbers in the event of abnormally dry conditions, sowing drought-resistant pasture plants and crops, choosing flock and herd structures and dates of lambing and calving that better relate the nutritional demands of the livestock to the available feed supply, providing shelter for livestock, conserving fodder or growing fodder crops, installing irrigation, and diversifying enterprises.

Strategies that are less risky in terms of production may be much more prone to financial risk. For example, low stocking rates may not allow enough income to be generated in the good seasons to enable a farmer to survive the poor seasons (White, 1987). Stocking according to season may result in the purchase of stock at high prices and its sale at low prices (Arnold and Bennett, 1975). Dates of lambing or calving that favour production may not favour marketing. Fodder may be conserved on the farm to support high stocking rates, but with the extra stock numbers, less surplus is available to be conserved (Bishop and Birrell, 1975). Irrigation

schemes will often be unprofitable, even though they reduce the production risk. Diversifying from wool or beef production, for example, into crops or specialist livestock enterprises, such as deer or alpaca farming, may require substantial capital investment and associated financial risk, and farmers who do diversify often do not have the necessary specialist skills.

Climate predictions may be used to reduce risk. For example, farmers planning to prepare land for sowing winter crops might not do so if they were given an adverse forecast in autumn. A farmer in desperate need of cash to meet financial commitments might sow a crop anyway, however, in the hope that the forecast was incorrect. A farmer might decide to feed a “failing” crop to livestock in the spring on the basis of an adverse forecast.

7.5.2 **Analyses of long-term weather data to identify occurrence of particular risk**

To identify the occurrence of particular risk (such as water stress, heat stress, cold stress – including frosts, freezing, floods and risk of wild fires), it is necessary to analyse long-term weather data. FAO (2005) developed applications and models to compute frost probability and risk of damage. An MS Excel application program (TempRisk.xls) was written, using the approach developed by Haan (1979), to make calculations of the probability and risk that temperatures will fall below a critical value for a user-selected time period. Another application program (FriskS.xls) computes the probability and risk associated with the last spring and first autumn frost dates, and the probabilities for the length of the growing season. A model, the MS Excel Damage Estimator application program (DEST.xls), is used to calculate expected frost damage and crop yield using site-specific maximum and minimum temperature climate data for crops having no protection against frost; it uses up to 11 different frost protection methods. Up to 50 years of maximum and minimum temperature data can be used in the analysis. Critical temperatures associated with 90 per cent and 10 per cent damage are available in the application and correspond to specific phenological dates.

7.5.3 **Disaster preparedness on the basis of weather forecasts**

One of the most effective measures for disaster preparedness is a well-functioning early warning system that delivers accurate information dependably and in a timely manner. Therefore, it must rely on:

- (a) Advanced, accurate, detailed and understandable forecasts of hazardous conditions;
- (b) A rapid, dependable distribution system for delivering forecasts, advisories, watches and warnings to all interested parties;
- (c) A prompt, effective response to warnings at the national to local levels.

WMO programmes related to monitoring the atmosphere, oceans and rivers provide the crucial time-sequenced information that underpins the forecasts and warnings of hydrometeorological hazards. The WMO global network of Regional Specialized Meteorological Centres (RSMCs) and World Data Centres (WDCs) supplies critical data, analysis and forecasts that enable the National Meteorological and Hydrological Services (NMHSs) to provide early warning systems and guidelines for various natural hazards, such as tornadoes, winter storms, tropical cyclones, cold waves and heatwaves, floods and droughts.

For example, the WMO network proved to be highly effective in 2004, during one of the most intense hurricane seasons in the Atlantic and Caribbean regions. Atmospheric data collected via in situ and space-based instruments were transmitted to the United States National Hurricane Center, one of the WMO RSMCs (RSMC-Miami), where forecasts and hurricane advisories were developed around the clock. These advisories were transmitted via the Global Telecommunication System (GTS), facsimile and Internet at intervals of three to six hours to the NMHSs of countries at risk. The forecasters at the NMHSs used these hurricane advisories to produce their national hurricane warnings, which were dispatched immediately to newspapers, radio and television stations, emergency services and other users. As a result of this information, many lives were spared through timely evacuations. There is no doubt that much more could be achieved by deploying resources to strengthen further early warning systems. The challenge is to ensure that all countries, particularly the Least Developed Countries, have the systems, infrastructure, human capacity and organizational structures to develop and utilize early warning systems to reduce risks of natural disasters.

7.5.4 **Anticipating risk on the basis of seasonal forecasts**

Temporal climate risk weighs heavily on many regions. Recent advances in model-based climate forecasting have expanded the range, timeliness and accuracy of forecasts available to

decision-makers whose welfare depends on stochastic climate outcomes. There has consequently been considerable recent investment in improved climate forecasting for the developing world (Lybbert et al., 2003).

The past decade has seen a great deal of progress in the understanding of our climate systems, and in anticipating climate events, particularly El Niño. This has resulted in a cultural change in those countries that experience high climate variability, not only within the meteorological community, but also among many farmers and their advisers. This has been particularly true in north-eastern Australia, where the impact of El Niño has been quite severe, and where many agricultural and other natural resource scientists have gained a significant appreciation of the underlying climatological concepts and have developed tools that would aid rural producers in their farm planning and decision-making. There has also been a major education programme involving the community.

Seasonal forecasts that may cover three or more months are derived in a completely different way from weather forecasts. Weather forecasts rely upon knowledge of the precise conditions of the atmosphere at the time when the forecast begins (initial conditions) in order to make forecasts for one to two weeks into the future. Given the strongly chaotic nature of the atmosphere, however, weather forecasts have virtually no skill after two weeks or so. Forecasts beyond this two-week weather forecast barrier rely on the fact that slowly changing sea surface temperatures (SSTs) or land surface effects (boundary conditions) are driving atmospheric circulations that affect certain regions of the world. Seasonal prediction therefore can be skilful in regions of the globe where the atmosphere is driven by local or remote sea surface temperature or land surface effects. Empirical as well as dynamical tools are used to make seasonal forecasts. Statistical models fall into the empirical category and have been used successfully in various parts of the world, as described below. General models of the ocean-land-atmosphere circulation fall into the dynamical category and are also discussed below.

7.5.4.1 Tools

7.5.4.1.1 *Statistical forecasts*

In 1989 the Australian Bureau of Meteorology began issuing seasonal outlooks for the next three months,

based primarily on the Southern Oscillation Index (SOI). Since 1997, this initial approach has been replaced by a method based on Pacific Ocean and Indian Ocean sea surface temperature patterns, although methods and systems using the SOI (or SOI “phases”) remain popular in eastern Australia, where strong relationships exist between the SOI and key rainfall periods for agriculture and variables such as the start and finish of the frost season. In addition, methods based on the SOI have proven more amenable to incorporation into crop and pasture simulation models, thereby providing increased capability for uptake by agricultural planners. The SOI is based on the long-term trend in the differences in atmospheric pressure between Darwin and Tahiti, and has proven to be a reasonably reliable indicator over much of eastern Australia, and elsewhere, with respect to winter, spring and summer rainfall (McBride and Nicholls 1983; Stone et al., 1996). Such information is used in other countries susceptible to the influence of the El Niño–Southern Oscillation (ENSO) effect, including Southern Africa, parts of South America, Indonesia, and India.

More recently a new forecast system has been developed on the basis of near-global patterns of sea surface temperatures. The system shows more skill than the former SOI-based system and is now in operation in some countries. The phase of the SOI (Stone et al., 1996) is proving to be another valuable tool for producing seasonal outlooks. Both rainfall-forecast methodologies (ENSO and SOI phases) were applied in the Pampas, located in central-eastern Argentina, one of the world’s leading areas in terms of agricultural and farming potential (Penalba et al., 2005). A lead time of three to six months, especially for November (0), appears to be feasible. The lead time found in the SOI phases methodology, however, does not improve the “forecast” provided by the ENSO methodology occurrence, given that the ENSO event has already entered into the development stage.

North-east Brazil is noteworthy as a region of the world where remarkable skill has been achieved for the seasonal prediction of wet-season rainfall anomalies. These forecasts are based on the observation that wet-season (February to May) rainfall in North-east Brazil is strongly affected by sea surface temperature anomalies in the Atlantic and Pacific oceans in the previous months (November through January). Statistical, real-time predictions of North-east Brazil wet-season rainfall have been issued by the British Met Office since the early 1990s, following the work of Ward and Folland (1991).

7.5.4.1.2 *General circulation models (GCMs)*

Forecast lead times in terms of years rather than months are needed to attain significant financial benefits in many pastoral systems. Therefore there is a robust case for further research to extend seasonal forecasts to annual timescales and beyond.

Coupled ocean–atmosphere GCMs of the global climate have been shown to offer more promise in extending forecasts from 3 to 12 months than the statistical SOI methods, particularly because they directly forecast changes in SSTs in the central and eastern tropical Pacific. Such longer lead times would certainly be more useful to livestock producers. GCMs have yet to be properly tested for rainfall prediction, although their SST predictions can be used statistically to estimate changes in the SOI and rainfall with reasonable success.

Generally speaking, dynamical seasonal forecasts require the performance of large ensembles of GCM simulations and an analysis of the results to look for regions where most simulations produce similar results. In such regions, atmospheric circulations may be more strongly driven by slowly varying ocean or land effects and therefore the prospect for making skilful seasonal predictions is improved. Our experience with seasonal forecasting has shown that, in general, the tropical regions of the world present more promise for seasonal predictability than extra-tropical regions, although when seasonal climate forecast systems can be integrated into agricultural simulation models, an increase in applicability of seasonal forecasting systems appears possible in extra-tropical regions and even some high-latitude locations (Meinke and Stone, 2005).

7.5.4.2 *Accuracy, timeliness and value*

The forecasts can influence decisions on when and what area to sow and whether to irrigate and/or fertilize a crop. Accuracy of forecasting does not necessarily equate with its value to resource managers. Obviously, if the information is not used, even though it may have value, no benefit is obtained. If the forecast is inaccurate, the information is likely to have negative value in the current season. Even accurate information can be of limited value, however, if the lead time is only three months, for example, since many livestock producers require lead times in excess of six months or even a year.

The value of seasonal forecasts to crop producers can be significant, but it varies with management

and initial conditions, as well as with cropping systems and location (for example, Hammer et al., 2000; Marshall et al., 1996).

Preliminary studies of the value of seasonal forecasts using models of grassland systems have shown that the financial benefits may not be easily realized based on existing skill levels, lead times (three months, for example) and decision points within a calendar year. These analyses also demonstrate, however, that the same level of cash flow could be achieved for a much lower risk of environmental degradation with the use of climate forecasting (Stafford Smith et al., 2000). In some areas, even high skill levels appear to offer low financial benefits in the medium term, despite increased animal welfare and protection for soils and vegetation (Bowman et al., 1995). This highlights the need for further research to determine whether and how the management of many grassland systems and the timing of the relevant decisions should be modified to take advantage of forecast information.

7.6

EXAMPLE OF RISK ASSESSMENT FOR PARTICULAR WEATHER AND CLIMATE EVENTS FROM LITERATURE

In north-western China, informal herder groups counteract risk and manage disaster situations by jointly preparing emergency plans and organizing pasture movements should an emergency situation, such as a snowstorm, occur (Yongong et al., 1999). “According to the herders, village leaders and production team leaders are the most active persons in dealing with the risk management. . . . They even fulfil extension tasks, since there are no township and village extension line agencies. . . . In those townships which have no concentrated village settlement pattern, there is another non-governmental informal organization locally called ‘zhangquan’ situated between the production team and households. A ‘zhangquan’ normally composes about 4–5 herder’s households on average. In general, ‘zhangquan’ are comprised of families or of neighbouring families settled in the same area. Generally, these individuals collaborate as unofficially formed herders groups. Such groups jointly organize the grazing, they exchange their labour force, share information, protect animals from theft, address risk avoidance, organize meetings and make decisions together” (Yongong et al., 1999).

Synoptic and mesoscale predictions of minimum temperature are usually undertaken by national or regional weather services, using large amounts of

equipment and manpower. These are usually public institutions that release frequent updates at no cost to the public. Local (microscale) forecasts are typically unavailable unless provided by private forecast services. At the microscale, complex energy-balance models have been used to predict short-range minimum temperature, with uncertain results (Sutherland, 1980; Cellier, 1982, 1993; Kalma et al., 1992). Simple empirical models calibrated locally, however, often give satisfactory results in the prediction of minimum temperature in a given day. FAO (2005) presents an empirical forecast model "FFST.xls", which can be easily calibrated for local conditions. The model uses historical records of air and dewpoint temperature at two hours past sunset and observed minimum temperatures to develop site-specific regression coefficients needed to accurately predict the minimum temperature during a particular period of the year. This model will only work during radiation-type frost events in areas with limited cold air drainage.

In coastal Asia where flood risk is severe, for example in Bangladesh and Cambodia, several projects have been built specifically focusing on people's perception of flood risk, the purpose and tools of community flood risk assessment, the strategies for community organization, and resource mobilization and capacity-building. In these cases, the underlying rationale can be traced back to the sequencing of disaster risk management activities, with an emphasis on local scoping studies and capacity-building that are to precede community interventions.

In India, following the cyclone of 1971 (which took the lives of 10 000 people), the government of the state of Orissa prepared a report outlining a series of measures to be taken to prepare for future cyclones, which later led to the Orissa Relief Code. This code provides the basic framework for the implementation of emergency measures under all types of emergency situations, as it details the specific responsibilities of the state's Special Relief Commissioner and its different line ministries. During the latest cyclone of 1999, planning responses were still hindered by a lack of updated and available vulnerability maps and databases on conditions on the coast.

In Nicaragua, the Asociación de Consultores para el Desarrollo de la Pequeña, Mediana y Microempresa (ACODEP), one of the largest micro-finance institutions (MFIs) in the country, has been learning from the experience of Hurricane *Mitch* in 1998 and more recent disasters. The association has developed a "disaster prevention plan" whose objectives are to identify, prepare for and

mitigate natural and man-made disasters in order to protect the institution, its clients and staff from possible losses. The plan is quite comprehensive, including measures to safeguard the institution's staff, portfolio, facilities, equipment and information systems and records, as well as measures to better respond to the many disasters that affect Nicaragua. The plan recognizes that priority should be given to assisting clients in finding medical aid, contacting relief organizations and joining food for work (FFW) programmes, but, in keeping with the sector's orthodox "best practices", it does not consider that the institution should provide relief directly.

Hurricane *Michelle*, the most powerful storm since 1944, ripped through Cuba in November 2001. But, in contrast to the 20 000 victims of Hurricane *Mitch* in Honduras, just five people died in Cuba. Successful civil defence and Red Cross planning ensured that 700 000 people were evacuated to emergency shelters in time. Search-and-rescue and emergency health care plans swung into action. In Havana, electricity and water supplies were turned off to avoid deaths from electrocution and sewage contamination. Cuba's population was advised in advance to store water and clear debris from streets that might cause damage (FAO, 2003).

The severity of the El Niño/La Niña phenomenon of 1997–1998 led to the establishment of the Andean Regional Programme for Risk Prevention and Reduction (PREANDINO), with the objective of promoting the development of disaster risk prevention and mitigation policies and new institutional arrangements aimed at incorporating prevention into development planning.

The Lempira Sur rural development project in the south of Honduras has promoted improved agricultural practices, river basin management, ecological sustainability, increases in on- and off-farm incomes, and economic resilience among poor families. This has been achieved with the introduction and appropriation of improved land-use practices, water management schemes, maintenance of biodiversity, local credit schemes, and the strengthening of local government and the ability to plan urban and rural development. The notion of disaster risk reduction was never considered in the project document. The project demonstrates, however, how ecologically sustainable, best-practice agriculture will lead to reductions in disaster risk, although this was not a defining characteristic of the project as such. Hazard reduction associated with flooding and landslides has been achieved, along with increases in the resil-

ience of the local population when faced with extreme conditions. During Hurricane *Mitch*, the area covered by the project suffered little damage thanks to the types of land-use and slope-stabilization methods that were utilized, and it was able to provide food assistance to other areas severely damaged by the hurricane.

An efficient telecommunication system is a prerequisite for an effective typhoon warning system. The Global Telecommunication System was developed by WMO under the World Weather Watch (WWW) Programme to collect data from the national observing stations and exchange these data with other countries. This elaborate telecommunication system also allows for the prompt dissemination of typhoon warnings, as well as the transmission of data for the monitoring of typhoons (Lao, 2006).

7.7 EXTREME CASES

Although there is a great deal of uncertainty involved in the assessment of climate-related human health risk, visible progress is being made. Climate-related health risks range from the direct effects of extreme temperature and flooding, which every year cause deaths and the spread of infectious diseases, to the more indirect effects of climate variability on the global distribution of infectious diseases such as malaria, dengue fever, cholera, Rift Valley fever, and hantavirus, among many others.

The role of climate and the environment in human disease dynamics has been clearly demonstrated for the case of cholera, an acute intestinal infection caused by the bacterium *Vibrio cholerae*. The dynamics of cholera outbreaks involve the *V. cholerae* bacterium and plankton in such a way that during periods of warm sea surface temperatures, *V. cholerae* is active and abundant and the number of cholera cases in certain geographical areas is elevated (Colwell, 1996). On a global scale, the clear link between cholera epidemics and climate variability phenomena, such as El Niño, offers the possibility of creating an early-warning system that could help prevent future cholera epidemics given reliable climate prediction.

Climate change can affect agriculture in many ways, for example: (a) through soil-plant processes, with an increase in soil water deficits caused by changes in soil water balance; (b) in the area of crop development, since crops will be affected by

temperature and soil humidity changes; (c) by contributing to the formation of weeds, pests and diseases (weeds are expected to benefit from higher CO₂ concentration, increases in precipitation and temperature are favourable to the development of early crop diseases, and the risk of crop damage by pests and diseases increases in all regions under climate warming); and (d) through economic and social effects. Rosenzweig and Liverman (1992) observed that the tropical regions could also be more vulnerable to climate change because of economic and social disparities. Greater economic and individual dependence on agriculture, widespread poverty, inadequate technologies and lack of political power are likely to exacerbate the impacts of climate change in tropical regions.

A number of global assessments of the impacts of climate change in agriculture and agricultural markets have been produced (Rosenberg and Crosson, 1991; Rosenzweig and Hillel, 1998; Mendelsohn and Neumann, 1999; Siqueira et al., 1999; Salinger et al., 2001; Reilly et al., 2001; Das, 2003a). It is expected that the concentration of atmospheric CO₂ will rise from its current level of 354 ppm to 530 ppm by the year 2050, and to 700 ppm by the year 2100 (Watson et al., 1990). Changes in the concentration of the infra-red absorbing gases in the atmosphere are expected to produce a general warming of the global surface ranging from 3°C–4°C by the year 2100 (Bretherton et al., 1990). According to Marengo (2001), in most of Latin America there are no regional studies that show conclusive effects of climate change. Some changes in atmospheric circulation at the regional level, however, were detected for precipitation and hydrological cycles in the Amazon region, for example (Marengo et al., 2001; Costa and Foley, 1999; Curtis and Hastenrath, 1999), and for temperature, including several Brazilian regions (Victoria et al., 1998; Marengo and Rogers, 2001).

Catarina, a powerful storm that affected parts of Santa Catarina and Rio Grande do Sul states in Brazil in March 2004, may be an early example of the effect of climate change in the South Atlantic Ocean. A technical note published by the Brazilian Centre for Weather Forecasting and Climate Studies (CPTEC) and the Brazilian National Institute of Meteorology (INMET) reports that the storm formed as a cyclone in the South Atlantic Ocean, acquiring hurricane characteristics while moving towards the South American continent. The storm (with winds of up to 180 km/h, which had never before been observed in the South Atlantic Ocean) caused unprecedented destruction

in that region. Damages were in excess of US\$ 350 000 000.

Climate change may therefore result in an increase in climate variability and climate extremes. Such climate changes will most certainly affect crop growth and productivity. There is not enough information about the potential impact of climate change in agriculture, however, because of the complex response of plant and soil processes to several weather variables.

Climatologists at the NOAA National Climatic Data Center in Asheville, North Carolina, have selected some of the most notable floods, typhoons, hurricanes, droughts, heatwaves, tornadoes, winter storms, blizzards and other climate events of the twentieth century. Factors taken into consideration included the event's magnitude and meteorological uniqueness, as well as its economic impact and death toll (NOAA, 1999). The list includes:

- (a) Recurring floods that occur in the middle and lower reaches of the major rivers in China and kill from several thousand to several hundred thousand people. During the last century, major flooding disasters occurred in 1900, 1911, 1915, 1931, 1935, 1950, 1954, 1959, 1991 and 1998, mainly in the Yangtze River Valley.
- (b) Yangtze River Flood, 1931. The summer flood along the Yangtze in July–August 1931 was the most severe, with over 51 million people affected (one fourth of China's population). Some 3.7 million people perished due to disease, starvation or drowning during what is considered the greatest disaster of the twentieth century. This flood was preceded by a prolonged drought in China during the period between 1928 and 1930.
- (c) Flood in Vietnam, 1971. Heavy rains caused severe flooding in North Vietnam, killing 100 000 people.
- (d) Great Iran Flood, 1954. A storm over Iran produced flooding rains resulting in approximately 10 000 deaths.

Many of the devastating floods that occur in parts of South-East Asia are also associated with typhoons or tropical systems. (See the typhoon section for more information.) In contrast, the United States Midwest Flood of 1993 caused 48 deaths.

Among the most devastating hurricanes of all time were Hurricane *Georges* (September 1998) and Hurricane *Mitch* (October 1998). A Category 5 hurricane, *Mitch* was one of the most powerful Atlantic hurricanes on record. With 290 km/h

winds, a minimum storm pressure of 0.1 mPa, and quite a long lifespan (14.5 days), Hurricane *Mitch* turned out to be the deadliest of the century. It caused loss of life, destruction of property and damage to food production, food reserves and transportation systems, as well as increased health risks.

Deadly typhoons and killer cyclones strike coastal areas along the Bay of Bengal with periodic frequency, much like the floods along the Yangtze River in China. They historically have also devastated the Chinese coast, Korea, Japan, the Philippines and South-East Asia. The list includes:

- (a) Bangladesh Cyclone, November 1970. The greatest tropical system disaster of the last century occurred in Bangladesh in November 1970. Winds coupled with a storm surge killed between 300 000 and 500 000 people. These cyclones usually cause the most devastation, loss of life, and suffering in low-lying areas of Bangladesh and coastal India.
- (b) Bangladesh Cyclone 02B, April 1991. Another cyclone struck the Chittagong region in Bangladesh in 1991, killing over 138 000 people and causing damage in excess of US\$ 1.5 billion. The tropical cyclone devastated the coastal area south-east of Dacca with winds in excess of 200 km/h and a 6 m storm surge
- (c) China typhoons, early half of last century. Several typhoons also struck the eastern China coast during the early half of the last century, causing great hardship. Deaths from some of the storms ran into the tens of thousands. For example, typhoons striking the China coast in August 1912 and August 1922 resulted in fatality counts of 50 000 and 60 000, respectively.
- (d) Hurricane *Mitch*, November 1998. One of the strongest late-season hurricanes on record formed in the western Caribbean in October 1998. Although the system eventually weakened before landfall, its slow passage westward over the mountainous regions of Central America unleashed precipitation amounts estimated as high as 1.9 m. The resulting floods devastated the entire infrastructure of Honduras and also had a severe impact on other countries in the area. The final estimated death toll was 11 000, the greatest loss of life from a tropical system in the western hemisphere since 1780.
- (e) Typhoon *Vera*, September 1958. This typhoon's passage over Japan in 1959 caused Japan's greatest storm disaster. The death toll reached nearly 5 000, with 1.5 million left homeless. Typhoon *Vera* dealt a staggering blow to Japan's economy, with tremendous damage

to roads, bridges and communications from wind, floods and landslides.

- (f) Typhoon *Thelma*, October 1991. *Thelma* was one of the most devastating tropical systems to affect the Philippines in the last century. Reports indicated that 6 000 people died as a result of catastrophic events, including dam failure, landslides and extensive flash flooding. The death toll exceeded that of the Mount Pinatubo eruption. The highest casualties occurred on Leyte Island, where widespread logging in recent years had stripped the hills above the port city bare of vegetation.
- (g) Hurricane *Katrina*, August 2005. *Katrina* was the deadliest hurricane to hit the United States since 1928, killing more than 1 400 people. *Katrina* inundated 80 per cent of the city of New Orleans and caused damages of over US\$ 70 billion.

Table 7.2 shows typhoon damages in North Central Viet Nam and Table 7.3 shows disaster impacts in the same area.

Losses from a single tropical cyclone may therefore run into the billions of dollars and such losses are forecast to rise due to the ever-increasing numbers

of people living in coastal areas. For example, in 1998, El Niño-related weather phenomena caused US\$ 6.6 billion in damages in Argentina, Peru and Ecuador, while Hurricane *Georges* alone caused US\$ 2.1 billion in damages in the Dominican Republic, and Hurricane *Mitch* resulted in damages of US\$ 2.4 billion in Honduras and Nicaragua (Charveriat, 2000).

In May 2002, the cyclone *Kesiny* hit Madagascar, affecting more than half a million people and leaving them homeless or in need of emergency food, shelter and drinking water. Up to 75 per cent of the crops were destroyed, 20 people died and 1 200 were injured (CIDI, 2002).

The cyclone on 17–18 October 1999 and the one following it on 29–30 October in Orissa, India, caused devastating damage. The second cyclone, with wind speeds of 270–300 km/h for 36 hours, was accompanied by torrential rain ranging from 400 to 867 mm over a period of three days. The two cyclones together severely affected around 19 million people in 12 districts (Roy et al., 2002). Sea waves reaching 7 m rushed 15 km inland. Some 2.5 million livestock perished and a total of 2.1 million ha of agricultural land was affected.

Table 7.2. Typhoon damages in North Central Viet Nam, 15° N to 20° N (Van Viet, 1999)

Year	No. of deaths	Value of losses (US\$ million)	Paddy fields submerged (in 1 000 ha)	Houses flooded (in 1 000)	No. of boats sunk
1995	57	106.3	139	131	528
1996	499	720	590	829	741
1997	63	16	82	43	54
1998	214	104		461	208

Table 7.3. Disaster impacts in North Central region of Viet Nam, 1979–1998 (Van Viet, 1999)

	Total killed		Typhoons		Floods		Flash floods		Tornadoes	
	No.	%	No.	%	No.	%	No.	%	No.	%
People killed	2 642	100	1 769	67	592	22	0	0	262	10
Houses collapsed	417 941	100	306 646	73	46 829	11	1	0	10 172	2
Paddy crop unharvested	399 531	100	253 775	64	52 583	13	390	0	10 524	3
Money loss (in 1 000 million vnd)	2 736	100	1 890	69	728	27	2	0	114	4

The effects of droughts, famines and heatwaves are much harder to quantify. The effects are devastating and impacts can span just a couple of months or stretch to a decade or more. Some historical drought/famines with loss of life are described below.

Numerous drought-related disasters have occurred over the Asian mainland during the last century. The most notable Asian droughts include:

- (a) Indian drought of 1900 – between 250 000 and 3.25 million people died due to drought, starvation and disease;
- (b) Chinese famine of 1907 – Over 24 million perished from starvation;
- (c) Chinese famine from 1928 to 1930 – Over 3 million perished in north-west China;
- (d) Chinese famine of 1936 – 5 million Chinese died in what is called the “New Famine”;
- (e) Chinese drought from 1941 to 1942 – Over 3 million perished from starvation;
- (f) Indian drought from 1965 to 1967 – Over 1.5 million perished in India;
- (g) Drought in the Soviet Union (Ukraine and Volga regions) from 1921 to 1922 – between 250 000 and 5 million perished.

The Sahel region of Africa has experienced drought in a number of different years. Famines/droughts have occurred in the Sahel in 1910–1914, 1940–1944 and 1970–1985. Drought in the Sahel claimed over 600 000 lives in 1972–1975 and again in 1984–1985.

The American Dust Bowl of the 1930s lasted almost an entire decade and covered virtually the entire United States Great Plains. The Dust Bowl drought and associated high temperatures, strong winds, duststorms and insect infestations resulted in an agricultural depression that further aggravated the country’s Great Depression of the 1930s, affecting the livelihood and health of millions of people. The rainfall deficits that caused the Dust Bowl are the result of natural cycles of the atmosphere in the Great Plains. In fact, paleoclimatic evidence points to the occurrence of multi-year droughts in the Great Plains at a rate of one or two per century, with even longer droughts, or mega-droughts that last for many decades, occurring at a rate of one to three per thousand years (Overpeck, 2000). Although the rainfall deficits during the Dust Bowl years were caused by natural variability of the atmosphere, poor land management and agricultural practices during the 1920s further aggravated the situation by making the Great Plains more vulnerable to wind erosion, depletion of soil moisture and nutrients, and drought. The Dust Bowl event highlights the importance of assessing risk on a regional basis

and putting in place land management and agricultural practices that will help mitigate the possibly devastating effects of drought (Warrick, 1980).

Severe and damaging tornadoes are mainly a North American phenomenon. The United States is the “tornado capital of the world” and has more tornadoes annually than any other country on the globe. Two notable outbreaks include the “Super Tornado Outbreak of 1974” (315 deaths) and the “Tri-State Tornado of 1925” (695 deaths).

A blizzard in Iran in February 1972 ended a four-year drought, but the weeklong cold and snow caused the deaths of approximately 4 000 people.

The European storm surge during the winter months of January and February 1953 was one of Europe’s greatest natural disasters. Violent winter storms caused storm surges, which resulted in flooding in areas of the Netherlands and the United Kingdom. Almost 2 000 people perished due to these storm surges.

The Great Smog of London occurred in December 1952. Stagnant air due to an inversion combined with industrial and residential emissions to create an air pollution episode without parallel in this century. Casualties, attributed to the poisonous air, rose to 4 000, with 4 000 additional fatalities due to related causes.

Significant El Niño effects were seen in 1982 and 1983. El Niño and La Niña events tend to alternate within every three to seven years. The time from one event to the next can vary from 1 to 10 years, however. The economic impacts of the 1982–1983 El Niño were huge. Along the west coast of South America, the losses exceeded the benefits. The fishing industries in Ecuador and Peru suffered heavily when their anchovy harvest failed and their sardines unexpectedly moved south into Chilean waters. Changed circulation patterns also steered tropical systems off their usual tracks to islands such as Hawaii and Tahiti, which are usually unaffected by such severe weather. They caused the monsoon rains to fall over central parts of the Pacific Ocean instead of the Western Pacific. The lack of rain in the Western Pacific led to droughts and disastrous forest fires in Indonesia and Australia. Winter storms battered Southern California and caused widespread flooding across the southern United States, while unusually mild weather and a lack of snow was evident across much of the central and north-eastern portion of the United States. Overall, the loss to the world economy in 1982–1983 as a result of the climate

changes due to El Niño amounted to over US\$ 8 billion. The toll in terms of human suffering is much more difficult to estimate (NOAA, 1994).

7.8 DEVELOPING AND IMPLEMENTING POLICY TO REDUCE THE RISK AND IMPACT OF EXTREME EVENTS

The Typhoon Committee, the first of the five tropical cyclone regional bodies, was established under the auspices of WMO and the United Nations Economic and Social Commission for the Pacific (ESCAP) in 1968. The Committee continues to work towards the reduction of damage caused by typhoons and floods in the western North Pacific and South China Sea region. In its more than 40 years of existence, substantial advances have been made by National Meteorological Centres in the region towards meeting their responsibilities for providing warnings of tropical cyclones and storms surges (Lao, 2006).

Public and private-sector institutions servicing government and rural communities have a role to play in helping rural producers cope with climate variability and extreme climate and weather events in terms of policy and implementation, and in preparing for and mitigating the impacts of these events. Specific ways in which they can be of assistance include:

- (a) Development of policy, implementation plans and infrastructure (related to meteorology, agriculture and natural resources);
- (b) Ensuring ready access to global, regional, national and local warning systems and broad dissemination of warnings (the tsunami in December 2004 is a case in point);
- (c) Understanding climate variability, preparing for and managing drought at national and regional levels, and mitigating the impact of drought, flood and wildfire (public awareness, training and education).

Drought planning is an integral part of drought policy (Wilhite, 1991, 2005). A generic set of planning objectives has been developed that could be considered as part of a national, state/provincial or regional planning effort (Wilhite, 2000). These include:

- (a) Establishing criteria for declaring drought and triggering various mitigation and response activities;
- (b) Providing an organizational structure that assures information flow among and within levels of government, as well as with non-governmental organizations, and defining the

duties and responsibilities of all agencies with respect to drought;

- (c) Maintaining a current inventory of drought assistance and mitigation programmes used in assessing and responding to drought emergencies, and providing a set of appropriate action recommendations;
- (d) Identifying drought-prone areas and vulnerable sectors, population groups and environments;
- (e) Identifying mitigation actions that can be taken to address vulnerabilities and reduce drought impacts;
- (f) Providing a mechanism to ensure timely and accurate assessment of drought's impacts on agriculture, livestock production, industry, municipalities, wildlife, health, and other areas, as well as specific population groups;
- (g) Collecting, analysing and disseminating drought-related information in a timely and systematic manner;
- (h) Keeping the public informed of current conditions and mitigation and response actions by providing accurate, timely information to media in print and electronic form;
- (i) Establishing a set of procedures to continually evaluate, exercise or test the plan, and to periodically revise the plan so that it remains responsive to the needs of the people and government ministries.

Drought plans in which mitigation is a key element should have three principal components: monitoring, early warning, and prediction; risk and impact assessment; and mitigation and response. A description of each of these components follows.

- (a) Production monitoring – remote-sensing, ground validation field observations, agronomic models;
- (b) Policies to promote land care and minimize soil erosion, weed invasion and salinization; likewise with water – safeguarding flows, minimizing algal blooms, deciding whether to dam or not to dam, improving water use efficiency, and the like;
- (c) Mitigating the effects of extreme events – for instance, by implementing a policy to limit grazing pressure and wind and water erosion, promoting the use of seasonal forecasts, promoting on-farm self-reliance and risk management, cultivating drought-resistant plants, and so on.

Owing to major advances in technology and notable progress in scientific understanding, the accuracy and timeliness of weather and flood warnings have significantly improved over the

last few decades. The accuracy of forecasts of large-scale weather patterns for seven days is today the same as those for two days in advance only 25 years ago (Obasi, 1998). Forecasts up to 10 days are nowadays showing remarkable accuracy, and there is now the capability to provide some skilful information on expected weather patterns several seasons in advance. For example, early information on El Niño episodes is now allowing advanced national planning, with considerable advantage in many sectors of the economy, such as in water resources management, tourism, and fisheries and agricultural production (Obasi, 1996). In the case of the 1997–1998 El Niño event, advances in El Niño-related science and in monitoring the sea surface temperatures in the Pacific Ocean enabled scientists to predict its formation further in advance than any of the previous events. With recent developments in communication technology, including the use of the Internet, information on El Niño was disseminated in a rapid and timely manner throughout the world. This enabled many governments to take appropriate measures and stimulated international cooperation and integrated efforts to address the associated impacts.

The accuracy of tropical cyclone track forecasts and the timeliness of warnings have also been steadily improving in the past few years. Global efforts, especially within the context of the WMO Tropical Cyclone Programme, have resulted in a noticeable improvement in the warning systems in many parts of the world and have helped to save many lives and limit property damage. For example, the decrease in the death toll in Bangladesh caused by similar tropical cyclones in 1991 and 1994, from about 130 000 to 500, respectively, was attributed by government sources in large part to improvements in early warning and evacuation systems (Obasi, 1997).

The evolving Internet has proven to be an invaluable tool in facilitating the exchange of global and regional climate monitoring and prediction information. Many users require assistance in the selection, interpretation and application of appropriate information, however. Effective early warning systems, coupled with community education for protective action, have reduced the potential human loss from these events. Because they represent disaster risk, floods also lend themselves well to both structural and legislative preparedness measures (land-use laws, zoning plans and urbanization). Preparedness in terms of life-saving techniques and evacuation plans should be

promoted actively in these high-risk zones (Sivakumar, 2005).

7.9 **ON-FARM PLANNING TO REDUCE THE RISK AND IMPACT OF EXTREME EVENTS**

Stigter et al. (2003) have emphasized the importance of on-farm preparedness.

7.9.1 **Crop selection and cropping sequence**

The method of selecting crop varieties based on agroclimatic requirements consists of comparing, on the one hand, the regional availability of agroclimatic resources and, on the other, the climatic requirements of certain crop varieties on the basis of which the selection is to be made. The selection of varieties of plants at local or regional levels should be based on agroclimatic studies carried out to determine the climatic requirements of the different crop varieties. Agroclimatic characterization of crops includes solar radiation, temperature, humidity and photoperiod, among the most important climatological factors.

There are large differences in sensitivity to frost damage among crops. On a farm scale, frost-sensitive species should, if at all, be planted on middle slopes. Valley floors and locations where cold air can flow should be avoided. Planting deciduous crops on slopes facing away from the sun delays springtime bloom and often provides protection. Subtropical trees are best planted on slopes facing the sun where the soil and crop can receive and store more direct energy from sunlight. Rootstock often influences how early deciduous fruit trees flower and therefore potential frost damage. On evergreen fruit trees, rootstock may be also related to frost hardiness. For example, navel oranges are more frost hardy when grown on trifoliate rootstock than they are when grown on sweet orange rootstock (FAO, 2005).

7.9.2 **Selection of varieties**

Intraspecific variability for resistance to drought, frost and heat stress is often large. Hence, there is often room for plant breeding for resistance to these risks. For example, in citrus growing, frost may not be avoidable; however, selecting for tolerance to sub-zero temperatures is a valuable option (Ikeda, 1982). The selection of an appropriate variety for a

given area should take into account the frost hardness of the varieties in the species.

7.9.3 Land preparation

As far as frost protection is concerned, deep ploughing has about the same effect as shallow ploughing on heat transfer, since the layer of soil that is involved in heat transfer to the surface by conduction, on a daily basis, is not thicker than about 0.3 m.

With regard to tillage methods, cultivation should be avoided during periods when frost is likely to occur, because it increases porosity of the soil and may contribute to more evaporation in the top layer. Since air is a poor heat conductor, when compared to soil matrix and water, cultivation reduces the amount of heat stored in the soil during the day and transferred to the surface during the cold night. If cultivation cannot be avoided, a roll should be used to compact the soil to counteract the increase in air space generated by the mobilization of the soil.

7.9.4 Crop management

With regard to irrigation management from a frost protection perspective, soils should be moist before a frost period is likely to occur. Hence, irrigation one or two days in advance of a frost night brings the soil to near field capacity, which results in an increased soil heat flux during a subsequent frost night. Various irrigation methods are also used during a frost night (namely, as active methods), with the objective of using the heat liberated as the water cools and freezes. For details see FAO (2005).

In terms of fertilizer management, the use of fertilizers, and in particular nitrogen, accelerates crop growth and helps crops develop profuse root systems, thus making plants more capable of withstanding drought. The time and method of application are important. Nitrogen and other nutrients are known to affect frost sensitivity. In general, nitrogen may reduce frost resistance, and phosphorus and potassium are likely to increase it (WMO, 1978). New growth is more sensitive to frost, because it tends to have less solute content in the tissues. Therefore, management should minimize new growth in frost-prone periods. Nitrogen may result in increased frost resistance, however, if the biophysical effect of a bigger canopy offsets the physiological effect (FAO, 2005).

As for weed management, during a dry spell or under water stress conditions, weed competition is a problem for crops because weeds also use the little moisture that is available. In dryland crops sown in

line, weed control through interculture operations is found to be beneficial under water stress conditions. Cover crops and weeds in orchards tend to trap air and thus reduce heat diffusivity of the ground. Hence, under these circumstances, minimum temperature is lower and frost risk increases. Mowing the plants, without removing them, or cultivation to remove them, has little if any effect on minimum temperature. Spraying with herbicide has a substantial positive effect on minimum temperature, however. It is possible that the presence of cover crops or weeds has a negative effect on frost resistance that results from a higher concentration of ice-nucleation active (INA) bacteria that is known to occur on cover crops and weeds. Fruit trees, namely citrus and grapevines, are known to have lower INA bacteria concentrations (FAO, 2005).

Early or delayed harvesting is a practical method to avoid frost damage that many farmers adopt to ensure that crops are harvested before a frost period is likely to occur. This is in general feasible on small farms, but often impossible on larger ones.

7.9.5 Pasture and livestock management

7.9.5.1 Preparing for and managing through drought

An essential part of farming in a variable climate is anticipating and preparing for the next drought. This needs to be incorporated into a farm's long-term management strategy, and a good manager should be cognizant of those factors that threaten the sustainability and long-term financial viability of the property.

At the farm level, it is essential that sustainable systems be developed and implemented to minimize the impact of drought on the soils and vegetation, and livestock need to be humanely cared for or disposed of as well. The well-being of farming families will also be enhanced through better financial and risk management. Although the threat of drought cannot be removed, its impact on the community and on soils, vegetation and livestock may be reduced.

Conditions conducive to soil erosion by wind and water are more prevalent in drought periods (Marshall, 1973). The area of bare ground within a pasture increases with stocking rate, particularly in adverse seasons (White et al., 1980). This is caused by the associated reduction in vegetative cover and the drying out of the surface soil. The decision to retain stock during drought may therefore intensify

the degradation of vegetative cover (Morley and Daniel, 1992). Wind velocity near the ground increases considerably when vegetation is removed. Further degradation can therefore follow, with soil erosion exacerbated by the action of wind or intensive drought-breaking rains on bare soil.

Self-reliant drought management is inextricably linked to the concept of economic and environmental sustainability. Rangelands and improved pastures should be managed so that degradation of soils and vegetation is minimized. This requires the choice of an appropriate long-term stocking rate and strategy for grazing management, destocking early in drought (Morley and Daniel 1992), and possibly planting perennial fodder trees. Only a nucleus of productive and breeding stock should be fed, and wethers and steers and the eldest age groups of breeding ewes and cows should be sold or destroyed, depending on the most profitable options. Failed crops can be harvested for grain, cut for hay or used for grazing.

7.9.5.1.1 *Planning for management in the face of uncertainty (with respect to climate)*

Budgeting is a vital part of managing risk and preparing for drought. At a minimum it involves planning for the year ahead based on assumptions of both an average or better season and a drought year, and then applying a probability to each. This can then be extended to a two- or even a five-year estimate of cash flow, possibly including a wider range of seasons. Where seasonal forecasts are being used, one can include the probability that a drought or an average or better season will be forecast, but then one must also include the probabilities that these forecasts will be perceived as being wrong (Table 7.4). It is essential that all possible outcomes be budgeted for in advance.

Meinke et al. (2003) point out, however, that management decisions based on seasonal forecasts will have positive outcomes in some years and negative outcomes in others. This should not be regarded as either a “win” or a “failure” of the strategy employed using seasonal forecasts, since each season or year is only a sample of one of a “not very well-defined distribution of possible outcomes”. They add that assessing the true value of this type of probabilistic

information requires a comparison of results in each season against outcomes that would have been achieved in the absence of such information. A large part of the perceived problem in the use of seasonal forecasts appears to stem from the fact that as a consequence of the delivery of weather forecasts, prediction information was initially issued as a deterministic forecast. Murphy (1993) stresses the need for uncertainties that are inherent in judgements to be properly reflected in climate forecasts.

Financial strategies identified by Blackburn (1992) as leading to greater self-reliance are summarized in Table 7.5. When frost protection is likely to be necessary, the appropriate method(s) to be used must be selected based both on the physical and economic risk. An MS Excel application (FrostEcon.xls), programmed in VBA, was developed by FAO (2005) to help farmers anywhere in the world conduct the cost-effectiveness and risk analyses essential to making wise financial decisions concerning the adoption of frost protection methods.

7.9.5.1.2 *Stocking rate and carrying capacity of the land*

Long-term stocking rates should be both biologically and financially sustainable after allowing for drought (Morley, 1981; White 1987). Stocking rates that fail to sustain pastures or viable vegetation are not economically feasible in the long term. In this regard, the sustainability of agricultural systems in some areas may need to be reassessed, given the underlying capacity of the land.

7.9.5.1.3 *Adaptation of livestock*

A variety of management adaptations are available for livestock production systems. For example, Hahn and Mader (1997) outline a series of proactive management countermeasures that can be taken during heatwaves (for instance, shades and/or sprinklers) to reduce excessive heat loads. Historical success in coping with climate variability suggests that livestock producers are likely to adjust to climate change successfully. Johnson (1965) provides examples from advances in genetics and breeding as related to the environment. These capabilities should allow adaptation to changing, less favourable circumstances associated with projected rates of climate change. Coping can entail significant dislocation costs for certain producers, however. For individual producers, uncertainties associated with potential climate change imply additional risks related to how and when to adapt current production practices (Lewandrowski and Schimmelpfennig, 1999).

Table 7.4. Determining seasonal probabilities when seasonal forecasts are available

Forecast –	Drought –	true v. false
	Good season –	true v. false

Confidence in the foregoing projections of the ability of livestock producers to adapt their herds to the physiological stresses of climate change is difficult to judge. The general lack of simulations of livestock adaptation to climate change is problematic, and the absence of a well-developed livestock counterpart to crop modelling of adaptation assessments suggests a major methodological weakness. Hence, we give only low-to-moderate confidence in projections of successful livestock adaptability (IPCC, 2001).

- (c) The El Niño-Southern Oscillation (ENSO), a global coupled ocean-atmosphere phenomenon that has a cycle of about three to seven years and has profound effects on global climate;
- (d) The Pacific Decadal Oscillation (PDO), a decadal oscillation of Pacific Ocean sea surface temperatures that affects climate in the northern hemisphere;
- (e) A 50–80 year variability associated with the tilt of the Earth's axis (hemispheric);
- (f) Milankovitch cycles (ice ages; inter-glacial periods) based on variation of the Earth's orbit around the sun.

7.10 SIGNIFICANCE OF CLIMATE CHANGE

7.10.1 Climate is always changing

Better understanding of weather and climate requires monitoring and analysis of the climate signals at different timescales. These include:

- (a) The Madden-Julian (30–50 day) Oscillation, or Intraseasonal Oscillation, which increases the likelihood of rain every time it passes over northern Australia;
- (b) The Quasi-Biennial Oscillation (QBO), a quasi-periodic stratospheric oscillation that affects the distribution of stratospheric ozone and monsoon precipitation, for example;

The overriding certainty is that climate has always changed and will continue to change. Whether climate change is natural or anthropogenic is relevant here only in the context of the likely direction and rate of change. The important issue at stake is the capacity of farmers and ranchers to adapt the management of crops, rangeland and grassland ecosystems to a changing climate so as to minimize adverse consequences.

Climate change will include changes in rainfall, temperature and atmospheric CO₂ concentrations. For instance, in Australia, which has the highest climate variability of any continent in the world, comparable with Southern Africa, it is anticipated

Table 7.5. Financial strategies to aid drought preparedness and management

Pre-drought	Build up cash reserves during good years
	Budget each year assuming both normal and drought years
	Stabilize income through off-farm investments
Drought forecast	Budget for a long-range forecast that is either (a) right or (b) wrong
	Unload prime or surplus livestock before prices drop
	Identify least-cost feed supplements
	Purchase fodder before its value increases
	Budget to compare feeding and selling strategies
	Sensitivity – drought duration, feed costs, stock prices
	Evaluate alternative strategies, such as droving, agistment
	Budget for selling all stock and investing off-farm
Drought	Minimize financial losses to facilitate post-drought recovery
	Continue comparison of feeding and selling strategies
	Consider raising capital by selling off-farm investments

that the most noticeable changes will be an increase in rainfall intensity and variability and an increased frequency of extreme high temperatures, with a likelihood of more severe droughts and a greater fire risk (Jones et al., 2000).

Some of the consequences of climate change are likely to be beneficial. For example, increased atmospheric CO₂ concentrations can offset the detrimental effects of drier seasons through increased water use efficiency and yields. For grassland systems, particularly those based on C₄ species, this can be reflected in higher carrying capacities and less variability in the stocking rate from year to year (Howden et al., 1999; Reyenga et al., 1999).

7.10.2 **Adaptation to climate change**

Knowledge of climate variability can assist in adapting to climate change. In eastern Australia there is a strong

correlation between the Southern Oscillation Index in winter and spring and subsequent spring and summer rainfall (McBride and Nicholls, 1983; Stone et al., 1996; Nicholls, 1998). If producers stock their land in response to changes in the SOI, and if climate change leads to either drier or wetter summer seasons, they will ipso facto adjust their stocking rates accordingly (McKeon et al., 1993). This of course assumes that the prevailing relationship between the SOI and summer rainfall remains unchanged, which may not be the case (Walsh et al., 1999). Other indices such as sea surface temperatures in the equatorial Pacific and Indian oceans could similarly be used.

Climate may also change outside the range of previous experience, especially with regard to the severity and frequency of extreme conditions. Longer-term adaptation will require some foreknowledge of the nature of the climate change, not simply reliance on recent experience.

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EFFECTS OF CLIMATE CHANGE ON AGRICULTURE

8.1 INTRODUCTION

Climate is constantly changing, and the signals indicating that changes are occurring can be evaluated over a range of temporal and spatial scales. Climate can be viewed as an integration of complex weather conditions averaged over a significant area of the Earth (typically on the order of 100 km² or more), expressed in terms of both the mean of weather represented by properties such as temperature, radiation, atmospheric pressure, wind, humidity, rainfall and cloudiness (among others) and the distribution, or range of variation, of these properties, usually calculated over a period of 30 years. As the frequency and magnitude of seemingly unremarkable events, such as rainstorms, change, the mean and distribution that characterize a particular climate will start to change. Thus the factors influencing climate, as defined here, range from events occurring over periods measured in hours on up through global processes taking centuries.

Changes in climate have over the millennia been driven by natural processes, and these mechanisms continue to cause change. "Climate change" as a term in common usage over much of the world is now taken to mean anthropogenically driven change in climate. Such climate change may influence agriculture in a positive way (CO₂ fertilization, lengthening of growing seasons, more rainfall) or in a negative way (more drought, faster growth resulting in shorter life cycles, salinization). This chapter will discuss:

- (a) Assessment of the available evidence about anthropogenically driven climate change and current thinking regarding global spatial distribution of changes that may occur;
- (b) The internationally adopted protocols for evaluating climate change impacts as set out by the Intergovernmental Panel on Climate Change (IPCC) and its parent/related international organizations;
- (c) The sources of data for conducting impact assessment and the techniques for regionalizing data to scales smaller than the resolution of global circulation models;
- (d) Examples of quantitative models available for assessing climate change impact on bioresource industries¹ and protocols for their use;
- (e) The types of impacts that should be considered when undertaking a climate change impact assessment;
- (f) The development of an approach to identifying how climate change can or should be managed by bioresource industries, and by agriculture in particular.

Issues that relate to the occurrence of extreme events and particular hazards have been considered in Chapter 7, and these are of most importance for operational and tactical planning, namely, deciding how to do things over a period of 12 months or so and looking forward for a period of perhaps five years. This chapter will consider issues that relate to regional policy development, long-term agricultural planning and adaptation of production systems to changing climate, in other words, strategic planning for bioresource industries. Strategic planning has to be based on a time horizon of approximately 10 to 50 years, which corresponds to the time concept of climate and represents a period comparable to human life expectancy. If complex weather conditions are changing sufficiently rapidly that climate is changing noticeably in a lifetime, whether this is anthropogenically driven or not, it is necessary for information to be available to end-users to allow for suitable strategic planning.

The operational tools required for climate change impact assessment are output data from global climate models, statistical techniques and simulation models of biological systems. In general, organizations that have the resources to employ personnel trained in the application of these tools, the use of which requires only moderate training, will be able to conduct climate change impact assessments. The products of research and planning programmes run at national or regional scales then have to be made available to end-users in a suitably interpreted manner in order to be of value as warning or planning information in a form appropriate for enterprise-scale management.

1 Industries producing fuel, feed, fibre and food using biological methods.

8.2 SUMMARY OF EVIDENCE FOR CLIMATE CHANGE

Although instrumental observations commenced in some parts of Europe in the seventeenth century, it was the Industrial Revolution that stimulated the initial growth of climate observing networks. In the crowded coalfield cities of northern Europe, public health considerations necessitated the development of piped water infrastructure. Reservoirs needed managing, which in turn required that rainfall and temperature measurements be undertaken. Approaches and equipment gradually became standardized and by the middle of the nineteenth century Europe and parts of North America had skeletal climate observing systems. The International Meteorological Organization was established in 1873 largely to oversee standardization of techniques in observing systems, a role also taken up by its successor, the World Meteorological Organization, in 1950. By then much of the globe was integrated into a coordinated observational network incorporating oceanic and upper-air components, supplemented in more recent times by radiosonde and satellite observations. Standardization of observing procedures enabled global trends to be established with greater confidence and a number of global temperature time series were developed and carefully processed to provide reliable estimates, which generally showed good agreement that climate was indeed changing significantly (Figure 8.1).

The instrumental records show that global mean surface temperatures have increased by 0.74°C over the period between 1906 and 2005, and since 1956 a rate of increase of $0.13^{\circ}\text{C}/\text{decade}$ has prevailed (IPCC, 2007). Warming has been most pronounced over the land masses and high northern latitudes, though the average temperature of the global ocean has also increased to depths of at least 3 000 m (IPCC, 2007). Consistent with this unequivocal trend, the 1990s constituted the warmest complete decade of the warmest century of the last millennium, although the period 2001–2008 is already 0.19°C warmer (CRU, 2009). Different combinations of stations are used to calculate the global average by various scientific groups and most identify 1998 as the warmest year in the instrumental records, closely followed by 2005. Some groups, however, place 2005 as equal first or clear first in the series, which is somewhat unusual as 2005 was not a marked El Niño year (Kennedy et al., 2006). El Niño is a large-scale ocean–atmosphere climate event that results in a marked warming in sea surface temperatures across the equatorial Pacific Ocean. Global average temperatures tend to be higher in the few months after such an event, which typically recurs every 2–7 years. Thirteen of the 14 warmest years in the instrumental record of global surface temperature (since reliable observations commenced in 1950) have occurred in the past 14 years (CRU, 2009). The average global surface temperature in 2008 was $0.33^{\circ}\text{C} \pm 0.05^{\circ}\text{C}$ above the 1961–1990 average (CRU, 2009). The warming has been greatest during the winter, spring and autumn seasons (Jones et al., 2001). Minimum

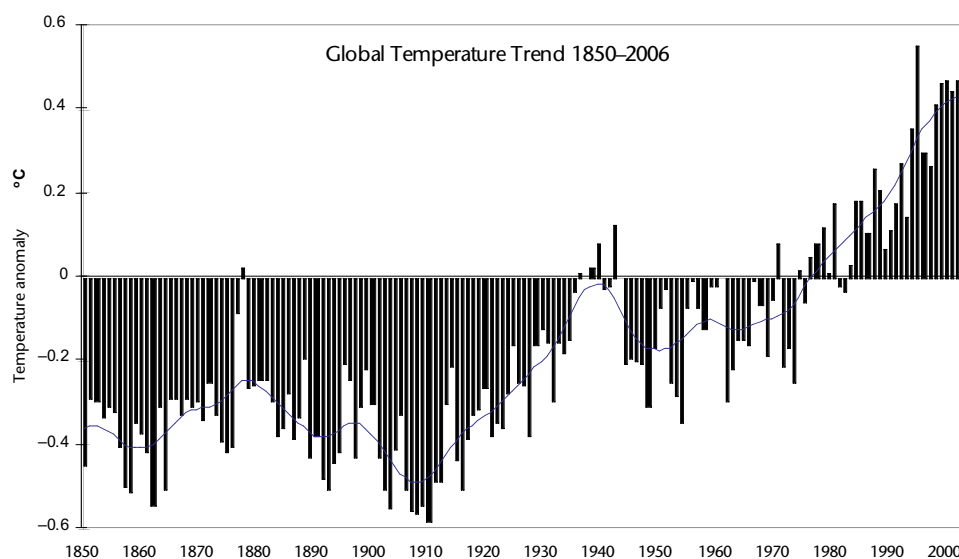


Figure 8.1. Annual global air temperature trend (difference from 1961–90 baseline) (Brohan et al., 2006)

temperatures have been increasing at approximately twice the rate of maximum temperatures, a phenomenon confirmed by many national-scale studies (Zhai and Ren, 1999; Sweeney et al., 2002; Vincent and Gullet, 1999).

Such decreases in the daily temperature range implicate cloud cover as a possible agent, and cloudiness has increased in most regions in recent decades. Associated with this, global land precipitation has increased by 2 per cent per over the past century (Jones and Hulme, 1996). Much more spatial variability is occurring with precipitation than with temperature, however. Over most mid- and high-latitude continental areas of the northern hemisphere, precipitation increases are occurring, while in the subtropics and tropics a downward trend is present, especially since the 1970s (IPCC, 2007). Associated with these precipitation increases in the land areas of the mid- to high latitudes is a tendency towards an increase in the frequency of more intense precipitation events (IPCC, 2007). Such events, more so than changes in the mean conditions, are likely to provide the most serious challenges for agriculture in the years ahead.

Since many observing stations have been located in urban areas, some concerns have periodically been voiced that global temperature changes might have been unduly biased by an urban heat island influence. This has been shown to be unfounded, with urban effects contributing only about 0.05°C to global temperature averages over the course of the twentieth century (Easterling et al., 1997; Peterson et al., 1999). Changes in solar irradiance of about 0.1 per cent also occur over the course of the 11-year solar cycle, which has been implicated in recent global temperature changes as well, though it is now believed that this contribution is not in itself capable of explaining the changes in global temperature of the past century (Tett et al., 1999). Uncertainties regarding the cooling influence of atmospheric aerosols have not yet been satisfactorily resolved, and these remain a major source of uncertainty for climate modellers. Of some significance for agriculturalists is the reduction in evapotranspiration and solar radiation receipt that anthropogenic aerosol loading on the atmosphere may have induced in recent decades in many areas, the so-called “global dimming” effect (Stanhill, 1998). As the application of air pollution controls becomes more widespread in the future, the aerosol load may decrease somewhat, thus further exacerbating warming trends.

Natural fluctuations within the climate system occur on a range of timescales from daily to multi-decadal to millennial, and over a large range of spatial scales. These variations have been revealed by a range of palaeoclimatic reconstruction techniques. Documentary sources, tree ring analysis, palynology, and ice and ocean core analysis have revealed windows into the past which show the longer-term temporal context into which present and future changes fit. Ice cores in particular have provided considerable insight into the climatic variations of the past 2 million years and have shown that astronomical forcing of climate is not in itself explanation enough. Climate sometimes changes in radical fashion within a few decades. Much more so than a decade ago, the capacity of the climate system to exhibit “abrupt” global-scale changes is now better appreciated. Regime shifts, often triggered by oceanic circulation changes, are now known to have occurred several times throughout the last glacial-interglacial cycle (Dansgaard et al., 1993) and there is a growing realization that human actions may prematurely reactivate some of these natural ocean-atmosphere mechanisms. On a shorter timescale, decadal modes of variability, including the Arctic Oscillation (an index of the pressure differences between the polar vortex and mid-latitudes), the North Atlantic Oscillation (an index of “westerliness” in Europe) and El Niño–Southern Oscillation (an index of atmosphere–ocean circulation changes in the eastern equatorial Pacific of which El Niño is the warm phase and La Niña the cold phase), are associated with significant changes in oceanic and atmospheric circulation, all of which may affect agricultural productivity over large regional scales.

The current scientific consensus attributes most of the recent warming to anthropogenic activities associated with increasing atmospheric concentrations of greenhouse gases (IPCC, 2007). The primary contribution has been made by CO₂, which has increased from pre-Industrial Revolution levels of 280 ppmv (parts per million by volume) to current levels of over 380 ppmv. This is a concentration that has not been exceeded during the past 420 000 years and most likely not during the past 20 million years (IPCC, 2007). A significant contribution to the atmosphere’s greenhouse gas loading also comes from methane. Methane concentrations have already doubled from their pre-industrial levels, with anthropogenic sources contributing over double the natural contribution. Over half the anthropogenic contribution comes from activities associated with bioresource exploitation. Due to methane’s relatively short residence time in the atmosphere, removing a tonne of this gas from the

atmosphere today would contribute 60 times as much benefit to reducing global warming over the next 20 years as removing the same amount of CO₂ (IPCC, 2001).

8.3 SUMMARY OF IPCC PROTOCOL FOR CLIMATE CHANGE IMPACT ASSESSMENT

Climate change impact assessments have traditionally been carried out by developing regionally specific scenarios and then using these to drive models in particular sectors of interest. Thus, for example, a global climate model (GCM) might be downscaled using a regional climate model (RCM) or statistical downscaling (SD) approach to generate high-resolution data for input to a hydrology model, a crop growth model, or a farm management model. To achieve this assessment, the assumptions made at the outset for the GCM are crucial. Central to this is the assumption about which future greenhouse gas emissions projections are likely to occur and what sort of future sulphate aerosol loading the atmosphere is likely to exhibit. In March 2000, IPCC approved a new set of emissions scenarios based on assumptions regarding future demographic, economic and technological “storylines”. These were presented in the Special Report on Emissions Scenarios (SRES) and the

family of SRES projections are widely used to provide the input for GCM runs (IPCC, 2000). The scenario-driven impacts can then be examined and further questions of adaptation, vulnerability and risk management addressed.

This conventional “top-down” approach yielding adaptation and vulnerability estimates is increasingly seen as somewhat restrictive. It may be that a particular result is the starting point and the steps necessary to either attain or avoid it form the objective of the exercise. For example, an impact involving the melting of the Greenland ice sheet might be considered catastrophic for coastal flooding and the scenarios necessary to avoid this could be elucidated by a “bottom-up” approach. Climate adaptation policies may be developed from either or both approaches (Figure 8.2). Most adaptation policies show top-down emphases whereby emission models drive scenario models, which in turn drive impact models. For agriculturalists a more individual, bottom-up, response is common, involving concepts of capacity, financial considerations and risk assessment. Farmers are well aware of the basic tenets of risk management or avoidance, and frequently show great willingness to adapt to changing circumstances. A possible risk management approach for agriculturalists based on the United Nations Development Programme (UNDP) Adaptation Policy Framework (Lim et al., 2005) is shown in Figure 8.3.

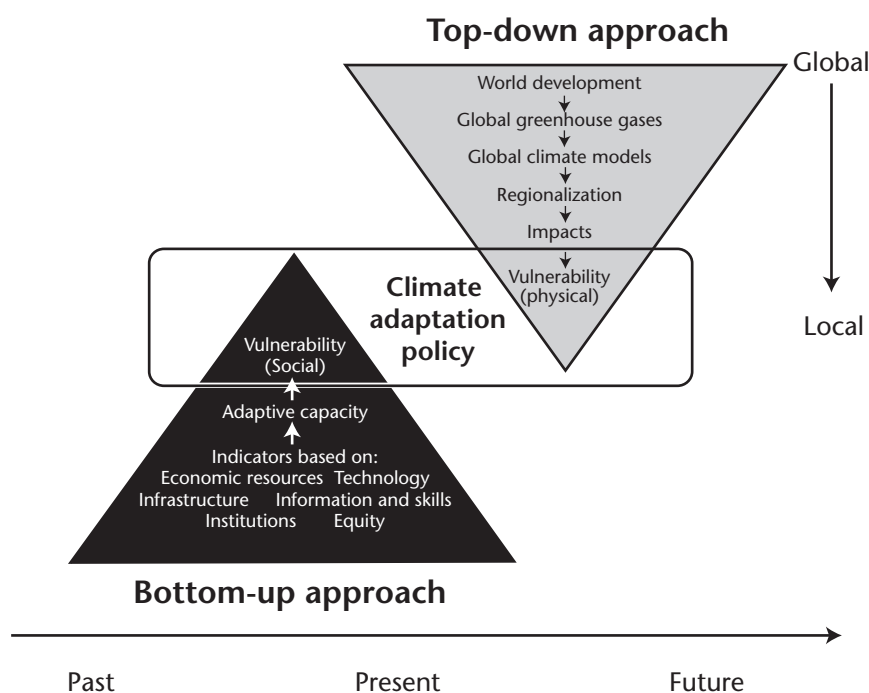


Figure 8.2. The top-down vs. bottom-up approach to climate adaptation policy (Dessai and Hulme, 2004)

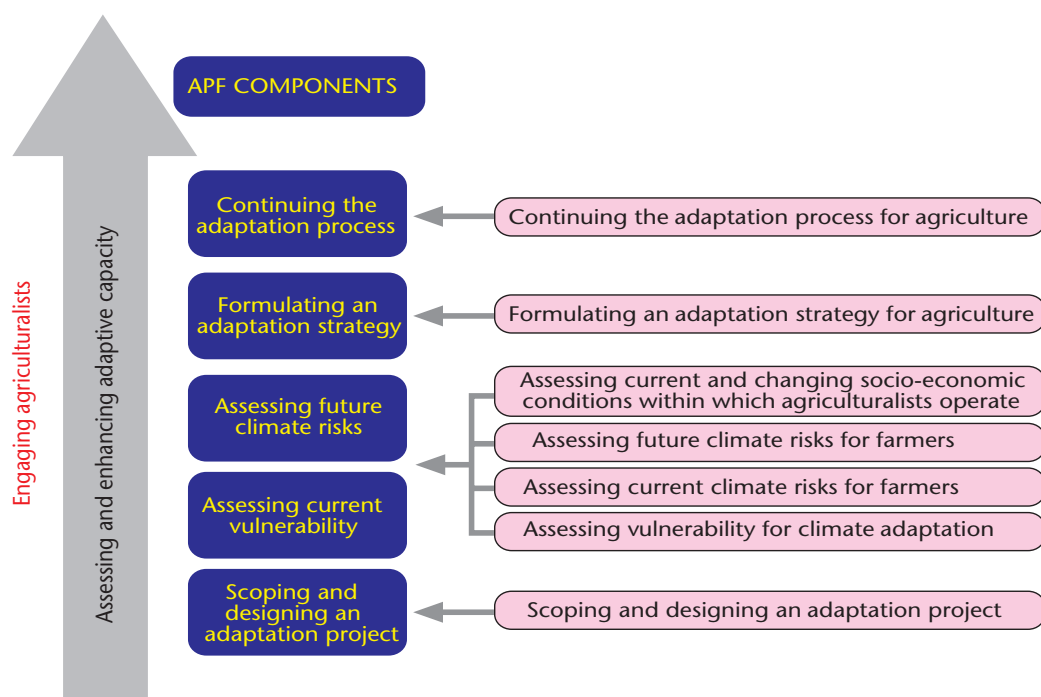


Figure 8.3. A climate change risk management approach based on the UNDP Adaptation Policy Framework (APF) (Lim et al., 2005)

8.4 SOURCES OF CLIMATE CHANGE DATA

8.4.1 Global climate model results

Global climate models (GCMs) provide the major pillar for the provision of future scenarios with which to assess the likely impacts of climate change on agriculture. Initially these were relatively crude representations of climate with gross simplifications of key processes and limited incorporation of aspects of the climate system such as the oceans, cryosphere and biosphere. The coupling of these components, and the incorporation of many more submodels, has been a major advance of the past three decades that was facilitated by exponential increases in computer power. In the past, runs of a model were often done on an equilibrium basis, that is, to compare a future climate mode, such as that after a doubling of CO₂, with the present. The ongoing processes and changes involved in reaching this point, such as gradual increases in greenhouse gas loading, or deforestation trends, were not simulated in any detail. Sophistication of these models has also resulted from an improved understanding of the underlying climate processes involved, so that today transient models incorporating many complex components of the climate system are operational. Using combinations of models and multiple simulations from a single model further enhances the utility of GCMs. At

present, GCMs are able to provide successful simulations of many aspects of current climate, an attribute that gives confidence in their ability to provide plausible future scenarios.

Typically, a GCM in 2009 had a grid size of 100–300 km, approximately 20 levels above the surface over land areas or below the surface over oceanic areas, and a time step of 10–30 minutes. There are four primary equations describing the movement of energy and momentum, together with the conservation of mass and water vapour, across the three-dimensional surface created. For many climatic processes, such as convective cloud formation, the resolution of several hundred kilometres is too coarse and simplifying representations are made. Inevitably, these limit the effectiveness of GCMs, particularly for users, such as agriculturalists, who need localized information.

GCMs provide an initial indication of key regional vulnerabilities for agriculture. In the developing world, such vulnerabilities compound already existing problems, which means that adaptive potential is inevitably less than in the developed world. In sub-Saharan Africa, GCM rainfall change projections are inconsistent among the various models, with some projecting decreases and others slight increases. Generally though, reductions in cereal potential of up to 12 per cent are expected by 2080 (Davidson et

al., 2003). Egypt, for example, faces reductions of 11 per cent in rice and 28 per cent in soybeans by 2050 (Eid and El-Marsafawy, 2002). Some areas, such as the uplands, fare better from a lengthening of the growing season, and livestock productivity may increase in some regions. For many areas, however, food-producing potential seems set to decline and Parry (1999) suggests that an additional 60 million–100 million people may be vulnerable to malnutrition by 2080. The complex interplay among socio-economic and climatic conditions renders African food security highly vulnerable to harvest failures over the coming decades.

Projected warming in Asia is most pronounced in the winter (Giorgi and Francisco, 2000). During winter, precipitation amounts are expected to decline significantly over many monsoon areas, although GCMs do not suggest that the summer monsoon rainfall will decrease in reliability significantly (Lal et al., 2000). Extreme events in Asia pose the greatest problem for farmers and there are some indications that extremes are already increasing in frequency (Lal, 2003). Rice yields are projected to decline by 5–12 per cent over India and China with a further 2°C rise in temperature (Lin et al., 2004), and overall rice production in Asia could fall by just under 4 per cent by the end of the present century (Murdiyarso, 2000). Wheat yields are also projected to fall in a similar manner and livestock farming will become difficult in some areas as pasture becomes less productive and migrates northwards (Christensen et al., 2004).

Global climate models are sophisticated and highly expensive to develop. As a result, they are maintained at only a relatively small number of research centres. At present these include three locations in the United States; two in France, Japan and Australia; and one each in Canada, China, Germany and the United Kingdom. Among the best known are CSIRO2 (Australia), CGCM2 (Canada), ECHAM5 (Germany), HadCM3 (United Kingdom) and CCSM (United States). GCM outputs are readily available through IPCC sources for most models (IPCC, 2006), and detailed instructions for downloading data can be found at the Websites of the Program for Climate Model Diagnosis and Intercomparison (PCMDI, 2006) and the World Data Center for Climate (WDC, 2008).

8.4.2 **Regional climate models for regional and local-scale bioresource applications**

The limitations imposed by computer processing capacity mean that GCM grid sizes are inappropriate

for policymakers and are especially inappropriate for agriculturalists. Farmers are well aware of the importance of local factors, such as soil differences, slope, aspect and shelter, which can be key determinants of crop yield. Many hazards, such as hailstorms or intense convective rainfall, typically occur at sub-GCM grid scale. Downscaling of GCM output to a finer-mesh resolution has thus become a major research objective, and achievement, of climate scientists over the past decade. It is, of course, inevitable that downscaling introduces a further set of uncertainties in the climate scenarios produced (Giorgi, 2005; Wilby et al., 1999).

Regional climate models (RCMs) are produced by nesting a secondary model within one or more of the grid spaces of the GCM. Outputs from the parent GCM, such as pressure, wind, temperature and water vapour, at various altitudes for the area bounding a specified domain of interest, are used to drive the RCM. Within this domain, more spatially detailed output may be produced by the functioning of the RCM. Typically, RCMs offer resolution of approximately 20–50 km. Even this may be too coarse for agriculturalists. In addition, the RCM suffers from any inherent deficiencies in the parent GCM, since only a one-way influence is allowed (GCM → RCM). Multiple GCMs and ensemble-based approaches are increasingly used for which weightings are attributed to individual GCMs, depending on their ability to reproduce present climate (Wilby and Harris, 2006).

Owing to their increased spatial resolution, RCMs have many advantages over GCMs for assessing climate change impacts on agriculture. Land-use data, elevation, rainfall events and soil conditions may all be better represented by RCMs than by GCMs, and some processes, such as convective cloud behaviour, cannot currently be simulated satisfactorily on GCMs, but may be simulated more effectively on RCMs. Resolution is crucial. If it is too coarse, important fine-scale processes, such as cloud formation and local winds, may be lost. If it is too fine, mesoscale features, such as storms, may not be adequately handled by the model.

Regional climate models are much less expensive to run than GCMs and so have been developed for many countries. In some cases, numerical weather forecasting models have been adapted to provide an RCM product. Often RCMs have been developed for specific areas and output data can be difficult to obtain. One such source of regional climate model data exists at the Website of the ENSEMBLES Project of the European Union (ENSEMBLES, 2009).

8.4.3 Statistical downscaling of GCM outputs for bioresource applications

Even the improved spatial resolution of RCMs is not adequate to inform decisions in farming. A grid cell of 20 km would, after all, encompass a large city or a wide range of farming landscapes. Therefore, a number of alternative approaches to downscaling have been developed to address this problem. The most elementary approach involves pattern scaling, for which the projected changes of the GCM are simply translated equally to each data point within the domain of interest. For example, a projected warming of 2°C from the GCM would be added to each data location point within the domain. This, however, freezes any geographical variation within the domain, meaning that the present climate spatial pattern remains immutable. It is an approach that is also rather unsuitable for some climate parameters, such as rainfall. A reduction in rainfall predicted by the GCM could, following this method, produce an output of negative rainfall in some instances. It may also fail to capture changes, for example, in rain days or drought lengths for particular locations.

A family of approaches collectively described as empirical statistical downscaling has become widely used where climate scenarios with high spatial and temporal resolution are required. The principles of statistical downscaling are based on the development of mathematical transfer functions or relationships between observed large-scale atmospheric variables, such as upper-air observations, and the surface environmental variable of interest. The relationship is initially established using present-day observational data, and then “forced” using GCM output in order to derive climate scenarios for future time slices. Statistical downscaling is done to a point location and may be achieved for a range of variables, such as wind speed, sunshine hours, precipitation and temperature, depending on the choice of predictor variables. This form of downscaling requires substantially less in the way of computational resources and produces results that are comparable with those based on output from RCMs. As a consequence, the use of statistical downscaling methodologies to produce climate scenarios from GCMs is now the favoured technique for many researchers.

The use of statistical downscaling requires that a number of assumptions be made, the most fundamental of which assumes that the derived relationships between the observed predictor and

predictand will remain constant under conditions of climate change and that the relationships are time-invariant (Yarnal, 2001). It also assumes that the large-scale predictor variables are adequately modelled by the GCM for the resultant scenarios to be valid. Busuioc et al. (1998), in their verification of the validity of statistical downscaling techniques, found that in the case considered, GCMs were reliable at the regional scale with respect to precipitation in their study area and that the assumptions of validity of predictor–predictand relationship held up under changed climate conditions. Von Storch et al. (1993) suggested that if statistical downscaling is to be useful, the relationship between predictor and predictand should explain a large part of the observed variability, as is the case with temperature, and that the expected changes in the mean climate should lie within the range of its natural variability. Due to the influence of “local” factors on precipitation occurrence and amounts, however, the relationship between the large-scale predictors used when calibrating the statistical model and site-specific variability is often obscured and hence reflects only a small part of the actual observed variability. This situation is further complicated in areas with significant relief effects on precipitation.

In addition to the regression-based method, a number of other downscaling techniques are included in the family of statistical downscaling. These include approaches based on weather pattern classification and weather generators. Weather pattern methods involve the characterization of atmospheric circulation according to a typology, such as the Lamb weather type (Lamb, 1972). The weather variable in question would then be matched to each type or category and changes in the future occurrence of these would be used to rebuild the climatology for the variable for that future time (Sweeney, 1997). An important assumption of this approach is that the present relationship between the variable concerned and the circulation typology is robust for the future: that the rainfall yield on westerly winds at present will be the same as rainfall yield on westerly winds in the future, for instance. This may not always be a valid assumption. Weather generators produce realistic time series of a climatic variable according to some predetermined statistical constraints. Again, these can be tailored to present conditions initially and then used to simulate future conditions constrained by GCM output. Such an approach is useful for producing large volumes of output data, which is desirable when examining extremes or sequences of particular weather types, such as dry spells, heat-waves and rain days.

8.4.4 Reliability of extreme event prediction

Developing robust future climate scenarios from the techniques described above involves a pathway littered with uncertainties. Uncertainties in the emissions scenarios, uncertainties in the internal functioning of the GCMs, inadequate or non-existent parameterization of various physical processes and neglected or badly handled feedback processes all constitute part of a cascade of uncertainty (Figure 8.4).

This means that great caution is needed in interpreting the reliability of scenarios for policy formulation purposes. This is especially relevant with reference to changes in the frequency of extreme events. Such changes often are dramatic and a very wide range in estimates may occur with even slightly different model runs. Despite this, it is important that likely changes in extreme event frequencies be quantified as far as possible to enable protective measures or alternative actions to be addressed. For example, if a farmer could be apprised of a change in the precipitation regime, such that the once-in-a-decade drought might change to a two-year return period, economic appraisals might suggest alternative crops or management practices. Once a farmer has an idea of the risk that an extreme event may occur, the potential severity can then be considered. For climate change considerations, an objective method of risk analysis can therefore provide a way of placing potential climate hazards in the context of other

hazards and enabling decision-makers to choose when and where to react to potential problems.

One way of extracting probability estimates of extreme events from GCMs is to undertake multiple runs with slightly different initial conditions. Each run will produce the same trend, but a slightly different pathway due to internal model variability and slightly different end points. These ensemble runs provide a basis for constructing probability distribution functions (PDFs), which provide a “best guess” as well as a confidence estimate for extremes (Figure 8.5). The PDFs may be further processed, multiple models may be added to the mix, and ultimately expert judgement may be used to characterize the reliability of an estimate of whether an extreme climate event will occur over a fixed period.

The reliability of extreme temperature prediction from GCMs is considered good and a number of studies show that the models perform satisfactorily in predicting current maximum/minimum temperature climatologies, as well as warm/cold spells (Kharin and Zwiers, 2000; McGuffie et al., 1999). The reliability of the prediction of precipitation extremes is much lower than that of temperature, however. This is to be expected, given the great spatial variability precipitation exhibits and the typical grid size of GCMs and even RCMs. Where projected daily precipitation amounts were correlated with grid-box average observations, more success was apparent (Hennessy et al., 1997). It would appear, though, that in the future reliable

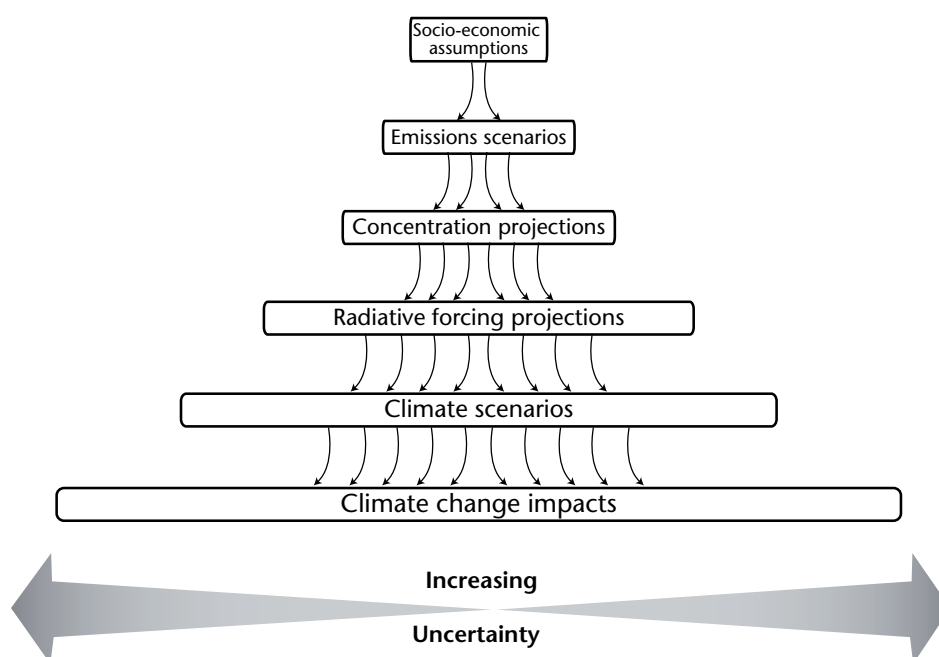


Figure 8.4. The cascade of uncertainty associated with evaluating impacts of climate change

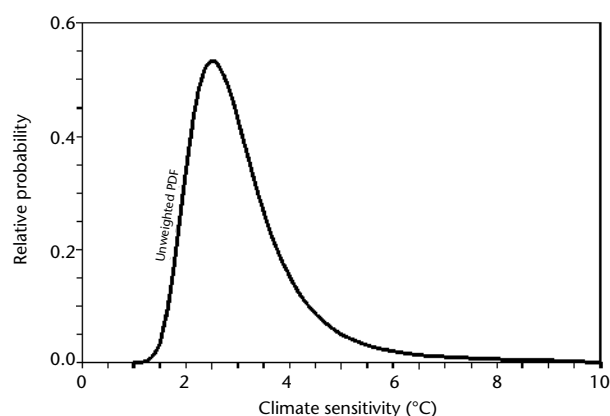


Figure 8.5. A hypothetical probability density function indicating a range of possible global temperature changes for doubling of global greenhouse gas concentration (climate sensitivity) based on multiple or ensemble runs of a climate model

extreme precipitation projections will be dependent on greatly improved grid-size resolution by GCMs. This is already occurring and will also further aid testing of climate change scenarios on crop, animal and forestry productivity and management.

8.5 MODELS FOR EVALUATING CLIMATE CHANGE IMPACTS

Top-down evaluation of climate change impacts (Figure 8.2) can be undertaken by means of three main approaches:

- (a) Using conceptual or theoretical concepts to qualitatively assess how climate change might influence agriculture. For example, if one knows that a certain minimum amount of rainfall is required to fall in a particular period for a crop to grow, this concept can be used to evaluate whether, based on global circulation model predictions, the crop will still be viable in the medium term. This approach has the advantages that an expert can integrate many concepts and form an overview impression of the situation, and very little hard data are required in order to apply it to a region. Some of the disadvantages are that interacting effects are difficult to balance, counter-intuitive concepts will not be considered, the real magnitude of the impact is difficult to judge, and for complex systems it is almost impossible for a single person to juggle all the concepts involved. The complexity of agriculture and most other bioresource industries, all of which have significant spatial and temporal interactions,
- (b) means that using a qualitative approach to evaluating climate change is not all that valuable for end-users.
- (b) Using small-scale quantitative simulation models, which can either be statistically based or mechanistic, to predict crop responses to climate change. In this case a conceptual model of how a crop grows and how it interacts with weather and soil might be defined, and then a series of mathematical/statistical equations that describe the conceptual processes could be built. This approach works well for considering primary interactions with climate, which are concerned largely with biophysical issues such as crop yield. The main advantages of this approach are that complex interactions can be more readily handled, a formal sensitivity analysis can be undertaken, the uncertainty associated with the model can be quantified, a quantified result can be presented, and a formal experimental design can be used to plan and undertake the exercise. The disadvantages are that quite large volumes of data are required; the models have to be tested and calibrated and doing this for future climates can be difficult; it can be difficult to assess the tenability of model assumptions for future climate predictions; the model might be amplifying uncertainty in the climate scenario data; and it is difficult for untrained end-users to treat precise quantitative output data as having associated uncertainty. The output of this approach to climate change impact assessment can be very useful to end-users, but can perhaps be misleading unless placed within an interpretive framework or considered in terms of second-order interactions that encompass whole systems, rather than just the primary yield component. It is possible that the impact of climate change on a complex mixed-farming system may be relatively small, namely, that the system has the flexibility to adapt to the change, but it may be quite significant in terms of individual crop yields. Rosenzweig and Iglesias (1998) provide a review of the use of crop models for climate change impact assessment.
- (c) Using system-scale quantitative modelling, which can be mechanistic, empirical, statistical or, more likely, a combination of all three. Such an approach to climate change impact assessment has the advantage that it should fully consider enterprise-scale interactions, but the amounts of data required and the tenability of assumptions can be limiting. In general, when using system models some parts of the system will be modelled in detail,

often mechanistically, and others will be kept very simple. For example, the CERES family of crop models (Jones and Kiniry, 1986) consider crop phenology in great detail, but treat the soil as a simple bucket. In contrast, the CENTURY model considers soil carbon and nitrogen dynamics in detail but treats the crop in a more generalized manner (Parton et al., 1992).

A state–pressure–impact–response–adaptation (SPIRA) model (Figure 8.6), as suggested by IPCC (2001), which is effectively a top-down approach, can be used to direct an impact assessment based on the three methods described (qualitative, small-scale model, system model).

For global-scale evaluation, Parry et al. (1999, 2004) used a technique of developing statistical transfer functions to predict yields in terms of predictors such as temperature and available water. This was achieved by using calibrated simulation models to evaluate yield response to climate parameters. The resulting transfer functions can be used to undertake spatial analysis of yield when spatial climate datasets (monthly data) are available. The crop yield results were interpreted by Parry et al. (2004) using a global economic model. The statistical transfer function approach was also used at the national scale by Iglesias et al. (2000) to spatially evaluate changes in wheat production in Spain. This works on the basis that once a model has been calibrated and tested using current climate data, it can be used to run “experiments” to predict yield with changes in temperature, available water and atmospheric CO₂. The results are then applied to derive predictor equations that can be used without recourse to daily weather datasets.

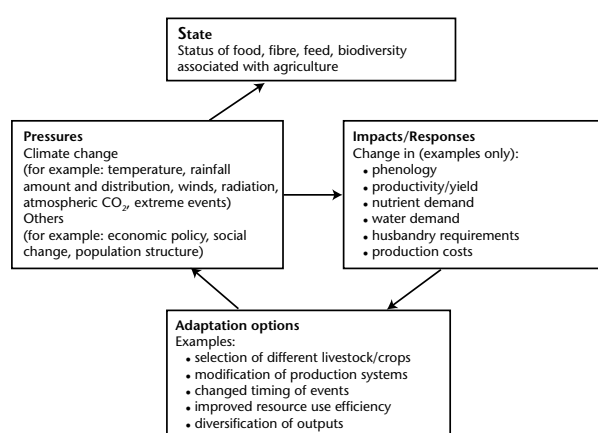


Figure 8.6. The SPIRA model (adapted from the example in IPCC, 2001) is a framework for conducting climate change impact assessments.

It is beyond the scope of this chapter to consider the full social and economic impacts of climate change on bioresource industries, particularly agriculture, where families are intimately linked to land management in a way that is not found with enterprises such as forestry. There are two main views regarding the presentation of results from a climate change impact assessment programme. On the one hand, results can be expressed in biophysical terms – changes in yield, predicted requirements for system adaptation – and on the other hand, results can be expressed in economic terms – the crop/system’s ability to yield more or less profit. This chapter will not consider economic and policy scenario testing, but will focus on the models available for biophysical system simulation. Parry et al. (1999, 2004) provide an example of a global approach to evaluating socio-economic impacts.

A further consideration is the issue raised by Hulme et al. (1999), who advocate that in order to avoid drawing erroneous conclusions from climate change impact assessment with models, an attempt should be made to identify the nature of “natural climate variability”, derived by using global circulation models without climate forcing, and “climate change”, derived using the same model but with climate forcing. They contend that in some circumstances natural climate variability will be more important to end-users than climate change impacts. From an operational and management point of view, it is perhaps irrelevant to worry about whether the conditions predicted to be encountered in the future will be driven by anthropogenically induced climate change or natural climate variability – all that is required are clear pictures of what is most likely to happen and an estimate of the uncertainty associated with the prediction.

8.5.1 Crop models

This section will not discuss all crop models that are available for simulating crop growth, but will consider some examples that have been used by scientists throughout the world and will review some desirable characteristics for a crop model that is to be used for climate change impact assessment.

For a crop model to be useful as a climate change impact assessment tool, it has to reliably predict yield as a function of weather variables and have a relatively limited number of essential variables and parameters – models developed to express understanding derived directly from research are not particularly suited to practical application where limited data might be available for parameterization, calibration and testing. It must also be available

to users in a robust yet flexible package that readily facilitates implementation, have a CO₂ response equation in the simulation, and operate at suitable spatial and temporal scales.

A review of literature for regional studies using the CROPGRO model (for a review of the model, see Hoogenboom et al., 1992), the CERES model (a user manual is provided by Goodwin et al., 1990) and the SUBSTOR model (described by Singh et al., 1998) reveals a predominance of work conducted for more developed countries (perhaps because the necessary data of suitable quality are available for these regions). The impact assessments focus mainly on the effects of elevated CO₂, temperature, precipitation and radiation on yield, but some authors have examined how these factors influence crop suitability and changing spatial distributions of crops (for instance, Iglesias et al., 2000; Rosenzweig et al., 2002; Jones and Thornton, 2003). While workers tend to conclude that increases in yield are likely, they discuss issues of importance such as timing of water in Indian monsoon, which can cause reduced yield (Lal et al., 1998, 1999), and the uncertainty of the yield forecasts (soybean and peanut yield increases, maize and wheat yield decreases) in the south-eastern United States (Alexandrov and Hoogenboom, 2004). The potential effect of the daytime vs. night-time rise in temperature is discussed by Dhakhwa et al. (1997), who suggest that an asymmetrical change, with greater change at night-time, would have less impact on yield than a symmetrical change. Another important issue is the potential significance of cultivar selection (Alexandrov et al., 2002; Kapetanaki and Rosenzweig, 1997). There have been studies for Africa and other developing regions (for example, Jones and Thornton, 2003), but authors recognize that a model to predict yield changes is unlikely to capture the true impact of climate change on smallholders and non-mechanized farmers in these regions.

Other crop models have been used for climate change impact assessment: EuroWheat (Harrison and Butterfield, 1996; Hulme et al., 1999) for wheat crops; the Hurley pasture model (Thornley and Cannell, 1997) for grass; GLYCIM (Haskett et al., 1997) for soybean; and CropSyst (Stöckle et al., 1994; Tubiello et al., 2000) for various C₃ and C₄ crops, mainly cereals. A characteristic of the work published in scientific literature is that most models are not well adapted to subsistence and low-input production systems, and therefore example studies tend to focus on agricultural production in more developed countries, where mechanization and

husbandry inputs are a significant part of the production systems used.

8.5.2 Animal models

A review of the literature reveals that there are many crop models available for climate change impact assessment, but there are few animal models that have been used to evaluate the impact of climate change on the animal. Most work focuses on how climate change affects animal production systems, with a particular emphasis on the supply of nutrients to the animal (for instance, the production of grass) and related environmental impacts (soil-water models). Two examples that can be found in the literature are:

- (a) SPUR (Wight and Skiles, 1987), which stands for Simulation of Production and Utilization of Rangelands. It is an ecologically based model designed to help optimize rangeland management systems. By considering hydrology, plant growth, animal physiology and harvesting, the model can forecast the effects of environmental conditions on range ecosystems, in addition to the animal simulation based on the Colorado beef cattle production model. The detail and complexity of the animal model mean that it may be excessively detailed for climate change impact work (Mader et al., 2002). The inputs for the animal component include breeding season, calving season, castration date and day of weaning. Animal parameters include birth weight, yearling weight, mature weight, milk production, age at puberty and gestation length. The climate data required are precipitation, maximum and minimum temperature, solar radiation, and wind run. The SPUR model can also be regarded as a system model, as it simulates soil, plant and animal interactions. It is placed under the category of animal model because it has been used for climate change impact assessment for animals (Hanson et al., 1993; Eckert et al., 1995).
- (b) National Research Council Nutrient Requirements of Beef Cattle (NRC, 1996). It was published as a book reviewing the literature on beef cattle nutrient requirements, and the accompanying computer models utilize current knowledge of factors that affect the nutritional needs of cattle and enable the user to define these factors to customize the situation for a specific feeding program. The model uses information on diet type, animal status, management, environment and the feeds in the diet. The effect of temperature on voluntary feed intake (VFI) is at the centre of the model. The model uses climate variables,

primarily average daily temperature, to generate an estimate of daily VFI. Based on daily VFI, estimates of production output (daily body weight gain) can then be produced. Frank et al. (1999) used the model to evaluate climate change impacts on animals in the United States.

Testing the validity of assumptions, parameterization and calibration of animal models for less-developed countries is of particular importance given the forecast of drought and heat stress on animals in tropical, semi-arid and Mediterranean regions, and the potential constraints that might hinder adaptation in these situations.

8.5.3 System models

The Decision Support System for Agrotechnology Transfer (DSSAT), which is currently available in version 4.0, is a good example of a system modelling tool. It has been used for the last 15 years for modelling crop (type and phenotype), soil, weather, and management or husbandry interactions (ICASA, 2006), and it has also been employed to assess climate change impacts (for instance, in Holden et al., 2003; Holden and Brereton, 2003).

The minimum dataset required for DSSAT consists of site weather data describing maximum and minimum air temperature, rainfall and radiation (stochastic weather generators are provided to create daily data if only monthly mean data are available); site soil data describing horizonation, texture, bulk density, organic carbon, pH, aluminium saturation and root distribution (basic soil descriptions can be used to parameterize a soil based on examples provided); and management data (planting dates, fertilizer strategies, harvesting, irrigation and crop rotations). Additional detail can be used as required by the research programme. The system then allows the user to define a crop/management scenario using a series of modules:

- (a) Land module – defines the types of soils and fields when the system is being used for site-specific work. Can be generalized for climate change impact assessment.
- (b) Management module – deals with planting, crop husbandry, rotation management, fertilizer, irrigation and harvesting.
- (c) Soil module – a soil water balance submodule and two soil nitrogen/organic matter modules including integration of the CENTURY model. For climate change impact assessment much of the detail can be ignored if suitable data do not exist.
- (d) Weather module – reads daily weather data or generates suitable data from monthly mean values.
- (e) Soil-plant-atmosphere module – deals with competition for light and water among the soil, plants and atmosphere.
- (f) Crop growth simulation modules – specific crop models (CROPGRO, CERES and SUBSTOR), each of which is well established in the scientific literature, are used to simulate the growth of 19 important crops (soybean, peanut, drybean, chickpea, cowpea, velvet bean, faba bean, pepper, cabbage, tomato, bahia grass, brachiaria grass, rice, maize, millet, sorghum, wheat, barley and potato).

The DSSAT systems can be regarded as a flexible system model, but there have been a number of other specific system models developed, many with a view to understanding more about climate change impacts. Typically, these models focus on a combination of agricultural production and biogeochemical cycling. Examples include:

- (a) PaSim (Riedo et al., 1998, 2000). The pasture simulation model is a mechanistic ecosystem model that simulates dry matter production and fluxes of carbon (C), nitrogen (N), water, and energy in permanent grasslands with a high temporal resolution. PaSim consists of submodels for plant growth, microclimate, soil biology and soil physics. It is driven by hourly or daily weather data. Site-specific model parameters include the N-input from mineral and/or organic fertilizers and atmospheric deposition, the fractional clover content of the grass/clover mixture, the depth of the main rooting zone, and soil physical parameters. Different cutting and fertilization patterns as well as different grazing regimes can be specified as management options.
- (b) Dairy_sim (Fitzgerald et al., 2005; Holden et al., 2008). Dairy_sim was designed to assess the interactions between climate and management in spring-calving milk production systems based on the grazing of grass pastures. The simulator comprises three main components: a grass herbage growth model, an intake and grazing behaviour model, and a nutrient demand model. The model has been improved to better account for soil water balance and field trafficability, but does not explicitly consider biogeochemical cycles. The level of detail was specified as appropriate for climate change impact studies, but is probably regionally constrained to the Atlantic Arc of Europe and areas with a similar climate.

- (c) CENTURY (Parton et al., 1987, 1995). The CENTURY model simulates carbon, nutrient and water dynamics for grassland and forest ecosystems. It includes a soil organic matter/decomposition submodel, a water budget submodel, grassland and forest plant production submodels, and functions for scheduling events. The model computes flows of carbon, nitrogen, phosphorus and sulphur. Initial data requirements are: monthly temperature (minimum, maximum and average in degrees C), monthly total precipitation (cm), soil texture, plant nitrogen, phosphorus, sulphur content and lignin content of plant material, atmospheric and soil nitrogen inputs, and initial concentrations of soil carbon, nitrogen, phosphorus and sulphur.
- (d) EPIC (Williams et al., 1990). The Erosion Productivity Impact Calculator (also known as the Environmental Policy Integrated Climate) model was designed to assess the effect of soil erosion on productivity by considering the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management. The model has a daily timestep and can simulate up to 4 000 years; it has been used for drought assessment, soil loss tolerance assessment, growth simulation, climate change analysis, farm-level planning and water quality analysis. Examples of its application include Mearns et al. (2001) and Brown and Rosenberg (1999).
- (e) DNDC (Zhang et al., 2002). The denitrification–decomposition model is a process-oriented model of soil carbon and nitrogen biogeochemistry. It consists of two parts, the first of which considers soil, climate, crop growth and decomposition submodels for predicting soil temperature, moisture, pH, redox potential and substrate concentration profiles driven by ecological drivers (such as climate, soil, vegetation and anthropogenic activity). The second considers nitrification, denitrification and fermentation submodels for predicting NO, N₂O, N₂, CH₄ and NH₃ fluxes based on modelled soil environmental factors.

8.5.4 Forest models

There are a large number of forest and related models that have been used to evaluate climate change impacts on natural and commercial forestry. Some examples will be used to illustrate the tools available.

ForClim is a simplified forest model based on the gap dynamics hypothesis (so-called “gap” models) that was designed to use a limited number of robust assumptions and to be readily parameterized so that it could be used for climate change impact assessment (Bugmann, 1996). It has a modular structure that considers environment, soil and plants separately but interactively, and was tested by evaluating whether it could simulate forest structures related to climate gradients. Examples of its use include Bugmann and Solomon (1995) and Lindner et al. (1997).

The FORSKA/FORSKA 2 models (Prentice et al., 1993) simulate the dynamics of forest landscapes with phenomenological equations for tree growth and environmental feedbacks. Establishment and growth are modified by species-specific functions that consider winter and summer temperature, net assimilation, and sapwood respiration as functions of temperature, CO₂ fertilization, and growing-season drought. All of the trees in a 0.1 ha patch interact through competition for light and nutrients. The landscape is simulated as an array of such patches. The probability of disturbance on a patch is a power function of time since disturbance. This model does not explicitly consider soil fertility but assumes uniform patch conditions and simulates the effect of nutrient limitation using maximum biomass curves. It is also used by Lindner et al. (1997).

It is necessary to recognize that forest models might not simulate meaningful changes from baseline over periods of 20–40 years due to the difficulty of capturing responses in complex ecosystems over relatively short periods. The impact of climate change is more likely to be visible over periods of 75–150 years. For commercial, monoculture forestry, the impact of changes in atmospheric chemistry, drought and high winds may become detectable by simulation modelling for a shorter period because the system is more readily modelled.

8.5.5 Other bioresource models

While most models used by the agricultural community (in its broadest sense) to assess impacts of climate change can be directly related to production aspects, there are models available that look at wider environmental issues that overlap with agricultural activity. A good example of such a model is SPECIES: spatial evaluation of climate impacts on the envelope of species (Pearson et al., 2002). This is a scale-independent model that uses an artificial neural network model coupled to a climate–hydrology model to simulate the

relationship between biota and environment and it is useful for examining the impact of climate change on the distribution of species and how this might change (Berry et al., 2002a). The approach requires quite intensive observations in the region being examined and thus is most useful where there is a well-established and dense meteorological observation network. The SPECIES model has also been used to evaluate forest responses to climate change (Berry et al., 2002b).

8.6 PREPARATION FOR CLIMATE CHANGE IMPACT ASSESSMENT

8.6.1 The global context

Growth in world agricultural production during the last three decades of the twentieth century averaged 2.2 per cent per annum, a rate of growth expected to fall to approximately 0.8 per cent per annum by 2040 (FAO, 2005). This slowdown reflects a decline in population growth rates and an attainment of medium to high per capita consumption rates in many countries, which will reduce the rate of increase in demand for agricultural products. China has a particularly influential role. The deceleration of population growth is expected to be rapid, approaching 0.34 per cent by mid-century (United Nations, 2009), resulting in greater food security globally and a fall in the numbers currently experiencing malnutrition (projected to decrease from current levels of 800 million people to less than half this value by mid-century (FAO, 2005)). When viewed spatially, the picture of decreased dependency on agriculture and other bioresources is less encouraging, with many sub-Saharan countries not being lifted by this “rising tide” of food productivity. In the period up to 2040, climate change is likely to exacerbate food production difficulties, primarily in tropical areas with unreliable rainfall; and as with most natural hazards, it is the poor who are most vulnerable and also the most constrained in terms of their options for adaptation.

8.6.2 Factors to consider for study design

When undertaking analysis to evaluate the potential impact of climate change and to prepare for climate change effects, a number of factors should be considered when designing a study:

- (a) The vulnerability of the human community. Is the area's food secure? Furthermore, is the community dependent on locally produced

food, does it require significant food imports, or is it a net exporter of some products and importer of others? An evaluation of post-production food miles might reveal something of the nature of the community, as might an economic analysis to evaluate whether money is available to diversify production and still enable the community to survive;

- (b) The likely climate change that might occur. This can be considered in two ways: are changes going to be a gradual shifting of mean values with little change in extremes and ranges, or will there be more extreme events? And how much uncertainty is there regarding the nature of the change? In areas where the only data available are the outputs from GCMs, the resolution at which evaluations can be made is quite coarse. RCMs and statistical downscaling (provided suitable field observations exist) permit the spatial resolution of the evaluation to be finer;
- (c) The likely socio-political situation of the area. If there are a range of possible economic and policy scenarios, can suitable modelling frameworks be developed to account for them, or can a theoretical framework for analysing the results be established? Economic uncertainty is probably as important as climate change uncertainty when interpreting the data collected for a climate change impact study;
- (d) The availability of suitable models to simulate primary and secondary impacts on agricultural systems. Models for subsistence and tropical garden crops tend to be lacking, and reliable simulation of CO₂ effects and complex interactions can also be troublesome;
- (e) The uncertainty associated with parameterizing and calibrating models to evaluate impacts. There is a trade-off with this issue in that it is desirable to model interactions that occur within a production system (for instance, elevated temperature and CO₂ impacts on yield and the interaction with pests and diseases), but as more detail is included in the model it becomes more difficult to be sure that the output of the study has captured a climate change impact rather than a result associated with uncertainty related to input parameter values. There is perhaps a case for keeping the quantitative modelling quite simple and developing a comprehensive yet qualitative interpretive framework, rather than trying to capture all interactions in a simulation system. A study design that provides a “response envelope” is perhaps the best way forward in areas where data are scarce or associated with great uncertainty.

The impact predicted as a result of the study will depend on the combination and interaction of vulnerability, physical environment, social environment and the hazard, which in this case will be climate change. When vulnerability and hazard coincide in an environment that resists adaptation, an adverse impact can be expected. The major climate hazards that might be expected and the general nature of their impact are considered in the following sections in order to provide a framework for initial impact study design; it must always be remembered, however, that elevated CO₂ and other environmental properties will have interactions with these factors.

8.6.3 Specific weather-related effects

8.6.3.1 Temperature effects

The effect of changing temperature as a result of climate change can be interpreted in terms of a number of interactions with crops and animals. Care should be taken when preparing scenario data for use with a model and when planning a modelling experiment to work out how temperature changes are likely to occur. If mean monthly temperatures increase due to increases in minimum temperature (for example, at night-time), the consequences for a crop may be quite different compared to situations in which the same change is caused by an increase in daytime temperature. Rising night-time temperature can lead to decreases in yield (Kukla and Karl, 1993), whereas increasing daytime temperature might increase yields in northern latitudes (by increasing growing-season length) but decrease yields in middle latitudes (due to earlier ripening) (Droogers et al., 2003). Impact assessment relying on mean monthly temperature data for future scenarios (for example, Holden et al., 2003) must be used carefully when stochastically deriving daily temperature data from monthly means. It is important to understand the consequences of using mean monthly data as opposed to mean monthly minimum and maximum data.

When choosing a model and designing an experimental approach, it is necessary to consider the nature of the likely temperature impact on a given crop. If a crop is sensitive to temperature thresholds, such as a requirement for a low-temperature vernalization period (for example, winter wheat), or has a critical maximum temperature for survival (such as 32°C for cotton fruit survival, as reported by Reddy et al., 2000), the modelling scenario has to be sensitive to these issues. It is perhaps easier to capture effects like overall elevated growing season temperature, but the simulation model used should

be sensitive to the known effects of thermal accumulation (normally expressed as growing degree-days, for example, in Keane and Sheridan, 2004). If growing degree-days accumulate more rapidly, the crop will normally progress through its growth cycle faster and the growing season will be shorter. For most crops, elevated temperature causes a reduction in yield as there is less time for the capture of light, water and nutrients by the plant (Lawlor and Mitchell, 2000). When simulating climate change impact, it is important to try to capture the effects of temperature sequences during critical vernalization and growth periods. Elevated temperature during early growth stages will often be beneficial, but during the time of maximum growth it can be detrimental because this period is shortened. An understanding of the development of the plant is crucial to developing a meaningful simulation experiment to capture climate change impacts.

Temperature increases will also have some direct consequences for animal productivity. Increased thermal stress will reduce animal eating and grazing activity (Mader and Davis, 2004) and can cause reductions in yield and fertility. These consequences are likely to be most severe in tropical, semi-arid and Mediterranean regions, rather than temperate areas where neutral or positive effects might be seen. Where cold limitations are removed in temperate areas, productivity might even increase. In order to capture the potential impact of climate change, it is necessary to model the plant and animal part of animal production systems where it is envisaged that temperature changes might cause stress to the animal. In general, higher temperatures during the growing season will be associated with higher radiation and a demand for more water, which along with elevated CO₂ are major interactions that have to be considered in any impact assessment exercise.

8.6.3.2 Water availability

The availability of water is fundamental to agriculture. The impact of climate change can occur through three major routes: drought, which is a lack of water for a period of time causing severe physiological stress to plants and animals; flooding, which is an excess of water for a period of time causing physiological and direct physical stress to plants and animals; and timing of water availability, that is, when a severe lack or excess of water does not occur, but its availability throughout the year changes so as to no longer be suitable for current agricultural practices, crops or animals. When evaluating climate change impacts in areas

typically using irrigation, the analysis of water availability must consider how the supply is buffered/stored for irrigation use. Irrigation demand is likely to rise in most regions with temperature increases, as a result of increased evapotranspiration and possibly related decreases in rainfall at critical times during the growing season.

Theoretically, C_4 crops should require less water per gram of carbon assimilated than C_3 crops (Young and Long, 2000) and this means that crops like sorghum and maize should be more tolerant of water stress than other cereal crops. In reality, maize suffers more irreparable damage due to water stress than does sorghum (Doggett, 1988) and is less suited to drought conditions due to its morphology and physiology. It is interesting to note that sorghum is also more tolerant of temporary waterlogged conditions than maize. There is evidence that soybean yields suffer with both early and late water stress in the growing season (for instance, Jones et al., 1985) and therefore timing of water availability might be important. These brief examples illustrate the importance of choosing the best possible model for the intended impact assessment. A model that cannot account for species or plant breeding effects may misrepresent the impact of climate change in a region; the cost of such detail in a model, however, is usually associated with a need for large amounts of data in order to parameterize and test the model. The temporal resolution of a model is also important because it should be sufficient to capture transient extreme events. Studies in the United States indicate that predicted decreases in yield are more extreme when short-term weather events are simulated than when predictions rely on mean data (Rosenzweig et al., 2002). Recent examples of extreme temperature and associated drought could be used to test the suitability of a model for climate change impact assessment. The 2003 drought in Europe (Ciais et al., 2005) and droughts since the mid-1980s in Africa (for example, Desta and Coppock, 2002) provide quantified evidence for the testing of models in these regions prior to future prediction of climate change impacts.

8.6.3.3 Wind effects

Wind can affect crops, forests, animals and the soil, in each case having a direct impact on the productivity and perhaps sustainability of a system of production. For most field crops, wind is important as a regulator of evapotranspiration and as a modifier of canopy structure. While agricultural crop models will tend to capture evapotranspiration effects, morphological influences are usually

regarded as being unimportant and are not explicitly modelled. The occurrence of a relatively continuous moderate wind is advantageous for the control of virus diseases in crops such as potato (Mercer et al., 2004), but such issues are very difficult to capture in a meaningful way by most modelling exercises. Wind can have both positive and negative influences on production livestock. In areas with cold stress, wind amplifies the problem, particularly for young animals. When heat stress is a problem, wind can effectively raise the temperature at which production declines by increasing heat loss from the animal. It has been stated that wind is the most important weather variable influencing forestry in western Europe (Ní Dhubháin and Gardiner, 2004), causing physiological, morphological and anatomical impacts. The impact of infrequent and quite short-term storm events will be quite different from that of long-term continuous wind. Short-term high wind speeds cause windthrow, while long-term continuous wind (in the range of $7\text{--}15\text{ m s}^{-1}$) can cause deformation and stunted growth. In areas where soil is poorly structured and dominated by silt or fine sand, continuous wind above 10 m s^{-1} can cause erosion to occur. Consideration should be given to whether such environmental consequences are likely to be important in a given region when designing a modelling experiment for impact assessment.

The most important question to ask when assessing climate change impacts is whether it is necessary to capture wind effects and if it is, whether this can be done reliably. The question relates to the two types of impacts: short-term high winds (such as hurricanes, tropical storms, tornadoes), and long-term changes in the wind climate (such as a progressive but slight increase or decrease in mean wind speed or a change in wind direction distribution). For situations where wind will affect drying rates and soil water content, which in turn will influence crop production and demand for water, wind climate must be considered, but might be captured in terms of a change in evapotranspiration rates. Where wind might have a devastating effect (for instance, in monsoon regions and the Caribbean) it is necessary to at least interpret the results of crop models in terms of the likelihood of a complete loss of crop output.

8.6.3.4 Photosynthetically active radiation

Photosynthetically active radiation (PAR) is that proportion of solar radiation (about 50 per cent) which actively drives photosynthesis (wavelengths between 0.4 and $0.7\text{ }\mu\text{m}$). Monteith (1977) established that biomass growth could be expressed as

a function of PAR, the fraction of PAR intercepted by foliage (fPAR), the radiation use efficiency of the plant (RUE) and time. Most models driven by weather data require an estimate of either incident solar radiation (usually expressed in terms of energy per unit area per unit time) or sunshine hours (for conversion using a suitable empirical formula) in place of a PAR value. In terms of photosynthesis it is actually the number of photons per unit area per unit time that is important because all photons in PAR have a similar ability to drive light reactions in photosynthesis (Finkle et al., 2004). The main issue to consider when simulating climate change effects causing changes in PAR is whether the plant is growing in conditions of saturated irradiance. If the plant remains in saturated conditions, a change in PAR will not have any effect; if PAR decreases to the point that the plant photosynthesis becomes related to photon flux density, however, it will be necessary to capture this in the simulation model. The nature of the relationship between photon flux density and photosynthesis and the amount of energy required for photosynthesis is specific to plant type (particularly C_3 vs. C_4) and cultivar. For intensively managed monoculture crops and forages, there is little need to consider plant competition for light with climate change, but for agriculture that is currently sustained by (semi-)natural ecosystems, changing plant competition for PAR may be very important, as might interactions with CO_2 and nutrient and water availability.

8.6.3.5 Elevated CO_2 effects

It is widely recognized that elevated atmospheric CO_2 will have a “fertilization” effect, increasing crop biomass and possibly crop yield, but not necessarily crop quality. Climate change impact modelling must take account of these effects and preferably what is known of CO_2 interactions with other factors. The direct effects of increased atmospheric CO_2 concentrations on plant productivity are substantial. In ideal conditions, photosynthesis can increase by 30–50 per cent for C_3 plants and by 10–25 per cent for C_4 plants (Ainsworth and Long, 2005). Such increases are not readily translated into crop productivity, however. In the real world, soil conditions, nutrient availability, pests and diseases, and competition from weeds and other crops render yields much reduced from these figures. Experiments with food crops growing in enriched CO_2 chambers suggest that doubled CO_2 concentrations boost wheat and rice yields by 10–15 per cent and potato yields by 30 per cent (Derner et al., 2003). Grasslands show an increase of 15–20 per cent in productivity (Nowak et al.,

2004). Similarly, positive results are obtained for many forest crops, especially many commercial species, if fertilizers are used (Wittig et al., 2005). It is interesting to note that many potential biofuel crops, such as miscanthus and willow, also thrive under enhanced CO_2 concentrations (Veteli et al., 2002). Less confidence exists that any increases in crop yields will automatically be translated into increases in nutrient quality, and some experiments suggest that reductions in mineral nutrients and protein content may occur (Wu et al., 2004).

It is estimated that yields for many crops will increase by the period 2010–2030 (CSCDGC, 2002), with a projected boost in rice yields of 15 per cent, and figures of 19 per cent for cotton, 15 per cent for wheat, 8 per cent for maize, 8 per cent for beet, and 12 per cent for tomato. On average a 17 per cent increase in yield across all crops might be expected when atmospheric CO_2 reaches 550 ppm (Long et al., 2004), which is possible before 2050 (IPCC, 1992). Such a simplistic approach to impact modelling is, however, unacceptable for situations in which the resources are not intensively managed, most specifically for open and rangeland grazing. In these situations the elevation of atmospheric CO_2 is likely to cause changes in the quality of food available to grazers (for example, in protein content) and the types of food (changes in plant communities) (Ehleringer et al., 2002). While major impacts such as thermal stress and drought are likely to overshadow a CO_2 influence on plant communities in tropical, semi-arid and Mediterranean climates, a change in plant communities and food quality may need to be captured when modelling extensively managed grazing systems in temperate situations. Changing plant community interactions will probably extend to pests and diseases and the interaction of elevated CO_2 and warmer temperatures will probably result in greater crop loss due to these factors (for example, in Stacey and Fellows, 2002).

Irrespective of the theoretical benefits of CO_2 for agriculture and bioresources, the secondary influences of climate change, namely temperature and precipitation change, will frequently be counter-productive. The extent to which these secondary influences will negate the positive direct influences of CO_2 fertilization is not at all clear, however, and further research is necessary to establish which influence dominates yield outcomes. The result is also likely to vary spatially, as well as for specific crops and management practices. Certainly, higher temperatures will extend the growing season in mid-latitudes, and signs of this are already apparent (Sweeney et al., 2002). Higher

temperatures will also increase substantially the potential crop yields in high mid-latitude locations and permit the agricultural margin to move to higher altitudes. Frost damage will be substantially reduced at some locations (Howden, 2003). Greater warmth in summer may also induce greater heat stress.

8.7 **ASSESSING THE EFFECT OF CLIMATE CHANGE ON BIORESOURCE INDUSTRIES**

A standardized approach for climate change impact assessment has been defined by IPCC (Parry and Carter, 1998; IPCC, 2001). It is probably best for most impact assessments to be based on these types of defined formats. Other approaches have been used in the scientific literature, however. There are a number of issues that need to be considered when examining the impact of climate change. These can be grouped under the following headings:

- (a) Spatial resolution – do you want to address issues on a regional, national, catchment or farm scale? At larger scales there is little point in choosing an approach that requires detailed model parameterization and vast amounts of data for testing and running the models. At smaller scales there is little point in using very detailed system simulations if they are not very sensitive to climate drivers and there are only poor climate data available for the simulation site. Care must also be taken when crossing scale boundaries if generalizing or becoming more specific in the interpretation of the results.
- (b) Temporal resolution – do you have suitable data to work at daily, weekly or monthly time steps? Is the time step appropriate for the types of impact envisaged for the system and to drive suitable models? Evidence suggests that predicted impacts are less severe when coarser temporal resolution data are used (for instance, in Carbone et al., 2003; Doherty et al., 2003), but if finer resolution data are not directly available, care must be taken to assess the uncertainty associated with data manipulation. If the expected responses are very time-dependent (for example, changes in timing and rate of change of growth during crop development), then finer temporal resolution data (for example, daily) will be needed. A simulation model that requires sub-daily time-step weather data will probably not be suitable for climate change impact assessment due to the uncertainty associated with moving from GCM to RCM/statistically downscaled data to achieve the fine temporal resolution.
- (c) Uncertainty – how certain can one be about the results of climate change impact studies? There is a cascade of uncertainty (Figure 8.4) associated with the process of assessing impact on agriculture; it starts with the GCM, progresses through the regionalization (RCM or statistical downscaling), feeds into the components of the yield or system model that is used (soil, plant, water and nutrient modules may interact and have different sensitivity to the main climate drivers), and finally influences the interpretation in light of the regional policy, social, political, infrastructure and economic framework. As the impact assessment becomes more quantitative and the models used become more complex, the uncertainty becomes less clear. It is necessary to choose tools for impact assessment that capture the essence of the systems of production in the region but do not require undue levels of detail in order to run the models.
- (d) Sensitivity – how sensitive is the model to the climate drivers? Most modellers will assess overall model sensitivity to input variables as part of the process of undertaking a modelling exercise. For complex system models, it is desirable to evaluate the sensitivity of each major component or module in order to understand how the model sensitivity may influence the interpretation of the results. For example, if a model is used that has a plant development component that is very sensitive to weather data, but a soil component that is not, the predicted impacts of water supply may be biased. For climate change impact assessment, it is important that the model be insensitive to less important parameters and variables, particularly those for which data are not readily available.
- (e) Socio-economic environment/trade buffers – consideration must be given to the framework in which the results are to be assessed. An increase/decrease in yield will be regionally important only if the region being assessed is very dependent on agriculture as a source of income and alternative crops cannot be found, if the region lacks food security and cannot import or grow substitutes, and if the product does not grow in any other region.
- (f) Adaptation options – after the impact of climate change on agriculture for a specific region or crop type is evaluated, the logical follow-up is to consider the adaptations that

are possible. There are a number of ways of doing this, ranging from using simulation models to expert knowledge. Adaptations can be viewed at a range of scales (global, national, regional, local, farm) and in terms of strategic adjustments and tactical adjustments (examples are presented in Table 8.1).

8.7.1 A proposed action plan for climate change impact assessment

Following this review of the necessary issues for the planning of a climate change impact study, the series of questions detailed in Table 8.2 provide a route towards a suitable plan of action. These questions require detailed consideration in light of local knowledge and data availability. Initially, the most important question is whether a study has the capacity to access and manipulate global climate model data in a manner meaningful for the intended impact assessment. Even if global climate model data can be accessed, this does not mean that the data are automatically going to be useful for impact assessment if the region has a number of distinct agroclimatic zones that need to be considered. If qualitative or semi-quantitative approaches have to be used, then significant work may still be undertaken that can be of value to end-users. It is very important that the results of the assessments

undertaken are interpreted and presented in a manner useful for the end-user.

8.8 CLOSING OBSERVATIONS

This chapter should provide a good starting point for undertaking a climate change impact assessment. It provides information on concepts that have to be considered during the planning stage, sources of information and data, modelling tools and other concepts for estimating impacts, and a structured framework for developing the process. These ideas are, of course, somewhat transitory in that current thinking in this area is rapidly evolving. Consultation with the latest Intergovernmental Panel on Climate Change (2007) publications and the academic literature is essential prior to commencing any impact assessment exercise in order to evaluate what is already known and to establish the state of the art with regard to approach and methodology. Once this has been done, the type of study undertaken will be dictated by the quality and resolution of climate forecast data and the availability of field data in the region for model parameterization, calibration and testing prior to making impact forecasts. Provided that a structured and planned approach is taken and data are interpreted in light of stated assumptions and limitations, useful results should be produced.

Table 8.1. Examples of potential agricultural adaptations to climate change at various scales

Scale				
Global	National	Regional	Local	Farm
Shifting centres of production	– Land allocation		– Type of farming	
	– Labour supply/demand		– Rotations	
	– Balance of food and non-food crops		– Crop “mixes”	
	– Policy to support farm-level adaptations		– Balance of cash vs. food crops	
			– Water management	
				– Variety selection
				– Animal breed
				– Timing of activity
Plant and animal breeding for heat and drought tolerance				– Water conservation

Table 8.2. Questions to ask as a route towards developing a climate change impact assessment project

<i>Do you have global climate model data for your region and a means to use them?</i>		
NO (1)		YES (1)
(a) Estimate climate change impacts from available global and regional map data, considering: temperature, precipitation, PAR, wind and CO ₂ elevation expected for the forecast time period.	Can you downscale to a finer resolution using regional climate models or statistical downscaling (do you have the tools and ground truth data available)?	
(b) Collate information on climate, policy, trade, social and economic factors.	NO (2)	YES (2)
(c) Define a series of forecast scenarios and define a series of response envelopes within which current production systems can continue to function.	You must be aware that quantitative predicted impacts can be less when using coarse-resolution climate data (e.g., Carbone et al., 2003; Doherty et al., 2003). A computer modelling experiment can be undertaken but should run in parallel with a qualitative/semi-quantitative analysis.	(a) Consider whether to use output from a single GCM or a range of models; how many emission scenarios? Compile climate data and derive daily values as needed by the simulation models chosen (downscaled output or stochastically from monthly mean values).
(d) Make qualitative and semi-quantitative estimates of the types of impacts that might occur.	Proceed using a suitable combination of steps from N(1) and Y(2).	(b) Collate information on climate, policy, trade, social and economic factors.
(e) Do the future scenarios evaluated suggest that current production systems remain within the response envelope?		(c) Define forecast scenarios and a series of response envelopes within which current production systems can function. Define optimization rules for finding the best system (this will be necessary if considering more detail than a primary yield response). Define the scope of the study.
NO: What other options are there? Go back to step N1(c) and evaluate them.		(d) Design a simulation experiment to evaluate the climate change impact. An iterative process may be a good idea. Consider factors such as: parameterization, calibration, testing, availability of data, sensitivity analysis, cascading uncertainty (Figure 8.4). Try to capture the range of possibilities in the region, commence with a generalized approach and develop specificity. Evaluate what can be left out and omit as much as possible. Some factors are perhaps best dealt with qualitatively.
YES: Will production be sustainable?		(e) Select a suitable model – use the simplest possible model that captures the system function. Test model sensitivity for properties lacking quantitative parameter values.
NO: What other options are there? Go back to step N1(c) and evaluate them.		(f) Quantify the impacts as the difference between a standard baseline (1961–1990) and the forecast period. Evaluate whether the response is a significant signal with respect to the model sensitivity, any uncertainties that can be identified and natural variations.
YES: Continue. Publicize the results. Alert farmers and producers in the region if adaptation is necessary, provide information to policymakers to ensure a sustainable production environment is fostered for the future.		(g) Evaluate the impacts with respect to the defined forecast scenarios and envelopes of response. Do the future scenarios evaluated suggest that current production systems remain within the response envelope? NO: What other options are there? YES: Will production be sustainable? NO: What other options are there? YES: Continue. Publicize the results. Alert farmers and producers in the region if adaptation is necessary, provide information to policymakers to ensure a sustainable production environment is fostered for the future.
What adaptation will be required?		

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CHAPTER 9

APPLICATIONS OF METEOROLOGY TO AGRICULTURE

9.1 INTRODUCTION

The application of meteorology to agriculture is essential, since every facet of agricultural activity depends on the weather. This chapter discusses many examples of the usefulness of applied meteorology in order to make users aware of the potential benefits that farmers can gain to improve efficiency and ensure sustainability of their farm management; to protect and ensure the continuing health of their crops, livestock and environment; to increase their yield and the market value of their crops; and to solve selected operational problems. Other agricultural decision-makers derive benefit from agrometeorological applications, including government policymakers seeking to ensure adequate food supplies, affordable food prices for consumers and sufficient farm income for farmers, and to reduce the impact of agricultural practices on the environment. Decision-makers in international agricultural organizations also use applications of meteorology to ensure food security and to react to potential famine situations. At any level, these objectives can be achieved only through active cooperation among National Meteorological and Hydrological Services (NMHSs), agricultural extension services, farmers and their associations, agricultural research institutes, universities and industry.

The topics discussed in this chapter are based on a classification of applications of micrometeorology to various agricultural problems given in WMO Technical Note No. 119 (WMO, 1972). They are grouped according to the general type of problem, namely, improving production; averting dangers to production; physiology and growth; strategy; and tactics. These main topics were retained for this edition of the Guide and only the subtopics have been modified depending on recent applications. The physiology and growth topics for specific crops are covered in Chapter 10.

The main objective of this chapter is give to brief overviews and examples of applications at the local or farmer level. There are also important applications that will be discussed at the government or international organization level, however. In selecting the examples of applications of meteorology to agriculture, priority has been given to those that are used operationally. Also, an attempt has been made

to cite examples for the different climates and regions of the world.

9.1.1 Users of agrometeorological information

The successful application of weather and climate information needs to integrate three components: data, analysis and users. Therefore, the ultimate goal of any application is to serve the needs of the users. A solid foundation of data is a prerequisite for successful agricultural meteorological applications (see Chapters 1 and 2). Then an analysis of these data that seeks to solve or address an agricultural problem is needed. These analyses are described in this Guide. Ultimately, the users of agrometeorological information and applications must be kept in mind when developing new applications. The user can be defined as any agricultural decision-maker such as a farmer, extension agent, government official, media person or the general public. Rijks and Baradas (2000) provide an overview of clients (users) of agrometeorological information. They discuss who the clients are, what they require, what products agrometeorological services can offer, and how to approach clients and assess the value of the product.

9.1.2 Temporal and spatial scales of agrometeorological information and applications

Agrometeorological information and applications can be considered in temporal and spatial contexts. In a temporal context, strategic applications are defined as those aiding in issues and decisions that are assessed on a seasonal or yearly basis or only once, such as in a planning process. These applications aid in the planning process whether the decision is choosing a specific crop variety to plant, if an area should be exploited for forage products and livestock, how to design and plan where or if greenhouses or animal shelters should be built, or how to assist governments in setting agricultural pricing policies. Such decisions can be based on climatological analyses, agroclimatic information, and the use of complex soil-plant-atmospheric models. Tactical applications are considered to be short-term operational decisions relating to a period ranging from a few hours to a few days. These often involve decisions, based on the state of the crop

and current or forecast weather, for such farm operations as cultivating, irrigating, spraying and harvesting.

Agrometeorological Aspects of Organic Agriculture, Urban Agriculture, Indoor Agriculture and Precision Agriculture (WMO, 2003) provides a good description of macroclimate and mesoclimate in the context of agrometeorological applications. Macroclimate is the largest and covers broad areas of a continent (millions of square kilometres), and deals with the interaction of large-scale topography (mountain ranges, large lakes and ocean influences) with airmasses. At this scale, climate characteristics should provide information on the suitability of a farm and whether the farm could be weather-limited by pest, disease and operational timing problems. Mesoclimate reflects the farmer's view of the weather experienced in a region. Local surface features such as hills, small mountains, large forests or extensive plains have a distinct effect at this scale. A country may have one or two macroclimate zones, but it will have many mesoclimates. It is at this scale that specific calculations can be made to define agroclimatic regions.

At the smallest scale, microclimate is defined by Rosenberg et al. (1983) as the climate near the ground, or in other words, the climate in which most plants and animals live. In terms of meteorology, *The Application of Micrometeorology to Agricultural Problems* (WMO, 1972) describes micrometeorology as dealing with the physical processes taking place within the boundary layers between the top of the plant, tree or animal and the bottom of the roots of the soil. Most of the applications in this chapter are based on micrometeorological principles.

A monograph by Gordeev et al. (2006) presents the results of an assessment of the bio-climatic potential in the Russian Federation, surrounding countries, Europe and the United States. Particular attention is given to climatic and agroclimatic peculiarities in these territories in relation to solving certain social and economic problems.

9.1.3 **Benefits derived from applications**

Many benefits result from the application of meteorological services to agriculture. The productivity of a region or of a particular enterprise may be increased by the reduction of many kinds of loss resulting from unfavourable climate and weather, and also by the more rational use of labour and equipment. Greater economy of effort is achieved

on the farm, largely through a reduction in activities that have little value or are potentially harmful. All of these increase the competitiveness of production, reduce risk and help to lower the cost of the final products.

In the developed world, a significant portion of recent work in agricultural meteorology has shifted from increasing yields to reducing the environmental impact of agricultural fertilizer and pesticide use and combating pests and diseases. In the developing world, much of the focus remains on increasing agricultural production, but there is also an emphasis on sustainable agricultural production and reducing the impact of diseases and pests such as desert locusts.

The following are brief examples of economic benefits of agrometeorological applications from Rijks and Baradas (2000). In Sudan, precise calculations of water requirements for the main irrigated crops (cotton, sorghum and groundnut) were compared with available irrigation water to allow for more accurate estimates of potential irrigated wheat area. The net result was an additional 8 000 ha of wheat grown, which added more than US\$ 2 million to the national economy at a cost of a few thousand dollars for data, analysis and staff. In the Gambia, groundnuts are stored in the open air and if the dry pods become wet, they are at high risk of developing aflatoxin, which can reduce farmer prices for the crop by up to 60 per cent. If farmers are warned of rainfall by forecasts transmitted via local radio, they can cover the crop with plastic sheeting. It is estimated that for each percentage point of production saved, the benefit is US\$ 60 000. In the Sahel, bush fires are common every year, but the bush vegetation is needed for cattle and sheep grazing. By using wind, temperature and humidity observations to indicate speed and direction of the fire, controlled burning can take place to prevent the fires from spreading. Reducing the burned area on 1 per cent of the grazing land allows 5 000 more sheep to graze, which represents an additional annual value of US\$ 100 000 to the national economy. A WMO report on meteorology and plant protection (WMO, 1992a) provides a framework for analysing costs and benefits of agrometeorological applications in plant protection.

The results of studying the peculiarities of climate and weather conditions to optimize various cultural practices (namely, determination of an advisable structure of areas under crops, dates and methods of soil treatment, optimum fertilizer application periods and doses) aimed at boosting the

productivity of plants growing in Russia, can be found in several papers by Fedoseev (1979, 1985). The economic efficiency of applied agrometeorological recommendations is given.

Other examples can be found in *The Economic Value of Agrometeorological Information and Advice* (WMO, 1980a) and in materials from a conference on the economic benefits of meteorological and hydrological services (WMO, 1994b).

9.2 APPLICATIONS FOR GOVERNMENTS AND OTHER LARGE ADMINISTRATIVE BODIES

Governments and other large administrative bodies need high-quality and reliable information for operational assessments of agricultural production. With regard to planning, this would involve questions about what kind of crops the country could produce economically and where they could be grown. Planning questions of this nature can be answered by macro- and mesoscale agroclimatic surveys.

9.2.1 Operational assessments

There are several examples of operational assessments of crop production that countries and international agencies perform. These examples highlight the utility of integrating data, staff and resources to produce reliable crop production assessments among different agencies at a country level and among different countries, non-governmental organizations (NGOs), and other organizations at an international level, as well as the need to do so. Boken et al. (2005) provide many examples of successful drought monitoring and crop monitoring applications at these levels.

The Food and Agriculture Organization of the United Nations (FAO) established the Global Information and Early Warning System (GIEWS) in 1975 in response to the global food crisis of the early 1970s. GIEWS provides information on food production and food security for every country based on crop monitoring assessments that involve remote-sensing and ground-based weather station data (Mukhala, 2005). A number of these assessments are based on the FAO Crop Water Requirement Satisfaction Index (WRSI) model that determines a cumulative water balance for 10-day periods from planting to maturity. The WRSI model is a combination of dynamic water balance and statistical

approaches and the index represents at any time of the growing season the ratio between the actual and potential evaporation.

The World Agricultural Outlook Board (WAOB) of the United States Department of Agriculture (USDA) is mandated to provide official monthly United States Government forecasts of agricultural commodities through the World Agricultural Supply and Demand Estimates (WASDE) publication (Motha and Stefanski, 2006). These supply and demand estimates are based on official country reports, United States embassy reports, travel reports of USDA personnel, economic analysis, remote-sensing information and, of course, global weather information. USDA meteorologists routinely collect, monitor and analyse global weather conditions and agricultural information to determine the impact of growing-season weather conditions on crops and livestock production prospects. These activities are supported by meteorologists from the United States National Weather Service who are located within WAOB offices to serve the agricultural community (Puterbaugh et al., 1997; Motha and Heddinghaus, 1986).

Rusakova et al. (2006) describe the application of an automated Russian forecasting system that allows for the presentation of information about observed weather conditions, state of crops, crop yield forecast and the total harvest in the various regions of Russia. Comprehensive application of climatic and weather information at the governmental and field levels is demonstrated with the Russian information and advice system meant for resolving some practical problems in the planning and organization of agricultural production (Zhukov et al., 1989).

In Brazil, several centres generate daily updated agrometeorological information to support decision-making, including Agritempo (<http://www.agritempo.gov.br>), which provides information for the whole country, and regional centres such as Cepagri/Unicamp (<http://www.cpa.unicamp.br>) and IAC (<http://www.ciiagro.iac.sp.gov.br>) for the state of Sao Paulo, IAPAR/SIMEPAR (<http://www.iapar.br/sma>) for the state of Parana, and Ciram (<http://www.chlimerh.rct.sc.br>) for the state of Santa Catarina. Farmers' cooperatives also provide agrometeorological information to their farmers and field technicians (for example, <http://www.fundacaoabc.org.br>) (Pinto, personal communication).

Other examples include the Famine Early Warning System, or FEWS (Rowland et al., 2005), the

European Union's Monitoring Agriculture with Remote Sensing (MARS) (Negre, 2006), the National Agricultural Monitoring System (NAMS) in Australia (Leedman, 2007), the Farmweather service (WMO, 2004) and agrometeorological services in Kazakhstan (WMO, 2004).

9.2.2 Agroclimatic surveys

Concerning macroscale agroclimatic surveys, the joint inter-agency project on agroclimatology sponsored by FAO, WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) has been very successful in producing five publications and is the foundation of current agroclimatic zoning studies. The most important practical applications of macroclimatic surveys include: choosing crops, varieties and domestic animals; determining favourable periods for sowing, haymaking and harvesting; establishing areas where dryland farming is possible and where irrigation has to be applied; planning afforestation and reforestation; finding the optimum range of climatic variables for increasing yields and agricultural production in general; establishing potentials for the agricultural use of rangelands; and determining requirements and potentialities for efficient storage and transportation of crops.

The agroclimatology in the semi-arid and arid zones of the Near East has focused on the estimation of the boundary areas where dryland farming is possible and where irrigation is needed (WMO, 1963*e*). The agroclimatology of semi-arid areas in West Africa has dealt with dryland farming in West Africa and the length of growing seasons, which is strictly associated the rainy season (WMO, 1967). The agroclimatology of the highlands of eastern Africa has focused on which crop water requirements are met in the various localities of this area (WMO, 1973). The agroclimatology of the Andes has looked at the unique effects of high elevation and high solar radiation input on crops (WMO, 1978*a*). An agroclimatology survey of the humid tropics of South-East Asia (WMO, 1982) illustrates the role of agroclimatology in determining strategies to increase food production in the humid tropics.

9.2.3 Mesoscale agroclimatic surveys

With the advent of widespread computing capability (personal computers) and Geographical Information Systems (GISs), climatic and agroclimatic mapping has become widespread. There are many examples of the use of these methods for climatological and agroclimatic analyses. The

European Union-sponsored European Cooperation in Science and Technology (COST) Action 719 on the Use of Geographic Information Systems in Climatology and Meteorology provides several examples of these agroclimatic mapping methods, including temperature mapping, climate parameter mapping in mountainous areas, and an agroecological decision system (Dryas et al., 2005). The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) has been used to map daily weather and climatic parameters in mountainous areas (Hunter and Meentemeyer, 2005; Daly et al., 1994).

Zoidze and Ovcharenko (2000) assessed the agricultural potential of climate in the territory of the Russian Federation and some of its regions for each crop, based on general indices of heat and water supply, radiation regime, unfavourable agroclimatic phenomena, soil fertility, and relief essential to develop strategic and tactical agricultural policies in different regions. These authors also reviewed measures to optimize environmental conditions.

Motroni et al. (2002) focused on the development of a methodology to assess climatic and agroclimatic risks. Land capability was classified for Sardinia by using climate, geographic and soil data. A climatic risk index was computed on the basis of 30-year averages of climatic data.

Petr (1991) described a mesoscale agroclimatic classification scheme for Czechoslovakia based on a hydrothermic coefficient, $HTC = R/(0.1TS_{10})$ where R is the rainfall sum in millimetres and TS_{10} is the degree-days above 10°C. Such an approach could be used with any degree-day base temperature and adapted for specific crops.

In Brazil, there have been recent nationwide efforts in agroclimatic risk zoning for agricultural crops that characterizes the potential and climatic risks for several crops, including maize, soybeans, beans, wheat, barley, rice, cotton, coffee, cassava and different species of fruits (Pinto, personal communication). The recommendations are used by the Brazilian Government to provide financing to the farmers at very low rates. Furthermore, those who follow the recommendation of the agricultural zoning can obtain official insurance at special rates. To be eligible for the bank credit, the farmers must also adopt the best agronomical practices recommended by the extension service. These efforts, combined with farmers' use of optimum planting dates, have increased the productivity of Brazilian agriculture (Pinto, personal communication).

9.3 APPLICATIONS FOR FARMERS OR GROUPS OF FARMERS

9.3.1 Improvements to production

As stated in the introduction, the original topics were based on a classification of applications of micrometeorology to various agricultural problems in WMO Technical Note No. 119 (WMO, 1972).

9.3.1.1 Irrigation

In its broadest terms, irrigation involves water balance calculations based on rainfall, estimation of water infiltration (effective rainfall), runoff, evapotranspiration (ET) and soil moisture. There are several reliable direct measurements for soil moisture, such as those obtained using manual gravimetric and neutron probe methods, which are suitable for routine application in agricultural practice (see Chapter 2). Indirect measurements based on remotely sensed information are also possible (see Chapter 4). Early irrigation and soil moisture applications can be found in HMSO (1967), Baier and Robertson (1965) and WMO (1958, 1968*b*). Over the years a great deal of attention has been given to irrigation issues, especially measuring and estimating evapotranspiration. A number of textbooks provide good overviews of this subject, including Rosenberg et al. (1983).

Smith (2000) provides a survey of the widely accepted practical procedures that have been developed by FAO et al. to estimate crop water requirements and yield response to water stress. The methodologies of crop water requirements were first published in 1974 as FAO Irrigation and Drainage Paper No. 24, and they were revised in 1977 (FAO, 1977). A review and update of the methodologies are contained in FAO Irrigation and Drainage Paper No. 56, which deals with crop evaporation (FAO, 1998). These methodologies use the Penman–Monteith equation, which estimates daily reference crop evapotranspiration (mm/day) based on net radiation, soil heat flux, average air temperature, wind speed, vapour pressure deficit, and other humidity parameters. The two publications listed above give details on estimating all these parameters based on weather and climate data and when data sources are limited. The FAO CROPWAT software program incorporates these methodologies and procedures to simulate crop water use under various climate, crop and soil conditions. This software is available from FAO at http://www.fao.org/nr/water/infores_databases_cropwat.html.

A report published by the WMO Commission for Agricultural Meteorology (WMO, 2000*b*) describes several operational applications to increase water use efficiency, including an irrigation advisory system in Israel calculated on the basis of a modified Penman potential ET equation. The same report contains a paper describing the Irrigation Planner, which has been developed into a computer software application for irrigation of grassland in the Netherlands (WMO, 2000*a*). Results show that using the system can reduce irrigation water by 15–20 per cent.

Kroes (2005) provides an overview of the soil–water–atmosphere–plant (SWAP) model, which integrates water flow, solute transport and crop growth. The SWAP model can be used at the local scale by farmers and extension agents for irrigation demand, potentials and strategies. At the regional level, it can be used by policymakers for spatial and sectoral irrigation strategies.

Venäläinen et al. (2005) used numerical weather forecast model data to model soil moisture for input into irrigation models. Potential evaporation was calculated using the Penman–Monteith equation based on data from a high-resolution, limited-area model. The data were input into the AMBAV and SWAP irrigation models.

9.3.1.2 Shelter from the wind

WMO Technical Note No. 59 (WMO, 1964) and Chapter 9 of Rosenberg et al. (1983) deal comprehensively with windbreaks and shelterbelts; van Eimern (1968) discusses problems of shelter planning. Grace (1977, as cited by Rosenberg) provides an overview of the direct influences of wind on plant growth.

Rosenberg et al. (1983) define windbreaks as structures that reduce wind speed, and shelterbelts as rows of trees planted for wind protection. Both of these can reduce physiological stresses on plants and animals due to wind. Rosenberg and his co-authors reviewed the literature and found that shelter effects on the microclimate include reduced potential and actual evapotranspiration; improved internal plant water relations (greater internal water potential and lower stomatal resistance); improved opportunity for photosynthesis; and finally, a general increase in yield as a result of shelter. These generalities are subject to variation depending on soil moisture, and the benefits may be most dramatic in dry years or under critical moisture shortages. Examples of the widespread use of windbreaks

can be seen in the Great Plains in the United States after the Dust Bowl years of the 1930s (Rosenberg et al., 1983), the Rhone Valley in south-eastern France and the Netherlands (van Eimern, 1968). Marshall (1967) has reviewed the literature on the effect of shelter on the productivity of grasslands and field crops, and showed how the proportional decrease in wind speed with distance from the shelter corresponds to a decrease in evaporation. Night-time temperature decrease, relative humidity and the increase in daytime air and soil temperatures vary with distance from the barrier, but decline to no effect at a distance of about 12 times the height of the shelter. In connection with these parameters, the greatest soil moisture availability and crop yield are found in the zone at a distance of 2 to 4 times the height of the shelter.

Windbreaks reduce the force of the wind in the sheltered zone. WMO Technical Note No. 59 (WMO, 1964) shows that a dense barrier may protect an area about 10–15 times the height downwind, and by increasing the porosity of the barrier to about 50 per cent, the downwind influence can be increased to 20–25 times the height. Rosenberg et al. (1983) state that for the best wind reduction and greatest downwind influence, the windbreak should be most porous near the ground and the density of the barrier should increase logarithmically with height in accordance with wind speed profile. Wind reduction is a function of shelter location as well as the height above the plants. Questions of orientation and spacing of shelter can be regarded as meteorological applications, particularly if mesoclimatic wind surveys are used in advance.

9.3.1.3 Shade

Shelters of various types can also be used to provide shade from the sun; a well-known example is the use of taller-growing “shade trees” to protect cacao, coffee or tea plants.

Agrometeorology of the Coffee Crop (WMO, 1994a) states that because coffee originally developed as an understorey shrub in the rain forests of central Africa, it might be assumed that shading or arborization of coffee trees is a well-defined cultural practice. There has been much discussion on the validity of this practice, however. Most of the commercial crop in Brazil is unshaded, while shading is a common practice in Colombia, Costa Rica, El Salvador, Guatemala, Uganda, Tanzania and in the higher-elevation areas of North-east Brazil. In most of Brazil, an

unshaded crop facilitates the harvesting and natural ground drying of the crop as the microclimate is sunnier, and hence warmer and drier. In most places, coffee berries are hand-picked at the cherry stage, and if this stage is extended it provides for an easier and longer harvest period. Therefore, shading can be advantageous since it increases the cherry stage of the crop because the microclimate is cooler and moist, which slows the maturation process. Shading also aids in maintaining high soil organic matter. This publication (WMO, 1994a) also cites several characteristics of good shading trees and several other advantages and disadvantages.

Shelters may also be used to reduce production losses from lactating dairy cows because of the heat load during the summer (Hahn and McQuigg, 1970).

9.3.1.4 Greenhouses (glass and plastic)

Greenhouses have been used in temperate climates for over 100 years and serve mainly to reduce heat loss and permit complete control over the watering of plants. Recently, CO₂ enrichment of the atmosphere has become an additional technique in greenhouse cultivation. A detailed discussion of greenhouses is presented in WMO (1974a) and WMO (2003).

A WMO publication on agrometeorological aspects of various types of agricultural activity (WMO, 2003) discusses many benefits derived from indoor agriculture (greenhouses): protection against damage by ultraviolet (UV) light; improved ambient temperature conditions; protection of crops from adverse climatic conditions; increased productivity; reduced production costs; controllable harvest; and better product quality. They also list several climate elements that must be managed for good performance from greenhouses. The covering of the greenhouse is important with regard to visible light transmission for plant photosynthesis. Knowledge of the climatology of a greenhouse site, including solar radiation, cloudiness, relative humidity, temperature and wind profiles, is important.

Turning to construction materials, most greenhouse coverings are made of glass, fibreglass and plastic, while plastic agricultural tunnels are less widely used (WMO, 2003). In order to choose the best covering suited to a geographical location, the maximum, minimum and average temperatures; the possibility of frost; the climatology of the wind and relative humidity, rainfall distribution and

intensity; solar radiation; and specific crops need to be taken into account.

A climatological analysis of solar radiation, temperature and relative humidity is important for siting greenhouses. These parameters will determine how much internal environmental control will be needed for optimum plant growth depending on the plants grown. Wind speed and direction are very important factors when designing a greenhouse. High winds could damage the structure or coverings. Wind is also used in simple greenhouse designs to maintain the thermal balance by reducing energy costs for heating or cooling. Wind ventilation can be used for balancing internal temperatures by means of air circulation, reducing relative humidity, promoting crop pollination, and replenishing carbon dioxide and removing oxygen for plant photosynthesis.

For some crops the degree of control is such that firm advice can be given on the optimum temperatures for different growth stages (tomatoes are a good example); it is possible to differentiate between the environmental temperatures that should be maintained during the day and during the night. This knowledge has led to the design of "blueprints" for the production of certain crops.

There is scope for further assistance by meteorologists in research on environmental control. Practical help can also be given at the advisory level, in terms of greenhouse siting, design, and fuel consumption. Meteorological factors are probably most useful in siting greenhouses. In analysing possible greenhouse sites, standard radiation data can be adjusted for latitude and mean cloudiness to give an estimate of the radiation input (and therefore plant growth) at each location. Such factors as shelter and radiation must be balanced; highly exposed sites are undesirable because of extra fuel consumption and the risk of physical damage. As for fuel consumption, if a crop requires the temperature to be kept at a given level, the quantity of fuel needed can be calculated from the number of degree-days below that temperature.

9.3.1.5 Ground cover (mulching)

Soil mulches of various kinds (namely, straw cover or artificial materials such as plastics) are used to modify the heat and moisture balance in the soil to benefit plants. WMO Technical Note No. 136 (WMO, 1975*b*) provides a good overview of the effects of mulching on plant climate and yield and states that mulches are particularly useful in conserving moisture, reducing temperature

extremes and minimizing erosion. Chapter 6 of Rosenberg et al. (1983) provides several examples of various mulches used with different crops.

Agrometeorology of the Coffee Crop (WMO, 1994*a*) lists the following advantages of grass-straw mulching with the coffee crop in Kenya: it protects the soil from excessive heating that destroys the soil structure; it lowers temperatures, which results in lower evaporation rates; it provides organic matter to the soil; and it reduces soil erosion from heavy rainfalls and minimizes weeds. It also cites studies indicating that mulching can reduce the frequency of irrigation. On the negative side, mulching requires a large amount of grass, and more importantly, straw mulches can aggravate frost problems as the air temperature above the mulch is much warmer during the day and cooler at night. The mulch also prevents the ground from absorbing heat during the day, which is subsequently released during the night. Studies on the effect of straw mulching on air temperatures indicate that at 5 cm above the ground, the maximum temperature is 6.6°C higher and the minimum is 1.7°C lower than the bare ground (WMO, 1994*a*). Gurnah and Mutea (1982, as cited in WMO, 1994*a*) tested the effect of different plastic coverings on the soil temperature and concluded that on areas subject to frost, transparent plastic should be used and white plastic should be used elsewhere, since it approximately has the same thermal regime as bare soil.

9.3.1.6 Animal housing

Meteorological data are required when assessing whether and how animal housing should be put into use. Evaluation should also take into account the potential economic returns, energy cost and availability (WMO, 1980*d*). Animal housing is utilized because thermal imbalances lead to adverse effects on animal productivity.

Weather and climate can determine the efficiency of livestock production by direct and indirect influences (WMO, 1980*d*). Direct influences affect the heat balance of the animal and include extreme meteorological events. Indirect influences are disease and parasites. Excessive heat or cold increases the metabolic energy required to maintain the animal's body temperature, thus reducing the energy available for productivity. This energy imbalance is usually corrected by increased feed, which entails an additional cost to the farmer. The use of climatological data and analysis is useful in this case. *Weather, Climate and Animal Performance* (WMO, 1980*d*) provides many examples of using weather and climate information

in the application of animal housing. It mentions that siting, external wind, temperature and humidity affect both entry conditions and patterns of internal air movement in environmentally controlled housing. Smith (1964) has shown the importance of the ventilation rate in animal housing, and how it may be estimated by a psychrometric method simple enough to be applied on a farm scale. The siting of animal shelters is also important, particularly in relation to other shelters, as alternating positive and suction pressures may result from nearby obstructions.

9.3.1.7 Storage

For some crops, storage is as important as production and weather may affect the quality of the food product and modify the storage environment, causing loss of product and economic value.

9.3.1.7.1 Fruit and vegetables

The Effect of Weather and Climate upon the Keeping Quality of Fruit (WMO, 1963a) states that the storage life of fruit is terminated by the onset of rotting caused by specific fungi, physiological diseases and senescent breakdown. The rate of development of these storage disorders is determined by storage conditions such as temperature and concentration of CO₂ and oxygen, and by pre-storage treatments. *Agroclimatology of the Apple Crop* (WMO, 1996) states that the maturity of the apple fruit has a major impact on the quality of fruit during storage and that there have been many studies on modelling apple maturity using climatic data.

A WMO survey of operational models for agrometeorological services related to potato production (WMO, 1990b) states that monitoring of the storage environment and weather forecasts are used in many countries to determine the optimum conditions for potato tubers. In the former Czechoslovakia, humidity and temperature data (the mean number of hours exceeding the limits of 3°C, 7°C and 10°C during the winter months) were used for the design and construction of large potato storage facilities. Another WMO report (WMO, 2002) contains a review of the scientific literature on the quality and storage of grapes and potatoes. It cites the most important meteorological parameters for grape quality as temperature and solar radiation and lists several quality models for these crops. Potato storage quality is determined by evaporation, transpiration, respiration and germination.

9.3.1.7.2 Grain

The previous WMO Technical Note on this subject has been revised (WMO, 1990a). Agrometeorology can provide guidance for the construction of grain storage based on local climate modification and environmental control. Stored grain interacts with its environment, exchanging heat and moisture. The level of biological activity of grain and potentially damaging organisms must be minimized. For safe storage, grain must be kept cool and dry, requirements that are affected both by the characteristics of the building or structure for housing and by the external environment. Heat uptake from outside must be minimized while heat loss from storage must be maximized. The moisture exchange between the grain and the external environment should generally lead to a reduction in grain moisture content. When hot dry grain must be cooled to prevent insect infection, the resulting moisture increase must be kept to an acceptable level.

The siting of storage facilities and their design and construction materials can all be influenced by meteorological factors. For example, in hot, dry regions with no refrigeration, there are advantages to storage facilities of high thermal capacity, with air space ventilated at night when the air is coolest. In warm, wet regions with small diurnal temperature ranges, good storage may be difficult to design.

Meteorological factors become more important to the farmer when natural air drying systems are used for grain. In the state of Ohio, United States, for example, best results for shelled corn occur when the climatic conditions provide temperatures in the range of -1°C to 10°C and relative humidities in the range of 60 to 70 per cent (Hansen et al., 1990). In most western Ohio counties, October and November provide high probabilities for good climatic conditions for natural air drying of soybeans and shelled corn.

There is also an impact of weather conditions due to rainfall before storage that can be important. High temperature and rain that occur shortly before harvest are the most important direct weather effects on the quality of spring barley (WMO, 2002).

9.3.2 Averting dangers to production

These dangers may be the direct result of weather (for example, frost) or they may be indirect and carried by biological agents that are affected by the weather (such as pests and diseases that attack plants and animals).

9.3.2.1 Direct weather hazards

9.3.2.1.1 Frost

The occurrence of frost has been studied in detail by many agrometeorologists mainly because of its economic effect on high-value crops, and because some crops can be protected. Some examples were taken from WMO publications (WMO, 1963*d*, 1971) in the previous edition of this chapter. Two WMO publications (WMO, 1978*b*, 1997*d*), Rosenberg et al. (1983), and a more recent FAO report on frost protection (FAO, 2005) provide overviews and examples of protection against frost damage.

Frost-risk maps and dates of first and last frost are simple but useful applications of climate data applied to agriculture. These maps are made at the macro- to mesoscale and are useful for specifying general planting dates for cereal crops and for the assessment of crop damage when combined with phenological data.

9.3.2.1.1.1 Sites

Assessment of potential sites for frost-sensitive crops, especially high-value crops such as tree fruit and coffee, is crucial since it will discourage growers from planting in frost areas. Topoclimatology and local-scale agroclimatic zoning are important tools and methodologies in this regard. An early overview of concepts and some examples are given in WMO (1974*b*). *The Effect of Temperature on the Citrus Crop* (WMO, 1997*b*) describes agrotopoclimatology as being concerned with the local differences in climate arising from topography, soil and vegetation within a uniform macroclimatic zone (this was defined earlier in this chapter as mesoclimate). They show some examples of using topoclimatological analysis to develop maps indicating the probability of frost occurrence over complex terrain. With the increase in availability and speed of personal computers in recent years, applications of this kind have increased (see Chapter 4 on GIS applications). One example uses a spatial interpolation method to determine the spring frost hazard in the hilly areas of French vineyards based on digital elevation data and weather station temperatures (Madelin and Beltrando, 2005).

9.3.2.1.1.2 Protection against frost damage

Rosenberg et al. (1983) describe two kinds of frosts that can affect crops and call for different protection techniques. Advection frost usually occurs

during or after a change in airmass and is accompanied by strong winds (cold front). The number of protection techniques against this kind of frost is limited. Radiation frost occurs under the influence of a high-pressure system and typically the winds associated with this kind of frost are very light. They list the following frost protection methods: site selection, radiation interception, thermal insulation, air mixing, direct convective air heating, radiant heating, release of the heat of fusion and soil manipulation. Most of these methods are effective only against radiation frosts, but some can be applicable to both advection and radiation frosts.

Techniques of Frost Prediction and Methods of Frost and Cold Protection (WMO, 1978*b*) describes many direct (or active) and indirect (or passive) frost protection methods, which are taken from mostly Russian and European sources. Direct methods of frost protection include: protective covers; smoke generation and artificial fogs; open-air heating of plants and areas; irrigation and sprinkling; and mixing air. Indirect methods include: biological methods such as hardening, seed treatment, selection of frost-hardy strains, development of new frost-hardy varieties and regulation of bud development. Ecological methods such as control of mineral nutrition and crop site selection are other indirect approaches.

The FAO publication *Frost Protection: Fundamentals, Practice, and Economics* (FAO, 2005) lists many recommended methods of passive and active frost protection along with detailed practical overviews of each method. It describes recommended passive methods such as site selection, managing cold air drainage, plant selection, canopy trees, plant nutrition management, pest management, pruning, plant and soil covers, soil cultivation, irrigation, removal of cover crops, trunk wraps and painting, and bacterial control. Recommended active methods of frost protection include the use of heaters, wind machines, helicopters, various types of sprinklers, surface irrigation, foam insulation, and some combination of these methods. It also provides a review of critical temperatures for annual, biennial and perennial crops, fruit and citrus trees, grapes, and other small fruits. A companion volume details several practical Excel software spreadsheets that help users to compute the probability that temperatures will fall below critical levels (TempRisk.xls) and the risk of frost damage specific to a crop (DEST.xls), and to determine the economic risk of frost damage protection (FrostEcon.xls).

9.3.2.1.2 Hail

Hail can destroy high-value crops within a short time and many countries have therefore sought to reduce its frequency or to reduce the damage that it causes. *Protection of Plants against Adverse Weather* (WMO, 1971) contains a short summary of the protection methods that involve adding condensation nuclei to hail-forming clouds, by means of missiles or aircraft, with the object of producing small hailstones or soft hail.

Large reductions in hail have been claimed by a number of groups. According to the WMO Commission for Atmospheric Sciences, the weight of scientific evidence to date is inconclusive, neither confirming nor refuting the efficacy of hail-suppression activities. It is recommended that interested parties consult the WMO Statement on the Status of Weather Modification for further information (http://www.wmo.int/pages/prog/arep/wwrp/new/documents/WM_statement_guidelines_approved.pdf).

9.3.2.2 Indirect weather hazards

9.3.2.2.1 Introduction to crop and animal pests/diseases

The application of meteorology to overcome the effects of pests and diseases on plants and animals involves a complete understanding of the complex life cycles of the pathogen and its host, as well as the environmental conditions that influence growth and development. Plant pathologists have developed a disease triangle with host (a susceptible animal or plant), environment (environmental conditions suitable for disease or pest establishment and development), and disease (the presence of the disease or pest) at the different points of the triangle, as depicted in Figure 9.1. These concepts help to describe the situation for virtually all known pests and diseases. All three sides of the triangle must exist for the pest/disease to be established and develop. If one of the sides is missing, then establishment of the pest/disease will not occur. Meteorological factors are very important for the growth and development of the host plant and animal species, for the pest/disease, and the airborne transport of the pest/disease. Orlandini (1996) lists temperatures, solar radiation, precipitation, leaf wetness and humidity, and wind as the major meteorological factors in relation to plant pathology. The duration of leaf surface wetness caused by dew, fog or rain is often a critical variable controlling the germination of disease spores. It must be computed

from standard meteorological data or measured with leaf wetness sensors (Sentelhas et al., 2004).

Meteorology can be applied via observation of temperature, relative humidity and rainfall. More sophisticated applications include numerical weather prediction models for wind direction and speed with regard to the disease or pest (see 9.3.2.2.1 on the desert locust and 9.3.2.2.4.1 on foot-and-mouth disease). For the host or plant food source, temperature can be used for phenological development, rates of infection and disease/pest survival (extreme temperatures). Rainfall is important for host plant and disease/pest development. All of these aspects can then be modelled and used in operational applications for the agricultural decision-maker.

One important use of weather and climate information is in the field of Integrated Pest Management (IPM). IPM strategies include avoiding the use of chemicals unless there is economic damage to the crop. There have been numerous studies and models of the influence of temperature on plant and insect growth and development. Pruess (1983) gives an overview of degree-day methods for pest management.

WMO Technical Note No. 192 (WMO, 1988b) provides many examples of agrometeorological aspects of operational crop protection, including protection against plant diseases, insect pests and weeds; meteorological data requirements; and application of weather forecasts. *Definition of Agrometeorological Information Required for Vegetable Crops* (WMO, 1997a) provides a brief overview of the meteorological factors relating to vegetable pests and diseases. Pedgley (1982) provides a good overview of the meteorology of windborne pests and diseases, accompanied by examples. Sections of

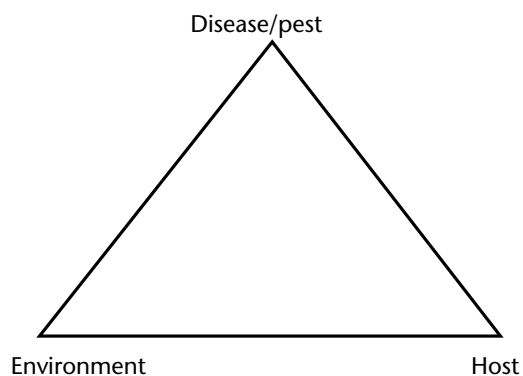


Figure 9.1. Disease/pest triangle

the book deal with weather at take-off, organisms staying airborne, downwind drift, insect flight within and above the boundary layer, swarms, dispersion and concentrations, and forecasting.

9.3.2.2.2 *Crop pests*

There are many applications of meteorology involving crop pests. Based on the concepts in the pest/disease triangle, applications focus on using temperatures to predict insect development and host plant development. Any additional weather parameters can then be added, depending on the nature of crop pest.

9.3.2.2.2.1 Desert locust

There has been much work on weather and desert locusts. Early studies include meteorology and desert locust migration (WMO, 1963c) and the accompanying training seminars (WMO, 1965). Later work focused on meteorology for locust control (WMO, 1991, 1992b, 1992c, 1997c).

Extreme Agrometeorological Events (WMO, 1997c) gives a good overview of the meteorological factors for locust control. Rainfall largely determines the extent and intensity of breeding and therefore is the most important factor in the development of an outbreak or plague. Rainfall location is more important than actual amounts, and this is where satellite rainfall estimates are particularly useful. Once there is a significant rainfall event in the desert (25 mm or more during a month or two), the tender grass vegetation, which is the main food source for desert locusts, starts to grow. It is these abnormal rainfall events that can trigger locust outbreaks and plagues. There have been cases in the Arabian Peninsula in which a tropical cyclone making landfall has spurred a locust outbreak, for instance in 1969. Temperature affects the rate of development of all stages of the desert locust life cycle. Since this pest is native to hot desert climates, temperatures gain in importance typically when swarm take-off is needed on a daily basis or when the desert locust migrates outside the desert climates. Likewise, wind direction and speed are needed to determine swarm flight and to perform tactical spraying applications from aircraft or the ground.

The biological activity of desert locusts determines the kind of weather data needed over a given period. The desert locust is normally a solitary insect and does not threaten crops and food security. This state is called the recession period and rainfall data are

needed to determine where locust control personnel should scout for locust activity. During a desert locust outbreak or plague, the type and amount of meteorological information increases to include daily temperatures and forecasts of temperature and rainfall, as well as wind forecasts, which are especially important. Recently, more attention has been given to high-resolution regional numerical weather prediction models.

9.3.2.2.2.2 Other crop pests

WMO Technical Note No. 41 (WMO, 1961) was prepared for the European and Mediterranean Plant Protection Organization to delineate the areas where the climate is suitable for the permanent settlement of the Japanese beetle in Europe. Most of the life of the beetle is spent beneath the ground as a grub. The appropriate environmental model therefore takes account of summer rainfall (as a substitute for soil moisture) and summer and winter soil temperatures. Volvach (1987) describes the model used to consider the effect of agrometeorological conditions on the principal characteristics of Colorado beetle activity: duration of development, reproduction and death of individuals. The preliminary amount of chemical treatments to be applied to potato is calculated on the basis of the forecast intensity of Colorado beetle reproduction, then it is corrected in the light of observed weather conditions.

There have been many studies relating meteorological factors to important crop pests, such as the cotton leaf worm and pink bollworm (WMO, 1980b), the Colorado potato beetle (WMO, 1975a), various pests of sugarcane (WMO, 1988a) and cassava mites (WMO, 1980c).

9.3.2.2.3 *Crop diseases*

The application of meteorology as an aid to the farmer in combating plant disease differs according to the mechanisms by which each pathogen is spread. The pathogen may be a year-round resident that increases and spreads whenever the weather is suitable for the pathogen and the host plant, which is the case with the fungal disease called potato blight, for example. In some areas a pathogen may not be capable of surviving the year, and may not reappear unless transported in sufficient quantity from a distant source, as in the case of black wheat rust, for example. In recent years the development of crop disease models has focused on crops with high economic value, such as fruit trees, vineyards and vegetables, since the

models need meteorological observations in field settings that usually require the establishment of costly automatic weather stations.

9.3.2.2.3.1 Potato blight

There are two approaches available for the forecasting of late blight with a view to reducing agrochemical use compared to routine 7- and 10-day spraying:

- (a) Simple meteorological rules related to the life cycle of *Phytophthora infestans* that use rainfall, temperature and humidity over 12–48 h periods to predict spore production (“critical periods”) and possibly subsequent periods when risk of infection is greatest. These methods can be used with either hourly observation data or synoptic weather maps;
- (b) Computer-based decision support systems (DSSs), usually utilizing the simple rules that rely on data from in-field automatic weather stations or available as digital files from (usually) Internet sources.

The rules (Table 9.1) differ only in detail and require some regional or site-specific calibration. Mercer et al. (2001) indicate that ideal conditions for spore production are relative humidity above 95 per cent and temperature above 10°C at night-time; free water must be available on the crop surface for serious infection to occur, so rainfall and prolonged high relative humidity are also required after spore production. Simple rule-based methods predict critical periods from late spring until late summer using the following general rules:

- (a) Minimum temperature >10°C for a period of between 12 to 48 hours;
- (b) Relative humidity >90 per cent for the same time period;
- (c) Rainfall in the period following (4 hours to 10 days later).

Evidence of disease is expected between 7 and 21 days after a critical period has been predicted and a suitable crop protection strategy can be put in place. If possible, prediction should be based on hourly observation of temperature and relative humidity. Synoptic maps can be used (particularly where observations are sparse) to make predictions based on the likelihood that current and forecast weather systems will create suitable conditions for a critical period to occur, such as the passage of warm, moist tropical air giving rise to high humidity and temperature, and slow-moving depressions giving rise to overcast, humid, rainy conditions (WMO, 1955; Austin Bourke, 1957).

The use of DSSs (Table 9.2) typically requires site-specific automatic weather station data, but interfaces with alternative data sources are also possible (Hansen, 1999). The systems automate the use of the simple rule-based methods and usually provide spray strategy recommendations as well.

9.3.2.2.3.2 Wheat diseases

WMO Technical Note No. 99 (WMO, 1969) provides an overview of the various wheat rusts that occur around the world and the meteorological factors that contribute to the transport of spores and disease outbreaks for various types of wheat rusts.

A WMO report (WMO, 2000d) provides a survey of many crop disease models, including several for wheat. It describes EPIPRE as a system devised to support decision-making in pest and disease control in winter wheat with the aim of reducing pesticide use. The system integrates six fungal diseases and three aphid pests of wheat. Spirouil-Epure was developed in France and has been used for many years to support extension services for brown wheat rust. The model uses meteorological data, along with some agronomic and phenological data, and provides advice on the dates for first fungicide application within microregions and well-defined crop zones.

9.3.2.2.3.3 Apple scab

Apple scab is caused by the *Venturia inaequalis* fungus and is an economically important disease for apple producers. *The Influence of Weather Conditions on the Occurrence of Apple Scab* (WMO, 1963b) provided one of first overviews of the disease, investigations in various countries and descriptions of the early warning systems. More recently, the apple scab model ASCHORF was developed in Germany. This model can be used to provide practical recommendations to plant protection services and apple growers (Friesland, 2005). The modelled infection risk is dependent on temperature and leaf wetness duration. Leaf wetness duration is calculated but not measured and is based on energy balance principles. The model uses a sliding 10-day time series by inputting data for the previous four days from the standard meteorological network and then inputting grid point data from numerical weather prediction models.

9.3.2.2.3.4 Downy mildew

Downy mildew (*Plasmopara viticola*) is one of the most important fungal diseases for wine grapes (*Vitis vinifera*) and can lead to considerable losses in

Table 9.1. Examples of “critical period” prediction methods indicating the types of modification made for various regions where potatoes are grown (not an exhaustive list)

<i>Method</i>	<i>Temperature</i>	<i>Humidity</i>	<i>Other</i>	<i>Rainfall</i>	<i>Reference</i>
Dutch rules 1926 Europe	>10°C min at night	4 h below dewpoint at night	8/10ths following day	Followed by >0.1 mm rain	van Everdingen (1926)
Beaumont periods 1947 United Kingdom	>10°C min for a minimum 48 h period	75% during the 48 h period			Beaumont (1947)
Irish rules 1953 Ireland	>10°C min for a 12 h period	>90% for the 12 h	Free moisture on leaves for 2 h after the 12 h period or the rainfall criterion	Between the 7th and 15th h around the end of the 12th h of the 12 h period	Keane (1982)
Hyre rules 1954 North-eastern United States	5-day average <25.5°C excluding days with minimum <7.2°C		Looks for 10 consecutive risk days	Total rain in 10-day period >30 mm	Hyre (1954)
Smith periods 1956 United Kingdom and Ireland	>10°C min for 2 × 24 h periods	>90% for 11 h in each of the 2 periods			Smith (1956)
Negative prognosis 1966	Uses temperature bands and multiplies the hours in each band by a weighting factor	At low temperature only use hrs when >90% or a rainfall limit for 4 h blocks. At higher temperature use a 10 h block	Can subtract from risk when RH is <70%	At low temperature only use h when >0.1 mm rainfall or RH limit for 4 h blocks. At higher temperature use a 10 h block	Ullrich and Schrodtter (1966)
Germany Young rules 1978 South Africa	>10°C and <24°C for 2 × 24 h periods	>70% at 2 p.m. during each of the 24 h periods			van Rij and du Preez (2004)
Forsund rules 1983 Norway	Maximum 17°C–24°C Minimum >10°C for 2 × 24 h periods	>75% at noon during each 24 h period		>0.1 mm during each 24 h period	Forsund (1983)
Winstel rules 1993 Belgium	Phase 1: Average daily >10°C and <23°C for 10 h and then 10 h >10°C Phase 2: Maximum daily >23°C and <30°C for 2 × 24 h between 1 and 10 days after Phase 1	Phase 1: >90%			Winstel (1993)
Washington State rules 1996 North-western United States	Rainfall indicators calculated for periods when minimum >5°C during April and May and then July and August		Calculates probability of a year being an “outbreak” year using discriminant functions and binary logistic regression	Days with >0.25 mm and temperature >5°C	Johnson et al. (1996)

Table 9.2 Examples of DSS-type systems for prediction and management of blight outbreaks (after Bouma and Hansen, 1999)

<i>Model</i>	<i>Country and e-mail</i>	<i>Original development year</i>	<i>Main target users</i>	<i>Input</i>	<i>Output</i>
Televis	Norway Arne.Hermansen@planteforsh.no	1957	Farmers, advisers	Weather data	Epidemiological data
Guntz-Divoux	France fredec.nord.pas-de-Calais@wanadoo.fr	1963	Advisers, extension service	Weather data	Advice line
Simphyt	Germany Bkleinhenz.lpp-mainz@agrarinfo.rpl.de	1982	Plant protection service, extension officers	Weather data Field data	Field data Advice
ProPhy	Netherlands info@Opticrop.nl	1988	Farmers, advisers, extension officers	Weather data Field data Other data	Weather overviews Field data Advice
Plant-Plus	Netherlands Plantplus@dacom.nl	1990	Farmers, advisers, suppliers, processors	Microclimate Crop + product information	Disease maps Fungicide protection periods
I.P.I.	Spain	1990	Farmers, advisers	Weather data	1st spray timing Epidemiological data
NegFry	Denmark JensG.Hansen@agrisci.dk	1992	Farmers, advisers	Weather data Field data	1st spray timing Fungicide applications
PhytoPRE + 2000	Switzerland Hansrudolf.forrer@fal.admin.ch	1995	Farmers, advisers, plant protection service	Weather data Field data Other data	Regional data Field data
Guntz-Divoux	Belgium pcg@ping.be	1996	Advisers, extension service	Weather data	Advice line

grape yield and quality. Friesland et al. (2005) developed the PERO model to calculate the start of infection of the grapevine disease *Peronospora*, which is determined by temperature and leaf wetness. The PERO model is based on laboratory and field experiments and the inputs are hourly air temperature, relative humidity, calculated leaf wetness, daily extreme temperatures and daily rainfall. The model outputs are infection dates and oil spot balances (lesions), which are used for agrometeorological advice.

PLASMO (*Plasmopora* simulation model) was developed to simulate the biological cycle and the disease leaf area of grapevine downy mildew, allowing for the best timing for fungicide treatments (Orlandini et al., 2005). Data inputs are hourly temperature, relative humidity, rainfall and leaf wetness. The results are expressed in percentage of leaf area covered by oil spot lesion. The PLASMO model has been developed into a computer program for distribution and is also available on the Internet for greater access. Weather data can be uploaded to the model Website for running of the model (Rossi et al., 2005).

9.3.2.2.3.5 Other applications

Norway has developed a Web-based site-specific warning system called VIPS that calculates warnings for several pests and diseases in selected fruits, vegetables and cereals (Folkedal and Brevig, 2004). The warnings are linked to over 70 weather stations and colour-coded warnings ranging from danger (red) to no danger (green) are given for each county for the previous five days and are forecast for the upcoming five days. VIPS incorporates previous work done in Norway on pests and diseases such as NORPRE (Magnus et al., 1991). NORPRE is a cereal disease and pest control system that uses daily weather data as input to a number of different submodels. The system uses field observations of pest disease occurrence from farmers to validate the models and adjust threshold values. The system includes the following pest models: cabbage moth, turnip moth, carrot fly and codling fly (WMO, 2000c).

There have been many surveys of crop disease models undertaken over the years. A WMO report (WMO, 2000d) contains a survey focused on fungal pathogens and lists 58 crops and 133 pathogens.

9.3.2.2.4 Animal pests/diseases

The approach of the meteorologist to problems of animal disease is basically the same as for plant

disease. *Weather and Animal Diseases* (WMO, 1970) provides a good overview of practical links between weather and animal disease that may be wind-borne, parasitic, fungal or the result of environmental or nutritional stress. More recent reviews include WMO (1989) and WMO (1980d), which detail internal animal parasites and cold and hot weather stress. *Weather, Climate and Animal Performance* (WMO, 1980d) states that there are two lines of enquiry in using climate information as a measure of disease incidence. The first uses climatic factors to develop climatic indices known to influence the development of the animal parasite during its life cycle outside the animal. The second uses biological development rates, calculated from the study of parasites under laboratory conditions in constant temperature chambers, to determine the influence of temperature variation on parasite development in actual field conditions. Besides the animal diseases listed below for which meteorological applications have been developed, this publication also provides information on nematodiriasis and parasitic gastro-enteritis.

9.3.2.2.4.1 Foot-and-mouth disease

The 1968/1969 foot-and-mouth disease epidemic in the United Kingdom led to research indicating that meteorological factors are major contributors to the spread of the virus during a foot-and-mouth outbreak (Smith and Hugh-Jones, 1969; Wright, 1969). The virus is spread when it is exhaled by animals as the nuclei of water droplets, which are then dispersed by winds. The most important meteorological factors are wind, humidity and rainfall; the synoptic situation will determine to some degree the distance over which the virus can spread. Wind speed and direction will determine the pattern of dispersion of the virus. Stable atmospheric conditions favour dispersion over large distances because vertical distribution is minimized, while high winds and turbulence usually reduce the transport range. Humidity will determine the duration that the virus remains protected by its water droplet. Maximum infectivity is associated with relative humidity above 60 per cent (Murphy et al., 2004). Rainfall will influence when the virus is deposited from the atmosphere. In rainy conditions the virus will be deposited on herbage within short distances of the source, rather than moving to infect other animals.

The more recent epidemic in the United Kingdom in 2001 resulted in the development, utilization and testing of models for predicting the spread of virus based on: the predicted viral load at a source location; the predicted spread due to surface weather

conditions (Gloster et al., 2003; Mikkelsen et al., 2003; McGrath and Finkle, 2001); and latitude and topography. McGrath and Finkle (2001) noted that older models depend on synoptic observations and thus suffer error due to potential remoteness of observation stations from outbreak sources. Mikkelsen et al. (2003) tested four dispersion models: (i) 10 km Gaussian Plume (Gloster et al., 1981); (ii) Nuclear Accident Model (NAME) (Ryall and Maryon, 1998); (iii) RISØ Mesoscale PUFF model (RIMPUFF) (Mikkelsen et al., 1984); and (iv) Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen, 1998). NAME and DERMA are long-range models driven by numerical weather prediction (NWP) output, and produced similar results despite being driven by different NWP models. The local-scale models, driven by nearby observation data, were also used to analyse local infection. It was concluded that 24-hour average virus concentrations do not adequately represent infection risk and that short-term high concentration levels are needed to account for the pattern of infection that was observed (Gloster et al., 2003).

For local-scale prediction, the most important observation/NWP output is 10 m wind speed, estimates of three-dimensional dispersion, the relative humidity and the chance of rainfall occurring. For regional-scale modelling, 1- to 3-hour NWP output is preferred and should include wind speed, wind direction, relative humidity, cloud cover and precipitation.

9.3.2.2.4.2 Facial eczema of sheep

A warning system for this fungal disease was devised in New Zealand (WMO, 1960, 1968a). Even before a definite link was established between the disease and fungus present in grass, soil temperatures and rainfall were used for warning. High humidities and ambient temperatures in the 21°C–27°C range are favourable for the spores, and the discovery of the fungus reinforced the empirical approach. Spore traps and counts are now being used to confirm the meteorological evidence.

9.3.2.2.4.3 Fascioliasis in sheep

Fascioliasis (commonly called liver fluke disease) is a parasitic disease that affects sheep and is caused by *Fasciola hepatica*. The complicated life cycle consists of the passing of fluke eggs in dung by infected sheep, and these eggs then hatch into free-swimming larva in the open pasture and infect the fluke's intermediate host, a snail, *Lymnaea trunculata*. This is the most sensitive stage of the life cycle. The larvae will die if they cannot enter a snail within

24 hours. Ollerenshaw (1966) describes a wetness index (Mt) based on monthly rainfall, potential transpiration and the number of rain days, which was developed in England and Wales. Data for the index are accumulated over a season, and based on comparison with historical disease statistics, thresholds for treatments can be established.

Part I of *Weather and Parasitic Animal Disease* (WMO, 1978c) provides an updated and thorough overview of the use of weather information in the various models of this disease in Europe, and states that the most important meteorological factors in the emergence of *Fasciola hepatica* are temperatures above 10°C for the development of the parasite inside the snail host and the presence of free water. *Weather, Climate and Animal Performance* (WMO, 1980d) also lists several analytical and simulation models that predict parasite populations in pasture and in the host. It cites the use of analytical models for strategic disease control policies and simulation models for tactical control procedures. Part II of *Weather and Parasitic Animal Disease* (WMO, 1978c) contains several examples of the use of weather information to study and/or model nematodiriasis in sheep, as well as tapeworms, ticks and nematodes.

9.4

OTHER APPLICATIONS

There are many other applications of meteorology for agriculture besides those already mentioned. They are covered in other chapters in detail because of their importance. One important group relates to the physiology and growth of plants, from germination to final yield. These are affected somewhat by the applications already dealt with, for example, irrigation, shelter, cover and disease. Other applications can be cited, including the use of degree-days or other indices to determine the phenological stages of crops, such as flowering, reproduction and maturity. These stages are very important for pest/disease management. Typically, growing degree-day or heat-unit calculations are made by subtracting a threshold temperature from the average daily temperature and then accumulating these units over time to model plant and insect development. The simplest form on a daily basis is:

$$\text{Degree-day} = [(T_{\max} + T_{\min})/2] - T_{\text{base}}$$

Hodges (1991) provides a good overview of modelling crop phenology for many crops. *Weather-Based Mathematical Models for Estimating Development and Ripening of Crops* (WMO, 1983) describes these calculations as temperature-remainder models

(TRIM) and lists many methodologies to calculate crop development. See Chapters 6 and 10 for a more detailed review of these concepts. Another group of applications concerns field operations. Since cultivation, drilling, spraying and harvesting are all highly weather-dependent, the meteorologist can give considerable help in assessing the probability of weather suitable for these operations, which may greatly affect the requirements for labour and machinery.

Fedoseev (1979) showed that lodging results in a significant crop yield drop (by as much as 20–30 per cent) and degradation of grain and straw

quality, and also creates problems for harvesting. Operation of harvesting units with lodged crops is extremely difficult and their efficiency decreases by 25–50 per cent, which results in longer harvesting times. But even under optimum harvesting conditions, the grain loss is in the range of 10–25 per cent. Depending on the lodging conditions, biological losses are between 5 and 40 per cent on average.

In all applications meant for the farmer, it is of the utmost importance that the meteorologist work closely with the specific experts on individual problems.

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CHAPTER 10

AGROMETEOROLOGY OF SOME SELECTED CROPS

10.1 **AGROMETEOROLOGY AND COTTON PRODUCTION**

10.1.1 **Importance of cotton in various climates**

Cotton is the world's most important fibre crop and the second most important oilseed crop. The primary product of the cotton plant has been the lint that covers the seeds within the seed pod, or boll. This lint has been utilized for thousands of years for clothing the people of ancient India, Asia, the Americas and Africa. Cotton fabrics have been found in excavations at Mohenjo-Daro in India and in pre-Inca cultures in the Americas (Hutchinson et al., 1947). Lint, the most important commercial product from the cotton plant, provides a source of high-quality fibre for the textile industry. Cotton seeds, the primary by-product of lint production, are an important source of oil for human consumption. They can also be turned into a high-protein meal that is used as livestock feed. The waste remaining after ginning is used for fertilizer, and the cellulose from the stalk can be used for products such as paper and cardboard.

Cotton is grown on every continent except Antarctica and in over 60 countries around the world. In many countries, cotton is one of the primary economic bases, providing employment and income for millions of people involved in its production, processing and marketing (United Nations, 2003). Worldwide, cotton production totalled 120.4 million bales (218.2 kg/bale) in the 2004/2005 marketing year, the largest output on record (FAS, 2005). It was produced on over 35 million hectares, primarily in 17 countries. China was the world's leading producer of cotton in 2004/2005, with an estimated output of 29 million bales. The United States was second, with just over 23 million bales. It was followed by India, with 19 million bales, Pakistan, with about 11 million bales, and Brazil, with almost 6 million bales.

10.1.2 **Agroclimatology of cotton production**

Adequate soil temperature and moisture conditions at planting are necessary to ensure proper seed germination and crop emergence (Table 10.1.1).

The recommended soil temperature at seed depth should be above 18°C to ensure healthy uniform stands (El-Zik, 1982; Oosterhuis, 2001). Soil temperatures below 20°C, however, when combined with moist conditions, can reduce root growth and promote disease organisms that can injure or kill the seedlings. Cotton requires a minimum daily air temperature of 15°C for germination, 21°C–27°C for vegetative growth and 27°C–32°C during the fruiting period. Current commercial cultivars generally need more than 150 days above 15°C to produce a crop. They become inactive at temperatures below 15°C and are killed by freezing temperatures (Waddle, 1984). Mauney (1986) states that all processes leading to square, blossom and boll initiation and maturation are temperature-dependent. Cool nights are beneficial during the fruiting period, but extremes in temperature (low or high) can result in delayed growth and aborted fruiting sites. Gipson and Joham (1967, 1968, 1969) show that suboptimum temperatures retard growth and fibre development.

At least 500 mm of water (rainfall and/or irrigation) is required to produce a cotton crop. For water not to be a limiting factor in terms of yield, cotton needs between 550 mm and 950 mm during the season in a consistent and regular pattern (FAO, 1984). Untimely rainfall and/or irrigation, as well as humid weather during later stages of cotton growth, primarily once the bolls begin to open, may complicate defoliation, reduce yield and quality, lower the crop's ginning properties (Freeland et al., 2004; Williford, 1992), or promote the attack of insect pests and disease organisms, such as boll rot (Boyd et al., 2004). Once the boll has opened, exposure of cotton lint to the environment causes weathering and the fibres can become stained, spotted, dark and dull. Parvin et al. (2005) state that yield is reduced by 10.10 kg of lint per hectare per centimetre of accumulated rainfall during harvest. The research of Williford et al. (1995) also measured a reduction in lint yield and grade for each successive rain event at harvest. Hence, the combination of warm, dry weather conditions, abundant sunshine and sufficient soil moisture from when the bolls start opening through harvest will maximize yield and quality potential. Figure 10.1.1 provides an example of the optimum climate needs for cotton.

Table 10.1.1. Optimum climate needs for cotton

Growth stage	Average daily temperature °Celsius ^a	Average daily temperature °Fahrenheit ^a	Daily crop water use (mm) ^a	Daily crop water use (in) ^a
Planting (soil)	18° Minimum	65° Minimum	>0	>0
Planting (air)	>21°	>70°		
Vegetative growth	21°–27°	70°–80°	1–2	0.04–0.08
First square			2–4	0.08–0.16
Reproductive growth	27°–32°	80°–90°	3–8	0.12–0.31
Peak bloom			8	0.31
First open boll			8–4	0.31–0.16
Maturation	21°–32°	70°–90°	4	0.16

^a Derived from listed sources.

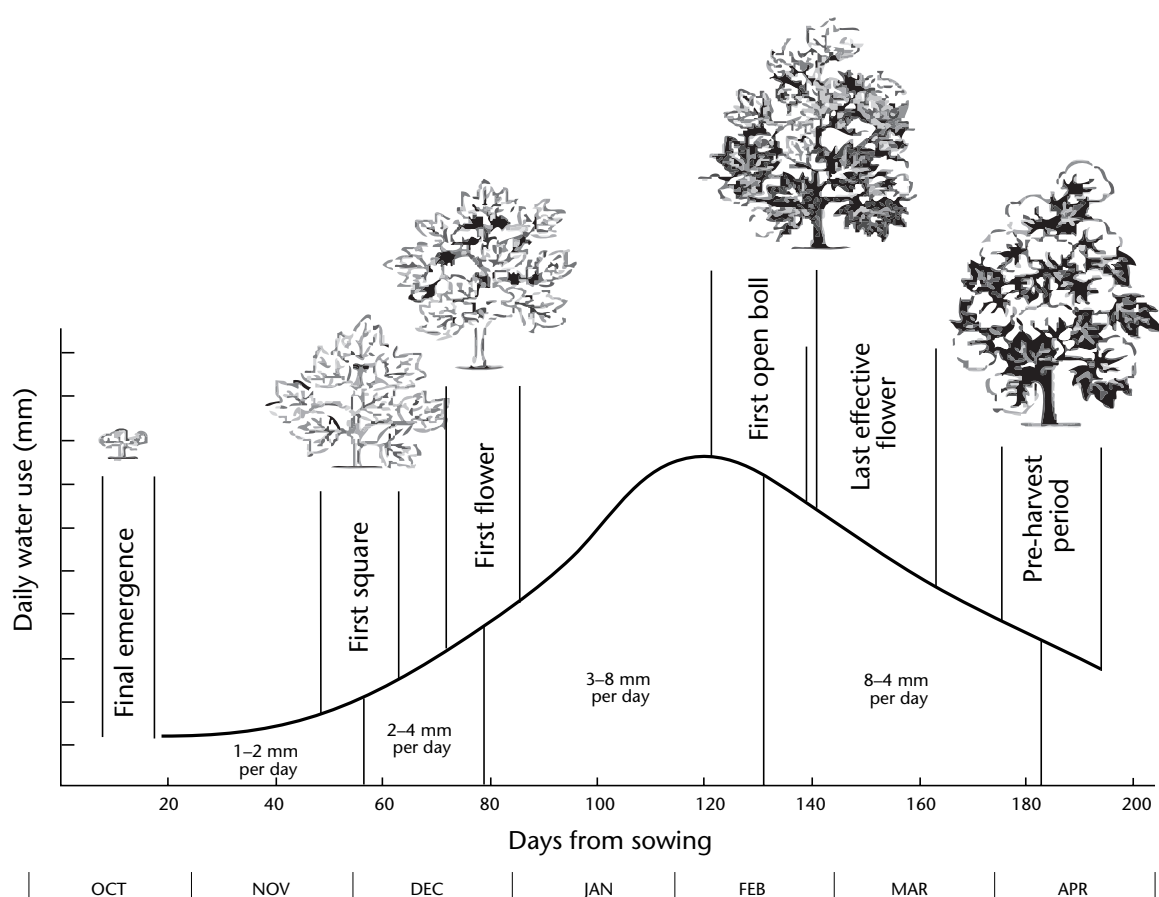


Figure 10.1.1. Graph of optimum climate needs for cotton over the course of seven months.
 (Months are applicable to a crop in the southern hemisphere, and days from sowing will differ based on heat unit accumulation for each location.) (From ICT International (1998), Abdulmumin and Misari (1990), Deltapine Seed (1998), Erie et al. (1981) and Hake et al. (1996))

Photosynthesis is the driving process in determining production potential. Under optimum conditions in controlled, naturally lit plant growth chambers, a research cotton crop produced a yield equivalent to nine bales per acre, approximately three times the yield of commercially grown cotton under good field production practices (Reddy et al., 1998). Lint yield is generally reduced as a result of reduced boll production, primarily because there are fewer fruiting sites producing bolls, but also because of increased fruit abscissions due to various environmental stresses (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner et al., 1986; Gerik et al., 1996; Pettigrew, 2004a). Environmental conditions such as overcast skies, rainy weather, water deficits and high temperatures (day and/or night) will decrease photosynthesis and the supply of photosynthate. The decreased supply of photosynthate increases square and boll shed, and thus reduces the total possible number of harvestable bolls. Plants with the highest boll load are the most sensitive to low light intensity due to their increased photosynthate requirements of (Guinn, 1998).

Water stress caused by a deficiency of water manifests its damage as reductions in photosynthetic activity and increases in leaf senescence (Constable and Rawson, 1980; Krieg, 1981; Marani et al., 1985; Faver et al., 1996). Drought stress causes severe shedding of small squares, resulting in a decrease in flowering. Water stress during the first 14 days after anthesis also leads to boll abscission, but large squares/bolls do not shed readily and flowers seldom shed. Therefore, even under severe stress, young plants can often continue to flower. Water stress from 20 to 30 days after anthesis results in smaller bolls and reduced seed weights (Guinn, 1998). Moisture deficit stress reduces plant growth, resulting in stunted plants with reduced leaf area expansion (Turner et al., 1986; Ball et al., 1994; Gerik et al., 1996; Pettigrew, 2004b). Water deficits can reduce fibre length when the stress is severe and occurs shortly after flowering (Bennett et al., 1967; Eaton and Ergle, 1952, 1954; Marani and Amirav, 1971; Pettigrew, 2004a). Drought stress can also reduce (Eaton and Ergle, 1952; Marani and Amirav, 1971; Pettigrew, 2004a; Ramey, 1986) or increase (McWilliams, 2003; Bradow and Davidonis, 2000) fibre micronaire depending on when it occurs. If the drought is severe late in the season, with the result that set bolls do not have the assimilates necessary for their full development, micronaire will be reduced. If the stress is during peak bloom, a reduced number of bolls will be set; if this is followed by rain later in the season, assimilates will be readily available for the reduced boll load, resulting in increased average micronaire of the field.

Water stress often occurs concurrently with excessively high afternoon temperatures. Reddy et al. (1991, 1992, 1999) demonstrate the detrimental effect that temperatures outside of an optimal range can have on a cotton plant and its fibre growth and development in closed environmental plant growth chambers. Cotton has the ability to mitigate exposure to high temperatures by evaporative cooling of the leaves via transpiration. High humidity, however, has a negative impact on the plant in certain growing regions, such as that found in the Mississippi Delta, and the response to irrigation can be affected by reduced evapotranspiration efficiency of the plant. This higher humidity reduces the level of evaporative cooling, making the plant more susceptible to heat stress at lower air temperature.

Cotton lint yields and fibre quality are also affected by the amount and quality of the solar radiation. Given adequate water and insect control, cotton grown under arid conditions such as those found in Australia, the Middle East and the south-western United States can routinely produce lint yields in excess of 3 to 4 bales per acre with the abundance of sunlight in each region. In humid areas in the south-eastern United States, however, where clouds can be much more prevalent, lint production is limited by the amount of sunlight received (Eaton and Ergle, 1954; Pettigrew, 1994). The lint yield reduction resulting from low light situations is primarily due to a decline in the number of bolls produced by the plants (Pettigrew, 1994). Not only is lint production reduced under low light conditions, but the fibre produced is often of inferior quality. Both Pettigrew (1995, 2001) and Eaton and Ergle (1954) found that shade treatments or reduced light conditions produced weaker fibre with a lower fibre micronaire. These fibre quality reductions were associated with alterations in various fibre carbohydrate levels, which are indicative of a reduction in the level of photoassimilates produced (Pettigrew, 2001).

Wind can also stress the cotton plant enough to reduce yield, although some wind may be beneficial in very hot and humid conditions. Wind modifies the temperature and humidity gradients around the cotton plant, which in turn changes the evaporative demand. Most wind damage to cotton plants occurs during the first 3 to 6 weeks after emergence, when the wind picks up soil particles and damages the young seedlings during impact. High winds can cause blowing sand that is capable of literally cutting the young plants off at the soil surface (Barker et al., 1985a, 1985b), thereby reducing the overall stand. In regions such as the Texas High Plains, where the winds blow hard and constantly, management practices that provide

protection for cotton plants are designed to improve plant growth and yield. Strip cropping, where taller crops are planted around the cotton seedlings, offers benefits related to the maintenance of soil moisture. Standing wheat and other stubble can also offer protection to the early seedlings (Barker et al., 1985a, 1985b). Extreme wind damage can sometimes occur in mature cotton crops, as was evident in 2005 when Hurricanes *Katrina* and *Rita* ravaged parts of the cotton crop in the Mid-South United States (JAWF, 2005a, 2005b). Immature bolls were beaten off of the plants and seed-cotton was blown out of mature open bolls. Leaves of the non-mature plants were stripped in locations where the strongest winds occurred.

Environmental factors have an impact on the growth not only of the cotton plant, but also that of pests and beneficial organisms. Both undesirable and beneficial plant and animal species are altered by factors that affect the crop, and should be considered during the growing season. Some climate regimes are unsuitable for beneficial plants, such as rotation crops or winter cover, as well as beneficial insect survival. On the other hand, weather patterns can encourage the growth of some pest insects and allow their populations to expand to a level that may damage crops. In areas that are not subject to freezing temperatures during the winter, disease and insect pests can overwinter and have a detrimental effect on young cotton. Knowledge of these interactions is essential when attempting to maximize cotton yields.

10.1.3 **Other background information on cotton**

The cotton plant is a deciduous, indeterminate perennial plant in the genus *Gossypium* of the family *Malvaceae*, or mallow family, and is native to subtropical climates. Two Old World diploid ($2n = 2x = 26$) species, *G. arboreum* and *G. herbaceum*, and two New World tetraploid ($2n = 4x = 52$) species, *G. barbadense* and *G. hirsutum*, have been domesticated independently for cultivation throughout the world. The most widely grown species worldwide is *G. hirsutum*, which is grown on over 95 per cent of the worldwide cotton hectareage, followed by *G. barbadense*. Upland cotton, *G. hirsutum*, is native to Mexico and parts of Central America; pima, Egyptian or American-Egyptian cotton, *G. barbadense*, is native to South America (Brubaker et al., 1999). India is an exception to most countries, with only 30 per cent of its cotton production area planted to *G. hirsutum*, 17 per cent planted to *G. arboreum*, 8 per cent to *G. herbaceum*, and the remaining area planted to interspecific and intra-specific hybrids.

Cotton is cultivated as an annual shrub in the temperate and even subtropical zones, and it develops in an orderly, predictable pattern. Plant development in cotton proceeds through five growth stages: germination and emergence, seedling establishment, leaf area canopy development, flowering and boll development, and maturation. Marur and Ruano (2001) define the growth process in four phenological phases: vegetative, squaring, flowering and boll opening. The seed contains two well-developed cotyledons, a radicle, a hypocotyl and a poorly developed epicotyl. The cotyledons will form the seed leaves that provide energy for the developing seedling and are photosynthetically active during early seedling development. Moisture from the surrounding soil is imbibed into the seed through the chalaza, an area of specialized cells at the broad end of the seed. The water follows the tissue around the embryo to the radicle cap at the narrow end of the seed. The seed/embryo swells as water is absorbed, causing the seed coat to split. Under favourable conditions, the radicle emerges through the pointed micropylar end of the seed in two to three days, becoming the primary root that grows downward into the soil. The hypocotyl grows rapidly and elongates, arching near the cotyledons. The cotyledons are located at the lowest node on opposite sides of the stem. As the hypocotyl becomes longer, the cotyledons and the epicotyl are pulled/pushed through and above the soil surface. Exposed to light, the cotyledons unfold, expand, turn green and begin to manufacture food.

Much of the early growth of the cotton plant is focused on the development of a substantial root system. The primary root, or taproot, penetrates the soil rapidly and may reach a depth of up to 250 mm by the time the cotyledons expand. Root development may proceed at the rate of 12.5 to 50 mm per day, depending on conditions, so the roots may be 1 m deep by the time the plant is only 305 mm tall (Oosterhuis and Jernstedt, 1999). The taproot continues to elongate until the plant is at maximum height soon after flowering. The bud above the cotyledon enlarges and unfolds to form the stem where true leaves and branches will develop. A fully developed cotton plant has a prominent, erect main stem consisting of a series of nodes and internodes. As the plant grows, the internode above the cotyledons extends, and a new node is formed, from which the first true leaf unfolds. This process continues at 2.5- to 3.5-day intervals. A single leaf forms at each node in a spiral arrangement. At the centre of this growth activity is the terminal bud. The terminal bud controls the upward pattern of stem, leaf and branch development. About four to

five weeks after planting, vegetative and reproductive branches begin to form between the leaf petiole and the main stem node (Oosterhuis and Jernstedt, 1999).

Under optimal conditions, flower buds can be seen five to eight weeks after planting, as small, green, triangular structures commonly or colloquially known as squares. The first square is formed on the lowest reproductive branch of the plant located at the fifth to ninth main stem node. New squares will continue to appear on the next reproductive branch up to the top of the plant every 2.5 to 3.5 days and will appear outwardly along each fruiting branch at approximately five- to six-day intervals. The research by Bednarz and Nichols (2005) on selected modern cultivars shows a horizontal fruiting interval of 3.2 to 4.4 days. The total time from plant emergence to the appearance of the first flower bud is about six weeks. Each flower bud develops into a bloom about three weeks from the time it is visible to the unaided eye.

The cotton bloom is a perfect flower with white petals on the day of anthesis. The ovary has 3 to 5 carpels or locules. Each locule contains 8 to 12 ovules that may develop into seed. Flowers open during the morning, and pollination occurs within a few hours. Fertilization takes place within 24 to 30 hours after pollination and the fertilized ovule develops into seed (Oosterhuis and Jernstedt, 1999). The white petals of the flower turn pink after 24 hours and die the following day, usually shedding from the developing boll within a week. The growth rate of a boll is temperature-dependent and a boll will reach its maximum volume in about 24 to 30 days after anthesis. After anthesis, approximately 50 days are necessary for the fibres inside the boll to mature and the boll to open.

Cotton fibres are formed from individual cells located on the seed epidermis. While firmly attached to the seed coat, the fibre elongates for 20 to 25 days after fertilization and then grows in diameter for another 20 to 25 days. The developing cotton fibre is like a hollow tube, with successive layers of cellulose deposited on the inner surface of the fibre wall in a spiral fashion. The amount of cellulose deposited determines the fibre strength, fineness and maturity. Micronaire, a measurement of both fibre maturity and fineness, can be more heavily influenced by the environment than other fibre traits. High temperatures or drought during the elongation phase of fibre development can shorten fibre length and reduce fibre uniformity, and can cause high, or even under extreme conditions, low micronaire (Ramey, 1999). Cotton lint is creamy white to white when the boll opens. Fibre quality is

at its maximum as soon as the boll opens, and declines thereafter until harvest due to environmental interactions.

10.1.4 **Management aspects of cotton production**

There are various management practices that should be followed to help mitigate some of the environmental risks associated with growing cotton. They include selection of adapted cultivars, planting within the recommended range of favourable planting dates and environmental conditions, use of seed and seedling protectants to avoid stress or early-season diseases and insects, use of effective pest management tactics to avoid competition and damage by weeds and insects, management for optimal soil moisture, proper fertility management, and management for maturity and readiness for harvest at optimum times. There is an abundance of university extension service recommendations and other government agency sources of information to assist a cotton grower in making good management decisions to avoid or minimize risk. These sources include environmental and climatological monitoring and forecasting services. Some risks will never be avoided unless the cotton is grown in a protected, controlled environment, such as growth chambers or greenhouses; this approach is not economical for commercially grown cotton at this time, however.

One of the tools used in reducing environmental risks and increasing the possibilities of a profitable yield is cultivar development through breeding and genetics. Successful cultivar development incorporates risk aversion into the genetic code of adapted varieties. Traditional breeding methods are used with aggressive selection pressure to develop genotypes with favourable traits for environments of interest. New cultivars are selected in the breeding programmes based on their yield, fibre quality and other desirable traits. The selection process ensures that new cultivars are developed within the current climate cycle or pattern and therefore have those recent environmental risks built into their genetics. When a new cultivar is released for commercial production, its primary selling point is its high and consistent yield. Producers are primarily paid for their crop based on yield, and therefore should choose to plant cultivars based on their yield history over the past few years in the given locality. One needs to remember that genotypes bred in one location or environment may not be the ideal cultivar for another location or environment.

Breeding also allows for traits to be bred into a genotype, or cultivar. For example, as reported above,

extreme heat results in delayed growth and loss of squares and fruit. Heat tolerance can be genetically manipulated in cotton. Certain cultivars have been identified that perform better under hot temperatures. Therefore, breeders have been successful in selecting for these traits and in developing heat-tolerant (Feaster, 1985; Lu et al., 1997) and drought-tolerant lines (Basal et al., 2005). For example, higher-yielding pima lines have been developed by selecting for increased stomatal conductance, thus allowing these lines to keep their leaves cooler (Radin et al., 1994; Percy et al., 1996). Salt tolerance is another inherited trait that cotton breeders have been successful in incorporating into new cultivars (Higbie et al., 2005). These cultivars will give growers greater success in increasing germination in salty soils. Cotton seeds with enhanced emergence force that break through soil crusts have also been selected by breeders (Bowman, 1999), with expectations that a higher percentage of the seedlings will emerge to produce even and uniform plant stands.

One of the largest contributions breeding has made to current United States Mid-South cotton production has been the development of earlier-maturing cultivars. These cultivars were bred to better fit the climate of this area and to mature as much as 30 days earlier than historical cultivars. These cultivars take better advantage of the normal weather pattern of the area by being in the fruiting stage while there is still moisture available in the soil, starting the maturation process during the drier times of the summer and being harvestable prior to the normal rainy period of the late fall and winter. These cultivars have also been created to produce yield despite the intense pest pressures of the area. A secondary contribution breeding has made is the introduction of pest-tolerant traits into the cultivars. These cultivars can produce toxins or tolerate toxins in order to control specific pests that previously would reduce yield. These cultivars were bred in the Mid-South, so were selected based on their ability to adapt to that environment.

Weather conditions often determine the type of pests that will have to be controlled in a given growing season, as well as the efficacy of control procedures. Weed pests of cotton change according to regional climatic conditions, cultural practices and local weather variables. Herbicides often require actively growing plants to achieve good control. Moisture and temperature generally control how actively weeds grow. Plant pathogens and insect pests in most cases require alternate hosts. The alternate host's growth is dictated by regional climatic differences and local weather variations. Insect pests, for example, move from the alternate

hosts into cotton when that host is less attractive to the pest than cotton, mostly when the host is dying or senescing. Spider mites, for instance, generally require dry weather. The dry weather prevents beneficial fungi from producing an epizootic, thus eliminating the spider mite population. Effective pest control requires good timing to be beneficial, and one of the largest obstacles to properly timed crop protection applications is weather. If improperly timed, crop protection products may fail and the resulting uncontrolled pest population could damage the crop. Each crop protection product is active only within a certain environmental regime or during a certain life stage of a pest. Temperatures that are too high or too low, or rain prior to or after application, may cause failures. Moisture and/or high winds can prevent the timely application of products and thus reduce control and yield.

Following local extension recommendations or governmental guidelines will help reduce environmental risks to producers. These recommendations and guidelines usually include planting and harvesting dates that consider risks of temperature and precipitation extremes and other general environmental factors. They also may include timing suggestions for certain practices that would have adverse effects if done at alternate times. Soil sampling, which helps to identify many soil issues that could limit production, is one of the recommended tasks. Sampling is a tool that may be used to identify limiting nutrient, pH or salinity factors that can reduce yields and/or fibre quality.

Since freezing temperatures kill cotton plants, the crop has to be grown between the last spring and first fall freezes. Climatological records can identify the growing period for a location and they can be used to compute the statistical probability of a freeze occurring before or after certain dates. Growers must realize and take advantage of these data in order to reduce the risk of the crop's being killed by freezing temperatures after planting in the spring, or prior to maturation in the fall. The National Climatic Data Center computed this dataset for many sites across the United States and the results are available for producers to utilize (Koss et al., 1988). The dataset provides three probability levels (10, 50 and 90 per cent) for the occurrence of a certain temperature (-2°C , 0°C and 2°C) after a certain spring date and before a certain fall date. Producers have to weigh those risks and decide whether or not to plant. Even though the current weather may be ideal for planting, producers should not plant if the likelihood that a freeze will occur after that date, expressed as a percentage, is higher than the risk they are willing to accept, also

expressed as a percentage. Producers should utilize this information to determine the last day they are willing to plant as well, since the crop has to have enough time to mature prior to the first fall freeze. Other information derived from climatological data is also beneficial to growers, such as the number of days a grower has to complete tillage and non-tillage operations during a season (Bolton et al., 1968; Zapata et al., 1997).

There are also certain cultural practices that may be utilized to reduce some of the environmental risks associated with growing a cotton crop. Seeding rates need to be sufficient to achieve an ideal plant population for all locations. Plant populations of 68 000 to 101 000 plants per hectare are recommended on bedded rows and populations of 197 000 to 247 000 plants per hectare are typical in the case of ultra-narrow row or broadcast cotton production. When planting, seed depth is critical and seeds should be placed at 10 to 25 mm, depending on soil type, crusting potential and moisture levels. If planting immediately precedes a rain, certain soils will crust and seal over, depriving the seedling of oxygen that is required for germination and root development, and making it more difficult for the seed to push through the soil for emergence. Planting seed at the shallower depth is recommended under these conditions to improve emergence (*Delta Agricultural Digest*, 2006). Even planting seed at greater depths, up to 30 mm, is not uncommon when planting to the moisture level in the soil in arid and dry areas. This, however, is not the ideal situation, as more seed may have to be planted to achieve the desired final plant stand. Strip cropping and interplanting may be utilized to reduce wind effects on seedlings. Skip-row planting may be used for better soil water utilization and a higher field-level drought tolerance.

The most obvious and beneficial cultural practice that can be utilized to reduce environmental risks is irrigation. Supplemental irrigation should be applied if needed during dry periods. Field drainage is also very important, as cotton cannot remain in saturated soil. Any practice

that can improve the surface or subsurface drainage is very beneficial. Tillage operations such as bedding or subsoiling, or inserting drainage tiles, may be utilized to improve field drainage.

10.1.5 User requirements for agrometeorological information in cotton production

User requirements for agrometeorological information will vary depending on the climate, cultivar and soil type of the region where the crop is grown. Commercial cotton production worldwide is in a constant battle to keep the cotton plant unstressed so that it is able to retain its fruit, while environmental factors are constantly stressing the plant, and certain requirements need to be followed in all locations. Current cultivars require between 1 195 and 1 275 degree-day (DD15.5C) heat units based on 15.5°C from planting to harvest to produce an acceptable yield (*Delta Agricultural Digest*, 2006). The degree-day baseline is derived from a very large pool of research that studied temperature effects on different growth stages (Mauney, 1986; Anderson, 1971; Young et al., 1980; Bilbro, 1975). Recent research has shown that a higher baseline temperature, combined with other weather variables, may better predict boll maturation (Viator et al., 2005). Degree-day heat units are calculated by taking the daily average temperature, (Max + Min)/2, and subtracting the base, Either 15.5 for Celsius or 60 for Fahrenheit, from the daily average. The resulting number is the number of heat units accumulated for that day. High-yielding cotton also requires between 508 and 1 016 mm of water during the growing season. If a location normally has little or no precipitation during the growing season, irrigation is necessary. Cotton also requires a soil with excellent water-holding capacity, aeration and good drainage, since excessive moisture and waterlogging are detrimental to production.

During germination, the soil must have reached a minimum soil temperature of 18°C and have moisture available, but not be saturated. Soil temperatures

Table 10.1.2. Growth stages indicated by accumulation of degree-day heat units
(Compiled from *Delta Agricultural Digest*, 2006; Boyd et al., 2004; Kerby et al., 1987; Young et al., 1980)

	DD15.5 – °C	DD60 – °F
From planting to emergence	25–35	50–60
From emergence to first fruiting branch	165–190	300–340
From emergence to first square	235–265	425–475
From square to white bloom	165–195	300–350
From emergence to peak bloom	770–795	1 385–1 435
From white bloom to open boll	415–610	750–1 100
From emergence to a mature crop	1 165–1 250	2 100–2 250

below 20°C reduce root growth and when combined with moist conditions promote disease organisms that can injure or kill the seedlings. Forecast daily average temperatures should be above 21°C for the five days immediately following planting in order to assist in quick germination and the establishment of a healthy plant stand. These requirements increase the possibility of growing a good radicle. Damage to the radicle at this point will cause a shallow root system, leaving the plants more susceptible to water and drought stresses (El-Zik, 1982; Oosterhuis, 2001).

After planting, optimum daily maximum temperatures for vegetative growth are 21°C–27°C with sufficient moisture. During fruiting, daily maximum temperatures of 27°C–32°C with sufficient moisture are optimal. Each boll requires 415–610 DD15C heat units to mature from a white bloom into an open boll. High temperatures above 32°C may decrease boll size and increase the amount of time for bolls to reach maximum weight (El-Zik, 1982; Oosterhuis and Jernstedt, 1999). Too much water from rain or irrigation early in the plant's growth will cause the plant to set its first reproductive branch too high on the main stem as a result of excessive internode elongation. On the other hand, early water stress or drought will cause the setting of reproductive branches too low on the stem because internode length is reduced. Rain, cloudy weather and excessively high temperatures can cause an increase in square and boll shedding (Reddy et al., 1998; Guinn, 1998; Eaton et al., 1954; Pettigrew, 1994). Rain or irrigation on open flowers during the pollination process can rupture the pollen, resulting in poorly pollinated flowers and, subsequently, square shed (Burke, 2003; Pennington and Pringle, 1987). Even without rain, cloudy weather decreases photosynthesis and may result in square and small boll shed. High temperatures prior to anthesis can prevent the production of viable pollen (Meyer, 1969) and cause the stigma to extend; this prevents fertilization, resulting in young square abortion. When the temperature rises above 35°C, more of the anthers produced are sterile and therefore flower survival and fruit production are poor during that time.

As this shows, there are a number of abiotic stress factors, particularly moisture surpluses and deficits, high and low temperatures, and low light, that impose limitations on the growth and development and therefore the yield of a cotton crop. Monitoring these factors is a requirement that allows growers to understand why yields may be reduced due to certain environmental effects. Climate and environmental monitoring should be done at the local level. The normal climate of a location remains

more consistent over time and therefore needs to be considered prior to the season. The normal weather patterns during the production season have to be identified and then taken advantage of in order to maximize production and profitability. Knowledge of the location's climate, both atmospheric and edaphic, verifies the location's suitability for sustaining crop production. Soil moisture and temperature need to be monitored prior to planting to promote quick and healthy germination and establishment of a healthy, uniform plant stand. Soil moisture during the entire season is critical in order to maximize yields and either extreme, of too much or too little, stresses the plant and potentially limits the plant's yield. Air temperatures are important throughout the growing season, but are most critical at planting time.

10.1.6 **Agrometeorological services available for cotton production**

Cotton that is grown commercially has to produce yields that are at or above a point at which a sustainable economic profit is attained. The economics of a particular region will ultimately determine what yield is acceptable. In order for growers to be able to monitor in-season environmental conditions, utilize historical climatic information and attempt to take advantage of or divert ill effects of weather, pertinent weather and crop information needs to be made available to them. Research on the interactions between existing and new cultivars and environmental conditions needs to be completed and released to growers in a timely and continuous manner. Agrometeorological information and products are vital tools for growers to have available for management and economical decision-making. Governments, agencies, universities and organizations are ideally positioned to make these data and products available to individual growers. Many countries or areas have groups such as these providing these services to growers, and some countries are developing the relevant programmes. These agrometeorological services need to be developed and maintained in all cropping areas worldwide.

Local weather information can be obtained from the Internet, national or regional weather services, and local meteorological professionals. Data may be collected near population centres and thus may not represent local agricultural interests or needs. Several areas have established agricultural weather station networks, however, and their data are available through the supporting group or agency. In the United States, agricultural weather networks are supported by individuals, cooperatives, corporations, agencies, universities and organizations. The data are usually

accessible via the Internet and agrometeorological products are made available to their users. Users may monitor current or historical weather data, depending on the network's capabilities, for decision-making in cotton production on matters ranging from planting, utilizing soil temperatures and harvesting, to monitoring heat units after a cracked boll for defoliation applications. Producers may also utilize the data in-season for monitoring square and boll shed or crop protection applications.

One example of a product provided to cotton producers by a university is a cotton-planting recommendation map that graphically depicts over the entire state when the next five-day forecast temperatures are suitable for cotton planting (MSU-DREC, 2006). Another example of a researched agrometeorological tool is monitoring maturity of the cotton plant utilizing the node above white flower (NAWF) mapping technique (Bourland et al., 2001). NAWF can be utilized effectively to plan and schedule sequential events, such as termination of crop-enhancing and protection applications, defoliation and harvest by monitoring both the physiological stage of the cotton plant and heat unit accumulation (Harris et al., 1997; Tugwell et al., 1998; Siebert et al., 2006). On a global scale, global weather and crop information is being compiled and distributed by the World Agricultural Outlook Board (WAOB) of the United States Department of Agriculture (USDA) in its publications, which are available through the mail or on the Internet at <http://www.usda.gov/oce/weather/pubs/index.htm>.

10.2 AGROMETEOROLOGY AND GROUNDNUT PRODUCTION

10.2.1 Importance of groundnut in various climates

10.2.1.1 General

Groundnut (*Arachis hypogaea* L.) is an annual legume that is also known as peanut, earthnut, monkeynut and goobers. It is the thirteenth most important food crop and fourth most important oilseed crop in the world. Groundnut seeds (kernels) contain 40–50 per cent fat, 20–50 per cent protein and 10–20 per cent carbohydrate. Groundnut seeds are a nutritional source of vitamin E, niacin, folic acid, calcium, phosphorus, magnesium, zinc, iron, riboflavin, thiamine and potassium. Groundnut is consumed directly as raw, roasted or boiled kernels, or in the form of oil extracted from the kernel and used for cooking. It is also used as animal feed (oil pressings, seeds, green material and straw) and as industrial raw material (oil cakes and fertilizer).

These multiple uses of the groundnut plant make it an excellent cash crop for domestic markets as well as for foreign trade in a number of developing and developed countries.

Cultivated groundnut originates from South America (Weiss, 2000). It is one of the world's most popular crops, and it is under cultivation in more than 100 countries on six continents (Nwokolo, 1996). It is grown on 25.2 million hectares with a total production of 35.9 million tonnes (FAO, 2006). The major groundnut-growing countries are India (accounting for 26 per cent of the total area devoted to groundnut cultivation), China (19 per cent) and Nigeria (11 per cent). Its cultivation is mostly confined to the tropical countries ranging from 40°N to 40°S. Major groundnut-producing countries are: China (with 40.1 per cent of total production), India (16.4 per cent), Nigeria (8.2 per cent), United States (5.9 per cent) and Indonesia (4.1 per cent).

10.2.1.2 Production environments in major producing countries

10.2.1.2.1 China

Groundnut has a long history of cultivation in China and historical accounts record its cultivation as early as the late thirteenth century (Shuren, 1995). Groundnut is now one of the main cash and oil crops in China. Area under groundnut in China accounts for about 25 per cent of the total area devoted to oilseed crops. In high-income provinces, groundnut is grown for oil production and export. In other provinces it is grown primarily for food, especially as a snack (Yao, 2004). Groundnut is becoming more attractive to farmers due to its higher net profit per unit area compared with other crops in several parts of China.

The main groundnut-producing areas in China are Shandong, Henan, Guangdong, Hebei and Guangxi, which account for more than 60 per cent of the cultivated area and total production. Shandong is the leading province (Shuren, 1995). It accounts for 23 per cent of the area and 33 per cent of total production in the country (Shufen et al., 1998). Groundnut is grown in rotation with various crops in diverse cropping systems in different regions. In Shandong province, groundnut is grown in summer following winter wheat. It is also rotated with sweet potato, corn, tobacco and vegetables in other regions.

As for production constraints, about 70 per cent of the total groundnut cultivation areas are hilly-mountainous, infertile, dryland low-lying areas that have a low capacity to withstand drought or waterlogging.

Poor farming practices such as the lack of quality seeds and continuous monocropping are considered constraints for groundnut production in China.

10.2.1.2.2 *India*

Among oilseeds crops in India, groundnut accounts for about 50 per cent of planted area and 45 per cent of oil production. In India, about 75 per cent of the groundnut area lies in a low to moderate rainfall zone (parts of the peninsular region and western and central regions) with a short period of distribution (90–120 days). Based on rainfall patterns, soil factors, diseases and pest situations, the groundnut-growing area in India has been divided into five zones. In India, most of the groundnut production is concentrated in five states – Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka and Maharashtra. These five states account for about 86 per cent of the total area under peanut cultivation. The remaining peanut-producing area is scattered among the states of Madhya Pradesh, Uttar Pradesh, Rajasthan, Punjab and Orissa. Although the crop can be grown in all seasons, it is grown mainly in the rainy season (*khharif*), running from June to September. The *khharif* season accounts for about 80 per cent of the total groundnut production. In the southern and south-eastern regions, groundnut is grown in rice fallows during the post-rainy season (*rabi*), from October to March. If irrigation facilities are available, groundnut can be grown from January to May as a spring or summer crop. Monsoon variations cause major fluctuations in groundnut production in India. Groundnut is grown under different cropping systems, including sequential cropping, multiple cropping and intercropping (Basu and Ghosh, 1995).

As for production constraints, because groundnut is grown mainly as a rainfed crop, there is a high level of fluctuation in production depending on the rainfall. Productivity is curtailed by drought stress, the use of low levels of inputs by smallholders and marginal farmers in dryland areas, a high incidence of foliar fungal diseases and attack by insect pests.

10.2.1.2.3 *United States of America*

Most of the groundnut produced around the world is consumed as food domestically. Although the United States produces about 10 per cent of the world's groundnut harvest, however, it is a leading exporter and accounts for about 25 per cent of the world's groundnut trade (Smith, 2002). Groundnut is grown in three regions of the United States: the South-East (including Georgia, Alabama and Florida), the South-West (Texas, Oklahoma and New Mexico) and the Virginia-Carolinas region (Virginia, North Carolina and South Carolina). Most of the groundnut-producing areas

are in the humid zone (the South-East), although some of them (mostly in the South-West) have semi-arid conditions (Hammons, 1982; Isleib and Wyne, 1991).

As for production constraints, temperature is the major limiting factor for peanut yield in northern states, since a minimum of 3 000 growing degree-days (with a base of 50°F) is required for proper growth and development (Robinson, 1984). A peanut crop will not reach optimum maturity for a marketable yield to justify commercial production in areas with fewer heat units during the growing season.

10.2.1.2.4 *Nigeria*

Groundnut is one of the most popular commercial crops in Nigeria north of latitude 10° N. Groundnut kernels, cake and oil account for as much as 20 per cent of the total export earnings of this West African country, while satisfying the local requirements for edible nuts. The husk (shell) is used as fuel, roughage, litter for livestock, mulch, manure and soil conditioner. The key areas of production have changed over the years.

Major groundnut-producing areas are located in the Sudan and Northern Guinea ecological zones, where the soil and agroclimatological conditions are favourable (Misari et al., 1980). Temperatures are moderately warm and relatively stable during the growing season at 20°C–25°C. The savanna zone in Sudan receives adequate rainfall for the production of groundnut. The crop is grown usually as a component of a variety of crop mixtures including sorghum, millet, cowpea and maize (Misari et al., 1988). There are two main varieties grown in Nigeria: long-season varieties maturing in 130 to 145 days and short-season varieties maturing in 90 to 100 days.

As for production constraints, groundnut production in Nigeria faces problems that are numerous and complex. Drought, coupled with the groundnut rosette epidemic in 1975, resulted in a decline in groundnut production. This has led to a southward shift of the suitable climatic zone for groundnut production. Heavier soils in the south compared with the sandy soils of the Sudan savanna make harvesting difficult, however. Diseases such as the rosette, early leaf spot, late leaf spot and rust have been on the increase. Leaf spot attack severely reduces yield.

10.2.1.2.5 *Indonesia*

Groundnut is the second most important food legume crop after soybean in Indonesia (Machmud and Rais, 1994). Groundnut is grown mostly at low Elevations (up to 500 m) in nine provinces: West

Java, Central Java, Yogyakarta, East Java, South Kalimantan, Lampung, Bali, West Nusa Tenggara and South Sulawesi. The total annual rainfall figures in the leading production areas range from 2 208 to 3 442 mm. Most of the groundnut (66 per cent) is produced under rainfed conditions (Saleh and Adisarwanto, 1995). In drier areas, groundnut is generally grown in mixed cropping with maize or cassava, whereas in wetter areas, it is generally grown during the dry season as a single crop. Farmers grow mostly small-seeded and early-maturing varieties (85 to 90 days).

As for production constraints, major climatic and biotic constraints identified for low production are: drought during the reproductive stage; diseases such as leaf spot and rust; and insects such as aphids, jassids and thrips. The major insect pest is *Aproaerema modicella*, and the most important diseases are bacterial wilt (*Pseudomonas solanacearum*), leaf spot (*Cercospora* sp.), rust (*Puccinia arachidis*) and groundnut mottle virus.

10.2.2 Agroclimatology of groundnut

Groundnut is essentially a tropical plant and requires a long and warm growing season. The favourable climate for groundnut is well-distributed rainfall of at least 500 mm during the crop-growing season, accompanied by an abundance of sunshine and relatively warm temperature. Temperature in the range of 25°C to 30°C is optimum for plant development (Weiss, 2000).

Once established, groundnut is drought-tolerant, and to some extent it also tolerates flooding. Rainfall of 500 to 1 000 mm will allow commercial production, although crop can be produced on as little as 300 to 400 mm of rainfall. Groundnut thrives best in well-drained sandy loam soils, as light soil helps in easy penetration of pegs and their development and their harvesting. The productivity of groundnut is higher in soils with pH between 6.0 and 6.5.

10.2.2.1 Rainfall or soil moisture

Rainfall is the most significant climatic factor affecting groundnut production, as 70 per cent of the crop area is found in semi-arid tropical regions characterized by low and erratic rainfall. Low rainfall and prolonged dry spells during the crop growth period were reported to be main reasons for low average yields in most of the regions of Asia and Africa, including India (Reddy et al., 2003), China (Zeyong, 1992) and several parts of Africa (Camberlin and Diop, 1999). Zeyong (1992) reported that drought is the most important constraint on groundnut production in

China, especially in parts of northern China where rainfall is less than 500 mm yr⁻¹. Naing (1980) reported that rainfall was the main factor determining yield in Myanmar. Camberlin and Diop (1999) reported that after removing decadal trends, almost half of the variance in groundnut production in Senegal can be explained by rainfall variability, especially during the early part of the rainy season (July–August). Persistent droughts and insufficient rainfall represent one of the greatest constraints on groundnut crop in Senegal. Groundnut requiring average rainfall of 600–1 200 mm per year under Senegal's climatic conditions is receiving 500–700 mm of rainfall per year (Badiane, 2001). Duivenbooden et al. (2002) reported that groundnut production in Niger is significantly determined by rainfall from July to September.

In India groundnut yields were reported to be vulnerable from year to year because of large interannual variation in rainfall (Sindagi and Reddy, 1972). Bhargava et al. (1974) reported that 89 per cent of yield variation over four regions of India could be attributed to rainfall variability in the August to December growing period. Challinor et al. (2003), analysing 25 years of historical groundnut yields in India in relation to seasonal rainfall, concluded that rainfall accounts for over 50 per cent of variance in yield. Gadgil (2000) observed that the variation in groundnut yield in the Anantapur district arises to a large extent from the variation in the total rainfall during the growing season. It was observed that seasonal rainfall up to 50 cm is required to sustain a successful groundnut crop in this region.

Yield in this region can be indirectly related to El Niño events: in 87 per cent of El Niño years the Anantapur region received less than 50 cm of rainfall, which in turn affected the groundnut yield. In Anantapur, the pod yield of groundnut showed a highly significant curvilinear relationship with the use of moisture, namely, adding rainfall and soil moisture (AICRPAM, 2003). A total moisture use of 350–380 mm was found to be optimum for obtaining a maximum yield; a moisture use of either less than this amount or more reduced pod yield. Nonetheless, Popov (1984) and Ong (1986) showed a poor relationship between groundnut yield and seasonal rainfall, thus highlighting that rainfall distribution is more important to groundnut yield than the amount of rainfall.

The importance of rainfall distribution to groundnut yield is well appreciated, but experimental evidence is poorly documented (Ong, 1986). Work in a controlled environment at Nottingham University, United Kingdom, showed a crop yield to be four times greater than the yield of a crop

that used the same amount of water, but was irrigated during the vegetative phase only (ODA, 1984). Results from a series of experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, 1984) showed that early stress or lack of rainfall/soil moisture between 29 and 57 days after sowing did not influence pod yield significantly, whereas pod yields increased by 150 kg/ha/cm of water applied during the seed-filling stage (93–113 days after sowing). The pod yield of groundnut and rainfall received between pod formation and maturity were positively correlated in a rainfed crop grown in the semi-arid region of Andhra Pradesh in India (Subbaiah et al., 1974).

In the subtropical environment of south-east Queensland, Australia, soil water deficits occurring during flowering and up to the start of the pod growth phase significantly reduced pod yields (in a range of 17–25 per cent) relative to the well-watered control plots for two Spanish and two Virginia cultivars (Wright et al., 1999). The reduction in yield was greatest when severe stress occurred during the pod-filling phase. Several other reports also observed the pod development stage to be most sensitive to moisture deficit (Rao et al., 1985; Stirling et al., 1989; Patel and Gangavani 1990; Meisner 1991; Ramachandrapappa et al., 1992). Analysis of the relationship between simulated groundnut yield and climate in Ghana showed that yield was predominantly influenced by rainfall from flowering to maturity (Christensen et al., 2004). Naveen et al. (1992) found that water stress imposed during the flowering and pegging stages of JL-24 produced the greatest reductions in pod yield, followed by water stress at early and late pod stages.

Prabawo et al. (1990) reported that irrigation applied before and/or after early pod-filling stages increased pod yields of Spanish-type groundnuts (100 day) to 2.4 t ha⁻¹ compared with 0.53 t ha⁻¹ in a dryland groundnut crop. Nageswara Rao et al. (1985) confirmed that irrigations could be withheld during much of the vegetative period without any apparent effect on pod yield, implying that water stress during the vegetative stage has no effect on yield. Nautiyal et al. (1999) proved that soil moisture deficit for 25 days during the vegetative phase was beneficial for growth and pod yield of groundnut, while Stirling et al. (1989) observed the insensitivity of pod yield to early moisture deficit. Sivakumar and Sharma (1986) imposed drought stress or a soil moisture deficit at all the growth phases of groundnut during three growing seasons and observed that stress from emergence to pegging gave increased yields relative to the control group in the three years of the study, while stress at other stages decreased the yield.

Not just yields, but other yield attributes, growth and development are affected by soil moisture deficit or water stress. The start of flowering and pod elongation are delayed by drought stress (Boote and Ketring, 1990). The rate of flower production is reduced by drought stress during flowering but the total number of flowers per plant is not affected due to an increase in the duration of flowering (Gowda and Hegde, 1986; Meisner and Karnok, 1992). Boote and Hammond (1981) reported a delay of 11 days in flowering when drought was imposed between 40 and 80 days after sowing. Stansell and Pallas (1979) found that the percentage of mature kernels was reduced to 34 per cent of the control when drought was imposed 36–105 days after sowing.

Moisture stress also affects physiological characteristics such as photosynthesis, stomatal conductance, leaf water potential, radiation- and water-use efficiencies, and partitioning of dry matter (Williams and Boote, 1995). Bhagsari et al. (1976) observed large reductions in photosynthesis and stomatal conductance as the relative water content of groundnut leaves decreased from 80 to 75 per cent (due to moisture stress). Subramanian and Maheswari (1990) reported that leaf water potential, transpiration rate and photosynthesis rate decreased progressively with increasing duration of water stress. Black et al. (1985) recorded lower water potential and stomatal conductance when moisture stress was imposed. Clavel et al. (2004) reported that water deficit decreased leaf area index, relative water content and transpiration about three weeks after the occurrence of water deficit at the soil level.

Collino et al. (2001) observed that the fraction of photosynthetically active radiation intercepted and the harvest index were reduced under water stress. In Argentina, under water stress conditions, groundnut varieties (Florman INTA and Manfredi 393 INTA) produced significantly reduced water use efficiency compared with the irrigated regime (Collino et al., 2000). Vorasoot et al. (2003) observed a drastic reduction in yield and also in yield-attributing characteristics such as total dry weight and shelling percentage when plants were grown at 25 per cent of the field capacity of the soil.

10.2.2.2 Growth stages and water use

The growth stages of groundnut were described and defined by Boote (1982). This widely adopted system describes a series of vegetative (V) and reproductive (R) stages. The total water use by a groundnut crop is controlled by climatic conditions, in addition to

agronomic and varietal factors. A summary of the reported water use of groundnut (reproduced from Sivakumar and Sharma, 1986) in Table 10.2.1 shows that water use varies from 250 mm in the rainfed conditions to 830 mm under irrigated conditions (with irrigation at weekly intervals). Naveen et al. (1992) reported that spraying of 3 per cent kaolinite during dry periods at 35 and 55 days after sowing showed significant yield increases over control.

From the lysimetric studies in groundnut (ICGS-76) at Rakh Dhiansar, in the Jammu region of India, water requirements for the crop were estimated at 494 mm and 500 mm in two individual years and water use for the crop was observed to be at its highest (crop coefficient 1.9) during the pod formation stage (AICRPAM, 1997, 1998). In FAO Irrigation and Drainage Paper No. 33 (FAO, 1979), Doorenbos and Kassam worked out water requirements for each growing stage, as well as the total water requirement for the crop. The water requirement of the crop ranged from 500 to 700 mm for the total growing period. The growing period of the crop is divided into five stages.

The stages, their duration and crop coefficients for individual stages are presented in Table 10.2.2. Data in this table show that the midseason stage (pod formation and filling) requires higher water quantities, as indicated by the high crop coefficient value. In a field experiment conducted during two summer seasons in eastern India with JL-24, a bunch variety, water use recorded for three treatments with applied irrigation of 0.9, 0.7 and 0.5 of cumulative pan evaporation was equal to 434, 391 and 356 mm, respectively (Bandopadhyay et al., 2005). A maximum average crop coefficient (K_c) value of 1.19 occurred around nine weeks after sowing in the same experiment.

10.2.2.3 Temperature

Temperature has been identified as a dominant factor for controlling the rate of development of groundnut (Cox, 1979). Every crop has its cardinal temperatures, which are the base (T_b), optimum (T_o) and maximum temperatures (T_m). These are defined respectively as: temperatures above which growth and development begin, temperatures at which growth and development are maximum, and temperatures above which growth

Table 10.2.1 Summary of reported values of total water use (mm) for groundnut (Sivakumar and Sharma, 1986)

<i>Reference</i>	<i>Total water use (mm)</i>	<i>Remarks</i>
Ali et al. (1974)	530	Irrigated at 60% water depletion
Angus et al. (1983)	250	Rainfed
Charoy et al. (1974)	510	Rainfed
Cheema et al. (1974)	337	Rainfed
	597	Irrigated at 40% water depletion
Kadam et al. (1978)	342	Rainfed
Kassam et al. (1975)	438	Rainfed
Reddy et al. (1980)	560	Irrigated, winter months
Reddy et al. (1978)	417	Rainfed
Reddy and Reddy (1977)	505	Irrigated at 25% water depletion
Panabokke (1959)	404	October to January
Keese et al. (1975)	500–700	Irrigated at 50% water depletion
Samples (1981)	450–600	Irrigated at 50% water depletion
Nageswara Rao et al. (1985)	807–831	Irrigated at 7–10 day interval during winter months

Table 10.2.2. Crop coefficients (K_c) per crop stage for groundnut

<i>Crop Stage</i>	<i>Duration (days)</i>	<i>Crop coefficients</i>
Initial stage	15–35	0.4–0.5
Development stage	30–45	0.7–0.8
Midseason stage	30–50	0.95–1.1
Late-season stage	20–30	0.7–0.8
Harvest stage	—	0.55–0.6

and development cease. Mohamed (1984) reported cardinal temperatures for seed germination in 14 contrasting genotypes of groundnut, which are shown in Table 10.2.3. These values indicate that T_b does not vary much across genotypes (ranging from 8°C to 11.5°C), whereas optimum temperatures (29°C–36.5°C) and maximum temperatures (41°C–47°C) vary much more. Base temperature was reported to be higher during the reproductive phase (3°C–10°C higher) than during the vegetative phase (Angus et al., 1981). In contrast, Leong and Ong (1983) showed T_b to be conservative for many processes and phases of groundnut cv Robut 33–1. Optimum temperatures for different growth and developmental processes of the crop are presented in Table 10.2.4. Optimum temperatures for different processes range between 23°C and 30°C. Optimum temperature for germination and leaf appearance was observed to be higher than for other processes. Williams et al. (1975) reported that the optimum temperature for vegetative growth of groundnut plants was in the range of 25°C–30°C, while that for reproductive growth was lower (20°C–25°C).

Table 10.2.3. Base (T_b), optimum (T_o) and maximum (T_m) temperatures of 14 groundnut cultivars for seed germination (Mohamed, 1984)

<i>Cultivars</i>	T_b	T_o	T_m
Valencia R2	8	35	43
Flammings	8	34.5	42
Makulu Red	8.5	29	42
ICG 30	8	36	44
EGRET	9	29	43
ICG 47	9	36.5	47
Robut 33–1	10	36.5	46
TMV 2	10	36	42
MK 374	10	36	44
Plover	10.5	34	42
ICG 21	11	35.5	45
M 13	11	34	45
Swallow	11	29	42
N. Common	11.5	29	41
Ranges	8–11.5	29–36.5	41–47

Table 10.2.4. Optimum temperature for vegetative and reproductive growth and development of groundnut

<i>Trait</i>	<i>Optimum t (°C)</i>	<i>Reference</i>
Seed germination	28–30	Mohamed et al., 1988
Seedling growth	28	Leong and Ong, 1983
Leaf appearance and leaf area development	28–30	Fortainer, 1957; Cox, 1979 Leong and Ong, 1983; Ketring, 1984;
Branching and stem growth	28	Leong and Ong, 1983
Flower production	25–28	Fortainer, 1957; Wood, 1968; Cox, 1979
Pollen production	23	Prasad et al., 1999
Pollen viability	23	Prasad et al., 1999, 2000; Kakani et al., 2002
Peg formation	23	Prasad et al., 1999
Pod formation, pod growth and seed yield	23–26	Williams et al., 1975; Cox, 1979; Dreyer et al., 1981 Prasad et al., 1999, 2003
Root growth	23–25	Ahring et al., 1987; Prasad et al., 2000
Harvest index	23–27	Prasad et al., 1999; Craufurd et al., 2002 Prasad et al., 2003
Nitrogen fixation	25	Nambiar and Dart, 1983

The duration of the crop is very much influenced by temperature. Bell et al. (1992) reported an early bunch variety that matures in 120–130 days after sowing at a mean temperature of 23°C, while the same variety matures in 105 days after sowing when grown in a coastal environment with slightly higher mean temperatures (25°C). Other authors have also reported such strong effects of temperature on groundnut phenology (Leong and Ong, 1983; Bagnall and King, 1991). Crop duration was shortest in humid tropical and subtropical environments, with crop maturity apparently affected by both high and low temperatures (Bell and Wright, 1998). Williams et al. (1975) reported that the total growing period of the crop was shortened from 176 days at a temperature of 18°C to 151 days at 23°C. The duration of groundnut cv Robut 33-1 from sowing to the end of seed filling increased from 95 days at 31°C to 222 days at 19°C. Not only was the duration of the crop influenced by temperature, but also the growth and yield traits. Craufurd et al. (2000) exposed eight genotypes to either high (day/night temperature of 40°C/28°C) or optimum (30°C/24°C) temperature from 32 days after sowing to maturity and reported that rates of appearance of leaves and flowers were faster at 40°C/28°C when compared with 30°C/24°C. As groundnut pods are developed under the soil, it is important to understand the influence of soil temperature. Prasad et al. (2000) reported that exposure to high air and/or high soil temperature (38°C/22°C) significantly reduced total dry matter production, partitioning of dry matter to pods, and pod yields in two cultivars. High air temperature had no significant effect on total flower production but significantly reduced the proportion of flowers setting pegs (fruit set), while in contrast, high soil temperature significantly reduced flower production, production of pegs forming pods, and 100-seed weight. Furthermore, the effects of high air and soil temperatures were mostly additive. Higher temperature promoted greater vegetative growth and higher photosynthesis in three genotypes of groundnut, but the reproductive growth was decreased due to greater flower abortion and smaller seed size (Talwar et al., 1999; Prasad et al., 2003).

The groundnut variety ICGV 86015 exposed to short episodes (1 to 6 days) of heat stress showed a strong negative linear relation between day temperature over the range of 28°C to 48°C and characteristics such as number of flowers, proportion of flowers setting pegs, number of pegs and pods per plant, pollen production per flower and pollen viability (Prasad et al., 1999, 2001). The periods of microsporangogenesis (3 days before anthesis) and flowering

were identified as the most sensitive stages of high temperature stress in groundnut (Prasad et al., 2001). Karunakar et al. (2002) reported that yield attributes such as number of effective pegs, developed pod numbers and pod dry weight per plant of groundnut grown under semi-arid tropical conditions in India were positively influenced by minimum temperature and relative humidity during the crop growing period. Among the four cultivars of Spanish or Virginia groundnut types (Chico, Manipintar, early bunch and McCubbin) tested in a subtropical environment in Queensland, Australia, all varieties except Manipintar showed lower radiation use efficiency (RUE) with a decrease in minimum temperatures (Bell et al., 1993). The responses of pollen germination and pollen tube growth to temperature were quantified by Kakani et al. (2002) for identifying heat-tolerant groundnut genotypes.

A modified bilinear model most accurately described the response of percentage pollen germination and maximum pollen tube length to temperature. Based on temperature response, genotypes 55-43, ICG 1236, TMV-2 and ICGS 11 were grouped as tolerant to high temperature and genotypes Kadiri-3, ICGV 92116 and ICGV 92118 were grouped as susceptible genotypes. Ntare et al. (2001) observed that the pod yield of most of the 16 genotypes of groundnut tested under actual field conditions of the Sahelian region of Africa declined by more than 50 per cent when maximum temperatures averaged around 40°C and occurred during flowering and pod formation. Craufurd et al. (2002) observed that high temperature (38°C/22°C) from 21 to 90 days after planting reduced total dry weight by 20 to 35 per cent, seed harvest index by 0 to 65 per cent and seed dry weight by 23 to 78 per cent. Genotypic differences in response to temperature were noticed and reductions in total dry matter, pod and seed dry weight and harvest index at high temperatures were noticed only in susceptible genotypes.

The interactive effects of temperature and other environmental factors are less understood and need further attention. Prasad et al. (2003) studied the effects of temperature in combination with elevated CO₂ on various physiological and yield processes of groundnut. At ambient CO₂ (350 ppm CO₂), seed yield decreased progressively by 14 per cent, 59 per cent and 90 per cent as temperature increased from 32°C/22°C (daytime maximum/night-time minimum) to 36°C/26°C, 40°C/30°C and 44°C/34°C, respectively. A similar percentage decrease in seed yield occurred at temperatures above 32°C/22°C at elevated CO₂, despite greater photosynthesis and vegetative growth at elevated CO₂. The seed harvest index decreased from 0.41 to 0.05 as temperature

increased from 32°C/22°C to 44°C/34°C under both ambient and elevated CO₂. A 30 per cent decrease in pod yield was observed due to lower thermal and photoperiodic conditions during the reproductive phase of groundnut (AICRPAM, 1998).

Similarly, temperature (expressed as degree-day) and rainfall during the reproductive period positively influenced the pod yield and together they explained 86 per cent of yield variation (AICRPAM, 1997). Temperature and light intensity affected flower numbers of groundnut varieties and these changes were also well correlated with growth-related changes in leaf number and pod dry weight (Bagnall and King, 1991). In crop models, the optimum temperature for canopy photosynthesis was between 24°C and 34°C (daytime mean temperature), with linear reductions below 24°C down to 5°C and with linear reductions above 34°C up to 45°C (Boote et al., 1986). Vijaya Kumar et al. (1997), while analysing the variability of groundnut yield at three locations across varied soil and climatic conditions in relation to temperature and rainfall, observed that the Bangalore region, despite experiencing higher rainfall than the Anantapur and Anand regions, had a lower average pod yield owing to mean temperatures that were lower than optimum.

10.2.2.4 Thermal time or accumulated heat unit requirements of groundnut

Phenological development of groundnut responds primarily to heat unit accumulation. Leong and Ong (1983) calculated heat unit requirements for different phenological stages (Table 10.2.5). Two papers reporting on heat units to flowering for groundnut have suggested a base temperature of 13°C–14°C, below which reproductive development stops (Emery et al., 1969; Mills, 1964). In 16 sowings ranging from the wet tropics in Indonesia to the elevated subtropics in Australia, the harvest date corresponded to the accumulation of about 1 800

(base temperature of 9°C) growing degree-days (GDD) after sowing (Bell and Wright 1998).

Thermal units required for groundnut cultivars to reach maturity were 2 247 GDD in Sudan (Ishaq, 2000). Ong (1986) reported a maturity index or thermal units of 2 000 GDD for the cultivars in warm regions of India – at a base temperature of 10°C. The varieties TMV-2 and Robut 33-1 grown in the semi-arid Anantapur region of India required 1 732 GDD and 1 839 GDD, respectively (AICRPAM, 1998). In the same year, Robut 33-1 grown in Bangalore, a semi-arid region of India, took 1 491 GDD. The thermal time requirement for maturity of the same variety seems to be different for different sowing dates and locations.

10.2.2.5 Photoperiod or day length

Early studies in controlled environments showed that phenology of groundnut is not affected by day length (Fortainer, 1957). Later studies showed that pod yield is significantly influenced by day length, however (Ketring, 1979; Witzemberger et al., 1988). It is now well established that long days promote vegetative growth at the expense of reproductive growth and increased crop growth rate, decreased partitioning of photosynthesis to pods, and decreased duration of effective pod-filling phase (Ketring, 1979; Witzemberger et al., 1988; Nigam et al., 1994, 1998). Some contradictory results on the influence of day length on the duration of reproductive growth were reported. While Sengupta et al. (1977) found that a day length shorter or longer than 10 h delayed flowering, Ketring (1979) did not observe any effect of day length (8, 12 and 16 h) on flower initiation. The contrasting results might have been obtained due to differences among cultivars, which are known to vary in response to photoperiod.

In a study by Bagnall and King (1991), flower, peg and pod numbers were consistently enhanced by

Table 10.2.5. Thermal time requirement in GDDs for several developmental processes of the groundnut variety cv Robut 33-1 (Leong and Ong, 1983)

<i>Developmental process</i>	<i>Thermal time (GDDs)</i>
Leaf production	56 per leaf
Branching	103 per branch
Time to first flowering	538
Time to first pegging	670
Time to first podding	720

short-day treatments for a range of groundnut varieties. Flower and peg numbers at 60–70 days from emergence were approximately doubled after 12 h day exposures compared to plants with 16 h days. The pod number, and therefore the yield, was more influenced by photoperiod than was flower or peg formation. Bell et al. (1991), while studying the effects of photoperiod on reproductive development of groundnut in a cool subtropical environment, observed that the numbers of pegs and pods and total pod weight per plant were reduced in long (16 or 17 h) photoperiods, but no effect of photoperiod was evident on time to first flower. It was further observed that the photoperiod responses were more significant in the environments where daily accumulations greater than 34°C–35°C were observed. Nigam et al. (1994) studied the effect of temperature and photoperiod and their interaction on plant growth, as well as partitioning of dry matter to pods, in three selected groundnut genotypes grown in growth chambers. It was observed that photoperiod did not significantly affect partitioning of dry matter to pods under a low temperature regime (18°C–22°C), but at higher temperatures (26°C–30°C) partitioning to pods was significantly greater under short days (9 h). This study provided evidence of genotypic variability for photoperiod–temperature interactions. In a field study on the effect of photoperiod on seed quality (Dwivedi et al., 2000), shelling percentage and palmitic acid increased under short-day (8 h) treatment compared with normal-day (12 h) treatment, while oil content, oleic and linolenic fatty acids and their ratio were unaffected.

10.2.2.6 Saturation deficit

Saturation deficit (SD) is an important agroclimatic factor for any crop, including groundnut, because it is a major determinant of potential evapotranspiration. Stomatal response to SD was found to limit the actual rate of transpiration (Black and Squire, 1979). Large SD accelerated the depletion of soil moisture reserves in the non-irrigated stands and greatly reduced leaf area index of groundnut, particularly in the driest treatment (Ong et al., 1985). Leaf number per plant and leaf size both decreased as SD increased, but SD had a greater impact on leaf size than on number. Turgor potential and leaf extension rate were also reduced at high SD. In another study on responses to SD conducted in glasshouses, developmental processes such as the timing of flowering, pegging and pod formation were found to be unaffected by SD, but the number of branches, flowers and pegs were reduced in the drier treatments (Ong et al., 1987). In the same study, in unirrigated stands, dry matter production in shoots was reduced by

40 per cent as the maximum SD increased from 1.0 to 3.0 kPa. Productivity per unit of water transpired decreased with increasing SD. Simmonds and Ong (1987) reported a strong dependence of transpiration on SD in groundnut and when SD exceeded 2 kPa, canopy expansion was restricted.

10.2.3 Further background information on groundnut

10.2.3.1 Relationship between diseases and weather

Several diseases and insect pests causing large losses in both yield and quality of seeds affect the groundnut crop. Weather indirectly influences the yield and quality through its effects on the occurrence and development of diseases and pests. Kolte (1985) reviewed diseases of groundnut in relation to weather conditions. The important plant diseases and meteorological conditions affecting them are described in this section.

10.2.3.1.1 Early and late leaf spots

Early and late leaf spots (*Cercospora arachidicola* and *Puccinia personate*) are considered the most important diseases of groundnut. They have been reported throughout the groundnut-growing areas of the world. Leaf spots cause huge yield loss in groundnut due to severe defoliation. Weather conditions conducive to the occurrence of early and late leaf spots as reported by different researchers are summarized in Table 10.2.6, which basically conveys that rainfall, leaf wetness and temperature are the most important factors for the occurrence and epidemiology of leaf spots.

10.2.3.1.2 Rust

Rust (*Puccinia arachidis*) has now become a disease of major economic importance in almost all the groundnut-growing areas of the world. It becomes devastating under conditions of high rainfall and humidity. In the *postrera* planting season in Honduras and Nicaragua of Central America (Arneson, 1970) and in Venezuela, this disease becomes severe when the rainy season is almost over or when dew is abundant (Hammons, 1979). In India, a continuous dry period characterized by high temperature (>26°C) and low relative humidity (<70 per cent) is reported to delay rust occurrence and severity, whereas intermittent rain, high relative humidity and 20°C to 26°C temperature favour disease development (Siddaramaiah et al., 1980). In the Parbhani region of Maharashtra, India, Mayee (1987) observed that if average temperature of 20°C–22°C, relative

Table 10.2.6. Summary of the relationships between leaf spots and weather conditions

<i>Country</i>	<i>Disease</i>	<i>Weather conditions</i>	<i>Reference</i>
India	Early and late leaf spots	High relative humidity and dew	Wangikar and Shukla (1977)
United States	Early and late leaf spots	Rainfall and leaf wetness	Jensen and Boyle (1965)
Nigeria	Early leaf spots	Rainfall, relative humidity and low temperature	Garba et al. (2005)
India	Early and late leaf spots	Max. temp.: 31°C–35°C, Min. temp.: 18°C–23°C mean monthly rainfall of at least 60 mm	Venkataraman and Kazi (1979)
United States	Early and late leaf spots	Rainfall	Davis et al. (1993)
United States	Early and late leaf spots	Rainy days between June and September	Johnson et al. (1986)
United States	Early leaf spot	Shortly after the onset of rainfall	Smith and Crosby (1973)
India	Late leaf spot	Leaf wetness index of 2.3 or more	Butler et al. (1994)
India (Central)	Leaf spots	200–500 mm rainfall, 25°C–30°C temperature and 74% to 87% RH during crop season	Lokhande and Newaskar (2000); Mayee (1985)
United States	Leaf spots	No. of hours with RH > or = 95% and minimum temperature	Jensen and Boyle (1966)
United States	Leaf spots	Temperature >16°C and leaf wetness	Alderman and Beute (1986); Shew et al. (1988)
India	Leaf spots	Decrease in maximum temperature and increase in relative humidity	Adiver et al. (1998)
India	Late leaf spot	Temperature	Mayee (1989)
United States	Leaf spots	Rainfall, RH 80% and mean temp. of 23.2°C	Frag et al. (1992)
United States	Early leaf spots	Temperature and duration of wetness	Wu et al. (1999)
United States	Early leaf spots	Nearly 100% humidity and 16°C–25°C temperature	Alderman and Beute (1987)
India	Leaf spots	Max. temp. <34°C, min. temp. <22°C, morning RH >82% and afternoon RH >78%	Samui et al. (2005)

humidity above 85 per cent and three rainy days in a week prevail for two weeks, an outbreak of rust is likely. In the same region, on the basis of long-term observations of rust and weather conditions, key factors in the outbreak of rust were outlined (Sandhikar et al., 1989). If these conditions prevail for a week, an outbreak of rust is likely to occur within the next 15 days.

Mayee and Kokate (1987) observed that the incubation period of *Puccinia arachidis* causing groundnut rust lengthened as the mean or maximum temperature rose, while it was negatively correlated with relative humidity. Multiple regression analysis of different combinations of environmental factors, including rainfall and evaporation rates, explained more than 96 per cent of the observed variation in incubation period. Mayee (1986) reported that the leaf rust epidemic commonly occurs during a prolonged dry spell after heavy showers. In their study of the influence of rainfall, temperature and relative humidity on groundnut leaf rust epidemiology, Lokhande et al. (1998) observed that rainfall of about 200 mm, temperature between 23.5°C and 29.4°C, and relative humidity in the range of 67 to 84 per cent are favourable weather conditions for initiation and development of this disease.

10.2.3.1.3 *Sclerotinia blight*

Sclerotinia blight (*Sclerotinia minor*) occurs throughout groundnut-growing areas of the world in the tropics and in warmer parts of the temperate zone. Moisture, temperature and inoculum in the soil exert considerable influence on the disease (Onkarayya and Appa Rao, 1970). Moisture, soil temperature, vine growth and foliar canopy have been identified as factors that contribute to the onset and progress of this disease (Dow et al., 1988; Lee et al., 1990; Phipps, 1995a; Bailey and Brune, 1997). A study by Phipps (1995a) showed that rainfall usually preceded disease onset by 6 to 15 days in non-irrigated fields. Maximum and minimum air temperatures over the 15-day period prior to disease onset fluctuated between 32°C and 20°C, while maximum and minimum soil temperatures were between 30°C and 25°C, respectively. Optimum temperatures for sclerotial germination and infection of groundnut by *S. minor* have been reported to be between 20°C and 25°C (Dow et al., 1988). In Texas, *S. minor* was reported to be inactive in groundnut fields when soil temperature exceeded 28°C at the 5 cm depth (Lee et al., 1990). Although both moisture and temperature are commonly mentioned as significant factors affecting development of sclerotinia blight, evidence in the Virginia groundnut production area suggests that plant growth and rainfall are the primary forces

at work in triggering outbreak of this disease (Phipps, 1995a).

10.2.3.1.4 *Collar rot*

High soil and air temperatures predispose the groundnut plants to collar rot infection (*Aspergillus niger*) (Kolte, 1985). Development of different symptoms is dependent on temperature. Maximum seed rot occurs from 15°C to 40°C, whereas the collar rot infection appears most severe at 31°C to 35°C (Chohan, 1969).

10.2.3.1.5 *Moulds causing aflatoxin contamination*

Aflatoxin contamination of groundnut is a major problem in most of the groundnut-producing regions across the world. The occurrence of drought during the late seed-filling period is a key contributing factor. It is caused by the growth of the moulds *Aspergillus flavus* and/or *Aspergillus parasiticus*. Toxicity of groundnut from aflatoxin endangers the health of humans and animals and lowers market value (for example, Abdalla et al., 2005). Hence, it is a problem for groundnut producers as well as consumers. The moulds are common saprophytic fungi found in soils throughout the major groundnut-growing areas of the world (Pettit and Taber, 1973; Griffin and Garren, 1974). Pettit (1986) reviewed the influence of changing environmental conditions on the activity of the moulds affecting groundnuts. Aflatoxin is more serious during and following alternating dry and wet periods, namely, droughts following showers.

Pettit et al. (1971) observed that peanuts grown under dryland conditions and subjected to drought stress accumulated much more aflatoxin before digging than peanuts grown under irrigation. Wilson and Stansell (1983) reported that water stress during the last 40–75 days of the crop contributed to higher aflatoxin levels in mature kernels. Sanders et al. (1993) reported aflatoxin contamination in groundnut when pods were exposed to drought stress, although roots of the crop were well supplied with moisture. In a field study in Niger, Craufurd et al. (2006) confirmed that infection and aflatoxin concentration in peanut can be related to the occurrence of soil moisture stress during pod filling when soil temperatures are near optimal for *Aspergillus flavus*.

Cole and his colleagues (Cole et al., 1985, 1989; Dorner et al., 1989) have shown that pre-harvest contamination of aflatoxin requires a drought period of 30–50 days and a mean soil temperature

of 29°C–31°C in the podding zone. In Sudan, the irrigated region (central Sudan) used to be free from aflatoxins, while the rainfed region (western Sudan) showed high levels of aflatoxin contamination (Hag Elamin et al., 1988). In the same study, temperature of 30°C and relative humidity of 86 per cent were identified as optimum conditions for aflatoxin production. Rachaputi et al. (2002) observed aflatoxin contamination to be widespread in the Queensland region of Australia during the 1997–1998 seasons, with severe and prolonged end-of-season drought and associated elevated soil temperature; they observed lower aflatoxin risk during the 1999–2000 seasons, which featured well-distributed rainfall and lower soil temperatures.

10.2.3.2 Insect pests

Major insect pests in groundnut are: termites (*Odontotermes*), white grubs (*Lachnosterna consanguinea*), thrips, jassids (*Empoasca kerri*), aphids (*Aphis craccivora*), leaf miners (*Aproaerema modicella*), tobacco caterpillars and red hairy caterpillars (*Amsacta albistriga*). Environmental conditions are important factors in the survival, rate of development and fecundity of various crop pests.

10.2.3.2.1 Leaf miner

In the Anantapur region of southern India, leaf miners emerge during drought periods with no rainy days for more than 21 days between 35 and 110 days after sowing (Gadgil et al., 1999; Narahari Rao et al., 2000). Ranga Rao et al. (1997) also observed leaf miner infestation to be severe during moisture stress conditions. The conditions favourable for leaf miner growth are long dry spells resulting in high temperature and low humidity (Amin and Reddy, 1983). At Anantapur under late-sown conditions, the groundnut leaf miner incidence was significantly and negatively correlated with rainfall and minimum temperature and positively with sunshine hours (AICRPAM, 2001).

10.2.3.2.2 *Heliothis armigera*

Heliothis armigera (Hübner) has become a serious pest on groundnut in recent years. A study of the relationship between seasonal incidence of *Heliothis* and weather parameters (Upadhyay et al., 1989) showed that the *Heliothis* population was positively associated with maximum and minimum temperatures.

10.2.3.2.3 Aphids

Aphid distribution across a drought-stress gradient created by a long line-source overhead irrigation

system (ICRISAT, 1989) showed that aphid density was much higher where most of the irrigation water had been applied and lowest at a point farthest from the water source, where plants were experiencing drought stress. Interestingly, rain falling on plants infected with aphids physically suppresses the aphids' population and a single heavy rainfall event can decrease their density by 90 per cent.

10.2.3.2.4 Red hairy caterpillars (*Amsacta albistriga*)

In the Anantapur region of India, a major groundnut growing region, emergence of red hairy caterpillar (RHC) was found to be closely related to heavy rainfall events (AICRPAM, 1997). The numbers of red hairy caterpillars reached a peak 3 to 4 days after a rain event and the outbreak of RHC could be predicted 8 to 9 days in advance. Red hairy and Bihar caterpillars appear after the onset of pre-monsoon showers in May/June (Padmavathamma et al., 2000).

10.2.3.2.5 *Spodoptera litura*

Under both laboratory and field studies at ICRISAT, Hyderabad, India, lower and upper threshold temperatures for development of *Spodoptera* in groundnut worked out to be 10.5°C and 30°C, respectively (Ranga Rao et al., 1989). The study also approximated the degree-day accumulation requirements for each stage of development of *Spodoptera*-like pre-oviposition females (30), eggs (55), larvae (315), pupae (155) and adult stages (generation time, 550).

10.2.4 Management aspects of groundnut in various environments

10.2.4.1 Protection measures

A history of leaf spot monitoring and forecasting and their increasing use in its control can be followed through the literature (Jensen and Boyle, 1966; Smith et al., 1974; Parvin et al., 1974; Phipps and Powell, 1984; Johnson et al., 1985; Smith, 1986). In 1989, a new advisory programme (89-ADV) that improved leaf spot control through better timing of fungicide sprays was released in Virginia (Cu and Phipps, 1993). This advisory programme was evaluated between 1990 and 1995. These evaluations showed that the programme saves on average three fungicide sprays per season, decreases input cost by 43 per cent and increases net returns by 26 per cent (about US\$ 9 000 per year) compared with the previous programme.

Another approach to providing advice for control of late leaf spots uses the number of days when rainfall exceeds a threshold (Davis et al., 1993). This was the basis for the AU-Pnut advisory developed to schedule initial and subsequent fungicide applications for control of early and late leaf spots. The AU-Pnut advisory uses the number of days with precipitation greater than 2.5 mm and the National Weather Service precipitation probabilities to predict periods favourable for the development of early and late leaf spots (Jacobi et al., 1995). The AU-Pnut advisory can be used to reduce the number of leaf spot fungicide applications and achieve disease control and yield similar to that achieved with the 14-day spray schedule. AU-Pnut advisory II, a modified version of this advisory for partially resistant groundnut cultivars, saved 0.5 and 2.5 sprays per season compared with 21-day and 14-day schedules (Jacobi and Backman, 1995). At ICRISAT, India, Butler et al. (2000), using information from controlled-environment experiments on the response of leaf spots to temperature and leaf wetness periods, formulated a weather-based advisory scheme (WBAS) for control of leaf spots in groundnut. Bailey (1999) developed weather-based advisories using temperature and relative humidity for determining conditions favourable for early leaf spot development in North Carolina, United States. Johnson et al. (1999) used leaf wetness counting for predicting occurrence of late leaf spot in groundnut in the Anantapur region of India. In this study, application of fungicidal spray according to a leaf wetness index resulted in the highest net returns and cost-benefit ratio.

Ghewande and Nandagopal (1997), based on a research review of integrated pest management of groundnut in India, reported that intercrops of groundnut with pearl millet and soybean suppress the population of thrips, jassids and leaf miner. Intercrops with castor suppress jassids and *Spodoptera*, while those with pigeon pea suppress early leaf spot, late leaf spot and rust. Wider row spacing of 50 × 30 cm and late-maturing and spreading-type varieties were found to be effective in reducing *Cercospora* leaf spot compared to narrow spacing (50 × 20 cm) and early-maturing and erect varieties under Nigerian conditions (Garba et al., 2005). Intercropping of groundnut with sorghum and pearl millet can reduce the incidence of *P. arachidis* (Reddy et al., 1991). Padmavathamma et al. (2000) suggest the following management for controlling hairy caterpillars in groundnut: pre-monsoon deep ploughing to expose hibernating pupae to sunlight and predators; growing trap crops like cowpea, castor and jatropha on field bunds to trap and kill caterpillars; forming a deep furrow trench around the fields and dusting with 2 per cent methyl parathion to prevent mass migration of caterpillars.

In Virginia, United States, an algorithm was developed to produce daily advisories for warning groundnut growers of the risk for *Sclerotinia* blight disease onset and the need for fungicide application (Phipps, 1995b). This algorithm uses environmental factors, such as RH and soil temperature, and the condition of the host plant, including vine growth and density of foliar canopy. Based on the success of this advisory programme in providing early warning conditions for disease onset at many locations, it was released to growers in 1996. In Georgia, United States, an algorithm was also developed for predicting outbreaks of *Sclerotinia* blight and improving the timing of fungicides to control it (Langston et al., 2002). In this algorithm, disease risk is calculated by multiplying indices of moisture, soil temperature, vine growth and canopy density each day. Algorithm-based sprayings have proven to be more efficient than the calendar-based sprays usually practiced.

The preceding steps are just examples of what is possible in combating groundnut crop blight and insect pests. Where farmers have successfully used these advisories, they are already examples of agrometeorological services. In Nigerian conditions, the significant relationship established between aflatoxin concentration and plant-extractable soil water (using the CROPGROW model) formed the basis for developing a decision support system to predict aflatoxin concentration in groundnut (Craufurd et al., 2006). Nageswara Rao et al. (2004) have used a similar approach to model the risk of contamination of aflatoxin in Queensland, Australia, using the Agricultural Production Systems Simulator (APSIM) crop simulation model; they have shown how farmers in Queensland can manage aflatoxin given a decision support system (DSS). In Queensland, Rachaputi et al. (2002) identified early harvest and threshing as best management practices for minimizing aflatoxin contamination under high aflatoxin risk conditions. In general, early sowing or early harvest and even supplementary irrigation (if available) are possible ameliorating practices for reducing the risk of aflatoxin.

10.2.4.2 Improvement measures

The paragraphs below provide some examples of management improvement issues. These are not in the form of any advice directed at farmers or decision support systems, however.

10.2.4.2.1 Sowing time

In Nigeria, when it is sown with early rains, the crop invariably takes advantage of higher solar radiation and warmer temperatures to become well

established. According to Kowal and Knabe (1972), the optimum time to begin cropping with little or no drought risk in Nigerian conditions may be defined in terms of latitude (X) and expressed by the equation $Y = 1.43X - 1.31$, where Y represents days in dekads (10-day periods). In India, sowing of rainfed and irrigated crop early in the season provided favourable weather conditions for proper growth and yield of groundnut. Delay in sowing by one week from 17 July to 24 July resulted in a linear decrease in pod yield of groundnut (Murthy and Rao 1986). In a crop sown at the normal time (first week of July), the pattern of flowering is regular with two distinct peaks of flowering, whereas in a late-sown crop (end of July), an erratic pattern of flowering occurs. In southern parts of India, November is the best period for sowing the *rabi* crop raised on residual soil moisture, and sowing between December and the end of January is most suitable for obtaining higher yields in irrigated summer crops.

10.2.4.2.2 *Varietal selection*

The choice of a groundnut variety for any particular area depends on matching the variety with the length of the growing season. Groundnut varieties whose growth cycle is longer than the duration of the growing season at a particular location either fail to mature or mature at a time when the soil is too hard to dig the pods. In a majority of the groundnut-growing regions, drought stress affects groundnut production. Under Indian conditions, ICGV 86699, K-134 and TMV-2 were considered drought-tolerant (Reddy and Setty, 1995). Ali and Malik (1992) reported that ICGS (E) 52 and ICGS (E) 56 were promising short-duration varieties that could escape end-of-season drought in rainfed areas of Pakistan. Schilling and Misari (1992) reported that short-duration and erect varieties like 55-437, released in Cameroon, Chad, Gambia, Niger and Nigeria; varieties 73-30 and 73-73, released in West Africa; and ICGS (E) 30 and ICGS (E) 60, released in Botswana, are drought-tolerant.

10.2.4.2.3 *Plant population*

The optimum population of groundnut differs with genotype. A short-duration Spanish cultivar, McCullin, showed yield response up to 40 000 plants ha^{-1} . The optimum population for Spanish bunch varieties under rainfed conditions in India is 33 000 plants ha^{-1} (NARP, 1992). Crops grown on residual soil moisture should be planted at lower populations than those grown during rainy seasons. An analysis of data drawn from across the main groundnut-growing areas of Nigeria indicates substantial increases in plant population from the

currently advised population of 47 000 plants ha^{-1} for yield benefits (Yayock and Owonubi, 1983).

10.2.4.2.4 *Scheduling and methods of irrigation*

Maintenance of optimum soil moisture at critical growth stages is the key factor in achieving higher yields. Peak flowering and pod formation stages are more critical stages. After adequate germination moisture is provided through irrigation, a "drought" is imposed by withholding irrigation for 20 days, and relief from the water stress is provided by two irrigations at an interval of five days. This method helps in the development of a deeper root system, synchronized flowering, higher biomass production and higher pod yield (Ghosh et al., 2005). The ratio of irrigation water and cumulative pan evaporation (IW/CPE) for groundnut ranges from 0.6 to 1.0. Ramachandrappa et al. (1993) reported that irrigation should be scheduled at 0.5 IW/CPE during the period 10–40 days after sowing and later on at 0.75 IW/CPE to realize higher pod yields. In the sandy loams to sandy clay loam soils of eastern India, 4 cm of water at 0.9 IW/CPE or 4 cm of water at a 7-day interval are suitable levels of irrigation for growing groundnut (Das, 2004).

The furrow method of irrigation is the most effective with maximum water use efficiency of 3.71 kg $\text{ha}^{-1} \text{mm}^{-1}$; it also saves 2–3 irrigations compared with the border strip and check basin methods (Kathmale and Chavan, 1996). The use of sprinkler and drip irrigation methods is becoming popular since the water requirement in these methods is about half of other irrigation methods, and water use efficiency is high. A yield advantage of 32 per cent over the check basin method was realized with a sprinkler irrigation system (Devi Dayal et al., 1989). Besides a 24.7 per cent savings of irrigation water, the groundnut yield under sprinkler irrigation was 18.8 per cent higher than the yield obtained under surface irrigation (CPRWM, 1984). In the Konkan region of Maharashtra, India, sprinkler irrigation increased pod yields by 20.8 per cent and resulted in a 33 per cent saving of irrigation water compared with the check basin method (Kakde et al., 1989). In the United States, groundnut yields with surface drip irrigation were 1.43 times the non-irrigated yield. The yield gain from surface drip irrigation was 10 kg $\text{ha}^{-1} \text{mm}^{-1}$ (Zhu et al., 2003). At Ludhiana, India, among the different irrigation systems, a trickle irrigation system showed a yield increase of 21 and 11 per cent over conventional and micro-sprinkler irrigation systems, respectively, for summer-planted bunch groundnut cv SG-84 (Narda et al., 2003). Sorensen et al. (2004) reported results of subsurface drip irrigation in the United States.

10.2.4.2.5 *Mulching*

In dryland conditions, traditional practices like contour cultivation in a sloping field, soil mulching, intercultivation and weed control help conserve soil moisture in groundnuts (WMO, 1988). In Rajasthan, Uttar Pradesh, Orissa and West Bengal in India, low soil temperature during the *rabi* season delays germination and high temperature at the pod-filling stage interferes with pod development.

Research conducted at the National Research Centre for Groundnut, Junagadh, India, showed that application of chopped wheat straw at 5 t ha⁻¹ on the soil surface immediately after sowing of groundnut raised soil temperature by 2°C–3°C at seedling emergence and lowered soil temperature by 3°C–5°C during the pod development phase. Under wheat straw mulch, the groundnut crop thus maintained good vigour and growth and gave a yield 20–24 per cent higher than the control (Ghosh et al., 1997). De et al. (2005) found that water hyacinth mulch conserved more soil moisture, maintaining low soil temperatures at soil depth and manifesting higher kernel yield in summer groundnut sown under rainfed conditions in West Bengal, India.

10.2.4.2.6 *Sowing methods*

In high rainfall areas with deep vertisols, broad bed and furrow methods of sowing were found to be more effective than other methods. On average, use of the broad bed and furrow system resulted in a groundnut yield that was 15 per cent higher than the yield from the flat bed method (ICRISAT, 1993). Similarly, in summer-sown groundnut under rainfed conditions of West Bengal, India, the ridge planting method not only maintained slightly higher soil moisture (8.4 per cent) compared with the flat planting method (7.3 per cent), but also produced higher kernel yield of groundnut (0.57 t ha⁻¹) than flat planting (0.42 t ha⁻¹) (De et al., 2005).

10.2.4.2.7 *Shelterbelts*

In drylands of northern China, data spanning 40 years on agri-silvicultural practices with trees, shrubs and woody plants (used as windbreaks) that were planted in combination with groundnut crops showed a groundnut yield increase of between 5.8 and 12.8 per cent due to the windbreaks or shelterbelts (Qi and Tishoon, 2004). A similar study by the Australian Government Rural Industries Research and Development Corporation suggested that incorporation of windbreaks in groundnut farming systems in the Atherton tablelands of Australia

increased groundnut yield by an average of about 12 per cent compared to the control.

10.2.5 **User requirements for agrometeorological information on groundnut**

Up-to-date services of accurate weather data can be an important decision-making aid for all segments of the groundnut industry. In groundnut-growing areas of the United States, before planting crops in the spring, growers routinely check soil temperature and weather forecasts to determine when conditions are favourable for seed germination and emergence of the crop. Groundnut seed should be planted in soils that reach 18°C or higher temperatures at 5 to 10 cm depth each day and when forecasts indicate that these conditions are likely to continue over the next 3 to 5 days.

Growers are also interested in reports of accumulated heat units and rainfall. These data are widely used to gauge the progress of crop development and to forecast the maturity date and yield potential of groundnut. In the Anantapur region of southern India, it was observed from long-term research on groundnut that rainfall of 500 mm was required to sustain a successful groundnut crop. Hence a prediction of seasonal rainfall of 500 mm is useful for groundnut growers in this region. As seasonal rainfalls of less than 500 mm are related to El Niño years, a prediction for El Niño has a potential for application in farm-level decisions in this region (Subbiah and Kishore, 2001).

Growers want accurate long-range weather forecasts with finer spatial and temporal scales for agricultural management applications, such as selection of varieties, choice of intercropping, increasing or decreasing the area to be planted, soil and water conservation techniques, and so forth. During the course of the crop-growing season, certain midterm corrections will be required to minimize yield losses. Hence, medium-range forecasts covering 5 to 7 days will provide critical information for undertaking corrective measures. Accurate short-range forecasts for weather aberrations like frost, hailstorms, and so forth should be made available to users. In Virginia, United States, a groundnut frost advisory programme uses separate algorithms to adapt the 7-day low temperature forecast to each regional site in the groundnut production areas (Phipps et al., 1997). Such types of advisories need to be made available in other regions that have a frost risk.

In the Gambia, farmers store groundnuts in heaps in open air for three months until a government agent

visits. During this time, the groundnut harvest is vulnerable to rain. Short-range rainfall forecasts would facilitate the protection of stored groundnuts by warning the farmers against impending rain (Kuisma, 1995). The value of one single good forecast for impending rain (even if only 10 per cent of the harvest is saved) would be US\$ 600 000. The weather-based advisories for making disease management decisions and weather monitoring networks available in United States should be extended to other groundnut-growing areas of the world.

In semi-arid areas, soil water balance affects almost all stages of production of the groundnut crop. Decision support systems based on real-time weather conditions, means of identifying moisture stress due to early or midseason dry spells and adaptation options suited to the circumstances need to be developed in semi-arid and arid regions. Developments in information technology have to be used in groundnut-growing areas for quick and cost-effective dissemination of weather-based agricultural advisories to growers. Chapter 1 and Stigter (2006a) discuss the initial and boundary conditions for such developments. Chapter 17 reviews communication of agroclimatological information.

In three south-eastern United States counties – Henry (Alabama), Jackson (Florida) and Mitchell (Georgia) – Fraisse et al. (2004) explored the use of crop growth simulation models in combination with climate forecasts to decide insurance coverage levels for groundnut producers. In Malawi, the World Bank drought index insurance seems to have been accepted by groundnut farmers, lenders and insurers as the best way for management of drought risk (<http://www.microinsurancecentre.org>). In Andhra Pradesh, India, rainfall insurance for payment of insurance compensation to (rainfed) groundnut farmers was implemented by ICICI (Lombard) Bank on the basis of a rainfall index. Weights were used for constructing a groundnut index in accordance with the commencement of the rainy season and period of sowing. Farmers receive payment if the index level falls below a predetermined threshold. Despite some problems, groundnut farmers are opting for this rainfall-based insurance scheme.

10.2.6 **Agrometeorological services for groundnut**

Operational decision support systems increase profit for groundnut growers. Groundnut yield, quality, and net farm income depend on optimum and timely management. Scientists from the Agricultural Research Service at the National Peanut

Research Laboratory (NPRL) operated by the United States Department of Agriculture in Dawson, Georgia, have developed and released, through a Cooperative Research and Development Agreement with the Peanut Foundation, an integrated decision support system (Farm Suite Version 2.0). This includes computer software for the management of irrigated groundnut production (Irrigator Pro), harvesting (Harv Pro), capital investment service (CIS), sprinkler operation and ownership costs, and curing (PECMAN). Over 100 copies of the software have been distributed as shareware to growers, extension agents and crop consultants throughout the groundnut-growing regions of the United States. Producers from New Mexico to Virginia using Farm Suite have optimized irrigation, pesticide applications and other production factors. Use of this decision aid tool not only increased groundnut yields by about 336 kg/ha but also improved the grade of harvests, decreased aflatoxin contamination and increased profits (US\$ 741 per ha) by comparison with the average groundnut grower.

The Website of the Southeast Climate Consortium (<http://www.agroclimate.org>) provides decision support tools such as groundnut outlook, yield risk analysis, management options and crop insurance for groundnut-growing states in the south-eastern United States. Another service is the Mesoscale Atmospheric Simulation System (MASS), which was used to predict hourly weather information 48 hours in advance for one-square-kilometre pixels at the geographic centre of two counties, Bertie and Gates, in North Carolina (http://cipm.ncsu.edu/cipm_projects).

Water balance/stress index models are applied rather routinely in West African countries for agrometeorological and food security assignment – groundnut is also one of the target crops. The creation of a regional Agrhymet centre on agrometeorological services in the Sahelian countries has provided solutions to some problems. This includes continuing earlier pilot projects for assistance to the rural population in Mali, where farmers have received and applied advice from the Multidisciplinary Working Group for Agrometeorological Assistance (GTPA) in the course of the rainy season (for example, Stigter, 2006b).

In Sudan, Ibrahim et al. (2002) did on-farm quantitative work on water waste in the Gezira irrigation scheme as an agrometeorological service to tenants and administrators, with the aim of assisting in the development of better local water use efficiency policies. They compared less labour-intensive groundnut irrigation methods, adopted because of

the necessity of working with sharecroppers who also had off-farm employment, to traditional modes of irrigation that were more labour-intensive and had been abandoned over time. They found that there was water waste in both methods of irrigation, but much more in the unattended fields and in the drier year of the two growing seasons investigated. In that year, the water waste was 50 per cent of the minimum water requirements determined. This did not yet include the readily available water still retained in the soil profile at the end of each growing season. Contrary to sorghum, the groundnuts also suffered from excess water.

For China, Stigter et al. (2006) reported that traditional farmers had recently used contour native grass belts for erosion reduction, in rotation with tilling the land for growing groundnuts for income and sweet potatoes for animals. Farmers appear to have obtained the innovative knowledge from a disaster in which erosion caused by very heavy rain seriously damaged corn-based cropping systems on hilly sandy soil, while narrow plots of groundnut between native grasses escaped the disaster. These contour belts are 2 m wide and the grasses are cut to feed working cattle. Local applied research would be able to improve these farmer-developed systems, leading to better agrometeorological services through design rules.

10.3 **AGROMETEOROLOGY AND MAIZE PRODUCTION**

10.3.1 **Importance of maize in various climates**

Maize is the world's third most important crop after rice and wheat. About half of this is grown in developing countries, where maize flour is a staple food for poor people and maize stalks provide dry-season feed for farm animals. Diversified uses of maize worldwide include: maize grain; starch products; corn oil; baby foods; popcorn; maize-based food items; maize flour; forage for animals; maize stalks providing dry-season feed for farm animals; maize silage for winter animal feed in cold temperate regions; and maize stalks as a soil mulch where it is in abundance. Maize grain is used as feed for beef, dairy, hog and poultry operations in developed countries. Maize can be classified on the basis of its protein content and hardness of the kernel. Varieties include popcorn and flint, flour, Indian and sweet corn.

In industrialized countries maize is largely used as livestock feed and as raw material for industrial

products; for instance, in Australia it is used for feed, silage, breakfast food and processing (breakfast cereals, corn chips, grits and flour), industrial starch and popcorn. In low-income countries it is mainly used for human consumption.

In sub-Saharan Africa, maize is a staple food for an estimated 50 per cent of the population and provides 50 per cent of the basic calories. It is an important source of carbohydrate, protein, iron, vitamin B and minerals. Africans consume maize as a starchy base in a wide variety of porridges, pastes, grits and beer. Green maize (fresh on the cob) is eaten parched, baked, roasted or boiled and plays an important role in filling the hunger gap after the dry season. The yields are low, however, fluctuating around 1.0 tonne per hectare (t/ha). Several African countries have focused attention on increasing maize production in the smallholding agricultural sectors, but such efforts have been ineffective because of heavy pre- and post-harvest losses caused by diseases, weeds and pests. In South Africa, in addition to the traditional uses, the country is considering maize fuel, an alcohol-based alternative fuel produced by fermenting and distilling the starch-rich grains of the crop.

According to United Nations Food and Agriculture Organization (FAO), maize yields currently average 1.5 t/ha in Africa, slightly more than 3 t/ha in Latin America and 1.7 t/ha in India. FAO indicates that grain yields have been recorded as follows: 5–6 t/ha (dryland) and 8–10 t/ha (irrigated). For silage, at 68–70 per cent moisture content, yields of 20 t/ha (dryland) and 42 t/ha (irrigated) have been recorded.

10.3.1.1 **Importance of maize in the United States**

Maize grain yields have exceeded 12.5 t/ha in the United States and in southern Ontario, Canada, without irrigation, and the value of this crop now exceeds US\$ 20 billion in North America. Corn refineries use 14 per cent of the United States maize crop, manufacturing such products as: corn oil; gluten for animal feed; corn starch; corn syrup; dextrose (used mainly by the pharmaceutical industry as the starting material for manufacturing vitamin C and penicillin); alcohol for beverages; bioethanol (which accounts for 12 per cent of all automobile fuels sold in the United States); high-fructose corn syrup (used mainly by the soft drink industry, surpassing the use of sucrose in the United States); biodegradable chemicals and plastics; paper; textiles; ready-to-eat snack foods and breakfast cereals; cornmeal grits; flour; and additives in paint and explosives. It is estimated that maize yields

4 000 industrial products and that there are more than 1 000 items in United States supermarkets that contain maize.

10.3.1.2 Yield gap and yield potential

In the developing world, most farmers have to accept low yields, as they are unable to consider the use of improved production methods because they operate at small-scale subsistence levels. Yield gap analyses will draw farmers' attention to lost production potential under the prevailing climatic conditions in their respective environments and which production practices (soil fertility, agronomic measures, cultivar selection, and the like) need to be improved. Yield differences among regions as shown in Table 10.3.1 should provide the incentive to manoeuvre toward yield improvement. (Yield potential refers to the highest yield achievable on farmers' fields – with the use of improved seed (high yield, tolerance to diseases and pests), appropriate levels of nutrients, water and weed control.)

According to Ofori et al. (2004), the difference between the actual and potential yield of a typical maize variety grown during the major cropping season (April through July) on a farm in Ghana over a nine-year period was just over 4 t/ha (that is, the actual yield varied from 0.9 to 1.4 t/ha and the potential for that season should have been 5.5 t/ha). The April–July rainfall varied from 570 to 790 mm over this nine-year period.

10.3.1.3 Maize production profile by region in the developing world

In the tropics and subtropics, small-scale farmers grow most of the maize, generally for subsistence as part of agricultural systems that feature several crops and sometimes livestock production. The system often lacks inputs such as fertilizer, improved

seed, irrigation and labour. In most developing countries there is very little purchased input for the cropping system and it essentially depends on the natural resource base. The soil nutrients in the natural resource base are dwindling faster than they are being replaced. Rainfall is the single most important natural resource input under this form of cropping. Increasing population pressure has resulted in an intensification of land use. Nutrients and organic matter in the soil have been depleted and crop yields have steadily decreased. To increase production it will be necessary to replenish soil nutrients and optimize the use of other resources such as seed, water, capital and labour. Land-use intensification is only feasible if nutrients depleted during cultivation are replenished. Inorganic fertilizer use in sub-Saharan Africa is generally limited by the lack of financial resources for the farmers. Table 10.3.2 shows the dominant constraints to bridging the gap between the actual and potential yield in the developing world.

Most maize-producing countries in the industrialized world employ extensive inputs and highly mechanized crop production systems; these countries commonly use hybrid maize seed.

10.3.2 Agroclimatology of the crop

Climate is interrelated with other production factors and should be understood either as a resource to be managed or a factor that needs to be manipulated. Sustainable use of soil, capital and labour should be balanced with use of climate and weather information.

The response of the maize crop to climate depends on the physiological makeup of the hybrid/variety being grown. Yield differences are the result of the genetic composition of the hybrid, the environmental conditions under which the crop is grown, and the infestation by crop pests (diseases, insects and weeds). The final yield will depend on hybrid selection, soil fertility, soil water and control of

Table 10.3.1. Yield potential (t/ha) relative to (current yield) in developing world (Prabhu et al., 2000)

<i>Ecological environment</i>	<i>Highland/transitional</i>	<i>Mid-altitude/subtropical</i>	<i>Tropical/lowland</i>
East and South-East Asia	5.0 (3.5)	8.0 (3.0)	5.5 (2.2)
South Asia	5.0 (0.7)	7.0 (2.6)	4.5 (1.4)
West Asia/North Africa		4.5 (3.2)	
Sub-Saharan Africa	5.0 (0.6)	7.0 (2.5)	4.5 (0.7)
Latin America and Caribbean	6.0 (1.1)	10.0 (4.0)	5.0 (1.5)

crop pests. These factors will be discussed in this order.

Each farmer has to select the hybrids that are most suitable for the climatic region in which his or her farm is located. In temperate regions of the world, the length of the frost-free season dictates the hybrids that are suitable, because the maize plant cannot withstand temperatures below about -2°C . Growing degree-day and heat-unit indexing systems have been developed for most temperate regions of the world, so that the maturing time required by

each maize hybrid can be matched with growing degree-day or heat-unit ratings for the frost-free growing season in each climatic region. In tropical regions of the world it is the rainy season onset that dictates the selection and optimum time to plant maize hybrids. They need to be selected to match the anthesis period to the time that the soil moisture is likely to be most adequate, unless there is water available to irrigate the crop when necessary.

The soil fertility needs to have an optimum balance of the three major nutrients, which are nitrogen,

Table 10.3.2. Dominant constraints to bridging the yield gap between potential and actual yields in the developing world (Bellon, 2001)

<i>Ecological environment</i>	<i>Highland/transitional</i>	<i>Mid-altitude/subtropical</i>	<i>Tropical/lowland</i>
East and South-East Asia	(a) Limited technological options	(a) Drought/moisture stress	
	(b) Banded leaf and sheath blight	(b) Soil acidity	(a) Limited superior early germplasm
	(c) Borers (<i>Chilo</i> spp.)	(c) Downy mildew	
South Asia		(d) Borers (<i>Chilo</i> , <i>Sesamia</i> spp.)	
	(a) Low and declining soil fertility	(a) High temperature	(a) Limited superior early germplasm
	(b) Limited technological options	(b) Drought/moisture stress	(b) High temperature
	(c) Turcicum blight	(c) Turcicum blight	(c) Drought/moisture stress
West Asia/North Africa		(d) Borers (<i>Chilo</i> , <i>Sesamia</i> spp.)	(d) Downy mildew
			(e) Borers (<i>Chilo</i> , <i>Sesamia</i> spp.)
		(a) High temperature	
Sub-Saharan Africa		(b) Drought/moisture stress	
	(a) Low and declining soil fertility	(a) Low and declining soil fertility	(a) Low and declining soil fertility
	(b) Limited technological options	(b) Grey leaf spot	(b) Drought/moisture stress
	(c) Turcicum blight	(c) Streak virus	(c) <i>Striga</i>
	(d) Rust	(d) Weevils	(d) Streak virus
		(e) Borers (<i>Chilo</i> , <i>Sesamia</i> spp.)	(e) Borers
Latin America and Caribbean		(f) Drought	
	(a) Limited technological options	(a) Soil erosion	(a) Low soil fertility
	(b) Drought/moisture stress	(b) Drought/moisture stress	(b) Soil acidity
	(c) Ear rot	(c) Turcicum blight	(c) Drought/moisture stress
	(d) Rust	(d) Borer (S.W. corn borer)	(d) Fall armyworm
			(e) Stunt

phosphorus and potassium, and the necessary micro-nutrients, such as boron, calcium, magnesium, manganese and molybdenum. The farmer should have the soils on his or her farm assessed for the three major nutrients every year or two to determine how much fertilizer should be added to maximize maize production. This is an important management practice in both temperate and tropical regions. The farmer should be aware of fertilization requirements and procedures with respect to the soil nutrient levels, the growth stage, the crop variety, the targeted yield and the agronomic practices.

In order to maximize maize yields, soil moisture should be maintained above 50 per cent of the available water capacity in the rooting depth of the soil profile throughout the growing season. This is not always possible in either temperate or tropical climatic regions as rainfall can be very scarce and sporadic in some years. It is essential, however, to have at least adequate soil moisture at the time of anthesis in order to have a full set of kernels on the ear at harvest time. This is the time when supplemental water through irrigation would be most beneficial.

Crop infection and infestation by diseases, insects and weeds can significantly reduce yields in both temperate and tropical regions, and agrometeorology is important in crop protection. Diseases are best controlled through maize breeding programmes that develop hybrids with resistance to such diseases as leaf blights (of which *Bipolaris*, *Colletotrichum* and *Excoehilum* strains are common examples); root and stalk rots (of which *Phytophthora*, *Fusarium*, *Gibberella* and *Diplodia* strains are representative cases); rusts (including *Puccinia* and *Polyspora*); and smuts (such as *Ustilago* and *Sphacelotheca* strains). Maize diseases are usually not controlled by spraying with fungicide chemicals, except that seed is often treated before planting with a fungicide powder to control soil pathogens that damage the embryo before germination. (These fungi include the *Pythium*, *Fusarium*, *Diplodia*, *Rhizoctonia* and *Penicillium* species). Wet and cold soil conditions (<10°C) at planting time are most favourable for these seed diseases.

The problem of disease and pest control among different production levels is particularly acute in the small-scale, resource-poor systems under which maize is typically grown in tropical regions of the world. The most inexpensive control measure for insects is crop rotation, which ensures that maize is not grown on the same land year after year.

Numerous species of weeds can infest maize crops and cause yield losses in both temperate and tropical regions. The *Amaramthus*, *Panicum* and *Butilon*

species are the most detrimental in temperate regions, while the *Striga* species have the greatest impact in tropical regions, especially in Africa. Among the 23 *Striga* species in Africa, *Striga hermonthica* is the most detrimental. In temperate regions, most of the time weeds are controlled by herbicide application. Since these chemicals are applied shortly after planting maize, when the soil needs to be moist but not too wet, weather conditions play a major role in the success of weed control in temperate climates. Some weed species have developed strains resistant to the "triazine" chemicals that are usually applied before emergence of maize seedlings, so it is sometimes necessary to apply alternative herbicides after emergence. Herbicides are often too expensive for farmers to use in tropical regions, so other cultural practices, such as crop rotation and hand cultivation, are used to control weed infestations.

Weather conditions play a role here too, but are not as critical as they are in herbicide application. According to several studies around the world (James et al., 2000; OMAFRA, 2002; Dogan, 2003) the best time to minimize the effect of weeds on maize yields is within 4 to 8 weeks after planting, when maize is in the 2- to 8-leaf stage. When weeds are controlled culturally during this initial period of maize growth, shading by the crop is quite effective in controlling weed growth during the remaining time to maturity.

10.3.3 Basic management aspects of the crop in various environments

Promotion of growth and yield will mean that an effort has to be made to reduce the effects of pests, diseases, drought and frost, which cause crop losses for both commercial farmers and smallholder, resource-poor farmers.

Drought stress alone can account for a significant percentage of average yield losses and is one of the greatest yield-reducing factors in production. There are two facets to drought resistance in maize:

- (a) Affordability of irrigation systems. Not all farmers have access to irrigation systems and the cost of these systems limits their use by resource-poor farmers;
- (b) Increasing pressure on water resources from other user sectors. As water resources for agronomic uses become more limited, the development of drought-tolerant varieties becomes increasingly more important (Wesley et al., 2001).

Apart from breeding and soil management, drought control measures include:

- (a) Timing of planting to coincide with the time of adequate soil moisture availability based

- on the availability and user appreciation of agrometeorological information;
- (b) Reduction of plant population with moisture scarcity (thinning);
- (c) Higher soil fertility to increase plant health and improve resistance to diseases and pests;
- (d) Weed control to reduce competition for water between the maize plant and the weeds. Weed control also creates suitable humidity levels for the maize plant environment.

There are considerable research efforts at both regional and international levels in developed and developing countries that are aimed at providing drought-resistant hybrids. Plant breeding and biotechnology can offer some flexibility in drought management for rainfed or dryland maize production. What is important is to characterize the hybrids according to their level of tolerance to allow for easy selection by farmers or farmer groups. Drought-resistant hybrids and their composites are often more promising in dryland environments than local maize varieties (Obeng-Antwi et al., 2002).

As a result of the warming and changing climate patterns, maize yield is going to be reduced, especially among smallholder maize farmers, who may lack the resources to cope with these situations. With the effect of climate change resulting in reduced rainfall amounts and increased soil and plant evapotranspiration, one important goal is to enhance drought resistance in maize and other cereal crops, which would greatly benefit regions with less favourable conditions for agriculture. Solutions must go beyond increasing production, as boosting the nutrient content of the maize is important as well. Breeding of high-yielding, high-nutrient varieties with limited water use could provide part of the answer.

It is clear that climate influences the incidence of pests, diseases and weeds, though the intensity of these effects differs among crops and regions depending on climatic conditions, crop resistance and crop management, which may include cultivation techniques, such as fertilization, water supply and crop protection. Protection measures should be targeted at managing weeds, pests and diseases. Can control be put within the reach of resource-poor farmers?

Weed control for yield increase can be quite costly to resource-poor farmers. Part of the solution lies in the use of biodiversity and biotechnology. To put stem borer and *Striga* control within the reach of African farmers, simple, inexpensive measures need to be developed that are tailored to the diversity of

African cropping and socio-economic systems. A sustainable solution would be an integrated approach that simultaneously addresses disease, pests and weeds.

Ndema et al. (2002) reported on weed grasses grown as trap plants in border rows around maize plots, which led to reduced pest densities in maize. This was due to an increase in plant-induced mortality occurring on grass species in both the humid forest and the derived savanna of western Africa. Yields per plant tended to be higher when grasses were present, with the highest increase of >100 per cent observed in Cameroon in the second year of the experiment, when the grasses were well established. The most promising grass species identified in the study were *Pennisetum purpureum* and *Panicum maximum*. The latter was the most efficient species for suppressing *S. calamistis* and *M. nigrivenella* infestations and enhancing egg and larval parasitism.

The new approaches utilize the benefits of biodiversity of graminous and leguminous plants in the cultivation of maize; how to manage these plants in order to reduce stem borer and *Striga* infestation and increase stem borer parasitization by natural enemies in cereal cropping systems has been demonstrated. The approaches rely on enriching the biodiversity of plants and the pests' natural enemies in and around the cropping environment. Based on an understanding of the volatile semiochemicals employed by the stem borers in locating suitable hosts and avoiding non-hosts, a novel pest management approach utilizing a "push-pull" or stimulo-deterrent diversionary strategy has been developed. In this habitat management system, which involves combined use of trap and repellent plants, insects are repelled from the main crop and are simultaneously attracted to a discard or trap crop. For maximum efficiency, these systems also exploit natural enemies, particularly parasitic wasps, which are important in suppressing pest populations. Plants that repel stem borers and also inhibit *Striga* weed have been identified as well.

Several plants have been identified that could be used as trap or repellent plants in a push-pull strategy, according to the study. Particularly promising are Napier grass (*Pennisetum purpureum*), Sudan grass (*Sorghum vulgare sudanense*), molasses grass (*Melinis minutiflora*) and the legume silverleaf (*Desmodium uncinatum*). Napier grass and Sudan grass have shown potential for use as trap plants, whereas molasses grass and silverleaf repel ovipositing stem borers. All four plant species are of economic importance to farmers in Africa as livestock fodder and have shown great potential for stem borer and *Striga* control in on-farm

trials. Napier grass, a commercial fodder grass, can provide natural control on stem borers by acting as a trap plant, and as a reservoir for their natural enemies. Napier grass has its own defence mechanism against crop borers. When the larvae enter the stem, the plant produces a gum-like substance, which causes the death of the pest.

Sudan grass, also a commercial fodder grass, can provide natural control by acting as a trap plant for stem borers and as a reservoir for their natural enemies. Planting Sudan grass around maize fields reduced stem borer infestation on maize and also increased efficiency of natural enemies (Khan et al., 1997a). Molasses grass, when intercropped with maize, not only reduced infestation of maize by stem borers but also increased parasitism, particularly by the native larval parasitoid *Cotesia sesamiae* (Khan et al., 1997b). The plant releases volatiles that repel stem borers, but attract parasitoids that cause no damage to the plants. Such plants with an inherent ability to release such stimuli could be used in ecologically sound crop protection strategies.

Molasses grass, which originated in Africa but spread to other tropical areas in the world, is well known to be a valuable pasture and hay grass. The grass also has high anti-tick properties, especially when green. The grass is familiar to farmers in eastern Africa and is reported to be preferred as fodder for both dairy and beef cattle. Silverleaf, a high-value, commercial fodder legume, when intercropped with maize, repelled ovipositing gravid stem borer females, and suppressed *Striga* by a factor of more than 40.

The habitat management strategy manifests important features that render it markedly more advantageous than other methods. The first of these features is its suitability to conditions of mixed agriculture, which is prevalent in eastern Africa. The cultivation of the grasses and legumes can increase both crop yield and livestock productivity. A second key feature of the proposed technology is that it introduces practices that are already familiar to farmers in Africa. The approach uses multiple cropping, and it is based on the use of economically valuable plants. For example, the cultivation of Napier grass for livestock fodder and soil conservation, recommended in eastern Africa, is already widespread.

10.3.4 Other background information on the crop

10.3.4.1 Growth stage monitoring

The maize plant described in Table 10.3.3 is representative of a lowland tropical variety, flowering

in 55–60 days and maturing in 115 days. Considerable variation exists among varieties in terms of morphology and growth habit, however. For example, an early-maturing tropical variety may reach a height of only 1.5 m, flowering in 45–50 days and maturing in 90 days. Growth stages in the pattern shown in Table 10.3.3 should be prepared as a management guide. It must be emphasized that environmental factors influence the length of the various growth stages and for this reason information about the environmental factors should also be part of the characterization. Familiarity with the names and locations of the plant parts is helpful in understanding how the plant develops.

Table 10.3.3 gives the approximate number of days after sowing in the lowland tropics where maximum and minimum temperatures may be 33°C and 22°C, respectively. In cooler environments, these times are extended. For each variety a phenological characterization such as this can be useful. Planting dates should be such as to avoid exposure to increased risk of plant diseases, pests and soil moisture stresses.

10.3.4.2 Growth monitoring – an illustration

All normal maize plants follow this same general pattern of development, but the specific time interval between stages and total leaf numbers developed may vary among different locations, hybrids, seasons and planting dates. For example:

- (a) An early-maturing hybrid may develop fewer leaves or progress through different stages at a faster rate than indicated here (Table 10.3.3). A late-maturing hybrid may develop more leaves or progress more slowly than indicated, however;
- (b) The rate of plant development for any hybrid is directly related to temperature, so the length of time between the different stages will vary as the temperature varies, both between and within growing seasons;
- (c) Environmental stress, such as nutrient or moisture deficiencies, may lengthen the time of vegetative stages but shorten the time between reproductive stages;
- (d) The number of kernels that develop, final kernel size, rate of increase in kernel weight and length of the reproductive growth period will vary among hybrids and environmental conditions.

10.3.4.3 Biotechnology

It is expected that the use of biotechnology in the improvement of maize production will mean

Table 10.3.3. Growth stages of the maize crop

<i>Stage</i>	<i>DAS^a</i>	<i>Features</i>
VE	5	The coleoptile emerges from the soil surface.
V1	9	The collar of the first leaf is visible.
V2	12	The collar of the second leaf is visible.
Vn		The collar of leaf number “n” is visible. The maximum value of “n” represents the final number of leaves, which is usually 16–23, but by flowering, the lower 4–7 leaves have disappeared.
VT	55	The last branch of the tassel is completely visible.
R0	57	Anthesis or male flowering. Pollen shed begins.
R1	59	Silks are visible.
R2	71	Blister stage. Kernels are filled with clear fluid and the embryo can be seen.
R3	80	Milk stage. Kernels are filled with a white, milky fluid.
R4	90	Dough stage. Kernels are filled with a white paste. The embryo is about half as wide as the kernel. The top parts of the kernels are filled with solid starch.
R5	102	Dent stage. If the genotype is a dent type, the grains are dented. The “milk line” is close to the base when the kernel is viewed from the side in both flint and dent types.
R6	112	Physiological maturity. The black layer is visible at the base of the grain. Grain moisture is usually about 35%.

^a DAS: days after sowing

collaboration between other disciplines and agrometeorologists. This should facilitate the development of suitable maize varieties for drought resistance and improved tolerance, as well as for low nitrogen availability, which occurs in most developing countries under rainfed production. The development of maize that is resistant to pests, diseases and weeds, as well as maize varieties with increased starch and protein contents, should be a feature of biotechnology advances. The direction of such biotechnology endeavours depends on regional production goals. Is production aimed at poverty alleviation, biofuel or increased protein content? Many questions of this kind may be asked.

Genetic engineering offers new possibilities for plant breeding for increased resistance to pests and pathogens, as well as other traits. New varieties resistant to pests, diseases and drought may lessen the dependence on pesticides and fungicides and help secure sufficient crop yields, especially among resource-poor farmers and in water-limiting environments. According to Sankula et al. (2004), there are reported cases of reductions in pesticide and herbicide use, by 62 per cent and 50 per cent, respectively, due to the cultivation of biotechnology-derived and herbicide-tolerant maize.

Under different climatic conditions and environments, varietal selection has to be based on a host of factors, for example, whether the crop is produced under rainfed/dryland conditions, unimodal or bimodal rainfall patterns, supplementary or fully irrigated systems or under sufficient or limited rainfall conditions.

10.3.5 Some management details

Agronomic practices that will improve soil fertility will increase yield dramatically. Examples include cultivation practices that will destroy the seeds of various weeds, encourage healthy plant growth and conserve soil moisture. These techniques may consist of mulching, residue management, no-till or zero tillage, reduced field traffic, organic matter addition, suitable fertilization rates based on proper soil assessments, and so on.

Another approach is to integrate a maize crop with crops suitable for crop rotation, mixed cropping or sequential cropping. These crops should be carefully selected based on their effect on weed, pest and disease control and soil fertility. Some management issues to consider are:

- (a) Selection of hybrids/varieties best suited to climate conditions and management practices;

- (b) Planting at the time most suitable to the farming area and at the correct seeding rates;
- (c) Use of agronomic practices suitable to the soil type;
- (d) Fertilization according to soil assessments for the desired production levels;
- (e) Use of cultural practices most suitable for the control of weeds, diseases and insects;
- (f) Following the recommendations provided by agronomic and agrometeorology extension specialists.

Transfer of improved technology may take place through demonstrations of improved crop production technology, Integrated Pest Management training programmes, seed production programmes, and provision of fungicides, herbicides, insecticides and other inputs. The maize technology transfer in the Ghana Grain Development Project was based on three types of activities (Morris et al., 1999): building linkages between research and extension, providing support to extension activities and strengthening seed production activity.

Available varieties are continually changing as new ones are being developed, so there is a need to have up-to-date varietal information. The choice of variety depends on market requirements, environmental conditions, socio-economic considerations, whether the crop is irrigated and the levels of disease and pest resistance required. For example, the state of Queensland, Australia, gives recommendations on factors to be considered as a guide to the selection of maize variety (Hughes, 2006). Time to flowering, cob height, husk cover, disease resistance, "standability", end use and isolation are mentioned. Hybrid selection should be understood by all and must also have socio-economic components. It is necessary to develop suitable characterization methods for all hybrids that will make the selection process much easier and convenient.

Management information requirements should include communication networks, which should be targeted at:

- (a) Information-sharing and communication on hybrid and varietal performance, with expert support;
- (b) Training for farmers on such matters as seed selection, management practices and agrometeorological services;
- (c) Assessing the performance of varieties in a systematic manner;
- (d) Agronomic, pest and soil fertility advisories for farm districts;
- (e) Information on newly developed hybrids for farmers;
- (f) The response of each hybrid or variety to any of the growth/yield limiting factors;
- (g) Information and training on the occurrence of diseases, insects and weeds, including the transboundary spread of diseases;
- (h) Disease cycle and climatology (for example, the occurrence of humid conditions);
- (i) Symptoms of infestation and crop damage.

For management purposes, the reporting of pests and diseases should include the name of the disease/pest (Latin and/or common), with a description of:

- (a) Crop damage;
- (b) Symptoms of infections and infestations;
- (c) Weather and microclimate conditions for their survival and multiplication;
- (d) Life cycle;
- (e) Dispersal/spread mechanisms;
- (f) Management procedures/regimes.

10.3.6 **User requirements for climate information**

The information has to be presented in a language and format that the user understands and it has to be issued at the appropriate time. For example, studies on the use of climate information for production planning examined rainfall dependability, using the coefficient of variation, at some selected centres in Ghana. This showed the months of the year when rainfall can be dependable (Ofori et al., 2004).

10.3.6.1 **Information to cope with climatic risk for maize production**

According to a study reported by Unganai (2000), any long-range forecast that will potentially benefit farmers has to contain the following information:

- (a) Onset date of the rainy season;
- (b) Ending date of the rainy season;
- (c) Quality of the cropping season rainfall, indicated by the rainfall amount using rainfall percentile studies. Rainfall percentile studies allow for good comparison of rainfall among farming centres or within agroecological zones as well. This also aids in production planning and in the delivery of advisory services;
- (d) Temporal and spatial distribution of important climate factors;
- (e) Probability, frequency and timing of adverse weather events (such as dry spells or mid-season drought, floods, windstorms, frost) within the season. This will include climatic risk zoning to determine adaptation or avoidance mechanisms during the season;
- (f) The patterns of rainfall, temperature, evapotranspiration, relative humidity, sunshine

hours, vapour pressure deficit and other agriculturally significant climate variables. This will include deviations, anomalies and timing of favourable climatic conditions;

- (g) Characterization of ecological zones suitable for climate manipulation and maize production purposes using the appropriate climate-based crop yield or growth models;
- (h) Interpretation of the above information in terms of which varieties to plant and when to plant.

Such agrometeorological services may be complemented by comparisons with long-term averages and recent seasons and with additional information that was recently shown to be appreciated by farmers and extension agents as described below.

Dry spells that substantially reduce the soil water reservoirs and affect crop yield cause problems for agriculture and other human water needs. Climatic-risk zoning must be used to determine the best planting time to avoid or reduce drought effects on crop development. The following determinations and assessments are thus suggested for coping with climatic risk:

- (a) Potential suitability of a specific variety for a given region;
- (b) Probability of drought and frost;
- (c) Phenological stage most susceptible to drought and frost;
- (d) Availability of meteorological data;
- (e) Zoning of production districts based on climatic and edaphic conditions;
- (f) A water requirement index for each phenological stage.

In addition to the above, water requirement and dryness indices, stored soil moisture and the risk of severe drought must be determined. For example:

$$\frac{ETR}{ETM} = \frac{\text{actual crop evapotranspiration}}{\text{maximum crop evapotranspiration}}$$

$$\text{Dry index, DI} = \left(1 - \frac{ETR}{ETP}\right)$$

Suitable drought monitoring and characterization indices therefore are:

- (a) Water requirement index;
- (b) Drought index;
- (c) Available stored water;
- (d) Probability of dry spell;
- (e) Rainfall anomaly;
- (f) Soil moisture-holding characteristics;
- (g) Growing period climate characteristics;

- (h) Maize fertilization – a methodology for maize fertilization needs to be developed that will have implications for drought/dry spell management or soil moisture storage and nutrient leaching, especially in humid regions.

User requirements for pest and disease management in a climate context are:

- (a) Pest and disease identification services;
- (b) Life cycle and mode of attack/infestation, simplified in chart form;
- (c) Pest and disease mapping for each locality showing the times of the year when climatic conditions favour their survival and multiplication;
- (d) Monitoring methods to determine pest and disease presence (visual identification methods must be disseminated);
- (e) Assessment of the effectiveness of control measures. This involves:
 - (i) Assessment of why the method worked or did not work;
 - (ii) Close consultation with pest advisers or extension officers;
 - (iii) “What if” analysis (“what if I lose?”, “what if I gain?”);
 - (iv) Reporting of resistance tolerance;
 - (v) Determination of environmental influences (rain, humidity, wind, soil, temperature);
- (f) Timing of the application of control methods to optimize their effectiveness;
- (g) Research on and documentation of social and economic costs of weeds.

User requirements for weed control in a climate context are:

- (a) Weed characteristics, including:
 - (i) Rapid vegetative regeneration;
 - (ii) Persistence in the soil for long periods;
 - (iii) Adaptation to varying environments;
- (b) Impacts of weeds in terms of:
 - (i) Crop yield reduction as a result of weeds competing for light, water and nutrients;
 - (ii) Danger to human beings and/or livestock through poisoning;
 - (iii) Harboursing of crop pests and diseases;
 - (iv) Increases in the cost of harvesting.

User requirements for soil and water conservation in a climate context deal with promoting cropping and farming practices, such as manuring and crop residue management, which increase the organic matter content of the soil. For both rainfed and irrigated maize production, the information should contain data on:

- (a) Seasonal variations in atmospheric water demand;
- (b) Maize crop water use throughout its life cycle and for all varieties;

- (c) Irrigation scheduling techniques;
- (d) Soil moisture monitoring techniques;
- (e) Measuring or calculating evapotranspiration using on-site evaporation pan or meteorological information;
- (f) Monitoring crop conditions;
- (g) Training in the “hand feel” method (dig–look–judge–respond) (Moore, 2005).

Other management considerations should include:

- (a) Knowledge of hardpans and of soil moisture-holding characteristics;
- (b) Knowledge of the crop rooting depths and characteristics, resistance level of hybrids and varieties to drought, disease, frost, and so on;
- (c) Water supply: if agriculture is rainfed, the sufficiency and dependability of rainfall during the season needs to be assessed and the months with higher dependability identified. If irrigation is used, then the reliability of the water source needs to be assessed.

User requirements regarding timing of farm operations should consider:

- (a) Timing and application of nutrients, especially in humid areas;
- (b) Weed control;
- (c) Effects of pollination timing on kernel and silk receptivity.

Tactical application of nitrogen after high rainfall at seeding and flag emergence, and application of phosphorus and potassium at seeding, increased crop yields by 79 per cent and 100 per cent at two locations, Boscabel and Orchid Valley, according to Hill et al. (2005). Similar treatment could be done to maize crops at specific locations.

User requirements for the resistance/tolerance level of hybrids include the assessment of resistance or tolerance of all hybrids to weed, pest, disease and drought levels under different environments and edaphic conditions for their overall potential. This will aid in varietal selection for a particular environment. In some cases, resistance or tolerance levels are quantified and acceptable levels developed. Factors to look at are:

- (a) Virus resistance level;
- (b) Insect or pest resistance level;
- (c) Fungal resistance level;
- (d) Bacterial resistance level;
- (e) Herbicide resistance level;
- (f) Drought or frost resistance level;
- (g) Weed infestation resistance;
- (h) Nitrogen use efficiency;
- (i) Response to nitrogen fertilization.

These levels should be quantified as an aid to farmers and other stakeholders in making decisions on which variety to use. The potential for breeding maize with greater nitrogen use efficiency, characterization of the nitrogen response to local and improved maize varieties, and identification of secondary traits associated with tolerance to low nitrogen stress may be required.

User requirements for agrometeorological information on the crop may be listed as follows:

- (a) Maturation periods in days or degree-days/heat units for all maize hybrids/varieties;
- (b) Climatic risk zoning to determine the best planting time to avoid or reduce the risk of encountering drought during crop development;
- (c) Matching crop water requirements with the season;
- (d) Information about the weather factors that are conducive to infestation by insects and pathogens to allow timeliness of control practices;
- (e) Drought/frost stress characteristics of the crop;
- (f) Growth stage characterization;
- (g) Strengthening farmer appreciation of crop growth/crop yield models;
- (h) Development of accurate models to estimate crop performance.

10.3.7 Examples of agrometeorological services related to this crop

Three case studies of on-station design trials of agroforestry systems with maize, provided as agrometeorological services to farmers in Africa, were identified in the literature. The first example was an alley cropping design on flat land in the semi-arid Machakos district of Kenya (Mungai et al., 1996). In the alley cropping system studied, every fourth row of maize was replaced by a row of *Cassia siamea* trees and loppings were incorporated into the soil at the beginning of each maize-growing season. In this kind of replacement agroforestry, it was found that the difference between yields in agroforestry systems and yields in systems that use monocropping controls is larger at higher rainfall levels and with better rainfall distributions.

This design on flat land proved that it was difficult to increase crop yields considerably by alley cropping in the semi-arid tropics in years other than those with appreciably above-average rainfall and with a beneficial rainfall distribution. There is even a relatively low rainfall level below which the controls often do better. Since the late 1980s and early 1990s, it has been clear that adoption of such

systems by farmers has been much lower than expected. This early work highlighted why farmers have such a negative view of alley cropping. Low biomass production that insufficiently improves soil conditions through mulching, and high competition for resources between trees and crops, are the main causes. Farmers are thus advised not to apply such systems on flat land in semi-arid conditions. That was the agrometeorological service delivered by this research in the late 1980s and disseminated in the early 1990s through extension channels of the (then) International Council for Research in Agroforestry (ICRAF) (Mungai et al., 2001).

In the second case study, *Senna siamea* contour hedgerows with inter-row distances of 4 m were used “on-station” for erosion control on a 14 per cent slope of an Alfisol at the ICRAF research station in the semi-arid district of Machakos, Kenya. For one of the two rainy seasons of each year, the hedgerows were intercropped with maize, without the use of fertilizers. There were four rows of maize in the alleys formed by the hedgerows. Cumulative results for four seasons showed that the most successful treatment for soil loss and runoff reduction was the combination of hedgerows and surface spreading of their prunings as mulch, done just before the start of the rainy seasons. This reduced cumulative runoff from close to 100 mm to only 20 mm and cumulative soil loss from more than 100 t/ha to only 2 t/ha (Stigter et al., 2005a). This was at the expense of 35 per cent of the maize yields.

These significant yield reductions were due to an increase in competition from hedges that were now more mature, compared to the competition from the younger hedges in earlier experiments. The planting of hedgerows alone, without applying the mulch, was appreciably less effective in both soil loss and runoff reduction and came at the expense of even more maize yield. Mulch appeared to be the main factor reducing soil evaporation, but under high soil evaporation of between 50 per cent and (an upper limit of) 65 per cent of the rainfall, evaporation reduction did not exceed the range of a relative 5 per cent and 10 per cent. This was due to the low biomass production in semi-arid conditions (Kinama et al., 2005). Experiments with *Panicum maximum* grass strips (and no mulch) instead of the low trees gave results for runoff and soil loss reduction that were half-way between the values for the hedges with and without mulch application, but the yield reductions recorded were the largest among all the treatments.

In highlighting the consequences of the system design for farmers, provided as an agrometeorological service, it should be kept in mind that alley farming on sloping land was earlier shown to be successful only if the system was adapted to the particular needs of the farmers concerned. The grass strips were more effective in preventing soil erosion than the hedgerows because of the compactness and thickness of the grass strips. They are more effective in reducing runoff speed and trapping soil than the thinner and appreciably less dense hedgerows. For lower-input farmers, grass strips and highly competitive trees with high biomass density close to the ground, even when less efficient in direct erosion control, may deliver highly needed thatching material and/or fodder and save money for durable erosion-control embankment stabilization (Stigter et al., 2005a).

In the third case study, in the semi-arid Laikipia District, Kenya, *Coleus barbatus* hedges solved existing wind problems where previously the wind had blown off maize stalk mulches and was mechanically shaking the maize. Protection was assisted by *Grevillea robusta* (silky oak) trees as used in the demonstration agroforestry plots with maize and beans (Oteng'i et al., 2000). In the demonstration plots, the hedge roots were pruned, as were half of the trees. The positive moisture effects were stronger closer to the pruned trees.

The agroforestry intervention with pruned older trees and maize stalks used for mulching did not negatively influence maize yields in the wettest season and showed a positive effect on maize biomass yields in the driest season. Comparison of yield differences in mulched and pruned plots in the wettest season indicated that, for maize, tree pruning was more effective than mulching under these conditions. A combination of the water conservation measures of root pruning, mulching and minimum tillage was to be preferred for the maize/beans intercrop in this agroforestry system for seasons with very low rainfall. More overlapping of depletion zones of the three root systems would have influenced the pruned plot yields of the intercrop more seriously (Stigter et al., 2005b).

The results showed that under the very difficult semi-arid conditions in Laikipia, the mulched tree-cum-hedge pruned agroforestry system helped to limit land degradation overall. The farming conditions are extremely marginal, however, and economically more viable systems must be developed as (agrometeorological) services to help the farmers concerned (Stigter et al., 2005b).

10.4 **AGROMETEOROLOGY AND PEARL MILLET PRODUCTION**

10.4.1 **Importance of pearl millet in various climates**

Pearl millet is a cereal crop that is widely grown under rainfed conditions in the arid and semi-arid regions of Africa and southern Asia. It is grown under intensive cultivation as a forage crop on other continents. Pearl millet is suited to hot and dry climates, and can be grown in areas where rainfall is not sufficient (200–600 mm) for maize and sorghum. Primarily a tropical plant, pearl millet is often referred to as the “camel”, because of its exceptional ability to tolerate drought. Even with minimal rainfall, millet will typically still produce reasonable yields. In many areas where millet is the staple food, nothing else will grow. In addition to millet’s use as food for human consumption, its stems are used for a wide range of purposes, including the construction of hut walls, fences and thatches, and the production of brooms, mats, baskets, sunshades, and so on (IFAD, 1999).

Pearl millet (*Pennisetum glaucum* (L) R. Br.) is one of the four most important cereals grown in the tropics (the others are rice, maize and sorghum) (Syngenta Foundation for Sustainable Agriculture, 2005). It is believed to have descended from a West African wild grass that was domesticated more than 40 000 years ago (National Research Council, 1996). It spread from there to East Africa and then to India. Today millet is a food staple for more than 500 million people. The area planted annually with pearl millet is estimated at 15 million hectares in Africa and 14 million hectares in Asia. Global production exceeds 10 million tonnes per year (National Research Council, 1996). The food value of pearl millet is high. Trials in India have shown that pearl millet is nutritionally superior for human growth when compared to maize and rice. The protein content of pearl millet is higher than maize and it also has a relatively high vitamin A content.

In addition to tolerating hot and dry climates, pearl millet is able to produce reasonable yields on marginal soils where other crops would fail. Low fertility and high salinity are frequent problems in millet-producing areas. At the same time, pearl millet responds very favourably to slight improvements in growing conditions, such as irrigation and tillage (Leisinger et al., 1995). For these reasons, it has the potential to spread to more areas of the world, namely the semi-arid zones of Central Asia and the Middle East, North and South America, and Australia (National Research Council, 1996).

Pearl millet is grown by millions of resource-poor, subsistence-level farmers (IFAD, 1999). The percentage of millet used for domestic consumption is rising steadily in Africa (World Bank, 1996). Pearl millet is the third most important crop in sub-Saharan Africa, and the main producing countries are Burkina Faso, Chad, Niger, Nigeria, Mali, Mauritania and Senegal in the west, and Sudan and Uganda in the east. In Southern Africa, maize has partially or completely displaced millet because of the predominance of commercial farming.

Pearl millet, which accounts for about two thirds of India’s millet production, is grown in the drier areas of the country, mainly in the states of Gujarat, Haryana, Rajasthan, Maharashtra and Uttar Pradesh (FAO, 1996).

In Pakistan, pearl millet is an important grain crop, especially in areas where drought is common. Millet is grown primarily south of latitude 34° N. Sixty per cent of the area is in Punjab, and 37.8 per cent is in Sindh. Ninety per cent of the grain produced is used as food and as seed. The little surplus is sold mainly as seed to producers who grow millet for fodder and do not have seed of their own (Pakistan Agriculture Research Council, 2006).

Outside Africa and India, millets are also grown in Australia, Canada, China, Mexico, the Russian Federation and the United States. In most of these other countries, pearl millet is grown primarily as a forage crop for livestock production (National Research Foundation, 1996; Syngenta Foundation for Sustainable Agriculture, 2005).

10.4.2 **The influences of agroclimatological variables on pearl millet**

The climate of most areas where pearl millet is produced can typically be described as hot and dry. Pearl millet has become the primary staple food crop in these areas because nothing else will produce a crop on a reasonably consistent basis. Five climatic factors are of particular importance to pearl millet production: rainfall, air and soil temperatures, day length (photoperiod), radiation, and wind. The impact of these variables is dependent upon the developmental stage of the crop.

The development of pearl millet can be broadly divided into three growth stages (Begg, 1965):

- (a) GS1: Growth stage one, or sowing to panicle differentiation;

- (b) GS2: Growth stage two, or panicle initiation to flowering (floral induction);
- (c) GS3: Growth stage three, or flowering to grain maturity.

10.4.2.1 Rainfall

Millet production depends almost entirely on rainfall as its moisture supply. Therefore, the amount and distribution of rainfall are important factors in determining the ultimate productivity of the crop. In West Africa, the onset of the rainy season is highly variable, while the end of the rains is more definite (Kowal and Kassam, 1978). Some of the agroclimatic features of rainfall distribution include:

- (a) Total rainfall during a season;
- (b) The onset of the rainy season;
- (c) The termination of the rainy season;
- (d) The distribution of rainfall during the rainy season, particularly early in the growth cycle.

At sowing, poor soil moisture reduces seedling emergence, leading to poor crop establishment. In addition, there can be extended periods between the initial rainfall and subsequent rains. If a poor stand results, farmers often resow when rains reoccur. Therefore, it is important that agroclimatic information include information not only on the onset of the rains, but also the expected weather during the period immediately following the onset of the rainy season.

During GS2, or the vegetative growth period, the crop is well adapted to water deficits (Mahalakshmi et al., 1988) and can tolerate intermittent breaks in rainfall, which are a common feature of the climate of millet-producing areas.

During the early flowering and grain-filling stages, the crop is most sensitive to water deficits (Mahalakshmi and Bidinger, 1985; Mahalakshmi et al., 1988). Both timing of stress in relation to flowering and intensity of stress determine the reduction in grain yield (Mahalakshmi et al., 1988). Most of the variation among environments in a multi-location trial was due to the availability of water during early grain filling.

10.4.2.2 Temperature

A large number of studies have been carried out over the years on the effects of air and soil temperatures on the germination, growth and yield of pearl millet (Ong, 1983a, 1983b; Gregory, 1983; Khalifa and Ong, 1990). Pearl millet development begins at a base temperature around 12°C, with an optimum

temperature between 30°C and 35°C and a lethal temperature around 45°C. The base temperature has been shown to be fairly constant, regardless of the stage of development (Ong, 1993a).

In the Sahel, temperatures are usually high because of a high radiation load and scarce rainfall. In some parts of India, however, soil temperatures can be a concern. Soil temperatures influence all aspects of early vegetative development; the emergence of seedlings; and the initiation, appearance and final number of leaves and tillers (Ong, 1993a).

With regard to the germination and emergence stage (GS1), soil temperatures must reach 12°C for germination to begin, as noted earlier. The germination rate increases linearly with temperature to a sharply defined optimum of 33°C and then drops sharply as temperatures increase (Ong, 1993a). High temperatures (>45°C) and soil surface crusting following sowing may also result in poor crop establishment due to seedling death (Soman et al., 1987). In West Africa, sand blasting and the burying of young seedlings under the sand further complicate the problem.

At the development stage (GS2), the temperature requirements of pearl millet depend on the cultivar. Diop (1999) found an optimum range of 22°C to 35°C for plant growth and a maximum of 40°C to 45°C. The optimum temperature for root elongation is 32°C. A WMO report on the agrometeorology of millet (WMO, 1993) states that pearl millet requires temperatures between 22°C and 36°C for a good photosynthetic response, with an optimum range of 31°C to 35°C.

Cantini (1995) reports that leaf appearance and expansion rates are positively correlated with temperature, and that the leaf area index (LAI) increases linearly with temperature in the optimum range. Tillers appear sooner and they form more rapidly as temperature increases to about 25°C (Pearson, 1975; Ong, 1983a). Above 25°C, the time of appearance of the first tiller does not change, but there is a decline in the number of tillers (Begg and Burton, 1971; Ong, 1983a).

The rate of leaf production was accelerated at high temperatures (Pearson, 1975), although the number of leaf primordia on the main stem apex does not change from 18°C to 30°C (Theodorides and Pearson, 1981). The duration of the GS2 phase of development is very sensitive to temperature, averaging 18 days in length (McIntyre et al., 1993). Each one-degree rise in temperature decreased the length of the period by about two days. There is also some evidence that the number of grains produced is

determined during the GS2 stage, and the amount of radiation intercepted during this phase is more important than the interception after anthesis (Ong, 1983*b*). This may explain why the number of grains produced is inversely related to temperature from 22°C to 31°C, since the duration of GS2, and therefore the amount of radiation absorbed, is greatly reduced by increasing temperature.

Leaf extension is also important in controlling dry matter production. Ong (1983*c*) found a linear relationship between the rate of leaf extension and the temperature of the meristem. The more rapid the development of the leaves, the more rapidly the LAI increases.

As for the reproductive stage (GS3), both the rate of spikelet production and the duration of the early reproductive phase are very sensitive to soil temperatures since the meristem is at or close to the soil surface. Grain setting is optimum from 22°C to 25°C and declines at temperatures below and above this range, while grain mass steadily declines with increasing temperatures from 19°C to 31°C (Ong, 1983*b*). Exposure of plants to prolonged periods of low temperature (<13°C during the booting stage) results in low grain set. High temperature during flowering results in a loss of pollen viability and can reduce the receptivity of stigmas and affect grain filling. This is due to sterility of florets and pollen grains induced by lower temperatures (Fussell et al., 1980; Mashigaidze and Muchena, 1982).

10.4.2.3 Day length/photoperiod

Day length, or photoperiod, is a critical control in the initiation of the reproductive phase of the millet in many pearl millet cultivars. Photosensitive cultivars are grown as long-season crops, while non-photoperiodic cultivars are grown as short-season crops (Syngenta Foundation for Sustainable Agriculture, 2005).

The two major millet-growing zones of the world lie in different latitudes, from 11° N to 14° N in western and central Africa and between 25° N and 30° N in north-western India. In both these zones, the length of the growing season varies from 10 to 18 weeks (Kowal and Kassam, 1978; Virmani et al., 1982). The length of the growing season is inversely related to the latitude and this relationship is more pronounced in West Africa, where season length changes markedly over a relatively small distance in latitude. Therefore, the roles of photoperiodic response differ in these regions. In West Africa, the onset of the rains is highly variable, while the end

of the rains is sharp (Kowal and Kassam, 1978). In such environments, photoperiodic control of flowering provides an opportunity to sow whenever the rains begin, but ensures that flowering and grain filling occur when the moisture regime is most favourable (Mahalakshmi and Bidinger, 1985). This helps minimize grain mould and insect and bird damage that affect early-maturing varieties, and avoids incomplete grain filling of late-maturing varieties due to any water shortages at the end of the season (WMO, 1967; Kassam and Andrews, 1975).

Because of photoperiod sensitivity, the growth cycle of local millet cultivars changes greatly with sowing date. If sown in May or June, when days are long, the millet plant remains in the vegetative state (GS1) until day length reaches an inductive threshold. On the other hand, when sown in August or under shorter days, the duration of the vegetative phase is very short, although there is a minimum value that represents the “intrinsic earliness” of the cultivar (Vaksmann and Traore, 1994). In addition, Kouressy et al. (1998) found that the number of leaves and the total biomass are higher with early sowing because of the extended development period. Bacci et al. (1998) indicate, however, that this greater biomass yield is mainly due to stalks and not to grain yield. In other words, higher biomass does not necessarily mean higher grain yields.

10.4.2.4 Solar radiation

Solar radiation is an important asset in crop production. The amount of incoming radiation sets the limits for the production of dry matter. Radiation has two roles in crop production. A segment of total radiation is called photosynthetically active radiation (PAR), which is required for photosynthesis. The solar radiation that heats the Earth's surface provides the thermal conditions necessary for physiological processes (WMO, 1996). Fortunately, radiation is seldom a limiting factor in the tropics.

Pearl millet is a C₄-type plant, which means that it has a high photosynthetic efficiency, particularly under high temperature conditions, because of reduced photorespiration (WMO, 1993). The efficiency of photosynthesis depends, however, on genotype, the age of the leaves and the degree of their exposure to direct sunlight. Direct sunlight is very important both in the morphogenetic processes of growth and in determining the flowering of pearl millet. Within the plant cover, the redistribution of solar radiation involves leaf area density, plant architecture, leaf angle and

planting density (Bégué, 1991). The fraction of the global radiation used for photosynthesis (PAR) has been suggested for the evaluation of pearl millet biomass, when water and nutrient supply is not limited (WMO, 1993). The following equation illustrates this relationship:

$$\text{Total biomass (g m}^{-2}\text{)} = \text{PAR}_a * E_c * t \quad (10.4)$$

where PAR_a is absorbed photosynthetically active radiation, E_c is conversion efficiency of PAR into biomass (g MJ^{-1}) and t is time.

The conversion efficiency of PAR (E_c), also called E_b (Birch, 1990; Sultan, 2002), is the slope of the linear relationship between accumulated dry biomass and absorbed or intercepted energy under optimal growing conditions.

With pearl millet, E_{ca} is not affected by day length or crop density. Even temperature, when its values are above 21.5°C , does not affect E_{ca} despite its effect on the growth cycle. High atmospheric water saturation deficit and/or lack of soil moisture, however, can lower the radiation conversion efficiency because of stomatal closure triggered by these environmental conditions (WMO, 1993).

Several studies have been conducted to determine the radiation use efficiency of pearl millet (McIntyre et al., 1993; Bégué et al., 1991). Radiation use efficiency (RUE) is defined as the dry matter production per unit of incoming solar energy. In a study in Niger (Bégué et al., 1991), measurements of the components of radiative transfer were combined with measurements of biomass and LAI. A linear relationship was found between PAR and LAI. Pearl millet does have a relatively low LAI, reaching only 1.3 in this study. The conversion efficiency varies with the stage of development, being highest during tillering and then gradually declining as the crop matures (McIntyre et al., 1993). When irrigated and non-irrigated responses to extreme temperatures and moisture stress were compared, RUE did not change under varying temperature regimes when irrigation was applied. The radiation use efficiency of the non-irrigated plots did decline under extremely high temperatures, however.

10.4.2.5 Wind

In West Africa, heavy winds associated with thunderstorms are common during the crop season. These winds are laden with dust particles that reduce visibility and the incoming amount and quality of radiation; these particles form deposits on leaf surfaces that may affect photosynthesis (WMO, 1996).

On the sandy soils in the southern Sahel, wind erosion owing to frequent sandstorms, especially at the beginning of the rainy season, is one of the constraints to crop growth (Michels et al., 1993). If sufficiently buried, these “pockets” of plants must be replanted. Surviving plants from partially covered pockets show delays in growth and development. The maximum plant height and leaf number are lower, with a significant reduction in the leaf area index. Grain yield from unaffected pockets is nearly twice that of pockets that are partially covered.

In shelterbelt studies in northern Nigeria, it was shown that *Eucalyptus camaldulensis* shelterbelts positively influenced yields of millet crops planted close to the belts. (Onyewotu et al., 1998). Experience showed that the shelterbelts would have to be no more than 100 m apart to fully exploit the protection of the crop from advected hot, dry air. Millet (this is not pearl millet) grown outside of the influence of the shelterbelts yielded about 50 per cent less when both methods of determining the onset of the growing season were used. Soil moisture availability early in the season was the largest determinant in yield differences among plots, as a result of its influence on growth, tillering and grain filling. Substantial yield differences as a function of the distance from the belts could be explained by soil moisture at sowing and the effects on crop growth conditions resulting from hot, dry turbulent air generated by the belts. The shelterbelts settled drifting sand and undulations and encouraged the return of soil-protecting grasses (Onyewotu et al., 2003). A number of the factors that should be taken into consideration in the design and development of shelterbelts are described by Stigter (2005).

10.4.3 Management aspects of pearl millet in various environments

Traditional cropping systems in the Sahel consist essentially of continuous pearl millet/cowpea intercropping with low plant populations and no chemical fertilizers. All production operations are done manually in these traditional systems (World Bank, 1996). On the sandy soils of Africa, pearl millet is typically planted either in a dry seedbed or immediately after the first rains. Rainfall can be sporadic, particularly early in the rainy season. Because prolonged droughts can occur after sowing and during early the early seedling stages, however, growth can be greatly hindered. Since the total rainfall in these areas is still limited, the timing of the early rains is very important for crop development. Drought conditions combined with high temperatures can be highly detrimental to the emergence and development of the young seedlings.

Strong winds can also cause damage to the young seedlings and cover them with sand.

In terms of land preparation and cultivation, in most cases little or no tillage is done and weeding is started right after emergence in Africa. In sandier soils, the ground is dug over with a hoe and weeded prior to planting. Warm soils are required since higher temperatures encourage rapid germination (Syngenta Foundation for Sustainable Agriculture, 2005). Millet is sown in hills, 10–15 cm deep, dug with a hand hoe, and weeding is carried out with a hoe that cuts the soil 2–5 cm under the surface. This not only cuts the roots of the weeds, but also breaks the surface crusts and facilitates water infiltration (De Rouw and Rajot, 2004). All these cultivation practices are common throughout the African Sahel, where millet is grown on sandy soils.

In Pakistan the use of tractors for the preparation of the land is becoming more common, but bullock power is still important (Pakistan Agriculture Research Council, 2006). The recommended practice is to plough the land twice immediately following harvest to bury the stubble and weeds, and once or twice at sowing to prepare a fine seed-bed. Land preparation is usually inadequate, however, particularly in moisture-stress areas farmed by resource-poor farmers, where the land is usually ploughed only once. Also, even for those areas where tractors are available, the specialized implements needed for cultivation and harvesting have not been developed.

Because prolonged droughts can occur after sowing and during the early seedling stage, growth can be greatly hindered. Once the crop is established, there are a limited number of options available to the producer in the event of problems with insects and diseases.

A major problem of rainfed agriculture in semi-arid regions with short rainy seasons is how to determine the optimum sowing date. Traditional farmers have developed their own definitions, using accumulated experience and/or calendars based on local beliefs (Onyewotu et al., 1998). Some more scientific methodologies have been developed. For defining the onset date of annual rain in Nigeria, Kowal and Knabe (1972) used a combination of accumulated rainfall totals and rainfall/evapotranspiration relationships as criteria. This was taken as the first 10-day period in the season when the amount of rainfall is equal to or greater than 25 mm, but with a subsequent 10-day period in which the amount of rainfall is at least equal to half the evapotranspiration demand. Traditional farmers in parts of northern

Nigeria define the onset of rains as the day of the first good rain after the Muslim fasting period of Ramadan, provided that it has been at least seven months since the date of the last effective rain of the previous season (Onyewotu, 1996). Discussions with farmers participating in the study found that not all farmers have the same definition of the first good rain. Yields were significantly higher using a more scientific approach to determining sowing date. The overall differences in yield between the two sowing dates must be due mainly to soil water availability, particularly during the seedling stage.

In Pakistan, millet fields in the rainfed *barani* areas are sown with the start of the monsoon rains, usually during the first fortnight of July. In areas irrigated by hill torrents, the sowing period is usually from mid-July to mid-August, depending on the arrival of the flood water. In central Punjab, irrigated millet (used primarily for fodder) is grown from May to July. In Sindh, millet for fodder may be grown from February to July, but for grain production, sowing is delayed to June–July to avoid flowering in July–August when the temperatures are extremely high (Pakistan Agriculture Research Council, 2006).

The most common soil fertility management practice with pearl millet is fallowing. Sometimes, manuring is practiced either through corraling (the animals spend the nights on the field during the dry season) or spreading the manure across the fields (DeRouw and Rajot, 2004). The cultivation practices are the same on manured and fallowed land and are common throughout the African Sahel where millet is grown on sandy soils.

Pearl millet responds well to additional plant nutrition. In a four-year study in Oklahoma, United States, to evaluate different summer forages, pearl millet was as productive as the average sorghum sudan but required one fifth the nitrogen (N) and was more efficient with the N it received (Johnson, 2006). Increased fertility also results in an increase in water use efficiency. In a four-year study at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Center in Niger, the increased yield due to the application of fertilizer was accompanied by an increase in the water use efficiency (WUE) in all four years. The beneficial effect of fertilizer could be attributed to the rapid early growth of leaves, which can contribute to a reduction in the evaporative losses from the soil and increased WUE (Sivakumar and Salaam, 1999). Over the four seasons, the average increase in WUE due to the addition of fertilizer was 84 per cent.

With regard to moisture conservation, evaporation from the soil surface constitutes a large proportion of evapotranspiration (ET) of pearl millet fields in West Africa. Practical methods of reducing evaporation from soils to conserve water are lacking in West Africa (Payne, 1999). The use of organic mulch during the growing season would be a simple solution except that most of the crop residues are fed to livestock or used for building materials during the long dry season. Plastic mulch would also be effective, but such materials are too expensive or generally unavailable in most of West Africa.

Pearl millet leaf area indices are typically <0.5 during the early growth stages in semi-arid West Africa, causing transpiration to be a relatively small fraction of evapotranspiration (Daamen, 1997). The probability of dry spells of ten days or more is high (Sivakumar, 1992), and crop water supply is often exhausted, necessitating resowing after the next sufficiently large rain event. Delayed sowing is generally associated with yield decline in pearl millet (Reddy and Visser, 1993). Any reduction of evaporation (E) during this and subsequent periods would increase water supply for crop growth and reduce the risk of resowing.

The hilaire is a shallow-cultivating, traditional hoe that has been used for centuries on sandy soils in West Africa to control weeds. It is pushed and then pulled by the user so that the blade cuts the roots of weeds 4 to 5 cm below the soil surface. The affected surface is pulverized and loosened. Furthermore, the colour of the soil's surface becomes darker because the underlying soil layer has greater organic matter pigmentation (Payne, 1999).

Hillel (1982) has suggested that one way to control evaporation during the first stage is to induce a temporarily higher evaporation rate so the soil surface is rapidly dessicated. This hastens the end of the first stage and uses the hysteresis effect to help arrest or retard subsequent flow. The use of the hilaire leaves the soil surface in a state close to what Hillel has proposed. In studies by Payne (1999) it was clearly demonstrated that ET was 45 mm less in tilled plots compared to untilled plots. In areas with 200–600 mm of precipitation, this represents a significant reduction in moisture loss. Because of limited labour resources, however, it would be unrealistic to expect subsistence farmers to till entire fields with the hand-operated hilaire after each rain event. In order to render this technique useful to farmers, an animal-drawn implement would need to be designed that reproduces the hilaire's effect.

A related issue is the practice of planting pearl millet in widely spaced rows. This is perceived to be a practice that reduces pearl millet crop failure. As a result, the LAI in most fields seldom reaches 1.0. Even in more intensively managed fields, LAI seldom exceeds 2, and the period during which LAI exceeds this value constitutes only a small portion of the entire growth period (Payne, 2000). Payne (1997) found that increasing plant density from 5 000 to 20 000 "hills" ha⁻¹ increased yield and ET efficiency significantly despite low fertility, even during 1984, the driest year on record. There appears to be no justification, at least in terms of crop water use, for wide spacing. Canopy cover can also be increased by the introduction of an intercrop. In semi-arid West Africa, pearl millet is most often intercropped with cowpea. Intercropping with cowpea has been reported to increase pearl millet grain yield by between 15 and 103 per cent in Mali.

Although pearl millet in India is the crop of the rural poor in the country's harshest agricultural environments, F1 hybrid seed is used to sow over half of the 10 million ha on which this crop is grown because the potential yield obtainable from such hybrids more than pays for the cost of the seed and other risks associated with hybrid cultivation (WISARD, 1999). Although pearl millet hybrids often give better grain yields than local open-pollinated cultivars, the genetically uniform single-cross hybrid cultivars currently available in India are more vulnerable to epidemics of pearl millet downy mildew. Such epidemics constitute the major risk to cultivation of well-adapted pearl millet hybrids. Losses in individual fields can reach nearly 100 per cent, and are estimated to average 14 per cent across 10 million ha in India.

Intercropping, or planting two or more crops in the same field, is one means of better utilizing limited resources. A study to quantify the use of resources in dominant millet-cowpea (M-C) and millet-sorghum-cowpea (M-S-C) intercropping systems was carried out by Oluwasemire et al. (2002) using standard farming practices under the low rainfall and poor nutrient supplies in the semi-arid zone of Nigeria. When intercropped, pearl millet used water more efficiently for grain production. It showed a better adaptation to moisture stress by producing similar harvest indices in comparison to single-cropped and intercropped millet. The harvest index was defined as the ratio of the yield of grain to the total dry matter production of the plant. Millet was also the dominant crop in dry matter production when intercropped. This was due to the faster growth and higher tillering rates of millet, especially at low plant densities.

10.4.4 **Other background information on pearl millet**

10.4.4.1 **Drought tolerance mechanisms**

Deep root penetration is an important aspect of the ability of pearl millet to survive under high stress. Pearl millet roots can penetrate up to 180 cm deep, with approximately two thirds of the root system in the top 45 per cent of the soil zone (Mangat et al., 1999). This deep root penetration may help millet species to exploit soil water more effectively and therefore overcome drought stress. Pearl millet root systems also have the ability to penetrate through hard clay pans in the lower soils. In addition, the photosynthetic rates are maintained through periods of severe drought (Zegada-Lizarazu, 2004).

Pearl millet has a typical monocotyledonous type of root system consisting of a seminal or primary root, adventitious roots, and crown or collar roots (Mangat et al., 1999). The seminal root develops directly from the radicle, adventitious roots from the nodes and the base of the stem, and crown roots from several lower nodes at or below the soil surface. The seminal root, an elongation of the radicle, is thin with a profuse fine lateral root system. These lateral roots develop within four days after radicle emergence and help in the initial establishment of the seedling. The seminal root is active up to 45–60 days, after which it begins to deteriorate.

The adventitious roots start appearing at the basal nodes of the stem 6 to 7 days after seedling emergence. These grow rapidly and form a root system of secondary and tertiary roots that are the principal route of absorption of water and nutrients during the major part of the life cycle of the plant. Crown roots develop from the lower nodes near the soil surface approximately 30–40 days after seedling emergence. The crown roots above the soil surface thicken and support the plant, preventing it from lodging.

In terms of leaf structure, stomata are present on both leaf surfaces. The colour of the leaves varies from light green to yellow to deep purple. The maximum leaf area (LAI) occurs at the time of 50 per cent flowering, when the majority of the tillers have produced leaves. After flowering there is a decline in leaf area, and during this time the leaves begin senescing. At physiological maturity only the upper 3–4 leaves may be green on the main stem (Mangat et al., 1999).

Stomatal sensitivity to evaporative demand is dependent upon leaf age and leaf area of the crop.

This suggests that the degree to which water use is controlled by stomata and leaf area is influenced by ontogeny so as to optimize crop water use for growth (Winkel et al., 2001). It appears that stomates tend to remain open even under high levels of moisture stress. The implication is that millet does not tend to conserve moisture but rather transpires freely as long as the root system can supply the water it needs (Wallace et al., 1993). Leaves will begin to senesce, however, thus reducing the LAI of the plant canopy. Stomatal regulation and leaf senescence are not mutually exclusive; stomatal conductance decreases as leaf area increases. Conversely, a reduction in transpiring area increases stomatal conductance in the remaining leaves.

10.4.4.2 **Diseases, pests and weeds**

Downy mildew, *Striga*, smut, ergot and rust are the major deterrents to pearl millet production, with the first two being by far the most important (Syngenta Foundation for Sustainable Agriculture, 2005; WMO, 1996).

Downy mildew (*Sclerospora graminicola* (Sacc.)) constitutes the major disease risk to the successful cultivation of pearl millet (WISARD, 1999), particularly in India. Up to 30 per cent of the harvest in India can be lost during years of severe attack, with losses in individual fields reaching nearly 100 per cent (CGIAR, 2006).

Although pearl millet hybrids often give better grain yields than local open-pollinated cultivars, the genetically uniform single-cross hybrid cultivars currently available in India are more vulnerable to epidemics of pearl millet downy mildew. Such epidemics constitute the major risk to cultivation of well-adapted pearl millet hybrids.

The soil-borne sexual spores or oospores that can survive in soils for several years are the primary source of inoculum for downy mildew disease. Their thick cell walls protect them from desiccation and serve as an impermeable membrane. During cool and humid nights, the systemically infected leaves produce abundant sporangia on the abaxial surface. The hot and dry environmental conditions favourable for pearl millet growth may not be conducive for sporangial production and survival, however (Singh et al., 1993).

Three strategies have been identified to assist in the control of downy mildew in pearl millet: the use of disease-resistant cultivars, seed treatment and/or early sowing. In a recent study in Nigeria, the

incidence of pearl millet downy mildew, its severity, and the yield losses of two pearl millet varieties (local and improved) due to the disease were determined in field studies (Zarafi et al., 2004). Significant reductions in the disease incidence and severity were recorded in plots sown with metalaxyl-treated seeds, indicating the efficacy of the fungicide. Metalaxyl protects seedlings for the first 20–30 days after sowing. Yield losses due to non-treatment of seeds were 40.88 and 45.39 per cent in a local variety and 43.00 and 18.60 percent in an improved variety in the 2000 and 2001 cropping seasons, respectively.

In a three-year study in Nigeria, Zarafi (2005) studied the efficacy of combining sowing date, seed treatment with metalaxyl and the use of host-plant resistance to control downy mildew in pearl millet. Early sowing gave lower disease incidence and higher grain yield than late sowing. The disease was controlled when metalaxyl-treated seeds were sown early. The highest disease incidence and lowest grain yields were obtained when untreated seeds were sown late. Use of a resistant pearl millet cultivar along with seed treatment using metalaxyl greatly reduced disease incidence and increased grain yield in comparison with the seed treatment of susceptible cultivars.

Striga is a parasitic weed that creates major problems across much of Africa and parts of Asia. Twenty-one million hectares of cereals in Africa are estimated to be infested by *Striga*, leading to an estimated annual grain loss of 4.1 million tonnes (Sauerborn, 1991). *Striga* is one of the major reasons that pearl millet productivity has remained at a subsistence level for so many years (IAPPS, 2007). *Striga* competes with the pearl millet plant for both water and nutrients. Consequently, low soil fertility and low rainfall favour *Striga* infestations. *Striga* can be partially controlled by pre-treatment of seeds with herbicides that reduce or prevent the germination of the *Striga* seeds. New sources of genetic resistance have only recently been identified in the wild progenitor of pearl millet. It remains to be explored whether and how this resistance can be transferred to varieties acceptable to farmers (Syngenta Foundation for Sustainable Agriculture, 2006).

Smut is a panicle disease (it attacks the flowering head of the pearl millet plant). The primary source of inoculum is spore balls in the soil from previously infected crop residue and surface-contaminated seeds used for sowing (Thakur and King, 1988). Moderate temperatures (25°C–30°C) rather than cool temperatures, high relative humidity (>80 per

cent) and long days seem to favour disease development (Kousik et al., 1988; Thakur, 1990).

Rust is a foliar disease. Occurrence of the disease during the seedling stage can result in substantial losses in grain and fodder yield and quality. Cooler temperatures and high humidity favour disease development (Singh and King, 1991). When rust appears late in the season, grain yield may not be affected, but the plant fodder is used as an animal feed after the grain is harvested. The disease causes a severe reduction in digestible dry matter yield of forage. Animal production could be improved by identifying rust resistance among popular and potential cultivars. In studies conducted in 1997 and 1998, several resistant varieties were identified. Of all the environmental parameters evaluated, only average temperatures below 27°C were consistently associated with the onset of rust epidemics (Panwar and Wilson, 2001).

10.4.4.3 Insects and pests

Pearl millet has relatively few menacing insect pest problems. In the Asian subcontinent, white grubs are the major pests (Rachie and Majumdar, 1980). In West Africa, there is a range of insect pests that damage the crop, resulting in economic losses; the major ones are the earhead caterpillar (*Raghuva*), stem borer (*Acigona*), midge (*Geromyia penniseti*) and several species of grasshoppers.

The white grub (*Holotrichia sp.*: Scarabidae) is an important subterranean pest that damages the root systems of several different crops, including pearl millet. Based on the severity of the infestation, the crop is either harvested early or uprooted for a second crop. Some control can be achieved by the use of pesticides, but they must be applied early in the season. The infestations do not become apparent until late August or early September when the grub attains its maximum size and becomes a voracious feeder (Parasharya et al., 1994). The use of pesticides recommended as a preventive measure against white grub must be applied at the time of sowing.

Pest surveys in West Africa indicate that crops are devastated by infestations of earhead caterpillars (*Raghuva*). The number of surviving diapausing pupae emerging from the soil is associated with soil temperature and moisture at different depths from November to May. In addition, there is a close relationship between moth emergence and the onset of rain and soil moisture, which are key factors in diapause termination. The increase in soil moisture content and lower soil temperatures in the upper

soil layers are associated with earlier termination of diapausing pupae in this soil layer (Nwanze and Sivakumar, 1990).

The time of the onset of rainfall and the total amount of rainfall during the crop season is related to the stem borer (*Acigona ignefusalis*) population (Nwanze, 1989). There is a need for knowledge of diapausing populations and the relationship between insect pests and rainfall during the season in regions where sporadic outbreaks occur in order to integrate the weather parameters with the population dynamics of the pests.

10.4.5. **User requirements for agrometeorological information**

As indicated in other sections, to be of use the agrometeorological information provided must meet several important criteria. The information must be timely and accurate, it must address specific needs, and it must be in a form that can be easily and accurately interpreted by the producer, extension service or whoever provides advice to the producers. User requirements will vary greatly with the area where pearl millet is being grown. The major areas producing pearl millet are located in the semi-arid tropics of Africa and India. As stated, a majority of those producers are subsistence farmers with very limited resources. The farms are small and usually cultivated by hand. But other millet-producing areas in mid-latitude areas involve more intensive production practices and are highly mechanized. The requirements for agrometeorological information can be separated into the current growing season, overall seasonal differences and longer-term features of the climate.

In terms of information for the current growing season, given limited means, both from a climate perspective and owing to economic constraints, it is extremely important to minimize risk and maximize the use of whatever resources are available. In the semi-arid tropical regions where pearl millet is grown, the initial establishment of the plant stand and the conservation of water are of vital importance. Farmers want to avoid replanting a crop because of drought conditions or hot, dry winds immediately following planting and seedling emergence.

Choosing what to plant and where to plant is the main way farmers can respond to rainfall forecasts. Ingram et al. (2002) have surveyed farmers in parts of West Africa to determine their awareness of seasonal forecasts and their interest in having that information. Farmers indicated that by itself a forecast of total

season rainfall is of limited usefulness. Farmers in all sites stressed that precipitation forecasts must include estimates of duration and distribution of rainfall over time and space to be most valuable. In addition, most farmers requested that such forecasts be issued 1–2 months prior to the onset of the rainy season. This lead time enables them to optimize labour and land allocations, obtain different varieties and prepare fields in different locations.

In order of declining priority, the most salient rainfall parameters farmers want in a forecast are: timing of the onset and end of the rainy season; likelihood of water deficits, that is, the likely distribution pattern over the growing season; and the total amount of rainfall. In the Sahel, information on seasonal rainfall quantities can help farmers know whether to plant millet in high or low water retention areas.

To be understood and useful, forecasts need not only to provide relevant information at the optimal time. They must also be delivered in the most appropriate form and language, by credible sources. This task becomes even more challenging because farmers have different levels of access to formal education, the availability of extension-type services varies, and there are differences in adherence to local religious beliefs. This affects the extent to which local knowledge, including local climate forecasts, remains a viable basis for farmer decisions.

Agrometeorological information required to cope with climatic risks for any given season would include:

- (a) The current climate regime and its effect on the onset of the rainy season, including the expected date of the onset of rain. This could also aid in the medium-term planting outlook. Information on regional climate dynamics might help improve crop production locally. It has been shown that the regional onset of the monsoon is very close to the ideal sowing date (Sultan et al., 2005);
- (b) The development/adaptation of more scientific approaches to determine when sowing should begin;
- (c) Timely information on the onset of the rainy season. Weather forecasts should include information on both temperatures and the likelihood of future precipitation;
- (d) Expected conditions immediately after the onset of rain. Wind and high temperatures are a common problem immediately following planting and seedling emergence;
- (e) Date of the end of the rainy season;

- (f) Development/adaptation of models for forecasting the development of critical disease and insect outbreaks;
- (g) Development of simple, practical methods of getting the appropriate information to farmers to help them maximize their limited resources.

With regard to long-term planning, research suggests reduced African food production if the global climate changes towards more El Niño-like conditions, as most climate models predict. Management measures include annual changes in crop selection and storage strategies in response to predictions calling for El Niño–Southern Oscillation and North Atlantic Oscillation conditions for the next growing season. Long-term planning can also be important in the development of agricultural policy by regional and national governments and international organizations. The development of longer-term policies must stem from baselines established by an analysis of historical conditions. From a climatic perspective, the development of climatic atlases and associated analyses become extremely important.

Under the conditions found where millet crops are cultivated, evaluation of rainfall in terms of probability estimates instead of arithmetic means is desirable, since, in most cases, rainfall becomes the key climatological element determining the suitability of a locality for millet production.

The derived rainfall parameters, such as the onset of rains, cessation of rains, duration of the rainy season, sowing rains and rainfall probabilities for specific phenological phases (sowing time, flowering, harvesting, and so forth), are very useful for long-term agricultural planning. Rainfall probabilities can be estimated using the gamma distribution since it fits better than other mathematical distributions for rainfall data (WMO, 1996).

Information required to cope with climatic risks for longer-term planning would include:

- (a) The probability, frequency and timing of adverse weather conditions, including the distribution of rainfall, windstorms and beginning and end of the rainy season;
- (b) The pattern of rainfall, temperature, evapotranspiration, relative humidity, sunshine hours, vapour pressure deficits and other agriculturally significant climate variables;
- (c) Agroclimatological analyses of these significant variables for evaluating additional production areas, particularly in the light of concern about potential changing climates.

Climatic risk zoning may be used to determine the best planting time to avoid or reduce drought effects on crop development. The following determinations/assessments are thus suggested for coping with climatic risk:

- (a) Potential suitability of a specific variety for a given region;
- (b) Probability of drought at critical points in the growing season;
- (c) Phenological stage most susceptible to drought;
- (d) Availability of local meteorological data;
- (e) Zoning of production districts based on climatic and edaphic conditions;
- (f) Information about the weather factors that are conducive to infestation by insects and infestation by pathogens to allow timeliness of control practices;
- (g) Suitable drought monitoring and characterization indices, such as:
 - (i) Water requirement index;
 - (ii) Drought index;
 - (iii) Available stored water;
 - (iv) Probability of dry spells;
 - (v) Rainfall anomaly;
 - (vi) Soil moisture-holding characteristics.

10.4.6. **Agrometeorological services related to pearl millet in Africa and India**

10.4.6.1 **Africa: Example 1**

The information presented in this example has been drawn from Oluwasemire et al. (2002) and Stigter et al. (2005). The major cereals that are adapted to the rainfed region of the Nigerian Sudan savanna are pearl millet and sorghum. These cereals are predominantly intercropped with cowpea and/or groundnut. The most dominant crop mixtures are millet/cowpea, millet/sorghum/cowpea, millet/cowpea/groundnut, sorghum/cowpea and sorghum/cowpea/groundnut. Cowpea has a dual purpose: the grain is used for human consumption and the remaining biomass as fodder for animals. Intercropping components adopted by farmers are grown at low densities, to minimize risks and exploit resources in a good cropping season. Experiments to determine what sort of improved answers local intercropping systems could give to land degradation were conducted during the 1994 and 1995 rainy seasons. The experiences highlighted the usefulness and desirability of an agrometeorological service that would be aimed at improving the cereal/legume systems in the Nigerian arid and semi-arid zones. In parallel, genetically superior crop cultivars and the manipulation of the component densities would be included in the suggested project, along with the improvement of microclimatic variables. An ameliora-

tion of the cereal/legume intercropping systems may involve a reduction in plant density of the tillering millet component, which accumulates dry matter more rapidly, while the density of the low-growing and ground-covering cowpea component is increased. The results showed that abundant organic manure in combination with agrometeorological services on microclimate improvements related to intercrop manipulation may control near-surface land degradation in northern Nigeria under acceptable sustainable yields. Appropriate policy environments, in economics and research, must enhance these efforts.

10.4.6.2 Africa: Example 2

This example is based on Onyewotu et al., (2003, 2004) and Stigter et al. (2005) and it illustrates failures in original attempts to protect millet crops in Sahelian Nigeria from advected heat by multiple shelterbelts. Farmers had to learn for themselves that the crops were sufficiently protected only in close proximity to the belts. Participatory experiments demonstrated as an agrometeorological service why this was the case, only at a much later date. At this same very late stage, while the farmers had long complained about allelopathy of the trees, it was shown that this did not exist and that root pruning and branch pruning did away indeed with all competition for resources between trees and millet. This showed the maximum benefits of the rehabilitation of the degraded land as originally designed. As the soil and crop protection measures were insufficient, the farmers of sheltered land were economically worse off. The research confirmed views that have been held for close to 20 years, namely, that a soil management and rehabilitation policy must be formulated. In the context of wider development objectives and a well-defined direction of social change. Although local adaptation strategies and contemporary science were jointly available, the policy environment was not conducive to useful information transfer, local initiatives and innovations. The answer to land degradation had initially been found in the establishment of the multiple shelterbelts. The answer of sufficient tree densities to prevent advected heat from spoiling pre-sowing soil water conditions and unprotected millet crop growth was only found as an agrometeorological service in the framework of this research, however.

10.4.6.3 India

The India Meteorological Department recognized the importance of meteorology in increasing food production and established its Division of Agricultural Meteorology (DAM) back in 1932. The Division has a wide network of agrometeorological

observatories, which generate various kinds of data on agrometeorological parameters. In 1977, in collaboration with various state agricultural departments, the DAM began issuing weekly/biweekly Agromet Advisory Bulletins. The bulletins contain specific agricultural advisories tailored to the needs of the farming community.

The primary aim of the service is to provide timely advice on the actual and expected weather and its potential impact on the various day-to-day farming operations. The advisories take into account the stage of the crops, agricultural operations in progress, the prevalence of pests and diseases, and the immediate impact of weather on crops. They are prepared in collaboration with agricultural experts and broadcast over All India Radio (AIR). The bulletins contain specific advice for farmers to help them protect their crops from adverse weather and make the best use of prevailing favourable weather to increase production.

In addition to the Agromet Advisory Bulletins, the Farmers' Weather Bulletin (FWB) is also regularly issued from Regional Meteorological Centres. This bulletin indicates the onset of rains; probable rainfall intensity and duration; weak or a break in monsoon conditions; and the occurrence of frost, hail, squalls and other conditions. The FWBs are issued throughout the year in different regional languages. The bulletins are also published in newspapers.

10.4.6.4 India: Example 1

This example is taken from <http://www.indiaweatherwatch.org/agroad/Jodhpur.pdf>.

Agrometeorological Advisory Services Central Arid Zone Research Institute (CAZRI), Jodhpur

Date: 16 March 2007

Weather Forecast:

In the next 3 to 4 days (16–19 March) Jodhpur and its surrounding 50 km area maximum and minimum temperatures rise by 3°C to 4°C and clear sky conditions will prevail. Wind direction is expected north-west with 4 to 6 km/h speed.

Agrometeorological Advisory:

Agrometeorological Advisory Services Committee of CAZRI suggested to farmers of Jodhpur region the following advisory:

- Weather is favorable for harvesting the *rabi* crops. So farmers are advised to harvest the crop and put it safest place in field for threshing.

- Farmers who have irrigation facility can grow fodder crops like fodder pearl millet and sorghum. For fodder pearl millet *Raj Chari*, *Rajaco Jayant*, *L-74* and for sorghum *Rajasthan Chari-3*, *Rajasthan Chari-3*, *Pusa Chri-6* and *M.P. Chri* are suggested for improved fodder. Seed rate should be used 12 kg/ha for pearl millet and 40 kg/ha for sorghum. For improving the quality of the fodder crop should be mixed with 10 to 20 kg seed of cowpea and then sown. Before sowing seed should be treated by thirum 3 gm per kg seed.

10.4.6.5 India: Example 2

This example is taken from <http://www.hindu.com/2005/06/17/stories/2005061701491400.htm>

Department of Agricultural Meteorology
Marathwada Agricultural University, Parbhani

Weather forecast and agricultural management

(For 04, 05, 06 and 07 August 2006)
Bulletin No. 42 Date: 04-08-2006

Past weather condition: The skies remained mainly cloudy and a total of 18.6 mm rainfall was recorded during last four days. The maximum temperatures prevailed between 26.0°C to 30.5°C, which were below normal by 0.0°C to 4.0°C. The minimum temperatures ranged between 20.5°C to 22.5°C, which were below normal by 0.0°C to 2.0°C. Total rainfall recorded from 1st June till to date is 255.4 mm as against normal 428.9 mm for the corresponding period.

Weather forecast: The skies are likely to remain complete overcast and a total of 110.0 mm rainfall is expected during next four days as predicted by the National Centre for Medium Range Weather Forecasting (NCMRWF). The wind speed is likely to remain in between 8 to 9 kmph, which will be below normal by 1 to 2 kmph. The predominant wind direction will be 290 degrees. The maximum temperatures are likely to remain in between 24.5°C to 26.5°C, which will be below normal by 4.4°C to 6.4°C. The minimum temperature will remain in between 20.0°C to 21.0°C, which will be below normal by 1.5°C to 2.5°C. There is a possibility of 140.0 mm cumulative rainfall during next 7 days.

Impact of weather on crops and weather based agro-advisories:

- Farmers are advised to apply 40 kg, 30 kg and 40 kg/ha N fertilizer to Sorghum, Pearl millet and Cotton crops, respectively, after cessation of rainfall.

- Farmers are also advised to undertake plantation of fruit crops.
- Infestation of leaf miner is noticed in soybean crop. For control of leaf miner, spraying of dimethoate or monochrotophos 10 ml in 10 litres of water is recommended.

Sd/-

Nodal Officer and Head

10.5 AGROMETEOROLOGY AND POTATO PRODUCTION

10.5.1 Importance of potato in various climates

The potato (*Solanum tuberosum* L.) is a member of the nightshade family (Solanaceae) and is a major world food crop and by far the most important vegetable crop in terms of quantities produced and consumed worldwide (FAO, 2005). Potato is exceeded only by wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and maize (*Zea mays* L.) in world production for human consumption (Bowen, 2003). Potato tubers give an exceptionally high yield and find their way into a wide variety of table, processed, livestock feed, and industrial products (Feustel, 1987; Talburt, 1987). Potato provides nutritious food in a diversity of environments. Potato can be an important food for the rising world population and has the potential for increased vitamin C and protein content.

The principal limiting factors for potato production are heat and water stresses. The effects of these factors on physiology, yield and grade of potato crop are thoroughly discussed herein. The meteorological elements governing growth, development, production and quality of potato tubers at a given site are basically air and soil temperatures, solar radiation, photoperiod, soil moisture and crop water use or evapotranspiration.

Potato originated from tropical areas of high altitude in the Andes. The crop is grown throughout the world but is of particular importance in temperate climates. Present world production is 329 106 Mg fresh tubers from 19.1 million ha (FAO, 2005). The major world producers, in order of production, are China, Russian Federation, India, United States, Ukraine, Poland, Germany, Belarus, Netherlands, United Kingdom, Canada, Turkey and Romania (FAO, 2005).

The above-ground stems of potato plants are erect in early stages of development but later become

spreading and prostrate or semi-prostrate. The tuber is an enlarged underground stem. The tubers have buds or eyes, from which sprouts arise under certain conditions. Tubers are harvested for both food and seed. The flowers and fruits are only important to potato breeders.

Potato has a relatively shallow, fibrous root system with the majority of the roots in the upper 0.3 m of soil (Lesczynski and Tanner, 1976; Tanner et al., 1982). The root system develops rapidly during early growth and achieves maximum development by midseason. Thereafter, root length, density and mass decrease as the plant matures. Rooting depths of 1.2 m or more have been reported for potato under favourable soil conditions (Durrant et al., 1973; Fulton, 1970). Potato extracts less water from the soil than barley (*Hordeum vulgare* L.) and sugar beet (*Beta vulgaris* L.) and the differences are more pronounced below 0.6 m depth (Durrant et al., 1973).

The origin of potato in cool climates with equatorial day lengths, as well as the shallow potato root systems, have consequences for the agrometeorological responses of the crop. Knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under site-specific atmospheric conditions. Crop weather models can be used to provide estimates of potato yield as a function of climatic factors at a particular locality. The SUBSTOR-Potato model, for instance, takes into consideration daily data of temperature, photoperiod, intercepted solar radiation, soil water and nitrogen supply. The model simulated fresh tuber yields ranging from 4 Mg ha⁻¹ to 56 Mg ha⁻¹ due to differences in climate, soils, cultivars and management practices (Bowen, 2003).

According to the Alberta Agriculture, Food and Rural Development Department (2005), the potato plant has five growth stages: sprout development (I); plant establishment (II); tuber initiation (III); tuber bulking (IV); and tuber maturation (V). Timing and duration of these growth stages depend upon environmental factors, such as elevation and temperature, soil, moisture availability, cultivar and geographic location.

At growth stage I, sprouts develop from eyes on seed tubers and grow upward to emerge from the soil, roots begin to develop at the base of emerging sprouts and the seed piece is the sole energy source for growth during this stage. At stage II, leaves and branches develop on emerged sprouts, roots and stolons develop below ground and photosynthesis

begins. Potato development in stages I and II lasts from 30 to 70 days, depending on planting date, physiological age of the seed tubers, cultivar, soil temperature and other environmental factors. At stage III, tubers form at stolon tips but are not yet appreciably enlarged, and in most cultivars the end of this stage coincides with early flowering that lasts roughly two weeks on average. At stage IV, tuber cells expand with the accumulation of water, nutrients and carbohydrates. During the tuber bulking stage, tubers become the dominant site for carbohydrate and inorganic nutrient storage. Tuber bulking can continue up to three months as a function of the cultivar and environmental conditions. During stage V, photosynthesis gradually decreases, leaves turn yellow, tuber growth rate slows and the vines die. Maturation may not occur in the field when a long-season variety like Russet Burbank is grown in a short-season production area.

10.5.2 **Agroclimatology of potato (and some management aspects)**

Kooman et al. (1996) report three phenological phases in the allocation of dry matter that is accumulated daily. Initially, dry matter is divided between stems and leaves (growth stage II). In the second phase, which starts at tuber initiation, an increasing amount of accumulated dry matter is allocated to the tubers and a decreasing fraction to the leaves (growth stages III and IV). In the third phase, all assimilates are allocated to the tubers (growth stage V). Leaf growth stops and photosynthesis eventually stops because of leaf senescence. Climatic factors influence all three phenological phases. The duration of the first phase, comprising the development period between emergence and tuber initiation, is shortened by short days and temperatures less than 20°C. Tuber initiation is slower at temperatures over 20°C. The duration of the second phase is affected by temperature, with an optimum between 16°C and 18°C (van Heemst, 1986) or 14°C and 22°C (Ingram and McCloud, 1984), and by solar radiation. Crop senescence is shortened by high temperatures, especially greater than 30°C (Midmore, 1990). The effects of agroclimatological factors on physiological parameters of potato, especially on tuber yield, grade and internal quality, will be discussed below.

10.5.2.1 **Air temperature, solar radiation and photoperiod**

Owing to the interactive effects of air temperature, photoperiod (day length), solar radiation and cultivar on the tuberization stimulus, these meteorological

variables will be discussed together, with an emphasis on physiological responses to one or another climatic element consistent with the specific objectives of each research project.

The review by Haverkort (1990) points out that potato is best adapted to cool climates such as tropical highlands with mean daily temperatures between 15°C and 18°C, as encountered in its centre of origin. Higher temperatures favour foliar development and retard tuberization. In addition, heat stress leads to a higher number of smaller tubers per plant, to lower tuber specific gravity with reduced dry matter content, and usually to a paler skin colour of the tubers.

De Temmerman et al. (2002) examined the effect of latitude, seasonal mean air temperature (ranging from 13.8°C to 19.9°C), global solar radiation (ranging from 12.0 to 21.3 MJ m⁻² d⁻¹), air humidity, soil moisture and atmospheric CO₂ concentrations on tuber yield in European experiments. Ignoring CO₂ enrichment, the yield of potato (cv. "Bintje") increased from southern to northern Europe. Marketable tuber yields increased at higher latitudes. The authors ascribed this result to lower temperatures, lower vapour pressure deficits and longer day lengths at higher latitudes, which in turn resulted in longer effective growing seasons.

Climatic conditions, as affected not only by the latitude but also by altitude, influence potato plant growth and development. Moreno (1985) found that plants grown at low (coastal) altitudes have a low yield of tubers per plant as compared with those grown in the Andean highlands. Tubers harvested from coastally grown plants had lower free amid acid and amide contents and a higher content of tuber protein than those from the Andean highland. Coastal tubers also had less total sugar content than Andean tubers.

Haverkort (1990) reports that an inconvenience of the short-day sensitivity of the potato is that cultivars that make use of the whole growing season and produce well in northern Europe (with a growing season of 5 to 6 months), may mature too early and senesce between 60 and 70 days after planting in the equatorial highlands and consequently yield less. Cultivars that perform well at low latitudes in a growing season of between 3 and 4 months start tuberizing late and mature too late at 50°N.

Photoperiodic responses are mediated by endogenous plant hormones. Relatively high gibberellic acid (GA) levels reduce or stop tuber growth and relatively high abscisic acid levels promote tuber

growth. In some potato cultivars and species, long photoperiods produce high GA levels that prevent tuber growth. This can be a problem for temperate regions, which have long photoperiods during their usual crop season. Fortunately, many of the North American cultivars are "day neutral" and presumably have lost the GA-photoperiod response (Dwelle, 1985).

Carbon dioxide concentration can also exert a strong influence on potato productivity. The influence of carbon dioxide depends on solar irradiance (Wheeler et al., 1991). Potato cultivars ("Norland", Russet Burbank and "Denali") were grown at CO₂ levels of 350 or 1 000 µmol mol⁻¹, irradiance of 400 or 800 µE m⁻² s⁻¹ photosynthetic photon flux (PPF) and photoperiod of 12 or 24 hours light. Increased CO₂ provided greater tuber yield at low PPF, but decreased tuber yields at high PPF. Increasing the PPF increased the tuber yield for Denali but decreased the yield for Russet Burbank. When averaged across all irradiance treatments, Denali showed the greatest gain in tuber and total weight (21 and 18 per cent, respectively) in response to increased CO₂ enrichment for the three cultivars tested. Norland showed the least (9 per cent for both), while Russet Burbank showed an intermediate response, with gains nearly as great as for Denali under a 12 h photoperiod (18 per cent), but less than Denali under a 24 h photoperiod. A pattern of greater potato plant growth was observed from CO₂ enrichment under lower PPF and a short photoperiod.

Crop-growing systems for space travel are needed to generate oxygen, purify water, remove carbon dioxide, produce food and recycle waste materials. Total irradiance has been suggested to be the largest limitation to crop productivity in these systems. Potato yield improvements might be obtained by increasing the net daily photosynthetically active radiation (PAR) through higher irradiance or longer photoperiod (Stuttle et al., 1996). The photoperiod duration doubles from December to June at 50°N, while PAR increases eightfold, from 211 to 1 701 MJ m⁻² d⁻¹, due to higher elevation of the sun above the horizon with lengthening days. Gross carbohydrate production on standard clear days increases from 108 to 529 kg ha⁻¹ d⁻¹ at 50° N, whereas it remains at about 420 kg ha⁻¹ d⁻¹ year-round near the Equator. Low solar irradiance is a yield constraint at 30° N to 40° N in winter when potatoes are grown to escape the summer heat (Haverkort, 1990).

Stuttle et al. (1996) studied the effect of photoperiod (12, 18, and 24 h light) on net carbon assimilation rate (A_{net}) and starch accumulation in newly mature canopy leaves of Norland potato under low and high PPF, 263 and 412 µE m⁻² s⁻¹,

respectively. Whenever the photoperiod was increased from 12 to 18 hours, there was a marked decline in A_{net} of 16.1 per cent and declines were most pronounced under high PPF. The maximum starch concentrations were obtained under high PPF treatments at a shorter photoperiod than under low light treatments. An apparent feedback mechanism exists for regulating A_{net} under high PPF, high CO_2 and long photoperiod, but there was no correlation between A_{net} and starch concentration in individual leaves. This suggests that maximum A_{net} cannot be sustained with elevated CO_2 enrichments under long photoperiod and high PPF conditions for Norland. Therefore, if a physiological limit exists for the fixation and transport of carbon, increasing photoperiod and light intensity under high CO_2 enrichment may not maximize potato yield.

Since the onset and early phases of tuber growth are important for the further development of potato, Dam et al. (1996) conducted a factorial experiment with two photoperiods (12 or 18 h) and four 12 h day/night temperatures ($18^\circ\text{C}/12^\circ\text{C}$, $22^\circ\text{C}/16^\circ\text{C}$, $26^\circ\text{C}/20^\circ\text{C}$ and $30^\circ\text{C}/24^\circ\text{C}$) to analyse photoperiod and temperature effects on early tuber growth, dry matter partitioning and tuber number for cultivars "Spunta" and "Desiree". They concluded that low mean temperatures (15°C – 19°C) with a short photoperiod (12 h) were most suitable for early tuber growth. Under these conditions, onset of growth and onset of bulking were early, and absolute tuber growth rates and dry matter partitioning were high. Slight increases in temperature strongly reduced partitioning rates, whereas further increases had a large impact on the onset of tuber growth and absolute growth rates. Differences between treatments in numbers of tubers initiated were inconsistent. The absolute growth rate under long photoperiod was higher for Spunta than for Desiree. Different genotype responses to temperature and photoperiod in tuber growth were also found by Snyder and Ewing (1989) using potato cuttings.

Midmore and Prange (1992) examined the effects of day/night temperature ($33^\circ\text{C}/25^\circ\text{C}$ or $20^\circ\text{C}/10^\circ\text{C}$), and 12 h high irradiance (430 – $450 \mu\text{E m}^{-2} \text{s}^{-1}$ PAR), or 12 h low irradiance (250 – $280 \mu\text{E m}^{-2} \text{s}^{-1}$ PAR), both with a 6 h photoperiod extension at $6 \mu\text{E m}^{-2} \text{s}^{-1}$, on relative growth rate, net assimilation rate and dry matter production of *Solanum goniocalyx* cv. "Garhuash Huayro" and DTO-33, a heat-tolerant clone of *S. tuberosum* x *S. phureja*. The highest relative growth rate was obtained at low temperature and low irradiance. At high temperature, low irradiance had the opposite effect, producing the lowest net assimilation and relative growth rates. Both tuber number and weight were markedly reduced

by high temperature. Low irradiance in combination with high temperature produced virtually no tubers. These data are consistent with field observations that reduced potato growth at high temperatures can be aggravated by lower irradiance. Both leaf area and net assimilation rate are reduced.

Manrique and Bartholomew (1991) carried out a potato genotype x environment experiment on Mount Haleakala, Maui, Hawaii, at three elevations, from 91 to 1 097 m, to assess the performance of four standard temperate cultivars and three heat-tolerant clones in warm to cool temperatures at photoperiods prevailing in the tropics. Dry weight of plant components and total dry weight per plant were measured at tuber initiation, 20 days after tuber initiation and 40 days after tuber initiation. Warm temperatures at 91 m hastened development such that, at tuber initiation, total dry weight per plant was 2 to 4 times greater than at 1 097 m in 1985 and 1986. Tuber dry weight increased significantly at the second two sampling dates with lower temperature at higher elevation. Dry matter partitioning to tubers generally was highly and significantly correlated with temperature, with the optimum of 15°C to 20°C for tuber growth. Potato plants lost their ability to allocate dry matter to tubers at higher temperatures.

Sarquis et al. (1996) stated that the magnitude of the effect of elevated temperatures on potato growth and final yield is determined by an intricate interaction among soil temperature, air temperature, solar radiation and photoperiod duration. Their data extended previous observations of reduction in photosynthesis rate under elevated temperatures. Under field conditions they concluded that a reduced carbon assimilation rate could not explain the yield reduction observed; the temperature effect on assimilation was not as dramatic as it was on growth or yield. Other workers have reported a severe reduction in the rate of assimilation at air temperatures above 30°C under controlled experimental conditions. In such cases, the reduction in the carbon assimilation rate was shown to correlate well with reductions in growth and yield (Ku et al., 1977; Midmore and Prange, 1992). These contrasting results reveal the complexity of plant responses to the combined effects of water and temperature stress, which inevitably occur in association under field conditions.

Thornton et al. (1996) examined the effect of two day/night air temperature regimes (low $25^\circ\text{C}/12^\circ\text{C}$ and high $35^\circ\text{C}/25^\circ\text{C}$) on dry matter production of three potato clones (Russet Burbank, Desiree, and "DTO-28") for five weeks, beginning

two weeks after tuberization, under controlled environmental conditions. Tuber growth rate was more affected by high temperature than was whole plant growth. All clones exhibited a decline in tuber dry matter production at high temperatures compared with low temperatures; however, Russet Burbank exhibited the largest decline. Potato clones varied in partitioning of dry matter to tubers at high temperatures. In addition to carbon assimilation, heat stress reduced tuber yields by affecting several plant processes, such as dark respiration.

Although high temperature stress is a major uncontrolled factor affecting growth, development and productivity of plants, relatively little is known about genetic diversity for heat tolerance in potatoes. Tolerance to heat stress may involve many complex relationships. An adapted genotype must have a diverse and complex combination of genes for tolerance to high temperatures and for superior performance in the field (Tai et al., 1994).

Potato cultivars and clones vary significantly in their ability to tuberize at elevated air temperatures and continuous irradiance. Tibbitts et al. (1992) carried out two experiments under controlled environments to determine the capability of 24 highly productive potato genotypes to tolerate continuous light and high temperature. Six cultivars grew well under continuous light while three cultivars were superior to the others at high temperature. Two cultivars were well adapted to continuous light and high temperature. These evaluations were made after only 56 days of growth, and further assessments should be made in longer-term productivity studies.

For some crop plants, leaf angle can be important for maximizing solar radiation interception. With potato cultivars that intercept as much as 95 per cent of incident solar radiation at a leaf area index of 4, one must question whether alterations in leaf angle would significantly improve light interception. Individual leaves can utilize only 50–60 per cent of incident radiation on a clear day. Following tuber initiation, the photosynthetic apparatus saturates by about $1\,200\ \mu\text{E m}^{-2}\text{ s}^{-1}$, or about 60 per cent of full light. Ideally, the top leaves of a potato canopy should absorb no more than $1\,200\ \mu\text{E m}^{-2}\text{ s}^{-1}$ and should allow the remaining light to pass to the lower canopy (Dwelle, 1985). Opportunities remain to modify potato plant architecture to increase productivity (Hawkins, 1982).

Gawronska and Dwelle (1989) studied the effect of high light levels (with maxima between 500 and $1\,200\ \mu\text{E m}^{-2}\text{ s}^{-1}$) and shaded low light levels

(approximately one quarter of the high light) on potato plant growth, biomass accumulation and its distribution. They observed that plants under low light did not produce auxiliary shoots, while those under high light did. Tubers of plants under low light were very small and irregular in shape. The most evident plant response to low light was greater stem elongation, as well as a reduction in total biomass accumulation and in tuber weights. The reduction in total biomass under low light was 34 to 45 per cent. Reduction in tuber dry weights under low light ranged from 39 to 57 per cent, depending on the growth stage and harvest time. In addition, at all growth stages, the percentage of biomass partitioned to the tubers was higher under high light than under low light conditions.

According to Gawronska et al. (1990), potato plants grown under low light generally had lower rates of photosynthesis (when compared with those grown under high light), reaching saturation for maximum photosynthesis at about $500\ \mu\text{E m}^{-2}\text{ s}^{-1}$. Some clones maintained the higher rates of photosynthesis compared to Russet Burbank at nearly all light levels, demonstrating the potential to breed for cultivars that maintain higher rates of photosynthesis and potentially higher tuber yields.

10.5.2.2 Soil temperature and soil temperature management

The rate of development of sprouts from planted seed pieces depends on soil temperature. Very little sprout elongation occurs at 6°C. Elongation is slow at 9°C and is maximized at about 18°C. The time between planting and emergence depends on soil temperature. Phytotron and field experiments carried out by Sale (1979) showed that emergence was linearly related to mean soil temperature and relatively independent of diurnal fluctuations up to an optimum of 22°C–24°C. Up to this optimum, emergence could be considered as a degree-day requirement calculated either from soil temperature at tuber depth or air temperature. At temperatures above the optimum, emergence was inhibited.

Sattelmacher et al. (1990) studied the effect of 20°C and 30°C root-zone temperatures on root growth and root morphology of six potato clones. Significant genotypical differences in the responses of potato roots to 30°C were observed, indicating the potential for selecting heat-tolerant potato clones. In both heat-tolerant and heat-sensitive clones, the size of the root system was reduced by a 30°C root-zone temperature, which can be explained by a reduction in the cell division followed by cessation of root elongation.

Tuberization stimulus favours both tuber initiation and tuber enlargement. Through artificially prolonged exposure to short days and cool temperatures, it is possible to attain such a high level of stimulus that induction is irreversible, even if potato plants are subsequently exposed to long days for weeks or months. The optimum soil temperature for initiating tubers ranges from 16°C to 19°C (Western Potato Council, 2003).

Reynolds and Ewing (1989) examined the influence of four air and soil day/night temperature treatments on root, tuber and shoot growth in growth chambers: cool air (19°C/17°C), with cool or heated soil (20°C/18°C or 32°C/31°C); and hot air (34°C/30°C), with hot or cooled soil (32°C/27°C or 19°C/17°C). Cooling the soil at high air temperatures neither relieved visible symptoms of heat stress on shoot growth nor increased the degree of induction tuberization by the leaves. Heating the soil at cool air temperatures had no apparent detrimental effect on shoot growth or induction of tuberization by the leaves. Under high soil temperatures, stolonization was substantially compromised and there was no underground tuber development. In one experiment, stolons grew up out of the hot soil and formed aerial tubers above the soil surface in the cool air. The induction of tuberization by the leaves was affected mainly by air rather than soil temperature, but the signal to tuberize might be blocked by high soil temperatures. According to Mares et al. (1985), it is expected that the effect of high soil temperature on growing tubers would be similar to that of exogenously applied gibberellin, inhibiting tuberization.

Tuber development declines as soil temperatures rise above 20°C and tuber growth practically stops at soil temperatures above 30°C. The number of tubers set per plant is greater at lower temperatures than at higher temperatures, whereas higher temperatures favour development of large tubers (Western Potato Council, 2003).

Little research is available on the effect of soil temperature during tuber growth on potato grade and quality. Kincaid et al. (1993), assessing the influence of the interaction between water management and soil temperature on potato quality in the Pacific Northwest region of the United States, observed that the critical period for tuber quality appears to be from mid-June to mid-July, based on measured soil temperature differences, and that frequent sprinkler irrigation reduced soil temperatures, along with the incidence of sugar-end tubers. Yamaguchi et al. (1964) found that yield, specific gravity and starch content of Russet Burbank and "White Rose" tubers were higher and the sugar content lower when grown at soil temperatures

between 15°C and 24°C, than when grown at higher temperatures.

Ewing (1981) reports that in many areas the sequence of temperatures that most often brings economic damage to potato crops is warm temperatures early in the season, followed by cool temperatures that induce strong tuberization, followed in turn by another period of high temperatures. These temperature oscillations lead to heat sprouts, chain tubers and secondary growth of tubers. Apparently, the fluctuations in tuberization stimulus cause tuber formation to alternate with more stolon-like growth.

Management practices such as planting population density, use of mulch and irrigation might substantially modify the soil temperature regime within the root zone in such a way as to affect stolonization and tuber initiation, bulking and enlargement at a given site, particularly where solar irradiance availability is shown to be a non-limiting factor for potato production. Increase of plant population through a reduction in between-row spacing was effective in raising tuber yields in the hot tropics, largely through the increase in amounts of intercepted solar radiation, which brought about a significant decline in soil temperatures during the tuber growth. Since the proportion of marketable tubers was scarcely affected by planting densities, Midmore (1988) reasoned that potato plant population in hot climates should be as high as possible without limiting the amount of soil available for hilling-up.

In order to quantify the effects of organic mulch on soil temperature and soil moisture regimes during the growth of potato, Midmore et al. (1986a) conducted seven experiments at three contrasting hot tropical sites (latitude varying from 5°S to 12°S, and altitude ranging from 180 to 800 m). Mulch retained more heat in the soil at night when combined with agronomic practices that themselves increased soil heat retention at night (that is, on the flat potato beds). The magnitude of soil cooling by mulch during the day and heat retention within the soil at night was dependent on solar irradiance levels and soil moisture content. Mulch was more effective in cooling dry soils, especially at high irradiance. Heat retention at night following days of low irradiance was greater in mulched plots, whereas at high irradiance heat retention of mulched plots was intermediate between those of moist and drier control plots.

Midmore et al. (1986b) showed that mulch increased tuber yield by 20 per cent during the summer in Lima, Peru. Manrique and Meyer (1984), studying

the impact of mulches on potato production during winter and summer seasons at the same site, found no effect on yields during the winter, but yield increases of 58 per cent and improvements in soil moisture retention were obtained in the summer with surface mulch.

Mahmood et al. (2002) reported that mulch at Islamabad, Pakistan, decreased daily maximum soil temperature at a 15 cm depth by 1.5°C to 4.5°C, resulting in faster emergence, earlier canopy development and higher tuber yields. Many other recent studies conducted in Asia point out the beneficial effects of mulch in potato production systems as an efficient alternative to obviate heat and water stresses in order to maximize crop yield (Jaiswal, 1995; Ruiz et al., 1999; Sarma et al., 1999).

10.5.2.3 Atmospheric humidity, wind and wind management

There are very few recent studies dealing with the direct effects of relative humidity (RH) on potato growth, tuber yield and grade. Most of the contributions related to the influence of RH on potato refer to potato storage where RH is an important factor in tuber weight loss and the occurrence and severity of diseases and pests. The same scarcity of research exists with regard to the wind regimes at a particular location as an agrometeorological factor affecting potato production systems.

Wheeler et al. (1989) studied the effect of two RH levels, 50 per cent and 85 per cent, on the physiological responses of three cultivars of potato (Russet Burbank, Norland and Denali) in controlled-environment rooms under continuous light intensity at 20°C. No significant differences in total plant dry weight were measured between the atmospheric humidity treatments, but plants grown under 85 per cent RH produced higher tuber yields. Leaf areas were greater under 50 per cent RH and leaves tended to be larger and darker green under drier atmospheric conditions than at more humid conditions. The elevated humidity appeared to shift the allocation pattern of photosynthates to favour allocation to the tubers over leaves and stems.

Gordon et al. (1999) estimated sap flow from solar radiation and vapour pressure deficit data for three field-grown potato cultivars ("Atlantic", "Monona" and "Norchip") at Nova Scotia, Canada, under non-limiting soil water conditions. Sap flow rates for all cultivars were closely linked with solar radiation under conditions where soil water was not limiting. The vapour pressure deficit (VPD), a function of relative humidity and air temperature, had less

effect on sap flow, although the magnitude of the VPD during the growing season was generally < 2 kPa. All cultivars maintained actual daily transpiration near the potential energy-limiting rate under well-watered conditions. When the soil was drier (per cent available soil water <30 per cent), Monona potato plants had a much more rapid decline in transpiration than the other two cultivars.

Another physiological parameter closely related to yield is water use efficiency. Bowen (2003) reported that potato farming in coastal Peru occurs during the winter, when the cool humid conditions favour growth and promote a more efficient use of irrigation water. During the winter, less soil water evaporation caused by a smaller VPD enhances water use efficiency when compared with that observed during the summer. Sinclair (1984) also showed that generally more humid environments provide greater water use efficiency because of a lower VPD.

Stomatal resistance governs photosynthesis and transpiration. Two major feedback loops are reported by Raschke (1979) as the direct controllers of stomatal resistance (r_{st}). The first involves photosynthesis, where a reduction in intercellular CO_2 occurs as PAR increases, the stomata open and r_{st} decreases. The second involves an increase in r_{st} whenever leaf water potential reaches a critical threshold as a result of transpiration intensity.

Stomatal resistance is affected by many factors, including PAR, the ratio of leaf to air water potential, leaf age, air temperature and the ambient CO_2 concentration (Kim and Verma, 1991). Gordon et al. (1997) studied the stomatal resistance of three field-grown potato cultivars (Atlantic, Monona and Norchip) in response to photosynthetic photon flux density, leaf-to-air vapour pressure difference and root-zone available water. Under the climatic conditions of their field experiment in eastern Canada, stomatal activity in potato was primarily driven by light intensity. As soil water became limiting, however, the soil/plant water status became increasingly more important. The absence of very high VPD values throughout the growing season is the probable main reason for the lack of potato r_{st} response to air vapour pressure differences. Significant differences were observed among cultivars in the response of stomata to changes in available soil water. Crop weather modelling needs to incorporate these differences into model systems because they might have a significant effect on eventual model performance at a given site.

Wind has important effects on potato. Pavlista (2002) reported that leaves injured by lower wind speeds

show bronzed areas, brown with a shiny surface, due to the rubbing of leaves against each other. The bronzed areas tend to become brittle from drying. When pressed, the bronzed areas crack, forming a sharp-edged rip through the affected tissue. Under higher wind speeds, leaves not only bronze but also tatter. Tattered leaves typically have tears measuring 6 to 25 mm with irregular brownish borders. Stems may also be affected by winds. When exposed to a mild wind, stems may just be flopped around, causing a slight weakness of the tissues. Under strong winds, vines might actually get twisted, bringing about a break or hinge-like weakness in the stems. If exposed to strong winds for several hours, the vine may twist all the way around and cause the stem to collapse, cutting off nutrient flow through the phloem between the vine and the tubers.

Wind also affects transpiration rates and, therefore, photosynthetic activity and crop yield. At sites where winds are frequently strong throughout the year, increased stomatal resistance can cause reduction in potato yield (Pavlista, 2002; Sun and Dickinson, 1997). At such sites, guidelines for the sustainable management of potato cropping systems need an emphasis on windbreak development, including height, porosity and orientation.

Sun and Dickinson (1997) studied the benefit of two 30-month-old windbreaks (one with two rows of trees and one with three rows of trees) for potato in tropical north-eastern Australia. Two *Eucalyptus* species (*E. microcorys* and *E. torelliana*) were found to be highly suitable for windbreaks since they showed rapid development in height and branch growth while retaining low branches. The porosity of three-row and two-row windbreaks was 37.2 per cent and 60 per cent, respectively. The optimum range of porosity for windbreaks is between 40 and 50 per cent (Marshall, 1967). Windbreaks increased potato plant growth in height and leaf number; they had limited effects on leaf length and width, however. Potato plants grown close to windbreaks yielded more than those grown at the farthest positions, with the highest production reported at a distance of three times the windbreak height. Windbreaks increased potato yield by up to 7.7 per cent, whereas Sturrock (1981) found windbreaks increased yield by 35 per cent.

Wright and Brooks (2002) examined the effect of windbreaks on growth and yield of potatoes over a four-year period in Australia, measuring the amount and severity of wind damage to leaves, plant height and leaf numbers on potato located at various distances from the windbreak in both sheltered and unsheltered positions. Windbreaks increased tuber

yield between 4.8 and 9.3 per cent for the sheltered portion of the field in seasons with higher than average wind speeds and caused a reduction in wind damage to leaves on protected potato plants. In seasons when wind speed was above average, windbreaks increased yield at distances away from the windbreak between 3 and 18 times the height of the windbreak. Cleugh (2003) reported that potato crop yields were significantly higher in the sheltered zone ranging from 2 to 18 times the height of the windbreak, compared with yields obtained in unprotected areas.

10.5.2.4 Crop evapotranspiration and irrigation requirements

Crop consumptive water use is the amount of water transpired by the plants, plus the water evaporated from the soil, plus the fraction of water held by the plant tissues. The amount of water retained by plant metabolic activity is about 1 per cent of the overall water taken up by the plants. Thus, in practical terms crop water consumption corresponds to crop evapotranspiration (ET_c). Potato ET_c can be estimated using weather data and is the amount of water to be replenished during the growing season in order to assure potential tuber yields at a given site. Potato ET_c is important to consider in irrigation planning and its use in irrigation scheduling is a well-developed strategy to improve the effectiveness of irrigation.

An adequate water supply is required from tuber initiation up until near maturity for high yield and good quality. Applying water in excess of plant needs compromises the environment, may harm the crop and is expensive for growers. Excessive irrigation of potatoes results in water loss and significantly increases runoff and soil erosion from production fields to rivers, streams and reservoirs. Leaching can lead to contamination of the groundwater due to lixiviation of fertilizers and other chemical products (Al-Jamal et al., 2001; Feibert et al., 1998; Shock et al., 2001; Waddell et al., 2000). Irrigation in excess of crop needs increases production costs, can reduce yield by affecting soil aeration and root system respiration, and favours the occurrence and severity of diseases and pests. Deficient irrigation promotes a reduction in tuber quality and lower yield due to reduced leaf area and/or reduced photosynthesis per unit leaf area (van Loon, 1981).

Local atmospheric conditions, surface soil wetness, stage of growth and the amount of crop cover are the factors that govern the daily fluctuations of potato ET_c , as reported by Wright and Stark (1990). They observed that ET_c increased as the leaf area

and transpiration increased and reached near-maximum levels just before effective full cover. The LAI reached 3.5 by effective full cover coincident with the highest daily ET_c of 8.5 mm. Seasonal total ET_c corresponded to 604 mm in southern Idaho (United States).

Potato ET_c varies greatly from region to region. Seasonal potato ET_c in the humid Wisconsin area for June through August ranged from 293 to 405 mm during three years of study (Tanner, 1981). At Mesa, Arizona, ET_c for February through June averaged 617 mm (Erie et al., 1965). The mid-season daily potato ET_c was 6 mm near Calgary, Alberta, in Canada (Nkemdirim, 1976), while the daily water consumption was 3 mm under the climatic conditions of Botucatu, in the state of São Paulo, Brazil, during the winter, with a seasonal ET_c of only 283 mm (Pereira et al., 1995a). Wright and Stark (1990) reported that seasonal water use in irrigated areas of Oregon and Washington (United States) ranged from 640 to 700 mm. For high yields at a given site, the seasonal water requirements of a potato crop with a phenological cycle varying from 120 to 150 days ranged from 500 to 700 mm, depending on climate (FAO, 1979).

The maximum daily potato ET_c measured by a weighing lysimeter in a sub-humid region in India was found to be 4.24 mm d⁻¹ (Kashyap and Panda, 2001). Under a hot and dry climate in north-eastern Portugal, peak ET_c rates reached 12⁻¹³ mm d⁻¹ on the days immediately following irrigation, but crop water use declined logarithmically with time to about 3 mm d⁻¹ within five days (Ferreira and Carr, 2002).

Wright (1982) developed improved crop coefficients for various irrigated crops in the Pacific North-west of the United States, including potato, using alfalfa to measure reference evapotranspiration (ET_o) and weighing lysimeters at an experimental field near Kimberly, Idaho. Growth-stage-specific crop coefficients (K_c) and the water balance method provided a valuable tool in scheduling overhead irrigation of Russet Burbank potatoes in the Columbia Basin of Oregon (Hane and Pumphrey, 1984). Simonne et al. (2002) reported that K_c values ranged from 0.3 at emergence to 0.8 during maximum leaf area, and declined as the crop matured. ET_c is usually calculated by the product of K_c and ET_o , or as a function of a number of climatic elements, to provide the atmospheric potential demand.

Apart from the crop coefficient approach, potato evapotranspiration can also be estimated by means

of multiple regression equations that take into consideration the LAI of potato crop and atmospheric evaporative demand depicted by ET_o or pan evaporation (Pereira et al., 1995b).

Potato can be sensitive to irrigation at levels that are less than ET_c and that result in soil water deficits. A study in three successive years on silt loam soil in eastern Oregon investigated the effect of water deficit on yield and quality of four potato cultivars grown under four season-long sprinkler irrigation treatments (Shock et al., 1998). The results suggest that irrigation water applied at rates less than ET_c in the Treasure Valley of Oregon would not be a viable management tool to economize water, because the small financial benefit would not offset the high risk of reduced tuber yield and profit from the reduced water application.

Potato cultivars may respond differently not only to deficit irrigation but also to total seasonal crop evapotranspiration under non-limiting soil water supply. Wolfe et al. (1983) reported that total seasonal actual crop water use at Davis, California, on a deep Yolo loam soil ranged from 316 to 610 mm for the "Kennebec" cultivar and from 331 to 630 mm for "White Rose", as a function of six levels of irrigation water supply established throughout the growing season. Shock et al. (2003a), comparing the performance of two new potato cultivars ("Umatilla Russet" and "Russet Legend") with four other cultivars grown in the Treasure Valley of Oregon ("Russet Burbank", "Shephody", "Frontier Russet", and "Ranger Russet"), observed that Umatilla Russet showed a higher yield potential at ideal water application rates, while Russet Legend was the only cultivar tolerant to deficit irrigation treatments.

ET_c is an essential agrometeorological index that can be used to determine both the amount of water to be applied and the irrigation frequency for a particular crop and site. Stöckle and Hiller (1994) compared a canopy temperature-based method, the neutron probe method and the computer-assisted method on the basis of evapotranspiration and K_c values to schedule irrigation for potato in central Washington State. A soil water depletion of 70 per cent was allowed before starting irrigation. They concluded that the most practical method was the computer-assisted method using estimates of ET_o and K_c values.

10.5.2.5 Soil moisture requirements and irrigation management

Soil moisture status is expressed by per cent available soil water (ASW) content or by soil water tension

(SWT). Available soil water content is defined as the amount of water that plants can extract from a given volume of soil, from the crop effective rooting zone. Available soil water is usually expressed as a percentage between “field capacity” (100 per cent) and “permanent wilting point” (0 per cent). Soil water tension is the force necessary for roots to extract water from the soil.

Curwen (1993) reviewed water management for potato and placed great emphasis on using the irrigation criterion of 65 per cent ASW. At “field capacity” (100 per cent ASW), the SWT is often between 20 and 33 kPa, depending on soil type and the method of determination. Soil water is assumed to no longer be available at the “permanent wilting point”, generally assumed to be at a SWT of 1 500 kPa.

The ASW approach works well for irrigation scheduling in regions with extensive areas of homogeneous soil. It is often a practical impossibility for growers to know when the soil is at 65 per cent ASW, even if they have soil water content sensors available. Usually the per cent water content that a given field contains at “field capacity” is unknown for a given part of a specific field. Similarly, the percentage of water content at the “permanent wilting point” for a given part of a specific field is also usually unknown. Both the “field capacity” and the “permanent wilting point” vary tremendously with soil type, from spot to spot within a field, with cultivation and over time. With neither “field capacity” nor “permanent wilting point” known, 65 per cent ASW cannot be known; the prescription of an irrigation criterion of 65 per cent ASW can become much like telling a grower to irrigate at the “right moment” and leaving the decision to intuition and experience.

Growers need direct and unambiguous irrigation recommendations to deal with crops that have negative responses to small variations in irrigation management. In contrast to the ASW, SWT can be measured directly using tensiometers or granular matrix sensors (Shock, 2003). The SWT irrigation criterion needed to optimize potato yield and quality can be determined by production region and generalized soil type.

Measurements of SWT that optimize potato yield and grade have been determined for a number of locations, some of which are wetter than 65 per cent ASW. Based on potato yield and grade responses to irrigation, ideal potato SWT irrigation criteria were found to be 50 kPa using furrow irrigation on loam in California (Timm and Flockner, 1966), 50 to 60 kPa using sprinklers on silt loam in Oregon (Eldredge et

al., 1992, 1996), 25 kPa using sprinklers on silt loam in Maine (Epstein and Grant, 1973), 60 kPa and 30 kPa using furrow and drip irrigation, respectively, for silt loam in Oregon (Shock et al., 1993, 2002), and 20 kPa using sprinklers on sandy loam in Western Australia (Hegney and Hoffman, 1997).

10.5.2.6 Irrigation scheduling

Irrigation of crops sensitive to water stress requires a systematic approach to irrigation scheduling. Information to answer irrigation scheduling questions may include atmospherically based, plant-based or soil-based data (Heerman et al., 1990; Shae et al., 1999). Examples of atmospheric irrigation scheduling information include weather forecasts, estimates of crop evapotranspiration, such as those provided by AgriMet (United States Bureau of Reclamation, Pacific North-west agricultural meteorological stations), pan evaporation and atmometers. AgriMet is an automated weather station network operating throughout the Pacific North-west of the United States that uses site-specific climatic data, the current stage of growth of local crops and models to estimate daily crop water use (Pereira and Shock, 2006). Access to daily weather data, crop water use charts and related information is available at <http://www.usbr.gov/pn/agrimet>.

Plant data may include canopy temperature, xylem water potential and visible wilting. Soil-based data may include soil water content and soil water tension. In practice, plant, soil and atmospheric data are often used concurrently, especially when changes in irrigation schedules are required to adjust for changes in crop water use.

Growers should pay attention to crop appearance, soil water tension, the rate of crop evapotranspiration, precipitation and the amount of water applied. With knowledge of these factors, irrigation can be well managed in order to obtain high yields of better-quality tubers, along with environmental protection (Pereira and Shock, 2006).

10.5.3 Other background information on potato (yield, quality) response to irrigation management

Potato tuber response to soil moisture conditions begins before tuber set. MacKerron and Jefferies (1986) have shown that increased duration of water stress before tuber initiation reduces tuber set per stem. Shock et al. (1992) demonstrated that reduced tuber set in the Treasure Valley was related to the duration of SWT drier than 60 kPa before and

during the beginning of tuber set. Where *Verticillium* wilt is present, there are advantages to keeping soils a little dry early in the season before tuber initiation (Cappaert et al., 1994; Shock et al., 1992).

Jones and Johnson (1958) described the reduction in potato yield caused by water stress. Through the use of a line-source sprinkler system, Hang and Miller (1986) showed how a moisture gradient affects plant-top growth, tuber yield and tuber grade. With sprinkler irrigation, water application had to remain near potential ET_c for maximum tuber yield and grade.

Potato varieties differ in their response to water stress (Shock et al., 2003a). Kleinkopf (1979) found that Russet Burbank was more sensitive than the "Butte" variety in forming misshapen tubers under water stress.

10.5.3.1 Assuring tuber grade

Fluctuations in water that stress the potato plant during tuber development can result in greater proportions of misshapen tubers of lower market grade. Corey and Myers (1955) determined that the proportion of misshapen tubers was directly related to drier SWT. Eldredge et al. (1992) found that a single transient SWT stress drier than 50 kPa increased misshapen Russet Burbank tubers. Pereira and Villa Nova (2002) studied the effect of three irrigation treatments on tuber yield and grade at Botucatu, São Paulo, Brazil. Potatoes irrigated to fully replace ET_c had higher yields and better grade and fewer physiological defects.

10.5.3.2 Assuring internal tuber quality

Tuber physiological disorders such as brown centre, hollow heart and translucent end, as well as secondary growth, growth cracks, bruise susceptibility and heat necrosis, have been associated with water stress and/or wide variations in soil moisture content (Eldredge et al., 1992, 1996; Hooker, 1981; Hiller et al., 1985; MacKerron and Jefferies, 1985; Rex and Mazza, 1989; Shock et al., 1993).

The sugar-end disorder is also known as dark ends, translucent ends, or in more severe incidences when stem-end tissue breakdown occurs, jelly ends. Jelly ends can occur in the field or during storage. These physiological disorders are often considered a minor production problem. When above-normal temperatures occur during the growing season, however, significant economic losses can result from excess reducing sugars (glucose and fructose) in the stem end of tubers. These reducing sugars react with free

amino acids during frying to form brown or black colours. For processors, dark ends result in reduced processing efficiency and profitability and in some cases, an unusable product (Valenti, 2002).

When dark ends, as measured at harvest, exceed contract specifications, grower returns are reduced by contract penalty clauses. Research has shown that the incidence of sugar ends in tubers was reduced substantially when irrigation scheduling was based on SWT measurements (Eldredge et al. 1996; Shock et al., 1993). Dark ends may become more severe after tubers have been stored (Eldredge et al., 1996). The timing of water stress is important; water stress before tuber initiation has no deleterious effect on tuber quality (Shock et al., 1992), while stress later during tuber bulking can cause dark stem-end fry colour and reduced specific gravity (Eldredge et al., 1992, 1996; Shock et al., 1993).

Penman (1929) was one of the first authors to discuss the importance of translucent-end potatoes. Numerous authors have suggested that translucent-end potatoes are caused by early-season moisture stress (Murphy, 1936; Nielson and Sparks, 1953; Kunkel, 1957; Kunkel and Gardner, 1958; Lugt, 1960). Iritani and Weller (1973a, 1973b) and Iritani et al. (1973) produced translucent-end potatoes by subjecting plants grown in Washington to two weeks of moisture stress in late June.

Sugar-end tubers result in French fries with "dark ends" and are related to tubers with translucent ends and jelly ends. Owings et al. (1978) reproduced the results of Iritani and Weller (1973a), demonstrating that late-June water stress could cause sugar ends. Shock et al. (1992) subjected potatoes to water stress in May and the beginning of June and found that stress very early in the season did not result in sugar ends. But short-duration water stress any time during tuber bulking, accompanied by heat stress, resulted in sugar ends (Shock et al., 1993).

Increases in reducing sugars occurred more than two weeks after the end of transient water stress (Shock et al., 1993; Eldredge et al., 1996), which suggests that water stress causes enzymatic or membrane changes that eventually result in the loss of cellular control of sugar metabolism and the onset of sugar ends and translucent ends. Sowokinos et al. (2000) demonstrated the importance of specific tuber starch and sugar enzymes in the development of sugar ends.

Paradoxically, season-long uniform stress does not have the same negative effect on potato tubers.

Painter et al. (1975) observed no fry colour differences between tubers irrigated at 25 ASW throughout the season and those irrigated at 65 ASW, which proved to be consistent with later findings where potato was stressed all season (Shock et al., 1998, 2003a). Kleinkopf (1979), Iritani and Weller (1977), Shock et al. (1993) and other researchers have demonstrated that reducing-sugar concentrations vary among varieties.

Kincaid et al. (1993) reviewed the role of temperature on tuber development and demonstrated that sugar ends are increased by rises in soil temperature. The relative roles of water stress and temperature stress on potato defects are poorly defined. Water stress is often associated with increased canopy temperature and soil heating in the field. In most field trials where water stress has been imposed and measured, canopy and soil temperatures have not been measured.

10.5.4 **Other management aspects of potato (irrigation and microclimate interaction with potato diseases and pests)**

Irrigation management practices can affect disease severity. The increased humidity from irrigation will have greater effects where the macroclimate is humid or sub-humid and will be of less importance where it is drier. For potato grown in hot areas, sprinkler irrigation can cool the environment, with possible reductions in physiological defects. Different irrigation methods, however, can contribute to the occurrence of diseases and pests on the crop depending on site-specific weather patterns.

Wet soil is conducive to most tuber-rotting pathogens. Excessive soil moisture following planting can promote seed-piece decay and erratic plant development. Excess soil moisture also encourages the incidence of blights, rots and wilts, and this is particularly true of prolonged excess soil water conditions.

Avoiding over-irrigation, or even keeping soils a little dry early in the season before tuber initiation, may reduce the amount of root infection by *V. dahliae*, a major component in early die. On the other hand, avoiding excessive plant water stress during the tuber bulking growth stage, which usually coincides with the warmest part of the season, may help decrease the severity of early die (Cappaert et al., 1994).

Potato vines that remain wet for long periods create a micro-environment conducive to early blight (*Alternaria solani*), late blight (*Phytophthora infestans*),

white mold (*Sclerotinia sclerotiorum*) and blackleg (*Rhizoctonia solani*) (Curwen, 1993). The timing of these diseases and associated crop losses vary regionally with yearly weather patterns, and can be affected by irrigation methods, which increase or decrease the duration of high humidity in the crop canopy.

Consistently rainy summer or fall weather promotes late blight. In the 1990s, however, epidemics of late blight developed in potato crops in arid production areas of the Pacific North-west region of the United States where late blight had not been a problem (Stevenson, 1993). Irrigation that tends to keep the foliage wet may contribute to this developing risk. Potatoes cultivated under centre-pivot irrigation can receive a relatively low volume of irrigation water for a long time near the pivot, favouring late blight occurrence. Johnson et al. (2003) showed that the incidence of late blight tuber rot grew significantly as the application of irrigation water increased, and was significantly greater within 30 m of the pivot than at greater distances. Long-duration sprinkler irrigation also favoured late blight in Oregon and California (Shock et al., 2003b). Cohen et al. (2000) showed that under overhead sprinkler irrigation, the proportion of potato leaflets containing late blight oospores and the number of oospores per leaflet were dependent on the soil water regime (rain plus sprinkler irrigation).

Long periods of leaf wetness or high relative humidity within the potato canopy favour infection by white mold (Powelson et al., 1993). Avoiding light, frequent irrigation of coarse-textured soils, and avoiding heavy, less frequent irrigation of fine-textured soils can diminish the risk of white mould.

Simons and Gilligan (1997) found irrigation to increase the incidence of stem canker, stolen canker and black scurf to a limited extent, although the effect of season tended to be more pronounced on these defects than any of the agronomic treatments tested.

While the development of high humidity in the canopy is to be avoided, adequate soil moisture is essential not only for potato yield and quality, but also for pest management strategies. Adequate soil moisture helps reduce the attack of cutworms (*Spodoptera litura*) and mites (*Tetranychus* spp. and *Tenuipalpidae* spp.). Potato tuber moth (*Phthorimaea operculella*) and its larvae are repelled by soil moisture. Soil moisture also reduces formation of cracks in the soil, which allow the entry of potato tuber moth and its larvae (Grewal and Jaiswal, 1990). Irrigation scheduling based on ET_c and/or SWT can take the

local climate into account and keep the soil from becoming too dry.

10.6. AGROMETEOROLOGY AND RICE PRODUCTION

10.6.1 Importance of rice in various climates

The cultivation of rice has been practised in many countries for over 6 500 years. Dryland rice culture preceded the adoption of wetland paddy culture. Two species of the rice genus have been domesticated: *Oryza sativa* and *Oryza glaberrima*. The former is widely cultivated and originated in the foothills of the Himalayas, while the latter, limited to Africa, originated in the Niger River delta. Rice is the most important cereal grain for human consumption, meeting the needs of 50 per cent of the world's population. The agricultural and industrial uses of rice include the use of rice straw and bran as cattle feed and as a growing medium for mushrooms; use of rice husks and hulls as a seedbed medium; use of bran for extraction of a healthful oil; and use of rice for making rice beer and rice-based wine. Only 5 per cent of the total global production of rice enters international trade. Thus, for many countries national self-sufficiency in rice production is a crucial matter.

Rice is grown from about 50° N to 35° S and from below sea level to above 2 000 m, covering a mean temperature range of 17°C to 33°C, a growing-season rainfall range of 0 to 5 100 mm, and a solar radiation range of 300 to 600 calories/cm²/day in the various growing areas and different seasons. Many of the rice-growing areas are served by major rivers and have alternating wet and dry seasons. The varieties used and cultural practices adopted in rice cultivation vary widely and are influenced by local climatology (rainfall, temperature and solar radiation regimes) and times and certainty of availability of water for main or supplementary surface irrigation. The variations in cultural practices may not, per se, affect the phenological or physiological responses of the crop to weather factors. The water, fertilizer and seed requirements of the crop, its field-life duration, extent of realization of potential yields, and susceptibility to pests, diseases and weeds are affected by cultural practices, however. The unravelling of the relationship between weather and various aspects of growth, development, yield and protection of rice crops is, therefore, complex.

Data on production, acreages and per capita consumption of rice for 29 countries that produce more than one million tonnes of rice are set out in Table 10.6.1. Of the total 620 million tonnes of global rice production, the 29 countries in the list account for about 580 million tonnes, with an average yield of 3.9 tonnes per hectare (t/ha). The following points are evident from Table 10.6.1. Nearly 90 per cent of the rice is produced in Asia. China and India account for 30 per cent and 20 per cent of global production, and 20 per cent and 30 per cent of the global cultivation area, respectively. The South-East Asian region extending from Pakistan to Indonesia and comprising 12 countries accounts for 60 per cent and 70 per cent, respectively, of the global area and production. In this region, rice yield averages 3.5 t/ha, with Indonesia and Viet Nam producing 4.5 t/ha and Cambodia and Thailand producing 2 t/ha and 2.5 t/ha, respectively. The yields in Egypt and Australia are 10 t/ha and 8 t/ha, respectively, while the yield in China, Italy, Japan and the Republic of Korea is in the range of 6 to 7 t/ha. Thus, a poleward increase in rice yields is discernible. The yields in African regions are very low and range from 1 to 2 t/ha.

It is estimated that rice production must increase by at least 40 per cent in the coming three decades to meet the global requirements. Over most of the regions, rice yields are beginning to decline. Irrigation can push up rice yields. But because of the substantial non-crop use, water losses in irrigated, puddle rice cultivation, and its very low water use efficiency, a shortage of surface irrigation available for catering to even current areas of puddled rice culture is a certainty in the future. The immediate need is, therefore, to increase gross rice acreage and out-turns through the optimal use of existing resources. In this context, the practice of growing irrigated rice under puddled conditions deserves critical examination.

10.6.1.1 Importance of rice in tropical Asia

Both the South-East and East Asian regions regularly experience cyclonic storms/typhoons, are subject to riverine floods, and are characterized by heavy rains of 100 mm per week or so over an extended period. Rice is the only suitable crop that can be grown under puddled soil conditions, that is, with standing water over bunded fields. In fact, certain varieties of rice, called floating rice, have the ability to elongate their stems with a rise in water level up to a height of 2 m and remain alive for a fortnight even when water levels reach a height of 6 m. The low yield in the South-East and East Asian regions is due to the preponderance of rainfed areas, which also leads to great interannual variability in out-turns. There are vast rice-growing areas in populous countries of

Table 10.6.1. Rice production and consumption statistics worldwide, 2002
(FAOSTAT service; <http://faostat.fao.org>)

<i>Country</i>	<i>Production (000 tonnes)</i>	<i>Area (000 ha)</i>	<i>Yield (t/ha)</i>	<i>Consumption (kg/capita/year)</i>
China	176 342	28 509	6.19	83
India	116 500	40 280	2.89	83
Indonesia	51 490	11 521	4.47	149
Bangladesh	37 593	10 771	3.49	164
Viet Nam	34 447	7 504	4.59	169
Thailand	26 057	9 988	2.61	103
Myanmar	21 805	6 381	3.42	205
Philippines	13 271	4 046	3.28	105
Japan	11 111	1 688	6.58	58
Brazil	10 457	3 146	3.32	35
United States	9 569	1 298	7.37	9
Pakistan	6 718	2 225	3.02	18
Korea, Rep. of	6 687	1 053	6.35	83
Egypt	6 105	613	9.97	38
Nepal	4 133	1 545	2.67	102
Cambodia	3 823	1 995	1.92	149
Nigeria	3 192	3 160	1.01	24
Iran, Islamic Rep. of	2 888	611	4.73	37
Sri Lanka	2 859	820	3.49	91
Madagascar	2 604	1 216	2.14	95
Laos	2 417	783	3.09	168
Colombia	2 348	469	5.01	30
Malaysia	2 197	677	3.25	73
Korea, DPR	2 186	583	3.75	70
Peru	2 119	317	6.69	49
Italy	1 379	219	6.31	6
Ecuador	1 285	327	3.93	47
Australia	1 192	150	7.95	10
Côte d'Ivoire	1 080	470	2.30	63
World	577 971	147 633	3.91	57

Yield = Total production/total area and an average across all rice environments and seasons.

tropical Asia. Puddled rice culture is labour-intensive and hence suited to the regions mentioned, which have low labour costs. Puddled rice is said to be of assistance in mitigating the effects of floods. The problem of weeds is minimal in puddled rice culture. Thus rice serves as a livelihood crop for millions of small, marginal farmers in tropical Asia who can afford only low-cost technologies.

10.6.2 **Agroclimatology of rice**

10.6.2.1 **Rice production ecosystems and main climate-related problems**

The main systems of rice culture are: irrigated lowland, rainfed lowland, rainfed upland, irrigated upland, seasonally flooded wetlands and tidal wetlands. On a global scale, rice grown in flood-prone and tidal wetlands, and under rainfed upland, rainfed lowland and irrigation conditions, constitutes 10 per cent, 10 per cent, 25 per cent and 55 per cent of the cultivated rice area, respectively. Irrigated rice, rainfed lowland rice, rainfed upland rice and rice from flood-prone areas account for 75 per cent, 17 per cent, 4 per cent and 4 per cent, respectively, of global rice production. For any given region or season, prevalent cropping systems cannot be considered ideal for optimal crop productivity. The sections that follow will examine, for each of the main rice ecosystems, their climatological requirements, the weather vagaries that impair operations, and the agronomic measures that have been established to cope with weather anomalies.

10.6.2.1.1 *Irrigated lowland rice ecosystem*

The coleoptile of the germinating rice seeds can elongate under anaerobic conditions (Apli and Beever, 1983) and rice can thrive under these conditions. Rice can, therefore, be raised with standing water over the soil. The system in which rice fields are bunded to ensure ponding of irrigation water for most of the crop's life, from sowing to a short time before harvest, is called the irrigated lowland rice ecosystem.

In this system in tropical Asia, an area equivalent to one tenth of the main field area is set apart as nursery. Seeds soaked in water for 24 to 36 hours are incubated for about 48 hours in a warm environment to facilitate germination, and the pre-germinated seeds are broadcast on the drained seedbeds of the nursery, which is kept wet for five days and gradually flooded thereafter. After a nursery time roughly equivalent to 3 and 2 weeks, for varieties with a duration of 4 to 4.5 months and 3 months, respectively, the seedlings are

transplanted in the main field. Prior to transplanting, the soil in the main field is puddled, that is, ploughed, harrowed and finally levelled, with standing water in the field. Water from the main field is drained only when the crop is ready to be harvested.

The irrigated lowland rice cultivated in the United States and Brazil is quite different from that of Asia. In the United States, rice is grown as a single crop per year in three main areas: the semi-arid Sacramento Valley of California, with less than 50 mm of rainfall during the growing season; the humid subtropical areas of the Gulf Coast of Louisiana, Texas and Florida, with a seasonal rainfall range of 700–1 000 mm; and Grand Prairie and the Mississippi and Missouri river deltas. Dry seeding with a mechanized grain drill is the most common method of planting in the southern United States. In California and south-western Louisiana, pre-germinated seeds are seeded into standing water. In Brazil, the lowland irrigated rice is concentrated in the southern states of Rio Grande do Sul and Santa Catarina. In the former state, in about 80 per cent of the area, two years of rice are rotated with three years of pastures; only one crop per year is established, in which dry seed is broadcast or line-sown in dry soil. In Santa Catarina, irrigated rice areas are planted once a year using pre-germinated seed in puddled soil.

10.6.2.1.1.1 Weather-related and other constraints and adaptive measures

The availability of water to raise the requisite area of nurseries ahead of the normal dates of availability of surface irrigation is a major constraint in many areas. In places with adequate groundwater availability, community or individual nurseries known as reduced-area wet-bed nurseries are raised. In places where groundwater is rather scarce, modified mat nurseries are raised. In both methods seedlings are ready for transplantation within about two weeks of sowing, the area required for the nursery area is one per cent of the main field area, and high seed rates are used to ensure the adequate number of sturdy seedlings for transplanting in the main field.

Transplantation shock delays phenological development of the crop, especially tillering. Recovery from transplantation shock and potential yield increase and decrease, respectively, with an increase in the age of seedlings. Irrigated lowland rice requires enormous amounts of water for field preparation. Thus, to properly time the commencement of nurseries, a firm indication of the date of

availability of canal water for irrigation must be known in advance. The latter in turn calls for a quantitative and reliable forecast of rains in catchment areas of the irrigation systems about two weeks in advance. Quantitative rainfall forecasts with a lead time of 15 days are not currently available.

To overcome weather-related constraints, direct wet seeding of rice is being resorted to with increasing frequency. In this system of culture, after receipt of canal water, pre-germinated rice seeds of varieties with suitable characteristics for direct sowing (Yamauchi et al., 1993), namely good germination under anaerobic conditions with good initial seedling vigour, are broadcast or line-sown with drills in drained fields. Random broadcasting leads to great variations in seedling density. Row seeding of germinated seeds is costly but helps in maintaining optimum density of seedlings, controlling weeds and ensuring better crop management. After sowing, the field is intermittently wetted for a week and flooded thereafter. Provided that a good vigorous stand of seedlings is established and weeds are kept in check, wet seedlings have a higher yield potential than transplanted rice (De Datta and Herdt, 1983).

Storms traverse the deltaic rice belts, often leading to flooding and occasionally causing storm surges. Avoidance of cyclonic weather is desirable. The times, duration, regions and frequency of stormy weather vary among the coastal rice belts, however, and the agronomic strategies to deal with them also vary. For example, in India, the coastal areas adjoining the Bay of Bengal experience cyclones, while the coastal areas of the Arabian Sea are practically free from stormy weather. The cyclones of the Bay of Bengal move in a westerly direction, show a southward shift in their origin in the bay with the progress of the Indian summer monsoon, and occur over specific, short, one-month periods. In such a situation, a short-duration rice crop is harvested a little ahead of the cyclone season. Copious rains from cyclones are then used for puddling of soil for nurseries for a second crop and transplanting of the second crop is done so as to ensure that the crop is short during the cyclonic season. For such a crop, arrangements are made for draining away the excess rainwater from storms. In the Philippines, typhoons occur from June to October in the eastern and northern parts of the country at the rate of about 20 per year. Only one of the four main rice-climate belts is affected by typhoon weather. The subtropical rice-growing region in the United States, namely, the Gulf Coast of Louisiana, Texas and Florida, is subject to violent storms from June to November. Warnings of stormy weather, required to effectively

cope with flooding of fields, are available and are quite accurate and timely.

10.6.2.1.2 *System of rice intensification*

Irrigated lowland rice requires an enormous amount of water for field preparation. In this system, loss of water through seepage can be reduced. Percolation loss through the soil is unavoidable and is independent of the season (Achar and Dastane, 1970), but it is influenced by soil type, depth of standing water and perimeter of the field area (Dastane et al., 1970). Percolating water from rice fields carries the risk of pollution of groundwater aquifers through the leaching of agrochemicals. Depending on soil types and cultural practices, the percolation and seepage losses are about 50 per cent of the consumptive (evapotranspiration) requirements of the crop. Thus, the water needs of puddled rice are two to three times those of an irrigated aerobic crop.

The system of rice intensification (SRI) was discovered following an accident and the observation in Madagascar in 1983 that transplanting rice seedlings of 8 to 15 days of age gave a very high number of tillers compared to the customary transplanting of seedlings of 30 to 35 days of age (Laulane, 1993). This discovery was followed up to formulate a set of practices that now constitute the SRI methodology (Satyanarayana et al., 2007). At present, even small farmers in more than 20 countries are using SRI.

In the SRI methodology, preparation of the main field is done in the same way as under the lowland irrigated ecosystem. The nurseries raised are similar to the reduced-area wet-bed or modified mat nurseries. Eight- to 12-day-old seedlings, with just two leaves and with seed, soil and roots intact, are removed by scooping and transplanted gently in a muddy field within 12 hours of removal from the nursery at a depth of 1 to 2 cm, singly in a square pattern of 25 cm × 25 cm, with the roots lying horizontally in the moist beds. Until the roots get established, a thin layer of water is let into the field at night and water is drained away in the morning. Afterwards the soil is kept moist but not saturated by irrigating the crop once every five to six days or by resorting to irrigation when surface cracks appear. A low level of water in the reproductive crop phase is not mandatory and alternate wetting and drying can be resorted to. Weeding, by rotary hoe, is done at 10-day intervals, starting from the tenth day after transplanting until the crop canopy closes. Weeds are returned to the soil to act as fertilizer and instead of chemical fertilizers, farmyard manure or compost is used.

The problems that arise in raising nurseries using the SRI method are the same as those encountered with the conventional method. The direct wet seeding of rice with pre-germinated seeds in moist soil has been suggested as an SRI procedure (Rao, 2004). SRI yields are dependent on strict adherence to geometry of planting and population density, however, and as these two features cannot be achieved by direct seeding, direct wet seeding is not advised (Satyanarayana, 2005). Beginning an SRI nursery at the same time that operations to prepare the main field are started will not depress yields as much as using the conventional method, however, because: SRI nurseries need only one third the nursery time that conventional nurseries require; minimization of transplantation shock in the SRI methodology further reduces the physiological age gap between conventional and SRI seedlings; planting young seedlings ensures preservation of tiller production potential of the seedlings; and an SRI crop matures 10 days earlier than a conventional crop.

Even when not exclusively used, SRI practices such as SRI irrigation with conventional planting or SRI planting with conventional irrigation, boost the yields of rice (Horie et al., 2005). From a review of water savings and yield increases in SRI rice compared with conventional methods in China and tropical Asian countries (Satyanarayana et al., 2007), one could surmise that with the same quantum of water as is being used in the conventional method, rice output can be doubled, trebled and quadrupled in areas with present yield levels of over 5 t/ha, 3–4 t/ha and 2 t/ha, respectively, with the aid of the SRI methodology.

10.6.2.1.2.1 Plausible reasons for yield increases and variations under SRI

From the limited experimental material available on rice and the influence of aerobic and anaerobic conditions on soil and plant processes in other crops, Satyanarayana (2005) has offered some explanations for the observed increases in rice production under SRI by comparison with flooded rice.

Young rice seedlings retain their potential for formation of tillers if they are transplanted before the start of the fourth phyllochron (Stoop et al., 1992), that is, before 15 days of age in tropical conditions. In each phyllochron one or more phytomers, namely, the set of tiller, leaf and root, are produced from the apical meristem; the number of tillers, leaves and roots will depend on the number of phyllochrons completed before flowering (Satyanarayana, 2005). This is especially true for

SRI rice, less so for flooded rice. Even under SRI, however, the number of phyllochrons completed in the vegetative phase can differ with variety, season and location. Thus, weather factors may significantly account for areal variations noticed in tiller density of rice cultivars under SRI culture.

Wider spacing of plants and daily wetting and drying: (i) expose the soil for better absorption of solar radiation, oxygen and nitrogen; (ii) deny the ideal microclimate needed by many pests and diseases; (iii) contribute to a greater interception of the full intensity of sunlight by the crop canopy and hence to better photosynthesis; and (iv) lead to greater soil aeration. For its part, greater soil aeration results in better and firmer root growth and an increase in aerobic microbes that facilitate increased solubilization of phosphorus, mineralization of nitrogen, availability of main and trace elements from the entire soil column to the crop, and suppression of nematodes and rice diseases. Under flooded conditions, 30 to 40 per cent of the cortex around the central stele disintegrates to form aerenchyma cells (air pockets) that enable oxygen to diffuse to the roots. Thus, a great deal of energy is spent in the development of air pockets. Under non-saturated soil conditions, this energy is diverted to grain production.

10.6.2.1.2.2 Constraints in use of SRI

The use of SRI requires skilled labour for more days, though for fewer hours per day. As labour cannot be hired on an hourly basis, the labour cost becomes substantial. SRI seedlings are highly vulnerable to inundation in the first few weeks of growth. Lack of drainage facilities in areas where SRI is replacing conventional flooded rice is a handicap. Since current SRI rice areas have been subject to waterlogging for long periods, soil amelioration and detection and correction of deficiencies of micro- and trace elements, particularly iron, pose problems. Incorporation of weeds as the sole source of biomass addition is inadequate. The organic system of rice crop fertilization is considerably costlier than inorganic fertilization. The heavy incidence of insects such as mealy bugs, thrips and stem borers under SRI has been reported. The micro-levelling of fields that has been advocated as a measure to control thrips and mealy bugs is not seen as practicable.

10.6.2.1.3 *Rainfed lowland rice ecosystem*

Rainfall is the only water source for the rainfed lowland rice ecosystem. Rainfed lowland rice is raised in places where surface irrigation is not avail-

able and there is a risk of inundation of fields from rains for significant periods of time in the crop season. In this cultivation system, rice is grown in banded fields with overflow arrangements to ensure that the depth of standing water remains less than 50 cm over a period of 10 consecutive days. The rainfed lowland system is characterized by uncertainty about the starting time of the crop season, and intermittent ponding, saturation, wetting and drying of the soil in a random manner. Methods for the establishment of crops are the same as in the irrigated lowland ecosystem. In the case of soils where rainwater tends to accumulate quickly on the soil surface, rainfed lowland rice may be established by direct dry seeding.

10.6.2.1.3.1 On-farm reservoirs

Due to rainfall vagaries, rice fields in the rainfed lowland system run the danger of drying up frequently during the active growth stage of the rice crop. The option of digging out a portion of the main rice field to collect surface runoff from rains, a method called on-farm reservoir (OFR), and using this storage to save the main rice field from drying out and to raise an aerobic crop after harvest of the rice crop, has been introduced and is in practice. The use of models for designing OFRs is of recent origin (Srivastava, 2001). For determining the fraction of field to be set aside for OFRs, it is necessary to know, for a given crop, when preparation of the main field for raising the crop will be started, as well as the temporal march of the quantum of rainfall deficiency by comparison with the crop's water need, and surface runoff from rains. In this effort, the assessment of daily runoff for a large number of station-years by standard procedure (USDA, 1972) constitutes a daunting task.

10.6.2.1.3.2 Rainfall budgeting

The parameters required for design of an OFR can be assessed through a modification of the daily rainfall budgeting procedure of Pandey et al. (2005), keeping the following aspects in mind:

- (a) The water need for land preparation (WNL), depending on soil type, will be 200 mm plus or minus 50 mm, while the need for raising the nursery will be 50 mm;
- (b) The budgeting will involve two phases – the unsaturated phase before ponding of water becomes feasible and the saturated phase with standing water;
- (c) The maximum moisture available for the crop will be between saturation moisture content and permanent wilting point;
- (d) Rainfall for ponding will be available only after saturation of the root zone;
- (e) Percolation (P) and seepage (S) will occur only with standing water on the field and will range from 2 to 4 mm per day, depending on soil types.

10.6.2.1.3.3 Methodology

The relevant methodology can be outlined as follows:

- (a) Cumulate on a daily basis differences between rainfall (RR) and potential evaporation (PE). Take negative values as zero. Set the limiting value of such cumulations as equal to saturated soil moisture content (SSMC).
- (b) Assign values in excess of SSMC as depths of water available for ponding (DW).
- (c) The time when cumulated DW reaches the value of WNLP is the start of the saturated phase.
- (d) In the saturated phase, starting with a given depth of water, add daily rainfall to depth of standing water and subtract the potential evapotranspiration (PET) seepage and percolation losses and assign excess values to runoff (RO).
- (e) The time when such cumulations lead to nil depth of water is the time of onset of water deficiency and the water need will be equal to the desired depth of water level (D).
- (f) Runoff collections in OFRs will also be subject to evaporation, percolation and seepage losses. Percolation and seepage can be prevented by lining the bottom and sides of an OFR with low-density polyethylene (LDPE) sheets.

In view of the plethora of terms and methodologies used in meteorological computation of peak crop water needs, FAO has prescribed a methodology to compute reference evapotranspiration ET_o as a standard datum. In the above example, PE will equal ET_o , while PET for crops will be equal to $K_c \cdot ET_o$, where K_c is a crop coefficient. Evaporation from pan evaporimeters, EP, is an easily available parameter that can be related to ET_o . Venkataraman et al. (1984) have presented a methodology for computation of ET_o using available data on net radiation components and the variations in time and space of the ratio of ET_o/EP . FAO (1998) gives procedures for calculating ET_o from EP recorded with different pans, their settings and surrounding environment, in combination with the values of K_c for peak water needs for various crops. The values for saturated soil moisture content, seepage, percolation and water needed for land preparation and optimal depth of standing water vary with soil types, but are readily available.

Applying the above methodology over a large number of years at a particular location will give, on a probability basis, the quantum of supplementary irrigation needed and the quantum of surface runoff that can be harvested. The two parameters can help in deciding the fraction of the main field that should be set aside for constructing the OFR.

10.6.2.1.3.4 Rice-cum-fish culture

Although FAO recognized the importance of rice-cum-fish culture as early as 1948, interest in this mode of farming was renewed only in the late 1970s (Ghosh and Saha, 1978). In India, where rice-cum-fish culture seems to have originated and which has the largest rice acreage, the percentage of rice area under rice-cum-fish culture is only 0.05 per cent, though the potential for this type of production is 45 per cent (Mohanty et al., 2002). In China, only 4 per cent of the rice area is under rice-cum-fish culture. Egypt, which has only 10 per cent of the area that India has under rice, has 75 per cent of the area under rice-cum-fish culture. Thailand has the highest area (3 million ha) and fraction of total area (32 per cent) under rice-cum-fish culture.

Irrigated lowland rice areas are suitable for rice-cum-fish culture. Fish culture requires a greater depth of standing water over the field than rice and will lead to a further reduction in water use efficiency. In deepwater rice areas and tidal rice wetlands, stocked fish may escape from the rice fields due to overflow of bunded fields by floodwaters. Thus, rainfed lowlands emerge as the only suitable system for rice-cum-fish culture.

When fish and rice are grown together, fish damage the rice crop and chemical control of biological setbacks to rice can harm fish. Again, the requirements of water depth, temperature, pH, oxygen and water turbidity for fish and rice for optimal performance are quite different. Also, water level in the fields cannot be allowed to fall below a specified minimum while fish stocks are present in the rice field. Thus, raising fish concurrently, but stocking them in OFRs, is called for. OFRs used as fish pens will require a higher depth of standing water. Therefore, a higher fraction of the main field has to be set apart for an OFR-cum-fish pen and this can be agroclimatically calculated (Bhatnagar et al., 1996). The fish catch from the fish pens will represent additional income for the farmer, however (Pandey et al., 2005), and will compensate for yield loss of rice from areas used for fish culture as well. Lining of the bed and sides of the OFR-cum-fish pen with LDPE sheets will be highly desirable.

10.6.2.1.4 Upland rainfed rice ecosystem

The upland rainfed rice ecosystem, in which the rice crop is raised in unbunded fields, is located in areas lying above the flood plain. A rainfall regime of 100 mm per month for four consecutive months is considered suitable for upland rainfed rice culture, which is mostly found in Asia, Africa and Latin America.

In upland rainfed rice culture, the crop is dry-seeded directly on ploughed land and the seeds are incorporated into the soil by ploughing or harrowing while the soil is still dry. Sometimes rice is dibbled, broadcast or row-sown in soil wetted by rains. In medium- and light-textured soil a dry nursery equivalent to 5 per cent of the main field area is raised. In this sector the seeds are sown dry and the soil is kept moistened; the seedlings are transplanted when rains start falling regularly.

Ideally, the completion of the vegetative phase of rice should coincide with the cessation of rains, with root-zone moisture at field capacity moisture status. The differences in duration among rice varieties are due to differences in duration of the vegetative phase. The reproductive and ripening phases are of 35 and 30 days, respectively, for most varieties. Since the evaporative power of air is 4.0 to 5.0 mm per day in the rainy season in the rice areas (WMO, 1967), the start of the cropping period for rainfed rice is the when rainfall begins and continues to exceed 30 mm per week; the vegetative period should end with the week in which rainfall drops below 20 mm. Therefore, the duration of the variety to be used is equal to the duration of the vegetative phase as delineated above, plus two months.

Maintenance of root-zone moisture of the rice crop is needed at saturation and not submergence (Venkataraman and Krishnan, 1992). In upland rainfed rice, this is not possible, as fields are not bunded. A budgeting of rainfall versus potential evapotranspiration of the rice crop, subject to the limiting plant-available soil moisture of the rice crop root zone, will give a measure of the climatological risks involved in raising rice as an upland rainfed crop at a given location.

10.6.2.1.5 Flood-prone rice ecosystem

There are two types of flood-prone areas: deep-water rice areas and tidal wetlands. The former are found in the lowland, deltaic areas of rivers where water accumulates for 30 days or more to depths of 0.5 to 3 m in the rainy season. Deep-water rice areas are common in South and South-East Asia and West Africa. In wetlands, soils remain flooded for several

weeks per year, often for more than 10 consecutive days, with medium (50 cm) to very deep (300 cm) flooding. Tidal wetlands are in coastal areas subject to risk of seawater intrusion as a result of storm surges. Tidal wetlands are more prevalent in Bangladesh and eastern India.

In deep-water rice culture, varieties known as floating rice are used. The seeds of such varieties are capable of germination even under 15 cm of water. Deep-water rice is directly dry-seeded but the seeds are not incorporated into the soil. The plants growing under non-flooded conditions can elongate their stems at a rate of 15 cm per day with a rise in water level up to 2 m in height. For this rate of elongation, however, the plants must be at least 6 weeks old. Deep-water rice can also survive submergence for 15 days.

10.6.2.1.6 *Irrigated aerobic rice ecosystem*

The irrigated aerobic rice ecosystem is a system of rice production that does not require puddling of soil and standing water in rice. Under aerobic conditions, various methods are adopted for supplying water for crop use, namely:

- (a) The soil is ploughed dry and the field is surface-irrigated when the soil moisture in the root zone reaches a tension of -30 to -50 kilopascals;
- (b) Alternate wetting and drying of the field is performed, in which the field is allowed to dry out for a few days after the standing water in the field disappears, before irrigation is initiated;
- (c) Rice is raised in beds divided by furrows. Beds are initially ponded to keep out weeds. Later, a shallow depth of water is maintained in the furrows to ensure saturation moisture for rice;
- (d) Rice is raised in beds initially wetted to saturation and water is later supplied to the root zone to replace the previous days' loss by crop ET.

Non-flooded soil leads to a reduction in rice yields. Therefore, the main criterion in the above system is that, by comparison with flooded rice, any reduction in yield should be more than compensated by a savings in irrigation water. This will ensure that, with the same amount of water required for flooded rice, a larger surface can be covered under aerobic irrigated rice and a larger rice crop produced. Ideally, studies comparing water used in flooded rice versus aerobic irrigated rice exposed to the same weather should be done during the dry season. Papers detailing the water use of aerobic, irrigated rice in comparison to flooded rice in the dry season seem to be extremely limited (Atlin et al., 2006; Bouman et al., 2005; De Dios et al., 2000). Some interesting features that emerge from such studies are outlined below.

A 30 per cent reduction in yield in the dry season has been reported under aerobic conditions compared with flooded conditions (Bouman et al., 2005). Atlin et al. (2006), however, noted no differences in grain yields between flooded and non-flooded methods in the dry season. Bouman et al. (2005) reported that the savings in water used for aerobic irrigated rice vis-à-vis flooded rice are mostly due to savings in water needed for preparation and seepage and percolation and that reductions resulting from evaporation and transpiration are marginal. Water required for puddling of soil in flooded rice culture is a one-time requirement independent of the duration of crop field life and season. The percolation and seepage losses vary with the soil, but little with the season and range from 2 to 4 mm per day (Yoshida, 1981). The total quantum of seepage-cum-percolation losses is dependent on both soil type and crop field life. For a rice cultivar that is raised for the same length of time on the same soil under flooded and irrigated conditions, the quantum of water saved due to non-flooded irrigation will depend upon the quantum of water consumed by the flooded rice, which will be higher in a drier, hotter and brighter environment. Thus, differences in the quantum of water saved are to be expected in the range of 25 to 60 per cent in raising aerobic irrigated rice without a moisture stress, as a fraction of water used for flooded rice. The savings in irrigation water in aerobic rice culture will always be more than the reduction in yield in comparison with flooded rice and can be translated into a larger area under rice for the same quantum of water, especially in situations where the farmers do not have access to enough water to grow flooded lowland rice. Thus, from the standpoint of making efficient use of water in boosting rice production, the adoption of aerobic irrigated rice culture is called for.

It is also claimed that aerobic rice varieties, which are upland varieties distinguished by their indica germplasm, higher yield potential, better response to fertilizer, improved lodging resistance, higher harvest index, and tolerance to occasional flooding, can give as high a unit area yield as traditional varieties under flooded conditions, and can produce more rice per unit amount of water used. Their maturity is reported to be delayed by 10 days, however. Considerable experimentation needs to be directed at the development of varieties for aerobic irrigated culture and the optimal site-specific crop and water management practices for sustained production of aerobic rice under continuous cropping, before aerobic varieties are widely adopted for upland irrigation.

10.6.2.2 Influence of critical climate and weather variables on growth and yield

10.6.2.2.1 Rice growth phases

As the weather requirements for optimal development are growth-stage dependent, it is necessary to delineate the growth phases and growth stages of rice in order to address the weather relationships affecting this crop. The main growth phases of rice are the vegetative phase, from emergence to panicle initiation (PI); the reproductive phase, from PI to completion of flowering; and the ripening phase, from end of flowering to grain maturity. The vegetative phase in rice is held to consist of a basic vegetative or juvenile phase, and a photoperiod-sensitive phase from the end of the juvenile phase to PI. The photosensitive vegetative phase is of short duration and the additional time due to the photoperiod factor, if and when operative, will make little difference to the total thermal time requirements of a cultivar (Venkataraman, 2004). Thus, the vegetative phase of rice can be treated as a single entity.

For rice, considering the postulations of Tanaka et al. (1964), Robertson and De Wille (1973), and Counce et al. (2000), the following growth stages can be delineated:

- (a) Vegetative phase, consisting of the seedling stage, from primary leaf emergence to fifth leaf stage; transplantation stage, from fifth leaf to recovery from transplantation; tillering stage, from tiller initiation to maximum tillering; and stem elongation stage;
- (b) Reproductive phase, consisting of the panicle initiation, booting (appearance of flag leaf), heading (exsertion of 50 per cent of the

panicles), and flowering (opening and closing of spikelets) stages;

- (c) Ripening phase, consisting of milk grain, dough grain and mature grain stages.

10.6.2.2.2 Temperature

10.6.2.2.2.1 Critical temperatures for rice growth stages

For delineating specific time periods suitable for maximal production of rice at a given location, it is necessary to know the cardinal (high, low and optimal) temperature requirements of various rice growth stages (Table 10.6.2). From the literature cited by Yoshida (1977), WMO (1983) and Venkataraman (1987), the low, high and optimal temperature requirements for important rice growth stages are given below.

The japonica cultivars of rice can tolerate temperatures 5°C lower than those of indica varieties, while their maximal values will be 5°C lower than those of indica varieties. The optimal temperatures will be the same for both japonica and indica varieties, however.

10.6.2.2.2.2 Duration of vegetative phase

The differences in duration of rice cultivars are due to differences in duration of their vegetative phase (Oldeman et al., 1987). In the phenology component of the ORYZA and CERES-rice models, a base of 8°C and 9°C mean air temperature is used, respectively, for computing thermal-time accumulations in rice crop phases. The above models have been reported to account for vegetative phase durations at individual locations. The CERES-rice model has been found to be

Table 10.6.2. Temperature requirements for important rice growth stages

Growth stage	Cardinal temperatures, °C		
	Low	High	Optimal
Germination	10	45	20 to 35
Emergence and establishment	12	35	25 to 30
Transplanting	>8	–	–
Rooting	16	35	25 to 28
Leaf emergence and elongation	7	45	30 to 31
Tillering	16	33	25 to 31
Flower initiation	15	–	24 to 29
Anthesis	22	35	30 to 33
Ripening	12	30	20 to 25
Fertility	14	38	–

superior to the ORYZA model and accurately accounts for variations in the duration of the vegetative phase ranging from 37 to 85 days, which arise from variations in varieties and locations (Mall and Aggarwal, 2002). The duration of the vegetative phase decreases with increases in temperature up to 33°C; a temperature rise above 33°C has no further decreasing effect (Alocilja and Ritchie, 1991).

The work of Reddy et al. (2004) indicates that vegetative phase durations expressed as growing degree-days above a base mean temperature of 10°C will be conservative across seasons. The degree-day requirements for completion of the vegetative phase can be expected to vary among cultivars. Thus, even limited and random phenological observations on growing degree-days in the vegetative phase of rice recorded on a few typical short- and long-duration cultivars, at a few locations and/or seasons, can assist in gauging the vegetative duration of different cultivars in various regions and seasons through temperature links.

10.6.2.2.3 Tillering

The number of tillers per unit area has a great bearing on rice yields (Yoshida and Parao, 1976). The duration of the tillering phase is influenced by temperature (Lalitha et al., 1999). At 23°C the duration is 8 weeks; it is only 5 weeks at a temperature of 27°C. The number of tillers per unit area is also influenced by temperature and shows a sharp rise at a temperature of 27°C (Lalitha et al., 2000). The contention (Owen, 1972) that the lower rate of production of tillers at low temperatures will be more than compensated by the increased duration of tillering is not valid (Reddy et al., 2007). Cumulated leaf area in the vegetative phase determines the quantum of intercepted photosynthetically active radiation, which is a yield-determining factor. The optimal leaf area index for photosynthesis in rice is 4.0 (Murata, 1967). The time required to reach an LAI of 4.0 from planting depends on tiller population and rate of tiller production, both of which are influenced by temperature. Again, the time between attainment of an LAI of 4.0 and the end of the vegetative phase becomes crucial and is dependent upon temperature.

10.6.2.2.4 Application of nitrogenous fertilizers

At temperatures optimal for tillering, leaf emergence will not be significantly affected, but elongation will be slower. Slower elongation will have little influence on cumulated leaf area,

however. The need to ensure adequate and timely supply of nitrogen to the crop for quick and proper leaf growth becomes important. The optimum time for application of nitrogenous fertilizers in rice is when the average internodal length is 6 mm; applications at internodal length up to 12 mm have little effect on yield. As reported in WMO (1974), the 12 mm internodal length corresponded to a value of 200 effective heat units, or EHUs, accumulated with lower and upper limits of 21°C and 31°C, respectively. Thus, if the daily temperature is 20°C, the EHU will be zero. Similarly, if the daily mean temperature is 33°C, the EHU will be only 31. Thus, the concept of EHU provides an agrometeorological tool for fertilizer applications.

10.6.2.2.5 Net biomass accumulation

The dry matter accumulated at heading has a significant influence on the grain yield of rice (Yogeswara Rao et al., 1999). Most of the dry matter in rice grain comes from post-floral photosynthesis. Part of the photosynthate is used as growth respiration, namely, in the formation of plant tissue, and the rest is used as maintenance respiration in the upkeep of existing tissues. Maintenance respiration is a function of both temperature and net biomass. In rice, maintenance respiration is 10 per cent of available photosynthates at 25°C (Mall and Aggarwal, 2002) with a Q₁₀ of 2.0 (Penning de Vries et al., 1989). Thus, temperature plays a major role in the creation of photosynthetic capacity in the vegetative phase and in the extent of utilization of the photosynthetic opportunity in the reproductive phase.

10.6.2.2.6 Reproductive phase

Work on the influence of temperature on growth stages and crop attributes in the reproductive phase (Best, 1959; Chang and Oka, 1976; Matsuo et al., 1995; Nishiyama, 1984, 1985; Yoshida, 1981) shows that non-optimal, low temperatures below 15°C for japonica varieties and below 20°C for indica varieties occurring during panicle initiation lead to a reduction in the number of florets per panicle and to the degeneration of panicle tips. After the formation of young panicles, they reduce the size of panicles; during booting they cause high sterility of spikelets; and in the booting and heading stages they delay heading, reduce the number and growth of spikelets, and lead to incomplete panicle exertion. In the flowering stage they delay flowering and lead to non-flowering of lower spikelets and incomplete fertilization; during anthesis, they reduce pollen maturity and floret fertility owing to inhibition of anther dehiscence (Nishiyama, 1984).

10.6.2.2.2.7 Ripening phase

From international experiments on rice covering many varieties, locations and seasons from 10° N to 20° N, Oldeman et al. (1987) found that the duration of the ripening phase was conservative and was characterized by a growing degree-day of 825 accumulated over a base temperature of 0°C. The work of Reddy et al. (2004) shows that despite temperatures in the ripening phase varying from 24°C in the rainy season to 31°C, the duration of the phase was constant at about 29 days across varieties and seasons. Optimum night temperature for this phase is thought to be 23°C (Ebata and Nagata, 1967) and minimum temperature in the 30-day period following flowering is viewed as an important yield-determining factor (Seshu and Caddy, 1984).

10.6.2.2.3 Solar radiation

10.6.2.2.3.1 Vegetative phase

The dry matter accumulated at heading, which has a significant influence on the grain yield of rice (Yogeswara Rao et al., 1999), is directly proportional to the quantum of intercepted photosynthetically active radiation (PAR). Now PAR is 45 per cent of solar radiation (Monteith, 1965). Thus, contrary to the popular notion, solar radiation in the vegetative phase is very important and the aim should be to maximize intercepted solar radiation in this phase.

10.6.2.2.3.2 Reproductive and ripening phases

A rise in radiation up to 500 calories/cm²/day increases the number of spikelets (Yoshida and Parao, 1976), which is an important indicator of dry weight at heading (Kudo, 1975). Solar radiation in the range of 300 to 600 calories/cm²/day in the post-flowering period was positively related to the number of filled grains per panicle, ranging from 50 to 180 (Oldeman et al., 1987). Solar radiation in the ripening phase influences both the percentage of well-filled grains and weight per grain. For equivalent yields, the radiation requirement in the ripening phase is lower than that of the reproductive phase because: (i) the amount of dry matter produced in the ripening phase is less than that at the start of the ripening phase; (ii) a substantial portion of photosynthates formed in the reproductive phase is used in grain yield (Yamada, 1963); and (iii) when photosynthesis gets restricted in the ripening phase, about 70 per cent of the stored carbohydrates at the start of the phase are translocated to grain (Yoshida, 1972). A cumulative solar radiation of 14 000 calories/cm² in the ripening phase (Moomaw and Vergara, 1964),

preceded by 6 to 7 hours of bright sunshine per day in the reproductive phase (Sato, 1956), is thought to be optimum for rice grain yield.

10.6.2.2.4 Rainfall

The type of rains needed for puddling of soil can come only from inland movement of depressions or with heavy rainfall-producing systems. In the absence of marine formations and/or inland movement of depressions or heavy rainfall systems, the area under puddled rice goes down. Since the soil surface of a rice field has standing water or is kept saturated, the consumptive-use (evapotranspiration) requirement of an established rice crop will be equal to the evaporative power of air (EPA). The value of EPA in the rainy season is 4.5 mm per day (WMO, 1967). Considering the percolation and consumptive-use needs of puddled rice, an amount of 50 mm of rain per week would be needed by an established, rainfed puddled rice crop. The ideal rainfall interval will be the saturated soil moisture content of the crop root zone divided by 50. In view of the nature of the climatology of the temporal march of short-period rainfall, collection of runoff from rains in OFRs for puddled rice becomes mandatory to deal with periods of moisture stress for the crop. In this sense, it is not the requirement of rainfall, but rather the management of rainfall that is of utmost importance in rainfed rice culture.

10.6.2.2.5 Water requirement

The physiological make-up of a crop plays a vital role in the water uptake of the crop during maturity. Limited data recorded with a volumetric lysimeter system show that varietal variations in the physiological control of water needs are likely (Venkataraman, 1982). As the soil is kept moist until the crop is harvested, however, there is no reduction in the water needs of rice during the maturity period. Thus, the water requirement of irrigated lowland rice will be the same as the rainfall requirement of rainfed lowland rice exposed to the same weather. Limited but critical field trials show that, under the aerobic irrigated system, savings in water will come from water for field preparation and percolation losses; these savings can range from 30 to 100 per cent.

10.6.2.2.5.1 Water-sensitive crop phases

For organizing water-saving measures, it is necessary to know the phases when rice is sensitive to water stress and to submergence. Moisture stress in the vegetative stage reduces plant height, tiller number

and leaf area, but the crop can recover without much loss in yield if adequate moisture is restored before flowering. Rice is most sensitive to moisture stress in the reduction division stage (panicle initiation through flowering) that leads to high spikelet sterility. The yield reduction due to submergence depends on the duration of submergence, the crop stage during submergence and the muddiness of the water. Reduction in yield is two times greater under muddy water compared with clear water. The panicle formation stage and ripening phase are the most and least vulnerable to submergence, respectively.

10.6.2.2.6 *Wind*

Only very low wind speeds are required for replenishment of the CO₂ supply to the rice plant through turbulence in the crop canopy. Strong winds cause too much fluttering and waving of the crop canopy, which interferes with the ascent of sap and hence affects mineral nutrition. This motion also reduces the formation of photosynthates and leads to poorer retention of assimilation product in ears. Dry winds desiccate ovaries and increase sterility, and they blow the pollen off stigmas, especially on plants with feathery stigma or with a long gap between the opening and closing of the lemma and palea (Saran et al., 1972).

10.6.2.2.7 *Relative humidity*

Relative humidity (RH) below 40 per cent inhibits flowering, which is best when RH is 70 to 80 per cent (Angladette, 1966). Relative humidity of even 60 per cent leads to faster senescence of leaves (Hirai et al., 1984). Higher RH increases stomatal aperture and leads to greater photosynthesis irrespective of the solar radiation regime (Hirai et al., 1984). Thus in the dry weather season, growing rice in puddled conditions would appear necessary to ensure a requisite RH regime. The influence of RH on rice crops has not been widely studied and this topic needs to be addressed.

10.6.3 **Other background information on rice**

10.6.3.1 **Climatic variability**

FAO (1992) uses the term “climate fertility” to stress the direct link between agricultural production potential and climate. Rainfall, temperature and solar radiation, directly or indirectly and singly or in combination, affect the growth, development and yield of rice cultivars. Climatic variability in the above parameters is the major reason for differences in the variations in

the yield potential of rice cultivars in various regions and seasons. Within the above broad picture, several types of climatic variabilities occur, and they need to be recognized for microscale planning in rice agronomy.

The first type of climatic variability is the one associated with regular weather systems that traverse specific regions in specified periods, such as the monsoons. Even when seasonal total rainfall or seasonal mean temperatures are considered, despite the annual fluctuations, an increasing or decreasing tendency over a period of years is often discernible. This gives rise to the concept of increasing or decreasing epochs of a weather parameter and constitutes the second type of variability. The third type of variability is associated with non-permanent systems, such as El Niño or La Niña, that have varying return periods, times and duration of occurrence, and interact with, add to and/or influence the regular systems so as to reinforce or mitigate their variability. For example, the tendency for drought to occur during the Indian summer monsoon in El Niño years practically disappeared during periods of above-normal rainfall (Kripalani and Kulkarni, 1997). The fourth type of variability is caused by differences in the coefficient of variation among the weather parameters. As an example, rainfall and the evaporative power of air are, respectively, the most and least variable in time and space. Climatic features over short periods of time, such as a week or a dekad (10 days), have to be considered for crop planning that is suited to the local climate. The in situ interannual variations over short periods constitute the fifth kind of variability. The above types of climatic variabilities lead to real and seasonal variations in climatic fertility for the production of rice.

10.6.3.2 **Climate change**

Puddled rice culture leads to anaerobic decomposition of organic matter and to the production of methane, a key constituent of greenhouse gases responsible for global warming and climate change. Under a wet undisturbed soil, the methane from soil does not escape into the air. Cultural practices associated with irrigated lowland rice account for 30 per cent of the soil methane released into the air, while aerenchyma cells of the rice plant provide the conduit for 70 per cent of the methane released into the air. Methane constitutes barely 2 parts per million (ppm) of air, compared with 350 ppm of CO₂. A methane molecule is 30 times more efficient in trapping heat compared with a molecule of CO₂, however. It has been reported (Reddy et al., 2005)

that higher biomass production of rice and higher incorporation of organic matter in puddled fields increase methane emissions. Lowland rice thus constitutes a significant source of atmospheric methane (Cicerone et al., 1983).

Climate change is expected to result in increases in rainfall variability, mean and night-time air temperatures, concentration of carbon dioxide and cloudiness – all of which will adversely affect growth, development and yield of rice (Peng et al., 1995; Matthews et al., 1996). The magnitude of increases in the above factors forecast for the worst climate change scenario can be seen even now, both intra-seasonally and inter-seasonally. In real time, though, aberrations in any weather parameter are limited to short durations and the effects of one period of abnormal weather are often offset by another period of an opposing trend – as for rainfall and temperature. Climate change, however, is a unidirectional perturbation that is superimposed on climatic variabilities.

10.6.3.2.1 *Impact assessment*

There is diversity of opinion on the expected rate of increase in climate change parameters. The parameters change in an interdependent manner. For example, an increase in CO₂ concentration will be accompanied by a rise in temperature and increased cloudiness. Ambient weather conditions influence the degree of responses of a given crop to a given change of a given parameter. Therefore, in assessing the impact of climate change on rice, it is necessary to: (i) carry out assessments for typical rice areas and seasons; (ii) work in terms of realistic, optimistic and pessimistic future climatic scenarios by assigning to each of the above climatic scenarios class-appropriate and specified increases or decreases of relevant parameters; and (iii) adopt a holistic approach involving assessment of an increase or decrease in rice yields due to the specified changes in yield-determining parameters. These steps will help assess the net change in rice yield in each scenario class for various areas and seasons of rice culture (Venkataraman, 2004).

The dynamic crop weather models, like CERES-rice and ORYZA, use inputs derived from field and laboratory studies to simulate growth, development, production of net biomass and partitioning of net biomass to rice grain yield. They are useful for assessing relative changes in yield of a rice cultivar due to climate change. Many impact assessment studies using the models are deficient in one or more aspects of the requisite methodology, however.

10.6.3.2.2 *Salient features for rice*

The temperature increase linked to global warming would be more pronounced in night-time temperatures (Karl et al., 1991), leading to higher night minima and a decline in the diurnal temperature range (DTR), which is the daily range in temperature expressed as a percentage fraction of the maximum temperature. Rice is sensitive to both minimum temperature (Seshu and Caddy, 1984; Lal et al., 1998) and DTR (Lal et al., 1998). Unlike for other crops, elevated CO₂ has little effect on transpiration of rice and the effects of moisture stress on rice will not be mitigated under an elevated CO₂ regime. Reduction in solar radiation will lead to an equivalent reduction in rice yields (Ritchie et al., 1987; Hundal and Kaur, 1996; Yogeswara Rao et al., 1999). There is little chance that rice will become CO₂-saturated by the middle of this century (Sinha, 1993; Baker et al., 1990). Maintenance respiration can range from 4 to 16 per cent over the temperature range of 15°C to 35°C (Mall and Aggarwal, 2002; Penning de Vries et al., 1989).

10.6.3.2.3 *Some observed features*

Some investigations indicate that the rice yield can either increase or decrease under certain climate change scenarios and in certain regions and cultivars. Long-term field experiments in Japan have shown a decline in rice yields because of the increase in spikelet sterility due to higher temperatures (Horie et al., 1996). Historical trends and long-term fertility experiments show a modest decline in rice yields in many districts of north-west India (Aggarwal et al., 2000) and the Indo-Gangetic Plains of India (Swarup et al., 1998). Simulation studies help ascribe the above decline to rising temperatures (Matthews et al., 1996; Aggarwal, 2003). Even given an optimistic future climate scenario, a decrease in rice yields in all parts of the rice belt and in all seasons is considered to be likely in India (Venkataraman, 2004).

A 10 per cent increase in rice yields is indicated with warming of 1°C plus 100 mm of rain in southern China (Zhang, 1989). The increase is attributable to the higher rainfall, however. With a CO₂ level of 460 ppm and a temperature increase of 1°C to 1.5°C, rice yields are set to increase by 2 to 5 per cent in India (Rathore et al., 2001). An increase of 4 per cent has been indicated for irrigated rice yields in north-west India due to climate change (Lal et al., 1998). An increase in rice yields in all regions of India has been projected, both under optimistic and pessimistic scenarios of climate change, leading to a levelling out of

differences in regional predicted rice yields (Aggarwal and Mall, 2002).

10.6.3.2.4 *Reasons for discrepancies*

The diverse results mentioned can be explained by the ecophysiology of rice. The effect of any weather aberration on the rice crop depends on the growth stage of the rice at the time of the event. For example, high temperatures after heading lead to a reduction in grain yield (Tashiro and Wardlaw, 1991) and the decrease in spikelet fertility owing to high temperatures is not ameliorated by the associated increase in CO₂ (Allen et al., 1995). In East Java, Indonesia, high rice yields are obtained in the wet season due to a shorter grain-filling period resulting from high temperatures (Daradjat and Fagi, 1991). The ambient conditions during which the weather aberration occurs determine the response of rice. For example, while mean temperatures above 33°C do not lead to any further reduction in the vegetative or reproductive phases (Alocilja and Ritchie, 1991), the duration of grain filling decreases with an increase in temperature beyond 33°C. The rice crop can use the higher amounts of CO₂ associated with temperatures above 33°C. Thus, given the envisaged climate change, the southern and western regions of India that currently have lower temperatures are likely to have increases in rice yields that are smaller than those in the northern and eastern regions of the country (Aggarwal and Mall, 2002).

Crop-weather simulation models show that the level of CO₂ enrichment required to offset the influence of the rise in temperatures depends on the level of CO₂, and the rise in temperature that can nullify the effects of CO₂ enrichment depends on the level of temperature increase (Crisanto and Leandro, 1994; Hundal and Kaur, 1996; Mall and Aggarwal, 2002). Therefore, whether an increase or decrease in rice yields will result from any analysis depends on the level of the changes in weather parameters assumed, often arbitrarily, in the climate change model.

10.6.3.2.5 *Extreme weather events*

Rice is the only crop that can be grown in tracts subject to storms and floods. Studies (IPCC, 2007) indicate that an increase in the frequency and intensity of extreme weather events, such as El Niño, La Niña, floods, droughts, cyclones, typhoons, heatwaves, frosts and high winds, will be a feature of the climate change scenario. In the Philippines, the declines in production and yield are seen to coincide with the occurrence of El Niño events (Philippines Research Institute and

Bureau of Agricultural Statistics, 2000). The lessening of the return periods of El Niño and La Niña and the recent occurrence of typhoons in the normally typhoon-free months of November/December in the Philippines is a cause for concern, as November and December are months when the rice crop is due for harvest and when the second crop is due to be planted (Lansigan, 2005). In India, the largely reduced formation of depressions in the Bay of Bengal and/or their subsequent lack of inland movement in recent years are affecting the acreage of puddled rice in some major rice-bowl areas.

Assessment of yield losses of rice under field conditions due to natural calamities is difficult because the quantum of reduction in yield is critically dependent on the stage of the crop's development during which the calamities occur. For example, even a temporary moisture stress for a week centred around the time of heading of the crop can reduce crop yields by 60 to 65 per cent due to a sharp decline in spikelet fertility and slowing down of peduncle elongation (Liu et al., 1978). Direct-sown rice is less prone to drought than a transplanted crop. Droughts are more harmful than flooding in reducing yields of rice. Between 1968 and 1990 in the Philippines, droughts, floods and tropical cyclones, and pests and diseases were seen to account for 50 per cent, 40 per cent and 10 per cent of the total rice losses, respectively (Philippines Research Institute and Bureau of Agricultural Statistics, 2000; Lansigan et al., 2000).

10.6.3.2.6 *Regional variations in actual and potential productivity*

The FAO Expert Consultation on Yield Gap and Productivity Decline in Rice (FAO, 2004) has assessed the actual farm yield, potential yield and yield gap of irrigated rice in various countries. These are illustrated in Table 10.6.3.

Since the gap figures relate to irrigated rice, moisture stress as a yield-influencing factor can be ruled out. The potential yield is that obtained at experimental stations with no physical, biological or economic constraints and with best management practices for a given time and given ecology. The actual yield is the yield on an average farmer's field given the same target area, time and ecology of the research station.

Table 10.6.3 shows that the yield gaps range from 10 to 60 per cent. Except in the Republic of Korea, the yield gaps between the actual and the potential in various rice regions range from 2.0 to 3.0 t/ha. Yields on farmers' fields under the system of rice

intensification are considerably higher than those of rice grown conventionally at nearby research stations. SRI can easily reduce the yield gap. The effects of climatic variability on the production potential of SRI rice have been limited, however. The differences in potential yield among countries can be ascribed to differences in the climatic regimes of the cropping period. Higher yields per unit area are often attained due to a longer field occupancy by rice, however. For unit areas with lower yields, more time is available to grow a second crop, subject to the availability of water. Thus for meaningful comparisons of rice crop productivity, values would be required for yield per day per unit area and net profit per year per unit area.

10.6.4 Management aspects of rice in various environments

Rice is grown in diverse hydrologic environments with different cultural and crop management practices in each of these environments. Management of the rainfed crop restricts the scope of rice management. Under irrigation, the scope for the management of crops to improve unit area and gross yields is better. Cultural practices and features having a bearing on crop production within irrigation systems are linked to major weather features and climatic factors, namely, rainfall, temperature and solar radiation.

The time and manner of the onset of rains and the seasonal rains in the catchment areas of the source of the irrigation system determine, respectively, the time of land preparation for the first rice crop and the quantum of water available for irrigation. Solar radiation and temperature, as important constituents of the EPA, determine the command area that can be

irrigated with water available for irrigation and optimal irrigation scheduling for crops in the crop season. The very high water needs for land preparation and meeting of percolation losses give little scope for adopting a seasonally varied command area for rice. The cropping calendar for the sequencing of rice and its rotational crops, and the duration of growth periods of these crops, vary from place to place as a result of variations in the phasic weather requirements of crops, the temporal march of radiation and temperature regimes, and the need to ensure that maturity periods of crops are sunny but not warm. Cropping intensity is the number of crops, including rice and its rotational crops, that can be raised in a year at a given place. The vegetative duration of rice, which determines the rice cropping period and the life duration of rotational crops of rice, is governed by the temporal march of the temperature regime. Fertilizer applications are timed as per phenological crop stages, which are influenced by temperature. Solar radiation and temperature are important for harvesting and crop processing, since sunny and warm weather is required in the pre- and post-harvest periods. These factors are tabulated schematically in Table 10.6.4 according to Bhuiyan and Galang, (1987).

10.6.4.1 Adaptive, protective and improvement measures

Adaptation of rice production systems to weather abnormalities and climate is an integral component of a balanced strategy to deal with climate variability. It is a measure of the degree to which adjustments to climate variability are possible in practices, processes or structures of systems. Adaptations are mostly agronomic. Protection measures relate to avoidance

Table 10.6.3. Gap between actual and potential yield of irrigated rice in various countries

Country	Yield(t/ha)		
	Actual	Potential	Gap
India (northern)	4.0	6.8	2.8
Republic of Korea	7.0	7.6	0.6
Philippines	5.5	7.5	2.0
Viet Nam	6.5	8.5	2.0
Egypt	8.5	10.4	1.9
Madagascar	4.1	6.0	1.9
Italy	6.0	9.0	3.0
Brazil	5.5	8.5	3.0

of unfavourable climatic features and mitigation of hazardous weather effects. Improvement measures relate to desirable future developments.

10.6.4.1.1 *Agronomic adaptation, commencement of cropping*

Rainfall vagaries result in uncertainty in starting the rice crop, in both irrigated and rainfed agriculture. Raising nurseries and transplanting seedlings with a view to preserving the physiological age of the crop are attempts to overcome this obstacle. The reduced-area wet-bed nursery and mat nursery are adaptations to overcome water constraints. For irrigated rice, low temperatures of less than 15°C prevent raising nurseries in high latitudes. Uncertainty in the use of young seedlings for transplanting is overcome by direct seeding. The inability of dry rice seeds to germinate under flooding is overcome by wet seeding with pre-germinated seeds of varieties suitable for direct seeding under anaerobic conditions.

10.6.4.1.2 *Choice of cultivars*

The combined duration of the reproductive and ripening phases is 55 days, plus or minus 5 days. The optimum life duration for rice is 135 days, plus or minus 5 days (Moomaw and Vergara, 1964; Tanaka, 1964). Therefore, the optimal duration of the vegetative phase is 80 days. The reproductive and ripening phases must have about 8 hours of bright sunshine with mean temperatures not exceeding 30°C. Agroclimatic analysis can help delineate the best possible growing period for irrigated rice and thus identify cultivars that would

perform optimally in a particular region and season given an early, normal or late start of the season.

The optimal duration for rainfed rice is very often not achievable as rice requires bright sunny weather during the ripening phase, and the crop must enter the ripening phase when rains cease, preferably with good root-zone moisture storage or with sufficient water available in the OFRs. This calls for the use of photosensitive varieties. Under lowland rainfed culture, delays in transplanting of photoperiod-sensitive varieties due to rainfall hold-ups have no significant effect on grain yield. It is agroclimatically possible to determine for any given location the time of commencement of the type of rains that will enable start of the lowland rice, and the time of cessation of significant rains. The former will derive the last possible date up to which transplanting/seeding of rice can be delayed without a reduction in yield potential, while the latter will provide the photoperiod regime for commencement of flowering and help in the choice of cultivars with appropriate photoperiod requirements for flowering.

10.6.4.1.3 *Optimization of population density*

The time from panicle initiation to about 10 days before maturity is the most critical period of solar energy requirement of the rice crop (Stansel, 1975; Stansel et al., 1965), when temperatures strongly interact with sunlight. Grain yield of rice is highly associated with dry matter at heading (Yogeswara Rao et al., 1999) and the increase in dry matter from the early start of panicle initiation to harvest (De Datta et

Table 10.6.4. Cultural practices for irrigated rice that are linked to major climatic factors

<i>Cultural practices for rice or related activities within irrigation systems</i>	<i>Climatic factors</i>		
	<i>Rainfall</i>	<i>Solar radiation</i>	<i>Temperature</i>
Land preparation and crop establishment	•		
Available water at irrigation system source	•		
Command area	•	•	•
Cropping calendar	•	•	•
Cropping intensity	•		•
Crop management	•		
Field water management	•	•	•
Fertilizer use and management			•
Irrigation delivery schedule	•	•	•
Harvesting and crop processing		•	•

al., 1968). Dry matter production is directly influenced by the amount of solar radiation received and the duration of the phases. Neither of these parameters can be manipulated. To maximize dry matter accumulation at the end of the vegetative period, the population density of rice and its nitrogenous fertilization must be such that the optimal cumulated leaf area index of 4.0 for photosynthesis (Murata, 1967) is reached as early as possible. Under temperatures that are non-optimal for tillering and/or leaf emergence and expansion, thicker sowings should be resorted to (Venkataraman, 2004). Such maximization of dry matter production in the vegetative phase will also aid the translocation of pre-flowering dry matter to grain dry matter due to non-optimal solar radiation and/or temperature regimes during the grain-filling phase (Cock and Yoshida, 1973; Yoshida, 1972). Thus, to make the best use of whatever solar radiation is available in the reproductive and ripening crop phase, adjustment of population density needs to be resorted to in harmony with the normal temperature regime at a given location.

10.6.4.2 Protection measures

10.6.4.2.1 Floods and droughts

Growing of puddled rice with standing water is in itself considered a bulwark against flooding. In rainfed lowland rice, risks due to flooding can be minimized by effective techniques for drainage of excess water in the field, such as openings in the field bunds at a level corresponding to the desired depth of standing water in the field, in tune with local aspects of plant and water management under excess moisture. This arrangement will result in a large quantum of rainfall becoming ineffective, however. Collection of runoff from rains in OFRs and introduction of water-saving techniques (Lansigan, 2005) are adaptive measures to mitigate drought situations caused by rainfall anomalies and to improve water use efficiency. The OFR system also provides an effective means of combating floods.

10.6.4.2.2 High winds

Strong winds lead to poorer mineral nutrition of the crop and enhanced spread of many diseases of rice. Establishment of windbreaks in strategic areas can help reduce wind damage in rice. For this action, information on prevailing wind direction in various months needs to be known, as windbreaks have to be erected perpendicular to prevailing wind direction. "Windroses" giving climatic information on a monthly basis regarding the frequency of occurrence of winds from eight cardinal directions and frequencies of occurrence of specified wind-

speed classes in each direction are widely available and can be used for proper orientation and structuring of windbreaks.

10.6.4.2.3 Pests and diseases

During night hours, owing to back radiation, the rice canopy can cool to a value below the minimum temperature at screen level. When relative humidity is high, 75 per cent or more, winds are light or absent and the crop cools to a temperature below the dewpoint. Dew forms and wets the leaves. The times of onset and evaporation of foliar dew are called leaf wetness duration, which has a vital bearing on incidence of diseases. Leaf wetness duration can be measured by instruments (WMO, 1963; Lomas and Shashqua, 1970; Monteith, 1972). The procedure suggested for computation of leaf wetness duration by Matra et al. (2005) is not practicable for real-time use. The extent to which crop minimum temperatures drop below the screen level minimum varies with seasons and places. Data on depression of crop minimum below the screen minimum are available for many areas and seasons and can be used for extrapolation. The hourly distribution of temperatures can also be calculated from maximum and minimum temperatures (Venkataraman, 2002). Therefore, data on maximum, minimum, dewpoint and depression of crop minimum below screen minimum can be used climatologically to avoid disease incidence through crop planning and operationally to ensure effective control operations.

Rice is susceptible to a given pest or disease at a certain growth stage only. The pest or disease organism does damage at a certain development stage only. The predisposing weather conditions for incidence and spread of many important pests and diseases of rice are also available (Venkataraman and Krishnan, 1992). Such information can be used to agroclimatically demarcate susceptible areas and periods for many major pests and diseases of rice. Along with the phenometeorological relationships of rice, this information can be used to avoid pests and diseases through a proper choice of sowing date or variety, or both.

10.6.4.2.4 Temperatures

Cold temperatures can arise from advection or local radiational cooling with a standing rice crop. Temperatures below 20°C and above 35°C for indica varieties and below 15°C and above 30°C for japonica varieties are potentially harmful. The extent of damage depends on crop growth stage, variety, temperature duration, diurnal range and physiological status of the plant. Cool weather

hazards to rice are often encountered in high-latitude regions. Low temperature incidence in hilly areas in the tropics and subtropics is a critical factor in rice production. Some types of cool weather damage to plants in typical growth stages of rice are indicated in Table 10.6.5.

In northern Japan, to overcome delays in the start of rice nurseries due to chilly winters, the nursery beds are covered with oil paper or vinyl films and the nurseries are drained and reflooded frequently to maintain equable warm day and night temperatures (Matsuo, 1954). The protected seedbed method helps in extending the rice season from early spring to late autumn (Inoue et al., 1965). In northern China, seedlings are raised in plastic-protected nurseries when the air temperature is around 10°C, and transplanted to the main field when the temperature rises to 20°C. In the Kathmandu Valley of Nepal, seedlings are raised in unprotected nurseries when the temperature is about 20°C, transplanted to the main field, and harvested before the temperature falls to 13°C (Yoshida, 1978) and causes high sterility of spikelets. Similar approaches have been reported for some areas of Japan (WMO, 1975). The following measures (Barfield and Gerber, 1979), singly or in combination, can be used to cope with risks to rice on account of cold weather: heating or mixing of the air layers in the crop canopy, sprinkler or flood irrigation, artificial fogging and insulation with suitable material.

Usually, heatwave conditions arise from advection associated with en masse movements of warm weather systems. Local heating of the surface leading to high air temperatures occurs in summer and generally after the harvest of the rice crop. High temperatures in the vegetative phase reduce the duration of tillering but enhance tiller production, with the result that the total number of tillers is hardly affected. A reduced tillering period will help the crop to mature under temperatures that are lower than normal. High temperature during heading is detrimental, however, and during the ripening phase reduces the grain-filling period. Protection against high temperatures has received considerably less attention than cold temperatures. This is because in the vegetative phase rice can tolerate temperatures of 44°C–45°C (Abrol and Gadgil, 1990). Unlike low temperatures, high temperatures allow rice to be grown, though with reduced yields. Heat stress can be minimized by irrigation, which exerts a cooling effect by converting sensible heat to latent heat and is the most promising and suitable measure in this context (Merva and Vandenbrink, 1979).

Sowing of pre-germinated seeds is routinely practiced in rice culture. High pre-sowing treatment temperatures induce early flowering, reducing the time to flowering to as little as 60 days in some varieties (Parija, 1943). Therefore, in incubating rice seeds to induce early germination for sowing in warm

Table 10.6.5. Cool weather damage to rice (Nishiyama, 1985, cited by Matsuo et al., 1995)

<i>Growth stage</i>	<i>Types of cool weather damage to rice plant</i>
Before nursery	Retarded cultivation
Nursery stage	Inferior germination and growth; withering and seedling rot; delay in transplanting due to freezing immediately after removing a cover on the protected nursery
Early stage: transplanting, tillering, panicle formation	Delay in transplanting; poor rooting; discoloration of leaves; decrease in tiller number; delay in growth and formation of young panicles; reduction in size of panicles
Panicle initiation to booting	Degeneration of rachis branches; decrease in spikelets; cessation of spikelet growth; delay in heading; non-heading; browning of leaf sheath
Heading stage	Delay of heading
Flowering stage	Delay of flowering, non-fertilization and non-flowering of lower spikelets
Ripening stage	Incomplete ripening; discoloration of unhulled rice grains; cessation of ripening due to early frost

weather, care should be taken to cool the temperatures of germination rooms to wet bulb temperature by injection of moisture from wet mats.

10.6.4.2.5 *Mitigation measures, crop insurance*

Covering risks in rice crop production by crop insurance is a mitigating measure. The fraction of farmers in developing countries who have crop insurance coverage is very low, however. For example, in India, only 14 per cent of the farmers are covered by crop insurance. In the Philippines, crop insurance covers only land preparation and establishment. To be meaningful, crop insurance for rice must cover all farmers and all the risks, from preparation of the nursery to harvest of rice. Insurance premiums will have to be higher for areas with unstable crop production. Higher crop insurance premiums would be an unbearable burden for farmers in areas of low rice yields with high interannual variability. Therefore, if crop insurance companies charge higher premiums, the crop insurance premiums or the difference in the cost of these premiums compared to the lowest premiums charged will have to be borne by governments. Such payment on behalf of farmers by governments does not attract the charge of subsidization of uneconomic crop production under the World Trade Organization (WTO) regulations.

Agroclimatic analyses using past series of meteorological data can help assess for any given area, season and crop, the extent of interannual variability in rice crop production on a relative basis. This approach is justifiable on the ground that differences among rice cultivars with respect to weather parameters are differences of degree, rather than of type. Use of satellite imagery for crop monitoring, calibrated against agrometeorologically analysed ground truth, has the potential to provide an independent verification for crop insurance firms of claims for crop yield losses. Thus, agroclimatic analyses have a role to play in the setting of rational insurance premiums for rice and in providing an unbiased picture for crop losses in rice on a regional and seasonal basis.

10.6.4.2.6 *Weather forecasting*

Even with careful agronomic planning for rice, through microscale agroclimatic analyses to suit local climate, the start of the rice season can be negatively affected by the variability of regular weather systems, such as monsoons, and irregular weather phenomena, such as El Niño and La Niña. Standing rice crops are subjected to weather vagaries on a year-to-year basis. Technologies to cope with climatic variabilities and weather anomalies

are available. The vulnerability of rice production to weather can be considerably minimized if expected weather situations can be accurately forecast on a long-range basis and the forecasts conveyed to farmers. The long-range weather forecast (LRWF) will give rice farmers sufficient time to organize and implement appropriate contingency cropping measures, at the start of the season, in tune with the expected weather. Due to the lack of sufficient data to validate its accuracy, LRWF technology is far from suitable for operational adoption in pre-seasonal planning of rice culture. Again, at present LRWFs only forecast what the anomaly of a weather situation will be at the end of the forecast period and give no indication of the temporal distribution by which the forecast anomaly will be realized. Hence they are of no operational use except for indications relating to early, normal or late onset of the season. Once the rice crop is planted, the production resources and technology get committed to a particular course of action. Medium-range weather forecasts, however, if they are properly interpreted for their likely agronomic consequences in light of the actual stage and state of a standing crop and quickly transmitted in real time, will help rice farmers to cope with and/or counteract the impacts of unfavourable weather and take advantage of favourable weather situations.

10.6.4.2.7 *Improvement measures*

The development of simple implements for intercultural operations, especially weeding, rapid harvesting and post-harvest handling (Pantastico and Cardenas, 1980), is a much-needed improvement measure. Biological improvement measures include breeding varieties for enhanced drought, heat and cold tolerance; with increased resistance to lodging; with morphological adaptations for better interception of solar radiation; with physiological improvements for more efficient use of CO₂ and solar radiation in photosynthesis; and resistance to specific pests and diseases.

10.6.5 **User requirements for agrometeorological information on rice**

Due to complex combinations of climate regimes and cultural systems of rice, the rice farmer's needs for agrometeorological information might be more specific in some respects than those of other farmers. At present, agricultural weather forecasts and advisories derived from these forecasts are being provided on the basis of the existing agronomic scenario of rice. The tacit assumption in this approach, which is

that the existing scenario is either optimal or unalterable, needs to be examined. Rice climate classification is the starting point to maximize and minimize, respectively, the positive features and hazards of local climate (WMO, 1983).

10.6.5.1 Rice climate zones

Rice climate classification involves the delineation of zones with intraregional differences in times and duration of the rice cropping period and potential yield levels under irrigated and rainfed conditions. Water, air temperature and solar radiation are the principal factors governing irrigated rice culture. The water factor is controllable. The other two are not. Thus the potential for irrigated rice, grown without any constraints and stresses, should first be established in various regions. Such a potential constitutes climatic fertility of rice (FAO, 1992), whose reduction due to water constraint must be assessed. Delineating these rice climate zones will help in: (i) quantitative assessment of the climatic risk due to late sowings; (ii) the prescription of cultivar-specific safe first and last dates of sowing; (iii) assessment of the probability of occurrence of critical climatic variables, such as minimum temperatures less than 15°C for early, normal and late sowings; (iv) drawing up contingency plans for late starting of the crop season; and (v) assessment of requirements for real-time agrometeorological information that will aid the farmers on a regional and period basis.

10.6.5.2 Irrigated lowland rice

The methodology for rice climate classification that has been described by Venkataraman (1987) is reiterated here. The requirements for maximal yields of rice grown without any moisture constraints are a crop life duration of 135 days, with a vegetative phase of 80 days, a mean air temperature that remains in the range of 15°C to 30°C, and about eight hours of bright sunshine in the last two months of the crop. Isoquant plots giving curves of equal predicted yields for combinations of minimum temperature and solar radiation during the ripening period (30 days after flowering) have been given by Seshu and Caddy (1984). Solar radiation is linearly related to bright hours of sunshine. Thus, from climatic data of actual or derived radiation and minimum temperature, the yield potential of rice can be assessed on a monthly basis. The month preceding the optimal ripening month can be assigned to the reproductive phase if it has seven to eight hours of bright sunshine. The 80-day period preceding the reproductive month can be assigned to the vegetative phase. By repeating this process

for all months, one can arrive at the times and duration of rice crop periods for various levels of productivity. There may be overlapping periods for the same level of productivity. In carrying out this exercise, one should bear in mind that for irrigated rice the start of the season is dictated by the date of release of water for first irrigation. The local traditional practice will give a real-time picture of the availability of water for the start of the rice season. Therefore, commencement of the vegetative phase cannot be earlier than the traditional first date of irrigation. Delineation of times and duration of rice crop periods for various levels of productivity at a network of stations can help in the demarcation of climate zones for irrigated rice.

10.6.5.3 Rainfed lowland rice

For rainfed rice climate zones, rainfall over weekly or dekadal periods has to be considered. In excess of these periods, the interannual variation of rainfall is such that one has to work in terms of probabilities and consider minimum assured rainfall amounts at various percentage probabilities. Fifty per cent probability is an acceptable risk levelling rainfed farming. Thus, first of all, at the 50 per cent probability level, the commencement can be taken as the week/dekad in which cumulation of rainfall minus evaporative power of air reaches the water requirement for field preparation. The end will be the week/dekad when rainfall sharply declines below the evaporative power of air. It is possible that such delineated periods may be more or less than the optimal vegetative life duration of rice crop of 80 days. If the periods exceed the optimal vegetative life duration, agrometeorological technologies to ensure sowing and harvest of more than one rice crop or other crop rotations have to be addressed. If the periods are shorter than the optimal vegetative life duration, the choice of cultivars and/or sowing dates must be such to ensure that the rice crop enters the reproductive phase when rains cease.

For a standing rice crop, considering the magnitude of evaporative power of air in the rainfed lowland rice areas and the rainfall requirements to meet the transpirational need of the crop from transplanting/sowing to harvest, a weekly rainfall amount of 50 to 70 mm and a dekadal rainfall of 70 to 100 mm, depending on soil types, would be required. Agroclimatic, rainfall budgeting exercises of temporal distribution of rainfall in the delineated period can help assess the period(s) of moisture stress and excesses, the feasibility of rainfall harvest, and adequacy of the harvested amounts to meet the water needs of the standing crop

during droughts and to raise another crop in the season that follows the rains. The results from such agroclimatic analyses at a network of stations can be used to demarcate homogeneous climate zones for rainfed lowland rice.

10.6.5.4 Biotic risks and weather hazards

For irrigated and rainfed rice, periods that promote and/or are susceptible to pests and diseases and weather hazards (storms, high winds, cold waves, heatwaves, and so on) can be delineated in each of the rice climate zones for suitable remedial, agronomic and other measures.

10.6.5.5 Forecast-based weather advisories for rice farming operations

Seasonal outlooks are usually expressed as expected deviations from normal conditions and give no indication of the temporal distribution by which the forecast anomaly might be realized. Long-range weather forecasting is still in the research and experimental stage and is far from suitable for operational adoption due to insufficient data about its accuracy. It would be prudent to advise potential users of the tentative nature of monthly and seasonal outlooks (WMO, 1981). Only medium-range weather forecasts offer scope for timely scheduling of farming operations to cope with expected weather.

The main weather-sensitive rice farming operations (WMO, 1983) are:

- (a) nursery activities;
- (b) land preparation;
- (c) seeding/transplanting;
- (d) irrigation and drainage;
- (e) fertilization;
- (f) crop protection;
- (g) application of agrochemicals;
- (h) harvesting;
- (i) threshing;
- (j) sun-drying and cleaning.

The weather situation, which is usually a combination of threshold values of weather parameters that affect farm operations, varies from place to place and from season to season. The current state of knowledge and evaluation of the response of the rice crop to weather variables is sufficient to lay down the threshold values of weather components such as rainfall, temperature, wind and cloudiness in relation to all activities of rice production.

Based on the combination of the several categories of sky condition, soil moisture status, leaf wetness

duration, temperatures and wind speed, the *Guidance Material for Agrometeorological Services to Rice Farmers* (WMO, 1983) indicated 72 weather features to cover all farming operations. Inclusion of too many threshold values for each weather element increases the number of weather forecast categories. The same agronomic advisory can be given for many combinations of weather elements, however (WMO, 1983). Again, the effects of a given weather situation are critically dependent on the rice crop stage. Implementation of any recommended farm operation takes time to organize. While weather can change on a daily basis, changes in crop state and stage will be gradual. Thus, agrometeorological advisories based on medium-range weather forecasts and the state and stage of crops are issued by the agrometeorologist in consultation with specialists such as pathologists, entomologists and agronomists once a week and updated if necessitated by the perception of a change in forecast weather. The issuance of agrometeorological advisories based on rice climate zones can help users to better benefit from these in real time.

10.6.5.6 Agrometeorological forecasting

Agrometeorological forecasting is concerned with the assessment of current and expected crop performance, including crop development stages (especially maturity) and yields (quantity and quality), along with other factors affecting production patterns (WMO, 1981). For the rice crop, two of the most important kinds of agrometeorological forecasting are phenological and yield forecasts. Phenological forecasts are important because of the relationship between the impact of any given weather situation and the rice crop stage during which it occurs. This in turn decides the type of advisory to be issued and the yield ultimately achieved. Yield forecasts sufficiently ahead of the harvest, in conjunction with an advance assessment of acreage planted to rice under various ecosystems, are crucial for timely and effective management of the rice food economy.

10.6.5.7 Phenological forecasts

The most important phenological forecast is the number of days up to flowering from sowing. This can vary with varieties. For any given varietal class, successful forecasting of rice crop phenology under field conditions has been reported. The DD50 computerized rice management programme uses the concept and computation of degree-days as a tool to predict phenological events with an accuracy of plus

or minus two days (Slaton et al., 1996) and to assist rice farmers with 28 management decisions based on growth stage, including herbicide application, scouting for insects and diseases, timing of application of nitrogenous fertilizers, and the like. The described degree of accuracy is quite high; it could most likely vary quite widely in different crop areas and yearly conditions. Mall and Aggarwall (2002) reported that CERES-rice accurately predicted vegetative-phase durations ranging from 37 to 85 days as a result of variations in varieties and locations in India. Since the predictions are based on variety-specific genetic coefficients derived from observed field data, such findings do not address the problem of real-time prediction of rice phenology.

10.6.5.8 Yield forecasts

The agrometeorological forecasts of crop yields are unit area yields. They constitute a very important tool to estimate the production of a given crop in a certain region or country by knowing the area planted. There are three approaches to modelling the impact of weather on crop yields (WMO, 1981), namely, the empirical statistical approach, crop weather analysis models, and crop growth simulation models.

10.6.5.8.1 *The empirical statistical approach*

According to this approach, the crop yield is related to levels of weather parameters, either singly or in combination, in selected calendar periods. Owing to rainfall and/or temperature vagaries, the selected calendar periods would relate to different rice crop phases in various years. Often there is no physiological significance between the selected periods and rice yields. For rice, drastic reductions even with normal vegetative growth can occur due to weather vagaries in the reproductive and ripening phases. Assessment of weather aberrations should be based on growth phase and not calendar dates. The empirical statistical approach will give highly misleading results in almost all years.

10.6.5.8.2 *Crop weather analysis models*

In this type of analysis the crop itself is used as a weather integrator in parallel with crop responses to selected agrometeorological variables at various growth stages. Such studies help identify crop growth attributes, which can be used as a measure of the likely yield and assess the influence of growth stages of a crop on the extent of reduction in potential crop yields due to weather anomalies and soil moisture stresses. While they cannot per se give

any yield estimates, they provide valuable inputs for designing sub-routines in the crop growth simulation models for the use of quantified crop attributes in yield assessment, and for assessing the effects of environmental stresses in terms of crop phase on the extent of reduction in yield by comparison with a non-stressed crop.

10.6.5.8.3 *Crop weather simulation*

The dynamic crop weather models simulate plant physiological processes, such as photosynthesis, transpiration, respiration, biomass partitioning, nutrient uptake and water use in daily time steps in a manner similar to the processes as they are visualized in the rice crop (Uchida, 1985) for conversion of seeds, water and fertilizers into rice grain and straw. Phenological stages are simulated in the models from considerations of thermal and photoperiod regimes. In crop yield forecasting, feedback information from fields on the observed stage and state of crops can then be input into the models. So only the part of the model relating to prediction of rice yield becomes relevant in real time. For the purpose of predicting rice yields, the models require individual calibration for the varieties used. The models constitute valuable research tools for studying the performance of rice cultivars under different environmental, soil and management conditions through meteorological links when weather is the only operating variable. The models, however, require cultivar-specific genetic coefficients for many parameters and development rates. The problem posed by varietal variations in vogue in rice culture can be overcome through the following considerations of phenological and physiological responses of rice to weather.

The dry matter accumulated in the vegetative phase is related to the final grain yield. The ratios in the quantity of dry matter available at the start of the reproductive phase among cultivars can reasonably be assumed to be the same as the ratios of duration of their vegetative phases. The percentage change in the duration of vegetative phase due to weather influences will be the same for all cultivars under the same weather regime. So the ratios will be conservative across yearly weather situations. The durations of the reproductive and ripening phases are nearly the same for all cultivars. One goal of agronomic planning is to ensure that all the cultivars are exposed to the same weather in the maturity phase. The actual quantity of dry matter produced in the reproductive phase can vary among cultivars. There will be no change in the ratios of production of dry matter in the maturity phase among cultivars, however. The change in duration

of vegetative phase at a location due to the temperature factor is never drastic. Thus, the percentage change in yield from the potential due to weather variations will be the same for different cultivars across locations and years. Therefore, validation of the models at a few locations and for a few cultivars can be used for assessment of yields of different cultivars across seasons and locations under irrigated and non-limiting nutritional conditions. The models assume that diseases and pests are absent, that there are no adverse soil conditions, and that extreme weather events such as typhoons and the like do not occur. Reductions in yield of rice often arise from biotic stresses and hazardous weather. So the final yield estimates have to be adjusted for losses due to biotic and abiotic stresses.

10.6.5.9 **Biometeorological models**

A combination of the crop weather analysis approach involving the use of yield-determining attributes, such as spikelet number at heading, and dynamic simulation models for assessing total dry matter accumulation may be necessary for predicting rice yields.

10.6.5.10 **Field-level data series**

For both rainfed and irrigated rice, yield prediction models must be validated at the level of technology the farmer uses, which on the whole is continuing to rise. Thus, for rice-yield forecasting, availability of data from recent years on yields of typical cultivars recorded on farmers' fields by properly designed crop-cutting experiments, and the archiving of such data for ready retrieval and use, are necessary. In the case of rainfed rice, the yield level will depend on the availability or absence of facilities for collection and re-use of runoff from rainfall. As a result, yield data for purely rainfed conditions and for rainfall harvest and re-use conditions have to be recorded separately.

10.6.5.11 **Use of forecast weather data**

Rice yield forecasts need to be issued preferably two months in advance of crop harvest and definitely at least one month in advance. Therefore, for use in the models, forecast levels of various parameters have to be provided on a weekly basis for a month or two in advance. As in weather forecasting, values of analogous years or climatic normals or forecast values can be used. It is very difficult to find a year that is completely analogous to the year under consideration. Instead of using climatic normals, it is preferable to use forecast probabilities of parameters, principally temperatures and sunshine/solar radiation.

10.6.6 **Agrometeorological services relating to rice**

The national weather services have the mandate to meet the climatic data needs for crop planning and the weather forecast requirements for agricultural operations. The forecast service is a matter of great daily urgency for farmers. Weather forecasts cannot be issued only for or even with special reference to rice, however. So agrometeorological services for rice farmers involve the following questions: "Who provides what information where?" "Who receives and interprets the routine flow of various types of forecasts with reference to available rice crop information and issues agronomic advisories?" "How do farmers access this information?" The answers lie in rice farmers' forming their own associations to appoint agents and/or seek advice from agrometeorological consultants who understand weather relations of farm operations, pests and diseases, and the like in relation to all crops and hence can interpret the forecasts in terms of rice and issue rice-specific advisories.

10.6.6.1 **Agrometeorological extension for rice farmers**

Medium-range weather forecasts (MRWFs) by themselves can be used in scheduling farm work in rice. Rice farmers can also take advantage of updated MRWFs. Rice farmers in developing countries are ill equipped to take action on daily weather forecasts or updated MRWFs on their own, however. Thus, it would be ideal to have working arrangements for cooperation between the meteorological centres and agricultural cooperatives and/or agricultural extension services, as well as local "extension agrometeorologists" who are trained to translate the forecasts in terms of farm operations for rice into a language understood by the farmers. The majority of rice farmers located in tropical areas are too poor to form associations and not literate enough to benefit from information conveyed through print media, Websites or text messages. The governments should, therefore, enable the rice farmers to form cooperatives and facilitate conveyance of agrometeorological advisories through community radio and television channels. In organizing such a set-up, the experience gained by rice farmers from a few countries in organizing self-help entities to derive benefit from weather-based precision rice farming should be of help and is described below.

10.6.6.1.1 **Brazil**

A three-month weather outlook is issued by a team of meteorologists, agrometeorologists and agronomists

to help rice farmers take several planning decisions in the southern region of Brazil (Berlato and Fontana, 2003). The Web page (in Portuguese) of the Laboratory of Agrometeorology (<http://www.cpact.embrapa.br/agromet>) offers some agroclimatological products for irrigated rice in the state of Rio Grande do Sul. These products include agroclimatic zoning for potential productivity and climatic risk according to the sowing period; the probability of minimum air temperature harmful to rice; a three-month weather forecast; management techniques to minimize the impact of the forecast weather; and application of the degree-day method to help farmers apply nitrogenous fertilizers at panicle differentiation. Maps are provided indicating the climatologically estimated dates of panicle differentiation for groups of short- and medium-cycle varieties, for emergence dates at 10-day intervals. Detailed information can also be found in a publication (Steinmetz et al., 2004) available as a PDF file.

10.6.6.1.2 *United States*

The computerized rice management programme called DD50 caters to rice farmers in the United States, principally in the states of Arkansas, Louisiana and Texas. The programme is open to individual rice farmers, farmers' agents and consultants. More than 2 000 Arkansas rice growers on more than 60 per cent of the state's rice area (Slaton et al., 1996) use the programme. To participate in the programme, farmers submit the variety, area sown and emergence date of each rice field to their local county extension office. Agents automatically receive a copy of all reports (via e-mail) generated for their county, regardless of who initiated the report (producer, agent or consultant). DD50 provides decision-management aids based on planting date, variety and weather information.

The main data contributed are the weather information provided by the National Weather Service and updated daily to the weather Website of the University of Arkansas Cooperative Extension Service. This programme utilizes the concept of degree-days (DD) or heat units to estimate when a certain stage of the rice crop will occur. The basic data used are: the emergence date(s) and the variety (or varieties) used by the farmer; the thermal units required to reach the main development stages of the most important varieties, which are determined in the research stations; and long series (30 years) of past daily maximum and minimum air temperature data and the current year's data for the crop season. In general, the events predicted by DD50 are held to be accurate within plus or minus two

days (Slaton et al., 1996). Nowadays, this programme assists farmers with 28 management decisions based on growth stage, including herbicide application, critical times to scout for insects and diseases, and N application. For example, the ability to predict growth stage, specifically internode elongation (IE), has reduced the physical labour required to sample fields to determine the accurate time for midseason application of nitrogenous fertilizers.

At the beginning of the season, the DD50 operates using the 30-year temperature averages. Then it is continually updated with the current year's temperature data to improve accuracy. Updated DD50 printouts are provided to farmers when temperature-based phenological dates are expected to deviate from the 30-year average by three or more days. In the three states mentioned, only registered users can avail themselves of the benefits of the DD50 programme.

10.6.6.1.3 *Japan*

In the Tohoku region of Japan, yield fluctuations of rice are strongly influenced by fluctuations in summer mean temperatures (Hayashi and Jung, 2000). An example of the use of crop model and meteorological data in monitoring the rice development and cool-summer damage in the Tohoku district of Japan has been reported (Yajima, 1996). The results obtained by combining the models on development stages and on spikelet sterility with the crop, meteorological and geographical data, emphasize the importance of the use of the crop model for the monitoring and forecasting of rice development stages and spikelet sterility at the regional level or in areas affected by cool-temperature damage. Extension staff can easily use this method to provide information on the possible occurrence of spikelet sterility in particular areas that may enable farmers to take the necessary measures to minimize the yield reduction due to cool temperature. An early warning system against cool-summer damage in northern Japan is in operation (Yajima, 2003).

10.7 **AGROMETEOROLOGY AND SORGHUM PRODUCTION**

10.7.1 **Introduction**

Sorghum (*Sorghum bicolor* (L.) Moench) is a cereal grass native to sub-Saharan Africa that has been

cultivated for centuries as a staple cereal grain (Menz et al., 2004). Other names for sorghum include durra, Egyptian millet, feterita, daza, sorgo, Guinea corn, jowar, juwar, W.C. Kaffir corn, milo, shallu and Sudan grass. The many subspecies are gathered into four groups – grain sorghums (such as milo), grass sorghums (for pasture and hay), sweet sorghums (formerly called Guinea corn and used to produce sorghum syrups) and broom corn (for brooms and brushes). Sorghum was initially cultivated possibly around 5 000 years ago and since that time, continuous human intervention has led to the development of the crop.

Sorghum is well known for its capacity to tolerate conditions of limited moisture and to be productive during periods of extended drought, circumstances that would impede production of most other grains. It has an extensive root system, waxy leaves and the ability to temporarily stop growing in periods of drought, recovering when moisture becomes available again. This makes it an important crop in arid or semi-arid environments, where it may not be economically viable or productive to grow other cereals. It is an important food crop in Africa, Central America and South Asia, and in both total area planted and production, sorghum is the fifth most important cereal crop grown in the world after wheat, rice, maize and barley (FAO, 2006).

Although sorghums is of tropical origin, plant breeding has developed cultivars adapted to growth outside the tropics and as a result the grain has been cultivated at latitudes from 45° N to 45° S. In 2005, the area worldwide given over to sorghums was 44.7 million hectares, which produced 58.6 million tonnes, equal to an average of 1.3 t/ha. The United States produced 9.8 million tonnes, followed by Nigeria with 8 million tonnes, though the yields were 4.3 t/ha and 1.1 t/ha, respectively. Argentina, however, although producing much less sorghum than the United States, did so at 5.1 t/ha. The main producer countries, their respective harvest areas and average yields are shown in Table 10.7.1. About 90 per cent of the area planted to sorghum lies in less developed countries, mainly in Africa and Asia, where it is grown generally for food by low-income farmers. The remaining 10 per cent is made up of large-scale commercial farms, most of them in the developed world, which produce sorghum mainly for livestock feed. These farms account for more than 40 per cent of global sorghum output.

Table 10.7.1. Main producer countries, harvest area and average yield of sorghum in 2005 (FAO, 2006)

<i>Country</i>	<i>Production (tonnes)</i>	<i>Area harvest (ha)</i>	<i>Yield (t/ha)</i>
United States	9 847 680	2 301 470	4.279
Nigeria	8 028 000	7 073 000	1.135
India	8 000 000	9 400 000	0.851
Mexico	6 300 000	1 909 090	3.300
Sudan	4 228 000	8 000 000	0.529
Argentina	2 900 000	558 000	5.197
China	2 592 800	672 600	3.855
Ethiopia	1 800 000	1 350 000	1.333
Australia	1 748 000	659 000	2.653
Brazil	1 529 600	758 356	2.017
World	58 620 842	44 703 950	1.311

Sorghum is one of the most versatile species of plant. It is an important part of the diets of many people in the world, mainly those living in the drier areas of Africa and India (Datke et al., 2003). Besides its use as food for humans, it is used as animal feed and as a raw material for the production of anhydrous alcohol, alcoholic drinks, glues, inks and biodegradable packaging materials. Sugar is also extracted from its stems. Sorghum is one of the best crops for silage because of its high yields (and being a C₄ plant it is an efficient source of biomass), while the sugar content and juiciness of its stalk, along with its adaptability to areas receiving too little rain to ensure crops of maize (Bakici and Demirel, 2004), also contribute to this. The ensilage of sorghum also usually prevents stock losses from prussic acid poisoning.

The flowering panicles of the plant are used as brushes, brooms and whisks, while the stems are used for weaving fences and mats and in the building of wattle houses. In Africa, the straw of the traditionally tall sorghums is used to make palisades in villages or around homesteads, and the plant residues are an important source of fuel for cooking. The stems of wild varieties are used to make baskets and fish traps. Dye extracted from sorghum is used in West Africa to colour leather red.

Sorghum starch is manufactured in the United States by a wet-milling process, similar to that used for corn starch, from which dextrose is produced for use in foods. Starch from waxy sorghums is used in adhesives and for sizing paper and fabrics and is also an

ingredient in oil drilling “mud”. In the United States, sorghum is a principal feed ingredient for both cattle and poultry. Its protein content is higher than corn and about equal to wheat. Its fat content is lower than corn but higher than wheat. Tannin, an acidic complex, can affect both the taste and nutritional value of sorghum, though historically sorghum with high tannin content was desirable only because it was unpalatable to birds, a great pest in sorghum production. High-tannin sorghum is still grown where birds represent a problem for production. In the United States, reduced-tannin sorghum has been developed, which has led to an improvement in its use for food by as much as 30 per cent.

Sorghum grains have a structure very similar to that of maize, although they are smaller and generally oval in shape. Both sorghum and maize have a floury endosperm and a large fat-rich germ, but unlike barley or rice, they lack a true hull (husk). Whole grains contain about 12 per cent protein, 75 per cent starch, 4 per cent fat and 4 per cent minerals. Sorghum has a very hard kernel, which makes it resistant to disease and physical damage, but also harder for animals to digest. To combat this characteristic, it is ground, cracked, steam-flaked and/or roasted, which enhances its nutritional value by 12–14 per cent.

10.7.2 **Agroclimatology of sorghum**

The main factors that affect sorghum production can be grouped into four general categories. Understanding how these affect production should increase both the plant's survival and growth and its production efficiency. The main categories and factors are:

- (a) Climatic factors: rainfall (water management), solar radiation, photoperiod and temperature;
- (b) Soil factors: chemical and physical soil properties and topography;
- (c) Crop management: fertilization strategy, plant arrangement, plant population, weed and disease control, and so on;
- (d) Genotype: potential of production, adaptability to the environment.

10.7.2.1 **Rainfall – water management**

Of all the factors that affect agricultural production, the deleterious effects of climate are the most difficult to ameliorate. Add to this the variability and unpredictability of climatic factors and this becomes the main risk to production. Abiotic stresses such as drought or excessive rainfall, very high or low temperatures, low insolation levels, and so forth, can significantly reduce yields and restrict the latitudes and the soils where

commercially important species can be cultivated. Of the climatic elements, water is the most important, its availability during the plant's growth cycle generally being the single factor that limits crop yield (Chiroma et al., 2006).

Water constitutes, in general, about 90 per cent of a plant's mass and is important for internal transport (minerals, photosynthates, and so on), temperature regulation, as a milieu for biochemical reactions and as a solvent; it also affects plant structure through plant turgor relationships.

The degree to which water deficit affects crop yield depends on the intensity and duration of the water deficit, the crop cultivar, the plant's development phase and interaction with any other yield-determining factors. Water stress affects several plant growth aspects, including the anatomical, morphological, physiological and biochemical. Drought conditions can affect a plant's water and nutrient absorption, seed germination, opening and closing of stomata, photosynthetic activity, transpiration, enzymatic activity and several other metabolic and physiological processes. The more obvious general effect with respect to water deficit, however, is the reduction of plant size and mass, leaf area and seed yield.

Sorghum is well known for its capacity to tolerate conditions of limited moisture and to crop during periods of extended drought in circumstances that would impede production in most other grain crops. It is one of the most drought-tolerant grain crops and is an excellent crop model for evaluating mechanisms of drought tolerance (Tuinstra et al., 1997). Sorghum is able to endure quite arid conditions through both drought-resistance and drought-escape mechanisms, as a result of its extensive root system, waxy leaves and ability to temporarily stop growing when the drought becomes excessive. A drought-escape mechanism is exhibited when sorghum becomes dormant under adverse water conditions, but resumes growth when water relations improve, even after relatively severe drought. Early drought stops growth before floral initiation and the plant remains vegetative, but it will resume leaf and flower production when conditions become favourable again for growth. Late drought stops leaf development, but not floral initiation.

To obtain high yields, cultivars with a cycle from 110 to 130 days require 450–650 mm of water (FAO, 1979). In order to maximize sorghum yields, soil moisture should be maintained above 55 per cent of the available water capacity in the

rooting zone of the soil profile throughout the growing season. When the growing period is long, stalking cultivars are capable of recovery through the formation of additional stalks with bearers, even if critical water deficits occur during vegetative growth. Extreme water deficits during the flowering period reduce pollination or cause spikes to dry out. The decrease in the resultant yield can be partially compensated for by additional stalks with spikes (FAO, 1979).

In general, the greatest water consumption coincides with the period in which sorghum plants present the greatest height and leaf area index. Severe water deficits during this vegetative growth phase reduce the plant's mass increase and leaf area development; this affects grain yield, even though the direct yield development phase that is susceptible to water stress is the reproductive period (flowering and seed filling). Cultivars used for the production of forage where green mass, rather than grain yield, is required, do not present such defined critical periods and can just be allowed to respond to the water availability during the growing season. In this case, the water requirement is more a function of the leaf area development and evaporative demand of the atmosphere.

10.7.2.2 Photoperiodism

Of all of the environmental factors that plants respond to, photoperiod (day/night length) is probably the most important, since this directly affects flowering. Photoperiodic control of flowering allows plants to coordinate their reproductive phase with their environment and with other members of their species (Childs et al., 1997). Most sorghums are sensitive to photoperiod and are classified as short-day plants, in other words, the night must be longer than a critical minimum. Photoperiod-sensitive cultivars have a terminal vegetative bud that remains vegetative until days shorten enough to initiate its differentiation into a floral bud. This initiation happens at the critical photoperiod, namely, when the day length is short enough to initiate flowering, but not long enough to prevent it. Genetically, sorghums vary in their critical photoperiod. For example, some tropical varieties have difficulty flowering in temperate regions where the day length is greater than 12 hours, that is, during the summer. On the other hand, photosensitive temperate varieties have a longer critical photoperiod of around 13.5 hours (Magalhães and Durães, 2003). Some sorghum hybrids, however, are not photoperiod-sensitive.

10.7.2.3 Temperature

Temperature is an important factor that affects sorghum growth and is directly related to solar radiation. Soil temperature affects the plant's growth: it influences root growth and metabolism and modifies the production of the growth promoters of the aerial parts and nutrient uptake. The germination and seedling establishment phase of sorghum growth is especially sensitive to cold temperatures and results in a reduced plant population and grain yield (Tiryaki and Andrews, 2001). Reduction of the soil temperature in the pollination and grain development periods reduces grain production. Adams and Thompson (1973) observed that grain production increased on the order of 10 per cent when they covered the soil with clear plastic, which kept the soil temperature about 2°C higher during the growth period. Peacock (1982) and other researchers have suggested that the best temperature for germination is between 21°C and 35°C and that temperatures of 40°C to 48°C have been lethal. Adams and Thompson (1973) also observed that when the soil temperature falls from 26°C to 23°C in the pollination and grain formation phases, it provokes a fall in productivity. This was attributed to the negative influence of temperature on nutrient absorption and the translocation process.

Because of its tropical origins, sorghum is very sensitive to low temperatures. Paul (1990) showed that for most sorghum cultivars, a minimum temperature of 16°C is necessary for all physiological processes to occur. Low temperatures (<10°C) cause reduction of the leaf area, stalking and plant height; decrease dry matter accumulation; and delay flowering, possibly owing to a reduction in chlorophyll synthesis and consequently photosynthesis. When compared with corn, sorghum is more tolerant of high temperatures and less tolerant of low temperatures. When the average daily temperatures are lower than 20°C, there is prolongation of the growth period from 10 to 20 days for each 0.5°C of fall in temperature. High and low temperatures stimulate basal stalking. Low and high temperatures (<15°C and >35°C) during flowering and grain formation cause reduced yields.

In the development period of the panicle, around 30 days after germination, temperature affects the number of grains produced by the panicle. High temperatures during anthesis can cause flower and embryo abortion, though floral development and fertilization can occur from 40°C to 43°C when the relative humidity is between 15 and 30 per cent. High temperatures, six to nine days after anthesis, reduce seed weight. Low temperatures during

anthesis affect panicle development, causing spike sterility through the effect on meiosis, which provokes pollen grain sterility. Both the intensity and duration of low temperatures are very important in influencing the extent of sterility. Peacock and Wilson (1984) show that the rate of leaf formation (leaves/day) increases when the temperature rises from 13°C to 23°C and then declines with temperatures over 34°C. Eastin et al. (1976) noted that night temperatures of 5°C above the optimum temperature reduced yield grains from 25 per cent to 33 per cent, and 10°C above the optimum reduced the yield by 50 per cent. The phase most sensitive to temperatures above the optimum temperature is floral differentiation.

It is worth noting that the optimum values of temperature proposed for sorghum crop development have been contradictory. While most authors cite optimum values around 33°C–34°C, Norcio (1976) established the optimum temperature for sorghum development in field conditions to be between 35°C and 42°C, although he emphasized that there are differences among genotypes. Peacock and Heinrich (1984) have found sorghum growing in the semi-arid tropics with air temperatures exceeding 40°C and soil temperature reaching values of 60°C to 68°C. Soil temperatures of 18°C at 5 cm soil depth for three consecutive mornings are recommended for even, vigorous seedling emergence (Amathauer, 1997).

10.7.3 **Other background information on sorghum**

Sorghum is a C₄ plant (fixes carbon dioxide into 4 carbon acids) of tropical origin. It is productive at high light intensities and high temperatures such as those that occur in the tropics. It has high nutritional values for the various forms it is used in – cut, pasturing, hay, silage or grains. It is considered an annual crop, although there are some varieties that can become perennial. It has a large number of varieties adapted to different climatic zones, including tempered (cold-climate) varieties. The crop requirements are very similar to those of corn, except that it has a greater tolerance to drought. The development of sorghum in semi-arid regions indicates that this crop can resist drought and high temperatures better than corn, so when the climatic conditions of a region are too hot and drought-prone for corn, sorghum becomes an excellent alternative. When established, sorghum plants are very drought-resistant and hence can succeed in arid soils.

While the sorghum crop prefers a slightly to moderately acid soil, some cultivars will grow

with a soil pH as high as 8. Sorghum plants are adapted to a wide range of soils varying from light loams to heavy clays, though they thrive best on light, well- drained, easily worked soils of high fertility, with moderate to high water availability. Small amounts of alkali in sandy soils reduce a crop's performance considerably despite the moderate tolerance of sorghum plants to saline soils. A basic dressing of nitrogen, phosphorus and potassium may be required for yield improvement and the crop usually responds well to additional dressings of nitrogen during growth. Rotation with a leguminous crop can provide a low-cost soil fertility increase. The effect of nitrogen deficiency on grain yield is greatest when it occurs early in the growing season. Low grain protein results when nitrogen deficiency occurs between anthesis and maturity.

During the plant's first growth phase (planting until panicle initiation), rapid germination, emergence and plant establishment are very important. Weed control when the plant is small and slow-growing is important if reduced yields are to be avoided. Hybrids generally have faster root and leaf formation, even though these are slower in fodder sorghum varieties than in grain sorghums. If growth processes such as leaf area, root system development, dry matter accumulation and seed number potential are negatively affected in the phase from panicle initiation to flowering, reduced yields will occur. The phase following flowering is a critical one, as seed number is a very important grain yield component. In this third growth phase (flowering to physiological maturity) the factors considered important to yield are those related to seed filling. The final yield is a function of both the duration of seed filling and the rate of dry matter accumulation (Magalhães et al., 2003).

The height of mature plants can vary from 40 cm to 400 cm. Temperature, water deficit and soil nutrient status can affect the expansion rate of leaves, leaf area duration and plant height, though this effect is mainly seen in photoperiod-sensitive genotypes. The growth habit of sorghum is similar to that of maize, but sorghum presents more side shoots and a more extensively branched root system. The root system of sorghum is very fibrous and can extend to a depth of up to 1.5 m, even though the plant extracts 75 per cent of its water from the top metre of soil. As a result, in dry areas, the plant's production can be severely affected by the water status of the soil. Compacted soils or those with shallow topsoil can limit the plant's ability to survive drought by limiting its root system development. Since these plants are physiologically suited for growing in hot dry areas, it

is essential that the soil has a well-cultivated topsoil and is kept from compacting to allow full exploitation of these characteristics. In acid soils and with high levels of aluminium, however, the formation of the root system is reduced.

10.7.4 **Management aspects of sorghum in various environments**

Productivity of the sorghum crop, when measured in terms of dry matter production, depends on the difference between photosynthate accumulation from photosynthesis and photosynthate losses through respiration. Any factor that modifies photosynthesis and respiration can have both positive and negative effects on productivity. This includes light, temperature, water and nutrient availability.

Dry mass production is strongly dependent on the plant's leaf area up to panicle initiation. Although there are not many studies into the relationship between leaf development and temperature, it is known that if water and nutrients are adequate, leaf development is highly dependent on temperature. Peacock and Heinrich (1984) showed that leaf emergence (leaves/day) increased when the temperature rose from 13°C to 23°C. It was also found that when the day and night temperatures climbed from 20°C/15°C to 35°C/30°C, there was an increase in leaf emergence. These authors also found that leaf expansion increases up to 34°C and that above this level, the leaf expansion rate starts to decrease. They also showed that below about 15°C, leaf expansion ceases. Generally, the leaf expansion rate has been observed to be approximately 60 cm² plant⁻¹ day⁻¹. The influence of temperature on the growth of roots has not been studied extensively and the few existing results suggest that the growth-temperature relationship is similar to the one for leaf expansion.

Knowing the maximum crop yield, technologies and/or management practices can be applied to try to approach or reach this figure. Appropriate crop management consists of practices that consider all the possible interactions that affect yield. There is no single set of practices that guarantees high yields, however. What is necessary, though, is a good knowledge of the crop and a sensible application of management practices, which are targeted at the factors limiting crop yield.

Soil management practices that have a positive yield effect should address the following:

- (a) The creation of good soil drainage and water storage, which encourage root system development. Such practices may include no-tillage systems and crop rotation;
- (b) An increase in the soil depth available to roots and enlargement of the water extraction layer in the soil through production of a larger soil water reservoir and, consequently, greater water availability to sustain plant growth during short periods of drought;
- (c) Elevation or re-establishment of the nutritional level of the soil, so that it is appropriate to the crop yield required;
- (d) The use of cultivars adapted to the region;
- (e) Planning of the sowing time to enable better utilization of solar radiation, prevailing temperatures and the water available for crop development, with reference to any sensitive phase. Water availability is particularly important;
- (f) Attention to pests and diseases that may reduce yield;
- (g) Weed control in order to reduce competition for water, nutrients and light.

In regions with irregular rainfall distribution and high evaporation to the atmosphere (characterized by high solar radiation levels, strong winds, elevated temperatures and low relative humidity of the air), the water availability in the soil, in the absence of irrigation, is fundamental to the success of agricultural productivity. Practices that lead to better soil structure and consequently a deeper plant root system help to increase the soil water availability to the plant. Chiroma et al. (2006) observed that combining the practice of flat bed cultivation with mulching may eliminate the need for ridging in order to increase the productivity of sorghum grain in semi-arid regions.

The no-tillage system (direct sowing) engenders better soil water storage conditions for growth and crop development and minimizes the adverse effects caused by small water deficits. The average soil pore diameter increases: this improves soil porosity and soil structure and increases the proportion of the soil water available to the plant. These factors, coupled with the reduced soil evaporation and increase in water infiltration rate, allow larger water storage in no-tillage system soils compared with the conventional management systems involving soil disturbance. Organic matter, which occurs in relatively small proportions in most tropical soils, contributes to increase the soil specific heat value and improves the soil's cationic change capacity, in addition to performing the important function of soil matrix formation. Soil matrix greatly influences soil water retention and the supply of minerals to the plant. While greater water availability favours biomass formation, it also allows greater transpiration losses, even though the

transpiration ratio (g water/g dry weight increase) for C₄ plants such as sorghum is low.

Crop management practices and other factors should be adjusted to minimize any negative effects on crop yield, although, more importantly, they should be altered to allow maximization of the crop yield potential. Any intervention in the crop production system should have an economic objective that is defined by pre-established criteria, however. Strictly speaking, in practice it is the economic criterion that ultimately dictates the crop management action.

Insect pests and diseases are important factors to contend with in sorghum production. In some regions, insects can be a major limiting factor in grain sorghum production. Common soil insects, stem borers, aphids, green bugs and shoot flies affect the crop. Growers must be prepared to inspect the crop for insect pests and prevent injury from them (Buntin, 2005). Sorghum diseases, such as seedling and foliage diseases, root and stalk rot, head blights and moulds, can and do occur each year in several parts of the world. Diseases may cause leaf spots or leaf blights, wilts and premature death of plants. Sorghum diseases can cause harvest losses, affect the quality of the harvested crop and lead to losses in storage. Diseases of sorghum, like those of other crops, vary in severity from year to year and from one locality or even field to another. Such variations depend upon environment, causal organisms and the host plant's resistance. To minimize losses due to sorghum diseases, it is important to correctly identify the disease or diseases present so that appropriate management steps can be taken (Bradley et al., 2007).

Appropriate crop management programmes can minimize losses from insects and diseases. These measures include: planting tolerant cultivars, conducting crop rotation, managing crop residues properly, timely harvesting, biological control and accurate and timely application of insecticides and fungicides.

Besides insects, birds are a major pest that can reduce yield considerably. Several types of birds can infest grain sorghum during the period from hard dough to maturity, as they perch on panicles and eat the seed. Birds will consume whole seeds but also will break the seed, leaving half of it on the panicle (Buntin, 2005). Cultivating hybrids with a higher tannin content, but also growing the crop in large field blocks, may help to combat birds.

10.7.5

User requirements for climate information

Although sowing time usually does not have an effect on production cost, it affects the yield and thus the farmer's profit. Decisions affecting the time of sowing should be based on the risk factors that can be minimized, as these represent efficient planning activities relating to production. In addition to management practices, however, sorghum productivity is a function of several integrated plant factors, such as the interception of solar radiation by the canopy, respiratory activity, leaf photosynthesis (the source) and translocation of photosynthate to the grain (the sink).

The relative activities of the source and sink are functions of environmental conditions – plants try to adapt to conditions by balancing their activities. The different responses of genotypes to environmental variability, in other words to the interaction genotype x environment, means that neither genotypic nor environmental effects are independent. Hence the importance of the sowing time is mainly with respect to the crop cycle, namely, through the relation of plant factors to the environment. For crop production, this means trying to estimate the effect of environmental conditions on all plant growth phases. The great problem, however, concerns unpredictable environmental variations. Environmental factors such as precipitation, air temperature, wind speed, solar radiation, cloud cover and so forth, can vary unexpectedly and vary spatially as well as temporally.

Climate and soil types are the variables that explain the regional differences causing water deficiency in the crops. Particular factors are available soil water capacity, rain distribution and amount, and the evaporative demand of the atmosphere (Farias, 2004). In spite of being considered a crop tolerant to water stress, sorghum can suffer water deficit effects that reduce its productivity considerably. Therefore "sowing time" refers to the period in which the crop has a high probability of growing in soil and climatic conditions that are both favourable.

Although it is practically impossible to control the climate, it is possible to define the season with the best climatic conditions for sorghum development. For this, based on the climatic history of the region, some presuppositions should be established to evaluate the likelihood of successful cultivation and thus define the best sorghum sowing time. Climatic considerations should include appropriate temperatures during all the crop growth periods, adequate photoperiod and a sufficient

water supply, especially during plant development phases that are more sensitive to water deficits.

10.7.6 Examples of agrometeorological services relating to sorghum

In the area of agrometeorological services, the climatic risk zoning of sorghum developed in Brazil has been contributing to sowing times that present a smaller climatic risk to the crop. In Brazil, sorghum is generally cultivated in the summer following another crop – the sowing date depends on the growing season of the preceding crop as well as on the sorghum growth cycle. Thus, for a definition of sowing time, it is important to know and to quantify the risk factors and to try to establish the conditions to minimize them.

To establish the sorghum climatic risk zoning in Brazil, the following were considered: (a) the characteristics and distribution of precipitation; (b) the available water capacity of the soils (resulting from the hydrological characteristics of the soil as well as the effective depth of the root system); (c) the water consumption of sorghum in its different growth phases; and (d) the cultivar's life cycle (Farias et al., 2003). With this baseline information, the risk was estimated for not attaining the crop water needs (expressed by the relationship between actual and maximum evapotranspiration) for each place and sowing time.

Figure 10.7.1 shows climatic risk maps in relation to sorghum in the Paraná State, Brazil. These studies were carried out for the main regions of sorghum production and this information now constitutes an important tool for providing guidance with regard to

the sowing date, as well as agricultural policies, since the information can be used to establish subsidies, credit concessions and agricultural insurance. All of the information for sorghum, as well as for some others crops, is available at <http://www.agritempo.gov.br>. Besides having information about climatic risk zoning, this Website also contains other important agrometeorological information relevant to agricultural production in Brazil.

Besides the quantification of the water deficit risk occurrence and the characterization of the climatic conditions of a certain region, this information allows one to define areas that are subject to economic risk because of pests and diseases whose appearance is related to climate.

Many other agricultural practices, such as soil management and soil preparation, weed control, harvest, and the like, can be affected by climatic conditions: these practices benefit from the availability of climatic maps and forecasting.

Another example of agrometeorological services relating to sorghum comes from Nigeria (Oluwasemire et al., 2002; Stigter et al., 2005). The hypothesis was tested, for the most abundantly occurring intercrops in semi-arid northern Nigeria, that these systems are generally more efficient in resource use under drier conditions than sole (monocultured) crops. This was done for dryland intercropping, with heterogeneous mixtures derived from patterns and varieties that farmers preferred, at low densities on-station. The most dominant crop mixtures are millet/cowpea, millet/sorghum/cowpea, millet/cowpea/groundnut, sorghum/cowpea and sorghum/cowpea/groundnut.

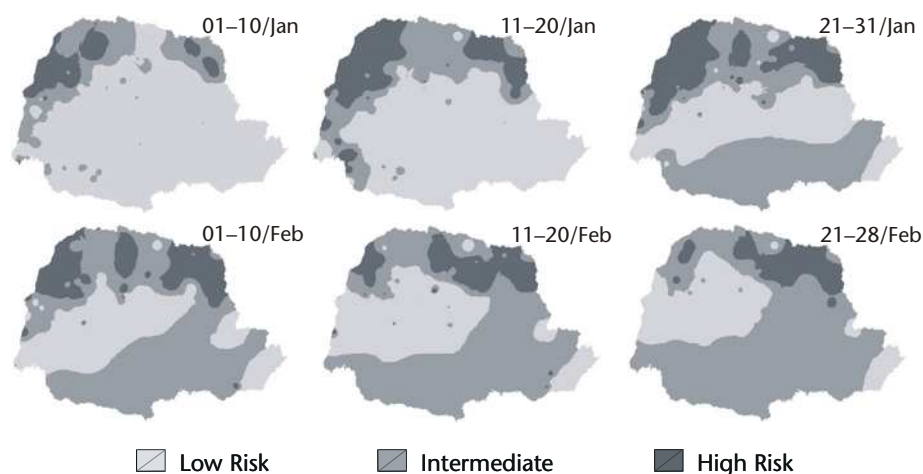


Figure 10.7.1. Climatic risk zoning for sorghum in Paraná State, Brazil: water risk during six sowing periods, with a cultivar cycle of 120 days and an available water capacity in the soil of 50 mm

The cereals are grown for consumption and cash. Intercropping components adopted by farmers are grown at low densities in order to minimize risks and exploit resources in a good cropping season.

When the rainfall was below normal, the sorghum intercropping systems showed better water use efficiency than all sole crops. All the sole and intercropped crops were sown and rooted beyond 1 m in the loose sandy soil. Sorghum root production was greater than for millet, while both cereals produced greater root densities than cowpea. Overlap of the roots of component crops suggests competition for resources. Cowpea produced greater root densities and achieved deeper rooting when intercropped with millet and/or sorghum than it did as a sole crop, suggesting adaptation and competitive ability under intercropping. Rooting depths of crops were shallower in a relatively wet season than when water was limiting. Root densities and proliferation of the cereals below the surface layer were much higher in low fertility soils than when nutrients were readily available. This is immediately useful knowledge as an agrometeorological service for designing such systems.

Another example of a sorghum-related agrometeorological service comes from Sudan (Ibrahim et al., 2000, 2002). In the Gezira irrigation scheme, modern irrigation approaches and less field attendance, especially for sorghum and groundnut fields, were accompanied by significant symptoms of water waste. A serious debate among authorities on a return to traditional irrigation methods or other possible solutions needed quantification of the wastes concerned. At their request, a quantitative study was undertaken on irrigation that was also meant to suggest ways to improve the situation in a manner compatible with the local socio-economics of the use of sharecroppers. To possibly strengthen, but at least to verify, the arguments of those who wanted to change the situation, it was thought useful to accurately quantify the problems under participatory on-farm conditions. Quantitative agrometeorology has sufficiently strong methods to accomplish this.

The study revealed wastage of irrigation water in both irrigation methods, but at different rates and in a different manner for each crop. The waste was higher in unattended irrigation of both sorghum and groundnut. Even much of the consumptive use was economically ill-invested in non-fertilized sorghum, because with higher inputs the same amounts of water would provide higher returns. The application differences were mainly due to the watering methods, causing different amounts of standing water, and the methods for determining the moment

of irrigation. Another type of non-productive water is the readily available water retained in the soil profile at the end of each growing season.

As an agrometeorological advisory it was stressed that more efficient water and farm management (such as weeding) in the scheme was crucial for obtaining the same or somewhat higher yields with other external inputs remaining at the present low levels. The most important measure in this respect would be to adopt a land-levelling programme to the practical limits possible and to apply partly or fully attended watering on small areas, as had been recommended in the traditional night storage system. A minimum practical level of standing water in the furrows during and immediately after each irrigation was desirable. The adoption of economic measures relating to the payment and price of irrigation water was also advisable.

A final example of an agrometeorological service related to sorghum also comes from Sudan (Abdalla et al., 2002a, 2002b; Bakheit and Stigter, 2004). In the country's central clay plain, traditional subsistence farmers and small farmers who also produce for the local market want to keep the region near self-sufficiency. They combine annual production of sorghum with underground pit storage of part of the harvest. With increasing climate variability, this food security is coming under more and more pressure. This encouraged farmers in central Sudan to experiment with possible improvements to their traditional underground storage pits (*matmuras*) for sorghum grain. These innovations were quantified as part of the agrometeorological service.

Microclimate measurements of grain moisture contents, grain temperatures and pit-air carbon dioxide contents in experimental pits made it possible, as another part of the agrometeorological service, to test and improve their designs. The innovations derived by farmers using shallower pits (50 cm in the experiments) and applying chaff linings at the bottom and sides of these shallow pits (of at least 25 cm before compression by the stored grain in the experiments), made safe storage possible during at least two consecutive bad rainy seasons. Wide protective caps on top of the pits (extending 1 m beyond the pit diameter in the experiments), which were aimed at diminishing the chances of cracks leading water to the grain, were a necessary precaution that had been highlighted by the research experience.

Improved *matmura* systems have the potential to increase the food security of farmers and bolster

their economic position. The initiatives showed that farmers in the Jebelmuoya villages could benefit from improved *matmuras*. Calculations indicated that improved sorghum *matmuras* could increase returns by up to 45 per cent, even in the case of small-scale farmers, and that the larger the *matmura*, the higher the benefits. A recent survey carried out in three villages in the area showed that farmers were aware of the advantages of developing the system. Forty percent of farmers questioned in the survey commended improved sorghum *matmuras* for their storage qualities and low cost. They particularly appreciated the reduced need for chemical protection and the security these storage pits provided against theft and fire.

10.8 AGROMETEOROLOGY AND WHEAT PRODUCTION

10.8.1 Introduction

From the earliest days of human civilization, wheat has played a significant role in nearly all societies. It was one of the first plants to be domesticated and cultivated by humans, possibly between 18 000 B.C. and 12 000 B.C. The domestication of wheat was critical in the transition from hunter-gatherer groups to stabilized societies with an agrarian foundation. Initial wheat production flourished in the “fertile crescent” region of the Tigris and Euphrates rivers. Since domestication, wheat production has dramatically expanded, so that wheat ranks as one of the most important crops worldwide and has the widest geographical distribution of any crop. Its unique gluten content and associated bread-making properties, along with use in many food products, assure its continued role in society.

10.8.1.1 Classification of wheat

Wheat belongs to the genus *Triticum* and groupings within this genus are based on the number of chromosome sets. Only three *Triticum* species have commercial significance: common bread wheat (*T. aestivum*); durum wheat (*T. durum*), which is used mainly for pasta; and club wheat (*T. compactum*), which is used primarily for pastry and household flour. Most wheat grown throughout the world is the hexaploid *T. aestivum*.

A number of derived species have been produced using *Triticum*. A cross of *Triticum* with rye (*Secale*) has produced *Triticale*; crossing with *Agropyron* has produced *Agrotricum* (Morris and Sears, 1967); and a cross with *Haynaldia* has produced *Haynaltricum*.

Some of this material has provided valuable genetic information or has contributed disease and insect resistance. The successful development of such wide crosses may be useful to the development of a perennial wheat and to gene diversity of cultivated wheat, but many are not useful at present.

Wheat is often characterized as being a “winter wheat” or “spring wheat”, with the normally recognized distinction being that spring wheat does not require a cold period (called vernalization) for the formation of flower primordia. Cultivars vary greatly in their vernalization requirement, and some “spring wheat” cultivars have a short vernalization requirement. Given the vernalization requirement of winter wheat, it is often planted in the fall and receives the vernalizing temperatures in late fall and early winter. Two problems can occur, however: (1) winterkill can occur at high latitudes; and (2) late frosts in the spring can significantly reduce yields as a result of damage to developing flowers. Winter cereals are preferred over spring cereals wherever it is possible for them to survive the winter period as they tend to produce higher yields (Hunt, 1980a, 1980b; Salmon, 1917).

Considerable research has gone into developing greater cold tolerance and altering management via fertilizer (especially at planting), tillage/residue cover (influencing snow catch), and planting date to reduce winterkill. As plant breeders succeed in producing cultivars with greater winter hardiness and as cultural practices provide greater protection against winter injury, the limits to winter wheat production will move into more extreme areas and may displace spring wheat. In North America, for example, increased winter hardiness has allowed winter barley to become more firmly established around the Great Lakes region (Hunt, 1980a). Except in favoured areas of the northern Great Plains region of North America, winter wheat production is unlikely to expand unless winter survival becomes more reliable. In the past, quantum jumps in winter hardiness have not occurred because of the multiplicity of genetic factors involved in winter survival.

A key advancement in wheat production has been the introduction of semi-dwarfing genes, and indeed this was fundamental to the Green Revolution because it allowed higher fertilizer inputs without the associated yield loss due to lodging (namely, tall stems falling over). The introduction of semi-dwarfing genes has changed the partitioning between the canopy and roots, and the harvest index (the ratio of the seed weight to the above-ground weight), among other traits (for example, Baenziger et al., 2004; Miralles and Slafer, 1995).

A notable development of the last decade has been the explosion of information being derived from molecular biology and genome mapping, allowing characterization of genes and genomes beyond just their phenotypic effects. Positional cloning of important wheat genes is rapidly advancing. For instance, three vernalization genes in wheat (*VRN1*, Yan et al., 2003; *VRN2*, Yan et al., 2004, and *VRN3*, Yan et al., 2006) have been cloned, as well as the *Ppd-H1* gene for photoperiod response in barley (Turner et al., 2005) and the *Ma3* maturity locus related to phytochrome B synthesis in sorghum (Childs et al., 1997). Gene networks controlling flowering are quickly emerging for crop plants such as barley (Laurie et al., 2004).

10.8.1.2 Adaptation of wheat

Wheat is among the world's most widely cultivated crops, occupying over 22 percent of the area devoted to crop grain production (FAO, 2007). It is harvested every month of the year somewhere in the world, from as far south as Argentina and as far north as Finland, and it is grown over a substantial area in almost every country of North and South America, Europe and Asia (Table 10.8.1). Wheat, a C₃ crop, is considered a cool-season grass. Therefore it is concentrated in areas between 30° N and 60° N latitude and 25° S and 40° S latitude (Briggle and Curtis, 1987), although varieties that can thrive within 20° of the Equator or lower at higher elevations have resulted from continued development of photo-period-insensitive wheat cultivars derived by the International Maize and Wheat Improvement Center (known by its Spanish Acronym CIMMYT, for Centro Internacional de Mejoramiento de Maíz y Trigo), along with other breeding efforts. Production, in terms of harvested area, remains remarkably consistent among countries, as rankings of countries changed little between 2004 and 2005 (Table 10.8.1).

Wheat is the cereal crop that accounts for the greatest volume of international trade, yet it is subject to political and economic factors, in addition to its environmental adaptation. Producers are guided in their decision-making process by the net returns to be obtained from wheat as compared to other farm products, in which biofuels and animal product prices may be a deciding factor. Net returns for wheat are influenced greatly by prevailing national policies, with the result that world production patterns are strongly influenced by a number of factors other than agronomic considerations. The recent interest in biofuels has affected the price of wheat, pushing prices to historic highs on global commodities markets.

10.8.2 Influences of agroclimatological variables on wheat

As with all crops, climatological factors such as temperature, precipitation, solar radiation (intensity, photoperiod and quality) and wind are important in influencing wheat production. While these and many other factors influence yield, the close association between yearly/seasonal weather and yield has often been noted. Therefore, weather (particularly temperature and precipitation) would likely be the first factor to explore in explaining differences in yields of over 100 per cent between 2004 and 2005 observed in the Republic of China and Ukraine (Table 10.8.1). As the climate continues to change in the twenty-first century, whether hotter and drier or cooler and wetter in different regions, wheat production should be impacted.

Breeding has resulted in considerable diversity of genotypes (that is, cultivars) that respond differently to the interaction of these environmental variables, and indeed, the genotype-by-environment interaction is important in selecting cultivars for specific environments. The ever-expanding genetic diversity is allowing for the expansion of wheat into new production regions. Selection of wheat cultivars, however, is still strongly influenced by the vernalization (low temperature period required to initiate flower formation) and photoperiod requirements, disease and pest resistance, and drought tolerance of the cultivar. Also, consideration of extreme environmental conditions such as late spring frosts during flower formation and hot, dry weather at anthesis and early grain growth is important. As mentioned earlier, winter wheat production may be limited by winterkill at high latitudes and spring wheat by high temperatures during the grain-filling period.

Better understanding of the variable responses of wheat to the environment is gained by considering the development and growth of the wheat plant. This is necessary because wheat has great plasticity (that is, there are many ways that final yield can be reached), and both the environment and management influence the path taken to final yield. The important yield components of wheat are number of plants per hectare and tiller number per plant (resulting in number of spikes/heads/ears per unit area), number of spikelets per spike and kernels per spikelet (resulting in number of kernels per spike), and kernel weight. In many production environments, particularly semi-arid environments, number of spikes per unit area is the most important yield component, followed by number of kernels

Table 10.8.1. The top 15 countries and selected additional countries ranked by production in 2004 and 2005 (FAO, 2007)

Country	2005				2004			
	Production 1 000 tonnes	Rank	Area Harvested 1 000 ha	Yield t/ha	Production 1 000 tonnes	Rank	Area Harvested 1 000 ha	Yield t/ha
China	97 445.25	(1)	44 793.46	2.18	91 952.24	(1)	19 005.36	4.84
India	72 000.00	(2)	26 493.06	2.72	72 060.00	(2)	26 616.63	2.71
United States	57 280.27	(3)	20 274.35	2.83	58 737.80	(3)	20 226.13	2.90
Russian Federation	47 697.52	(4)	24 619.09	1.94	45 412.71	(4)	22 804.13	1.99
France	36 840.81	(5)	5 272.50	6.99	39 692.94	(5)	5 230.87	7.59
Canada	26 775.00	(6)	9 828.05	2.72	25 860.40	(6)	9 866.73	2.62
Australia	25 090.00	(7)	12 625.50	1.99	21 905.11	(8)	13 400.18	1.63
Germany	23 692.70	(8)	3 174.02	7.46	25 427.21	(7)	3 111.50	8.17
Pakistan	21 612.30	(9)	8 357.97	2.59	19 499.80	(10)	8 216.14	2.37
Turkey	21 000.00	(10)	9 300.01	2.26	21 000.00	(9)	9 300.06	2.26
Ukraine	18 699.20	(11)	11 216.49	1.67	17 520.20	(11)	5 531.64	3.17
United Kingdom	14 877.00	(12)	1 868.90	7.96	15 473.00	(13)	1 989.87	7.78
Iran, Islamic Republic of	14 500.00	(13)	6 499.25	2.23	14 000.00	(14)	6 798.82	2.06
Argentina	12 579.15	(14)	12 854.36	0.98	15 959.58	(12)	6 069.33	2.63
Kazakhstan	11 066.00	(15)	8 324.63	1.33	9 936.93	(15)	12 388.43	0.80
Egypt	8 185.00	(17)	1 261.98	6.49	7 177.86	(19)	1 094.74	6.56
Hungary	5 088.22	(21)	1 132.24	4.49	6 006.82	(21)	1 168.66	5.14
Denmark	4 887.20	(22)	675.71	7.23	4 758.50	(26)	666.39	7.14
Czech Republic	4 145.04	(25)	820.44	5.05	5 042.52	(25)	863.14	5.84
Mexico	3 015.18	(29)	634.55	4.75	2 321.20	(34)	518.30	4.48
Saudi Arabia	2 648.47	(31)	490.07	5.40	2 775.68	(29)	524.34	5.29
Sweden	2 246.80	(34)	366.97	6.12	2 412.30	(33)	403.24	5.98
Belgium	1 768.41	(39)	213.75	8.27	1 913.18	(38)	213.04	8.98
Netherlands	1 174.69	(47)	137.00	8.57	1 223.90	(47)	137.29	8.92
Ireland	798.10	(53)	94.70	8.43	1 019.20	(49)	102.70	9.92
New Zealand	277.00	(63)	39.00	7.10	271.00	(66)	39.07	6.94

per spike, and least important is kernel size (for example, Fischer et al., 1977; McMaster, 1997; Shanahan et al., 1984). Final yield is the result of development which creates the yield potential (the number of spikes and kernels present in the plant), and the ability of the plant, interacting with the environment, to realize that potential by filling the grain (that is, the kernel size).

Many reviews of important developmental and growth processes exist (for example, Kirby and Appleyard, 1984; McMaster, 1997; Simmons, 1987) and will not be repeated in detail here. Several points merit mentioning, however. The first is that developmental events creating the yield potential occur throughout the life cycle of the plant. It begins with seed production in the previous year, where seed viability and size are important in successful seedling emergence. Tillering begins

about when the third leaf appears and continues until the growth stage of jointing (when the plant grows from the prostrate rosette form to upright form because of stem growth). Tiller abortion generally begins at jointing, and the tillers remaining at anthesis determine the number of shoots that produce spikes. Flower primordia begin to form prior to jointing, and subsequent flower differentiation and abortion continue until anthesis. Grain set at anthesis (the successful fertilization and survival of florets) determines the number of kernels per spike. After grain set, the ability of the plant to supply carbohydrates and nutrients to the grain (which is a function of both the canopy and root system) determines the final yield and quality.

The second point is that development is orderly and predictable (Hay and Kirby, 1991; McMaster, 2005; Rickman and Klepper, 1995). The genetics

determine the order and sequence of events, and the environment (primarily temperature and photoperiod) is used to predict this sequence.

The last point is characterization of the environment: plant responses to environmental factors depend on the timing, degree and history of the environmental factor being considered. For instance, gradual changes in the factors allowing acclimatization usually are not as stressful to the plant as sudden significant changes, or the timing and intensity of the stress may result in greater plant responses at certain growth stages.

10.8.2.1 Temperature

Temperature is important in all plant processes and is the dominant factor controlling wheat development (McMaster, 1997). In most discussions of temperature, the reference is to air temperature just above the canopy, with the assumption that tissue or whole plant temperature is equal, or very closely related, to air temperature. The assumption of a close relationship between air and plant/tissue temperature is normally reasonable when the plant is not under water deficits or the tissue is not below ground – the tissue meaning the roots or the crown, where the shoot apex is located until the growth stage of jointing, when the apex is elevated from the crown into the canopy and ultimately above the canopy at heading/anthesis. Recognition that the relationship is not always consistent led to interest in the 1990s and early 2000s in measuring or estimating soil temperature at the depth of the crown for use in plant-temperature response curves when the shoot apex was located in the crown. For a variety of reasons, however, it appears that using soil temperature is not necessarily more accurate than using air temperature (McMaster et al., 2003b).

Temperature response curves for various physiological processes of wheat normally follow a curvilinear pattern (for example, Cao and Moss, 1989; Friend et al., 1962; Streck et al., 2003; Yan and Hunt, 1999), with a frequent simplification of a linear segmented model approach often sufficient for many purposes (for example, Jamieson et al., 2007; Porter, 1993). Regardless of the function assumed, a minimum temperature exists (T_{base}), below which the rate of the process is zero. A linear development or process rate from T_{base} to a lower optimum temperature (T_{optl}) is often observed, and from T_{optl} to an upper optimum temperature (T_{optu}), the development or process rate is maximum and the rate declines from T_{optu} to an upper maximum temperature (T_{max} , the temperature above which the rate of the process is again assumed to be zero). While these cardinal

temperatures are difficult to determine precisely, vary among cultivars and possibly change with growth stage, generally T_{base} is about 0°C, the optimum temperature range is between 18°C and 24°C and T_{max} is above 35°C for wheat.

Regardless of the temperature response function used, temperature effects on development and many other processes are usually quantified by some measure of thermal time, which is used as an indicator of the internal biological clock. Many equations are used in calculating thermal time, which is the time integral of a temperature response function that is accumulated over time. Often it is expressed as growing degree-days and uses daily maximum and minimum air temperatures as estimates of daily mean temperature.

In most instances, the mean monthly air temperatures are gradually changing during wheat development and growth. For example, up to jointing, temperatures are normally within the optimum range of 0°C to 25°C, but temperatures for later growth stages such as anthesis and grain filling can be above the optimal range. Therefore, a lack of yield response to temperature is not observed in many of the earlier parts of the life cycle, but often is observed for later phases (for example, Johnson and Kanemasu, 1983; Warrington et al., 1977). Of particular note for yield, temperature is very important for grain set and grain filling. High temperatures decrease grain set, increase the grain-filling rate and decrease the duration of grain filling, with the usual result being lower yield under high temperatures (for example, Herzog, 1986; Wardlaw et al., 1980; Wiegand and Cuellar, 1981). High temperatures during grain filling also often have a negative effect on grain quality (Asseng et al., 2002; Martre et al., 2003, 2006).

Discussions of wheat and temperature must include two aspects of low temperatures: vernalization and freezing temperatures/frosts. Vernalization has been well documented to vary among cultivars, and as mentioned, is commonly used to distinguish among winter and spring wheat types. Generally, a linear segmented model is used for the temperature response function, where temperatures from about 4°C to 8°C are most effective for vernalizing, with linear decreases at temperatures below 4°C and above 8°C (Porter, 1993; Ritchie, 1991).

Both spring and winter wheat seedlings will withstand reasonably low temperatures without adverse effects. Frost from just prior to jointing

(when flowers are being formed) and thereafter can severely damage the reproductive organs and result in sterile florets. A late-season frost may cause kernel discoloration, hinder development and result in lower grade and quality.

Freezing temperatures during the winter period can induce winterkill as a result of mechanical injury, desiccation of the protoplasm, chemical effects or suspension of metabolism. Salmon (1917) and Fowler and Gusta (1982) showed the importance of phosphorus in improving winter hardiness. As our understanding of the mechanisms increases and predictions improve (Fowler et al., 1999), breeding efforts may result in extending the geographic region where winter wheat may be reliably grown. Whether or not low temperatures injure plants depends on a number of factors.

One of the key factors involves the site and structure of ice crystals in the cell wall. Hardy winter wheat plants contain soluble polysaccharides that hinder ice crystal formation in the cell wall and intercellular spaces. Ice crystal formation can penetrate the cytoplasm and disrupt cell structure. Cells damaged by low temperatures have a typical water-soaked appearance, because membranes have been ruptured, allowing cell contents to flow out. Such cells become dehydrated and wilt when exposed to the sun.

Moisture content is another important factor. Winter wheat seedlings can become conditioned to survive low-temperature stress conditions through an acclimatization process associated with cell differentiation. Acclimatization involves complex biochemical changes triggered by environmental signals such as low temperatures (0°C to 5°C) and shortened day lengths. The biochemistry of the plant cell is changed from promoting active growth to promoting high stress tolerance, which involves gums and resins to resist freezing damage. The potential winter hardiness of any cultivar depends on the success of these various biochemical changes or the degree of acclimatization or cell differentiation.

External moisture content is another important factor that may influence freezing susceptibility. Following a midwinter thaw, winter wheat and barley plants were more susceptible to low-temperature injury because of high moisture content in the crown (Metcalf et al., 1970).

Thawing conditions may also reduce the effect of acclimatization. Cold tolerance in winter wheat and rye was reduced an average of 5°C after two thawing and freezing cycles (Gusta and Fowler, 1977). Reductions in hardiness, however, were variable.

The rate of freezing and thawing plays a role as well. A sudden drop in temperature before acclimatization has occurred or a sudden rise in temperature of frozen tissue will have a more detrimental effect than a slow drop or rise in temperature. The shoot apex is the part of the plant most vulnerable to freezing injury. The shoot apex contains the meristematic tissue that produces new leaves, tillers and inflorescence parts. The crown, containing the shoot apex until internode elongation begins, is a diverse part of the plant, and different patterns of freezing occur simultaneously in its various tissues (Everson and Olien, 1975). A protective snow cover may prevent plant cells from experiencing rapid and wide temperature fluctuations. A light snowfall lodged in the crown of winter cereals can provide some protection against damage by low temperatures.

Another factor is the duration of freezing. The longer the tissue is exposed to sublethal temperatures, the more severe the freezing stress becomes. McKersie (1981) reported that at -12°C the ability of plants to survive began to decline after 12 hours, and at -16°C after only one hour.

10.8.2.2 Precipitation

Successful cultivation of wheat involves the interplay of stored soil water and precipitation. Stored soil water at planting will be a function of prior precipitation, pre-plant tillage and residue cover management, and prior land use (namely, whether the tract was fallow, what the previous crop was, when it was harvested, and so on). Wheat is normally grown where annual precipitation averages 25 to 175 cm, but about three-quarters of the land area in wheat averages from 38 to 88 cm, and often wheat is grown in semi-arid regions with highly variable precipitation (both among and within years) and where water deficits are common.

Because yield components are developing and growing over the entire life cycle of the plant, water deficits at any time will likely reduce final yield. Obviously, a critical period of undesirable water stress is seed germination and emergence. If soil moisture in the seedbed zone is below optimal, germination and seedling emergence rates will be reduced, leading to slower and delayed emergence, which has many negative ramifications for the remainder of the growing season and final yield (McMaster et al., 2002).

The period from anthesis to maturity (and therefore grain-filling duration) is also critical in wheat yield and quality. Water deficits (particularly if coupled

with high temperatures) cause significant deterioration in pollen viability and grain set (that is, fertilization). Water deficits during grain filling not only reduce carbon assimilation rates, but increase canopy temperature via reduced transpiration rates (see temperature effects above) and canopy senescence via accelerated leaf senescence. The result is a significantly lowered yield under water deficit conditions. Even irrigation or high rainfall during this period can be insufficient to completely meet the plant demands for water. The importance of the grain-filling period in yield has resulted in extensive breeding efforts to select for drought tolerance and selection of cultivars with the ability to store and retranslocate stem reserves prior to anthesis as a means of counteracting reduced assimilation rates during grain filling (Blum et al., 1994; Haley and Quick, 1993; Nicolas and Turner, 1993).

The effects of water deficits on wheat phenology are fairly clear now (McMaster and Wilhelm, 2003; McMaster et al., 2005). Generally, water deficits must be moderately severe to result in a significant change in wheat phenology for early growth stages up through about flag leaf appearance. For later growth stages such as heading, anthesis and physiological maturity, however, water deficits will result in earlier occurrence of these stages by as much as 16 days.

Wheat yield can be affected not only by water deficits, but also high rainfall conditions, especially if accompanied by moderate-to-high temperatures. Some reasons for this are that high rainfall intensifies disease and insect attacks, causes harvesting difficulties, induces undesirable seed sprouting in the field and is usually associated with a lower protein content and reduced bread-making quality. For soft wheat production, adequate rainfall during growth and development promotes high yield and low protein, with the latter considered a desirable factor for pastry production.

10.8.2.3 Photoperiodism and solar radiation

Three aspects of solar radiation are important for plant processes: intensity, duration (photoperiod or day length) and quality. Intensity is most involved in influencing growth by altering the size of organs, as a result of its effect on photosynthesis. Photo-synthesis is responsive to photosynthetically active radiation (PAR) ranging from about 380 to 680 nm, with the most effective wavelengths being in the blue (around 400 nm) and red (around 640 nm) ranges. Numerous shading studies (for example, Fischer and Stockman, 1980; Kemp and Whingwiri, 1980; McMaster et al., 1987) have demonstrated the positive relationship between

radiation and yield. Both photoperiod and quality are primarily involved in developmental events such as leaf appearance rates (for example, Baker et al., 1980) and phenology (for example, Nuttonson, 1948), although the duration of day length is positively related to the amount of daily radiation that can be important in total assimilation. Light quality in the red and far-red spectrum and photoperiod are particularly important in the phytochrome system. Photoperiod is primarily influential in controlling the phenological stages of flower formation (signalling the switch at the shoot apex from producing primarily vegetative primordia to reproductive primordia) and the timing of flag leaf appearance.

10.8.2.4 Wind

Wind has many impacts on wheat production. It influences the energy balance of the canopy and soil surface, altering both evaporation and transpiration, so that it influences water and temperature conditions of the plant (Grant et al., 1995; McMaster et al., 2000). As mentioned previously, wind can significantly reduce grain set, and therefore yield, if hot and dry winds occur during the period of pollination. This is a common problem in many semi-arid wheat production regions.

Wind can also result in harvest losses due to lodging (stems falling over due to wind). This problem is most common for standard tall cultivars grown under high nitrogen conditions, as the stems tend to grow tall and are more easily knocked down by wind or other disturbances. For this reason, cultivars with semi-dwarfing genes are commonly used because of the reduced stem height under high nitrogen conditions and the reduction in lodging potential.

10.8.3 Management aspects of wheat production in various climates

10.8.3.1 Planting date, seeding rate and plant density

A positive relationship between spike density and yield is often found up to fairly high densities with a slight negative relationship at very high densities (for example, Briggs and Aytenfisu, 1979; Ciha, 1983; Darwinkel, 1978, 1980; Holliday, 1960; Laloux et al., 1980; Shanahan et al., 1984). Spike density is a function of planting rate, seedling emergence and tillers that produce spikes; in addition, all of the environmental factors discussed above influence these processes. Planting date also influences seedling emergence and tillering in several ways, however. As planting date is delayed in the fall, temperatures are

usually lower, which delays seedling emergence. Delayed emergence further slows canopy development as fewer leaves are produced in the fall. Since the appearance of tillers is related to the appearance of main stem leaves, delaying leaf appearance results in delayed appearance of fall tillers (Klepper et al., 1982, 1984). Delaying tiller appearance decreases the likelihood that tillers will survive to produce a spike, with tillers appearing in the spring more likely than fall-appearing tillers to abort before producing a spike. In general, if a tiller can survive to anthesis, it will produce a spike with reasonable yield (McMaster et al., 1994; Power and Alessi, 1978). Other factors influencing tiller appearance and survival include plant density, environmental conditions and cultivar differences. As a result, the management of final spike number must account for the complex interplay of planting rate and date, seedling emergence, environmental conditions, time of tiller appearance, and survival of tillers to produce a spike. As planting date is delayed, generally planting rates should increase to offset the fact that fewer tillers will appear and survive to produce a spike.

The preceding discussion gives some qualitative guidelines for seeding rate. Fortunately, seeding rates can vary greatly without modifying final grain yield, and it is often best to plant at higher rates given that seed cost is relatively minimal when compared to reducing the risk of having too few plants.

10.8.3.2 Soil fertilization and plant nutrition

Nitrogen, phosphorus, potassium and a variety of micronutrients are essential in wheat production. Interaction of these nutrients with the climate, soil and management (previous crops, tillage, residue cover, fertilizer, and the like) determine the availability of nutrients needed for development and growth. Soil pH is important in determining the availability of nutrients to the plant. Numerous studies have shown that growth and yield increase with fertilizer application up to some level and then generally, fertilization has no further positive influence; at very high levels of application, yield reductions can occur (for a review, see Halvorson et al., 1987). While it is difficult to over-fertilize the wheat plant from the perspective of reducing growth and yield, doing so has many negative environmental and economic implications. This has spurred a great deal of research on how (and when) to apply the optimal amount of fertilizer for the specific production environment (for example, Fischer et al., 1977). Under more uniform conditions of irrigation or high rainfall evenly spread out throughout the growing season, fertilizer recommendations are more easily made, whereas in

rainfed semi-arid production regions with highly variable precipitation, a priori estimates of optimal rates are very difficult to put forward. This has promoted the concept of split fertilizer applications, where a portion is added at planting and a later application at about the jointing growth stage is “matched” to the weather to date and best guess (usually the average) for the remainder of the growing season, to meet a yield goal. Split applications reduce the likelihood of over-application of fertilizer at planting, thereby saving on fertilizer expenses and reducing the negative environmental impacts of excessive nutrient application. For winter wheat, applying nitrogen in early spring can stimulate leaf, tiller and root growth, but excessive nitrogen can result in abundant vegetative growth, increased incidence of disease and crop lodging.

10.8.3.3 Tillage and residue cover management

Tillage practices and the resulting impacts on residue cover have a great influence on the micro-environment of the wheat plant; they are increasingly being considered as an integral component of soil and water conservation practices in semi-arid wheat production systems (for example, Black and Unger, 1987; Farahani et al., 1998a, 1998b; McMaster and Wilhelm, 1997; McMaster et al., 2000, 2002; Van Doren and Allmaras, 1978). Pre-plant tillage practices usually result in increased convective exchange of water vapour at the soil-atmosphere interface, thereby reducing soil water in the seedbed zone and germination rates in semi-arid regions. Loss of standing residue cover by mechanical damage or burying of residue by tillage practices continues to affect the soil surface boundary layer for quite some time following seedling emergence. This will increase convective soil evaporative losses, creating water deficits that severely reduce yields and exposing the soil to water and wind erosion. Residue cover also influences soil temperature and albedo, further influencing both root and canopy development and growth processes. Lastly, residue cover in no-till systems increases snow catch, which both adds soil moisture available to the growing crop and reduces winterkill.

10.8.3.4 Cropping systems

Cropping systems are increasingly being integrated with changes in tillage practices, particularly in semi-arid production regions. There are many reasons for a shift from the more traditional wheat-fallow system used in many regions. Of primary importance are the impacts of creating greater

biodiversity in agricultural systems, with the benefits of better weed, disease and pest control and optimal use of available water in the system. These, and other benefits, typically result in greater sustainability of wheat-based cropping systems and higher economic returns to farmers (Halvorson et al., 1994; Nielsen et al., 2002; Peterson et al., 1993).

10.8.3.5 Weed, disease and pest management

Wheat production systems must deal with a variety of biotic factors that influence final yield. Weeds, diseases and various pests are common issues limiting wheat production. A complex interaction exists among the occurrence and degree of biotic factors and the weather (for instance, temperature, precipitation and solar radiation), soils and management practices (for example, tillage and residue cover, cropping systems selected, fertilizer and irrigation applications). The relative importance of weeds, diseases and pests can vary significantly within and among years and locations. For instance, Russian wheat aphid (*Diuraphis noxia*) infestations are highly variable in the Central Great Plains of the United States depending on the temperature during the winter period, with colder winters reducing the infestation level. Weed infestations vary greatly based on the tillage and chemical control practices, amount and timing of precipitation, and previous crops used in rotation (Canner et al., 2002). Often high wheat production regions such as the Pacific Northwest of the United States have much more disease problems under no- or low-tillage practices than the semi-arid regions of the Central Great Plains.

Changing climates in the future will likely significantly influence weed, disease and pest pressures on wheat production. As temperature and precipitation change, pest populations will respond accordingly. A striking example of this is the introduction of the Russian wheat aphid into the United States in 1986. It was thought that winter temperatures in the Central Great Plains were too low for the Russian wheat aphid to survive. As winter temperatures in the Central Great Plains have been warmer than normal since its introduction into the United States, however, then Russian wheat aphid has often reduced yields quite substantially in recent years. The continued warming that is predicted for this region will likely exacerbate the problem and the same is true for many other weed, disease and pest problems.

10.8.4 User requirements for agrometeorological information

There are increasing demands for timely and effective agrometeorological information for on-farm

applications. Decision-makers are interested in monitoring the agricultural season to assist the farming community during adverse years, to manage risk and to provide agroclimatological information for agricultural planning. Providing agroclimatological information entails the conversion of meteorological data associated with crop yields, presentation of weather data in formats suitable for agricultural decision-making and insulation of marginal farmers with smallholdings from the adverse impact of the vagaries of weather. Meteorological data are also necessary in the development and adoption of digital technology, such as simulation models, decision support systems and commodity forecasting. These digital technologies are rapidly emerging for use by scientists, producers, agricultural consultants, agribusiness and policymakers, and rely on accurate and readily available agrometeorological data. The need for agrometeorological data will further increase with expected climate shifts.

A holocoenotic approach to agrometeorological data on a global basis would provide many benefits. Schwabe and Kellogg (1982) discuss how this would aid in rapidly and reliably assessing global crop yields to match areas with surplus production to areas of demand, as well as in monitoring production patterns that accompany climatic shifts. Another benefit would be to improve the judicious application of expensive inputs (such as fertilizers, irrigation and pesticide application) in terms of amount and timing.

10.8.4.1 Use of agrometeorological data in simulation models and decision support systems

Early success in crop forecasting as noted by Bauer (1979) has spurred research in the area of crop simulation modelling and decision support systems. A brief overview of some of these efforts is provided here, as these digital technologies provide an important user demand for agrometeorological data.

Early modelling efforts were commonly based on regression, or statistical, approaches, but beginning in the mid-1970s more mechanistic, or process-based, simulation models began to appear. To date, more wheat simulation models exist than for any other crop (McMaster, 1993). Regardless of the type of model, all normally require at least daily maximum and minimum temperature and precipitation, and many require daily solar radiation and wind run data as inputs. A precursor to crop simulation models was the daily canopy photosynthesis model of de Wit (1965) that was

used at least in concept in many initial simulation models (and in most even today). These models tend to be carbon- or energy-driven models that use canopy leaf area index to absorb solar radiation to produce carbon, which is then distributed to different plant components such as leaf, stem, root and seed tissue. Examples of these models include SUCROS (and earlier models of ELCROS and BACROS) (van Keulen et al., 1982), CSM-Cropsim-CERES-Wheat (Hoogenboom et al., 2004; Hunt and Pararajasingham, 1995; Jones et al., 2003; Ritchie, 1991) and Sirius (Jamieson et al., 1998*a*, 1998*b*). Beginning in the 1980s, an alternative approach towards more development-driven models was taken, leading to the creation of such models as ARCWHEAT1/AFRCWHEAT2 (Porter, 1984, 1993; Weir et al., 1984), SHOOTGRO (McMaster et al., 1991, 1992*a*, 1992*b*; Wilhelm et al., 1993; Zalud et al., 2003) and MODWht3 (Rickman et al., 1996). Often a simulation model is incorporated into decision support systems. Two examples with extensive adoption include the Australian APSIM DSS (Asseng et al., 2002) and the United States GPFARM DSS (Ascough et al., 2007; McMaster et al., 2003*a*; Shaffer et al., 2004).

10.8.5 **Examples of agrometeorological services relating to wheat**

The technology for a holocoenotic approach to global crop-climate relationships has been aided by satellite monitoring and weather collection networks. Satellite technology allows for remote-sensing of the reflected solar radiation to estimate the areas planted with specific crops and it also provides for the collection of some climatological data (Idso et al., 1977). When combined with local weather network data, this technology offers a powerful database with great potential.

One early illustration of how this functions is provided by work in the United States. Based on 8 100 surface weather observations, as well as information from satellites, United States scientists are able to compare deviations in current

weather variables from the expected or long-term average (Richter, 1982). Survey data determine whether rainfall is lighter or heavier than normal; how soil moisture levels compare to those of previous years; thermal time accumulated; and if weather occurrences in general are normal or represent departures from the expected for a given area. The area planted to a specific crop, the disease situation, the level of technology and general agronomic practices can be used for yield determination and global crop estimates using various digital technology tools and other forecasting techniques. The success of this approach rests not only on weather information, but on the assembling of high-quality, historical databases for all the major regions of the world. Early efforts to use agrometeorological data in global crop forecasting showed great promise. For example, production estimates were within 10 percent of the measured estimates 90 percent of the time, and this level of accuracy was achieved 1.5 to 2 months before harvest (Bauer, 1979).

Since these early efforts, much agrometeorological information is now readily available, particularly in the Western world, via weather networks, databases and reported statistics. Indeed, there is a danger of an information overload. Agrometeorological information is available from governments, businesses and the scientific community, and ranges from local to global scales. Global climate change models have projected climate change for many regions across the globe. One caution to note regarding this information is that quality assurance and completeness are not always guaranteed. It is certain that many weather networks and databases have missing data and occasionally the methods for estimating missing data are questionable. Other chapters in this Guide provide excellent guidelines dealing with the collection of agrometeorological information and its presentation to users. They also show that in developing countries, much still remains to be done in the area of services to end-users.

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CHAPTER 11

APPLICATIONS OF METEOROLOGY FOR FORESTRY AND NON-FOREST TREES

11.1 INTRODUCTION

Every stage in the development, growth and harvesting of forest and also non-forest trees is in a large measure controlled by weather and climate. The establishment of a new forest, whether by seeding and planting or by natural means, depends on the proper sequence of weather events as they interact with soil conditions, on the one hand, and the plant material (seed, young seedlings), on the other. As the young forest grows, the incidence of plant diseases, the development of insects and other pests, and the occurrence of destructive forest fires all depend on weather and climate. Added to this is the fact that when the trees are finally harvested, rain and/or snow may affect the efficiency – or indeed even the possibility – of cutting and removing the crop trees. Non-forest trees typically receive more attention and therefore the knowledge of weather may have even more impact on crop operations. Real-time weather data may be input to expert systems, management models or simple applications to support the decisions of the forester or grower. Climate data are widely used to assess probability and risk of extreme events and to compute statistics of the relevant weather events.

While in some situations foresters and growers may utilize data from their National Meteorological Services, in others they may have to rely on their own observations and knowledge of weather and climate. In many cases, weather data collected for agricultural purposes may be used by the forester or grower; in other situations, specialized observations are necessary. Specialized observations are usually needed for pest management, local frost forecasts and fire danger rating systems. In the following sections, most of the issues mentioned that are relevant to forestry and non-forest trees are discussed in some detail. Climate variability and change are also very important for forestry and non-forest tree sustainability. In some regions, some crops may have too much damage too often, or may become unavailable under climate change conditions. Information on these and other topics in forest meteorology is contained in a number of WMO publications (WMO, 1978*a*, 1988, 1994*a*, 2000).

11.2 CLIMATE AND WEATHER ANALYSIS FOR FORESTRY AND NON-FOREST TREE OPERATIONS

11.2.1 Tree response to meteorological elements

11.2.1.1 Temperature

Together with light, water and nutrients, temperature is a key environmental factor controlling plant function. Temperature is a measure of the concentration of heat energy within a medium, such as air, water or soil. It thus affects physical characteristics of these media, including atmospheric humidity, the viscosity of liquid water (as well as freezing and thawing) in soils, and molecular and turbulent exchanges of heat, water vapour and CO₂ (from the scales of individual leaves up to entire regions). Changes in environmental temperature manifest themselves primarily through changes in air temperature, driven by seasonal and diurnal variations in incident solar radiation, coupled with downwelling long-wave radiation from the atmosphere and clouds, which drive surface heating of vegetation and soils. Some of the heat arriving at the surface is transmitted downwards into the soil, contributing to soil warming. Heat loss occurs through convective exchange of sensible and latent heat, coupled with long-wave reradiation from all natural surfaces. The temperatures of plant tissues and organs are thus intimately coupled to changes in environmental temperature, both reacting to changes and contributing to them. For more detailed explanations of these processes, see standard texts such as Monteith and Unsworth (1990), Jones (1992) and Campbell and Norman (1998).

Temperature is the major environmental factor affecting the activity of enzymes (such as ribulose diphosphate carboxylase, which is responsible for CO₂ fixation). It therefore strongly influences the rates of all biochemical reactions that occur in plant cells, including those involved in the complex pathways of cellular respiration (both for maintenance and for growth) in the mitochondria, and photosynthesis and photorespiration in chloroplasts. These processes are directly linked to stomatal functioning and root activity and hence to controls of the movement of water and photosynthate

through and within the plant. Temperature also strongly influences rates of cell division (both mitotic at apical and cambial meristems and meiotic in the formation of pollen and ovules) (see Salisbury and Ross (1992) for more detailed explanations). Some of these effects contribute to “macroscale” phenological responses, such as the timing of cambial activity (namely, the onset of growth), leaf emergence, flowering, seed production and dispersal. Many of these have been shown to require species-specific critical “heat sums”, generally computed as integrals of daily mean temperatures above a threshold value from the beginning of the growing season. These processes then influence competition among and within species, survival and growth.

Extreme temperatures (see also 11.2.3.2) can cause denaturing of enzymes and hence contribute to cellular and tissue damage and in some cases mortality of the entire plant. The definition of an extreme temperature in this context is difficult because most plant species are able to tolerate a range of temperatures, which tends to vary with latitude and elevation. Most vascular plants will die when exposed to temperatures above 45°C, though some can survive appreciably higher temperatures. Many tree seeds can tolerate substantially higher temperatures for brief periods, notably those of fire-adapted species that produce serotinous structures. Extreme low temperatures pose other risks. In regions with strong seasonal variations in temperature, native species will typically exhibit some form of seasonal acclimation, to avoid tissue damage due to cellular freezing during winter. In cold climates, many species can avoid freezing down to -40°C by super-cooling internal water. In extremely cold regions, such as the boreal zone, native tree species are able to withstand much lower temperatures due to mechanisms of extracellular frost tolerance (FAO, 2005).

11.2.1.2 Radiation

Solar radiation has great importance in the establishment and growth of forest and non-forest trees. Radiation is captured by canopies and its energy is used to convert carbon dioxide into sugar-like structures in a process called photosynthesis. Radiation may also induce movement or govern some formative processes. Photosynthesis requires higher radiation intensity than photo-stimulus processes, but both are of major importance for plant growth and development. Formative processes are often determined by the relative lengths of light and dark periods to which plants are exposed, a phenomenon known as photoperiodism, whose

importance to forest and non-forest trees will be discussed in 11.2.1.5.

Global radiation is composed of direct and diffuse radiation, and has wavelengths between 0.3 μm and 3.0 μm . It is determined by the amount of radiation that reaches the top of the atmosphere, which depends on latitude and day of the year, cloudiness, cloud type and atmospheric turbidity. Estimates of global radiation and thus of visible radiation are possible using appropriate models (Linacre, 1992).

The region of the solar spectrum that is more important to photosynthesis is the visible band, also known as photosynthetically active radiation (PAR), which consists of wavelengths between approximately 0.4 μm and 0.7 μm . The photons in the visible light are all absorbed by the photosynthetic system, but photons in the yellow and green bands have lower absorptivities.

Solar spectrum varies with solar altitude, atmospheric turbidity and cloudiness. The fraction of visible radiation in direct radiation, in terms of energy, for a solar altitude between 30° and 50° is about 0.5 for clean air and 0.4 for very turbid air. The fraction of visible radiation in global radiation is close to 0.5 under clear sky conditions. This ratio increases with cloudiness, especially in the tropics, where it may reach 0.63 under very cloudy skies (Monteith and Unsworth, 1990).

The fraction of the global radiation that reaches the canopy level is reflected by the canopy and soil and is often termed albedo. Typical values for forests and orchards range from 12 to 18 per cent (Monteith and Unsworth, 1990). Another fraction of the radiation is absorbed by the canopy elements, and the remaining fraction is transmitted through the canopy and absorbed by the soil and transformed into heat. Often it is useful to consider another fraction, f , which is the fraction intercepted by the canopy ($f = 1 - \text{fraction transmitted}$). All these fractions may be computed using simple models that are presented in most textbooks of environmental physics (for example, Monteith and Unsworth, 1990; Campbell and Norman, 1998).

Once global radiation (or visible radiation) is known, the computation of the radiation capture by trees may be achieved using models of different complexity (Ross, 1981; Monteith and Unsworth, 1990; Campbell and Norman, 1998). The most complex models of light interception in forests account for the distribution of phytoelements in the canopy and their optical properties. Orchard interception of radiation, due to the regular

distribution of the trees and similar size and form, allows some simplifications to be introduced, namely the definition of envelopes of known geometry where phytoelements are distributed and radiation extinction takes place (Charles Edwards and Thorpe, 1976; Norman and Welles, 1983; Oker Blom et al., 1991; Mariscal et al., 2000, 2004). Many operational models, however, use simpler approaches that lack the generality of more sophisticated models, but are easier to understand, construct, parameterize and use (see 11.4.1 and 11.4.2).

Monteith (1977) observed that, for a number of crops including fruit trees, when biomass accumulation was plotted as a function of intercepted radiation, an almost straight line would result. Therefore, he suggested that biomass accumulation could be modelled as

$$\sum B = e f \sum S_i \quad (11.1)$$

where $\sum B$ is the accumulated biomass, $\sum S_i$ is the sum of daily total solar radiation, e is the radiation use efficiency for the crop and f is the fraction of incident radiation intercepted by the canopy.

In the absence of stress, e is often conservative, typically ranging between 1.0 and 1.5 g MJ⁻¹ for C₃ species in temperate environments, 1.5 to 1.7 g MJ⁻¹ for tropical C₃ species and up to 2.5 g MJ⁻¹ for tropical C₄ cereals under favourable conditions. Oil palm, rubber, cocoa and coconut achieve a maximum of 0.9 g MJ⁻¹ (Squire, 1990). Gower et al. (1999) report radiation use efficiencies of forests in boreal, temperate and tropical environments.

Lopez (1989) gives an example of a simple light distribution profile in a forest consisting of four layers. In the first layer the canopy receives all the incident radiation, of which 60 to 90 per cent is absorbed. The absorbed fraction depends on many factors, including leaf development. In the second layer, the canopy receives approximately 25 per cent of incident light in the forest. The third layer consists of trees of smaller height. The intensity of the light decreases to 3 per cent of incident light. In this layer, strong competition for light occurs. The fourth layer is next to the forest floor. The intensity of light is often less than 1 per cent and owing to this limited illumination, there are few leaves and flowers and many sprouts.

The radiation requirement of species varies widely. Some typical forest trees, such as birch, larch and pine, have high requirements, while beech and spruce are examples of forest trees with

low radiation requirements. Knowledge of the relative light requirement in forest tree species is important in forest management. For example, shade-tolerant species need shade in order to thrive, while species with high radiation requirements need high levels of radiation, because these plants frequently grow in full sunlight in their original habitat. The light regime in forests may be controlled by selective cutting in order to increase the penetration of light and facilitate reproduction.

Radiation affects the growth and production of trees and radiation also has a deleterious effect on many microorganisms that are plant pathogens. Fire danger indices often incorporate net radiation since radiation energy dries the fuel, which increases the probability of ignition and the acceleration of the rate of spread and intensity of a fire (see 11.5).

11.2.1.3 Humidity and precipitation

Rain is the most common form of precipitation in forests, but other forms of precipitation, such as snow, fog and hail, can also be significant. Indeed, extra inputs of moisture stripped from fog by trees (especially conifers) may be considerable (Bruijnzeel, 2001). Rain, snow and fog also supply a certain quantity of nutrient elements to forests and act as a means of transporting nutrients trapped on foliage to soil. Generally, the quantity of phosphorous transported by precipitation is small, but inputs of potassium, calcium and nitrogen may not be insignificant compared to nutrient cycling by forest stands (Miller, 1983). Precipitation may also carry significant amounts of atmospheric pollutants, with potentially destructive effects on commercial forestry (such as acid rain). Atmospheric humidity is also an important factor in the hydrology of forests and growth of trees. As with precipitation, the amount and distribution of atmospheric water vapour content is variable over space and through time. This variability is normally related to meteorological conditions, season of year and topography, and in some local circumstances it may even be related to the presence and structure of forests. Not only is atmospheric moisture a basic element in hydrological processes and the biosphere, but it also has other roles that affect forests. Moisture in the air helps moderate temperature extremes because it absorbs or reflects about half of the incoming short-wave radiation during the day and helps trap outgoing long-wave radiation during the night and day. Atmospheric moisture also influences transpiration rates from leaf stomata,

thereby affecting soil water storage and hence, the water status of trees.

11.2.1.3.1 *Humidity*

Atmospheric humidity can be generally described as the content of water vapour in the atmosphere at a given pressure and temperature, and can be expressed, for example, as relative or absolute humidity. As air becomes warmer, the capacity of the atmosphere to hold water vapour increases and vice versa, as air cools the capacity of air to hold water vapour decreases and cloud droplets may grow and coalesce to fall as rain. Atmospheric humidity is critical to determining the adaptation and productivity of trees in water-limited areas through application of the water use efficiency ratio (WUE), which describes the ratio of carbon assimilation to transpiration. Humidity levels and relative evapotranspiration affect the water and nutrient status of developing trees. Stomatal conductance of water vapour, especially in C_3 plants, which include virtually all woody plants, decreases as the vapour pressure deficit close to leaf surfaces increases and, hence, humidity also decreases. Experimental studies indicate that WUE per unit of biomass may increase substantially with changes in atmospheric CO_2 concentrations and temperature, implying a reduction in transpiration (Morison, 1987). Therefore, it is important either under present climate conditions or future global climate change in determining the WUE of the forest stand in the field based on stomatal response to air humidity and CO_2 concentrations, for detection of changes in forests' water use per unit of land.

The influence of atmospheric humidity, expressed as relative humidity (being the ratio of the mass of water vapour in a given volume of air to the mass of saturation water vapour in the same volume, expressed as a percentage), on fuel moisture content of trees under dry conditions is an important factor in determining such things as the rate of spread of forest fires (Byram, 1957). The effect of relative humidity includes the fuel combustion rate, rate of spread of the flame front, smoke production and the rise of smoke plumes in the atmosphere, and the increase or decrease in probability of ignition from spotting and hence, the acceleration of rate of spread and intensity of a fire.

11.2.1.3.2 *Precipitation*

Forestry–precipitation interactions change throughout the course of a forest plantation's life cycle, and this is especially true of the partitioning of available precipitation through stages of canopy

development in a forest ecosystem. Changes to coniferous upland forest plantations begin with transformation of land as a result of rough grazing, followed by drainage, planting and subsequent forest development, and then canopy closure and clear-felling. These variations in forest stands produce significant changes in the water and nutrient status of growing trees, the hydrological balance and hydrochemical function of the catchment. Several useful long-term case studies from both a hydrological and biological/ecological perspective have been established. These include Coalburn (for example, Robinson et al., 1998) and Plynlimon (for example, Neal, 1997) in the United Kingdom and the Hubbard Brook experimental catchment (for example, Likens and Bormann, 1995) in the United States.

The operations of non-forestry agriculture, such as tree nurseries and orchards, in many respects are similar to the production of any other agricultural crop. Many of the principles applicable to intensively cultivated garden crops also apply to production of non-forest trees. Forecasts and information on precipitation amounts, intensity and duration allow management of water resources under circumstances in which nurseries require irrigation or drainage installation for optimum development of seedlings or fruit. For example, water stress on trees will affect both the growth and quality of the final product during drought periods, and waterlogged ground is potentially destructive to sensitive tree species.

Changes in climate may significantly affect the development and management of forests by altering tree physiology and tree development. Current weather indicators based on the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (IPCC, 2001a) for changes in twentieth-century climate suggest that increases in precipitation of between 5 and 10 per cent in the northern hemisphere will be very likely, although some regions will experience decreases in precipitation (for instance, parts of the Mediterranean). An increase in heavy precipitation events is also expected to be likely at mid- and high northern latitudes. Biological consequences reported by IPCC (IPCC, 2001b) that affect forestry include: observed lengthening of the growing season in the northern hemisphere by 1–4 days per decade during the last 40 years; the poleward shift of plant ranges and also plant ranges extending to higher elevations; and the observation in the northern hemisphere of earlier plant flowering. Therefore, changes in precipitation coupled with temperature changes may have important

implications for forest management in the commercial sector, such as the species and provenance of trees used in forestry and the non-forest tree sector.

11.2.1.4 Wind

Over the last 50 years or so, much work has been devoted to understanding the effects of wind on trees in forests and, to a lesser extent, in non-forest situations. Interesting examples may be found in Ruck et al. (2003). Another good up-to-date source is Coutts and Grace (2005), a collection of research papers covering the physics of airflows over forested terrain, the mechanical and physiological effects of wind on trees, and the nature and extent, and management implications, of damage caused by storms. A collection of papers in Part II of Hutchison and Hicks (1985), though somewhat dated, provides a good basis for current research on the aerodynamics of forest canopies. Although new computational fluid dynamics approaches are available (for example, Wang and Tackle, 1997; Wilson and Flesch, 1999), Wisse and Stigter (2007) note a lack of knowledge in developing regions of the aerodynamic properties of local biological shelter (see also Stigter et al., 2005). The unfortunate reality is that data on wind effects in hot climates are generally sparse (Wisse and Stigter, 2007; but see Biona et al., 2001).

11.2.1.4.1 Role of wind in forested ecosystems

Wind couples vegetation to the atmosphere, mixing air from above the turbulent boundary layer with that close to the leaves and stems. In the process, it transfers momentum energy into the canopy, while reducing concentration gradients of atmospheric constituents, including oxygen and CO₂, water vapour and heat, between vegetation surfaces and the atmosphere. These functions are crucial to the maintenance of plant growth and survival. It has been said that without turbulence, life on Earth would be impossible, because all organisms would suffocate in their own CO₂.

The effects of wind on trees can be grouped as ecophysiological (for example, supply and removal of CO₂ and oxygen for photosynthesis and respiration; losses of water vapour in transpiration) and physical (for example, exchanges of kinetic, sensible and latent heat energy). The average thickness of the laminar boundary layers surrounding leaves and other objects increases with their size, but is inversely related to wind speed (for instance, Campbell and Norman, 1998). The laminar boundary layer presents a resistance to exchanges of mass

and energy in series with the stomatal and mesophyll terms. It follows that wind has relatively little impact on heat and mass exchanges of small leaves (which always have a thin boundary layer), and the greatest effects will be for large leaves at low wind speed (for instance, Grace, 1977). Increases in wind speed may increase or decrease transpiration rates at both the leaf and canopy scales, depending on the relative changes in the leaf-air differentials of temperature and humidity (for instance, Chang, 1974; Monteith and Unsworth, 1990; see also discussion of the Penman-Monteith equation in 11.4.1.2). Wind-tunnel studies by Aubrun et al. (2005) have demonstrated the important role of wind in canopy-atmosphere exchanges of biogenic trace gases (volatile organic compounds).

In addition, mechanical stresses on leaves, flowers and stems cause bending and leaf-fluttering, and may lead to tissue damage (hence stimulating growth of callus and “reaction wood”, such as stem buttresses). Mechanical stresses also contribute to the shedding of dead material (for example, Staelens et al., 2003) and the dispersal of pollen and seeds (for example, Greene and Johnson, 1989) and of pests and pathogens. Strong winds, possibly in combination with snow and ice accumulation, often cause physical breakage of tree stems and branches, while frequent winds in a prevailing direction (such as in some coastal regions, or on hill slopes) can cause stunted or deformed growth (Chang, 1974; Pereira et al., 2002).

Cordero (1999), for example, studied wind effects on development of potted *Cecropia schreberiana* saplings at high elevations in Puerto Rico. He found numerous morphological and physiological adaptations to cope with higher wind loading, including: increased root/shoot ratio, leaf abrasion and epinasty, and reduced leaf area and height (namely, lower stem height to diameter ratio, particularly in windward trees). Wind decreased photosynthesis and respiration per unit leaf area (but not per unit mass), resulting from a higher light compensation point and lower quantum yields, as well as reduced nitrogen use efficiency (in spite of higher leaf N). Wind-exposed stems were of lower density and more flexible, with higher water contents. Puigdefabregas et al. (1999) noted banding structures in primeval *Nothofagus betuloides* forest on Tierra del Fuego (perpendicular to the prevailing wind direction). Trees on exposed windward edges of these bands were typically decadent and dying, with basal area and mean tree size reduced by up to 50 per cent (compared with sheltered locations), while seedlings were found mainly at the leeward edges. The banding patterns

evidently result as trees become more vulnerable to wind damage with age and lose protection from older windward trees.

In many regions, wind is a natural disturbance agent contributing to changes in structure of natural and managed forests (for example, Dyer and Baird, 1997; Grove et al., 2000; Peterson, 2000; Proctor et al., 2001; Scheller and Mladenoff, 2005; Nagel and Diaci, 2006). Some studies, however, indicate that the impacts of storm damage on natural vegetation succession are often benign (for example, Castelli et al., 1999; Cooper-Ellis et al., 1999; Peterson, 2000). In Melbourne, Australia, Harper et al. (2005) found that high wind exposure in remnant *Eucalyptus* forests increases the likelihood of hollows occurring in live trees, providing critical habitat for small mammals and birds, notably in suburban locations.

Wind is also a major factor influencing the establishment and spread of forest fires (for example, Taylor et al., 2004; Wisse and Stigter, 2007; see also 11.5). Areas previously burned by severe fires can also suffer accelerated wind erosion, resulting in soil loss and air quality problems (for example, Whicker et al., 2006).

11.2.1.4.2 Wind profiles in forest canopies

The wind speed (u) observed above a plant canopy is a function of synoptic processes moderated by local topography and the proximity to coasts (of oceans or large lakes). Under thermally neutral atmospheric conditions, mean velocity increases logarithmically with height for several metres above the surface (bare soil or vegetation), following the wind profile equation (for example, Monteith and Unsworth, 1990):

$$u(z) = \frac{u_*}{k} \ln \frac{z-d}{z_0} \quad [\text{m s}^{-1}] \quad \text{with} \quad z \geq z_0 + d \quad (11.2)$$

where

u_* = friction velocity (m s^{-1})

z = height of wind measurement (m)

d = zero plane displacement height (m)

k = von Karman constant (0.41) (dimensionless)

z_0 = roughness length (for momentum) (m).

In Figure 11.1, the horizontal axis expresses wind speed relative to that at the top of the canopy

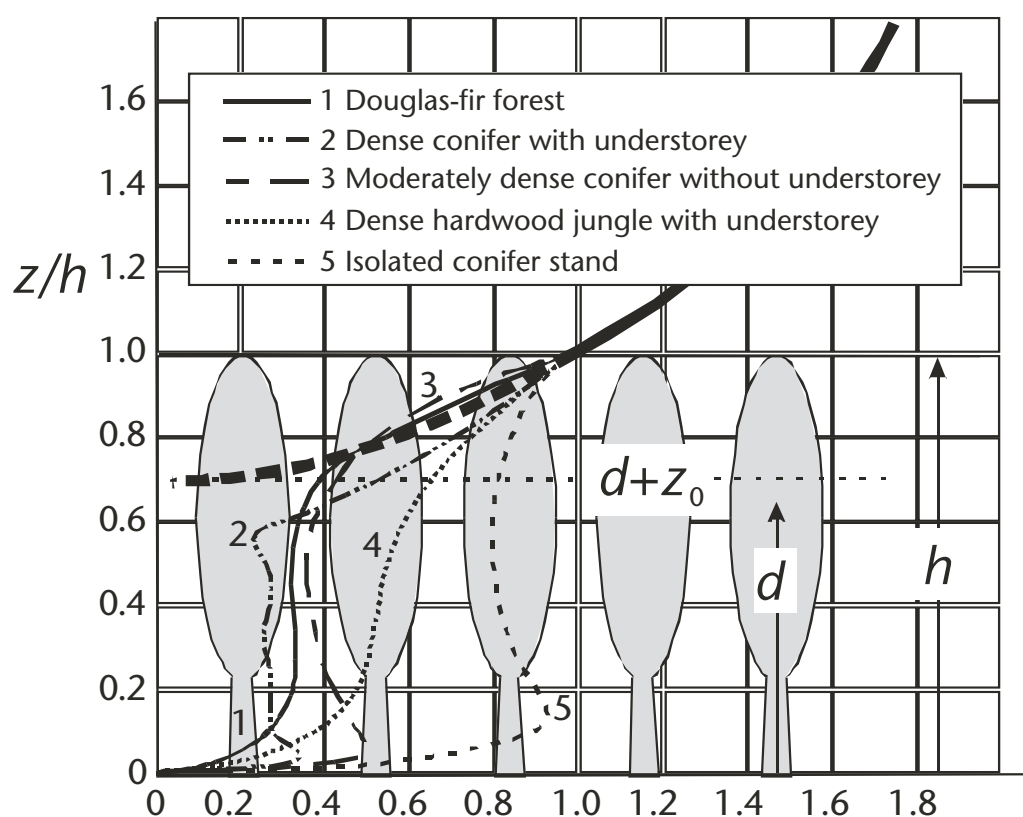


Figure 11.1. Characteristic wind speed profiles above and within different forest canopies, adapted from diagrams in Fritschen (1985), Lopez (1989) and Monteith and Unsworth (1990)

($z = h$), that is, where uz/uh is 1.0. At $z > h$, wind speed follows the logarithmic profile, but below this height, the actual wind speed is determined by canopy structure, including the presence or absence of understorey vegetation. The thick dashed line indicates the extrapolation of the theoretical logarithmic profile to $z = d + z_0$, where $u \rightarrow 0$. The thinner curved lines are based on observations summarized by Fritschen (1985) as indicated in the legend. The height of $d + z_0$ is assumed to be $0.7 h$, which is typical of many forests, such as the Douglas-fir forest indicated by curve 1. Data sources for the canopy profiles are: (1) Fritschen et al. (1973); (2) Gisborne (1941); (3) Fons (1940); (4) Latimer (1950); and (5) Reifsnnyder (1955).

The zero plane displacement parameter (d) is the height at which momentum is considered to be completely absorbed by the individual elements of the plant stand. The ratio d/h generally decreases with stand density. The roughness parameter (z_0) is a complex function of stand density, uniformity of tree heights and leaf area index, but defined in such a way that the logarithmic profile indicates $u = 0$ at $d + z_0$ (for example, Monteith and Unsworth, 1990). Values for d/h and z_0/h for various canopies of *Pinus* species are presented by Lopez (1989): d/h ranges between 0.67 and 0.92, such values being typical for many closed forests; z_0/h ranges between 0.02 and 0.92 (the latter representing a smooth bare surface). The friction velocity, u_* , is related to the frictional force due to air flow over the surface of the canopy, as affected by roughness and air stability, the latter being a function of vertical temperature gradients.

In general, daytime surface heating creates unstable conditions and hence upward movement of warmer air; conversely, night-time cooling creates a layer of colder, stable air closest to the surface. This daily cycle then contributes to variations of wind speed and turbulence within the canopy, as well as to diurnal changes in the height of the planetary boundary layer (for example, Oke, 1987).

Thermal stability effects are generally unimportant in forest canopies at moderate to high wind speeds, although Onyewotu et al. (2004) found that instability reduces the protection from hot air provided by shelterbelts. At low wind speeds, and particularly in more open canopies where significant surface heating can occur, vertical convection contributes to turbulence, which interacts with air movement above the canopy to produce complex effects on mass and energy exchanges with the atmosphere. Interestingly, some recent research by Zhu et al. (2003) has revealed a strong correlation

between canopy light interception measured using hemispherical photography and wind speed within the canopy relative to that measured above.

Aerodynamic roughness is key to the sheltering effects provided by tree cover and can be an important feedback on local climate. Work by Branford et al. (2004) shows that cloud and aerosol deposition are strongly influenced by roughness at forest edges. Studies by Chase et al. (1996) and Pielke (2001) suggest that land conversions (notably large-scale deforestation) affect roughness as well as albedo, leading in some regions to detectable changes in precipitation patterns.

11.2.1.4.3 Sheltering mechanisms

Clearly trees provide shelter, meaning that average wind velocities below the zero plane are typically much lower than those in the free airstream above (Figure 11.1). Sheltering stems from the absorption of wind momentum energy by the stand, which involves a complex combination of factors.

Flesch and Wilson (1999a, 1999b; Wilson and Flesch, 1999) investigated the processes contributing to shelter of remnant spruce in experimental cutover strips adjacent to natural aspen-spruce boreal forest in northern Alberta, Canada. They compared mean wind speeds and turbulent kinetic energy (TKE) affecting “tree sway” along transects perpendicular to the edge of the unharvested forest. At half canopy height (that is, of the unharvested trees, $0.5 h$), the best shelter was provided nearest the windward edge, with 80 per cent reduction in average TKE and 90 per cent reduction in average velocity (u). Wind speeds increased gently with downwind distance, but TKE increased rapidly, attaining near-constancy at about $3 h$, with a value slightly greater than that of unimpeded air flow. In a second study, Flesch and Wilson (1999b) found that the interaction of tree movement and local turbulence caused “resonant sway” 10–35 per cent greater than the displacement due to instantaneous wind force alone. Tree sway was well correlated with the standard deviation of the wind force, $\sigma_{u|u}$. It was found that the wind velocity in the open needed to cause uprooting varied from 30 m s^{-1} at the upwind edge in a narrow ($1.7 h$ wide) cutover to only 13 m s^{-1} near the downwind forest edge in a wider ($6.1 h$) area. The best shelter was obtained within $3 h$ of the upwind protective forest, leading to a recommendation that cutover areas be less than three tree heights wide to provide useful shelter at heights below $0.5 h$.

Also in Alberta, Rudnicki et al. (2001, 2003) observed over 60 tree collisions per minute in a lodgepole pine stand, at a mean wind speed of 4.5 m s^{-1} (with gusts to 10 m s^{-1}), noting that the “collision overlap” amounted to about 25 per cent of stand area. These collisions inhibit lateral shoot growth and hence influence crown asymmetry and “shyness” (the tendency to avoid crown interlocking), and contribute to the formation of canopy gaps. It was also established that slender trees have proportionately greater sway distances, causing greater collision overlaps, an effect exacerbated by thinning. James et al. (2006), investigating safety of urban trees in Australia, measured dynamic wind loads on a range of species (with different crown shapes and branching habits), including *Eucalyptus grandis* and *E. teretecornus*, a palm (*Washingtonia robusta*), a slender Italian cypress (*Cupressus sempervirens*) and hoop pine (*Araucaria cunninghamii*). Using a model developed from their observations, they concluded that branch mass generally damps excessive stem sway, and hence increases mechanical stability of individual trees.

11.2.1.5 Photoperiod

Photoperiod is for most forest tree species from the cool and temperate regions a key factor affecting the induction of dormancy, the abscission of leaves and the cessation of cambial activity (Koski and Selkäinaho, 1982; Koski and Sievänen, 1985). A number of angiosperms and gymnosperms cease growth when exposed to short photoperiods, and long days extend the growing period. Under these conditions, for example, the shoots of some species of *Pinus*, red maple (*Acer rubrum*), birch (*Betula*) and elm (*Ulmus*) grow continuously. Even though long photoperiods are maintained continuously, some species of *Pinus* and *Quercus*, however, stop growing and form terminal buds, which produce leaves after a period of inactivity (Downs and Borthwick, 1956; Borthwick, 1957). Campbell and Sugano (1975) and Nizinski and Saugier (1988) confirmed that longer photoperiods accelerate development of *Pseudotsuga* and *Quercus*, respectively.

Rivera and Borchert (2001), based on indirect evidence, attributed the induction of flowering of deciduous trees, in a semi-deciduous tropical forest, to the rapid decline in photoperiod of 30 min or less. Borchert and Rivera (2001) observed that bud break of vegetative buds of tropical stem-succulent trees was not induced before the spring equinox, despite their high water status. Highly synchronous bud break regularly occurred soon after the spring equinox, often weeks before the first rainfalls of the wet season. Based on these

observations and experimental variation of the photoperiod, it is hypothesized that seasonal development and endo-dormancy of vegetative buds in stem succulents are controlled by the photoperiod.

Photoperiodic control of growth and development of cool and temperate forest tree species may limit their north–south movement. There is little or no evidence of photoperiodic control of flowering among those species, however (Fowells and Means, 1990).

Dormancy of fruit trees and vines is sometimes initiated by decreasing photoperiod (Gur, 1985; Wake and Fennell, 2000). The photoperiodic response of deciduous fruit trees of the Rosaceae family varies even within the same species (Gur, 1985). For example, apples and pears are insensitive to photoperiod (Heide and Prestrud, 2005).

11.2.2 Pests and diseases in relation to weather

This section considers disease agents, pest insects and weeds. These factors can directly threaten a tree’s structural integrity, water and food (photosynthate) transport systems, above- and below-ground growth, food production and storage (for instance, seeds) and wood and fibre quality. Variation in moisture, temperature, radiation and wind, on both short (weather) and long (climate) timescales often have critical influences on the tree damage and mortality caused by pests and diseases. Weather affects the build-up of many pests and disease agents by determining the rates at which their populations grow and spread (Harrington et al., 2001), and it provides opportunity for many pests and diseases when it stresses susceptible host trees (for example, during drought).

Disease agents can be infectious (for example, fungi, bacteria, viruses, nematodes and parasitic plants) or non-infectious (for example, pollution). Section 11.2.3 covers the direct effects of extreme weather that can also produce disease (for example, enduring moisture deficits are key contributing causes of diebacks and declines). Disease symptoms almost always involve necrosis (dead tree tissue), or growth that is either excessive (hypertrophy, for instance, galls) or inadequate (atrophy, for instance, chlorosis). Sometimes a disease agent associates with an pest insect and together this association is much more successful at attacking trees than either would be on its own (for example, Wikler et al., 2003). Bark beetles and the plant pathogenic fungi they carry are an example (Wermelinger, 2004).

Pest insects can harm trees directly by consuming their foliage, roots, seeds or cambial material, and indirectly by transporting disease organisms (Speight and Wainhouse, 1989). Besides the variety of fungal species transported to susceptible host trees by bark beetles, some bacterial and most viral diseases are also spread by insects. Weather affects the mortality, dispersal and activity of insects and is thus often a critical influence on their populations' rates of change. Because of their large spatial extent, weather systems can provide simultaneous "shocks" to the cycles of widely separated populations of an insect pest, thus synchronizing these cycles in space and creating regional outbreaks.

Weeds come in various forms depending on the context (Anderson, 1983). In tree nurseries and seed orchards, weeds are typically forbs and grasses. For site preparation or rehabilitation, or tree release from competition, many weeds are herbs, shrubs or weed trees. Weeds are most prevalent as fast growing invaders of recently disturbed sites on which the trees of the regenerating coniferous forest are less than 10 cm diameter breast height (DBH). Weed species use at least three reproductive strategies to colonize these sites quickly (Stewart, 1987): producing large quantities of seed that are easily dispersed by wind or animals; producing durable seeds that remain viable for long periods in the soil or surface litter; and spreading vegetatively (for instance, from sprouts, suckers or tubers).

11.2.2.1 Moisture (humidity, dew, rain, snow, sleet)

All fungi need water to grow, but the amount needed varies widely among species. To avoid desiccation, bacteria must associate with host plants or tissues during dry periods.

Wind-splashed raindrops are important in spreading fungal infective stages and the bacteria that cause forest diseases among plants (Tainter and Baker, 1996). Often weeds grow fastest in conditions of low moisture stress (Radosevich and Osteryoung, 1987).

Salt compounds are often applied to icy roads during winter in North America. The salt spray generated by passing traffic is particularly injurious to conifers. The surge from tropical storms and hurricanes can flood large areas with salt water. Much of this salt is eventually absorbed by roots, causing salt burn, which can lead to mortality.

During storms, heavy wind and rain can wash small insects (for example, scales, adelgids and aphids) off

trees, increasing their risk of mortality (for example, from starvation or predation). In addition, prolonged episodes of high humidity and wet weather are ideal for the increase and spread of populations of some natural enemies of insect pests, such as insect pathogenic fungi, for example (Tainter and Baker, 1996). In winter, heavy rain can flood soils, drowning the overwintering stages of vulnerable species (for example, larch sawfly). On the other hand, snow can insulate overwintering stages from extreme cold and break conifer branches, providing potential breeding sites for bark beetles. Rain is a hazard during many pest control operations because it can wash sprayed materials off target vegetation too soon for them to be effective. This can lead to exposure of non-target organisms, and sometimes (for instance, with herbicides) injury to the crop trees. On the other hand, high humidity often facilitates the absorption of herbicides by weeds.

11.2.2.2 Temperature

Most fungi can survive but cannot grow when temperatures fall below freezing. Like higher plants and animals, they grow best at 20°C–30°C. Nematodes increase their population growth by completing their generations more quickly as soil temperatures rise (to an optimum of 25°C–30°C for many species). Sufficient snow depth can provide enough insulation to allow certain diseases to thrive underneath, however, such as snow moulds, for example, (Senn, 1999; Karlman, 2001).

Temperature is the most critical weather variable for insect pests (Ayres and Lombardero, 2000). It controls all facets of their development and activity. Where summers are short or temperatures relatively low all year, many species cannot complete their development without special adaptations (Logan et al., 2003). For instance, the green spruce aphid can live through the harsh winters of continental Europe only as an egg, but in Britain's milder climate, the insect has abandoned the egg stage. On the other hand, during exceptionally warm summers, insect pests can sometimes produce an extra brood of young or even complete additional full generations (Harrington et al., 2001).

Temperature variability is also important for insect survival. For instance, during British winters, which are mostly mild, the green spruce aphid acclimates to the mild conditions. But this leaves the species vulnerable to occasional bouts of cold, which can cause much mortality. Many defoliating insects (for example, spruce budworm) specialize in attacking particularly nutritious stages of their host tree's

foliage (Volney and Fleming, 2007). To do this, insect feeding stages must appear when the host tree's foliage is in the correct stage. The development of both the insect and its host tree's foliage depends on temperature, though usually not in exactly the same way, so unusual temperature patterns in time can disrupt this synchrony and leave the insects to starve or consume low-quality foliage (Volney and Fleming, 2000).

11.2.2.3 **Radiation (light, day length, cloudiness, lightning)**

Fungi do not need light to grow, but many need at least a little to complete their life cycle. Sudden exposure of shade-tolerant tree species to full sunlight (for instance by thinning or intermediate harvest), especially on poor sites, can cause green foliage to fade (chlorosis). Opening a closed canopy can also stimulate shade-intolerant weeds (for example, many shrubs), resulting in reduced growth of the remaining overstorey and site preparation difficulties after the final harvest. Sun and wind can make foliage surfaces very dry for the insect pests that feed there. Some (for example, leaf miners, sawflies, gall formers) go inside the tree's tissues for the most vulnerable parts of their life cycle. Drought often stresses trees, which are then less capable of defending themselves (for example, against bark beetles). A lightning strike can leave a tree susceptible to insects and infectious disease. For instance, lightning strikes are thought to have initiated many small, localized southern pine beetle infestations. Cloudiness can reduce the advantage that many weeds have in growth rate compared with the forest trees on the site. In addition, concentrations of herbicide sprays tend to be higher in leaves when light is reduced (Walstad et al., 1987).

11.2.2.4 **Wind**

Wind plays three key roles in the context of pests and diseases. First, it is critical as a longer-distance dispersal agent. Many, if not most, important weeds, insects and infectious disease agents rely at least partially on wind for transport into favourable environments. Wind also disperses pollution from urban centres to downwind forest areas. In addition, by dispersing aggregation and mating pheromones, wind provides a medium for chemical communication of many important insect pests (for instance, the mountain pine beetle). Wind also causes spray drift, an important environmental and efficacy consideration during pest control operations (Stewart, 1987). Second, through interactions with temperature, wind has important effects on moisture (such as dew and

humidity). Wind and moisture levels are both important considerations in using prescribed burning (11.2.6) for weed control (Walstad et al., 1987). Third, windthrown trees are often rapidly invaded by stain and decay fungi and secondary insects (for example, ambrosia beetles) that reduce wood and fibre quality.

11.2.2.5 **Selected simulation models**

There are a huge number of purely research models on this topic, but they are not discussed here because this chapter is not directed at researchers. Instead, the paragraphs below focus on management models that may be useful to the forester, forest manager and non-forest tree growers. Rather than a comprehensive coverage of the underlying research, the references are meant to provide this audience with initial access to using these models. Even so, because of space limitations, it is possible to describe only a few of the many management models in existence.

The Gypsy Moth Decision Support System, GypsES, (Gottschalk et al., 1996) is a tool for organizing and evaluating information to be used in gypsy moth control, suppression, prevention or eradication efforts in North America. It is built around a visual display of information through the Geographic Resources Analysis Support System Geographical Information System (GRASS GIS) and several simulation models.

Models integrated into GypsES include a stand-damage model and a gypsy moth phenology model. The stand-damage model (Colbert and Sheehan, 1995) simulates tree diameter and height growth, and tree mortality for each year of a simulation. Users supply information on defoliation history and describe defoliation scenarios for each species each year as a percentage for the overstorey and for the understorey. Each year, the model calculates the diameter growth of trees as a function of relative stocking, shading, heat and defoliation. Weather drives photosynthesis and tree growth. A cumulative heat unit measure, degree-days above a single threshold (4.4°C), is used for all tree species as a primary driver of diameter growth. Default constant weather data can be overridden by entering weather variation for each year simulated. The gypsy moth phenology model, GMPHEN (Sheehan, 1992), predicts the timing for gypsy moth and host development. This model simulates gypsy moth egg hatch, larval and pupal development, and budbreak and leaf expansion for six eastern hardwoods. GMPHEN reports the percentage of gypsy moths in each life stage, mean life stage,

mean per cent leaf expansion, and for each host species, per cent budbreak and leaf expansion. The model uses daily maximum and minimum temperatures to calculate heat accumulation measured in degree-days. Built-in 30-year averages can be used for gross estimates of timing of egg hatch and larval development, or users can input the actual temperature data up to the current date and then run the model to simulate into the future.

CLIMEX is a dynamic simulation model that enables researchers to estimate the potential geographical distribution of a species, plant (for instance weeds) or cold-blooded animal (for instance insects), by using climatic parameters inferred from an observed distribution (Sutherst and Maywald, 1985). Using climate information and knowledge about the biology and distribution of a particular species in its original habitat, CLIMEX enables an assessment of the risks posed by the introduction of that species in a new habitat and can be used to forecast locations to which the species could spread (Sutherst et al., 2000). CLIMEX can also be used to identify possible collection and release sites for biological control agents.

CLIMEX has a built-in database of records from about 2 400 meteorological stations worldwide. It needs monthly long-term average maximum and minimum temperatures, rainfall and relative humidity. It allows the user to edit lists of stations into subsets, and add new data for specific locations of interest (Sutherst et al., 1999). CLIMEX uses minimal datasets and simple functions to describe the species' response to temperature and moisture (Maywald and Sutherst, 1989). For each species of interest, the year is split into a favourable and an unfavourable season. A growth index describes the potential for population growth during the favourable season, and four stress indices (cold, hot, wet and dry) describe the probability of the population surviving through the unfavourable season. Combined, the growth and stress indices provide an overall indication of the favourableness of the location or year for the species of interest. Results can be presented as tables, graphs or maps.

BioSIM (Régnière et al., 1995) is a software tool for use in forecasting events in the seasonal biology of insect pests. Forecasts are made by simulation models provided by the system and are based on regional air temperature and precipitation interpolated from nearby weather stations, adjusted for elevation and location differentials with regional gradients. BioSIM produces geographically specific temperature forecasts using historical and real-time

temperature information and uses these forecasts within temperature-driven simulation models to forecast insect development over the season. BioSIM is embedded in a number of modelling systems for managing forest insects, including spruce budworm, gypsy moth and mountain pine beetle.

The Weed Invasion Susceptibility Predictor, or WISP (Gillham et al., 2004), was developed to forecast the potential risk of invasion by individual weed species in rangelands. This risk is estimated by comparing the growth requirements of each weed species with respect to nine site characteristics obtained from geographic data layers: distance from water and disturbance sources, elevation, annual precipitation, soil texture and pH, aspect, slope and land cover. WISP has some applicability to certain orchards and forest plantations.

Landscape Vulnerability to Forest Insect and Pathogens is a system developed by Hessburg et al. (1999) for assessing landscape vulnerability to defoliator, bark beetle, dwarf mistletoe, root disease, blister rust and stem decay in the Columbia River basin. Factors affecting patch vulnerability in this system include site quality, host abundance, canopy layers, host age or size, patch vigour, patch (stand) density, connectivity of host patches, topographic setting and visible evidence of logging. This approach to assessing landscape vulnerability could potentially be adapted in other landscape or watershed analyses to evaluate or monitor change in the magnitude and spatial pattern of vegetation vulnerability to insects and pathogens, and in planning to compare potential futures associated with alternative vegetation management scenarios.

Site quality was used as a vulnerability factor because hosts on poorer sites are often more vulnerable to a particular pathogen or insect than those on more productive sites. By frequently distinguishing cool-moist sites from warm-dry sites, the integrated effects of climate are implicitly included in site quality. For instance, cool-moist sites are modelled as being generally more vulnerable than warm-dry sites to root disease and the stem decay known as rust-red stringy rot.

The situation is modelled as more complex for rusts, mistletoes and insects. In the model, vulnerability to white pine blister rust is often different on cool-moist and warm-dry sites, but the host species determines on which type of sites the greater vulnerability exists. Douglas-fir and western dwarf mistletoes are modelled as greater hazards on warm-dry sites than on cool-moist

sites. The opposite holds for western larch mistletoe. Areas most vulnerable to insect defoliation are characterized in the model by low annual precipitation, droughty growing season conditions, cold winters and cool spring and fall temperature regimes. The areas least vulnerable to insect defoliation are characterized by higher annual precipitation, mild winter temperatures and warmer spring and fall temperature regimes. Bark beetle outbreaks are associated in the model with large winds, fire, extended drought periods or defoliation events. In endemic populations, each bark beetle species attacks low-vigour, diseased, weakened or injured trees and recent windthrown or collapsed trees. In outbreaks, vigorous hosts are mass-attacked and killed, occasionally across large areas. In pine-dominated patches, stressed trees are commonly associated with high-density growing conditions, droughty growing seasons or protracted droughts. In successional advanced patches comprised of shade-tolerant species, an abundance of beetle-vulnerable stressed trees can be maintained in the model by root pathogens, dwarf mistletoes, drought and overstocking.

The Phenology and population SIMulator, or INSIM (Mols and Diederik, 1996), is a simulation environment for developing pest-forecasting models of the phenology and population development of an insect species. INSIM is menu-driven and generates age-structured models to calculate the number and development of insects. A simple phenological or population model needs information on the life cycle, development rate and standard deviation of each insect stage, sex ratio, life expectancy of the adult and age-dependent reproduction. The required weather inputs are the minimum and maximum daily temperature. The output of the chosen variables (relative or absolute numbers of each stage and temperature sums) can be presented graphically or numerically. User-supplied programming in QuickBASIC allows the simulation of predator–prey interactions.

The Monitoring and Risk Assessment of the Spruce Bark Beetle methodology was developed by Netherer et al. (2003), who used a modelling approach to describe the development of the spruce bark beetle, *Ips typographus*. This approach combines topoclimatic aspects of the terrain with the insect's ecophysiological characteristics. By correlating air temperature and solar irradiation measured at a reference station, along with topographic data and microclimatic conditions of terrain plots, topoclimatic models of a given research area are established.

Solar irradiance is a key variable. For example, beetles observed developing in a sun-exposed tree situated at the forest edge at an elevation of 1 000 m were able to complete two generations successfully, with offspring emerging up until August. Nearby in a shaded tree, offspring reached only the larval stage of the second generation within the same period.

Many universities with agricultural programmes maintain Websites with integrated pest management (IPM) information, including a large number of integrated tools and models that have been developed to assist non-forest-tree growers with IPM activities (for example, <http://ipm.ucdavis.edu>; <http://fruit.wsu.edu/>; <http://pnwpest.org/>).

Within the scope of the modelling, GIS is used for data processing and visualization. The output is meant to aid in monitoring, retrospective analysis and prognosis of brood development at any site.

11.2.3 **Weather hazards to forest and non-forest trees**

11.2.3.1 **Snow and ice**

Snowfall and heavy ice storms damage trees principally by causing branches to break or bend from the extra weight of snow/ice on the tree structure. Trees bent more than 60 per cent generally do not recover sufficiently to be retained as crop trees, but they often remain alive for many years (Brewer and Linnartz, 1973). Furthermore, with the extra weight of snow or ice, high winds may also cause significant windthrow in stands of trees. For tree nurseries, broken or bent branches may result in misshapen trees as they develop. Freezing and thawing processes may also fracture trees (bark splitting) and damage roots through soil heaving, which pushes shallow roots to the soil surface, exposing them to cold and desiccation.

While trees may survive this process, they are potentially more prone to infection and disease afterwards. Indirect forest stand damage may occur from soil acidification following spring snowmelt. In upland forest plantations, especially on acidic bedrock or where a prolonged and heavy winter snowfall has occurred, spring snowmelt from the snowpack will release 50–80 per cent of ions in the initial 30 per cent of meltwater (Johannessen and Henriksen, 1978). If winter snowpacks are acidified, soils can become flooded with protons, causing an acid pulse into soil, which may not only damage roots, but may also release toxic amounts of

aluminium and manganese for uptake by root systems, resulting in permanent damage to commercial forestry.

11.2.3.2 Temperature extremes

Compared with neighbouring treeless areas, forests reduce diurnal amplitude of air temperature through modification, by tree canopy, of the amount and penetration of solar radiation to the ground (Ní Dhubháin and Gardiner, 2004). This effect usually helps buffer trees from extreme temperatures. Such regulation of air temperature by forests is reduced considerably, however, when the canopy is opened either through clear-felling or leaf fall of deciduous trees, or from planting of young seedling trees. Windy nights also reduce this effect by air mixing, and specific geographical locations (such as latitude or mountainous/hilly terrain) and seasonal factors will inevitably expose forests to temperature extremes. Extreme temperature conditions are of concern to forest managers and silviculture, as for example, spring or autumn frosts may be sufficient to cause significant damage to young plantations.

While extreme high temperatures can, under certain circumstances, help generate dry conditions for forest fire ignition (such as drought conditions), the particular weather parameters that appear to have the greatest influence on the degree of fire risk are precipitation and relative humidity. It is common practice now for forest services to report indices relating fire danger to weather conditions (see 11.5.6). Prolonged high temperatures in conjunction with reduced precipitation will also lead to water and nutrient stress on trees by reducing water availability and causing desiccation of the tree structure.

By contrast, extreme low temperatures can lead to frost, which can damage trees, especially young trees and saplings or new growth. Two different types of frost may form depending upon the meteorological conditions: advective frost and radiation frost. Advective frosts are associated with cold air currents and may cause damage, especially to young saplings or new growth (Day and Peace, 1946). At most locations, however, radiation frosts are more common and occur on calm-clear nights. Heat is lost from soil and vegetation rapidly by radiation, which escapes through the atmosphere, thus cooling the soil surface. Radiation frosts can be damaging to plantations during spring and autumn (Ní Dhubháin and Gardiner, 2004). Furthermore, in undulating terrain, cooled air can pool as a result of poor air drainage, and temperature

inversions develop. Under these circumstances, frost hazard may be a significant recurring problem that requires particular attention from forest managers.

In mountainous terrain, when synoptic conditions are favourable, forestry can be subject to distinctive winds blowing down the lee slopes of mountain ranges – called fall winds – of which the foehn, chinook and bora winds are the most well known. These winds have a considerable effect on temperatures. In simple terms, the foehn wind is defined with reference to a downslope wind that causes temperatures to rise (and relative humidity to fall) on the lee side of a mountain, whereas the corresponding bora causes temperatures to fall. The seasonal but rapid changes in temperature associated with these winds can have considerable desiccating effects on vegetation and soil moisture. In the case of the chinook wind, desiccation can extend approximately 50 km from the foothills of the Rocky Mountains (Riehl, 1971).

11.2.3.3 Windthrow

Significant effort has been invested in trying to understand causes of wind damage, particularly in Northern Europe, where storm damage (uprooting and stem breakage) is frequent. There appears to have been limited success in applying the knowledge gained to reduce impacts.

Windthrow refers to stem breakage or tree uprooting caused by wind. Windthrow involves complex interactions among tree and stand characteristics, site conditions, topography and storm conditions (wind speed, duration and gustiness) (Mayer, 1989). Regional wind climates also vary greatly; coastal regions, those in storm tracks, either for the passage of major depressions or subject to thunderstorms and tornados, and mountainous regions are often subject to damaging wind speeds. Locally, topographic conditions can funnel winds, creating high wind speeds on upper mountain slopes and saddles, in converging valleys, and adjacent to landform discontinuities, including forest edges. Most windthrow is caused by turbulent gusts that are much stronger than the mean wind speed.

Soil conditions are important for tree anchorage, both in terms of root strength and the mass of soil adhering to the root plate. Shallow, impervious, anaerobic, stony or infertile soils can restrict root development, increasing windthrow susceptibility. Also, wetter soils provide less shear strength than drier soils, so storm precipitation and wind are a factor.

Wind firmness generally decreases with tree height and root or stem decay, and increases with stem taper and root development. Trees in exposed places physiologically adapt to wind, developing shorter, thicker, more tapered stems. Greatest windthrow often occurs when trees growing in sheltered locations are suddenly exposed to wind. Tree species also vary in windthrow susceptibility depending on size, crown structure, rooting habit and foliar characteristics (for example, deciduous as compared to evergreen).

Stand characteristics affect windthrow by influencing the degree to which wind penetrates the canopy, the mutual support of bending stems, the height and roughness of the canopy (which generates turbulence) and species composition. Dense, uniform stands, while composed of trees with little stem taper and limited root development, provide considerable wind protection through mutual stem support and aerodynamically smooth canopies. Windthrow susceptibility is also affected by the proximity, size, shape and structural characteristics of adjoining stands and by landscape heterogeneity.

In some regions, windthrow hazard classifications have been used to assess windthrow potential and guide forest management. The United Kingdom classification combines site windiness (wind zone, elevation, topographic exposure and aspect) and tree anchorage (soil type) to define hazard class, and relates this to tree height (Quine and White, 1993). Mathematical risk assessment models for windthrow, based on bending and resistive moments, have also been developed (Gardiner et al., 2000) and applied (for example, Achim et al. 2005). Pellikka and Järvenpää (2003) and Zhu et al. (2006) found varying sensitivities among species to snow and wind damage in Finland and north-eastern China, respectively. Zeng et al. (2004), working in Finland, combined a mechanistic wind damage model and an airflow model with forest databases containing information at the tree, stand and regional levels. They found that newly exposed edges were particularly vulnerable to increased wind if the stand was harvested at minimum allowable rotation age or basal area. The risk of damage was actually most increased for older stands, however, because these tended to be exposed when younger stands were harvested. Finally, handbooks for mitigating windthrow damage have been published by several jurisdictions (for example, Stathers et al., 1994; Navratil, 1995; Quine et al., 1995).

11.2.3.4 Flooding

The frequency of floods is related, but not identical to, the frequency and return period of major

rainstorms, substantial spring snowmelt, or both. While no clear pattern of changes in flooding has emerged as a result of forestry (for example, Robinson, 1998), rainfall runoff is modified to an extent through higher infiltration and forest interception losses. Flood events, depending upon the magnitude, can produce destructive effects on tree stands, as flood currents may be sufficient to topple trees. In addition, flood currents, waves and suspended particulate matter may cause significant quantities of soil around the base of trees to be washed away. Such secondary impacts from flood scouring include exposed root systems, which can lead not only to tree stress, but can also make trees more vulnerable to windthrow. By contrast, flood sedimentation from deposited silt or sand may seal or smother tree roots and limit oxygen supply to root systems. Further secondary impacts from flooding may include a period of waterlogging (although this may occur without a flood event). In waterlogged ground, oxygen deficiency to root systems from poor soil aeration is likely the most important environmental factor that triggers growth inhibition and injury in flooded trees (Smith et al., 2001). Waterlogged soil will also alter soil pH, rates of organic decomposition and supply of nutrients, which can damage root systems and affect tree development.

11.2.3.5 Other biophysical controls affecting forest growth

The constraints on forest and non-forest tree growth and productivity imposed by dominant meteorological factors have been discussed above. There are numerous other biophysically regulated environmental factors that directly or indirectly affect a forest's status and they are briefly highlighted in this section. They include forest fires, air pollution and soil effects.

11.2.3.5.1 Forest fires

Forest fire can be a dominant factor that has a detrimental or rejuvenating effect on the forest status in northern boreal and tropical forests, in varying degrees. Pyne et al. (1996) define fires as those ignited by natural causes, such as lightning, or unintentionally by human actions. On the other hand, prescribed burning refers to those fires that are intentionally created to burn a particular forest area in order to achieve predetermined objectives (Weber and Taylor, 1992), which will be discussed in detail in 11.2.6. Studies reveal that both frequency of fires and the total area burned in the boreal forest have increased over the last 20 to 40 years. In 1994, Canada lost 4 million hectares of forests due to fires.

Average annual property losses in Canada from forest fires between 1990 and 2000 are estimated to have exceeded \$7 million, while fire protection costs averaged over \$400 million per year (Canadian Forest Service, 2001). Several reviews highlight specific mechanisms and effects mediated by fires affecting forestry (for example, Viereck, 1973; Heinselman, 1981; Weber and Taylor, 1992; Pyne et al., 1996).

Ecological and environmental effects of forest fires are highly variable, difficult to predict and influenced by fire behaviour, vegetation type, topography, climate, pre- and post-burn weather and other factors (Weber and Taylor, 1992; McCullough, 1998). Fires can be classified by their behaviour and intensity. Surface fires burn through material like litter, shrubs, dead wood and the like on the soil surface. Crown fires are invariably ignited by surface fires and burn through the crowns of standing trees. Ground fires burn in subsurface organic fuels such as duff layers under Arctic tundra or taiga or in organic soils of swamps and bogs (McCullough, 1998). Forest fuels directly influence fire intensity (for instance, production of heat per unit area) through fuel accumulation (or fuel load), distribution and moisture content characteristics. Fuel includes wood such as dead trees, logs and slashes (tree tops, branches and other logging debris). Fine fuels include dead needles, leaves and litter. In areas with a high accumulation of fuels, fires may burn hotter, move more slowly and have more profound ecological effects than in areas with low fuel accumulation.

Distribution and extent of fuels, wind, aspect (direction of slope orientation), topography and other factors interact and affect fire intensity and behaviour, typically creating different types of post-fire conditions. Though studies to understand the post-fire vegetation growth have been attempted, very little has been done to understand the canopy temperatures and vegetation stress after the occurrence of fires. Interactions of fire and insects can delay or redirect forest succession and can have significant consequences for forest productivity and biological diversity. Fires can affect insects by killing them directly or by altering soil properties, overstorey or understorey vegetation, tree density or other aspects of their habitat (Mitchell, 1990; McCullough, 1998).

Pest outbreaks can also dramatically affect the likelihood and severity of forest fires. This could be explained by the formation of dead wood, litter and debris as a result of plant damage caused by enhanced pest infestation in forests. Solar radiation

will enhance evaporation of the moisture on materials such as dead wood, fallen needles, leaves and litter (Mitchell, 1990). Tree mortality or dead tops resulting from insect attack determine the availability of fuels on the soil surface (such as dead wood and vegetation on the ground) and ladder fuels (vertically distributed dead wood). These factors play a large role in determining the risk of fire ignition, behaviour and intensity. The monitoring and management of forest fires by micrometeorologists warrant the adoption of powerful remote-sensing techniques. Advantages including large synoptic coverage, medium to high temporal and spatial resolution, monitoring of inaccessible burning areas and low costs enable remote-sensing to be effectively used for the precise mapping of forest fire boundaries and for understanding the fire regimes and post-fire plant regeneration ratios (Díaz-Delgado et al., 2002).

11.2.3.5.2 *Air pollution*

Asher (1956) observed unexplained foliar symptoms on ponderosa pine, which was then described as “x-disease”. The field experiment discussed by Miller et al. (1963) and the ozone fumigation experiments of Richards et al. (1968) confirmed that ozone was the cause of the chlorotic mottle and early abscission of affected needles and demonstrated the relationship between urban smog containing high levels of ozone and the disease.

Air pollutants could be speculated to have an important role in declining tree health and forest status. In a study conducted in Europe by Muller-Edzardz et al. (1997), one quarter of the coniferous trees assessed were damaged (20 per cent defoliation) and damage was worst in central Europe where the probability of air pollution is the highest, although crown condition has improved in regions of eastern Europe where atmospheric SO₂ concentrations have been reduced significantly. Severe deterioration in the crown condition of broadleaved trees has also been observed. Skarby et al. (1998) speculate that ozone might play an important role in the deteriorating foliar status of trees in Europe. A feature of atmospheric ozone is that as soon as it is deposited on a surface, it disappears, causing the oxidation of other chemical compounds.

Other studies include physiological responses (Grulke, 1999), deposition of multiple pollutants to forest canopies (Bytnerowicz et al., 1999), nitrogen saturation, stream water nitrate export trends (Fenn and Poth, 1999) and biochemical changes (Tausz et al., 2000). Most of this work was summarized in the report *Oxidant Air Pollution Impacts in the Montane*

Forests of Southern California: A Case Study of the San Bernardino Mountains (Miller and McBride, 1999). Work since then has begun to examine the effects of multiple pollutants on carbon allocation and sequestration (Arbaugh et al., 1999; Grulke et al., 1998). These studies indicate that ozone and nitrogen may cause a shift in pine tree foliar biomass allocation towards that of deciduous trees (Grulke and Balduman, 1999) and acceleration of litter accumulation (Arbaugh et al., 1999; Takemoto et al., 2001).

11.2.3.5.3 **Soil effects**

Landslides and soil erosion are serious challenges for forest management in areas with steep slopes, unstable soils and high rainfall. A landslide is the movement of a mass of rock, debris or earth down a slope (Cruden et al., 1991). Landslides are a fundamental concern for forest development planning and operations in mountainous terrain (Wise et al., 2004). This is primarily a function of topography, soil type and soil water content. Landslides may be viewed as a biophysical phenomenon because of the strong coupling induced by soil hydrology and soil physical properties mediated through changes in precipitation patterns. Most of the time, however, landslides adversely affect social, environmental and economic values in mountainous forestry or agroforestry systems and therefore can be a limiting factor. This concern relates mainly to the potential effect of landslides on elements such as forest resources (for instance, water quality), infrastructure (for instance, buildings and transportation and utility corridors) and people (Wise et al., 2004). Forest development involving forest roads and trails, as well as the harvesting of hillslope areas, can significantly contribute to the occurrence of landslides. Soil erosion in humid regions, especially in tropical pristine ecosystems or agroecosystems, could affect forest growth and tree health. It could remove the surface soil, leaving surface roots exposed, which decreases the tree anchorage and increases the susceptibility of trees to windthrow and other types of natural hazards.

11.2.4 **Tree nursery location and operation**

11.2.4.1 **Introduction**

A forest nursery is an area of earth or plot designed and prepared to raise and produce various kinds of tree seedlings using many methods, with a view to readying them for planting out in the field. The goal is to produce the largest possible number of good-quality seedlings in a limited area. There is a

strong need to raise tree seedlings in nurseries because: (a) newly raised seedlings from direct sowing of most tree species fail to establish or withstand field competition (winds, sun scorching, insect pests, soil conditions, diseases, fire, and so on); (b) seedlings of introduced species are not adapted to new sites and must first be raised in nurseries; and (c) economic losses may occur if there is failure of forest establishment by direct sowing in the field.

At present nurseries are easy to establish because of the availability of technological aids; they are widely distributed because of the ever-increasing demand for tree seedlings for urban uses (private and public) and for special types of plantations (for example, for planting on road and canal sites, for sand dune fixation). Traditionally, forest nurseries were divided into temporary, permanent and extension or educational nurseries (FAO, 1955, 1959; Evans, 1982). Temporary nurseries with a lifespan of less than five years were established for specific planting programmes in the field and did not need sophisticated installations; permanent nurseries concentrate efforts (capital, labour and technologies) in one area for bulk production of seedlings and efficient management.

11.2.4.2 **Location, design and equipment**

Many points have to be considered when planning to establish a nursery (FAO, 1955, 1959; Evans, 1982; Landis et al., 1999). The nursery must be placed in an accessible location, preferably in or near the plantation area. The ground must be flat with a gentle slope of about 3° to guarantee free drainage, both vertically into the ground and on the surface. In hilly or hummocky areas, the land should be freed from stones and levelled off by constructing terraces. The area must be oriented in an east-west direction to allow exposure to maximum radiation; mid-sections of slopes are the most suitable for nurseries in hilly areas, while summits and deep valleys are to be avoided for fear of strong desiccating winds and permanent shading, respectively (Evans, 1982). Areas prone to frost are also to be excluded. Where naked-rooted seedlings (conifers mostly) are raised, the soil must be fertile and free of weeds, pests and diseases; fertilizers and products to kill these agents may be used.

The shape of the nursery should be quadrilateral, preferably rectangular or square. It should be spacious, particularly if it is a permanent one, to accommodate many installations, such as seedbeds, stores, offices, irrigation devices and systems, reserve yards and space for the manoeuvring and

stationing of vehicles and equipment. Thorough protection of a nursery enclosure may be provided by an appropriate fencing system (barbed wire, wood or thorn, a live hedge, and so forth). Nursery beds may be rectangular, with an east-west orientation, between 1.2 m and 1.5 m wide, and of any convenient length (for example, 5 m); they should be separated by pathways to permit easy movement of personnel and equipment. In dry areas, the beds are covered by wire or wooden thatching works to provide partial shading to seedlings in order to mitigate excessive heating and drying conditions.

Many types of containers of different materials (such as ceramic, earth, wood, plastic, tin, cardboard) and of various sizes and shapes are commonly used in nurseries to contain seedlings (Landis et al., 1999). Adoption of a particular type of container depends on the context in which the containers are routinely employed, because there are advantages and disadvantages to using various types that are related to resistance to handling in the nursery and during transport to the field, durability, and suitability for producing high-quality seedlings (proper shoot/root ratio, undistorted root system). Porosity of containers is important to allow free drainage of excess irrigation water and to avoid root asphyxiation; as a result, some containers are made of pervious materials. Impervious containers are usually perforated to permit evacuation of excess water. Use of polyethylene tubes is becoming more popular, especially in dry areas, because they are light, easy to handle, durable and can retain moisture for long periods. Their main disadvantage, as with many containers, is that the thinner ones are pierced by roots and then need regular lifting to cut extruding roots; thicker containers may cause coiling of the root system.

Growing media used to fill the containers are of a wide variety of materials, including soils, peat, compost, sawdust, and so on. It is preferable that the material selected be of good porosity (high water retention, but allowing good aeration), light enough, fertile and free of diseases, pests and weeds (FAO, 1955, 1959; Landis et al., 1999). Sand and silt are the best growing media, but may need to be replenished with nutrients if seedlings will stay for a year or more in the nursery or if exigent tree species are raised. Clay, salty and contaminated soils are not to be used as growing media. Organic materials should have the required characteristics of porosity, water retention, lightness and rate of nutrient release through progressive decomposition. The major fear related to their use is the possibility that they may harbour pests and diseases that would

be detrimental to seedlings. At present, however, there are appropriate technological means to destroy such damaging agents.

11.2.4.3 Operations and management

One of the basic tasks in nursery management is to deal with seed stocks, including their procurement, handling, treatment, viability testing and storage. Many seeds need treatment (by soaking in cold and hot water, acid corrosion, mechanical scratching) to break seed coat dormancy, or some may need to be stored for a period until complete maturation. Thus, there ought to be adequate installations to accommodate seed-handling activities.

Bare-rooted seedlings are raised in beds filled with soil, or in adjacent yards, and kept there until they are transplanted. Seeds of most broadleaved tree species are sown in beds, trays or directly in containers. Large seeds are inserted not very deep in the growing media and covered. Small seeds (such as *Eucalyptus* sp., *Canocarpus* sp., *Casuarina* sp.) are thinly scattered on the growing medium and lightly covered by the medium or fine sand. This is done to avoid washing out of the seeds by irrigation water; in such cases watering may be provided by capillary ascension. When the seedlings attain appropriate sizes, after two weeks or a month (depending on the species), they may be transplanted or placed individually in other containers, leaving one seedling per container and keeping it there until final delivery.

Vegetative propagation (by cuttings, layering, budding, suckers) is common for tree species that do not produce seeds or are difficult to propagate by seeds (such as *Ficus* sp., *Euphorbia* sp.), or in order to produce clones. Reliable water sources and irrigation systems are indispensable in any nursery. Permanent modern nurseries are equipped with sophisticated irrigation systems, including over- or under-plant sprinklers or microsprinklers, surface irrigation and drip irrigation. In dry areas, it is better to irrigate the young seedlings with abundant water several times a day; in the later stages of the life of the seedlings, frequency of irrigation may be reduced.

Weeding is done routinely in nurseries. It is best done by hand, because herbicides are not recommended in most cases, as the substances they contain may harm the seedlings, especially those of broadleaved species. Roots extruding out of the containers may be cut using scissors, after lifting up the seedlings. Large, modern nurseries are equipped with underwire or vertical blade devices, which can

carry out root cutting mechanically. Before transplanting or delivery, seedlings are subjected to an operation termed hardening; this is done to make seedlings sturdy enough to withstand field conditions in the future. Seedlings are moved out of the shade progressively into open, sunny yards and left to lose some of their humidity, but not to the wilting point. For some species (for example, *Terminalia* sp., *Khaya senegalensis*, *Tectona gaudis*), the tips of the growing shoots are cut to allow better development of the root system.

In well-organized nurseries, records should be kept not only for personnel purposes but also for all the input and output items and activities. Efforts should be made to estimate the cost of all operations and of the seedlings that are the product of the nursery operations.

11.2.5 **Applications of meteorology and climatology for forestry and non-forest tree operations**

Climate and weather influence the planning, establishment, tending, harvesting and regeneration of forests. Most operations conducted on non-forest trees, including orchards, are also affected by weather, starting from the time of establishment until the end of their productive life.

The survival of a germinated seed or a planted seedling depends on the microclimate in its immediate vicinity. The forester can exert considerable control over this microclimate by such cultural activities as scarifying the soil or planting a seedling so that it is partially shaded by residual vegetation or logging debris. The type of regeneration cut will affect the microclimate at seedling level. For example, in an area where frost may be a potential hazard after a clear-felling, shelterwood cut may reduce the hazard by diminishing the nocturnal net radiation loss from the ground surface. A discussion of the microclimate in relation to forest regeneration can be found in WMO (1978a).

Harvesting is highly dependent on weather for its efficacy and security and for the maintenance of good soil conservation practices. Hence, weather is also often identified as the most important cause of unused logging capacity. In order to have real-time, on-site weather information, a forestry manager needs Internet access to be able to review weather sites and thereby assess the conditions for felling for the period ahead.

Suitable soil conditions may be necessary for successful harvesting of crop trees; for example,

harvesting operations may be difficult if soils are too wet to sustain heavy logging machinery. Moreover, under wet weather conditions, in order to avoid soil erosion and compaction and the impact of landslides, a set of good practices should be implemented. On wet sites and soils prone to compaction, lightweight harvesting equipment that exerts low ground pressure should be used and/or the number of skid trails should be minimized; operations should be conducted preferably in dry weather or when the ground is frozen.

When fire danger is unusually high, fire restrictions and closures are declared by the agencies that have jurisdiction. Shutting down of logging, clearing and some other forest operations is usually among the restrictions that are enforced for high and extreme danger ratings. In some countries, the danger class value for regulated forest operations must be derived from weather data representative of the site on which operations are being conducted.

Stems and trunks of trees exposed to moderate and persistent wind become deformed, and hurricane force winds break or uproot trees (see 11.2.3.3). Three steps are required to reduce damage produced by strong winds: (1) assessment of the risk of wind damage; (2) prediction of the effects of wind on trees; and (3) adoption of measures to increase the resistance of a forest to damage. Risk of wind damage is related to regional windiness, elevation, relative exposure of the site (topex), and soil nature and condition as related to root distribution and depth. The effects of wind on forest trees depend on wind speed, turbulence and the dynamic response of trees. The bending moment that is created and applied to the base of the trunk originates mainly from the frictional drag of the tree crown and the weights of the crown and trunk. When the bending moment exceeds the maximum resistive bending moment of the trunk, it breaks. On soils where the root depth is small, because the soil is shallow or the root growth is restricted, it is more common that the roots and/or the soil break, thus uprooting the tree. Implementing appropriate practices may safeguard resistance of forest trees to damage, as follows:

- (a) Fellings should be arranged so that successive adjacent areas proceed against the prevailing wind, thus avoiding the creation of significant gaps in the forest that are exposed to the wind (Matthews, 1991);
- (b) Large clearings or small scattered coupes in mature stands should be avoided. Instead, when necessary, narrow coupes should be done at right angles to the direction of the gales (Matthews, 1991);

- (c) Thinning should be confined to the early stages of plant development and halt before the critical height of the trees for the particular site is attained (Matthews, 1991);
- (d) Seedlings that are used for regeneration should be identified and protected from competition with neighbouring trees to allow their stems to grow strongly (Matthews, 1991);
- (e) When waterlogging is limiting root depth, and soils are not too shallow or consist of clays with very low hydraulic conductivity, drainage may be used to allow deeper rooting. Also, the adoption of measures to control root-rotting fungi may bring interesting results;
- (f) If the wind is funnelled by the forest itself, resulting in the Venturi effect, compact borders in the windward direction should be developed, thus shunting the wind up and above the forest. In order to drive the air up and above, it is best to have trees of increasing height in the leeward direction (Smith et al., 1994);
- (g) When the funnelling of the wind is caused by the form of the landscape, modifications of the landscape may be undertaken, if the circumstances allow it.

Humans have long recognized the value of forest plots and woodlands to provide protection of soil, crops and animals from wind effects, either in the lee of relatively closed stands, or, in more open stands, among the trees themselves. In hot arid climates, protective shelterbelts or higher tree densities are often essential if successful intercropping is to be achieved (Onyewotu et al., 2004). In Kenya, tree cover and surrounding hedges prevent mulch from being blown away, thereby allowing maize/bean crops to be protected from mechanical damage (Stigter et al., 2003). In Sudan, Mohammed et al. (1996) described the use of an irrigated *Eucalyptus* shelterbelt 12 km long and 300–500 m wide for combating wind-induced sand invasion into agricultural areas and irrigation canals. Careful wind observations in contrasting seasons with opposite wind directions showed wind protection from wind reduction details near the sand-facing edge (Stigter et al., 2002). Further work by Al-Amin et al. (2005, 2006) has helped to identify the best species and management requirements needed to control sand movement in regions prone to desertification.

Rainfed shelterbelts of *Eucalyptus camaldulensis* were instrumental in reclaiming desertified land in northern Nigeria, though better planning, possibly using alternative species or scattered trees, would have resulted in greater economic benefits to local

millet farmers (Onyewotu et al., 2003; Stigter et al., 2003). Further work by Onyewotu et al. (2004) found that crop yields may decline significantly if the shelterbelts are established too far apart, or at the incorrect angle relative to prevailing winds. Problems occur particularly when air is very hot, because increased turbulence in the unprotected wake zone (McNaughton, 1988) exacerbates soil moisture loss and heat stress on the crops. The conclusion is that shelterbelts in arid regions must be well planned in consultation with local experts, including farmers/producers, and properly maintained, if maximum benefits to crop production are to be realized.

Kainkwa and Stigter (1994) investigated the wind protection provided by a savanna woodland edge in northern Tanzania, also showing the influence of diminishing tree densities due to tree felling. Considerable initial wind tunnelling effects were found due to variations in the distribution of tree biomass, but wind speed was reduced by at least 50 per cent at distances of 110 m or more from the leading edge. The saturation wind speed was the same at 1 m and 2.5 m heights and relatively uniform in canopy gaps as large as 50 m, due to the association with wind fields above the trees.

In some cases, studies show that shelterbelts are not necessarily the best solution. For example, Zhao et al. (2006), working in Inner Mongolia, found that planting perennial grasses with shrubs on shallow soils provided better soil protection against wind erosion than tree cover, which is difficult to establish. Stigter et al. (2002), working in Nigeria, suggested that higher densities of scattered trees would be more effective in soil and crop protection in areas of western Africa where parkland agroforestry is traditionally practised.

The influence of weather on non-forest tree operations is also very important and is often similar to that reported above for forest trees. Since the economic value of these plantations is usually higher, however, extra care and protective measures may be implemented.

Orchard trees are often protected against frost damage, using direct or indirect methods. Indirect methods include site selection and management, plant selection, canopy trees, proper pruning, cooling or use of chemicals to delay blooming, plant covers, avoiding soil cultivation in the days preceding a frost event, removing cover crops, irrigation prior to a frost event, painting trunks with a water-based latex white paint, and trunk wraps. Among

the direct methods, the most popular are wind machines and the use of sprinklers or surface irrigation on the frost night. All direct methods rely heavily on accurate frost forecasts. When there is a high probability of frost (or hail) damage to fruits, and these are almost ripe, anticipatory harvest is necessary to avoid severe loss of production. This is often difficult to accomplish on big farms, however (FAO, 2005). Orchard pest management, and hence the need for pesticide application, its timing and efficacy, are dependent on temperature, moisture and wind (see 11.2.2 and 11.3.2). Frost forecast and IPM models require the availability of real-time weather data.

At windy sites, orchards are protected by windbreaks or shelterbelts (WMO, 1964). Windbreaks may be inert or comprised of trees of various species. Windbreaks are positioned perpendicularly to the wind, with the objective of reducing mechanical and physiological damage, and thus increasing fruit production. In general, they provide for a reduction in evaporation and plant transpiration, temperature increases during the day, and shelter from cold or hot wind or from particles that are transported by it (for example, sand or salt). Permeable windbreaks are more effective and allow for a significant reduction in wind up to 15 or 20 times their height; impermeable windbreaks do not offer protection above 10 or 12 times their height and they generate unwanted turbulence in the leeward side. Unfavourable effects that may occur include the loss of usable crop area, reduction of solar and net radiation interception by the crop, increased risk of frost and dew, and use of nutrients and water by the trees in the windbreak.

Some fruit species (for example, apples, pears, and citrus and stone fruit) need the application of growth regulators to reduce the number of fruits, in order to obtain bigger, high-quality fruit, and to overcome alternate-year or biennial bearing. Several different chemicals and combinations are used during the bloom or post-bloom period. Many factors affect the degree of thinning and the effect on return bloom the following spring. The temperature at the time of application and the next days should be above a certain threshold, which depends upon the chemicals used and the species and variety involved. High temperatures and slow drying conditions enhance the thinning effect and may result in over-thinning. Care should be taken to spray during the appropriate phenological phase, and heavy rain or any operation that washes away the product, within several hours after the spray dries, should be avoided (Wertheim, 1998, 2000).

After precipitation has occurred and before fruits are dry, harvest is not recommended. All operations that involve heavy machinery, including fruit harvest, should consider soil conditions to avoid compaction and soil erosion and should not be carried out under wet conditions if soils are adhesive and prone to compaction.

11.2.6 **Prescribed burning**

Fire plays an important role in many forest ecosystems. The use of controlled fire by forest managers to achieve management outcomes is well established. Examples of such uses include preparation of seedbeds, disposal of logging slash, opening of serotinus cones, removal of fuel hazards and disease control. The meteorological controls on fire behaviour for prescribed burning operations are the same as for wildfire. Temperature, wind speed, atmospheric moisture and soil moisture are factors that should be considered prior to setting a controlled fire. Many fire weather indices have been developed to provide fire managers with a guide to how the meteorological variables are interacting and how they may affect fire behaviour. Forecasts of these indices can be produced from numerical weather prediction models several days in advance. End-users should ensure that they are using an index adapted for local conditions and that values for weather-related variables fall with prescribed burning guidelines.

Fires produce smoke in varying quantities, depending upon fuel characteristics, type of combustion and the amount of fuel consumed. The smoke may be a local hazard, reducing visibility and interfering with vehicular traffic or aircraft operations, or it may be a wider regional community hazard. Smoke contains particulates, and approximately 90 per cent by volume are less than 1 μm in diameter. Fine particles less than 10 μm (PM10), and particularly those smaller than 2.5 μm (PM2.5), are considered potentially hazardous to human health. Many countries now have regulatory standards for PM10 particulate levels and place restrictions upon activities that result in the emission of particulates into the atmosphere. These restrictions may also apply to the use of fire for forest management purposes. Smoke contains many chemical compounds, including carbon monoxide (CO) and volatile organic compounds (VOCs) such as formaldehyde, which may also affect human health. Accordingly, foresters should consider the likely contribution of controlled fires to local and regional air pollution and plan their burning activities to minimize potential harmful community impacts. Smoke also

contains greenhouse gases, including carbon dioxide (CO₂) and nitrogen oxides (NO_x), the production of which may have long-term implications for climate and could be subject to future regulation.

A general introduction to the role of the atmosphere in dispersing pollutants is contained in two older WMO publications: *Dispersion and Forecasting of Air Pollution* (WMO-No. 319) and *Application of Meteorology to Atmospheric Pollution Problems* (WMO-No. 672). Information on the effect of air pollutants on plants is contained in *Air Pollutants, Meteorology and Plant Injury* (WMO-No. 234) and *Review of the Present Knowledge of Plant Injury by Air Pollution* (WMO-No. 431). For its part, the World Health Organization (WHO) has published air quality guidelines for Europe. These are available online (http://www.euro.who.int/air/activities/20050222_2) and present health risk assessments for many of the chemicals contained in smoke.

The development of Web-based fire management resources has allowed the wide dissemination of fire-based management strategies and fire weather research. The United States Forest Service has a searchable list of online publications dealing with fire-related issues, including prescribed burning (<http://www.treesearch.fs.fed.us/pubs>). The Global Fire Monitoring Center (GFMC) Website (<http://www.fire.uni-freiburg.de/literature/Fire-Management.htm>) contains fire management guidelines for sub-Saharan Africa and temperate, boreal and tropical forests. This site also provides online health guidelines for vegetation fire events and contains information about fire management programmes.

Smoke dispersion forecasts are routinely produced in several countries, including the United States and Australia, providing information about the likely path followed by the smoke plume and some indication of the expected smoke concentrations (<http://capita.wustl.edu/FSAN/BlueskyRAINS.htm>; <http://www.arl.noaa.gov/smoke>). A description of the Australian smoke forecasting system, together with validating case studies, is available online from the Bureau of Meteorology (<http://www.bom.gov.au/bmrc/pubs/researchreports/RR117.pdf>).

Most of these smoke forecasts concentrate on regional transport (1–500 km) over periods of less than 36 hours. As smoke particulates may remain in suspension for many days, however, plumes may have impacts at locations far removed from the original fire locations. The widespread haze experienced in South-East Asian countries is a demonstration of this.

11.2.7 Implications of climate change for forestry production

Climate change involves increased atmospheric CO₂ and O₃ (ozone) levels, increased temperatures, changes in precipitation patterns and more frequent storm events. These changes will affect forest production directly, interactively and through myriad feedbacks involving ecosystem processes and functions. Doubling of atmospheric CO₂ is expected to increase temperate forest net primary production (NPP) of developing forest stands by 20–25 per cent over the short term (Norby et al., 2005), but in many ecosystems gains will decrease as soil nutrients become limiting (Hungate et al., 2003). Interactions with global change-related increases in N deposition may be important, but not necessarily beneficial (Bauer et al., 2004). There is less certainty about implications for tropical regions or for larger, mature stands (Korner et al., 2005). Elevated ozone levels decrease forest production and may largely offset CO₂-induced gains in some forest regions (King et al., 2005).

Global warming is expected to be greatest at higher latitudes, leading to large-scale changes in species composition, plant migration and forest production. Northward movement of boreal species into the tundra and increased forest cover in the taiga should increase production, as should extended growing seasons associated with warmer temperatures in many boreal and northern temperate forests (Jarvis and Linder, 2000). This increase, however, will be gradual, and may be limited by soil nutrient and water availability, and by tree migration rates (Starfield and Chapin, 1996; Solomon and Leemans, 1997). In drier continental regions, increased temperatures may induce droughty conditions, decreasing forest production (Loustau et al., 2005) and encouraging the replacement of closed forest with grasslands, savannas or semi-desert in some places. In other areas, agriculture may supplant forest production on better soils.

Large-scale disturbance, including fire, insect and pathogen outbreaks, drought, flooding, and wind and ice storms affect forest production both by damaging existing forests and by altering competitive dynamics. Disturbance frequency, type, intensity, size and duration are strongly affected by climate change (Dale et al., 2001), and will likely have greater effects on overall forest production than climatic effects on physiological processes (Thornton et al., 2002). In many cases, climate change is expected to increase disturbance regimes, often reducing forest production (Flannigan et al., 2001).

Longer-term forest community response will reflect tree life spans, dispersal abilities, phenotypic plasticity, genetic variability, competition and disturbance. Substantial lags in community response are expected: tree species are usually long-lived, tolerant of climatic variability, and often grow well in warmer temperatures, although locally adapted provenances may experience growth declines. Hence, in the absence of climate-induced changes in disturbance regimes, catastrophic diebacks are unlikely and forest production may remain largely unaffected as communities begin to reassemble (Loehle and LeBlanc, 1996). Changing disturbance regimes, however, are likely to have greater effects. For instance, changing fire regimes, pest outbreaks or dispersal abilities may competitively disadvantage more productive species. This could lead to alterations in stand dynamics, successional trajectories and temporal developments in forest production.

11.3 METEOROLOGICAL OBSERVATIONS FOR FORESTRY APPLICATIONS

11.3.1 Measurement of wind and precipitation

11.3.1.1 Wind

Commercial forestry and silviculture measurements of wind are important for the viable production of forestry or non-forestry tree commodities (for example, timber and fruit). Wind flow, especially at speeds greater than 15 m s^{-1} , can produce extremely destructive effects on a forest through tree fall (windthrow) or snapping (windsnap). Trees exposed to consistent wind flows above 7 m s^{-1} , on coastal or elevated sites for example, develop differently from trees of the same species developing under sheltered conditions, and this can potentially affect crop yields from trees. Furthermore, specialized fire weather observations of wind speed may be used in an attempt to correlate fire spread with wind speed, slope and fuel characteristics in areas susceptible to forest fires (see 11.3.3).

Meteorological records generally describe surface wind characteristics in statistical terms, using average values taken over long intervals. The wind is defined in terms of a vector of its direction and speed, with continuous wind measurements taken, in accordance with an international agreement (WMO, 2008), at a height of 10 m above the ground. Forested areas complicate wind characteristics, however, based on airflows over the top of a stand (primary airflow) and the flow penetrating the trunk space (secondary

airflow). Furthermore, the effect of forest stands on the terrain roughness is also a decisive determinant in the vertical profile of the wind speed. Therefore, to minimize the effect of forest vegetation on airflow, the anemometer mast should be located in the centre of an opening in the forest with a diameter at least 20 times the height of surrounding trees. If this is not possible, the size of the opening and height of surrounding trees should be recorded. It is not considered appropriate to locate anemometers at a height of 10 m above the tops of the trees in a closed forest because wind profiles are significantly different from those over solid ground owing to the effect of the tree surface profile.

11.3.1.2 Precipitation

Precipitation measurements for forestry operations are important for estimating the water balance of areas of forested land, water status and water use efficiency of trees. Too much or too little precipitation will cause problems for foresters. Drought stress, waterlogged ground and flood conditions can have serious consequences for the health and development of trees and commercial crop yields from trees. Measurement of precipitation in forested areas is subject to many of the same difficulties as the measurement of wind speed, however. It should be noted that rainfall measurements, in general, are subject to systematic and random errors from both instrumentation and sampling. The aerodynamic effects of wind turbulence over raingauges produce significant errors of rainfall sampling among rain-gauges at a site (Rodda, 1967; Robinson and Rodda, 1969) and forests may exert a significant impact on precipitation measurement because of the effect of tree stands on wind profiles. Further errors in precipitation measurement in forested areas may occur when recording snowfall or rainfall at higher elevations (Sevruk and Nevenic, 1998).

The measurement of precipitation comprises two aspects: first, the point measurement of precipitation at a gauge and, second, use of the catches at a number of gauges to estimate areal precipitation. For point measurement of precipitation in forested areas, a precipitation gauge should be located so that surrounding objects are not closer than a distance equal to four times their height. At exposed sites, the effect of wind can be reduced through further techniques, such as construction of turf walls or use of a ground-level gauge. Additional precipitation measurements may also be undertaken to determine specific hydrological processes or research questions. To measure inputs from fog and dew, especially in areas prone to fog (for example, maritime areas), a number of different fog/dew gauge designs have

been used, including wire harps, cylindrical screens and louvered metal gauges (Bruijnzeel, 2001).

Determination of the areal pattern and quantity of rainfall may be achieved with a well-designed network of rain gauges or by using additional information from remote-sensing (such as weather radar and satellites). Estimation of areal precipitation using rain gauges alone is difficult, as errors will occur due to the random nature of storms and their tracking between gauges. In general, estimates of areal precipitation will increase in accuracy as the density of the gauging network increases. Broad guidelines for the minimum gauge density of precipitation networks in various geographical regions are outlined in WMO (1994b) and are presented in Table 11.1. For forestry applications, gauge density for estimation of areal precipitation will normally fall between 25 and 600 km², depending on the geographical location of forestry plantations and non-forest tree agriculture (for instance, nurseries). However great the density of existing precipitation networks, they can only give an approximation of the actual spatial pattern of precipitation. Increased accuracy and reduced error in the areal distribution of precipitation for the forester and agronomist can be achieved through a combination of rainfall calculations from satellite imagery linked to measurements at radar stations, which, in turn, are calibrated with several rainfall gauges.

Further information on the location and sampling of rainfall gauges is contained in the WMO *Guide to Meteorological Measurements and Methods of Observation* (WMO-No. 8) and the WMO *Guide to Hydrological Practices* (WMO-No. 168).

11.3.2 Specialized observations for orchard pest and disease management

Weather governs the development of pests and diseases that affect forest and non-forest trees.

Temperature, humidity, rain, radiation and wind are the main meteorological variables that influence the development of insects, weeds and plant pathogens. Temperature is the key factor in insect development. Temperature and moisture are the major factors to be considered in the infection and spread of a disease. Temperature before, during and after the application of herbicides tends to alter the susceptibility of the weeds and pesticide efficacy. During herbicide spraying, wind and turbulence increase off-target drifts; rain during and up to some hours after spraying washes away the pesticide, strongly reducing its effectiveness (WMO, 1988).

Pest and disease management, using real-time weather information, is done for fruit orchards on an exclusive basis. When a nearby, representative, automated weather station is available, meteorological elements may be used for the forecast and management of pests and diseases. It should be kept in mind, however, that air temperature and humidity obtained at such a station are likely to be rather different than their canopy counterparts, and rain and wind speed and direction may change abruptly over short distances. When on-site measurements are not contemplated, simulation models may be used to generate agrometeorological variables needed for input in the pest or disease simulators, using some of the available variables. Hence, air temperature and humidity in the canopy and leaf wetness may be predicted using appropriate models (Weiss, 1990).

If a representative weather station is not available, or is not satisfactory for the research application or pest and disease management scheme, it is necessary to install a specialized station. The WMO guidelines on type of instrument, specifications and layout of the instruments for weather stations generally apply for the specialized station (WMO, 2008). Air temperature

Table 11.1. Guidelines for precipitation gauge density in precipitation networks in various geographical regions (WMO, 1994b)

<i>Geographical region</i>	<i>Gauge density (km²)</i>
Small mountainous islands with irregular precipitation	25
Mountainous areas (temperate, Mediterranean, tropical climates)	100–250
Flat areas (temperate, Mediterranean, tropical climates)	600–900
Arid and polar climates	1 500–10 000

and humidity should, however, be measured in the environment where pests and diseases develop (that is, the canopy). Precipitation should be measured over a grass surface and free from the influence of the canopy and any other obstacles. Wind speed and direction should be measured above the crop canopy and with adequate fetch (about 100 m upwind fetch for each metre of anemometer elevation above the crop top) (Gillespie, 1994).

Surface wetness duration (SWD) is a specialized measurement that is very important for disease management. Modern electronic sensors were reviewed by Sutton et al. (1984, 1988). The widespread principle of operation consists, basically, of measuring surface water deposition by a change in sensor resistance. Two or more conductors are placed alongside one another on a plate (for example, a circuit board, film or leaf), leaving a small gap between them. When the gap is filled with the water from dew or rain, a resistance drop is recorded. Since there is no standard sensor, numerous designs and sizes of sensors are in use (Weiss and Lukens, 1981; Huband and Butler, 1984; Weiss et al., 1988). The placement and orientation of the sensors are important. In general, sensors should be located in representative spots in the canopy and may be wired in parallel to save data logger channels, if necessary. Using the worst-case scenario approach, when the number of available sensors is small, half of them may be located in spots of greater accumulation of dew (that is, the top part of the canopy) and the remaining sensors may be deployed in shady spots, located deep in the canopy, where water from rain tends to resist evaporation. Flat sensors should be tilted at an angle to the horizontal (for instance, 45°) to avoid excessive puddling of water (Gillespie, 1994).

11.3.3 **Specialized fire weather observations**

11.3.3.1 **Weather data for fire management**

Fire managers need weather data to determine primarily the ignition and spread potential of a fire on a given landscape. Many of the weather variables that are recorded, such as hourly temperature, relative humidity, global radiation, wind speed and precipitation, are common to agricultural interests. What makes fire weather observations unique is the type of locations at which the data are usually required. These tend to be remote, uninhabited areas, more often than not in complex terrain.

11.3.3.2 **A specialized fire weather network**

Fire weather interests in the United States have given rise to a weather network specialized for fire management. Remote automatic weather observing systems are dedicated to fire danger rating through strategic placement of weather stations and frequent and consistent reporting of fire weather observations. In the early history of fire danger rating, fire weather observations were collected manually once daily, usually in the early afternoon. Now, computer-controlled sensors gather weather data at programmed intervals that can capture localized diurnal effects. Nearly 2 000 remote automatic weather stations now populate the fire weather network in the United States (Figure 11.2).

11.4. **COMPUTER SIMULATION MODELS APPLIED TO FORESTRY AND NON-FOREST TREES**

The application of computer models in forestry can be split broadly into two parts. First, there are numerous different modelling approaches developed originally as research tools. These are used to consolidate and expand scientific understanding of how plant organs, entire trees and complex ecosystems respond to environmental factors – including meteorological variables operating at timescales ranging from seconds (in the cases of photosynthesis and stomatal function) to climatic cycles and trends lasting decades to centuries (in the cases of fire regimes and vegetation succession). Second, there are rather fewer examples of models developed as decision support tools (DSTs). In many cases these are derived directly from the researchers' models, although some may be created from the outset as applied models for forest management.

The following sections offer an outline of the range of computer models currently used in both forest research and forest management, subject to the important criterion that they require some form of climatic or meteorological input data (or "forcing"). The discussion therefore excludes conventional, statistically derived growth and yield models constructed from mensuration data alone. These growth and yield models treat climate as a component of site quality, and hence implicitly assume that the mean climate at any site does not change over periods of a stand rotation or longer. Such models have served the practising forester well in the past.

Global atmospheric concentrations of some greenhouse gases (GHGs) have increased

significantly since 1850, however; in 2006, carbon dioxide (CO_2) concentration was close to 40 per cent higher. It is now generally accepted by the scientific community that these increases in GHG concentrations have already contributed to appreciable changes in annual mean temperature and rainfall patterns in many parts of the world (IPCC, 2001a). In addition, higher CO_2 levels may have possible direct effects on photosynthesis. Simulations of future climate carried out using global models of atmospheric and ocean circulation, forced by projected increases in GHGs due to burning of fossil fuels and land-use change (primarily tropical deforestation), indicate that greater climatic changes will inevitably occur within the twenty-first century. This need not imply that all growth and yield models are now useless, but it does bring their application for forecasting future timber yields into question (for example, see Matala et al., 2003; Hall et al., 2006). This section attempts to address this issue by highlighting some recent examples of process-based “hybrid” approaches to yield modelling, as described by Landsberg (2003a), in which the traditional approach is merged with some form of climate sensitivity. The vast literature on dendrochronology, in which regression models are frequently used to relate interannual and longer-term variations in annual diameter increment to historical climate trends, is excluded.

The categorization used in the following sections is intended to identify the major types of models that have been developed, but inevitably many omissions will occur. There will also be overlaps, particularly in the description of larger-scale (landscape to

continental) vegetation models, which attempt to integrate the effects of all the important climate-dependent processes affecting forest structure and function.

11.4.1 Growth and production models

11.4.1.1 Canopy process models

The primary function of a plant canopy is to intercept and use solar energy to create carbohydrates from CO_2 and water. Understanding of leaf-level biochemistry has advanced greatly over the last 30 years. Physiological models developed by Farquhar and co-workers (for example, Farquhar et al., 1980) are at the core of many present-day canopy process models. These biochemical models also provide the basis for a mechanistic representation of stomatal functioning that operates as the primary control of transpiration. Scaling up from the leaf to stand level is accomplished by some representation of canopy light interception, integrated over space and time. This may be the simple Beer’s Law approach, first proposed by Monsi and Saeki (1953), which expresses light absorption as an exponentially decreasing function of leaf area index (LAI, that is, total foliage area expressed per unit of ground area). More detailed light interception models account for vertical profiles in structural variables, including leaf angle distribution and specific leaf area, and the separation of incident short-wave radiation into beam and diffuse components, which are in turn reflected and backscattered within the canopy. Other important canopy variables include photosynthetic capacity (often correlated to foliar

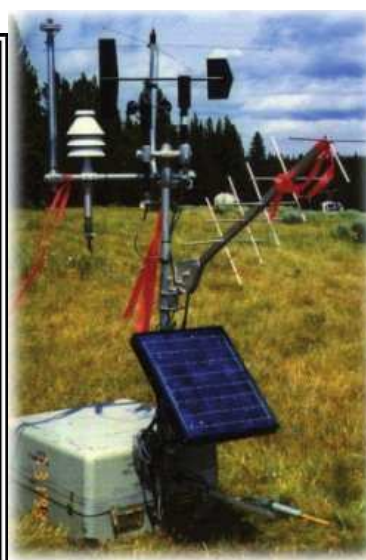
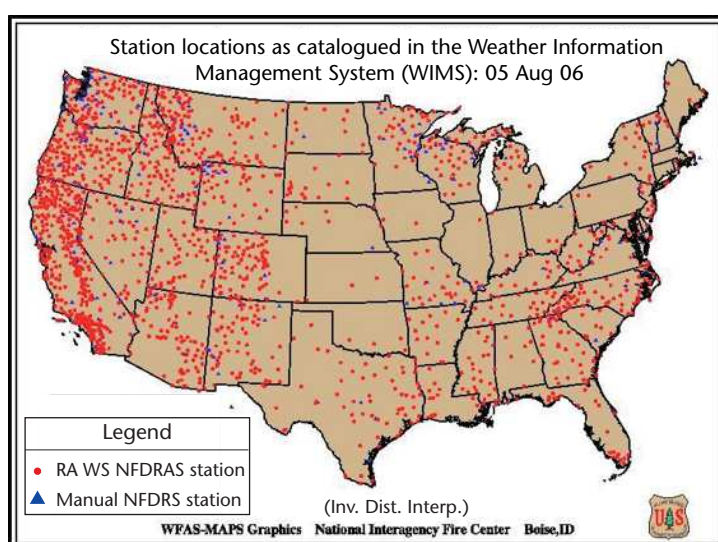


Figure 11.2. Fire weather station locations in the continental United States (left). Most of the stations are automated, like the one shown (right), a necessity in the remote areas in which they are located.

nitrogen (N) concentrations), and the gradients in temperature, humidity and leaf boundary layer conductance, resulting from the turbulent exchanges of heat, water vapour and wind energy.

Cannell and Thornley (1998) provide a useful review of the interacting effects of temperature, irradiance and CO₂ responses of leaf and canopy gross photosynthesis in C₃ plants, which are key to understanding the principles of canopy process models applied to forests. More detailed explanations of these principles and their applications in models can be found in Landsberg and Gower (1997) or Landsberg (1986). Many of these models are developed and validated in conjunction with detailed measurements of canopy level exchanges of heat, water vapour and CO₂. The models can then be used to fill in periods of missing data, or to predict canopy responses for combinations of environmental factors not observed in reality, including scaling up in time and space. Examples include: (1) the CANOAK model of Baldocchi and Wilson (2001), which is used to estimate fluxes of CO₂, water and energy over multiple years; it captured 80 per cent of observed variance when forced by hourly meteorological data and demonstrated the importance of leaf clumping and growing season duration in annual net ecosystem exchange (NEE); (2) a model reported by Williams et al. (1998), who compared eddy covariance measurements with a model applied to undisturbed rainforest in Brazil, obtaining good agreement and providing a physical explanation of dry season fluxes; (3) the use of a suite of models by Arneth et al. (1999) to simulate NEE of young *Pinus radiata* at a drought-prone site in New Zealand, finding it was sensitive to changes in PAR on short timescales, but interannual variations were related to humidity deficit and soil water as affected by summer rainfall; and (4) Wang et al. (2004), who combined measurements in a *P. sylvestris* stand in Finland over three years with a model of canopy transfer resistance and energy balance to assess intra- and interannual variations in fluxes of water, heat and net radiation at the forest floor.

The required inputs to such models vary, but will typically include daily or hourly temperature, radiation and humidity, as well as some representation of available soil water. In most cases, biophysical variables, such as plant and soil hydraulic characteristics, must be prescribed, but others, such as leaf area index and foliar nitrogen content, may be simulated. Various “weather generators” have been developed to disaggregate climate data recorded at daily or longer time steps into high-frequency meteorology (for example, Richardson, 1981; Geng et al., 1985; Wilks, 1992;

Semenov and Barrow, 1997; see also Semenov et al., 1998). Clearly, measurements are preferable to modelled data, but the latter can often provide acceptable results, particularly if observed variances can be used to influence the distributions of simulated extremes, and the covariances of the simulated variables (radiation and precipitation, for instance) can be preserved.

Other canopy process models developed over the last 15 years or so include: MAESTRO (for example, Wang and Jarvis, 1990), FOREST-BGC (for example, Running and Gower, 1991; Running and Hunt, 1993), PnET (for example, Aber and Federer, 1992), TREGRO (Constable and Retzlaff, 2000), BEPS (for example, Liu et al., 1997, 2002) and CABALA (Mummery et al., 2002). Grant’s *ecosys* model (for example, Grant et al., 2001) has been applied successfully to a wide range of crops and forest systems, and is arguably one of the most detailed process models currently available, although it does not presently account for competition among species.

11.4.1.2 Hydrological models

Vegetation cover provides a crucial link in the water cycle between soil and atmosphere. Surface hydrology models therefore often include a canopy process component as a control on evapotranspiration, which may range from a simple empirical representation to a fully coupled model of canopy photosynthesis and stomatal control. A distinct subgroup is known as soil–vegetation–atmosphere transport (SVAT) models, which simulate water movement via roots, stems and canopy, but typically lack a detailed representation of photosynthesis and carbon allocation (for example, Williams et al., 2001, who simulated drought responses of sap flow in ponderosa pine trees of different ages and sizes). The following discussion focuses on the important linkage between vegetation and surface hydrology.

The Penman–Monteith equation (P–M) (Monteith, 1964) is perhaps the most famous and most widely used example of a biophysical model. Its representation of stomatal conductance (at the leaf or canopy level) is necessarily simplistic, meaning that it needs to be parameterized for application to specific conditions, but the equation is theoretically correct in its combination of radiative and convective drivers of evapotranspiration (ET). There are numerous derivatives of the P–M, which have been applied to forest systems in many different ways (for example, Bosveld and Bouten, 2003; Hogg, 1994, 1997; Irvine et al., 1998; Martin et al.,

1989; Spittlehouse and Black, 1981). One modification that has been used successfully for many vegetated systems is the Priestley and Taylor (1972) formulation of potential evapotranspiration (PET). Originally developed for irrigated agricultural crops, it has since been applied to natural ecosystems, including forests, with relatively straightforward calibration of its alpha parameter. Fisher et al. (2005) provide a comparison of PET models, noting that soil moisture controls are crucial for correct estimation of evapotranspiration. It should also be noted that ET models derived from the P-M generally require measurements or estimates of net radiation above the canopy.

Hatton et al. (1993) modified FOREST-BGC to account for evaporation from the soil and from wet canopies (following McNaughton and Black, 1973). They applied this model to *Eucalyptus* forests in south-eastern Australia, validating it against data for both coastal and inland semi-arid forests. The predicted water deficits agreed well with observed data in both systems, suggesting that the model could be used to estimate impacts of changes in land cover or climate on water balances over large regions.

Statistical correlations between ET and productivity have been noted for some time, while recent advances in modelling the linkage between leaf-level photosynthesis and stomatal functioning provide strong theoretical support. Spittlehouse (2003) developed a simple approach to modelling the dependence of forest productivity on growing season moisture availability computed from rainfall and soil data. He used this approach to correlate site characteristics to site productivity and then infer the site-level sensitivity to climate change, based on projected changes in rainfall and ET (as a function of temperature). Richardson et al. (2002) used a simple water balance model to explain effects of broom understorey on the growth of *P. radiata* in New Zealand. Broom was removed from some plots and this evidently resulted in greater water availability, supported by model and nitrogen probe measurements. Similar work was carried out in western Canada by Kelliher et al. (1986), who investigated the effects of an ericaceous understorey shrub (salal, *Gaultheria shallon*) on water relations and growth of Douglas-fir (*Pseudotsuga menziesii*).

Forest hydrology is concerned with aspects of water movement within and through forested catchments, with applications including water management (quality and quantity), erosion control (for example, Benda and Dunne, 1997; Connolly et al., 1999),

forest engineering problems, and management of riparian and freshwater habitats (see 11.4.1.8). Approaches to modelling forest hydrology are similarly varied, but generally require some representation of the water balance applied to the region of interest. Reviews by Xu (1999) and Xu and Singh (2004) discuss traditional methods (going back to Thornthwaite's original approach to estimating ET, as reported, for example, in Thornthwaite and Mather, 1957), and compare these to the newer generation of spatially distributed hydrological models. They also discuss the need for validation methods suited to the target application, citing as an example a model developed as part of the Scandinavian Northern hemisphere climate Processes land-surface EXperiment (NOPEX) programme (Xu et al., 1996).

Recent developments in Geographical Information Systems and the easy access to high-resolution digital elevation models now allow accurate prediction of catchment-scale water balances from relatively few weather inputs. Some of the many spatialized forest hydrology models available, focused at the watershed or catchment scale, include: the Regional Hydro-ecologic Simulation System (RHESSys) model (Coughlan and Running, 1997; Baron et al., 1998); the Forest Hydrology Model, or ForHyM (Arp and Yin, 1992; see also Balland et al., 2006, for coupling of soil hydrology to thermodynamics); the Distributed Hydrology Soil Vegetation Model, or DHSVM (for example, Storck et al., 1998); and a watershed-scale hydrologic model called DRAINWAT (Amatya et al., 2006).

11.4.1.3 Soil decomposition models

Many models of forest ecosystems require a representation of soil decomposition processes. These accept simulated litterfall from above- and below-ground components of the forest, and then simulate heterotrophic decomposition of the litter material, typically as a function of soil temperature and moisture content, splitting it into multiple pools, decaying at different rates, and classified according to substrate quality and/or chemical composition. These pools then transfer carbon content to the simulated soil profile, with the net rates of C accumulation contributing to the calculation of net ecosystem productivity.

Given the incomplete knowledge, and considerable complexity, of soil decomposition processes, these models are often used as much to test ideas as to make predictions. Some notable examples include CENTURY of Parton and co-workers (for example, Parton et al., 1992); the RothC model from the

United Kingdom (used by Jones et al. (2005), for example), coupled to different general circulation models (GCMs); the models of Verberne et al. (1990), as used in the Integrated Biosphere Simulator (IBIS) dynamic vegetation model reported by Kucharik et al. (2000); and ROMUL of Chertov et al. (2001). Falloon et al. (2002) used both RothC and CENTURY to compare estimates of C uptake under different land uses, including afforestation, with a regression model, finding some major differences. The Q model of Ågren and Bosatta (1998) is rather different in that it treats the organic component as a substrate that changes continuously in quality and over time (rather than as discrete pools in which decomposition is a simple first-order decay function of the current pool size).

Closely related to models like CENTURY are the Peat Decomposition Model (PDM) and Peatland Carbon Simulator (PCARS) models of peat accumulation and decomposition in peatland ecosystems, developed by Frohling et al. (2001, 2002), and Wetland-DNDC, which refers to DeNitrification-DeComposition (for example, Zhang et al., 2002). These models are specifically designed to account for the annual deposition and anaerobic decomposition of organic material characteristic of wetland ecosystems. The DNDC model of Cui et al. (2005) simulates dynamics of forested wetlands in response to environmental and plant physiological factors, as well as decomposition processes.

Numerous models also exist that link soil decomposition to nitrogen cycling and hence provide feedbacks to forest productivity at stand-level or larger scales. Examples include VEGIE (Aber et al., 1991), work by Kang et al. (2003), the spatial model of Fan et al. (1998), the submodel for IBIS developed by Liu et al. (2005) and EFIMOD (Chertov et al., 2003; Komarov et al., 2003), which is based in part on ROMUL.

11.4.1.4 Phenology models

Models of plant phenology typically operate on the basis of degree-day sums starting from the beginning of the year (or 1 July in the southern hemisphere), although other climatic criteria may also be used, including soil temperature, soil water status and day length. Tree growth processes that may be predicted include emergence from dormancy, seed germination, leaf expansion, flowering, leaf fall and the onset and cessation of height growth. Phenology models are useful as predictors of tree or crop suitability for particular regions, both for present-day management and for assessing how suitability might change with possible future

climates. They are also important components of large-scale vegetation models to determine the approximate timing of leaf emergence and leaf fall of deciduous tree species.

The continental phenology model of White et al. (1997), applied initially to the continental United States, has potential application to other regions, although regionally specific parameterization and validation (using satellite remote-sensing data) will be required. De Melo-Abreu et al. (2004) compared several models of flowering phenology in different olive varieties in Spain, of which a “chill–heating model” gave the most plausible predictions and should be applicable to other woody species. Arora and Boer (2005) developed a new approach to predicting leaf phenology, in which leaf appearance occurs only when environmental conditions would result in carbon gain. Conversely, leaf fall is caused by unfavourable conditions that cause C losses, including shorter days, suboptimal temperature and drought conditions. This representation is considered sufficiently robust to work at global scales and in simulations of transient climate change.

11.4.1.5 Population models (single-tree, gap-phase dynamics)

Simulation of forest stands and forests as collections of individual trees has been of interest for almost as long as digital computers have existed. Adopting this approach, the ground-breaking JABOWA model of Botkin et al. (1972) led to the development of an entire class of forest stand models used mainly for representing growth dynamics of natural or extensively managed forests, over long periods, and under projections of climate change. More recent examples include FORSKA (Prentice et al., 1993), FinnFor (Vaisanen et al., 1994), FORCLIM (Fischlina et al., 1995; Bugmann and Solomon, 1995), GUESS (Smith et al., 2001), SORTIE (for example, Canham et al., 2004) and PICUS (for example, Lexer and Hönninger, 2001). A key feature of many of these models (though not all) is that trees of multiple species are simulated within small (ca. 0.1 ha) sample plots, without predetermined spacing or timing. They are allowed to seed, grow, compete for environmental resources, including light, water and nutrients, and ultimately die (leaving gaps for regeneration). This contrasts with the rather smaller group of spatially explicit stand simulators (such as TASS, DFSIM), which attempt to model the interactions among individual trees in a managed even-aged stand, predicting effects on stem form, branchiness and wood quality within a single rotation and validated against detailed measurements. Almost certainly, however,

some models bridge the divide between these contrasting approaches.

Recent reviews of many of the features of the current generation of gap-phase dynamics models are provided in a collection of papers edited by Bugmann et al. (2001). Inputs to these models typically include mean temperature and temperature range (that is, maximum minus minimum), precipitation, and cloud cover fraction (if not solar radiation), although other inputs, including humidity, are possible. Monthly data are typically used, but some studies have shown that daily input can produce rather different results – suggesting that these are to be preferred if available.

11.4.1.6 Disturbance models

Disturbances to managed and unmanaged forest ecosystems include wildfire, outbreaks of insect pests, and storms and floods. Of these, fire models are also discussed in 11.4.3, and therefore will not be addressed further here.

11.4.1.6.1 Insects

It is possible that the great biodiversity of tropical ecosystems, supported by relatively even seasonal temperature regimes, serves to protect them from major insect epidemics. Insect-driven disturbance events are certainly more common at higher latitudes, particularly in mid-continental boreal ecosystems. Boreal forests typically are composed of relatively few tree species (for example, see Nikolov and Helmisaari, 1992) and are subjected to very cold winters and short summers, which impose a strong seasonality on insect life cycles.

Moreover, stands are often large and more or less continuous across the landscape – which contributes to the propagation of the next stand-replacing disturbance. But this large-scale contiguous nature also results partly from the important role that natural disturbances, both fire and insects, play in boreal stand regeneration and development. It is for these reasons that much of the interest in models of forest insect disturbance originates in boreal nations – where calculated commercial losses due to insect pests can be comparable to those from fire.

Malmström and Raffa (2000) present a review of modelling approaches and point to the need to represent disturbances as dynamic responses to climate, particularly those caused by insects. Examples of these approaches include Økland and Bjørnstad (2003), who have used non-parametric

spatial covariance functions to analyse the endemic spatial distribution of spruce bark beetles with climate. They found inverse relationships with latitude (implying that temperature is an important factor), as well as correlations with forest productivity and drought-prone soils, and the occurrence of windthrow events. In Canada, Fleming and Candau (1998) adopted a process-based perspective on factors controlling spruce budworm (SBW) outbreaks, including natural selection, extreme weather events, phenology, interactions between pest and host, and “threshold behaviour” (the factors causing the shift from endemic levels to serious outbreaks).

More recently, Candau and Fleming (2005) used classification and regression tree (CART) models to analyse high-resolution spatial data and determine climatic controls on SBW defoliations. Climate warming is now considered a significant factor influencing many of these processes, with profound implications for natural biodiversity and forest management. Williams and Liebhold (2000) investigated spatial and temporal correlations of SBW outbreaks in eastern North America for 1945–1988, finding that synchrony approaches zero at distances over 2 000 km. The east–west pattern correlated to monthly temperature and precipitation data over the same period, but this also decreased with increasing distances. They then developed a spatially explicit lattice model for a single pest species occupying multiple patches of forest, using this to determine that observed distributions of SBW outbreaks are synchronized through a combination of high dispersal rates with a spatially autocorrelated Moran effect (local and regional stochasticity). Gray (2004) developed a model of gypsy moth phenology tested at 4 500 locations and found that the northern and southern limits of its range would likely shift northward with climate warming.

A recent huge outbreak of the mountain pine beetle (MPB) in central British Columbia (in which several million hectares of forest were destroyed) has also been attributed in part to recent climate warming. Carroll et al. (2003) combined a model of climate impacts on conditions favouring MPB with a spatially explicit climate simulator. Analysis of historical climate then showed a clear increase in benign beetle habitats over the period 1921–2000, which evidently explains observed occupations of new areas by MPB and suggests that further climate warming will allow a wider spread into eastern and northern Canada and to higher elevations.

Stahl et al. (2006) investigated the role of synoptic-scale circulation and large-scale climatic modes as

factors causing MPB mortality events in British Columbia. They found that the occurrences of daily minimum temperatures had not reached those needed for 100 per cent MPB mortality at several climate stations in recent years, which was related to reduced occurrence of winter outflows of frigid Arctic air affecting central British Columbia. This behaviour appears to be due to increased frequency of strongly positive Pacific Decadal Oscillation events, and of corresponding negative phases of the Arctic Oscillation, which may in turn be a consequence of a global warming trend.

11.4.1.6.2 *Storm damage*

Hall et al. (1992) were early users of spatially explicit information to model responses of tropical forests in Puerto Rico to climate and hydrology (including hurricanes), as influenced by topography, soils, land use and vegetation type. They were able to show that over several centuries, after taking hurricane damage into account, these ecosystems effectively “pump” carbon from the atmosphere to the ocean at an average rate of $\sim 90 \text{ kg C ha}^{-1} \text{ yr}^{-1}$.

Winter storms are a major concern at high latitudes. For example, Peltola et al. (1997) developed the HWIND model to calculate critical combinations of snow loading and wind speed for boreal tree species in Finland. They found that less-tapered trees were more vulnerable to damage and that snow loading was more important than wind speed. Evergreen conifers were much more susceptible to damage than deciduous birch. Other work from Finland includes that of Jalkanen and Mattila (2000), who used logistic regression models to predict susceptibility of stands to combined effects of wind and snow loading.

Talkkari et al. (2000) have developed an integrated suite of models at tree, stand and regional scales to assess risks of wind damage at forest margins. The system includes a mechanistic model to predict the critical wind speeds needed to cause damage (using tree height, DBH and stand density as inputs), a regional wind climate model (based on site location, topography and surface roughness, and using climate station records), and GIS data on the probability distribution of extreme wind speeds. The integrated approach appears to have great potential for predicting areas at risk and hence for targeting silvicultural prescriptions to reduce damage in high-risk areas.

Ancelin et al. (1999) developed the mechanistic individual tree-based FOREOLE model to simulate effects of wind on heterogeneous stands (that is,

where not all trees are damaged in the same storm event). The model accounts for wind gusting and predicts stem breakage or uprooting from comparisons to data on critical bending moments and critical compressive stresses, respectively. The FOREOLE simulations of critical wind speeds compared favourably to other models, including HWIND, and indicated that irregular stands suffer scattered damage at a range of wind speeds, whereas regular even-aged stands tend to fail as a single entity once the critical wind speed is exceeded.

Olofsson and Blennow (2005) have developed a prototype decision support tool to identify spruce stands at high risk of damage in southern Sweden. Decision trees were calibrated for a 1 200 ha forest based on stand-specific factors, including mean stem taper, gap sizes at the stand edge and direction of wind exposure. Independent testing of the model at a separate site showed only limited success in application, considered to be due to its failure to capture the underlying complexity of causes of wind damage.

11.4.1.7 *Biogeography models*

The emergence of biogeography models goes back to the mid-1980s, when the feedbacks of terrestrial vegetation to global climate were first being considered in GCMs. Important questions included the role of forests compared with deserts or grasslands, and the feedback effects resulting from tropical deforestation (for example, Henderson-Sellers et al., 1988; Shuttleworth et al., 1989). Models such as BATS (Dickinson et al., 1993), SiB (Sellers et al., 1989), LSM (Bonan, 1996) and CLASS (for example, Bartlett et al., 2003) were important developments that indicated how vegetation characteristics could affect global climate. Wang et al. (2001) enhanced the CLASS model to account for canopy photosynthesis, N uptake, respiration and senescence, explaining 80 per cent of observed variance (eddy covariance data) over a three-week period, and 85 per cent over two years at a boreal deciduous forest site in central Canada. Some researchers have used such models to investigate the sensitivity of global climate to large-scale changes in forest cover, notably Bonan et al. (1992) for deforestation and Betts (2000) for afforestation.

While the initial focus for GCMs was on static vegetation schemes (that is, parameterized with constants for the key variables), parallel developments led to a series of continental-scale vegetation models that would respond to climatic drivers. These included “equilibrium projection” models,

which correlate vegetation distribution to climatology, such as BIOME (Prentice et al., 1992), as well as large-scale derivatives of stand-level canopy process models (notably BIOME-BGC, derived from Running's FOREST-BGC), and the EXE model of Martin (1992), which links physiology, water balance and ecosystem dynamics to couple to larger-scale climate models.

The global equilibrium projection models were designed to be computationally efficient and capable of simulating responses to scenarios of future (stabilized) climate. But a major limitation in the concept of the equilibrium distribution of vegetation is that it would likely take centuries for full adjustment to new conditions to occur (for example, see Overpeck et al., 1991), even if the notion of a “constant climate” were plausible. Hence, these models are not suitable for projecting the short-term transitional responses of forests to a changing climate, which are needed to assess near-future impacts and to plan management adaptations.

Other models, such as CENTURY (for example, Parton et al., 1992) and the Terrestrial Ecosystem Model, or TEM (Raich et al., 1991; McGuire et al., 1993), were more focused on biochemical processes contributing to nutrient cycling and vegetation productivity, but could be applied at continental to global scales given appropriate climatic data. By the mid-1990s, dynamic vegetation models (DVMs) were being developed to address these limitations. Such models include many of the principles embedded in the biogeochemistry models, together with ecosystem responses analogous to those captured in forest gap models. Their objective is to simulate the short-term transitional effects of a variable and changing climate, so that vegetation responses can be projected over periods of years to decades, rather than centuries to millennia.

These models also integrate more or less detailed representations of canopy processes and phenological controls, as well as litter and soil decomposition and nutrient cycling, and possibly surface hydrology. Most also attempt to account for the effects of disturbances operating over periods of decades to centuries. Examples include later versions of TEM (for example, Tian et al., 2000; McGuire et al., 2001), as well as IBIS (Foley et al., 1996; Kucharik et al., 2000), MC1 (Neilson, 1995), Hybrid (Friend et al., 1997), LPJ (Sitch et al., 2003) and CTEM (for example, Arora and Boer, 2006). An intercomparison of six different dynamic models was reported by Cramer et al. (2001) for the global scale. Some of these models are now routinely “coupled” to GCMs – to simulate transient (continuous) vegetation

feedbacks to the atmosphere (water vapour, heat, momentum transfer, reflected and re-emitted radiation, GHGs) at hourly timescales. The objective is to increase understanding of the role of forests and other vegetation in maintaining the global environment, and to assess the impacts of human-caused changes in land use (such as deforestation and afforestation) on atmospheric composition (GHGs and other pollutants).

11.4.1.8 Biodiversity and habitat models (including riparian systems)

Globally, forests, and particularly tropical rainforests, provide habitat for a greater number of animal and plant species than any other terrestrial ecosystems. This is largely because a mature forest protects its inhabitants from climatic extremes, while providing a range of microhabitats and food sources. Hence, there is wide interest in modelling the effects of forest cover on microclimate, particularly as it affects habitats for fish and wildlife. In general, the models are empirical, relying on statistical relationships. Examples include principal component analysis applied to genetic variation of *Lupinus* species in Mt Hood National Forest in the United States, with topography and climate found to be key variables (Doede, 2005). Working in mountain ranges in Nevada, Fleishman and co-workers, (for example, Fleishman et al., 2001, 2003; Mac Nally and Fleishman, 2004) used a variety of statistical approaches, with GIS-based digital terrain data and microclimatic models, to predict resident butterfly populations in the state. Statistically significant models were developed for 64 per cent of 56 species, and elevation was found to be significant in more than half. These models were found to be applicable outside the range in which the statistical relationships were derived.

In Washington State, Sridhar et al. (2004) developed a physically based model to predict stream temperatures in forested watersheds in the Cascade Mountains. The model uses GIS databases to estimate low flows, which are normally correlated to higher stream temperatures. The worst-case scenario combines low flow conditions with high irradiance and air temperature. The model can then be used to determine effects of forest structure and stream buffer width on water temperature. Adams and Bury (2002) investigated factors influencing abundances of stream amphibians in Olympic National Park, also in Washington State. Three species were found to be associated with climatic gradients. In Sweden, Eggers et al. (2005) found that daily nest survival rates of Siberian jays decreased with reduced vegetation cover in northern Sweden due to habitat

loss. The causes included greater exposure to low temperatures and increased losses due to corvids. In the Brindabella Range of south-eastern Australia, Shine et al. (2002) investigated the effects of forest clearing on egg-laying reptiles. In this case, reduced vegetation cover increased radiation loads and temperatures at potential nest sites, generally raising the upper elevational limit (that is, hatching and survival increased), and possibly leading to changes in genetic structure and demography of populations.

11.4.1.9 Carbon budget models

A carbon budget model seeks to track some or all of the processes contributing to net changes in ecosystem carbon pools occurring over measured time periods (typically one year). The realization that the global community needs to reduce its emissions of greenhouse gases, followed by binding international commitments imposed by the Kyoto Protocol, has contributed to widespread interest in the use of forests as a temporary means of offsetting a portion of global GHG emissions. Forest carbon budget models are a crucial element in determining both the actual and potential carbon sequestration capacities of forests, because they must be applied at large scales (regional to national or larger), while providing acceptably small error limits that can be verified if the model results are audited.

Carbon budget models typically fall into one of two classes, although many models have features taken from both. On the one hand, there are stock-based “bookkeeping” models, of which the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), developed by Kurz and Apps (1999), is a well-established example. The CBM-CFS is now freely available in a user-friendly format and has been applied to forested regions around the world. The model enables effects of different management options and natural disturbance scenarios to be investigated. For example, Price et al. (1997) examined the responses of a managed boreal forest in western Canada to different rates of harvesting, fire losses and soil decomposition rates, and concluded that management would likely contribute to an increase in the long-term accumulation of soil carbon. Such models rely on large-scale inventory databases (often spatialized), including forest inventories, soils classification data and records of planting, harvesting and losses due to forest fires and other natural disturbances. The data are used in combination with a forest growth model and soil organic matter decomposition model to estimate changes in carbon pools (for example, soils, litter, biomass, harvested products) over a specified

period. This approach is analogous to that of an empirical growth and yield model used in a wood supply calculation.

The alternative approach is to use a combination of process models, such as CENTURY, and/or a biogeography model, forced by soils data and historical records of climate and disturbance events. In general, the bookkeeping model will produce smaller errors when the estimates are verified independently, but the process-based method has the advantage that it can be used more easily to project future changes in response to scenarios of climate change. Churkina et al. (2003) used BIOME-BGC to perform regional C budget analyses of four European forests, on daily and annual timescales, while attempting to account for the uncertainties resulting from inadequate data. They found that the model could underestimate respiration rates, possibly exaggerating its estimates of a net C sink. The results were sensitive to N and CO₂ fertilization levels, which are likely to be important factors in projecting future forest C balances. Vetter et al. (2005) also used BIOME-BGC to investigate the C budget of conifer forests in Thuringia. Like CBM-CFS, a particular feature of this model is that it accounts for the “legacy effect” of the present-day age-class distribution. Results indicated that net biomass increment increased over the period 1982–2001, turning the system into a C sink, which was attributed to pollutant N deposition in high-elevation systems and to CO₂ fertilization at lower elevations. The results agreed closely with average biomass growth rates estimated from inventories.

Tian et al. (2000) applied the transient version of TEM to assess C storage in undisturbed Amazon ecosystems. They found that about 83 per cent of total uptake occurs in tropical evergreen forest, typically split 3:1 between vegetation and reactive soil organic matter. These ecosystems sequestered about 0.2 Pg C yr⁻¹ between 1980 and 1994, although deciduous forests actually take up more carbon per unit area. Interannual variations in precipitation were evidently the major cause of interannual variations in annual net ecosystem exchange. Interestingly, Tian et al. (2000) recommended that C budget studies should extend over at least one El Niño–Southern Oscillation (ENSO) event cycle to account for interannual variability.

11.4.1.10 Applications to agroforestry and non-forest trees

There is a wealth of literature on modelling agroforestry systems that takes account of the physiological and ecological aspects previously

discussed, in addition to forcing meteorology (particularly of radiative distribution below the tree canopy, as in Zhao et al., 2003, for instance). Nygren et al. (1996) reported a whole-canopy CO₂ exchange model, driven by standard meteorological input, to simulate changes in canopy structure and its effects on canopy assimilation of poro (a leguminous forage tree of Central America, *Erythrina peoppigiana*) under different pruning regimes. De Reffye et al. (2004) describe several complementary approaches used to model growth of tree architecture to better capture interactions between canopy structure and environmental factors, while van Noordwijk and Purnomosidhi (1995) and Ozier-Lafontaine et al. (1999) have used fractal branching models to predict root growth in a range of species.

Not surprisingly, agroforestry models are most frequently applied to tropical systems. Van Noordwijk and co-workers have applied their comprehensive WaNuLCAS (“water, nutrient and light capture in agroforestry systems”) model to a wide variety of agroforestry systems in South-East Asia (for example, van Noordwijk and Lusiana, 2004). Kusumandari and Mitchell (1997) assessed soil erosion in West Java using the Agricultural Non-point Source Pollution (AGNPS) model, concluding that agroforestry was an optimal land use to minimize soil loss.

In Costa Rica, Mialet-Serra et al. (2001) worked on cocoa (*Theobroma cacao*) and coconut (*Cocos nucifera*) systems and Beer et al. (1990) on cocoa and poro. In Africa, McIntyre et al. (1996) applied the EPIC (Environmental Policy Integrated Climate, formerly Erosion Productivity Impact Calculator) model to simulate canopy light interception and hence estimate transpiration rates in different cropping systems of cowpea (*Vigna unguiculata*), maize and cassia (*Senna spectabilis*) in semi-arid Kenya. Cannell et al. (1998) (see also Mobbs et al., 1998) used a detailed process model to simulate relationships between light interception and water in West Africa, finding that in regions with less than 800 mm annual rainfall, agroforestry may improve overall water use, though it is unlikely to increase crop productivity. On the other hand, Wallace et al. (1999), also working in Kenya, constructed a simple water balance model to predict soil evaporation in systems with and without tree cover, and they concluded as well that trees can contribute to water conservation.

11.4.2 Management models

The previous sections have examined some of the many ways in which models requiring meteorological

input are developed as part of understanding various aspects of forest science. Specific models that have been applied, or that could have direct application, to solving problems in forest management will now be discussed.

11.4.2.1 Growth and yield models

Landsberg (2003a, 2003b) has reviewed the potential application of forest process models to growth and yield modelling, and has often highlighted the distinctions between site-specific empirical (statistical growth and yield, G and Y) models and mechanistic models, such as the canopy process models described earlier (see also Landsberg and Gower, 1997, or Landsberg, 1986). He argues that most process models contain too many poorly known parameters to be useful for practical application in forestry. Research over the last 30 years, however, has uncovered general principles relating to canopy light interception, photosynthesis, stomatal functioning, water relations and nutrition, which can be combined to develop practical process-based models useful for forest management applications. Conventional forest mensuration data will still be required to validate such models, but it may be possible to maintain fewer sample plots (perhaps measured to higher standards) to support G and Y models that will be generally applicable over much larger regions and will also be responsive to changes in environmental conditions, such as climate change. Landsberg concludes that the future lies in hybrid models where weather data, GIS-based inventories and multitemporal remote-sensing products (for instance, of leaf area index and species composition) are all used as inputs.

In general, these models are developed by researchers aiming to explain the processes by which photosynthetic uptake of CO₂ is transformed and allocated into harvestable material. Hence, many of the studies reported here link field measurements and meteorological datasets with assessments of model performance, often involving comparison with traditional G and Y predictions. Some researchers also point to the need for continued monitoring to support further model testing.

The Physiological Principles Predicting Growth (3-PG) model of Landsberg and Waring (1997) is based on a radiation use efficiency (RUE) approach, in which maximum net primary productivity (NPP) is expressed as a simple product of absorbed photosynthetically active radiation (APAR) and an adjustable coefficient, often denoted ϵ . Haxeltine and Prentice (1996) also proposed that variations in

foliar N and carboxylase activity over time and within the canopy tend to support a simple relationship between APAR and NPP. Reductions in productivity from maximum, for instance, due to water stress or nutrient limitations, can then be represented as simple multipliers between one and zero. The 3-PG model is easily calibrated to different sites and source code is freely available via the Internet. Both these factors contribute to its wide adoption and modification for numerous species around the world, with applications in Australia, Brazil (for example, Almeida et al., 2004), Canada (Bernier et al., 2002; Hall et al., 2006), South Africa (Dye, 2001) and the United States (for example, Coops and Waring, 2001).

Many researchers working in this field attempt to link high-quality measurements at specific sites with remote-sensing data as a means of scaling productivity estimates. Examples include Chen and co-workers, who developed the Boreal Ecosystems Productivity Simulator (BEPS) model for Canada (for example, Liu et al., 1997, 2005), and Law et al. (2001, 2004), who have worked with BIOME-BGC and data obtained from eddy covariance measurement sites across Oregon. A major problem though is that accurate measurements of forest NPP are difficult to make and are rarely available in sufficient quantity to validate the models adequately. Coops and Waring (2001) used 3-PG, and Hall et al. (2006) used StandLEAP (a variant of 3-PG developed by Raulier et al., 2000), combining satellite remote-sensing with forest sample plot and inventory data.

Other work in this area includes that of Rötzer et al. (2005), who used field data to validate a process-based tree-growth model called BALANCE, which was applied to several sites in southern Germany. Agreement with tree mensurational data was variable among species but proved generally acceptable over several simulated years, while the water balance submodel evidently produced very good results at all sites. Briceño-Elizondo (2006) used a process-based model to compare interacting effects of management and climate variations on productivity and carbon sequestration of boreal forests in northern and southern Finland. Tharakan et al. (2000) reviewed process-based growth and yield modelling of *Salix* plantations in the eastern United States. Peng et al. (2002), working in Ontario, linked three separate models (3-PG, CENTURY and the TREEDYN3 model of Bossel (1996)) to create a new integrated model called TRIPLEX, which has been used successfully to predict biomass and wood volume production of jack pine (*P. banksiana*). Models for the simulation of non-forest tree growth

and yield have been constructed and used mainly by researchers and seldom by farm advisers (Grossman and DeJong, 1994).

11.4.2.2 Fire ecology and fuels management

Many of the gap models described earlier have been adapted for fire management applications. The Landscape Disturbance and Succession (LANDIS) model (He and Mladenoff, 1999) simulates effects of fire, windthrow and harvesting on species-level succession, using a stochastic approach to simulating patterns over long timescales. When applied to six different landscapes in northern Wisconsin (United States), each with different species environments and different fire return intervals, the model predicted responses at different temporal scales, ranging from stand-level succession up to big fires, causing a coarse-grained pattern that persists over long periods.

The authors concluded that this approach should be applicable to the investigation of landscape-scale responses to management, as well as changes due to human land-use pressures and global warming. Miller and Urban (2000) developed a spatially explicit gap model that simulates tree growth and litter production. They used it to examine management alternatives for restoring forests in the Sierra Nevada region, where 100 years of fire suppression has resulted in unnaturally large fuel accumulations (see also articles by Bridge et al., 2005, and Schoennagel et al., 2004). Similarly, Stephens (1998) applied the Fire Area Simulator (FARSITE) spatial fire behaviour model to Yosemite National Park (United States) to assess different methods of controlling fuel build-ups, and hence determine best methods to limit uncontrolled fire hazards.

Other models are frequently used in fire management, both in assessing hazards and during active fire suppression. Fuel loadings are often related to the current moisture status of surface litter or upper soil layers. Goodrick (2002) modified the Fosberg Fire Weather Index (FFWI), based on temperature, relative humidity and wind speed, to account for precipitation effects by incorporating the Keetch–Byram Drought Index (KBDI) to formulate “fuel availability”. This improved the relationship between the FFWI and areas burned in Florida. Kafka et al. (2000), working in southern Alberta, used climate station input, topographic data and fuel distributions to compute potential head fire intensity (HFI) for every day, or for percentiles of occurrence. The

resulting quantitative maps can be used to identify areas of extreme fire behaviour potential for fire and forest management – either before or during a fire.

11.4.2.3 Insect pest management

Harrington et al. (2001) present a valuable review of the role of models in large-scale insect pest management. Although these authors focus on the sensitivity of insect pests to a warming climate, many of the principles are applicable to variations in climate (primarily temperature) as a driver for insect attacks. For a more detailed discussion of models applied to insect pest management, see also 11.2.2.5.

11.4.2.4 Storm damage control

Models have been applied to the operational problem of determining stand vulnerability to windstorm effects (see the discussion of the United Kingdom windthrow hazard classification under 11.2.1.4.2), and to the question of determining how natural forests subjected to storm damage should be managed. For such a determination, Kramer et al. (2001) applied a GIS-based model to pristine temperate rainforest on Kuiu Island, Alaska, to simulate long-term windthrow effects at landscape scale. Slope, elevation, soil stability and exposure were inputs, and effects on stand age and structure were considered. The model was validated against independent windthrow data from a nearby island, correctly classifying 72 per cent of landscape. They concluded that large-scale stand replacement is a natural process in areas prone to catastrophic windthrow (see also Grove et al., 2000), suggesting that harvesting in such areas should “emulate” these natural disturbance events.

11.4.2.5 Habitat, biodiversity management

Chen et al. (1996) modelled air temperature, wind speed, and direct solar radiation effects on the biological processes of managed Douglas-fir in the North American Pacific North-west region, concluding that the resulting landscape structure depends on transfers of energy and mass, as well as species interactions, all of which need to be captured in models or assessment methods. They argued that such information is useful for habitat management and species conservation.

In the eucalypt forests of south-eastern Queensland (Australia), Eyre and Goldingay (2003) used Poisson regression to detect the influence of climate and other habitat factors on activity by

yellow-bellied gliders (*Petaurus australis*), which feed on the sap of five different tree species and whose conservation is considered an important management objective. These authors found that flowering, productivity and stand density were important determinants of tree use, and hence were able to make recommendations for local forest management of these food resources.

Optimal habitat requirements for protecting the cinereous vulture, a species at risk in the Republic of Georgia, were determined using GIS-based data and logistic regression models (Gavashelishvili et al., 2006). The best sites were relatively dry, north-facing slopes of more than 30°, close to existing protected areas, and remote from humans. Low rainfall areas were found to provide better conditions for soaring and breeding. The researchers concluded that breeding ranges might be expanded if seasonal grazing areas were also managed appropriately.

11.4.2.6 Soil erosion assessment and control

The model of Connolly et al. (1999) was developed to study rain erosion of forest roads in subtropical Queensland. It includes a rainfall generator and outputs information on particle size distribution in gravel and dirt roads, and how these change with different rainfall intensities. This model has direct management implications for road maintenance in high rainfall areas, and can be used to assess the effects of alternative approaches to reducing sediment movement, for example, through stand-level manipulations to increase water infiltration on hillslopes.

11.4.2.7 Regeneration

The model developed by Childs et al. (1987) does a good job of simulating site water balances with minimal inputs. They used this model to investigate the impact of various options for reforestation treatments (such as shading, mulching, vegetation control), comparing their effects on seedling water stress to those occurring with normal planting.

11.4.2.8 Climate change impacts and adaptation

11.4.2.8.1 Productivity, drought and losses due to disturbance events

Romme and Turner (1991) were among the first researchers to attempt the application of a conceptual model to assess impacts of different plausible future climate scenarios on vegetation structure,

and hence biodiversity and management, in the Yellowstone region (United States). One of their principal outcomes was to suggest monitoring approaches to detect ecosystem responses to a changing climate, something that is as relevant today as it was then. The need for continued monitoring exists not least because it must be understood that models cannot be relied upon to predict changes in forest characteristics in uncertain future environments. Much of the debate concerning climate change results from uncertainties, such as those related to projecting how greenhouse gas emissions may progress, and those arising from the incomplete collective understanding of the responses of the physical climate to changes in atmospheric composition. Using ecological models to predict responses of forests to these climatic changes adds a third level of uncertainty. It is widely accepted that one approach, possibly the only approach, to addressing these uncertainties is to perform factorial intercomparisons of models driven by multiple climate scenarios.

In central Germany, work by Lindner and colleagues focused on the application of a modified version of the FORSKA gap model linked to GIS and driven by gridded climate data to investigate risks and adaptation potential of natural forests, and hence to assist in making management decisions. In Lindner et al. (1997), two gap models, FORSKA-M and FORCLIM (for example, Bugmann and Solomon, 1995) were compared to assess responses to multiple scenarios of future climate. They concluded that FORSKA was better at representing the role of soil water in determining the potential natural vegetation, whereas FORCLIM was better at imposing climate limits on species distributions. Later they used FORSKA-M to investigate risks for the long-term management rotations under a combination of two climate scenarios and three management scenarios for the period 1990–2100 (Lindner et al., 2000; see also Lasch et al., 1999, for a description of the statistical method for developing climate scenarios). In general, the results showed that increasing drought would likely result in appreciable changes in forest composition, requiring adjustments to management and wood production planning.

United States forest researchers have used PnET-IIS (a process model running on a monthly time step) to assess effects of climate change on water use by loblolly pine forest in the south-eastern United States (McNulty et al., 1997). They validated simulated results against observed historical variations of forcing climate and drainage responses and then investigated responses to two GCM scenarios of

future climate. The results indicated that these forests would increase water use at the northern edge of their range, but suffer declines in much of the southern region, where loblolly pine was not sustainable.

The Lund–Potsdam–Jena (LPJ) dynamic vegetation model was developed for global-scale applications, but has its metaphorical roots in gap models such as FORSKA. A variant of this model, LPJ-GUESS (Smith et al., 2001) is suited for stand- to landscape-scale applications and has the capability to parameterize individual species. For example, Hickler et al. (2004) applied it to the Great Lakes region of North America, finding that disturbances (wind and fire) are major controls on species composition and biomass production. The model can be used to investigate climate change impacts on these processes.

In Europe, Nabuurs et al. (2002) compared multiple process-based models driven by a single climate scenario and alternative management scenarios at 14 forest sites. The results were used as input to the European Forest Information Scenario (EFISCEN) model, designed for large-scale forest resources, to project climate change impacts over 50 years for 130 Mha of forest.

11.4.2.8.2 *Carbon management*

The extensive work of Kurz and Apps (1999) has been targeted at the development of a comprehensive tool for assessing forest carbon budgets and providing direct input to management and policy development questions. This work is now encapsulated in the user-friendly CBM-CFS3, which is applicable at the scale of forest management units and may be downloaded from the Canadian Forest Service's Website.

Other work previously mentioned has also investigated the potential impacts of forest management scenarios on GHG mitigation at national to global scales (for example, Betts, 2000; Falloon et al., 2002; Turner et al., 2004; Vetter et al., 2005; Briceño-Elizondo, 2006).

11.4.3 **Fire weather applications and models**

11.4.3.1 **Fire danger rating and fire behaviour prediction**

In the United States and elsewhere, good fire weather information is crucial for fire management planning under two different circumstances. Before any fires occur, the risks posed by the fire

environment – basically the combination of fuel, topographic and weather conditions in a given area – are assessed by means of fire danger rating. After an active fire is identified, on the other hand, its growth potential and the consequent risks are assessed by a fire behaviour prediction system, which also depends on fuel, topographic and weather inputs. In either case, various mathematical models relate fire potential or fire behaviour characteristics to observable characteristics of the fire environment. The predominant fire danger rating tool in the United States is the National Fire Danger Rating System (NFDRS), described in section 11.5 below. A relatively new system deployed in the United States for fire behaviour prediction is FARSITE, which inherited the core fire model used in NFDRS. As a result, NFDRS and FARSITE share the same weather data requirements in many respects. On the other hand, these requirements differ radically in terms of spatial and temporal resolution. This section compares how weather data are used in each system.

11.4.3.2 An evolving fire danger rating system

The Forest Service of the United States Department of Agriculture (USDA) introduced NFDRS for national application in the United States in 1972 (Deeming et al., 1972). Major modifications occurred in 1978 (Deeming et al., 1977) and 1988 (Burgan, 1988). Changes since then have been evolutionary, and have been based on improvements in information processing and dissemination resulting from progress in computing and telecommunications technologies. Section 11.3.3 describes how remote automatic weather stations have improved fire danger rating. This technology takes advantage of satellite communications and computer-controlled monitoring of weather conditions.

11.4.3.3 High-resolution fire danger rating

A secondary benefit that fire danger rating has derived from computing advances is the proliferation of high-resolution weather forecasts resulting from accessible supercomputing. In 2001, the USDA Forest Service funded five prototype high-resolution weather modelling centres to support fire and air quality managers in the United States. They produce experimental gridded fire danger forecasts down to a 4 km grid interval in selected areas of the country (see <http://www.fs.fed.us/fcamms/>).

The modelling centres independently run the MM5 weather model, which has its origins in a research

model from Pennsylvania State University (Anthes and Warner, 1978). MM5 generates most of the weather data needed by NFDRS in the surface layer of the model. A post-processor extracts the weather data at hourly intervals of a 48-hour forecast period and computes the corresponding NFDRS indices over the area of interest. This process requires topographic and fuels data on the same grid as the weather data.

Studies of the MM5 applications so far have had mixed results. Mass et al. (2002) examined MM5 performance in predicting surface temperature, wind, pressure and 24-hour precipitation over the United States Pacific North-west. They found that decreasing the model's horizontal grid spacing from 36 km to 12 km significantly improved forecast accuracy, but that a further decrease of spacing to 4 km did not. They noted, however, that the 4 km simulations produced more realistic mesoscale structures. With smaller and more pronounced features, they suggested that timing errors in forecasting the movement of the features might have degraded the skill scores. Yang et al. (2005) compared MM5 simulations for the island of Hawaii at grid intervals down to 3 km with mesoscale data collected for the Hawaiian Rainband Project in the 1990 summer. They concluded that the model did well overall in representing thermal, wind and precipitation fields, but local errors occurred for various reasons, including misspecifications of the initial fields and land-surface characteristics.

Hoadley et al. (2006) used the Pacific North-west MM5 simulations to compute NFDRS indices for Idaho and Montana during the 2000 fire season. They found that the 4 km grid spacing improved predicted indices compared with the 36 km grid interval, but the predictions were consistently low. The simulations represented the trends well, which is an important consideration for fire management applications.

11.4.3.4 Fire behaviour prediction

The near future will likely see increasing use of fire behaviour prediction systems capable of simulating the growth of fires on the landscape. High-resolution weather data are critical for this application. In the United States, the FARSITE system is now being introduced in operations for wildfire incident management. The weather data requirement for FARSITE defines a key role for high-resolution weather modelling, but an integrated fire weather/fire behaviour modelling system for operational use is still in the research and development phase. A significant gap exists

between the grid spacing of the weather fields (4 km) and the typical FARSITE terrain and fuels data (30 m). At the given resolution of the weather field, it is currently assumed that weather conditions are uniform over the more detailed subgrid of the fuels and terrain data. This problem requires more research.

A case study by Fujioka (2002) compared the observed growth of a Southern California fire with an integrated weather/fire simulation of the fire in its early pre-suppression phase. He used a mesoscale spectral weather model (MSM) adapted from a regional model operated by the United States National Weather Service (Juang, 2000), with a horizontal grid spacing of 2 km. FARSITE simulated the fire growth with the weather fields from MSM and gridded terrain and fuels data spaced at 30 m intervals. The simulated fire perimeters can be displayed graphically with the input wind field (Figure 11.3).

The simulated fire growth compared marginally with the actual fire growth. Neither the magnitude nor the direction of fire growth was well represented. The complexity of the real fire environment, especially the steep terrain, posed a

serious challenge in this study. Under these conditions, it is important to predict both wind speed and direction accurately, because fire spread depends critically on wind/slope interactions. Moreover, even a 2 km grid interval might be inadequate for a weather model in steep terrain with narrow canyons and valleys. The study described statistical methods to quantify the fire growth simulation errors. Uncertainties in fire spread predictions are represented by probability-weighted error bounds. This kind of information will be needed to qualify fire spread predictions, given the complexity of fire growth modelling.

11.5 FUEL STATE ASSESSMENT FOR FOREST, BUSH AND GRASS FIRES

11.5.1 Introduction

Wildland fires, including bush, forest and grass fires, intrinsically involve agricultural meteorology and the operational tailoring of meteorological forecasts to suit the needs of firefighting agencies. In addition to accidental or unscheduled fires, there is also a need for prescribed fires, which, in some ecosystems,

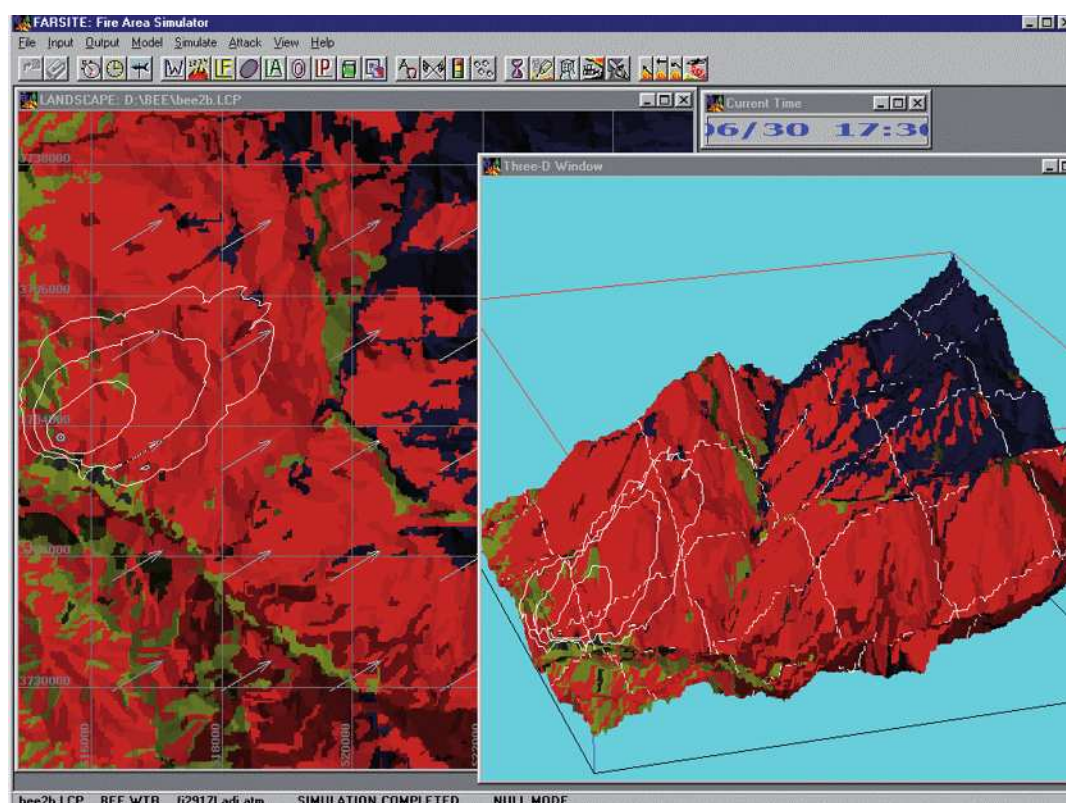


Figure 11.3. MSM/FARSITE simulation of the Bee Fire, 29 June 1996, in the San Bernardino National Forest, California. The vectors in the left frame represent the wind field from the MSM model and the closed loops are the simulated perimeters over time.

form an important element in the management of the ecology, economy and protection of forests and other ecosystems, including agricultural and pastoral systems. The task of the agricultural meteorologist is to understand the role of weather and climate in the production of fuel such as grass, bushes and forests, as well as the weather-related needs of all fire management agencies.

The necessary ingredients to maintain a fire are given in a fire triangle concept; this concept portrays a triangle with each side sequentially labelled fuel, oxygen and heat. The absence of fuel, oxygen or the heat produced causes the fire to burn out. Firefighting methods are based on breaking the triangle by cooling the heat component, smothering the oxygen or removing fuel.

Nature provides omnipresent oxygen and can also provide a source of ignition, for instance, the strike of lightning; however, humans can sometimes control the fuel component. The controllability of fuel highlights the importance of fuel in all fire management considerations.

Fires can be considered in either of two broad categories:

- (a) Those whose behaviour can be predicted with some success taking account of weather, terrain, and so forth;
- (b) Those whose behaviour is erratic or unpredictable.

It is convenient to define wildland fires, either controlled or uncontrolled, as:

- (a) Ground fires, such as those burning at or below ground level in organic soil, peat, tree roots, or coal or sulphur seams;
- (b) Surface fires that burn in grass, scrub or forest litter;
- (c) Dependent crown fires that burn in treetops supported by surface fires directly below; they do not progress ahead of the main surface fire;
- (d) Independent or running crown fires that burn in treetops without the support of ground fire and progress independently from and ahead of the initial surface fire.

Each type of fire can display a varying degree of intensity, for example, when the geometry of a fire changes from an essentially two-dimensional surface fire to a three-dimensional crown fire. Extreme fire activity may be termed a "blow-up fire". The essential characteristics of a blow-up fire are violent convection and extensive spotting, together with uncontrollable and anomalous

fire behaviour. A fire has been found to change from two to three dimensions when the energy conversion rate in the convection column as a function of height above the fire (for a height of about 300 m) exceeds the rate of flow of kinetic energy in the wind field (Davis, 1959). A firestorm is a blow-up of such size and intensity that it can be considered as a heat cyclone with cyclonic wind circulation evident in the indraughts. The convection column may be capped with a cumulonimbus anvil. The best-known example is the "Hamburg firestorm" described by Ebert (1963). A large forest fire experiment conducted in Siberia (the 1993 Bor Forest Island Fire Experiment) generated a firestorm described by the Fire Research Campaign Asia-North (FIRESCAN) Science Team (1996). The provision of a meteorological service to assist firefighting and fire management organizations in fire-prone areas is probably the most important application of operational agrometeorology.

11.5.2 Weather-related elements

Of all the factors listed by both Foster (1967) and McArthur (1962), the two most important weather aspects, or weather-related elements, affecting the behaviour and rate of spread of wildland fires are undoubtedly wind velocity and fuel moisture. The main effects of the wind include acceleration of the supply of oxygen and movement of combustion products, thereby increasing fire intensity and spread, and a fanning and bending over of flames, which in turn focuses radiation onto unburnt fuel, greatly increasing the rate of spread of a fire. In the case of large fires with active convection columns, the transport by wind of burning embers from the top of the convection column (generally with the velocity of the low-level jet, possibly 500 m high) causes spot fires ahead of the main fire front.

Byram (1954) states that the most consistent feature of the wind field associated with extreme fire behaviour is a low-level wind jet. Because wind varies during the day and from one day to another, Byram classifies wind profiles into about ten categories; a feature of most profiles is the low-level jet, which implies a layer of decreasing wind speed with height, namely, a negative wind shear above the jet stream. The most dangerous profiles can be considered to have a jet close to the ground. Byram wind profiles vary diurnally and in highlands may have a different classification due to elevation. Because of inherent difficulties in forecasting, the Byram wind profiles have been used more to explain a past event than to facilitate the forecasting process. Perhaps when fire weather meteorologists regularly attend

fires and measure winds in situ, more use will be made of the Byram classification (see also 11.5.7.3).

When air flows from higher to lower elevations as with a foehn wind, air that has lost moisture on the windward side of a mountain range warms adiabatically on descent on the lee side and can cause severe fire weather conditions. Local winds such as sea breezes and upslope and downslope winds, together with those funnelled through mountain barriers, all play a part in fire weather (see also 11.5.7.2).

Relative humidity may vary greatly from one spot to another depending on topography and the presence of irrigated fields, streams and other features. Beneath a temperature inversion, relative humidity, for instance, generally decreases with height. Byram (1957) points out a dual role for relative humidity in the rate of spread of a fire in certain types of extreme behaviour (through its influence on fuel moisture content), such as the effect on fuel combustion rate and the rate of spread of the flame front, as well as increasing or decreasing the probability of ignition from spotting and hence, the acceleration of rate of spread and intensity of a fire.

The ignition probability for most fuel can be essentially zero at 25 to 30 per cent relative humidity and reach the maximum for oven-dried material. Low ambient relative humidity helps to bring fuel toward the latter state. On bad fire days it is usual for relative humidity to be very low and temperature to be high. The combination of low relative humidity and high temperature promotes the rapid loss of water from dead fuels and can also lead to a high transpiration rate for living vegetation, which will lower fuel moisture content drastically, especially if the available soil moisture is near depletion.

Although high ambient air temperature has some effect in raising fuel temperature, insolation is much more important in this respect; air temperature acts indirectly on fire behaviour through thermal turbulence. As a general rule, convective activity is greater on hot days, facilitating the removal of combustion products from a fire and hence favouring its development, and creating updraughts to carry burning embers well above the fire tops.

Atmospheric stability in the lower layers is closely related to fire behaviour and it may either suppress or promote vertical air motion. Air mass subsidence can bring very dry air from high to low levels in the

atmosphere; if this dry air subsidence reaches the ground at night, wildland fires often burn as actively overnight as during the day.

Atmospheric instability and cloud formation can result in lightning strikes, which are extremely important for fire occurrence, especially in inaccessible, high-elevation and high-latitude localities during the fire season.

Countries that are threatened by wildfires have adopted or developed fire danger indices that usually combine elements such as wind speed, air temperature and humidity, along with fuel state and quantity, to give an indication of the rate of spread of a fire once it has been started. It is obvious that not all salient features of fire spread are contained in the fire danger indices. For this reason, ancillary comments/forecasts, and preferably a briefing to fire authorities, must accompany each statement passed to firefighting organizations. As stated in *Systems for Evaluating and Predicting the Effects of Weather and Climate on Wildland Fires* (WMO-No. 496), the physical laws that control the behaviour of wildland fires are the same in both tropical and subtropical areas. The main difference is the relative importance of natural and man-made fires. A review entitled *Wildland Fires Particularly in Tropical Regions* (WMO, 1982) reports that over 90 per cent of fires are caused by human activities.

11.5.3 Grassland fuel state assessment

11.5.3.1 Growth of fuel

The fuel component of the fire triangle merits consideration because it lends itself to modification at all times of the year. Oxygen is always available, but its supply is enhanced by certain stability and wind situations; the source of heat is generally an imposed factor, such as lightning, and does not lend itself to overall control. The climate of a region determines the type, amount, distribution and state of fuel available for the outbreak of fires. Fuels are found in almost infinite combinations; any organic material that will burn can be considered as fuel, whether it is below or at ground level, such as peat, coal or sulphur seams; at surface level, such as grasses and shrubs; or above the ground, as with forests and trees. Every fuel has an inherent inflammability potential, which can generally be realized, depending primarily upon the amount of water in the fuel. It is necessary to consider both living and dead fuel and the role played by water in each type. In living plants, the interaction of the environment with plant function and structure is basic to an understanding of fuel production.

11.5.3.1.1 *Plant function*

Plants are composed of microscopic cells, each with its own specific function; an interaction of these cells is necessary for the survival and growth of each plant. A typical plant cell has a rigid surrounding wall made of cellulose, which encases a pliable membrane; within the membrane there is a nucleus that regulates the activity of all the cellular structures, such as the chloroplast, which is associated with photosynthesis, and the mitochondrion, which regulates the respiratory functions of the plant. Most cells also contain a centrally located, large fluid-filled sac within the membrane, which is called the vacuole. Each cell entity is interconnected with others by small strands that pass through the rigid cell wall, allowing fluids to pass from one cell to another. In order to survive, plants must collect and retain water and be able to exchange gases and produce their own food and energy. Water is the vehicle by which nutrients are transported from the root system throughout the entire plant. In the leaves some of the water is used in the production of plant material as a result of photosynthesis; some of the water then transfers the manufactured hydrocarbons to growing tissues and storage points. Some water is also transpired through leaf pores in the form of water vapour.

In order to perform essential functions, plants have developed three basic structures: roots, leaves and stems. The leaf structure may vary from plant to plant, but it must carry out the essential functions of the exchange of gases, photosynthesis and transpiration. The roots absorb water and minerals from the soil and transport them to stems and leaves; they also provide storage and act as a support system for plants. The stem supports foliage, provides storage, transports substances between foliage and roots, and also absorbs gases from the atmosphere. Transport within the plant occurs via the xylem or phloem; the latter transports more complex materials such as sugars, while the xylem transports water and any dissolved substances. Xylem tissue is often called wood and has been referred to as the “plumbing” of the plant. The phloem operates in parallel with the xylem system and transports materials in many directions throughout the plant according to supply and demand.

The energy for growth comes from the carbohydrates that are produced in photosynthesis, less the energy needed for respiration. Plant cells divide and form two new cells, identical with the parent, through the process of mitosis occurring at the tips of stems, branches and roots, and in various buds. This type of plant growth is known as primary

growth. Herbaceous plants have only primary growth; grasses, for example, have meristems located at the base of their leaves and this enables grass to produce new tissue after being cut or grazed by livestock.

In other plants, the cambium provides for lateral growth, increasing the diameter of roots, branches and stems; this is termed secondary growth. The growth of woody perennials that develop into trees is dependent on the deposition of new tissue over old. The old system ceases to function and forms the older wood at the centre of the tree, while the old phloem, which is no longer functional, is shed by many plants as bark. Parts of plants may cease to grow and may be shed by abscission; although this commonly occurs in leaves, flowers and roots, the shedding of branches may also occur.

The moisture content of all new foliage is highest at the time of emergence; it is commonplace for the moisture content of new foliage to be two or three times that of the dry weight. Moisture content normally declines rapidly during leaf growth and development, with a subsequent slower decline as leaves become drier. In an annual species the plant dies, while in deciduous shrub and tree species the foliage dies. In evergreens, only some leaves die and fall away over a given period. A plant, on reaching maturity, may remain at that stage for days, weeks or even decades, depending upon the species. When a plant becomes overmature either in total or in part, deterioration begins in both the structure and function of the plant and its tissues. When this process, known as senescence, occurs, the plant begins contributing to the dead fuel load.

11.5.3.1.2 *Live fuel moisture*

It is important to note that any living vegetation can be burnt, provided that the associated fire has sufficient intensity. Nevertheless, it is generally accepted that green fuel does not significantly contribute to the rate of spread of fires. The Australian McArthur Grassland Fire Danger Meter (Mark 4), for instance, only features a degree of curing between 70 and 100 per cent. At 70 per cent cured, with an air temperature of 41°C, a relative humidity of 10 per cent and a wind of 25 km/h, the rate of spread of a fire, on the McArthur scale, only reaches the upper limits of moderate, or a rate of spread of a little less than 1 km/h.

Finocchiaro et al. (1969) reported on grass fires that occurred in Victoria, Australia, on 8 January 1969. The fires were unusual in that they occurred after three weeks of cool weather with considerable

rainfall. The grass fuel report on 6 January 1969 was at least 50 per cent green over the fire site; these grass fires caused the loss of 22 lives and a great amount of property damage, and they burned out approximately 3 000 km² of grassland. Schroeder and Buck (1970) stated that after the moisture content of grass has dropped to 30 or 40 per cent during the curing stage, grass will burn on a good burning day. The severity of the 8 January 1969 fire, considering the fuel state, was most unexpected and demonstrates the need for continued research into fire behaviour.

Annuals, such as grasses, have a limited growth season and are much more sensitive to seasonal and short-term weather variations than most other fuels. Grasses have shallow roots and primarily depend on adequate surface soil moisture for full top development; these grasses have a limited growth season, reach maturity, then come to seed and subsequently cure or dry. Whenever surface moisture at the beginning of the season is deficient or depleted by a spell of hot, dry weather, the growing season is shortened markedly; in this case the curing season may range from three weeks to two months, depending upon prevailing weather. Grasses may reach a highly inflammable stage while broadleaf foliage is still in prime growth.

Perennial grasses have deeper and stronger root systems than annual grasses and are thus less sensitive to short-term surface-soil moisture depletion. In climates that have a marked growing season limited by hot, dry weather, however, the cycle of perennial grasses is similar to annual grasses, but only the leaves and stems down to the root base are affected. Normally, the moisture in live fuel acts as a sink for energy produced by the parent fire and consequently the overall heat of the fire is reduced. Some live fuel absorbs nearly as much heat to vaporize the water content of the fuel as that produced from the combustion of the live fuel.

11.5.3.2 Initial measurement practices

Practices associated with the measurement of grassland fuel state and amount have evolved slowly. The earliest assessment of fuel state in Australia begins with a visual appraisal, usually by a long-term resident of the area. The Bureau of Meteorology sends out a supply of prepaid and addressed cards; the observer only has to tick an appropriate box to signify whether the fuel is partially or totally cured in steps of about 20 to 25 per cent. A small bundle of grass that is representative of the surrounding countryside has to be selected; the sample is then

carefully examined and the degree of curing finally established and reported on a weekly basis. A space on the card is provided for general comments such as "the dry spell during the past week has accelerated curing". An operational agrometeorologist then examines all the cards and assigns a curing status to each region under his control after liaison with all relevant fire authorities. As an approximation, fully cured grass is once more considered to be 100 per cent cured within hours after rainfall has cleared.

11.5.3.3 Weighing methods

Another method employed by fire authorities to assess fuel quantity and state is that of weighing the amount of grass per unit area. In general, a relatively large area of grassland that can be regarded as representative of a particular region is selected. From this selected area, a random point is obtained by an observer who simply throws an object over his shoulder and uses this as a central point to place a prepared frame that measures one square metre; all of the grass within this frame is collected and placed within a labelled plastic bag for weighing. For analysis purposes, this process is repeated within the region over a number of places. Each plastic bag (with contents) is weighed before and after drying. The accepted method to measure the moisture content of a fuel is to express as a percentage the deduced amount of water in the fuel, divided by the oven-dry weight of the fuel. From such observations it is possible to provide information such as:

- (a) Average height of fuel (from observation);
- (b) Average tonnes of fuel per hectare;
- (c) Average fuel moisture content.

11.5.3.4 Satellite-derived vegetation indices

With the advance of satellite technology, it is now possible to use satellite images to evaluate the curing of herbaceous fuels over an extended area. For herbaceous vegetation, the drying of plants follows a decrease in chlorophyll activity, which can be monitored from satellite images using standard vegetation indices. The most common are those that measure the spectral contrast between the red (600–700 nm) and the near-infrared reflectance (700–900 nm). Other indices that are more related to plant water content use the spectral contrast between the near-infrared and the short-wave infrared (1 200–2 500 nm). Until a few years ago, the most commonly used sensor for fuel moisture estimation was the Advanced Very High Resolution Radiometer (AVHRR) on satellites operated by the

United States National Oceanic and Atmospheric Administration (NOAA), with 1.1 km resolution for vertical observations. More recently, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the Terra and Aqua satellites, with 500 m resolution and additional spectral bands, has been providing more precise information for fuel water estimation. To reduce the effects of clouds in the images, processing of both AVHRR and MODIS is commonly based on multiday composites (between 10 and 15 days being the most common). These composites are created by selecting the less cloudy pixel within the daily series, which frequently entails identification of the day with the maximum vegetation index value in the daily series. Both AVHRR and MODIS provide daily world coverage, by comparison with the 16-day cycle of LANDSAT or other medium-resolution satellites, which may be reduced in cloudy areas. Ground-truth observations are needed to validate estimations of fuel moisture content provided by satellite imagery.

11.5.3.5 Use of fields of solar radiation

Solar radiation is the ultimate cause of vegetation growth and also of the drying out of annual grasses and other fuels. Solar radiation supplies the energy to change liquid water into vapour in evaporation and evapotranspiration and to build chemical energy into carbohydrates that later can be released as heat in a bush fire.

Solar radiation over large areas has been estimated in the past from observations such as cloud cover and sunshine hours. There have, of course, been routine point measurements of direct and diffuse global radiation, but the density of observations has always been too sparse to extrapolate the results over significant areas. Extraterrestrial radiation for all latitudes and longitudes has been tabulated in the past, but never before has such comprehensive cloud coverage been available. Cloud coverage from geostationary satellites can now generally be obtained at least once or twice a day and possibly every hour or half-hour during daylight hours. Computer programs exist that can be used in conjunction with satellite imagery to provide a field of total daily radiation. If the amount of radiation that is reflected back to the satellite by cloud cover is assessed and subtracted from the extraterrestrial value, a field of global radiation can be deduced from satellite cloud imagery.

The energy field obtained on a daily or weekly basis, apart from being invaluable for climatological reasons, can be used to estimate drying stages of fuel. Once an

empirical model has been established, operational aspects of the model can be used to advantage.

Radiation is the principal component of the energy balance equation as applied to the calculation of evapotranspiration. The most accurate way to obtain the net radiation component at a point is by measurement with a net radiometer. Because this approach is quite impractical on a scale required for fuel state consideration, an approximate value must be used. The outgoing long-wave radiation is approximated by the Stefan-Boltzmann equation; the incoming global radiation, derived from satellite imagery, can be obtained within 10 or 15 per cent of the actual value. Thus a field of evapotranspiration for grassland could be approximated and a good estimate of wilting point or moisture loss obtained.

11.5.3.6 Estimating dead fuel moisture

It is not convenient to measure dead fuel moisture in the field directly, so it is usually estimated indirectly by various methods. Very fine dead fuels such as cured grass, well-aerated pine needles and the surface layer of larger fuels may be in approximate equilibrium with the immediate environment. It is possible to use either actual or prognostic values of environmental air temperature and humidity to obtain a reasonably accurate estimate of the moisture content of this type of fuel and hence its inflammability.

11.5.4 Forest fuel state assessment

Moisture content is important in determining whether fuels will ignite and burn and thus strongly influence fire behaviour. Fuels are found in a great number of combinations of shape, size, amount, arrangement and species. Variations in climatic factors, along with local factors such as latitude, slope, aspect, soil types and hence vegetation, have ensured that many countries have developed their own means of assessing forest fuel states. The nature of the problem has meant that countries concerned with fires have also developed their own systems and consequently, the transfer of a method developed for a particular latitude or country, in all probability, will not totally solve the problem for a different latitude or country. A number of indices will be considered.

11.5.4.1 Keetch-Byram index

This index (Keetch and Byram, 1968) was developed from a theoretical basis for a subtropical summer rainfall forest or wildland area in the south-eastern United States. The Keetch and

Byram method makes several assumptions in developing equations to describe the degree of drought or soil moisture deficiency. The assumptions include:

- (a) No loss by runoff when the soil is below field capacity;
- (b) The significant moisture relationship that exists in the upper soil-duff layer has a field capacity of about 200 mm; it is assumed that 200 mm of rain would completely saturate the soil;
- (c) The lowest soil-duff moisture content level is at wilting point; this layer is assumed to gain moisture by rainfall and lose it by evaporation;
- (d) The vegetation density is a function of annual rainfall amount, and this determines the rate at which vegetation can remove moisture from the soil-duff layer when weather variables are constant;
- (e) No evapotranspiration takes place below 10°C (probably because that is about the minimum dewpoint for places such as Florida);
- (f) A uniform allowance is made for interception of the first 5 mm per rain period;
- (g) Once interception is separated from evapotranspiration, there is no evidence to justify the assumption of greater evapotranspiration with higher annual rainfall.

The basic idea behind the Keetch–Byram index is that evapotranspiration losses are related to daily maximum temperature. This approach seems to have worked fairly well in practice, even though in theory the simple input, which is similar to the Thornthwaite and Holzman equation (Thornthwaite and Holzman, 1939), should not be used for periods of less than a season or even a year.

The Keetch–Byram index was incorporated by McArthur (1967) into his Forest Fire Danger Meter (Mark 4) in 1966. The daily meteorological input required is maximum temperature and rainfall. Despite the lack of theoretical soundness, the Keetch–Byram index is still being used, even in non-forested areas, by some Australian fire authorities.

11.5.4.2 Tasmanian soil dryness index

Mount (1972), using the Keetch–Byram index as a base, derived an index of soil dryness that estimated the amount of rain needed to bring the soil profile back to field capacity. Mount used the difference between the observed rainfall and the observed runoff as a true measure of the soil dryness before onset of the rain. Observed runoff was used to compare estimates made from the soil dryness

index and the Keetch–Byram estimate. Tables were compiled to provide daily estimates of evaporation and daily maximum temperatures. The meteorological input is similar to that required for the Keetch–Byram index.

Judging by the observed runoff, the soil dryness index gives a better result than the Keetch–Byram index for mid-latitudes. The approximation for evapotranspiration can be estimated by using a Thornthwaite type of equation on a daily basis, or a long-term monthly evaporation pan value adjusted for daily values. Both methods indicate areas where improvements could be made to reflect daily evapotranspiration better.

11.5.4.3 The Palmer index

Palmer (1964) developed a meteorological drought index that is calculated weekly during the growing season in the United States. Palmer notes that an arid region can always use more rain and his drought index is given for a particular location. The Palmer index is based on Thornthwaite's method of estimating potential evapotranspiration. The index is directly proportional to the previous index on a given timescale, plus a moisture anomaly index. This index is proportioned to precipitation minus normalized values of evapotranspiration, soil recharge, runoff and loss (that is, moisture is removed if there is no rainfall). The Palmer drought index can range from values greater than 4, which is extremely wet, through 0, where values are near normal, to negative values. A value below –1 is a mild drought, below –2 indicates a moderate drought, below –3 a severe drought and below –4 an extreme drought. Negative values of the Palmer drought index lend themselves to a measure of dryness that can be applied to fuel on a broad scale.

11.5.4.4 Other methods

11.5.4.4.1 Fuel moisture indicator sticks

A practical means of estimating the moisture content of medium-sized fuels can be achieved by using wood moisture indicator sticks. Generally, the indicator sticks chosen consist of a set of four cylindrical pieces weighing about 100 g and measuring approximately 500 mm × 12.5 mm; these sticks are spaced about 6 mm apart and are suspended in the open on a wire rack exposing them about 250 mm above a typical bed of forest litter. The sticks are weighed on a daily basis and the moisture content of the fuel is then estimated from the known oven-dry weight of the indicator

sticks. Trends of moisture content are used along with derived empirical relationships involving precipitation, number of days without rain, daily drying conditions, and so forth, to assess moisture content of large fuels.

11.5.4.4.2 *Direct measurement*

A pamphlet issued by the USDA points out that microwave ovens can be used to dry fuel, if care is taken to prevent charring (McGreight, 1981).

11.5.5 **Treatment of fuel state after precipitation**

Even though a fuel has been completely dried out, compensation may have to be made for the amount of moisture incorporated into the fuel after precipitation. It is possible for a dry fuel to be considered 100 per cent cured one day and then, after precipitation, as the equivalent of a 100 per cent green fuel. Then, as drying occurs, the fuel progressively contains less moisture until it is again considered 100 per cent dry. The time taken for a fine cured fuel to dry out again after rain is considered to be a matter of hours, while heavy fuel can take days or even months.

11.5.5.1 **Grassland fuel moisture**

Schroeder and Buck (1970) also provided a method that they called the time-lag principle, which expressed absorption and drying rates based on both equilibrium moisture content and fuel characteristics. According to this principle, the approach to equilibrium values from moisture content either above or below equilibrium follows a logarithmic rather than a linear path, as long as liquid water is not present on the surface of the fuel. If a fuel is exposed in an atmosphere of constant temperature and humidity, the time needed to reach equilibrium may be divided into periods in which the moisture change $(1 - 1/e) = 0.63$ of the departure from equilibrium, where e is the base of natural logarithms, 2.7183. The duration of these periods is a function of the fuel and is referred to as the time-lag period. It is pointed out that although successive time-lag periods for a particular fuel are not exactly equal, the principle is a useful method for expressing fuel moisture responses if average time-lag periods are used.

An example is given where a fuel with a moisture content of 28 per cent is exposed in an environment in which the equilibrium moisture content is 5.5 per cent. At the end of the first time-lag period, the initial moisture content would be reduced by

$0.63 (28 - 5.5) = 14.2$, thus the moisture content would be reduced from 28 to 13.8 per cent. Similarly, at the end of the next time-lag period, the moisture content would be 8.6 per cent. The moisture content at the end of five or six time-lag periods very closely approximates the equilibrium moisture content. For a fine fuel such as grass, the average time period in this case would be a matter of minutes, while for logs of 115 cm diameter the time lag is on the order of 36 days. Cured grass with a short time-lag period can be expected to achieve an equilibrium moisture content in a relatively short time after rain has completely dried from the surface. This illustrates the contradictory use of soil moisture as an indicator of grassland fuel state. Even though fine cured grass is considered to dry rapidly after heavy rain, there is still the problem of a saturated soil beneath the dry grass, which is not accounted for in estimates of fuel moisture that are used in the calculation of fire danger.

If a fire burns dry grass above a very moist soil, some energy from the fire would no doubt be used to evaporate the moisture in the soil into vapour and thus have some effect on the fire. In general, at least one or two days elapse after precipitation before dangerous fire weather recurs; by this time there is probably a fine, dry tilth on top of the moist soil and a fire would be reasonably well insulated from a previously wetted subsoil. Dew plays an important role in wetting fine fuel such as grass in early morning situations (Hicks, 1983). Fire danger meters, such as the McArthur Grassland Fire Danger Meter, use mid-afternoon meteorological values and assume that any moisture has been dried from the fuel. Whenever the grass temperature falls below dewpoint, dew can be expected to form on grassland vegetation; this is a frequent occurrence in mid-latitudes. Cheney and Sullivan (1997) provide further information on weather, grass fuel moisture and its impact on grassland fire behaviour.

11.5.5.2 **Forest fuel moisture**

When senescence (or browning) affects an entire plant, although growth and water circulation cease, the resultant dead vegetation retains the original structure of cells, intercellular spaces and capillaries, or "plumbing". The processes described below are explained by Schroeder and Buck (1970). Dead vegetation can soak up water like blotting paper until all spaces are filled, although the process is much slower. The next, equally important aspect of fuel wetting is the fact that materials constituting dead cell walls are hygroscopic; these dead cells have an affinity for water, which makes it possible

for them to absorb water vapour directly from the atmosphere. The latter process is one of chemical bonding. The hygroscopic character of the cell material attracts water vapour and causes several molecular layers of atmospheric water to adhere to the cell walls; these molecular layers are called bound water. The layer of water molecules immediately adjacent to the cell wall has the strongest bond and the lowest water vapour pressure; successive molecular layers have progressively weaker bonds and higher water vapour pressure until the cell walls become saturated.

At the level of saturation, the vapour pressure in the outer molecular layer of water on the wall is equal to the vapour pressure of free water and is thus at saturation vapour pressure. This amount of bound water at the fibre saturation point varies with different materials, but for most plant substances it is in the range of 30 to 35 per cent of the dry fuel weight. It is not possible for free water to persist in a cell until the bonding phenomenon has been completed; it is then possible for free water to pass through the cell wall by the process of osmosis. Before saturation level is reached, moisture is evaporated from cell walls of higher moisture content and taken up by dry cell walls of lower moisture content until an equilibrium vapour pressure is achieved. This process is characteristic of moisture transfer within fuels in the vapour phase and always operates in the direction of equalizing the moisture throughout a particular fuel sample.

The reverse process of drying wetted dead fuel takes place in three distinct phases. In effect, essentially each phase is accomplished by evaporation in a drying atmosphere, in which the direction of the vapour pressure gradient is essentially outward from the wet fuel to the surrounding atmosphere. The moisture can potentially be raised to 30 per cent of dry weight by contact with liquid water (rain or dew, for instance). The first phase proceeds independently of both the actual moisture content and the hygroscopic nature of the fuel. Drying takes place by evaporation at the same rate as that from a free water surface. Although wind speed does increase the rate of evaporation, it does not affect the amount of evaporation required to reach the end-point of this first phase. The intermediate phase is a transition step in which there is a variable change in moisture-loss rate. The rate begins changing slowly, within the defined limits of the linear rate of the first phase, to the orderly decreasing rate characteristic of the last phase.

The final phase depends totally upon an outward gradient between the bound-water vapour pressure and the existing ambient vapour pressure. As

moisture removal progresses below the fibre saturation point, the bound-water vapour pressure gradient declines and as a consequence, the outward vapour pressure gradient is gradually reduced. Either of two conditions must prevail to assure continued significant drying:

- (a) Maintenance of a surrounding ambient vapour pressure appreciably below the declining bound-water vapour pressure;
- (b) Heating of the fuel at a rate that will increase its temperature and correspondingly its bound-water vapour pressure, so as to maintain the outward gradient.

Both processes operate in real-life situations, sometimes in the same direction, as for a bush fire when the fuel is heated by radiant heat from the fire, increasing the bound-water vapour pressure. The ambient vapour pressure is reduced by the marked drying associated with the fire.

11.5.6 Discussion of climate-based indices

Climate-based fire danger rating systems attempt to provide an answer to the following questions:

- (a) How serious is the danger of fire starting?
- (b) How fast will it spread?
- (c) How much damage will it cause?

"The process of systematically evaluating and integrating the individual and combined factors influencing fire danger is referred to as fire danger rating. Fire danger rating systems attempt to provide qualitative and/or numerical indices for fire potential that are used as a guide in a variety of land management activities" (Stocks et al., 1988). Fire danger rating is concerned with those elements that cause day-to-day changes in fire danger. Constant factors are normally built into the index/meter and although they vary from place to place, include items such as:

- (a) Fuel type characteristics, for example, quantity, size, arrangement and inflammability;
- (b) Topography, for example, slope, aspect, elevation;
- (c) Ignition sources.

Variable fire danger rating factors can include:

- (a) Fuel moisture content;
- (b) Wind velocity;
- (c) Air temperature;
- (d) Relative humidity;
- (e) Recent rainfall effects;
- (f) Condition of the subordinate vegetation.

The following subsection presents the most commonly used climate-based fire danger systems

and, in particular, the meteorological aspects of these systems.

11.5.6.1 Historical perspective

There have been three broad phases in the development of fire danger rating systems. Objective assessment began in the late 1920s when Gisborne (1928) developed a fire danger meter in the United States. Similar fire danger meters were developed in Canada in the early 1930s. These provided national assessments until the late 1940s, when regional systems were developed for different United States and Canadian forest/climate types. In the late 1960s, national systems were developed in each of these countries, and these systems have gone through minor revisions over the last two decades. Other significant fire danger systems were developed in Australia in the 1960s by McArthur (1966) and by Peet (1965).

11.5.6.2 Canadian system

Canadian fire danger research began in the mid-1920s, and the Canadian Forest Fire Danger Rating System (CFFDRS) has been under development by the Canadian Forest Service since 1968 (Canadian Forestry Service, 1984, 1987). The Canadian system was built using an empirical approach to fire danger rating, based primarily on experimental burn and

wildfire field data. The CFFDRS currently has four subsystems (Figure 11.4):

- Canadian Forest Fire Weather Index (FWI) System;
- Canadian Forest Fire Behaviour Prediction (FBP) System;
- Canadian Forest Fire Occurrence Prediction (FOP) System;
- Accessory Fuel Moisture System.

The FWI System (Van Wagner, 1987; Van Wagner and Pickett, 1985) was the first subsystem developed in the CFFDRS and it provides numerical ratings of landscape-level, relative fire potential based solely on weather observations. The FWI System has been in use throughout Canada since 1970. The second major subsystem is the FBP System (Forestry Canada Fire Danger Group, 1992), which was first introduced in 1984. It integrates the effects of fuel type, weather (using FWI System outputs) and topography to predict stand-level fire behaviour, including fire rate of spread, fuel consumption and head fire intensity. The FBP System also provides secondary outputs related to fire spread distances, perimeter and area growth. The FOP System and Accessory Fuel Moisture System are under development.

The FWI System uses four daily weather inputs collected at noon local solar time (LST): temperature,

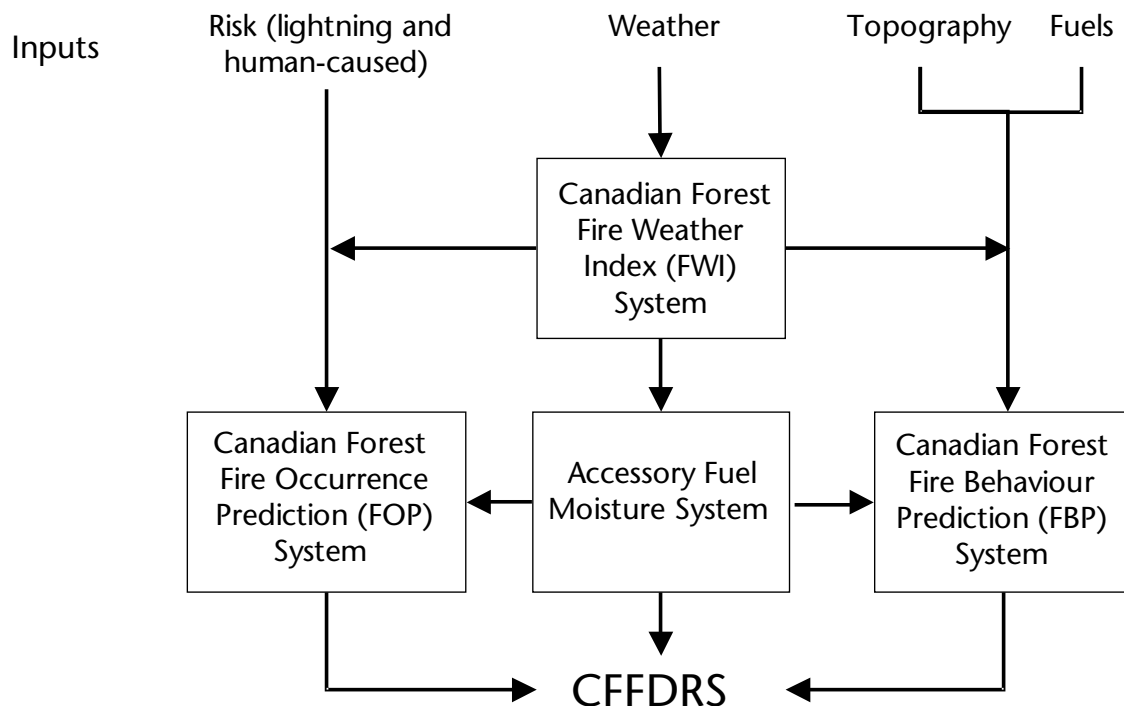


Figure 11.4. Structure of the Canadian Forest Fire Danger Rating System (CFFDRS) (Canadian Forestry Service, 1987)

relative humidity, 24-hour cumulative rainfall and 10 m open wind speed (Figure 11.5). The FWI System component values are valid for the heat of the day (approximately 1 500–1 700 h). Computation depends on the previous days' output, so daily readings must be taken. The FWI System is comprised of six components, including three fuel moisture codes representing different layers in the forest floor, and three fire behaviour indices: the Fine Fuel Moisture Code, a numerical rating of the moisture content of surface litter and other cured fine fuels on the forest floor; the Duff Moisture Code, a numerical rating of the average moisture content of loosely compacted organic layers of moderate depth in the forest floor; the Drought Code, a numerical rating of the average moisture content of deep, compacted organic layers in the forest floor; the Initial Spread Index, a numerical rating of the expected rate of fire spread; the Buildup Index, a numerical rating of the total amount of fuel available for combustion; and the FWI, a numerical rating of fire intensity that is used as a general indicator of fire danger. As stated by Stocks et al. (1988), however, it is almost impossible to communicate a complete picture of daily fire potential in a single number. The FWI System has been applied or adapted widely around the world in

many different countries (Taylor and Alexander, 2006).

11.5.6.3 United States system

Fire scientists in the United States began exploring the relationship of fire danger and hazard with weather, fuel moisture and ignition probabilities as early as 1916 (Hardy, 1983). A national system was first introduced in 1964. The current version of the United States National Fire Danger Rating System (NFDRS) was implemented in 1978 (Deeming et al., 1977), with optional revisions in 1988 (Burgan, 1988). A simplified diagram of NFDRS is given in Figure 11.6. NFDRS provides an indication of seasonal fire potential for large administrative areas. NFDRS is a climatology-based system, and as such, analysis of historical fire danger is required for proper interpretation and application of indices.

Fire behaviour prediction calculations were first made available to the field as nomograms (Albini, 1976). Current fire behaviour prediction systems, including the BehavePlus fire modelling system (Andrews et al., 2005) and the FARSITE fire area simulator (Finney, 1998), are designed to model time and site-specific fire characteristics, such as

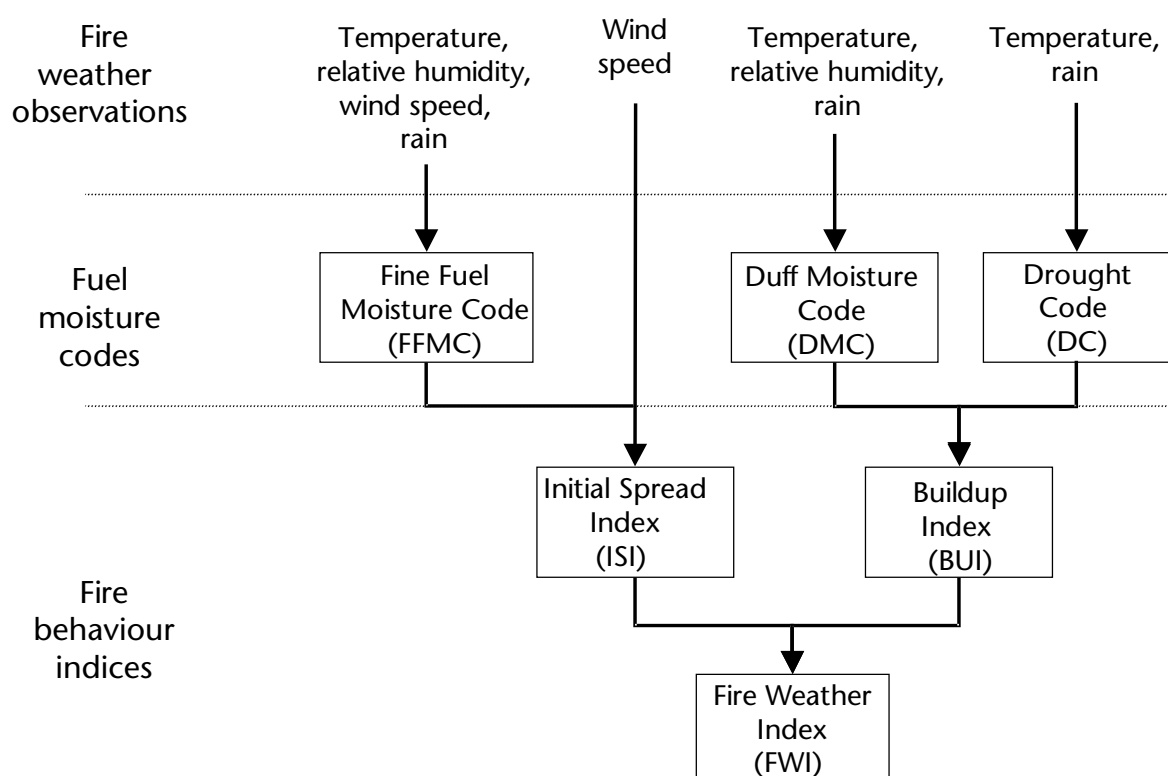


Figure 11.5. Structure of the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service, 1984)

rate of spread, intensity, flame length, spotting distance and fire growth.

Both fire danger rating and fire behaviour prediction systems are used in the United States to support fire management decision-making in fire prevention, fire suppression and fire use (Andrews, 2005). The basis of both fire danger and fire behaviour systems is a physically based mathematical fire spread model (Rothermel, 1972). Differences lie in the source and resolution of the inputs and interpretation of the outputs.

NFDRS provides a systematic way to integrate and interpret seasonal weather trends; fuel and terrain factors are essentially held constant. NFDRS uses daily weather observations and next-day forecasts to produce indices (Figure 11.6). Weather readings are taken daily at the same time and location. Fuel moisture values are calculated for live grasses and shrub foliage and several size classes of dead fuel. The fuel moisture values are then used to calculate the indices. The Spread Component (SC) is

influenced most by the moisture content of fine dead fuel (1-h), and wind speed is included in the calculations. On the other hand, calculation of the Energy Release Component (ERC) is weighted towards heavy dead fuels (100-h and 1 000-h), and wind is not part of the calculation. SC therefore reflects daily variations in fine fuel moisture and wind, and ERC reflects longer-term drying. The Burning Index is related to flame length and is a function of SC and ERC.

The Wildland Fire Assessment System (WFAS) is an Internet system that provides maps of seasonal fire potential on the basis of a network of fire weather stations and remote-sensing (Jolly et al., 2005). Integration of National Weather Service gridded weather forecasts into the WFAS is under development.

11.5.6.4 Australian system

The fire danger rating systems used in Australia are those developed by McArthur (1967) for forests and

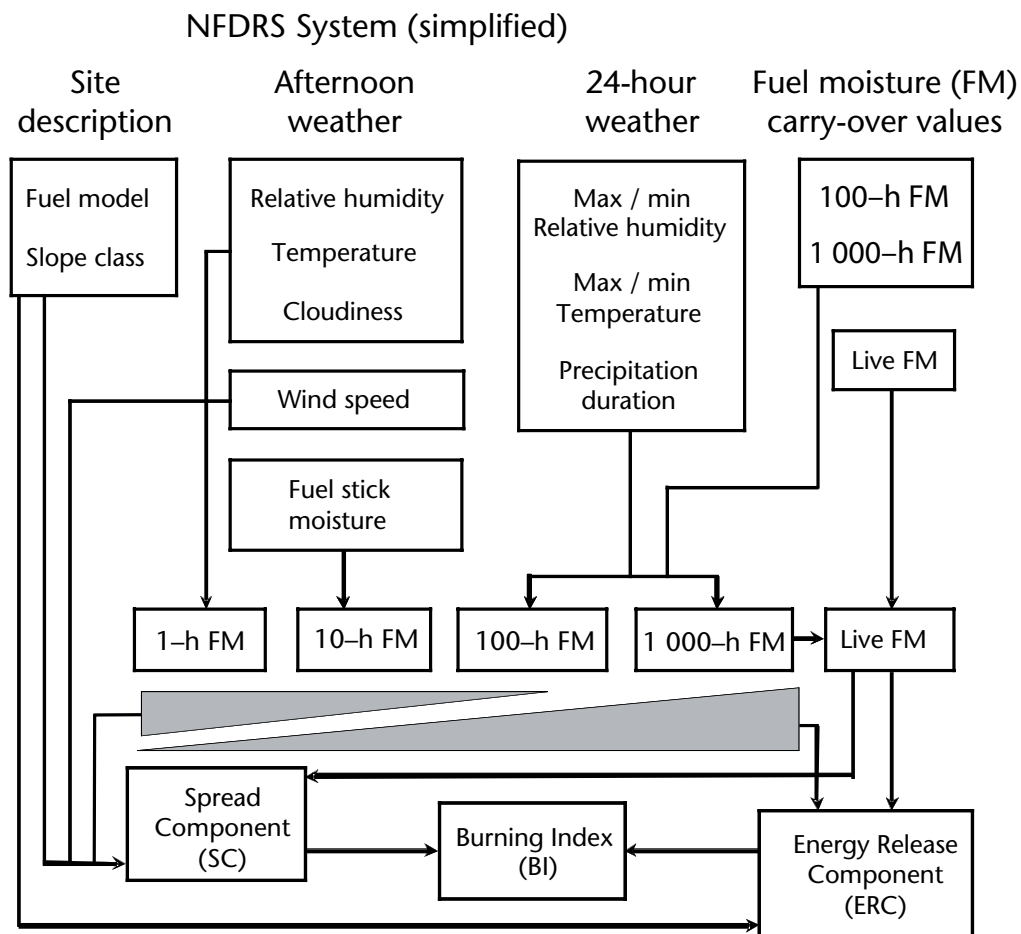


Figure 11.6. Simplified information flow for the United States National Fire Danger Rating System. Weather data and site descriptors are utilized to calculate fuel moisture values, which are used to derive indices. The wedges indicate the weighting of the dead fuel moisture size classes in the calculation.

grasslands, and the Western Australia forest fire danger rating system for jarrah forests developed by Peet (1965). The most widely used are the Mark 5 forest (McArthur, 1975) and Mark 4 grassland (McArthur, 1973) systems, which predict a rate of spread of fires in a standard fuel. Extensive descriptions of the McArthur system are given in McArthur (1967), Bureau of Meteorology (1964) and Luke and McArthur (1978).

11.5.6.4.1 *McArthur forest fire danger rating system*

The index used in the system is based empirically on several thousand experimental fires in dry sclerophyll forest with a 12.5 t ha⁻¹ fine fuel rating. A schematic diagram representing the Australian system and the various inputs is shown in Figure 11.7. The Forest Fire Danger Rating (FFDR) System uses the following elements of fire danger:

- Long-term seasonal dryness, which is expressed by a drought index;
- Short-term rainfall effects based on quantity of rain and when it fell;
- Temperature;
- Relative humidity;
- Wind.

Long-term seasonal dryness effects are incorporated by the use of a drought index system developed by Keetch and Byram (1968) that requires measurement of daily rainfall and maximum temperature. While it may be criticized on theoretical grounds, it does give a practical measure of soil moisture deficiency and the drying rates of various types of fuels.

The drought index, combined with cumulative rainfall over the last several days, defines the drought factor. Once the drought factor is set, the other meteorological variables used are air temperature, relative humidity and wind velocity measured in an open exposure at 10 m. Fuel moisture content (FMC) is indirectly computed by the relationship among temperature, relative humidity and the drought factor. The FMC incorporated in the meters is based on clear sky conditions and temperature and humidity conditions prevailing between about 1 p.m. and 4 p.m. local time.

Short-term drying effects are based on the expected changes in moisture content of surface litter less than 6 mm in smallest dimension. The wind speed value is an average value over at least five minutes. The relationship between the fire danger index and wind is not linear and the index increases rapidly with increasing wind speed. The indicator is designed to measure fire danger on a linear scale so that ignition probability and rate of spread are directly related to the index. Thus, the chances of a fire starting, the rate of spread and the difficulty of suppression are exactly doubled at an index of 50 compared with one at 25. The index represents rate of spread and thus is a measure of fire line intensity. The flame height is directly determined by the fire intensity.

11.5.6.4.2 *Grassland fire danger rating system*

This system is designed for use in temperate regions with relatively finely textured annual grasslands that go through a curing process. The meter applies

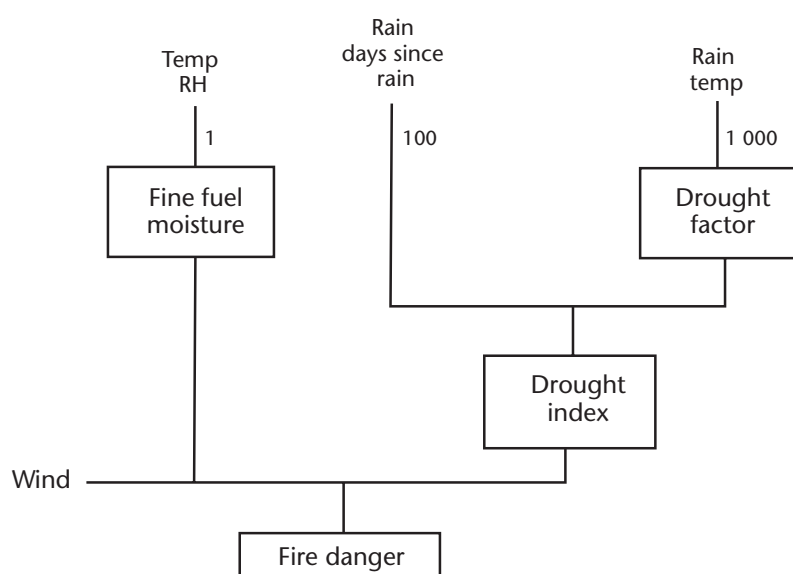


Figure 11.7. Australian forest fire danger rating system (McArthur, 1967)

to fairly dense stands of improved pastures carrying a total fuel loading of 4–5 t ha⁻¹. The effects of recent rain, which can be significant when grasses are fully cured, are not taken into account by the meter. Fully cured grass is considered to return to its pre-precipitation cured value as soon as precipitation ceases. This leads to overestimation of fire danger for several days after significant precipitation has fallen.

11.5.6.5 Comparison of fire danger rating systems

Valentine (1978) compared the Australian, Canadian and United States systems in a review of the New Zealand fire danger rating system in place at that time. Some pertinent findings are:

- (a) All the systems are hierarchical, but the Canadian and United States ones are more sophisticated and elemental in nature;
- (b) The United States system is quasi-theoretical, while the Australian and Canadian systems are empirically based;
- (c) The Canadian and Australian systems are similar in response and differ from the United States system in several ways;
- (d) NFDRS, in spite of its variety of fuel models, is best suited to grassy open forests, while the Canadian system is suited to forests with a full canopy and substantial duff layer;
- (e) The Australian system is probably most relevant to Mediterranean and subtropical climate forest types.

Additional reviews of fire danger rating systems for other global regions are provided by Viegas et al. (1999) and Lin (2000).

11.5.7 Phenomena associated with fires

11.5.7.1 Curing of fuel by radiation from ongoing fires

Any fire burning in dry conditions in a prolonged drought period can be brought under control as long as strong winds do not occur. Once wind speed increases, fire behaviour changes dramatically. Wind velocity gives a fire forward momentum and it acquires dynamic forward progress. In no-wind conditions, the flames tilt slightly backwards towards the centre of the burning area and the resulting convection column is located over the centre of the burning area. The convection column draws wind into the base of the rising air and the fire spreads outward in a circular pattern. When wind increases, the fire pattern becomes increasingly elliptical in shape.

The effect of increasing wind velocity can be summarized as follows:

- (a) Flames tilt forward and provide more effective radiation to the unburnt fuel. This causes the unburnt fuels to pre-heat, thereby reducing fuel moisture;
- (b) The convection column shifts to the head of the fire and the spotting process begins;
- (c) An optimum oxygen supply is maintained in the combustion zone;
- (d) Flame contact with unburnt fuel is maintained;
- (e) The rate of spread appears to vary as the square of the wind speed – except at low and very high wind speeds.

11.5.7.2 Topography

A fire ignited on level ground with no wind and an even fuel distribution will burn outwards in a circle. If a slope is encountered, the shape will elongate in the upslope direction. McArthur (1967) states that a 10° slope will double the rate of spread of fire and a 20° slope will increase the spread four times. Similarly, each 10° downslope will halve the forward rate of spread. This can be explained physically by the pre-heating of fuels by radiation due to the decreased flame angle. Also, convective heat transfer is increased and burning embers are blown into the fuel ahead of the fire. The rate of spread is much slower on downslopes, as the flame angle is generally negative.

Topography greatly influences wind, channelling winds into preferred directions and increasing or decreasing wind speed, depending on atmospheric stability. In mountainous areas, the prevailing winds are often the result of this channelling by the physical features of the landscape. Mountain passes, stream beds and valleys serve as routes for moving air and often develop localized circulation patterns dominated by the topography.

Some of the most severe fire weather in the world occurs in foehn wind and mountain wave situations. Physical barriers modify the wind fields in these situations to produce warm, dry, gusty winds on the lee side of the barrier (see also 11.5.2). In addition to these mechanical effects, topography is also responsible for differential heating in mountainous areas, resulting in local circulations such as katabatic (downslope) and anabatic (upslope) winds. At low speeds these systems dominate the wind flow in mountain areas.

The differential heating affects diurnal changes in the stability of the lower atmosphere, as well as

changes in relative humidity. In spring, lower elevations warm and dry earlier than higher elevations. In the southern hemisphere, north-facing slopes dry faster than south-facing slopes, and the opposite is true in the northern hemisphere. Differences based on slope, aspect and elevation diminish as the season progresses from spring to late summer. In mountainous areas, the range of relative humidity is greatest in the valley bottoms and least at higher elevations. These effects have important consequences for fire behaviour; fires at low elevations may burn better during the day than at night, while those at higher elevations may continue to burn well because humidity remains low, temperatures remain relatively warm and wind speed due to exposure is generally higher.

11.5.7.3 Spotting and low-level jet streams

One of the most important factors affecting fire behaviour is the mechanism of heat transfer. According to Luke and McArthur (1978), tree bark characteristics are the dominant factor influencing spotting; but the quantity and continuity of surface fuels, arrangement of aerial fuels, atmospheric stability and upper winds should also be considered, as well as the convective driving force of the fire intensity.

Under severe conditions, spotting has been reported up to 24 to 32 km ahead of the main fire front; in Australian eucalypt forests, fires and spotting to 3.5 km is not unusual. The major factors that affect the spotting process may be summarized as follows:

- (a) Tree species – any forest composed of a species that produces large quantities of loose bark that is light and has good aerodynamic properties can contribute to long-distance spotting;
- (b) Rate of energy release – the higher the combustion rate, the faster crown fire formation will occur, with an associated strong convection column lifting burning embers high into the atmosphere.

Byram (1954), while studying atmospheric conditions related to “blow-up”, drew attention to the importance of a negative wind profile (see also 11.5.2). Ordinarily, wind speed increases with height (positive wind shear). Byram found that the most consistent feature of the wind associated with extreme fire behaviour is the low-level jet stream. The existence of a low-level jet implies a layer of decreasing wind speed with height, that is, negative wind shear above the jet. The depth

of the layer can range from 300 to 2 500 m or more. Extreme fire behaviour is associated with low-level jets at a height of 450 m or less above the fire.

The low-level jet is not a necessary condition for a major fire to maintain its intensity, but it is thought to be a necessary condition for a small fire to blow up. Byram (1954) found the critical height to be around 450 m, with wind speeds in the 19 to 29 km h⁻¹ range. Other factors, such as wind speed at the elevation of the fire, wind speed at the jet stream maximum, and the quantity and degree of inflammability of the fuels, were also considered to be critical in determining the optimum height of the low-level jet.

Aronovitch (1989) showed that Byram’s negative wind profile was favourable to wildfire blow-up conditions. Using ground and aerial data from the Idaho Butte Fire (August 1985) and the Sundance Fire (September 1967), Aronovitch showed that it may be possible to routinely forecast whether or not a wildfire will blow up by determining the ratio of rate of conversion of thermal to kinetic energy in the column of a wildfire to the rate of flow of kinetic energy in the wind field at some elevation above the fire.

Byram’s work demonstrates the importance of low-level wind observations above fires and reveals the general inadequacy of synoptic observations for fire weather forecasting. Full use of this research will be possible only if specialized fire weather forecasters are available at large fire sites.

11.5.7.4 Fire whirlwinds

Spontaneous overturning of the atmosphere can occur when the lowest layers of the atmosphere in contact with the ground have an autoconvective lapse rate (about 36°C/km, or three times the dry adiabatic lapse rate). Superheated air columns or chimneys develop and entrainment from sides of the columns initiates a spiralling motion because this horizontally moving air is out of balance. Whirlwinds result and may remain stationary or move, but die out when they lose their source of energy. The size can vary but is generally on the order of 3 to 30 m in diameter and can reach up to 3 km in height. Velocities are usually in excess of 10 m s⁻¹ but can reach 25 m s⁻¹, and upward currents of 10 to 15 m s⁻¹ are adequate to lift large debris. Whirlwinds are common in recently burned areas and often on the lee side of ridges. They can be caused by topographic as well as atmospheric variations. Whirlwinds have been well documented as well as mathematically modelled and duplicated in laboratory experiments (Byram and Martin, 1970;

Church and Dessens, 1980). Attention has also been focused on horizontal vortices in fire (Haines et al., 1987). These vortices can generate large-scale secondary flows capable of transporting firebrands and therefore are an important consideration for fire-fighter safety.

11.5.7.5 Smoke production and smoke management

The burning process can be divided into four phases that produce various emissions, some of which are visible as smoke. These phases are described as pre-ignition, flaming, smouldering and glowing. Generally in a vegetation fire, the smoke produced consists of water vapour, gases (CO_2 , CO , NO_x , SO_2), volatile organic compounds (VOCs), such as methane and other hydrocarbons (aliphatics or aromatics, such as ethane, benzene, toluene, xylene), oxygenated compounds (alcohols, aldehydes, ketones, such as phenol, as well as guaiacol, acetaldehyde, formaldehyde, acrolein, 2-butanone, furans, carboxylic acids and esters), and halogenated compounds (such as chloromethane), semi-volatile organic compounds (SVOCs), such as polyaromatic hydrocarbons (for example, benzo[a]pyrene), and particulate matter (PM_{10} , $\text{PM}_{2.5}$), which usually consists of absorbed or condensed organic and inorganic compounds.

Specifically, in the pre-ignition phase, fuels ahead of the fire are heated, leading to evaporation of water vapour and drying. As the temperature rises, parts of the wood decompose, releasing a stream of combustible organic gases and vapours. When the hot gases from the pre-ignition phase mix with oxygen, they ignite and the burning process moves to the flaming combustion phase. The products of flaming combustion are predominantly carbon dioxide (CO_2) and water vapour. The water vapour is not the result of fuel dehydration as in the pre-ignition phase, but of chemical reactions in the burning process. Molecules with higher molecular weights are produced and many molecules of low molecular weight remain as gases and move downwind. Some compounds with higher molecular weights cool and condense into tar droplets and solid soot particles (aerosol). These particles make up visible smoke, which is usually black due to the presence of elemental carbon. During flaming combustion, most of the particles produced are coarse (diameter $>10\text{ }\mu\text{m}$).

During the smouldering (slow flameless combustion) phase, the temperature drops and some of the vapours condense. The resulting condensation also

appears as visible smoke that is white or grey in colour due to the particles produced, which are poor in elemental carbon (soot-free). Those particles are mainly fine (diameter $<2.5\text{ }\mu\text{m}$). The more inefficient the burning, the greater the production of smoke because of incomplete combustion. The heat release of a smouldering fire is seldom sufficient to sustain a convection column.

In the final phase (glowing combustion), carbon monoxide and carbon dioxide are the main products. Although the burning process can be described in terms of the four phases of combustion, it is important to recognize that combustion in forest fires is not a chemically efficient process. The combustion temperature is reduced through moisture in the fuel and heat lost to the soil and to fresh air movement in and around the fire.

A large proportion (by mass) of vegetation fire smoke is composed of particulate matter finer than $2.5\text{ }\mu\text{m}$ ($\text{PM}_{2.5}$). Exposure to particles in this size range has been identified in several studies as being linked to respiratory diseases such as asthma, and to increases in hospital admissions (Core and Peterson, 2001; Johnston et al., 2002). Health impacts are more severe for the firefighters and the sensitive groups in the general population (infants, children, people with respiratory problems, the elderly, pregnant women) (Breysse, 1984; Goldammer and Statheropoulos, 2008). Air quality standards in many countries now impose limits on $\text{PM}_{2.5}$ concentrations, thus necessitating improvements in smoke management practices.

Smoke management is the combined use of meteorology, fuel moisture, fuel loading and fire management techniques to keep visibility and air-quality impacts of smoke within acceptable limits. Anyone who uses prescribed fire should consider smoke management practices.

The National Wildfire Coordination Group in the United States has published an extensive smoke management guide (Hardy et al., 2001), which summarizes strategies to manage smoke from prescribed fires. Other sources, including the *Health Guidelines for Vegetation Fire Events* (Schwela et al., 1999), are listed in 11.2.6 above. While many recommendations are focused on fuel management, attention to meteorological factors can assist in redistributing the smoke through:

- (a) Avoidance: conduct prescribed burning on days when smoke intrusion into sensitive areas is highly unlikely, that is, when transport winds will carry smoke away from sensitive areas;

- (b) Dilution: reduce smoke concentration by mixing it through a greater volume of air, either by scheduling burns during periods of good vertical dispersion, or by burning at slower rates.

11.5.8 **Conclusion**

A review of any system inevitably results in the discovery of a need to maintain research into the application of modern techniques to improve the system. Of the three components of the fire triangle, the element most susceptible to control is fuel; hence the need to understand the processes associated with fuel curing, fuel build-up and decay, and also the processes involving wetting and drying of fuel. Remote-sensing can be used to help establish vegetation indices, radiation fields and fields of evaporation, all of which can be used to deduce fuel states. Methods used to deduce moisture in forest fuels such as the Keetch–Byram and the Tasmanian soil dryness indices appear to be over-simplifications and should be improved through research.

Fuel state is the only element in weather meters that is not forecast, while wind speed and fuel state are the two most influential weather-related elements affecting fire behaviour using derived indices. The meter used in the United States is a theoretical unit and can accommodate 13 to 20 fuel models. The McArthur-type meter uses only two basic fuel models, one for grass and one for forest. The United States National Fire Danger Rating

System, in spite of its variety of fuels, is best suited to grassy open fires. The Canadian system is best suited to forests with a full canopy and substantial duff layers. The McArthur system is probably most relevant to Mediterranean and subtropical climate forest types.

In general, derived weather indices do not take into account important factors such as the curing of fuel from ongoing fire radiation, upper-wind profiles or the instability of the atmosphere, nor do these calculations indicate the occurrence of fire whirlwinds or the transition of a fire from a two-dimensional to a three-dimensional fire, namely, crowning. There are other meteorologically related aspects that require face-to-face briefing to be effective. The value of a fire weather meteorologist on site using direct communications with the main forecast centre cannot be overestimated. Sudden wind changes can threaten the lives of firefighters and other persons who are involved with ongoing fires.

In the tropics, most fires are used by humans as an important tool in land management. In the subtropics, lightning is one of the main causes of fire outbreaks, while in the tropics fires started from lightning are rare. Whether fires occur in the tropics or subtropics, the same physical laws controlling wildfire behaviour still apply. The awareness level of the damage that can result from the indiscriminate use of fire is very low in certain areas, especially from the environmental viewpoint, as stated in WMO (1982). The need for supplementary fire weather observations exists in many places.

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CHAPTER 12

WEATHER AND CLIMATE AND ANIMAL PRODUCTION

12.1 INTRODUCTION

Weather and climate influence both farm animal production and agronomic production. There are many differences, some obvious and some subtle, in the way animals and plants respond directly and indirectly to given environments, however. Chapter 9 focuses principally on the applications of meteorology to agronomic agriculture. This chapter is biometeorologically oriented: it explores the applications of weather and climate information to sustain or improve on-farm animal performance, such as survival, growth, reproduction, and milk and wool production. Management intervention is needed not only to improve the genetic potential of the animals, but also to help overcome the constraints on production set by the climate, the physical environment and the health hazards in a region. On-farm decisions usually involve selection, design and management of production facilities, while the collective impacts may guide regional or national policy, determine responses to potential large-scale changes, or influence other decisions. The case for understanding the implications of regional and local climates affecting those decisions is self-evident, as is the need for timely forecasts to trigger management anticipation and response to adverse conditions.

12.1.1 Background

Animal production problems associated with weather and climate go beyond an understanding of the processes and variations in the atmospheric boundary layer and the role of local ground cover and topography in those variations. Knowledge of how potential environmental stressors (ambient temperature, humidity, thermal radiation, air speed) can directly and adversely affect animal performance, health and well-being when coping capabilities of the animals are exceeded is also required (Figure 12.1). The indirect consequences of weather episodes, such as their impact on feed quality and availability, must also be recognized.

Factors for consideration in animal production include:

- Thermoneutral ranges of environmental variables for important classes of livestock in the light of weather and seasonal variations that can occur. Past weather data (both conventional and derived climate data) should be analysed and interpreted for the specific purpose of establishing risks and probabilities;
- Evaluation of detailed energy budgets for individual animals and groups of animals, which can indicate imbalances between

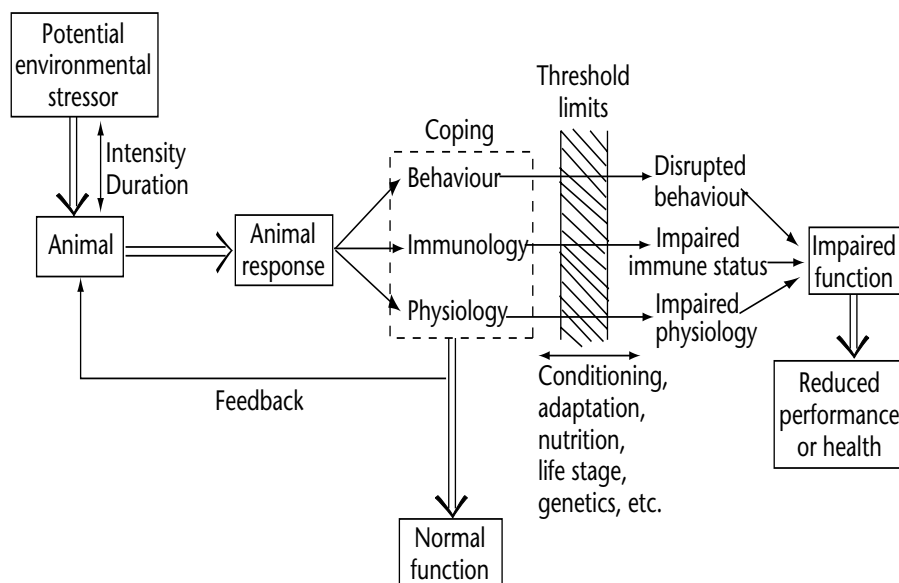


Figure 12.1. Responses of animals to potential environmental stressors that can influence performance and health (adapted from Hahn and Becker, 1984)

metabolic heat production and heat losses to the environment under various realistic combinations of weather variables. Associated weather data must be at an appropriate resolution, for example daily, or perhaps hourly, values. For each class of animal, but particularly for young or newborn animals, the maximum possible (peak) rate of metabolic heat production is of considerable interest, together with the length of time it can be sustained. The likely duration of weather outside the thermoneutral zone of an animal needs to be known, while the accumulation of such periods over a season (when interpreted in terms of implied weight loss, and so on) will provide some measure of economic performance. Extended weather episodes that affect the availability of feed or amount of feed intake can have marked impacts on performance. If restrictions on feed are also linked with thermal stress and if there are competing demands for body reserves (as in pregnancy), then induced metabolic disorders may have effects that extend beyond the weather episodes themselves, and may not be fully recognized until the young are born;

- (c) Development of an understanding, preferably quantitative, of how environmental variables affect the heat budget of animals. The heat budget, which is based on heat exchanges that depend on factors in Table 12.1, should suggest how the ambient environment might be manipulated by natural and man-made shelter against wind, sun and precipitation; by site selection to increase or decrease exposure; and by artificial aids that would directly provide additional heating or cooling;
- (d) The possibility that animal housing offers improved animal and economic performance. A plan to change the external macro-environment into an acceptable micro-environment also calls for an energy budget approach, with the house and its animals as the unit, and ventilation (natural or fan-assisted) as the primary control variable;
- (e) The weather dependency of disease and parasitism, especially the timing and scale of the problem; whether exposure to a new infection results in disease depends, among other factors, on the number of infectious organisms taken in and the occurrence of

Table 12.1. Physical factors influencing energy transfer from the surface of an animal (Hahn, 1976)

	<i>Mode of heat transfer</i>			
	<i>Radiation</i>	<i>Convection</i>	<i>Conduction</i>	<i>Evaporation</i>
Surface area of animal	X ^a	X	X ^b	X ^c
Temperature of animal surface	X	X	X	X ^d
Temperature of surroundings		X	X ^e	
Velocity of air		X	X	
Vapour pressure of air		X	X	X
Shape factor of radiation source or sink	X			
Emissivity of animal surface	X			
Conductivity of surroundings			X ^e	
Emissivity of surroundings	X			

^a Area of animal directly exposed to the radiation source or sink

^b For standing animals, conduction heat transfer is negligible; for animals lying down, the area of animal surface in contact with the supporting structure becomes a factor

^c The wetted area of the animal surface, including the respiratory passages

^d The temperature of the animal surface is an indirect factor since vapour pressure is a function of temperature

^e Only that portion of the surroundings actually in contact with the animal

environmental distress (particularly thermal stress) around the time of infection. The development of integrated production systems in which the understanding of interactions among husbandry practices, facilities, disease control and environmental factors is applied in complementary ways. Chapter 9 also discusses the relationship of weather and animal diseases.

Active cooperation among professional services (meteorologists, engineers, veterinarians, nutritionists, and so on), advisory services and farmers is required to successfully include these factors as a basis for strategic and operational management control decisions to improve production systems. Specific problem areas for the meteorological services (forecasting, data acquisition and archiving, and liaison and research) are explored more fully in the context of animal health and production in two WMO publications: WMO (1988, 1989*a*). Additional background material is available in WMO (1964, 1967, 1970*a*, 1970*b*, 1972, 1973, 1978*a*, 1978*b*, 1982, 1986 and 1989*b*).

12.1.2 **Applications of biometeorological information for rational planning, design and management**

12.1.2.1 **Characterization of the environment**

The animal's environment is complex. Scientists attempt to define and measure it in terms of a single parameter or a small group of parameters considered of primary importance, however; two WMO publications (WMO, 1970*a*, 1972) discuss instrument applications and procedures used up to 1972. In order to understand and explore relationships between organisms and their environment, biologists should be familiar with the principles of the environmental sciences. The books of Monteith and Unsworth (1990) and Campbell and Norman (1998) describe the physical micro-environment in which animals live. They present a simplified discussion of heat transfer models and apply them to exchange processes between animals and environment. An introductory book to animal bioclimatology also has been issued in Portuguese (Da Silva, 2000*a*).

Of various measures of the biological environment, dry bulb temperature is generally considered to be the principal thermal measure. High humidity or solar radiation worsens the effect of high temperature, however. High humidity reduces the potential for skin and respiratory evaporation by the animal, while solar radiation adds to the heat

from metabolic processes that must be dissipated to maintain body temperature. Strong winds or drafts, especially in combination with precipitation, amplify adverse effects of cold temperature. Conversely, thermal radiation from warmer surroundings can offset the effects of cold temperature to some extent.

Integrative measures have been developed to evaluate the microclimates of animals in hot weather, such as the black globe thermometer, for example, which combines the influence of air temperature, air movement and radiation (Vernon, 1932; Bedford and Warner, 1934; Bond and Kelly, 1955). The globe temperature, however, is a consequence of the specific thermal behaviour of a globe with given dimensions, made of a given material and exposed to circumstantial conditions in a given space point, while animal bodies are of very different and variable size, shape and structure. Thus, the black globe should not be taken as a general model for animals, as for the exchange of thermal energy with environment. An adequate integrative measure of the thermal environment, in either hot or cold weather, must be based on knowledge of the thermal exchange mechanisms of a given animal type. Electrical animal analogues have been suggested for this purpose (Burnett and Bruce, 1978; Webster, 1971; Clayton and Boyd, 1964; McArthur, 1987; Da Silva, 2000*b*; McGovern and Bruce, 2000; Turnpenny, 2000*a*, 2000*b*).

Various indices derived from primary meteorological measures have also been developed: Wind-Chill Index (Siple and Passel, 1945), Temperature-Humidity Index (Thom, 1959), Black Globe-Humidity Index (Buffington et al., 1981), Effective Temperature for dairy cows (Yamamoto, 1983), Equivalent Temperature Index for dairy cows (Baeta et al., 1987), Thermal Comfort Index for sheep (Da Silva and Barbosa, 1993), Heat Load Index for beef cattle (Gaughan et al., 2002) and Environmental Stress Index (Moran et al., 2001). A comprehensive review of the assessment of thermal indices for livestock was presented by Hahn et al. (2003).

Sensors and indices do not adequately represent the complex physiological, behavioural and adaptive capabilities of the animals in question, however. The indices must be appropriately tested for each environment and animal species. For example, a test carried out by Da Silva and co-workers (2005, unpublished) with Holstein and Jersey dairy cows of several herds in North-east Brazil (approximately 5° S latitude) showed that the Equivalent Temperature Index (Baeta et al.,

1987) performed much better than the other indices cited above. The selection criterion used was the association of the calculated index value with the measured physiological responses of the animals. In addition, the Mean Radiant Temperature of the environment (MRT) was correlated much more closely with animals' physiological responses than were the black globe temperature and the dry bulb temperature.

Indices such as those mentioned above are very useful devices to evaluate the general climate of an area, but require local meteorological measures of the air temperature and humidity, wind speed, MRT and solar radiation. All of these are variables, but MRT can be obtained from meteorological stations. MRT can be calculated from the black globe temperature, air temperature and wind speed by using the formulae given by Da Silva (2002), which take into account the effect of natural convection as well as that of forced convection. As for solar radiation, when its direct measurement is not available from the meteorological stations, it can be estimated easily as a function of latitude, season and time of day (see Monteith and Unsworth, 1990; Campbell and Norman, 1998).

Meteorological values for design purposes are seldom based on the most extreme values experienced at a site, but are used to allow an acceptable level of risk to be included. Appropriate livestock housing can be designed to accept a certain level of

risk of the seasonal extreme values, especially in temperate areas.

12.1.2.2 Characterization of farm animal performance

The fate and partitioning of dietary energy intake are shown schematically in Figure 12.2. The main thrust of work in recent times has been to quantify the identified components of energy use. Figure 12.2 makes it clear that thermal energy exchanges between the animal and its ambient environment interact with the residual dietary energy available for productive purposes. A representation of partitioned heat production and losses across a range of thermal environments is shown in Figure 12.3. Animals function most efficiently within their thermoneutral zone, while above the upper and below the lower critical temperatures, the animal is stressed and the environment constrains the production process. Those critical temperatures are not fixed characteristics for any species or animal type, however, and they may change with age and physiological conditions. Natural and artificial selection in extreme environments can improve adaptation for those conditions, by changing the adaptive morphological and physiological traits of livestock, sometimes in a few generations. For example, Holstein dairy cows bred in tropical and subtropical zones have differences in their hair-coat characteristics relative to the cows bred in temperate regions.

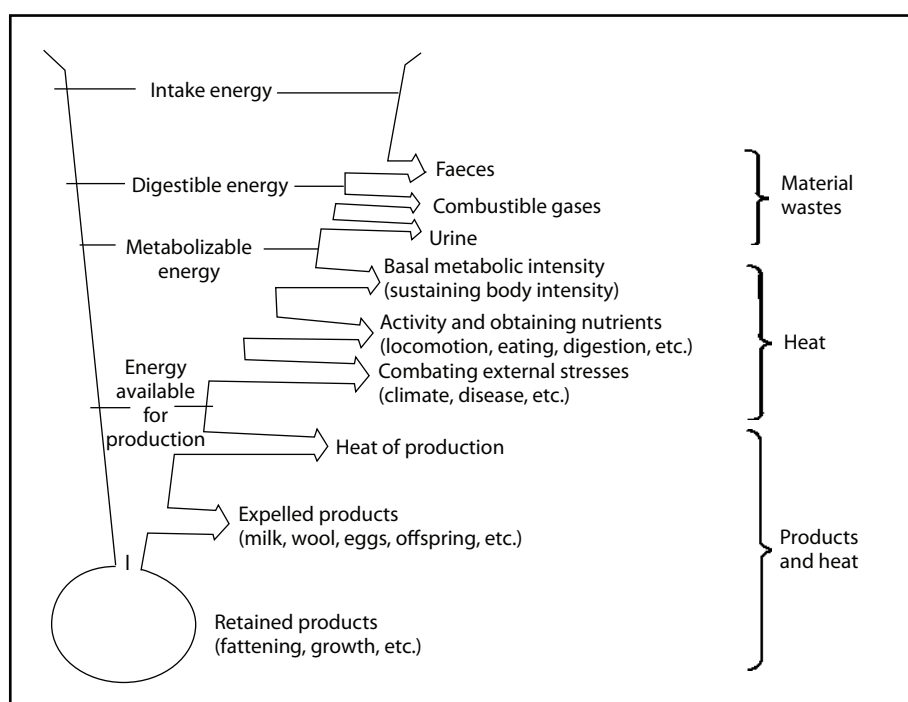


Figure 12.2. Funnel model of the partitioning of dietary energy in animals (after Young, 1975)

Specific responses of an individual animal are influenced by many factors, both internal and external. Growth; reproduction; feed intake and conversion; mortality; and milk, egg and wool production have traditionally served as integrative performance measures of response to environmental factors. Thermoregulatory measures (such as body temperature rhythms) have recently been used to establish thresholds for disruptions in feeding activities during hot weather, which ultimately affects performance (Hahn et al., 1991). Behavioural measures (posture, orientation, shelter-seeking, huddling or dispersion) relate to thermoregulatory responses of animals to their environment; Hafez (1962), Ansell (1981), Blackshaw and Blackshaw (1994), and Kadzere et al. (2002) provide more detailed discussion.

Morbidity and injuries have been emphasized in recent years, particularly as they relate to animal health and well-being. Endocrine, immune function and other physiological measures, energy balances, and quality evaluations of the final consumable product also serve as response measures, but are often difficult or impossible to relate directly to performance or health measures. Since the latter measures are also of economic importance to the producer, performance or health response relationships to environmental factors remain the primary basis for evaluating the consequences of

ambient conditions for farm animals. In estimating those consequences, it is important to consider the resilience of animals, within limits, to maintain normal functions through adaptive and compensatory capabilities (Hahn, 1982). In the longer term, therefore, the animal's adaptive and compensatory mechanisms tend to maintain biological processes such as growth, despite short-term adverse factors. These mechanisms blur the sharp changes noted in the short term, so that losses in growth and efficiency are minimized over a range of temperatures on either side of the maximum (illustrated in Figure 12.4).

Care must be taken in comparing different types of animals with respect to their performance in a given environment. For example, tropical and European breeds of livestock can hardly be compared one to another for their growth rate or their reproductive performance in a tropical environment. In fact, for a long time, most of the native tropical livestock were not objects of artificial selection processes (there are exceptions) for economic aspects of breeding, such as greater growth rates, higher milk yields or higher fertility rates. These are "modern" aspects, associated with what we can call the capitalist or Western point of view, whose adoption is very recent in developing countries of Asia, Africa and Latin America. Livestock native to these countries have been subject to natural selection in their

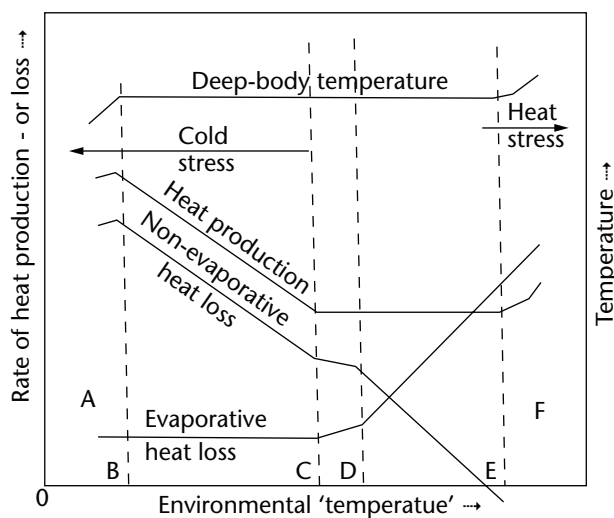


Figure 12.3. Diagrammatic representation of components of the energy balance of a homeotherm (Monteith and Mount, 1974): A, zone of hypothermia; B, "temperature" of summit metabolism; C, lower critical "temperature"; D, "temperature" associated with marked increase of evaporative loss; CD, zone of least thermoregulatory effort; E, upper critical "temperature"; F, zone of hyperthermia; CE, zone of minimal metabolism (thermoneutral zone)

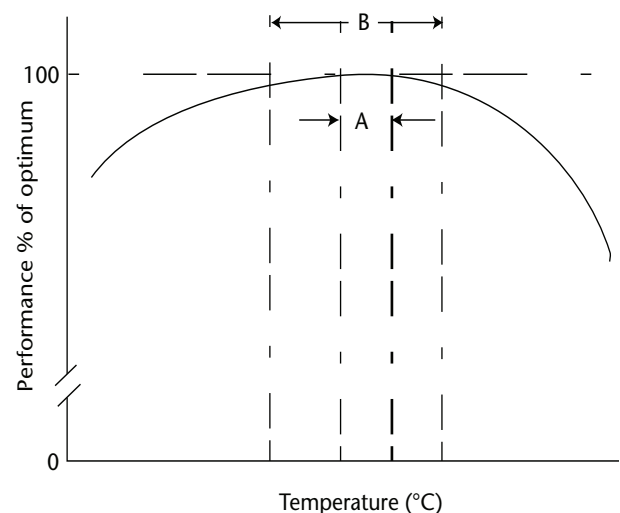


Figure 12.4. Typical performance response as a function of ambient temperature. Although an optimum temperature may exist for an individual animal at a given time and under specific management practices, optimal conditions for a group of animals involve a slightly wider zone of temperature (A). In addition, performance curves usually show only slight decreases (typically 1–2 per cent) from optimum over a somewhat broader range of temperatures ("nominal loss" zone, B).

environments and high economic performance of animals is not a choice for nature – it is a human choice, because many of its aspects can unfairly influence the animals' fitness. As for nature, females must give a milk yield that corresponds exactly to the quantity needed by their young: a yield in excess of this quantity can adversely affect the physiological balance. Thus, the low producing ability of native livestock is not a sign of inferiority, but of a perfect adaptation to their specific environment. On the other hand, the high productive performance of the European breeds of livestock is only the consequence of hundreds of years under artificial selection for a given purpose.

Yousef (1985) presented a comprehensive review of stress physiology in livestock, covering the basic physical, physiological and behavioural aspects of thermoregulation, and the responses of ungulates and poultry to thermal stress. In this connection, the book by Louw (1993) provides an interesting introduction to physiological animal ecology.

12.1.2.3 Decision-making

Strategic decisions include evaluation by the farmer (or the farmer's agents) of any need to alter the naturally varying environment, and, if a need is perceived to limit adverse consequences, to select a practice or technique from among those available. Figure 12.5 illustrates the managerial decision process through evaluation of the consequences of doing nothing, adopting measures to protect against loss of animals, or selecting practices to actively counter the effects of hot environments. Penalties

for inaction and benefits from various actions, as developed from animal response relationships based on environmental factors, provide the basis for a decision. The key to the process is the animal response relationship, which defines the altered performance and health when threshold limits are exceeded. Such relationships are useful tools that establish environmental requirements and help to guide rational management decisions (Hahn, 1976; WMO, 1988). Other strategic decisions include those oriented towards engineering design and regional or national policy (for instance, responding to potential global change).

Tactical (operational) decisions are short-term (for example, daily) decisions by managers to use or operate facilities and equipment acquired as a result of strategic decisions. Examples include moving animals to shelters when a blizzard is forecast or the operation of sprinklers for animals during a heat wave. Suppliers of electricity or other weather-sensitive services to livestock facilities may also be faced with tactical decisions to match changing demands.

Other important considerations include the availability and limitations of biometeorological information to support rational decision processes. Much information is available about farm animal responses to environmental factors (see WMO, 1989a). A summary of optimal performance and nominal performance loss thresholds for several classes and species, based on such information, is given in Figure 12.6. There are still few quantitative response relationships available to assess the impact

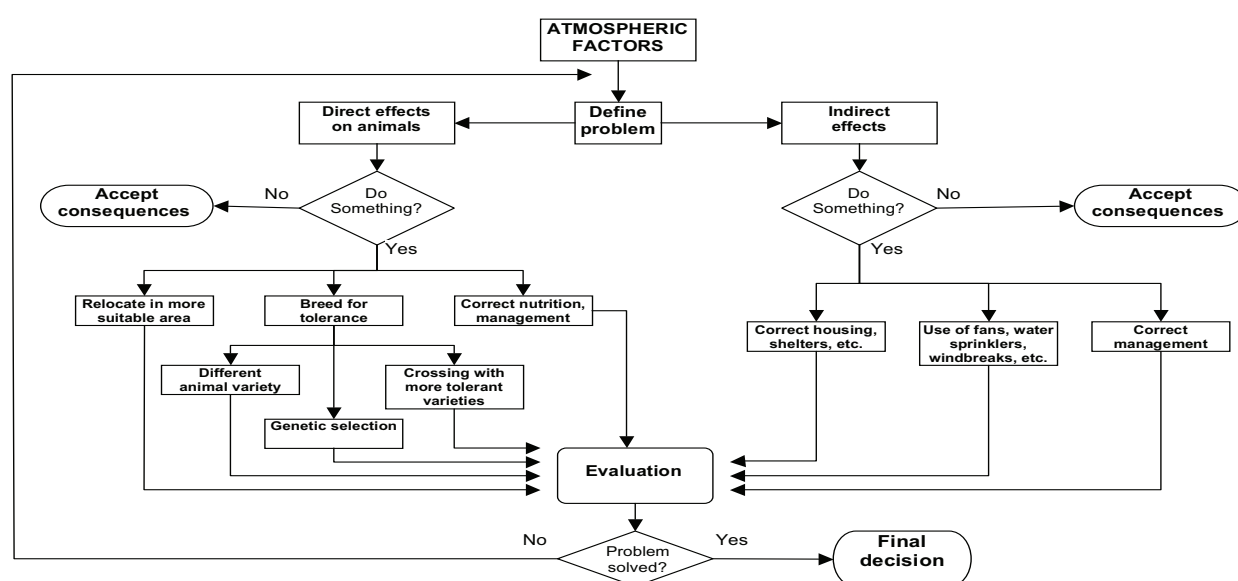


Figure 12.5. Decision diagram for managers considering livestock environment modification

of climate on animal performance in given locations, however; *Weather, Climate and Animal Performance* (WMO, 1988) summarizes those available for dairy cows and poultry. A series of memoranda by Smith (1972a, 1972b, 1973a, 1973b, 1973c) move

progressively from a determination of critical environmental temperatures for animals to identification of areas and months in which the animals would be at risk, including some generalization and the calculation of critical temperatures for a range

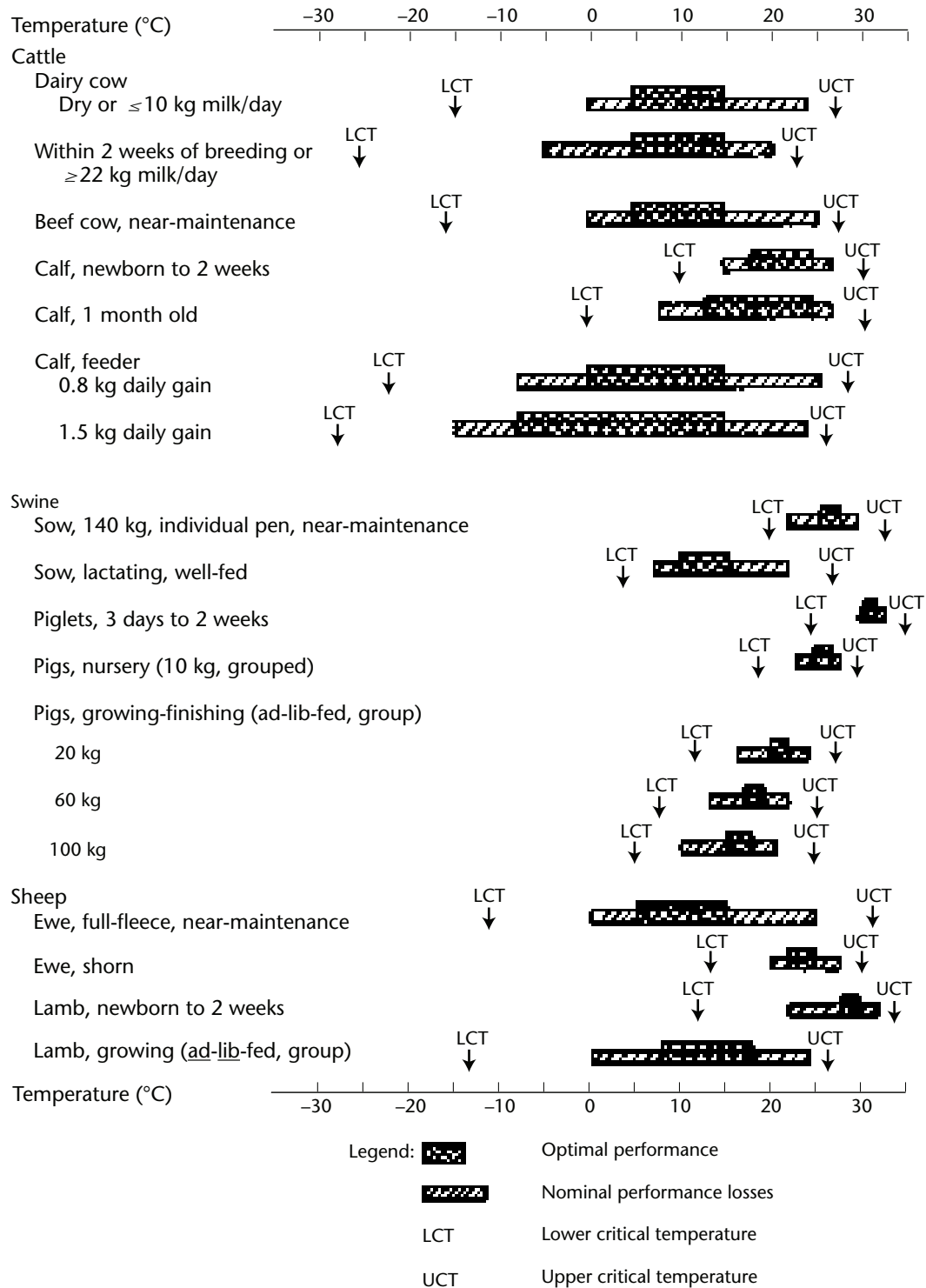


Figure 12.6. Ambient temperature zones for optimal performance and nominal performance losses for several classifications of cattle, swine and sheep (WMO, 1989a). Nominal performance losses are generally considered to be so small as to be negligible in terms of impact on management decisions.

of field conditions. This leads to a quantification of the performance loss imposed by environments colder than the lower critical temperature and is followed by benefit/cost studies of steps that might avoid performance losses, such as additional feed or the provision of shelter or housing.

Climatological and meteorological information, while readily available for a number of reporting stations, is often of limited usefulness when those stations are not representative of rural areas or do not adequately report primary measures needed to calculate appropriate derived index values.

12.2 APPLICATIONS FOR FARMERS

12.2.1 Animal traits and physiological responses

12.2.1.1 Traits

The characteristics of the outer surface of an animal's body are of great importance in the relationship between the animal and its ambient temperature. Animals living in deserts and extremely dry environments must have an efficient protection against the loss of water vapour and the intense solar radiation; those living in cold regions must be protected against the loss of body heat; those in tropical regions must be able to dissipate heat excess through the skin and from the respiratory surfaces, and at the same time they must avoid incoming thermal energy from the environment. Such protective properties depend on the morphological characteristics of the skin (colour, thickness, sweat glands, and so on) and of the hair coat (especially the thickness of the coat, number of hairs per unit area, diameter of the hairs, length of the hairs and angle of the hairs to the skin surface), which allow the animal to exchange heat with the environment through the four transfer modes noted in Table 12.1.

In certain kinds of animals such as pigs and water buffaloes, which do not present hair coat (their skin is scarcely covered by bristles) or sweating, heat exchange occurs mainly by convection, although the animals can eventually moisten their body surface with water or mud in order to increase heat loss by evaporation.

Cattle in temperate regions have in general thick hair coats (more than 10 mm) whose hairs change during the year: in the spring the long, thin winter hairs fall and are replaced by the shorter, thicker summer hairs, which will fall in the late autumn. If

cattle of such temperate breeds are transferred to a tropical region, however, their hair coats tend to reduce thickness significantly (Da Silva et al., 1988; Da Silva, 2000a), thereby improving transfer of metabolic heat from the body to the atmosphere, which is achieved by convection, evaporation and radiation. Such a reduction is an adaptive response of the population and in many cases is associated with increased sweating ability. Respiratory heat loss by evaporation seems to be of some importance in tropical environments: under air temperatures between 10°C and 35°C, sensible heat loss by respiratory convection decreases from 8.24 to 1.09 W m⁻², while the latent heat loss by evaporation increases from 1.03 to 56.5 W m⁻² (Maia et al., 2005). Similar results were found by Da Silva et al. (2002) in sheep.

The role of pigmentation and other skin and hair-coat characteristics in heat transfer by radiation in animals has been extensively studied (Hamilton and Heppner, 1967; Hutchinson and Brown, 1969; Hutchinson et al., 1975; Kovarick, 1973; Cena and Monteith, 1975; Walsberg et al., 1978; McArthur, 1987; Da Silva et al., 1988, 2003; Hansen, 1990; Gebremedhin et al., 1997; Hillman et al., 2001). In particular, skin pigmentation is of utmost importance to protect deep tissues against excess exposure to solar short-wave radiation in tropical zones. In general, it is accepted that dark-coated animals acquire greater heat loads from solar radiation than do the light-coloured ones (Stewart, 1953; Finch et al., 1984; Hansen and Lander, 1988); consequently, light coats have been considered the most desirable ones for livestock in tropical areas (Goodwin et al., 1995, 1997), notwithstanding the contradictory conclusions of several studies. In fact, it has been observed (Kovarick, 1973; Cena and Monteith, 1975; Walsberg et al., 1978; Gebremedhin et al., 1997) that short-wave radiation could be transmitted within the coat and that this transmission is stronger in the light coats than in the dark coats.

Da Silva et al. (2003) used a spectroradiometer to evaluate the thermo-physical properties of the skin and the hair coat of cattle, water buffalo and deer (Pantanal deer, *Blastocerus dichotomus*) from populations in south-eastern Brazil. The results showed that short-wave radiation (300 to 850 nm) penetrates light hair coats much more than dark coats, especially in the shorter wavelengths.

European cattle breeds have the almost the same level of pigmentation in the hairs as in the skin beneath, while tropical cattle types present in general light hair coats over highly pigmented skins; thus, predominantly white Holstein cows, for example, are largely affected by the intense

short-wave radiation in tropical areas. As a result, predominantly black cows are preferred, despite the increased temperature of the body surface when exposed to sun. A noticeable exception is the Jersey breed, in which the pigmentation of the skin is independent of that of the hairs. It is not a coincidence that among the European cattle breeds, this breed is considered the most adaptable to the tropics. A short, well-settled, light-coloured hair coat on a highly pigmented skin constitutes the most desirable body surface for livestock in tropical environments.

12.2.1.2 Response to stress

Traditionally, comparisons within the same livestock breeds across several countries and environments have yielded large differences in their physiological and production performance, especially for dairy cattle. The increase in milk yield and resulting increase in heat production over the last half-century, however, together with the genetic improvement of the herds even in tropical countries, require re-evaluation of the relationship between milk yield and sensitivity to thermal stress.

Animal physiological behaviour during exposure to environmental stress has been measured by variations in the body temperature, respiratory rate and heart rate. Sweating has also been used to evaluate the response to heat stress in some mammal species, such as cattle, sheep and horses (Schleger and Turner, 1965; Pan et al., 1969; Amakiri, 1974; Finch et al., 1982; Da Silva et al., 1988, 1990; Titto et al., 1994). Methods for the analysis of hair-coat characteristics were described in detail by Udo (1978) and Da Silva (2000a).

New tools have become available to assist in evaluating stress in livestock, however, and recent reviews have been published on this subject (Nienaber et al., 1999; Collier et al., 2003). One example is infrared (IR) thermometry, which permits the evaluation of animals' skin temperature even at some distance; radiotelemetry and data loggers have also been very useful means of evaluating animals in the field.

Temperature, humidity or movement sensors of minute size can be implanted in one or more places on an animal's body and connected to a radio emitter that sends the data to a remote receiver. This is radio telemetry. Another approach involves the storage of the quantities measured by the sensors in a digital device, such as a data logger, which can be attached to the animal's body and recovered later.

Temperature measurements made by radio telemetry and data loggers need direct contact with the target surface, and in this process electronic devices are used as thermocouples or thermoresistors. Infrared thermometers are non-contact devices that measure the heat emitted by the target as infrared energy. They have very fast response and are especially suitable for the measurement of moving and intermittent targets and targets that are inaccessible due to a hostile environment, geometry limitations or safety hazards. The best IR thermometers have a control that allows for their adjustment to the emissivity of the target surface. Some of them are relatively inexpensive models that are able to measure surfaces at a distance of several metres, with a laser light used to point them at a target. Common uses are measurements of canopy temperature of plants, cutaneous temperature of free animals, temperature of very hot surfaces, and so forth.

More recently, infrared digital cameras have been used to measure the temperature gradient of large surfaces. Thermal imaging is a means for performing remote health and fertility diagnostics of cows and other animals and for monitoring the body temperature variations in free animals.

12.2.2 Reducing impacts of climate on livestock production

For an animal to maintain homeothermy (no change in body temperature, other than normal circadian rhythms), the ambient environment and the animal must exchange heat at a rate that permits balancing the metabolic heat production and the energy gains/losses from the four transfer modes noted in Table 12.1. Ruminant animals primarily adjust evaporative heat loss to maintain homeothermy during brief exposures to adverse weather, but will reduce feed intake to lower heat production during prolonged hot weather. Swine and poultry primarily adjust heat production to maintain homeothermy.

Quantitatively, the level of heat exchange by each heat transfer mode is dependent on the magnitude and direction of the gradient involved. In hot environments, energy exchanges by radiation are dominant, while convective energy exchanges tend to dominate in cold environments. To alter the microclimate of an animal effectively through housing or environmental modification, alteration of one or more of the following factors must be considered: temperature and/or emissivity of the surroundings; air temperature; air velocity; air vapour pressure; radiation or shade factors; and conductivity of surfaces that animals might contact.

Success in improving production and efficiency in most climates is possible if a rational approach is followed.

12.2.2.1 Site selection

The selection of a site for housing or another intensive production system is fundamental to minimizing the effects of local weather. Climatic factors vary with height above the ground at a specific location and with varying terrain in a general location. Observations of the microclimates in a general location will reveal much variation in thermal conditions resulting from terrain features, differential exposure, wetlands, rivers, type and height of vegetation, human activities and other factors. Proper selection of a site to emphasize factors for enhanced heat dissipation (minimal radiation, air temperature and humidity, maximal air velocity) will have long-term protection benefits. It must be remembered, however, that seasons change: in temperate regions a site selected to enhance heat dissipation in the summer may be detrimental to heat conservation in winter; in low-latitude tropical regions, heat dissipation must be enhanced year-round, but in many cases there is a wide variation in the air humidity.

12.2.2.2 Windbreaks

Grazing animals or animals giving birth will seek shelter from strong winds, especially during cold weather. Structures or trees can markedly reduce wind speed and can be beneficial to the survival of exposed animals (especially newborns). Windbreaks have an importance far beyond these benefits, however, especially in tropical and subtropical regions.

First, high temperatures accompanied by dry winds may damage grass plants. Studies of the effects of wind on grass plants grown in controlled environments have shown that strong wind reduces grass growth as the result of damage to leaf surfaces, which affect the water relations of the plant (Grace, 1981); in addition, the physical shaking of the plant by wind is an even stronger adverse indirect effect.

Second, while they also depend on the available soil moisture, the harmful effects of high temperatures, high vapour pressure deficits and moderate to strong winds can increase the loss of water from evapotranspiration (WMO, 1992; Onyewotu et al., 2004). Evapotranspiration, which includes evaporation from the soil and transpiration from plants, has been reported to account for about 70 per cent of the water loss in the continental

United States (Yao, 1981). Below sparse crops in hedgerow agroforestry, Kinama et al. (2005) measured evaporation that reached 65 per cent of rainfall in semi-arid Kenya.

Third, in a semi-arid region, the land is most vulnerable to wind erosion when vegetation cover is sparse and the soil is dry. Wind erosion is in fact one of the most important causes of desertification (for example, Onyewotu et al., 2003b; Zheng et al., 2005).

A windbreak acts as a barrier that lowers the wind speed near the ground surface and diverts and splits the air stream. The protection achieved is determined by the configuration, height, density and thickness of the trees in a belt. The higher the windbreak, the greater the distance of its downwind (and upwind) protection, which involves reduction of the soil erosion and the soil moisture loss by evapotranspiration. The shelter effect on grassland growth has been reported as an increase in growth on the order of 20 per cent (WMO, 1996). There is a depression in the immediate proximity of the trees: a maximum growth benefit can be observed at a distance of 2 to 5 times the height of the trees and little effect is seen at distances greater than 15 times the height (WMO, 1994).

In using trees as windbreaks, however, there is a trade-off between any enhanced growth of the associated grassland and the area occupied by the shelter trees, unless they have associated timber or fuel value (for example, Onyewotu et al.,). The use of leguminous trees or shrubs can be a practical means to counteract the effects of wind and heat stress, as well as to improve animal diet.

12.2.2.3 Shades

Shades and other minimal measures should be thought of as a form of insurance for protecting farm animals in hot climates. In a tropical region, the solar irradiance is high even during the winter, when its value is often the double ($1\,000\text{ W m}^{-2}$ or more) that observed in a location at 40° latitude (500 W m^{-2} or less).

In an incident in California (Oliver et al., 1979), where more than 700 dairy cows died in a three-day period, adequate shades reduced the amplifying effects of direct solar radiation coupled with high air temperature and humidity, so that death losses were only one-third of those in areas where cows had inadequate shade. As a matter of fact, when dairy cows are given access to adequate shades, milk production is increased (Roman-Ponce et al., 1977; Ingraham et al., 1979; Buffington et al., 1983; Igono,

1986; Davison et al., 1988). Even in a subtropical region, Holstein cows chronically exposed to sun reduce their production by 1.5 to 3.3 kg/cow/day (Hansen, 1990). Blackshaw and Blackshaw (1994) conducted a review of the effect of shade on the behaviour and performance of cattle.

The radiant environment in a shaded area has four constituent parts: the cold ground in the shade; the hot ground outside the shade; the lower (inner) surface of the roof; and the sky. The radiant temperature of the clear sky is in general much lower than that of the air and even in a tropical location this difference may be equal to 25°C or more. Thus, in areas with clear, sunny afternoons, shades should be 3 to 4.5 m high in order to permit maximum exposure to the relatively cool sky, which acts as an efficient radiation sink (Bond et al., 1967). On the other hand, in areas with cloudy afternoons, shades 2 to 2.5 m in height are better, in order to limit the diffuse radiation received from the clouds by animals beneath the shade (Hahn, 1981).

As for the materials used, hay or straw shades are the most effective (and cheap) artificial materials; solid shade provided by sheet metal painted white on top is next in effectiveness (Bond et al., 1961). But aluminium sheets are better than a white-painted surface (Bond et al., 1969). Slats or other shade materials with less than total shading capabilities are considerably less effective; for example, slatted snow-fencing with approximately 50 per cent openings is only 59 per cent as effective as new aluminium sheeting for shading animals (Kelly and Bond, 1958).

The ground cover around a shade is a factor of importance. The level of thermal radiation above a grass field is less than that above a dirt ground (Bond et al., 1969), thus shades are very important for animals in a corral in a hot, sunny environment.

The most effective shades are trees, as they provide protection from sunlight, combined with beneficial cooling as moisture evaporates from the leaves. There are differences among the species with respect to the protection given, however. Waldige (1994) observed some species (*Mangifera indica*, *Caesalpinia* sp., *Pinus* sp. and *Casuarina* sp.) in Brazil, showing that the mango tree (*Mangifera indica*) provided the best shade with the least radiant heat load; the *Pinus*, which presented high heat loads, afforded the worst type of shade. In spite of its best performance, the mango tree was discarded as a shade for cattle, for its fruit is as dangerous to the cows as any other fruit of similar

size and consistency. When swallowed by a cow, the mango fruit closes the oesophagus tightly, leading rapidly to an acute state of meteorism and subsequent death by heart stroke. Da Silva (2004) presented formulas to predict orientation, shape and area of the shades projected by trees of different canopy shapes, considering location, season and time of day.

As for the area of shade needed by cattle, different figures have been presented by several authors. Buffington et al. (1983) recommended at least 4.2 m² per cow, but agreed with Bond et al. (1958) that 5.6 m² per cow was desirable. Hahn (1985) suggested only 1.8–2.5 m² per cow, which may cause crowding and does not represent adequate values for tropical environments. Actually, in sunny, hot environments, the animals avoid crowding because they need to dissipate body heat, and they spend much time in the shade, especially cattle of European origin. If the shaded area is not sufficient to shelter all animals in a pen, several of them could remain unprotected and subjected to heat stress. The best way to know the area of shade that is adequate for a given location/environment, is to observe the behaviour of the animals on the range, recording the average distance between them. The observed value can then be used in the planning of corrals and housings.

12.2.2.4 Partially or totally enclosed shelters

Enclosed shelters are not recommended for tropical climates because of the decreased natural air velocity and sanitation. In temperate regions, partially enclosed shelters can reduce the thermal radiation received by animals during hot weather. Under clear-sky conditions, the average radiant heat load over a seven-hour period was reduced almost 10 per cent by the addition of a west wall to a simple shade; adding more walls helped, but to a lesser degree (Hahn et al., 1963). Provision of a partial west wall has been demonstrated to improve productive performance of housed broilers in hot weather, while a partial east wall did not (Oliveira and Esmay, 1982). One can suppose that with cloud conditions, the benefit from a walled shelter should be even more pronounced since the contribution of diffuse radiation would be reduced. There are no guidelines for evaluating the benefits to animal performance of open-walled shelters, as opposed to those that are partially or fully enclosed, as the relative merits depend on many factors of the specific situation.

For installations in temperate regions subject to both hot and cold weather, open-front structures

facing to the south (northern hemisphere) or north (southern hemisphere) with large doors or panels in the north or south wall, respectively, are an acceptable compromise. Use of fans in hot weather should be considered if natural air velocity is less than about 2 m s^{-1} . General and specific problems of the environmental aspects of shelter design are discussed by Clark (1981).

12.2.2.5 Genetic improvement for adaptation

Acclimation and adaptation are different processes. Animals are considered acclimated to a given ambient temperature when body temperature returns to pre-stress levels (Nienaber et al., 1999). Systemic, tissue and cellular responses associated with acclimation are coordinated, require several days or weeks to occur, and are therefore not homeostatic in nature (Bligh, 1976). Furthermore, when stress is removed, these changes decay. Adaptation, on the other hand, requires modifications of the genetic structure and is a process involving populations, not individuals. Intriguing, however, is the fact that in poultry, the exposure of chicks to high environmental temperatures during embryonic development results in permanent changes in responses to heat stress in adults (Moraes et al., 2003). In addition, it is not well understood whether the genes associated with acclimation are also associated with adaptation to thermal stress.

Genetic improvement is an evolutionary action; evolution should be defined as a continuous process of adaptation of the populations of organisms to the ever-changing geological, biological and climatic conditions (Dobzhansky, 1970). Because of the almost infinite number of combinations of environmental factors, organisms must have a great variety of genetic types that can deal with a range of climatic, nutritional or other conditions. In short, any population must be genetically heterogeneous – in other words, it must have great genetic diversity – in order to be able to survive under the challenges of the changing environment. Therefore, any population in a specific environment is composed of a majority of well-adapted individuals, while a minor number of individuals present genotypes that are not a good match for that environment, but are well suited to different conditions. This is the basis for genetic improvement in livestock.

Rhoad (1940) was probably the first to propose the selection of livestock for traits related to heat tolerance. Da Silva (1973) estimated the genetic variation of some traits in Brazilian beef cattle, observing that the increase in body temperature after exposure of

the animals to the sun in the hottest period of the day presented a moderate heritability coefficient (0.443) and a high negative genetic correlation (-0.895) with the average daily weight gain. Da Silva et al. (1988) determined the heritabilities of the sweating rate (0.222), skin pigmentation (0.112), hair-coat pigmentation (0.303) and thickness (0.233), and hair length (0.081) of Jersey cattle bred in a tropical region. For Holstein cattle in a similar environment, the heritability of hair length was rated at 0.20 by Pinheiro (1996). On the other hand, evidence has been found that supports the existence of a major dominant gene that is responsible for producing a very short, sleek hair coat in cattle (Olson et al., 2003).

Little attention has been paid to the genetic aspects of the adaptation of livestock to their environment, however. It has generally been considered faster and easier to improve production through alterations of the environment and most of the research efforts have been focused on environment modification. Numerous arguments have been used against animal breeding options, but there seems to be no a priori reason why genetic progress for adaptation is not possible. Present programmes for genetic improvement of livestock in tropical countries should take into account not only production traits (milk yield, weight gain, egg or wool production), but also those traits related to interaction with environmental factors such as solar radiation, wind, air temperature and humidity. Additional research on this subject will likely provide answers that may enable livestock production to register significant progress in the years to come.

12.2.3 Environmental modification

Many forms of environmental modification are available. In hot weather, water can serve as an effective cooling agent for farm animals, especially for species that maintain homeothermy primarily by regulating heat production (such as swine). Direct wetting of animals is often used as an emergency measure and can be a very effective protective device. Swine, as well as water buffaloes, are naturally wallowing animals and wallows for them have been shown to improve performance. The wetting by sprinklers has been used as a routine technique for swine (Nicholas et al., 1982) and beef cattle (Morrison et al., 1973) with measurable benefits, but not in other cases (Morrison et al., 1981). Fogger nozzles, sometimes recommended for wetting animals, are a less effective method of cooling, as the fine droplets cling to the outer hair coat where the heat for evaporation comes from the air rather

than from the body. This is a minor problem for animals with very short, sleek hair coats, however.

Air cooling using evaporative coolers designed to reduce ambient temperatures in livestock shelters can be quite effective. A correctly designed evaporative cooler will reduce the dry bulb temperature of air entering the cooler by 80 per cent of the wet bulb depression. A study carried out in Arizona (United States) by Igono et al. (1992) involved two dairy herds, one of which was exposed to evaporative coolers during the hottest period of the day, but not the other. The results showed that the average milk yield was almost the same for both herds during the cold months, but during the summer the production of the cows in the non-cooled herd was significantly lower than that of the cooled one. Shades, sprinklers and fans are very effective methods of improving thermal environment for dairy cows in hot, humid climates (McFarlane and Stevens, 1972; Bucklin et al., 1991). Strickland et al. (1989) found that cows maintained in a shelter cooled with fans and sprinklers yielded 11.6 per cent more milk than control cows.

Because high water demand and wastewater runoff are a concern for dairy plants, however, a decrease in the use of water for sprinkling and fan cooling systems is desirable. Adequate cooling can be attained using the lowest water application rate of 313.4 L/h per nozzle or 215.9 L average daily water use per cow (Means et al., 1992). This is a significant decrease in comparison with the amount of water used by Strickland et al. (1989). According to Means et al. (1992) one of the most inexpensive adjustments of a cooling system is reducing the size of the nozzle, thus saving significant amounts of water and reducing pumping costs.

Other options exist for hot environments, up to complete mechanical air conditioning. While air conditioning is technically feasible, high initial and operating costs preclude its use in almost all areas and situations. Cooling of roofs or other surrounding surfaces by evaporation of water (using water sprinklers on the roof, for instance) can effectively reduce the radiant heat load on animals. Theoretically, cooling floors beneath animals to increase conduction and radiation heat loss is also a means of microclimate modification. The condensation of moisture on the floor surface of dairy shelters would create unsanitary conditions, however. For pigs, cooled floors at air temperatures above 24°C provided increased conduction heat dissipation, with the increase being greater at colder floor temperatures (to 10°C), as pointed out by

Restrepo et al. (1977). The increased heat dissipation by conduction was accompanied by a decrease in the evaporative heat loss at colder floor temperatures, however, so the overall benefits to the animals were almost unchanged. No performance benefits were measured in a separate field trial (Bond et al., 1964).

For cold weather, the benefits of environmental modification beyond shelters or windbreaks to minimize the effects of weather extremes are less clear. Neonates of all species are vulnerable, and require some protection for survival. Growing and mature animals can survive relatively severe cold if they are adequately fed and disease problems are absent (Figure 12.6). Production efficiency can be markedly reduced, however (National Research Council, 1981). Controlled ventilation systems in enclosed housing can use minimal sensible heat to buffer extremes of cold for improved efficiency, while added artificial heat is essential for survival or economically beneficial.

The selection and use of a specific environmental modification practice or technique must be carefully evaluated, as not all will be cost-effective. Hahn and McQuigg (1970) have used probability techniques to establish the economic benefits that would result from environmental modification for dairy cows in hot weather. The work was based on the temperature-humidity index (THI), with values derived from hourly dry bulb and dewpoint temperatures. The distribution function of THI allows the probability of a given summer line THI to be computed, together with the associated decline in milk production in naturally varying conditions based on a validated response function. For Columbia, Missouri (United States), the total loss per 122-day summer season was approximately 90 kg for a cow producing 22.5 kg per day and 150 kg for a cow producing 45 kg per day. The technique used is applicable to any species, season and location for which an appropriate response function and climatological database exist, and provides a rational basis for estimating the benefits of environmental modification alternatives.

Gates et al. (1991) also used the THI method to assess the feasibility of employing misting systems for growing-finishing hogs, and they observed that the potential improvements to the growing environment due to misting at minimum THI indicate that misting systems warrant further research as a cost-effective alternative method of cooling growing-finishing hogs.

For tropical regions subjected to intense solar radiation, the black globe humidity index (BGHI, proposed by Buffington et al., 1981) will probably be better than THI for evaluation of the livestock housing/environment, if the black globe temperature is easily available.

12.2.4 Forage and pasture

Changes in weather and climate patterns in rangeland and semi-arid lands, which occupy nearly 50 000 000 km², or about 30 per cent of the entire land surface of the globe (WMO, 2000), can have important implications for livestock. Because livestock breeding plays a primary role in the economic structure of many developing regions, and the frequent onset of droughts causes considerable losses of animals due to scarcity of fodder, it is vitally important to supplement pasture amelioration with fodder trees and shrubs in order to minimize such losses (WMO, 2004a). These trees and shrubs will not only supply food for animals, but also serve as a shelter from the solar radiation and create a microclimate more favourable for regrowth of grass spoiled by the dry conditions (for example, Onyewotu et al., 2003b).

On the other hand, information about drought probability can help efforts to overcome or minimize those problems. In WMO (1987), Rao designed probability maps with special reference to India. More information on agrometeorology of pastures and grasslands in tropical and in temperate regions can be found in WMO (1994). Further discussion of this topic is available in WMO (1997). Recent developments in pasture production in arid and semi-arid regions are highlighted in a number of WMO publications (WMO, 2000, 2002, 2004b).

12.3 REDUCING IMPACTS OF LIVESTOCK PRODUCTION ON CLIMATE

In recent years the increasing use of intensive livestock production systems has become a source of solid, liquid and airborne emissions that can be both a nuisance and environmentally harmful. The most important greenhouse gases are methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂). In spite of the low amount of CH₄ in the atmosphere relative to that of CO₂, its importance as a pollutant is considered to be 21 times greater than that of CO₂, while that of N₂O is 310 times greater (Hartung, 2003).

It is estimated that nearly 20 per cent of CH₄ comes from livestock production, which is also the source of close to 77 per cent of the anthropogenic N₂O. These estimates are uncertain, however, because of the large variations in emission rates and the many influencing factors. According to data from the European Environment Agency (2001a), nearly 50 per cent of the overall amount of CH₄ released in Europe originates from agriculture and stems mainly from ruminant animals. On the other hand, N₂O is produced mainly by organic and synthetic fertilizers and leguminous crops (European Environment Agency, 2001b). As a consequence, the soil is generally the most effective N₂O emission surface (see Table 12.2).

Table 12.2. Relative contribution of various sources to the global emission of methane (CH₄) and nitrous oxide (N₂O) (adapted from Monteny, 2003)

Gas	Natural sources	Anthropogenic sources	
		Livestock production	Others
CH ₄	30	20	50
N ₂ O	30	35	10

Methane is generated mainly as a by-product of the fermentation of the digestible organic matter in ruminants, especially those with forage-based diets; by contrast, grain-based diets reduce the emission of CH₄. Animal diet composition is, therefore, an important influencing factor. Manure – and especially that of cattle – is a much more important source of CH₄ emission than enteric fermentation,

Table 12.3. Methane emission from livestock production facilities (kg/animal/year)

(adapted from Hartung, 2003)

Species	Enteric fermentation	Manure
Dairy cows	100	345
Pigs	1	32
Poultry	0.1	2.4

however, as illustrated by Table 12.3. This problem is due to liquid manure storage in tanks, pits or lagoons. Important factors are: the amount stored; the surface area of the stored manure; ambient and core manure temperature; and strength and frequency of manure agitation (Hartung and Monteny, 2000).

Possible strategies for reducing emissions of CH₄ and N₂O are the following:

- (a) Replacement of roughage in the cattle diet with concentrates;
- (b) Development of low-emission production system facilities, including filters, scrubbers, covered manure pits and shallow manure application. See Monteny (2003) for a detailed discussion of these points;
- (c) Reduction in the concentration of animals in intensive production units to the extent possible, by using more pens and pastures;
- (d) Use of feed additives to reduce CH₄ emissions (research results have shown that some additives can have this effect). Lower amounts of nitrogen in manure and urine can reduce N₂O emissions (Clemens and Ahlgrimm, 2001; Grandhi, 2001; Kebread et al., 2001).
- (e) Increase in feed digestibility and feed conversion efficiency (CH₄).

The problem of CH₄ and N₂O emissions has increased in western Europe and North America with the widespread use of concentrates, chemical fertilizers and intensive systems of animal production. Ground and surface water pollution, excessive use and losses of nitrogen and phosphate from animal and chemical manures, and the emission and deposition of ammonia are also

related and growing problems. Livestock production is now growing in developing regions of Asia and especially in South America, however, where the extensive management of cattle in pastures contributes to the maintenance of low gas emissions, despite the very large cattle populations.

A comprehensive review of the management strategies for mitigation of greenhouse gas emissions can be found in WMO (2004b).

As for carbon dioxide, it is generally considered the principal greenhouse gas, but it is produced mainly from the combustion of fossil fuels and cannot be sufficiently absorbed by growing biomass, a problem of increasing importance because of expanding deforestation. The contribution of livestock farming to the current amounts of CO₂ in the atmosphere is very low. Some studies have been carried out on this subject, however. Kibler and Brody (1954) measured the respiratory CO₂ of Holstein cows exposed to 20°C (153 L/h/cow), 27°C (151 L/h/cow) and 35°C (139 L/h/cow). For cows of the same breed, Yousef and Johnson (1967) found average amounts of 174.6 L/h/cow and 136.2 L/h/cow, for ambient temperatures of 18°C and 35°C, respectively. Those figures show that CO₂ emission is reduced as the animals are exposed to a rising temperature. Cows of the same breed were measured by Loureiro et al. (2005) in a tropical environment (20°C–33°C), with lower results (128.2 and 131.9 L/h for milk yields of <20 kg/day and >20 kg/day, respectively. The observed skin CO₂ elimination was 0.17 L/h/m² on average. Those are very low figures, confirming that CO₂ plays no role in the livestock production sector.

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CHAPTER 13

APPLICATION OF AGROMETEOROLOGY TO AQUACULTURE AND FISHERIES

13.1 INTRODUCTION

The products of fisheries have been an important component of the world food supply for centuries. The number of global capture fisheries has increased in response to the demands of rising human population. The Food and Agriculture Organization (FAO) of the United Nations began keeping statistics on world fisheries production in the 1950s; since then, the annual catch from capture fisheries has increased from about 25 million tonnes to approximately 95 million tonnes. Most authorities feel that capture fisheries around the world are exploited to or possibly beyond their sustainable limit. For its part, aquaculture has been growing in importance: in 2004 the supply from aquaculture reached 59 million tonnes, or 38.1 per cent of world fisheries production. The world's population will continue to grow and demand for products from fisheries will also rise accordingly. Aquaculture must step in to meet this increasing demand, for the catch by capture fisheries apparently cannot be increased.

Meteorology plays an important role in fisheries because solar radiation and air temperature influence water temperature, which in turn affects the natural productivity of inland and marine waters and the growth of fisheries species (Kapetsky, 2000). Weather conditions also have a tremendous effect on the ability of fishermen to capture fish and other aquatic organisms, and on the safety of fishermen. Nonetheless, fishing, like hunting and gathering, primarily involves the exploitation of living resources from natural populations; the management of these resources is limited largely to regulations on capture.

Aquaculture will soon surpass fisheries as the major source of aquatic protein, just as agriculture surpassed hunting and gathering as a source of meat, grain and other foods. Agrometeorology has become an important tool in agriculture and it can be equally useful in aquaculture. Meteorological data are already used in aquaculture (Szumiec, 1983; Boyd and Tucker, 1998; Kapetsky, 2000). Nevertheless, there have been few attempts to organize the effort so that the acquisition and application of meteorological data may also serve as a tool for practical aquaculturists and become an important part of the training of aquacultural scientists. The purpose of this report is to discuss the application of meteorological data in fisheries

and especially in aquaculture. It is hoped that this discussion will encourage the application of existing agrometeorological information to aquatic animal production and stimulate research on the topic.

13.2 CAPTURE FISHERIES

Most of the commercial catch of fisheries products is of marine origin; in 2004, 87.2 million tonnes were taken from the oceans, compared with 8.7 million tonnes from inland waters. The Asian region accounted for nearly half of the production. China was the top fishing country, and four other Asian nations were in the top ten. During the past 10 years, the world production of capture fisheries has fluctuated between 88 million tonnes and 96 million tonnes, with no upward or downward trend. Many species have been overfished and pollution of the oceans and coastal waters has negatively affected productivity. The production of wild fish populations is dependent upon optimum temperature and other favourable weather conditions. Meteorological data can be used in attempts to explain observed changes in fisheries production. Forecasts of temporary or long-term changes in climate can also be used to predict changes in fisheries populations that could influence the future catch.

Most fishing methods require operation of boats in large bodies of water and are inherently dangerous activities because of storms. Short-term weather forecasts can be extremely useful for planning fishing activities. Moreover, information on the intensity and tracks of storms is critical to the safety of fishermen. Historically, many fishermen have perished because of inadequate information about storms or because of a failure to heed warnings.

13.3 AQUACULTURE

Total world aquaculture production was 59.4 million tonnes in 2004. Of this, 32.2 million tonnes originated from freshwater aquaculture and 27.2 million tonnes from marine aquaculture. The top five countries in the world in terms of aquaculture production are in Asia, as are 11 of the top 15 producers, and China accounts for over one half

of the world aquaculture production. Although aquaculture is vital to the domestic food supply of many nations, aquaculture products also are important international commodities. For example, the United States imports nearly 80 per cent of its seafood, and many of these products are from aquaculture. Aquaculture production systems vary greatly both among and within species. An overview of the common production systems will be useful to readers who may not be familiar with aquaculture.

13.3.1 Pond culture

Aquatic animals are stocked in ponds, and fertilizer and feed are used to promote rapid growth. Undesirable species can be excluded and water quality maintained within a desirable range. Production per unit area greatly exceeds that of natural waters and culture animals can be harvested easily. Three basic types of ponds are used in aquaculture: watershed ponds, embankment ponds and excavated ponds. The water budget for ponds may be expressed by the hydrologic equation:

$$\text{Inflow} - \text{outflow} = \Delta H \quad (13.1)$$

The hydrologic equation for ponds may be expanded as follows:

$$(P + R + S_{in} + A) - (E + S_o + O + C + Q) = \Delta H \quad (13.2)$$

where P = precipitation; R = runoff; S_{in} = seepage in; A = intentional additions from wells, streams, lakes or other sources; E = evaporation; S_o = seepage out; O = overflow; C = consumptive use for domestic use, irrigation, livestock watering or other purposes; Q = intentional discharge for water exchange or harvesting; and ΔH = change in storage. Depending upon its design, construction, location and use, one or more of the terms listed above may not apply to a specific pond.

Watershed ponds are made by building a dam across a watercourse to impound surface runoff. They vary greatly in area, but most are greater than 0.5 ha and less than 10 ha in area. These ponds also have been called terrace ponds, and it is common to construct a series of them on a watershed so that the overflow from one pond will be captured by another at a lower elevation. Watershed ponds fill and often overflow during the rainy season, but the water level may decline drastically during dry weather. The minimum ratio of watershed area to pond volume necessary to maintain watershed ponds varies from about 0.3 ha/1 000 m³ in mountainous, humid areas to over 40 ha/1 000 m³ in

arid, plains regions (United States Soil Conservation Service, 1979). The fluctuation in water level in watershed ponds ranges from a few centimetres to more than a metre, with the greatest fluctuations occurring in arid climates, during droughts, and in ponds that seep excessively (Yoo and Boyd, 1994). Some ponds are never drained, while others may be drained annually for harvest. Sometimes, ponds may have multiple uses, and water may be withdrawn for domestic use, livestock watering or irrigation.

Excavated ponds are made by digging a basin in which to store water. Ponds may be filled by rainfall, runoff and infiltration of ground water. Such ponds cannot be drained, but sometimes water may be removed with a pump. Small, excavated ponds of a few hundred square metres in area are widely used for aquaculture in rural areas of India, Bangladesh and some other Asian countries. These ponds also may serve as sources of water for home and farm uses. Where direct rainfall is the major source of water for excavated ponds, ponds may dry up or become very shallow during the dry season.

Watershed and excavated ponds rarely receive inflow from wells, streams or other external bodies of water. Fisheries production in such ponds often is referred to as "rainfed" aquaculture. Rainfall, overland flow, evaporation and seepage are critical factors regulating the amount of water available for rainfed aquaculture. Small, rainfed ponds are the most common aquaculture systems used by poor, rural people in tropical nations.

Embankment ponds are formed by building an embankment around the area for water storage. Surface areas of these ponds often are 0.2 to 2 ha and seldom over 10 ha. Watersheds consist of the above-water, inside slopes of embankments, and little runoff enters ponds. Embankment ponds in inland areas are supplied with water from wells, streams or reservoirs. In coastal areas, embankment ponds are filled with brackish water from estuaries or seawater. Drain structures consist of pipes with valves or gates with dam boards. Embankment ponds are popular for commercial aquaculture because water levels can be controlled and ponds drained easily to facilitate harvest. These ponds usually are dedicated to aquaculture use and are not sources of water for other activities.

13.3.2 Flow-through systems

Flow-through systems for aquaculture include raceways, tanks and other culture units through which

water flows continuously. The culture species is stocked at densities much greater than those used in ponds (Table 13.1). Water flow rates normally are two or three times the volume of the culture units per hour. Water sources are springs, streams and other bodies of surface water. Incoming water is the main source of dissolved oxygen for fish and wastes are flushed from culture units by the flowing water. A constant supply of water is essential for flow-through systems. These systems are especially popular for the culture of trout in freshwater.

13.3.3 Open-water culture methods

Aquatic organisms also are cultured in open waters of oceans, estuaries, lakes and streams by confining them at high density (Table 13.1) in enclosures or by placing sessile organisms on bottom plots or attaching them to a structural framework. Cages and net pens are constructed of netting secured to a supporting framework. Cages vary in size from 1 m³ to more than 2 000 m³, and they float on or near the water surface. Fish in cages are supplied with manufactured feed daily. Pens are made by installing vertical poles and attaching netting to form an enclosure in which to culture fish. Pens are larger than cages and stocked at lower densities than cages (FAO, 1984). The fish in pens usually are fed, and they have free access to natural food organisms in the water and sediment of the enclosed area.

Bivalve shellfish such as oysters, clams, mussels and scallops can be laid on bottom plots in coastal waters for grow-out. It is more common, however, to place young shellfish, called spat, on stakes, rocks and racks, or to attach them to ropes hanging from long lines, rafts or other structures for grow-out by off-bottom culture methods. These structures are placed in coastal waters in areas often used for navigation, fishing or other purposes. Seaweed is usually attached to ropes or netting for grow-out in coastal waters.

13.3.4 Water-reuse systems

There are two basic types of water recirculation systems. One type is built outdoors and consists of culture units from which water passes through a sedimentation basin and then into a larger, earthen pond for treatment by natural biological processes before being returned to the culture units for reuse. Mechanical aeration sometimes is applied in the treatment pond to enhance dissolved oxygen concentration and promote microbial activity. The other type of water-reuse system usually is placed in a greenhouse or other structure: water from culture units passes through mechanical and biological filters and is aerated before being reused in culture units. Effluents may overflow from outdoor systems during rainy weather, and water must occasionally be discharged from indoor systems when new water is applied to lower salinity or filters are cleaned.

Table 13.1. Typical standing biomass ranges for different kinds of aquaculture

<i>Culture method</i>	<i>Standing biomass</i>
Ponds (fish and shrimp)	
Extensive	0.025 to 0.05 kg m ⁻³
Semi-intensive	0.05 to 0.5 kg m ⁻³
Intensive	0.5 to 5 kg m ⁻³
Flow-through systems	
Trout	160 to 240 kg m ⁻³
Channel catfish	75 to 150 kg m ⁻³
Carp	200 to 300 kg m ⁻³
Cages	
Trout	20 to 40 kg m ⁻³
Tilapia	150 to 250 kg m ⁻³
Channel catfish	100 to 200 kg m ⁻³
Water-recirculating systems (finfish)	100 to 200 kg m ⁻³
Shellfish plots	0.5 to 150 kg m ⁻²

13.4 CLIMATE, WEATHER AND HYDROLOGY

Aquaculture depends upon a constant supply of water and the total volume of water used is great compared with traditional agricultural crops. Consumptive water use in aquaculture is much less than total water use and consists of water removed in animals at harvest, about 0.75 m³ per tonne of production, and water lost in seepage and evaporation. Most water is discharged from culture units and passes downstream (Boyd, 2005). The value of aquaculture products per unit of consumptive water use is greater than for traditional agricultural crops (Boyd, 2005). Nevertheless, aquaculture facilities should be designed for efficient water use and aquaculturists should be knowledgeable about local hydrologic conditions.

13.4.1 Precipitation

All water sources for inland fisheries and aquaculture are derived from precipitation, and the amount and annual distribution of precipitation is a critical factor (Kapetsky, 2000). Ponds and other production systems should be managed in harmony with rainfall so that adequate water levels can be maintained. The depth of precipitation measured in a raingauge is the same as the depth of water falling directly into a water body near the gauging station. It is well known that precipitation varies greatly among locations and temporally at a given place. In fisheries and aquaculture, the precipitation excess or deficit is a more important variable than precipitation alone (Boyd, 1986; Yoo and Boyd, 1994). This variable is the difference in precipitation and pond evaporation measured on a monthly or annual basis. At most sites, there will be periods with a precipitation excess, and other times, there will be a precipitation deficit (Figure 13.1). Annual precipitation excess usually occurs in humid climates and an annual precipitation deficit occurs in arid ones. For example, the annual precipitation excess averages 16.5 cm in humid central Alabama (United States). The precipitation deficit is 54.6 cm in semi-arid southern Kansas and 158.8 cm in the desert region of Southern California. There are few places in the world where direct rainfall will sustain a pond. There usually must be one or more external water sources, such as runoff from a watershed, inflow from seepage or additions from wells or other water bodies.

Drought can be particularly devastating in watershed ponds. Where groundwater is not available for refilling ponds, water levels may decrease drastically, causing overcrowding of fish.

The drought of 2000 in the south-eastern United States was especially severe, and in eastern Mississippi a 38 to 40 cm rainfall deficit and above-average evaporation because of summer temperatures that were warmer than usual caused many ponds to shrink to about 40 per cent of normal volume. There was no means of replacing this water. It was estimated that the economic loss to catfish farmers resulting from the drought was US\$ 11.3 million (Hanson and Hogue, 2001). In the western Delta region of Mississippi, water levels in ponds could be maintained during the 2000 drought by additions from wells. Higher pumping costs were incurred, however, because more water than normal was pumped to offset the rainfall deficit, which was 25 cm above the normal figure for the period from June through October (Hanson and Hogue, 2001).

13.4.2 Evaporation

Lake evaporation is often estimated by multiplying 0.7 by Class A pan evaporation, and several techniques have been used to adjust the pan coefficient for local conditions (WMO, 1973). Boyd (1985) measured daily evaporation from a plastic-lined, 0.04 ha pond at Auburn, Alabama, and compared the values with daily evaporation from an adjacent Class A evaporation pan. The correlation (R^2) between pan and pond evaporation increased with the length of the period of measurement: 0.668 for daily measurements, 0.902 for weekly totals and 0.995 for monthly values. The pan coefficient ranged from 0.72 in March to 0.90 in September, with an annual average of 0.81. The pan coefficient for estimating evaporation for small ponds is larger than the pan coefficient for estimating lake evaporation because the physical conditions of a small pond more nearly reflect those of the evaporation pan than do those of a larger body of water.

Monthly mean air temperature and average monthly solar radiation also were correlated with pond evaporation (Boyd, 1985). The regression equations were:

$$E_p = -2.15 + 0.268 \text{ Rad} R^2 = 0.642 \quad (13.3)$$

$$E_p = -4.406 + 5.753 T R^2 = 0.862 \quad (13.4)$$

where E_p represents monthly pond evaporation (mm month⁻¹), Rad is mean monthly solar radiation (g-cal cm⁻² day⁻¹) and T is air temperature (°C).

The normal way of reducing evaporative loss of water stored in ponds for irrigation and other uses is to make them deeper. Ponds that are 9 m and 4 m

deep and are exposed to the same conditions will have the same amount of evaporation from their surfaces. Nevertheless, the evaporation loss per cubic metre of water storage will be more from the shallower pond by a factor of 9/4. In aquaculture, it usually is not possible to use this approach to reduce water loss by evaporation because deep ponds stratify thermally, making management more difficult.

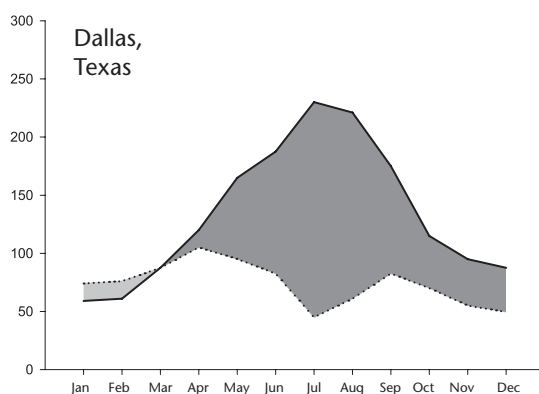
Evapotranspiration usually is not a major factor in aquaculture ponds because vascular aquatic plants are discouraged by deepening pond edges, by turbidity resulting from plankton and by application of aquatic weed control techniques (Boyd and Tucker, 1998). Nevertheless, in hydrologic assessment of aquaculture projects, evapotranspiration on watersheds is an issue. Yoo and Boyd (1994) recommend the Thornthwaite method to estimate evapotranspiration for aquaculture and fisheries purposes because it requires only information on mean monthly air temperature. Other methods of measuring

evapotranspiration require equipment or data seldom available to aquaculturists.

13.4.3 Overland flow and runoff

The amount of overland flow entering ponds depends upon the watershed area, amount of precipitation, infiltration, evapotranspiration and the runoff-producing characteristics of watersheds. Individual watersheds vary greatly with respect to the percentage of precipitation that is transformed to overland flow. Steep, impervious watersheds may yield 75 per cent overland flow, while flat watersheds with sandy soils may yield less than 10 per cent overland flow. Estimates of overland flow can be made using the curve number method (United States Soil Conservation Service, 1972). In this method, the depth of overland flow is estimated from the depth of rainfall produced by a given storm, antecedent soil moisture conditions, hydrologic soil group, land use and hydrologic condition on a watershed.

Precipitation and
pond evaporation, mm



Precipitation and
pond evaporation, mm

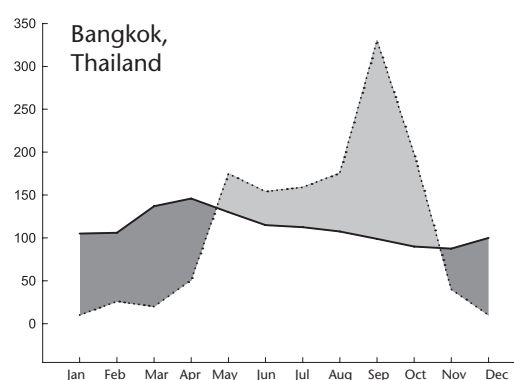
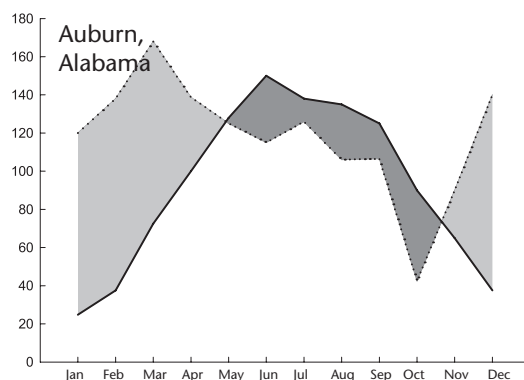
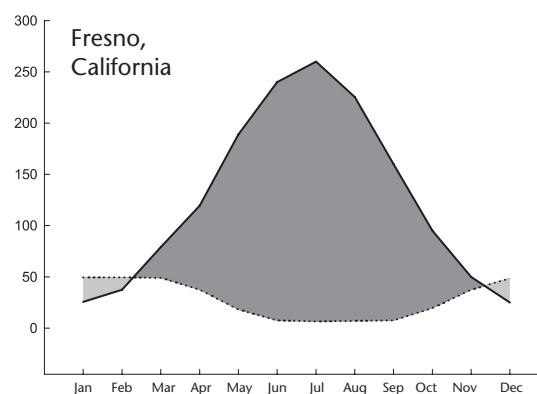


Figure 13.1. Pond evaporation (solid line) and precipitation (dotted line) at four sites. Dark shading indicates an evaporation excess, while light stippling indicates a precipitation excess. (Data from Wallis, 1977; Farnsworth and Thompson, 1982; Boyd, 1985; and Meteorological Department of Thailand, 1981)

Estimation of peak discharge is important in pond design and construction to prevent damage or destruction of dams and pond banks by erosive water overflows during intense storm events. In particular, spillways must be adequate to bypass excessive runoff and prevent dam failure. The selection of the rainfall return period for use in spillway design should be based on the human and environmental consequences and expense of dam failure. The rational method (also known as the Lloyd–Davies formula or the design peak runoff method) developed to design storm drainage systems is widely used to design overflow structures and spillways in watershed ponds. The equation for the rational method is:

$$Q = CiA \quad (13.5)$$

where Q = peak runoff discharge, C = runoff coefficient, i = maximum rainfall intensity for the concentration time of the watershed and the selected return period, and A = watershed area. Runoff coefficients and the equation for estimating the variable i can be found in most hydrology texts. An intensity–frequency–duration plot for area rainfall is also required for solving the rational method equation.

Runoff consists of overland flow plus groundwater discharge, and the two sources make up stream flow. Thus, stream gauging provides the most reliable estimates of runoff. Runoff usually is between 15 and 40 per cent of annual rainfall for catchments large enough to support permanent streams. Rough estimates of annual stream flow can be obtained by subtracting evapotranspiration from precipitation. Overland flow is only a fraction of runoff and one or two of the largest rainfall events during a year may contribute most of the overland flow. In Alabama, the average annual runoff for watersheds of the Piedmont Plateau region is 52 cm year⁻¹, and average overland flow for typical watersheds within this region is 22 cm year⁻¹ (Boyd and Shelton, 1984).

Water levels in aquaculture ponds should be maintained 10 to 15 cm below overflow structures so that most rainfall and runoff may be conserved. In arid climates, the savings of water may be small, but in humid climates, rain falling directly into ponds often is almost enough to replace losses to seepage and evaporation (Boyd, 1982).

Rainfed aquaculture ponds usually are drained at intervals of one to several years for harvest. At most sites, the year can be divided into periods on the basis of the amount of precipitation. Ponds should be

drained near the end of the dry season so that they will refill during the rainy season when water is abundant. In the south-eastern United States, the period between December and March has the most rainfall and least evapotranspiration, and the majority of overland flow occurs during this time. Ponds in this region typically are drained for harvest in the fall to ensure that they will refill in winter and spring.

Storage of runoff in ponds lessens stream flow, but once ponds are full, water entering ponds flows through them and into streams. Overflow structures usually release water slowly, and water is detained in ponds for a few hours to a few days. Ponds on the catchment of a stream usually do not reduce annual stream flow appreciably (Silapajarn and Boyd, 2005), but they will tend to lengthen the time that runoff enters streams (Schoof and Gander, 1982). This flattens the stream hydrograph and can reduce flood levels.

Embankment ponds often are constructed on flood plains. If a large proportion of the area of a flood plain is occupied by ponds, the cross-sectional area for flood flow will be reduced and flood levels will increase. Some countries restrict the extent to which flood plains can be obstructed. In the United States, the Natural Resource Conservation Service has a rule that no more than 40 per cent of flood plains can be blocked. Embankments of ponds on flood plains should be high enough to prevent floods from overtopping them.

13.4.4 Hydroclimate

The study of hydroclimate embraces the influences of climate on water availability (Langbein, 1967). In some places, more rain falls each month than is lost by evapotranspiration. The excess water either infiltrates the land surface or becomes stream flow. In other places, monthly rainfall never meets the demands of evapotranspiration. Such regions have no permanent streams, and runoff is limited to unusually heavy rains. Most places have a hydroclimate between these two extremes, in which some seasons have excess rainfall and others have a precipitation deficit.

A common way of describing the hydroclimate of an area is to plot monthly rainfall totals and monthly potential evapotranspiration estimates over an entire year. A net gain in soil moisture occurs in any month in which precipitation exceeds potential evapotranspiration. When the soil is at field capacity, some rainwater infiltrates deeper to become groundwater, while the remainder becomes overland flow. The proportion of rainwater that

infiltrates more deeply depends upon the rate that water moves downward through the soil and underlying geological material. Net loss of soil moisture occurs when rainfall is less than potential evapotranspiration. If the period of net water loss continues, soil moisture depletion may limit plant growth. Soil moisture recharge occurs when precipitation exceeds evapotranspiration and the soil moisture content is below field capacity. The annual hydroclimate of a locality in Alabama is given in Figure 13.2. The figure illustrates periods of water surplus, soil moisture utilization, water deficiency and soil moisture recharge.

For the hydroclimate illustrated in Figure 13.2, it is clear that most overland flow and aquifer recharge occur between mid-December and May. The peak discharges of streams also occur between December and May. From early May until mid-December, streams are sustained primarily by base flow. Many small streams cease to flow during this period. Unusually heavy rains during the summer and fall generate some overland flow and may recharge aquifers slightly.

13.4.5 Water budgets

The hydrologic equation and local climatic data can be valuable in planning hydrologically responsible aquaculture projects. The size of an aquaculture project should not exceed the availability of water, for if water shortages occur, aquaculture crops may be damaged or lost (Boyd and Gross, 2000). Water budgets should be estimated for planning and designing new projects. The following example illustrates how the hydrological equation may be

used to estimate the water budget for a project. Suppose that a fish farm with 20 embankment ponds, each with a water surface of 5 ha and an average depth of 1.5 m, is to be built on loamy clay soil where annual rainfall and Class A pan evaporation are 120 cm and 100 cm, respectively. It is assumed that seepage will be 0.25 cm day^{-1} (Yoo and Boyd, 1994), because properly constructed ponds on loamy clay soil should not seep much. Pond evaporation will be taken as 0.8 times pan evaporation. Ponds will be drained once per year for harvest, water exchange will not be used and storage volume will be sufficient to prevent overflow after rains. Runoff from the embankments can be neglected. The storage change (ΔH) will be 1.5 m because ponds will be filled and drained once each year. The water source will be groundwater from wells. The total amount of well water needed in an average year can be calculated as:

$$\text{Inflow} - \text{Outflow} = \Delta H$$

$$(A + P) - (E + S_o) = \Delta H$$

$$A = (\Delta H + E + S_o) - P$$

$$A = 150 \text{ cm} + (100 \text{ cm} \times 0.8) + (0.25 \text{ cm day}^{-1} \times 365 \text{ days}) - 120 \text{ cm} = 201.25 \text{ cm.} \quad (13.6)$$

For the 100 ha farm, $2\,012\,500 \text{ m}^3$ of water must be supplied by the well. Suppose the plan also requires a capacity to fill all ponds within a 60-day period. Ponds are 1.5 m deep, and $1\,500\,000 \text{ m}^3$ would be required to fill 100 ha of ponds over 60 days. This is a continuous pumping rate of $17.4 \text{ m}^3 \text{ minute}^{-1}$ from the wells.

The above example was based on average conditions. Reference to the historical rainfall and evaporation data for the site could suggest the driest conditions normally expected. This would allow for the design of extra well capacity so that plenty of water will be available during dry years. If such data are not available, a safety factor of 1.5 is recommended.

Many governments are developing water quality regulations for aquaculture effluents, and the volume of water discharged by ponds has become an important variable. Suppose that a 1 ha pond of 1.5 m average depth has a 20 ha watershed. Rainfall in the area is $1\,100 \text{ mm yr}^{-1}$, Class A pan evaporation is 980 mm yr^{-1} and watersheds typically yield 18 per cent of annual rainfall as overland flow. The pond is constructed on tight clay soil, and the seepage rate will be taken as 0.1 cm day^{-1} . The pond is drained only at intervals of several years. Assuming

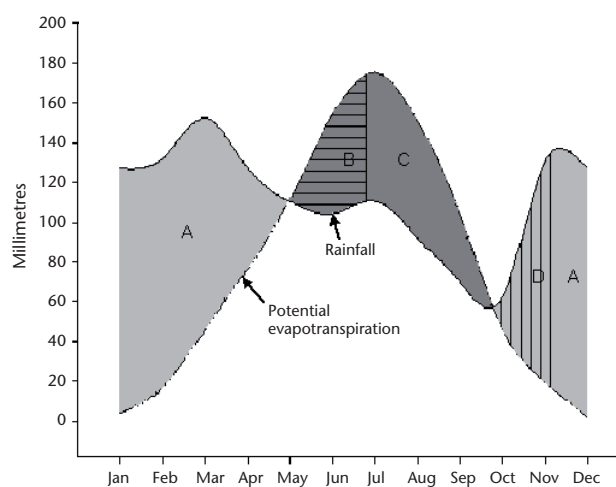


Figure 13.2. Hydroclimate at a site in Alabama. Soil moisture status: (A) surplus, (B) utilization, (C) deficiency and (D) recharge. Runoff occurs primarily when there is a soil moisture surplus.

that the pond typically is full but not overflowing on 1 January of each year, that is, $\Delta H = 0$ cm, the overflow for a year will be estimated. The appropriate form of the hydrologic equation and its solution are:

$$(P + R) - (E + S_o + O) = \Delta H$$

$$O = \Delta H - (P + R) + (E + S_o)$$

$$O = 0.0 \text{ cm} - (1.1 \text{ m} \times 1 \text{ ha}) - (1.1 \text{ m} \times 0.18 \times 20 \text{ ha}) + (0.98 \text{ m} \times 0.8) + (0.001 \text{ m day}^{-1} \times 365 \text{ days}) \times 10^4 = 39 \text{ } 100 \text{ m}^3 \text{ year}^{-1}$$

$$O = -39 \text{ } 110 \text{ m}^3 \text{ year}^{-1} \quad (13.7)$$

The overflow has a negative sign because it represents water lost from the pond. This volume of overflow is more than twice the pond volume.

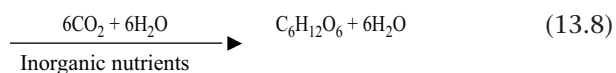
The overflow estimated in the example above is for an entire year. The spillway design, however, should be based on the most runoff expected following the largest single daily rainfall event for a selected return period, namely, the 25-year, 50-year or 100-year rainfall event (Yoo and Boyd, 1994).

13.5 CLIMATE, WEATHER AND WATER QUALITY

Solar radiation is necessary for aquatic plant growth and is a major factor regulating water temperature. Wind mixing has a strong influence on the thermal and chemical dynamics of water bodies. Finally, extreme weather events such as floods, droughts, hurricanes and unseasonable temperatures can adversely influence water quality and have negative impacts on fisheries and aquaculture.

13.5.1 Solar radiation

Phytoplankton are the base of the food chain that culminates in fisheries production in natural systems. Planktonic algae require solar radiation, water and inorganic nutrients to conduct photosynthesis, a process by which they use chlorophyll and other pigments to capture photons of light and transfer the energy to organic matter. The photosynthesis reaction is provided below in its simplest form:



Organisms use oxygen in respiration in order to oxidize organic nutrients and release biologically useful energy. Ecologically, respiration is basically the opposite of photosynthesis. During daylight, photosynthesis usually produces oxygen faster than oxygen is consumed in respiration, and dissolved oxygen concentration increases from morning to afternoon (Figure 13.3). Photosynthesis stops at night, but respiration continues to cause dissolved oxygen concentration to decline at night (Figure 13.3). Differences in dissolved oxygen concentration between day and night become more extreme as phytoplankton abundance increases (Figure 13.3). Aquaculture ponds typically have dense plankton blooms and wide daily fluctuations in dissolved oxygen concentration.

Organic matter from photosynthesis is the source of organic compounds used by phytoplankton and other plants to elaborate their biomass. The oxygen released by the process is a major source of dissolved oxygen needed in respiration by aquatic animals, bacteria and aquatic plants living in water bodies. In aquaculture, fertilizers may be applied to ponds to increase phytoplankton productivity and permit greater aquatic animal production, but manufactured feeds may be offered to culture animals to increase production beyond that achievable from natural food.

Although it is well known that short-term variations in the photosynthesis rate result from the effect of cloud cover on the amount of incoming radiation, it has not been demonstrated that the growth rate in aquatic animals is affected by this variation. For most fisheries species, there is a time lag between primary production and its use in fish

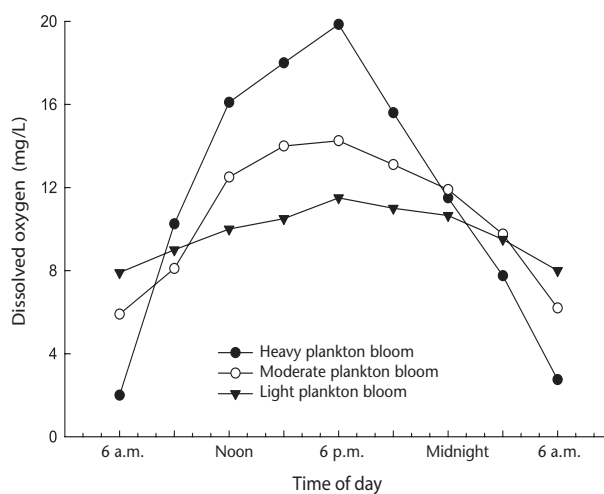


Figure 13.3. Effect of time of day and phytoplankton density on concentrations of dissolved oxygen in surface water

production (McConnell, 1963), and short-term fluctuations in solar radiation are not reflected in fluctuations in the growth of fish, shrimp and other fisheries species. Fisheries production integrates short-term fluctuations in solar radiation and photosynthesis, but differences may be obvious on an annual basis. Doyle and Boyd (1984) studied sunfish production in three ponds at Auburn, Alabama, each stocked, fertilized and managed the same way for eight consecutive years. Fish production averaged 362 kg ha^{-1} and varied from 270 to 418 kg ha^{-1} over the period, with a coefficient of variation of 27 per cent. Several factors, including dates of stocking and harvest, water temperature, fish size at stocking and amounts of aquatic weeds in ponds, varied among years and no doubt influenced production. Average daily solar radiation data for the period April through September at a nearby site, however, exhibited a positive correlation ($R^2 = 0.51$) with sunfish production.

Many types of aquaculture are based on feed inputs. Annual variation in production among channel catfish ponds to which feed was applied was much less (coefficient of variation = 8 per cent) than in fertilized ponds where fish growth depended upon primary productivity (Doyle and Boyd, 1984). Production of channel catfish in ponds with feeding was not correlated with solar radiation.

It is well known that prolonged cloud cover lessens the rate of photosynthesis and dissolved oxygen production. Several days with overcast skies can result in dissolved oxygen depletion in ponds. Mechanical aeration often is used to enhance the dissolved oxygen supply and prevent dissolved oxygen stress to cultured species. Historical data on the amount of solar radiation, the frequency of overcast skies or the duration of sunshine per day at a particular site can suggest if cloudy weather is likely to be a common problem in a particular region. Forecasts of periods with heavy cloud cover could be useful in alerting aquaculturists to the likelihood of dissolved oxygen depletion and the need to prepare for the events.

Boyd et al. (1978b) provided an equation for estimating the decline in dissolved oxygen concentration in ponds at night. Romaine and Boyd (1979) developed an equation to predict the daytime increase in dissolved oxygen in ponds based on solar radiation, chlorophyll-*a* concentration, Secchi disk visibility and percentage saturation with dissolved oxygen at dawn. The two equations were used to produce a model (Romaine and Boyd, 1979) for predicting

the number of consecutive days necessary for dissolved oxygen concentrations to decline to 2.0 mg l^{-1} and 0.0 mg l^{-1} in ponds with different Secchi disk visibilities and solar radiation inputs (Table 13.2). Romaine and Boyd (1979) also used local solar radiation records to calculate the probabilities of the number of days with low solar radiation, as illustrated in Table 13.3 with data for Auburn, Alabama.

The Secchi disk mentioned above is a disk 20 cm in diameter that is painted on its upper surface with alternate black and white quadrants, weighted on its underside, and attached to a calibrated line. It is lowered into the water until it just disappears from view and raised until it just reappears. The average of the depths of disappearance and reappearance is the Secchi disk visibility. In most aquaculture systems, plankton is the major source of turbidity, so Secchi disk visibility provides an indirect measure of plankton abundance (Almazan and Boyd, 1978). The transparency of lakes and other water bodies is often compared by the extinction coefficient (K) calculated from light intensity at the surface (I_0) and at another depth (I_z) in metres (Wetzel, 2001) as follows:

$$K = \frac{\ln I_0 - \ln I_z}{Z} \quad (13.9)$$

The Secchi disk visibility provides a simple means of estimating the extinction coefficient because Idso and Gilbert (1974) found that the following relationship existed between the two variables:

$$\bar{X} = \frac{\sum x}{n} i = 6 \quad (13.10)$$

where Z_{SD} = Secchi disk visibility (m).

Light penetration to the bottom of ponds can result in growth of undesirable aquatic weeds. The most common procedure for preventing weed growth is to encourage phytoplankton turbidity, which restricts light penetration. The depth limit of aquatic weed growth usually is about twice the Secchi disk visibility (Hutchinson, 1975). The target Secchi disk visibility in ponds varies among culture species and methods, background turbidity of waters and preference of managers, but 30 to 45 cm usually is considered optimum. Plankton abundance in aquaculture ponds usually will restrict underwater weed growth where water is 90 cm or more in depth. Unless pond edges are deepened, shallow water areas in ponds may become weed infested in spite of turbidity. Aquatic

Table 13.2. Number of consecutive days (simulated) necessary for dissolved oxygen (DO) concentrations to decline to 2.0 and 0.0 mg l⁻¹ in ponds given varying amounts of solar radiation and Secchi disk visibilities^a (from Romaine and Boyd, 1979)

Secchi disk visibility (cm)	Solar radiation (langley/day)						
	50	100	150	200	250	300	400
DO = 0.0 mg l ⁻¹							
10	1	1	1	1	1	2	>8
20	1	1	1	1	1	5	>8
30	1	1	1	2	2	6	>8
40	1	1	1	2	3	6	>8
50	1	1	2	2	3	6	>8
60	1	2	2	3	4	6	>8
70	2	2	2	3	4	6	>8
80	2	2	3	3	4	7	>8
DO = 2.0 mg l ⁻¹							
<30	0	0	0	0	0	0	0
40	1	1	1	1	1	1	1
50	1	1	1	1	1	1	3
60	1	1	1	1	1	2	4
70	1	1	1	1	2	2	5
80	1	1	1	2	2	3	6

^a Assumptions are: (1) the initial average DO concentration at dusk is 10.0 mg l⁻¹; (2) pond is 1 m in depth and contains 2 240 kg/ha of catfish; (3) water temperatures are 30°C at dusk and 29°C at dawn.

weeds, such as *Eichhornia crassipes* (water hyacinth) and *Lemna* spp. (duckweed), that float on the water surface are especially troublesome in aquaculture ponds because they cannot be controlled by manipulating turbidity.

Some species of planktonic algae respond to changes in light intensity by altering their position in the water column. The effects of light on some species of blue-green algae, such as *Anabaena* spp., can lead to adverse impacts in aquaculture systems. Gas vacuoles filled mainly with carbon dioxide form in these algae in response to low light intensity. The increased buoyancy causes the algae to rise until higher light intensities increase the rate of photosynthesis, thus removing carbon dioxide and collapsing gas vacuoles (Fogg and Walsby, 1971). Lack of turbulence during calm weather in shallow ponds allows algae to rise more rapidly than photosynthesis can cause gas vacuoles to collapse and lessen buoyancy. The algae float to the surface where they encounter excessive light intensity. Rapid photosynthesis by phytoplankton that

accumulates at the surface removes carbon dioxide, causing pH to rise and dissolved oxygen concentrations to increase (Boyd and Tucker, 1998). Abielovich and Shilo (1972) and Abielovich et al. (1974) demonstrated that the combination of intense light, low carbon dioxide concentration, high pH, and high dissolved oxygen concentration caused death in blue-green algae through disruption of enzyme systems and photo-oxidation. Boyd et al. (1975) demonstrated that sudden die-offs of blue-green algae in channel catfish ponds occurred during periods of calm, clear weather when scums of blue-green algae accumulated on pond surfaces. In some cases, almost all blue-green algae suddenly die, or in other situations, only a small percentage of the algae die (Boyd et al., 1978a). The dead algae will be decomposed rapidly by bacteria, and in many cases, bacterial respiration will cause dissolved oxygen concentration to decline to a critical level.

Benthic algae often form mats on the bottoms of clear water bodies. These mats of algae are called "lab-lab", and they can be an important source of

Table 13.3. Probabilities of consecutive days (D) of low solar radiation intensities at Auburn, Alabama.^a The values are calculated from 14 years of observations (1964–1977). (From Romaine and Boyd, 1979)

<i>Probability of consecutive days</i>	<i>May</i>	<i>June</i>	<i>July</i>	<i>August</i>	<i>Sept.</i>	<i>Oct.</i>
Radiation <100 langley day ⁻¹						
P(1D)	0.016	0.000	0.005	0.000	0.050	0.067
P(2D)	0.000		0.000		0.029	0.023
P(3D)					0.021	0.000
P(4D)					0.001	
Radiation <200 langley day ⁻¹						
P(1D)	0.062	0.016	0.028	0.039	0.110	0.175
P(2D)	0.014	0.000	0.005	0.009	0.124	0.138
P(3D)	0.000		0.000	0.000	0.097	0.097
P(4D)					0.067	0.009
P(5D)					0.060	0.000
P(6D)					0.029	
Radiation <300 langley day ⁻¹						
P(1D)	0.122	0.062	0.106	0.134	0.255	0.394
P(2D)	0.069	0.014	0.060	0.069	0.247	0.392
P(3D)	0.007	0.000	0.021	0.009	0.221	0.366
P(4D)	0.000		0.000	0.000	0.171	0.313
P(5D)					0.131	0.219
P(6D)					0.057	0.152
P(9D)					0.000	0.083
P(12D)						0.028

^a The following equation was used to determine the probability of n consecutive days of the specified radiation values (Amir et al., 1977): $P_i(nD) = [F_i(nD/M_i(y/n))]$ where $P_i(nD)$ = probability of n consecutive days (D) at the specified radiation for the i-th month; $F_i(nD)$ = frequencies of n consecutive days at the specified radiation value for the i-th month; M_i = number of days in the i-th month; y = number of years of readings (14 years in this study); n = number of consecutive days of interest.

primary production in some water bodies. Lab-lab is usually considered undesirable in most aquaculture ponds, however. During periods of rapid photosynthesis, oxygen bubbles may form in these mats and buoyancy induced by bubbles may cause pieces of the algal mat to separate from the bottom and float on the pond surface. Wind drives the pieces of algae to the leeward sides of ponds, resulting in a scum of algae and attached soil particles. Decay of these scums can cause localized problems with water and bottom soil quality.

Fish, shrimp and other aquatic animals usually react to light by moving to deeper water where light

is subdued. This probably is a response to escape bird predation, for aquatic animals in deeper water are less visible to birds. In shallow ponds, development of plankton blooms can provide turbidity that makes the organism invisible from above the water.

The amount of light also may affect fish and shrimp in other ways. Shrimp from ponds with clear water often are lighter in coloration than those from turbid waters. Coloration is important, for some markets prefer light-coloured shrimp. Carp mobility often increases in response to low turbidity during sunny, warm days. Their movements resuspend sediment to increase turbidity in the water

column – a process called bioturbation (Szumiec, 1983).

Exposure of fish eggs and larval stages to excessive ultraviolet radiation may result in direct DNA damage, which can cause mortality. Excessive sunlight can also cause indirect oxidative stress, phototoxicity and photosensitization (Zagarese and Williamson, 2001).

13.5.2 Water temperature

Fish, shrimp and most other aquatic animals are poikilothermic (cold-blooded), and their body temperature rises and falls in response to changes in water temperature. Warm-water species grow best at 20°C or more, while cold-water species thrive at lower temperatures. Each species has a characteristic range of tolerance to temperature and will die when exposed to temperatures outside this range. Respiration and growth of aquatic organisms are chemical reactions, and within the temperature tolerance range of a species, these two processes roughly double in rate with a temperature increase of 10°C in accordance with van't Hoff's law. Phytoplankton, bacteria and other microorganisms in aquaculture systems respond to warmth by increasing their metabolic activity. Photosynthesis, respiration, nitrification, denitrification and most other biological processes are sped up by increases in temperature. Rates of chemical reactions among abiotic substances also double with a 10°C increase in temperature. The ability of water to

hold dissolved oxygen decreases with temperature, however (Table 13.4). The likelihood of dangerously low dissolved oxygen concentrations in aquaculture ponds or in natural ecosystems increases appreciably during periods of abnormally high water temperature.

Aquatic animals exposed to temperatures near their limits of tolerance will be stressed and more sensitive to diseases and parasite infestations. They will spend more energy to maintain homeostasis and less energy can be used for growth and reproduction. Unusually low or high temperature can negatively influence reproduction, survival and growth of fish and other aquatic animals in both natural ecosystems and aquaculture facilities. It is important to select species capable of tolerating water temperatures at the site where they are to be cultured. Bolte et al. (1995) developed a bioenergetic model that uses mean air temperature, photoperiod and wind velocity to predict the number of crops possible per year for several important freshwater aquaculture species worldwide.

Water temperature in aquaculture ponds closely follows air temperatures, as shown in Figure 13.4, with data from Pemberton, Western Australia (Morrissey, 1976). The monthly air temperatures were about 0.5°C to 2.0°C higher than monthly water temperatures, but the trends of increase and decrease over the year were identical. It is widely recognized that the large seasonal changes in air temperature in temperate regions (Figures 13.4 and

Table 13.4. The solubility of dissolved oxygen in freshwater at different temperatures from moist air at standard sea-level pressure (760 mm Hg) (from Colt, 1984)

<i>Water temperature (°C)</i>	<i>Dissolved oxygen (mg l⁻¹)</i>	<i>Water temperature (°C)</i>	<i>Dissolved oxygen (mg l⁻¹)</i>
0	14.60	22	8.73
2	13.81	24	8.40
4	13.09	26	8.09
6	12.44	28	7.81
8	11.83	30	7.54
10	11.28	32	7.29
12	10.77	34	7.05
14	10.29	36	6.82
16	9.86	38	6.61
18	9.45	40	6.41
20	9.08		

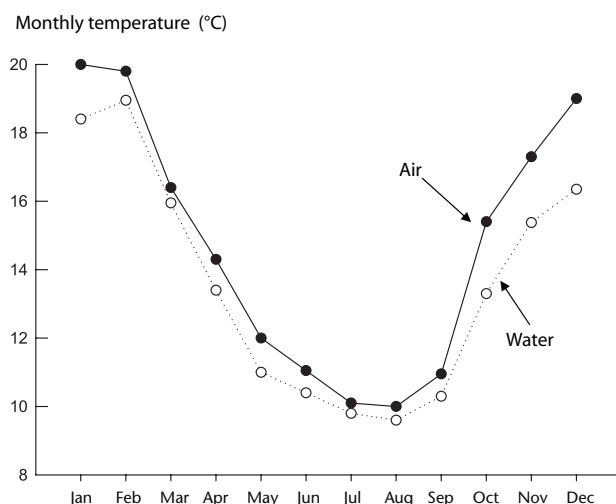


Figure 13.4. Average monthly air and water temperatures at Pemberton, Western Australia. Values obtained by averaging minimum and maximum temperature data. (Data from Morrissey, 1976)

13.5) markedly affect water temperature and growth of aquatic animals. Relatively small changes in water temperature among different periods of the year in the tropics (Figure 13.5) also influence water temperature and growth, however. The rainy season in coastal Ecuador, typically between December and May, is characterized by clear, hot days, with rainfall occurring mostly at night. The rest of the year is dry and features heavily overcast skies and lower air temperature than in the rainy season. Water temperature in culture ponds falls in the dry season (Figure 13.5), and shrimp grow only about half as fast as in the rainy season.

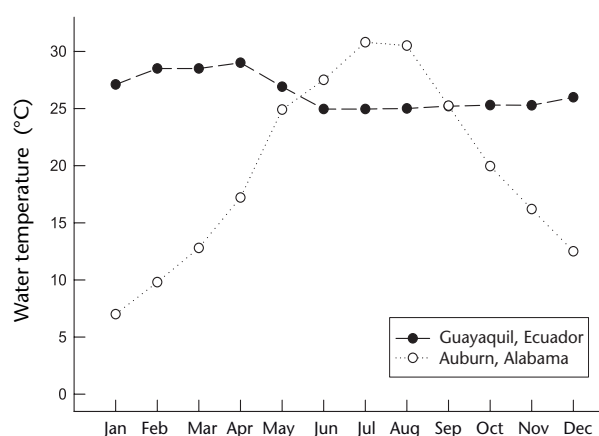


Figure 13.5. Average monthly water temperatures at Auburn, Alabama (32.5° N latitude) and Guayaquil, Ecuador (2° S latitude)

Air temperature can be used to estimate pond water temperature (Klemetson and Rogers, 1985; Wax and Pote, 1990). Equations developed by Wax and Pote (1990) for estimating the surface water temperature (°C) in ponds at dawn and mid-afternoon follow:

$$T_{dawn} = 2.218 + 0.062(A_{max}) + 0.285(A_{min}) + 0.561(P_{aft}) \quad (13.11)$$

where T_{dawn} = water temperature at dawn, A_{max} is the maximum air temperature on the previous day, A_{min} is the minimum air temperature on the previous day, and P_{aft} is the pond water temperature on the previous afternoon, and

$$T_{aft} = 2.071 - 0.068(a_{min}) + 0.373(a_{max}) + 0.651(P_{dawn}) \quad (13.12)$$

where T_{aft} = afternoon water temperature, a_{min} is the minimum air temperature on the same day, a_{max} is the maximum air temperature on the same day, and P_{dawn} is the pond water temperature at dawn of the same day.

Historic air temperature data are available for thousands of sites from government weather services, but less information is available on water temperature. Equations such as the two given above could be useful for predicting pond water temperatures. Pond water temperature regimes developed on the basis of these equations could be used to predict the lengths of growing seasons, suitability of sites for various culture species and the potential for abnormally high or low temperatures.

Warm-water species in temperate climates decrease physiological activity when water temperature declines in winter. Many tropical species are physiologically different from warm-water species in temperate climates in that they cannot tolerate low temperature. Tropical species such as tilapia, certain species of shrimp, and ornamental fish have been introduced into the temperate zone for aquaculture. These species usually will die when water temperature falls below 10°C to 20°C. Cold-water species have been introduced into mountainous regions of tropical nations. For example, rainbow trout is cultured in the mountains of Ecuador where there are water sources with a temperature below 20°C year-round.

Cold-water and warm-water species alike are stressed by abnormally high temperature. Prolonged exposure to high temperature will lead to diminished food intake and growth, disease susceptibility will increase and mortality may occur. At high

temperature, the respiration rate of the culture species and associated biota increases with high temperature and more dissolved oxygen is needed (Neill and Bryan, 1991).

Mean monthly air temperatures tend to be similar from year to year, but temperature variation is much greater for shorter periods. Sudden episodes of cool weather can cause water temperature briefly to fall well below the monthly average and negatively impact survival and growth of aquaculture species. Szumiec (1981) observed that a difference of 1°C from the mean seasonal temperature may correspond to a difference in carp production of 1 000 kg/ha in intensive systems.

Some farmers in the south-eastern United States produce tropical marine shrimp in inland ponds filled with water from saline aquifers. Shrimp post-larvae are stocked in the spring when water temperatures rise above 20°C. Cold fronts may pass through the region after shrimp have been stocked, causing water temperature to decline and stress or kill shrimp. Early stocking is essential because of the relatively short growing season for the tropical shrimp, but if stocked too early, a cold snap may kill the postlarvae. Shrimp also must be harvested in the fall before the onset of lethally low water temperatures.

Green and Popham (2008) estimated probabilities that a minimum air temperature less than or

equal to 14°C would last for one, three or five days during stocking and harvest seasons for inland shrimp in the United States. The critical temperature of 14°C was chosen because shrimp mortality was observed in ponds where water temperatures fell to 13.5°C–15.3°C for one night following a cold front in early October. Eight sites in the southern United States were identified and 100-year datasets of minimum air temperature were obtained from the United States National Oceanic and Atmospheric Administration. Probabilities for one of these sites, Greensboro, Alabama, are provided in Figure 13.6. At this location, the probability of a one-day period with water temperature below 14°C is less than 10 per cent only from mid-May until mid-September. Thus, the safest growing season for marine shrimp at Greensboro, Alabama, is only about 120 days. These probabilities can assist inland shrimp farmers to manage risk and refine management decisions at the beginning and end of the growing season.

It has been observed that problems with low dissolved oxygen concentration in channel catfish culture in the south-eastern United States are frequently related to high temperature (Tucker, 1996). A worse scenario is a period of unusually hot days in summer followed by one or more calm, cloudy days. Under such conditions, dissolved oxygen concentrations will be low at a time when fish biomass, plankton abundance and feeding rate are high.

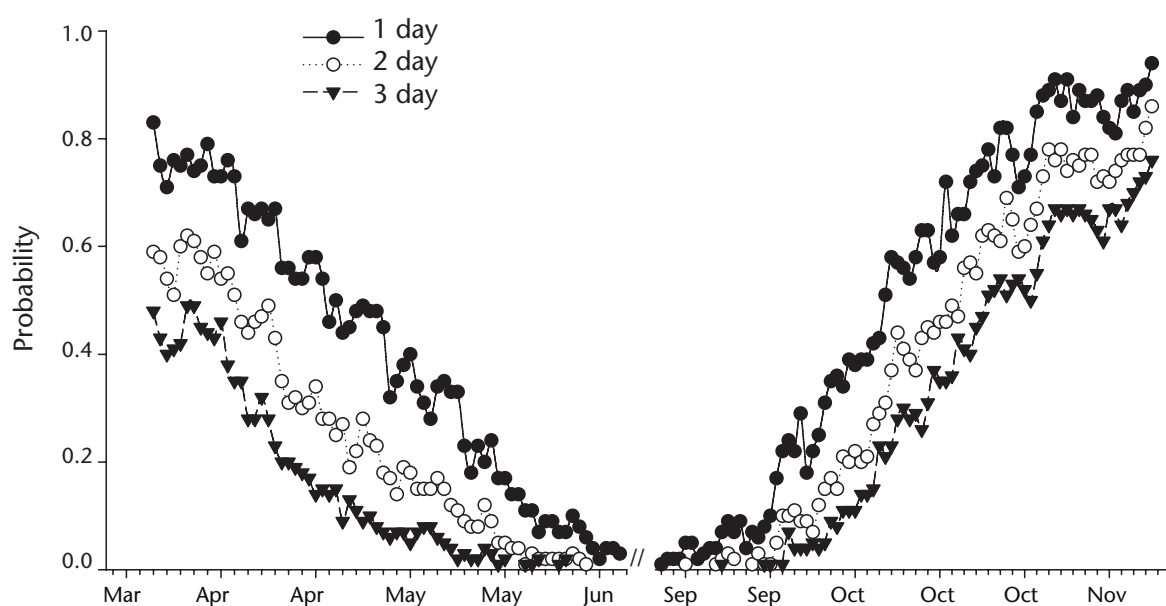


Figure 13.6. Probabilities of a minimum air temperature of 14°C or less for 1 day and 3 or 5 consecutive days during the spring and fall in Greensboro, Alabama

Water temperature plays an important, indirect role in the health of aquatic animals because it strongly influences the occurrence and outcome of infectious diseases. The relationship between temperature and aquatic animal epizootics is complex because temperature affects both the host and pathogen, as well as other environmental factors that may influence host immunocompetence. These relationships vary greatly among animal species and specific pathogens and by type of culture system. The immune system of aquatic animals generally functions most effectively at temperatures roughly corresponding to the range for best growth rate. At higher and lower temperatures, immunocompetence is diminished, while non-specific mediators of immunity are the primary means of preventing disease. Rapid temperature changes may also impair immune function, even if changes occur within the optimum range. Each pathogen also has an optimal temperature range for growth (or replication) and virulence, and it is the interaction between the effects of temperature on pathogen and host that determines the outcome of the epizootic. This interaction can lead to a pronounced seasonality of epizootics of certain diseases. For example, enteric septicaemia is the most important bacterial disease of pond-raised channel catfish. The disease is caused by the bacterium *Edwardsiella ictaluri*. Channel catfish are most susceptible to the disease when water temperatures range from 22°C to 28°C (Thune et al., 1993). In the catfish-growing areas of the south-eastern United States, pond water temperatures in that range typically occur in the spring and autumn, so there is a pronounced seasonal pattern of disease incidence. Pond waters are generally too cool to support disease outbreaks in the winter and too warm in the summer; major outbreaks of the disease occur primarily in the spring and autumn. There are many other examples for other species of increased incidence of disease during periods when the air and water temperatures are either rising or falling.

Water temperature is also a key factor in hatchery management and the production of aquatic animal larvae. The production of larvae for culture purposes often involves the inducement of ovulation and stimulation of milt production using exogenous hormones. While other environmental factors such as photoperiod and flow rate play a role, temperature is the crucial factor determining the rate of ovulation and milt production under natural and induced situations. Timing of this physiological reaction is related to the degree-hour response (water temperature multiplied by the number of hours from the onset of ovary maturation, or dosing, until ovulation).

Ovulation in common carp, *Cyprinus carpio*, requires 240 to 290 degree-hours, while in grass carp, *Ctenopharyngodon idella*, 205 to 215 degree-hours are required. The degree-hour response has been determined for several species (Horvath, 1978). Calculation of the time between administration of hormone and ovulation at 25°C for common carp is illustrated below:

$$\begin{aligned} \text{Time to ovulation} &= \frac{240^{\circ}\text{C} \cdot \text{hours}}{25^{\circ}\text{C}} \text{ to} \\ &\frac{290^{\circ}\text{C} \cdot \text{hours}}{25^{\circ}\text{C}} = 9.6 \text{ to } 11.6 \text{ hours} \end{aligned} \quad (13.13)$$

Understanding the relationship between temperature and mature gamete production and the associated effects is important for successful production of aquatic animal larvae.

13.5.3 Winterkill

Fish kills that occur in bodies of water with a winter ice cover are known as winterkill. When small water bodies are completely covered with ice and snow blankets the ice, light cannot penetrate into the water. There is no oxygen production by photosynthesis because of the lack of light, and respiration by organisms in the water and sediment will cause the dissolved oxygen concentration to fall. The dissolved oxygen concentration will decline slowly because of the low temperature, but it is not replenished because the ice prevents re-aeration from the atmosphere. Dissolved oxygen depletion is most likely to occur in shallow, eutrophic water bodies because they contain a large amount of organic matter and living biomass and have a small volume of water and a correspondingly small reserve of dissolved oxygen (Mathias and Barica, 1980).

Aquaculture ponds in cold regions are likely to experience winterkill because they receive large contributions of nutrients and organic matter and tend to be shallow. Snow removal from ice is one way of lessening the probability of winterkill. Another method is to aerate ponds to circulate water and prevent ice from covering the entire pond surface (Boyd, 1990). In more temperate climates, a brief period of unusually cold weather causing ice cover usually does not lead to winterkill.

13.5.4 Thermal stratification

Ponds and lakes stratify thermally because heat is absorbed more rapidly near the surface and the warm upper waters are less dense than cool lower waters (Table 13.5). Stratification occurs when

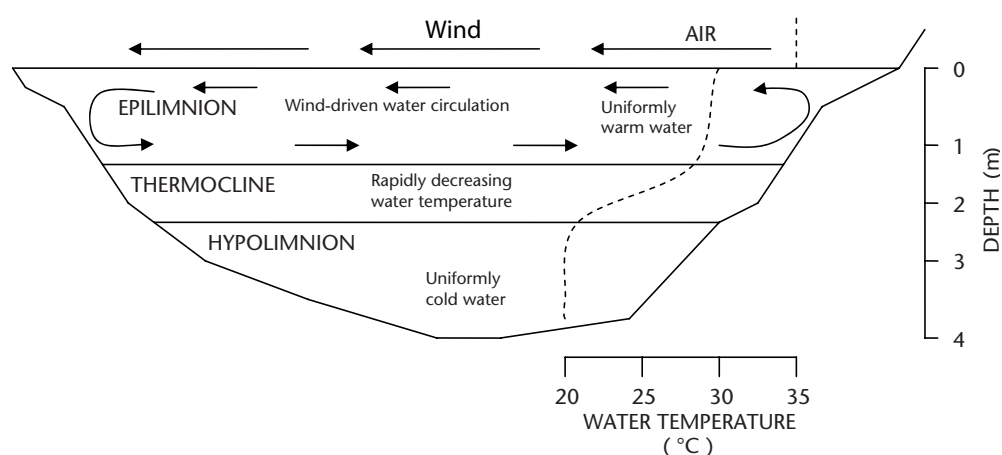
Table 13.5. Density of freshwater at different temperatures (from Colt, 1984)

°C	$g\ cm^{-3}$	°C	$g\ cm^{-3}$	°C	$g\ cm^{-3}$
0	0.9998679	11	0.9996328	22	0.9977993
1	0.9999267	12	0.9995247	23	0.9975674
2	0.9999679	13	0.999404 0	24	0.9973256
3	0.9999922	14	0.9992712	25	0.9970739
4	1.0000000	15	0.9991265	26	0.9968128
5	0.9999919	16	0.9989701	27	0.9965421
6	0.9999681	17	0.9988022	28	0.9962623
7	0.9999295	18	0.9986232	29	0.9959735
8	0.9998762	19	0.9984331	30	0.9956756
9	0.9998088	20	0.9982323		
10	0.9997277	21	0.9980210		

differences in the density of upper and lower strata become so great that the two layers cannot be mixed by wind. The classical pattern of thermal stratification of lakes in temperate zones is described by Wetzel (2001). At the spring thaw, or at the end of winter in a lake or pond without ice cover, the water column has a relatively uniform temperature. Heat is absorbed at the surface on sunny days, but there is little resistance to mixing by wind and the entire volume of water circulates and warms. As spring progresses, the surface water absorbs heat

more rapidly than heat can pass downward through the water column by conduction and mixing. The surface water becomes considerably warmer than deeper water.

The difference in density between the upper layer of water and the deeper water becomes so great that wind is no longer powerful enough to mix the two strata. The upper stratum is called the epilimnion and the lower stratum the hypolimnion. The stratum between the epilimnion and the hypolimnion

**Figure 13.7. Thermal stratification in a relatively deep pond**

is termed the metalimnion or thermocline (Figure 13.7). Temperature changes at a rate of 1°C or more per metre of depth across the thermocline. The depth of the thermocline below the surface may fluctuate from less than 2 m to 10 m or more depending on the area, depth, turbidity and morphometry of water bodies and local weather conditions. Most larger lakes do not destratify until autumn. Air temperatures decline and heat is lost from the surface water to the air during autumn. The difference in density between upper and lower strata decreases until mixing finally causes the entire volume of water in the lake to circulate and destratify.

Tropical lakes also stratify. There are two annual maxima in solar radiation, but the variation in radiation flux is small, and factors other than solar radiation may be of major importance in regulating patterns of thermal stratification (Hutchinson, 1975; Wetzel, 2001). Large, shallow lakes in windy regions may not develop persistent stratification. At the other extreme, small, deep lakes may stratify and only destratify at irregular intervals of several years when abnormal cold spells occur. Most tropical lakes stratify, but destratification occurs one or more times annually as a result of wind, rain or changes in air temperature.

Ponds are shallower, more turbid, more protected from wind, and have a smaller surface area

than lakes. The ordinary warm-water fish pond seldom has an average depth of more than 2 m, a maximum depth of more than 4 or 5 m, and a surface area of more than a few hectares. Marked thermal stratification may develop even in shallow ponds, however, because turbid conditions result in rapid heating of surface waters on calm, sunny days.

The stability of stratification is determined by the amount of energy required to mix the entire volume of a body of water to a uniform temperature. The greater the energy required, the more stable the stratification. Aquaculture ponds are relatively small and quite shallow, and stratification is not as stable in them as it is in lakes and larger ponds. For example, 0.04 ha ponds with average depths of about 1 m and maximum depths of 1.6 to 1.8 m on the Fisheries Research Unit at Auburn, Alabama, will stratify thermally during daylight hours in warm months, only to destratify at night when the upper layers of water cool by conduction (Figure 13.8). Large, shallow aquaculture ponds (0.5–20 ha or more) stratify and destratify daily in the same manner.

Stratification and destratification of water bodies can be associated with biological activity and its effect on light penetration. A small, clear pond may stratify when a plankton bloom develops because the planktonic organisms suspended in the upper layer of water absorb heat and cause the upper layer of water to heat rapidly (Idso and Foster, 1974).

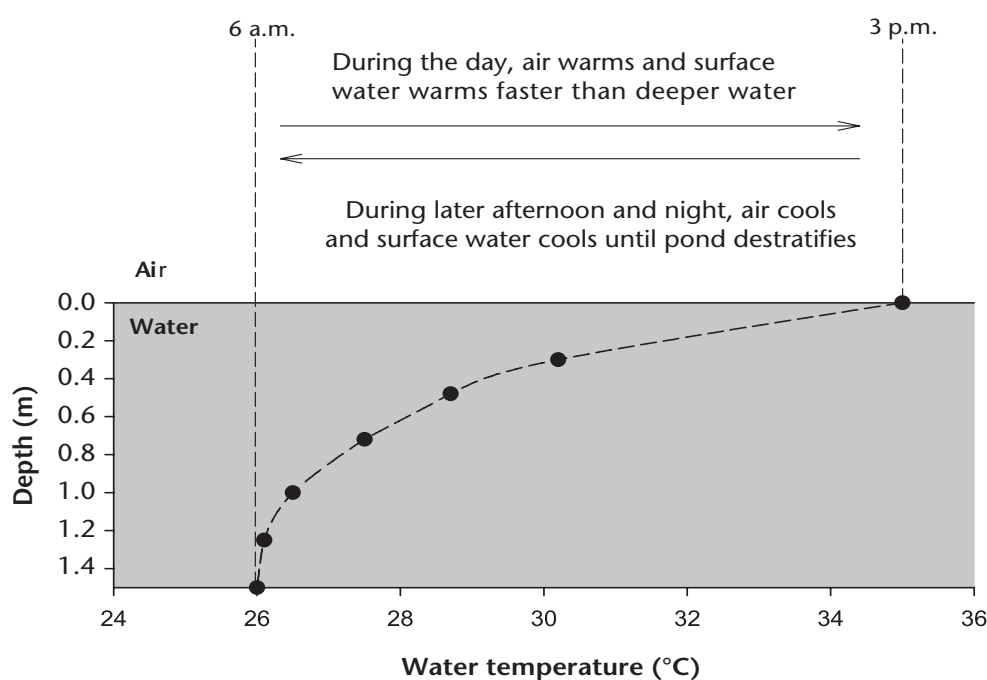


Figure 13.8. Daily thermal stratification and destratification in a shallow aquaculture pond

Light will penetrate deeper into the pond if the plankton bloom disappears, and destratification may occur.

13.5.5 **Rainfall and water quality**

Rain is normally acidic, for it is saturated with carbon dioxide. Pure water saturated with carbon dioxide has a pH of 5.6 (Boyd and Tucker, 1998). Rain more acidic than pH 5.6 contains a strong acid. Strong acids found in rainwater are formed by non-metallic oxides and hydrides of halogens. There are naturally occurring oxides of nitrogen, sulphur and chloride in the atmosphere. These can result in the formation of nitric acid, sulphuric acid and hydrochloric acid, respectively. In some areas, the natural background of strong acids can depress the pH of rainwater below 5.6. The combustion of fuels increases the concentration of nitrogen and sulphur compounds in the atmosphere and causes a marked depression in the pH of rainwater. In areas affected by heavy air pollution, the pH of rainwater may be below 4.

There are many reports, primarily from the north-eastern United States, eastern Canada and northern Europe, demonstrating the adverse effects of acid rain on aquatic ecosystems (Cowling, 1982). In regions where the acid-neutralizing capacity of soils and waters is low and rainfall is highly acidic, the pH and total alkalinity of lakes and streams has decreased. In the north-eastern United States and Canada, where the rainfall has a pH of 4.2 to 4.4 (Haines, 1981), many lakes and streams have declined in pH by 1 to 2 units during the last 30 to 40 years (Seip and Tollan, 1978). Many bodies of water in this region have a pH below 5.0 and aquatic organisms at all trophic levels have suffered adverse effects (Beamish and Harvey, 1972; Haines and Akielasek, 1983). Reproductive failures, skeletal deformities, reduced growth and even acute mortality has been observed in fish populations (Haines, 1981).

The effects of acid rain on fish populations have been expressed mainly in areas where total alkalinity of surface waters is below 10 to 20 mg l⁻¹ (Boyd and Tucker, 1998). Marine fisheries are unaffected by acid rain because coastal and oceanic waters are highly buffered. Freshwater aquaculture ponds with low-alkalinity water usually are treated with agricultural limestone (Boyd and Tucker, 1998), and this neutralizes the acidity from rain. Trout culture often is conducted in raceways, and the water source may be streams. There have been instances in North Carolina when runoff from heavy rainfall caused a sudden decline in the pH of stream water

supplying raceways and resulted in stress or death of trout.

Rain falling directly into ponds affects the surfaces by splashing water into the air and increasing the surface area for gas transfer. Depending upon the degree of oxygen saturation, dissolved oxygen concentrations may increase or decrease during a rainfall event. Night-time rainfall is more likely to increase dissolved oxygen concentration than daytime rainfall.

Erosion on watersheds during storm events may result in a turbid runoff that enters streams, ponds and other water bodies. Although coarse particles settle quickly, clay particles remain suspended for hours or days and create considerable turbidity. Settling particles can smother benthic organisms, and fish eggs that usually are deposited in depressions on the bottom can be destroyed by sediment. Prolonged turbidity reduces light penetration, lessens primary productivity, and ultimately reduces fish production (Buck, 1956). Sediment accumulation in ponds also reduces depth and storage volume.

Ponds for production of marine species often are sited along estuaries and brackish water is pumped into them or sometimes introduced by tidal flow. Shellfish plots also are established in estuaries. The salinity at a given location in an estuary usually increases during rising tide and decreases with falling tide. Salinity also declines in response to increasing freshwater inflow. In tropical locations with distinct wet and dry seasons, salinity in coastal aquaculture ponds differs markedly between seasons (Figure 13.9). Large and medium-sized aquaculture projects are usually located at a place where the water is saline enough throughout the year. Small-scale projects are usually installed where space is available and little thought may be given to salinity, as other sites are unavailable.

Unusually heavy rainfall can cause extremely low salinity that stresses culture animals and leads to disease outbreaks or even causes direct mortality. Sometimes, heavy rainfall and associated runoff can cause rivers entering estuaries to change their course, which may affect aquaculture projects. Heavy rainfall during a cyclone at a shrimp farm in Madagascar caused a diversion in a river upstream of the farm to increase its catchment area and direct a greater flow of freshwater into the area where the pump station was located. Under the new hydrological conditions, the site of the pump station had freshwater continuously for two to three months

during the year. This situation was unacceptable for shrimp culture, and therefore the pump station was moved to a more suitable location at considerable expense.

El Niño events result from increases in the temperature of the ocean by 1°C or 2°C above normal. El Niño events are rather common in the Western Pacific Ocean along the North and South American coasts. Between 1950 and 2004 there were 13 events, or an average of about one event every four years. Heavy rainfall during El Niño events causes low salinity that can stress or kill shrimp, but there also are benefits. The slightly warmer temperature of ocean waters may favour greater production by native fisheries and aquaculture operations. Increased rainfall and runoff also may flush pollution from estuaries that normally do not rapidly exchange water with the sea.

Blue-green algae excrete compounds into the water that impart an off-flavour to the flesh when adsorbed by fish and shrimp, which lowers market acceptability (Boyd and Tucker, 1998). Blue-green algae seldom are abundant in coastal shrimp ponds when salinity is below 10 parts per thousand (ppt). During the rainy season in tropical nations, salinity in shrimp ponds may decline below 10 ppt while blue-green algae abundance rises, resulting in an off-flavour (Boyd, 2003).

13.5.6 Wind

Wind creates waves on the water surface to increase the area for exchange of gases between air and water. Wind also mixes the water column, causing the movement of dissolved gases throughout a

water body. During the night and at other times when the dissolved oxygen concentration may be low, wind re-aeration is an important source of dissolved oxygen in ponds. When water is super-saturated with dissolved oxygen or other gases, however, wind action increases the rate of diffusion of gases into the air.

Boyd and Teichert-Coddington (1992) deoxygenated two ponds at the El Carao National Aquaculture Center, Comayagua, Honduras, by treatment with sodium sulphite and cobalt chloride; they also suppressed biological activity by application of formalin and copper sulphate. Wind speed, water temperature and dissolved oxygen concentration were monitored with a data logger system during the four-day re-aeration period. The wind re-aeration coefficient was calculated at intervals, and coefficients increased linearly ($R^2 = 0.88$) with wind speed between 1 and 4.5 m s⁻¹ (Figure 13.10). The regression equation was:

$$W = 0.153X - 0.127 \quad (13.14)$$

where W = standard wind re-aeration coefficient for 20°C and 0.0 mg l⁻¹ dissolved oxygen (g O₂ m⁻² h⁻¹) and X = wind speed at 3 m height (m s⁻¹). The following equation can be used to calculate the wind re-aeration rate for a specific pond:

$$K_w = W \left[\frac{C_s - C_p}{9.07} \right] 1.024T^{-20} \quad (13.15)$$

where K_w = wind re-aeration rate (g O₂ m⁻² hr⁻¹), C_s = dissolved oxygen concentration in pond water at saturation (g m⁻³), C_p = measured dissolved

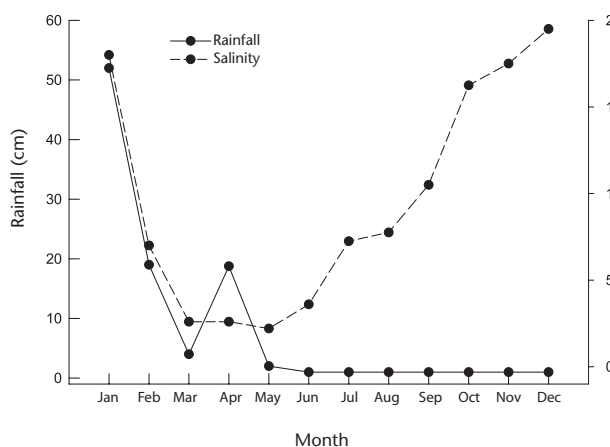


Figure 13.9. Relationship between rainfall and salinity in shrimp ponds near Guayaquil, Ecuador

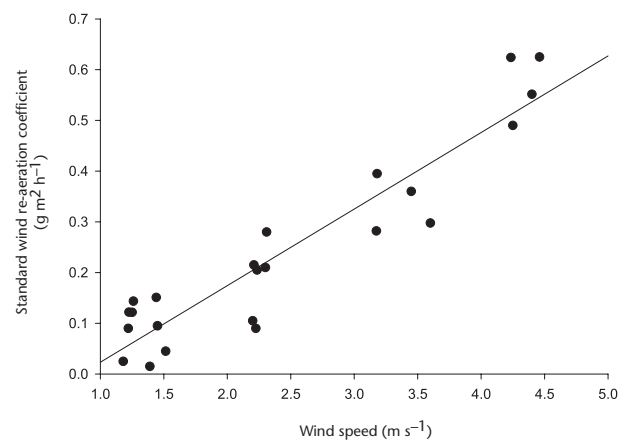


Figure 13.10. Regression of standard wind re-aeration coefficient on wind speed at a height of 3 m above the pond water surface

oxygen concentration in pond (g m^{-3}), and T = water temperature ($^{\circ}\text{C}$).

Wind also creates water currents in ponds that are beneficial because they mix the water column, thus providing more uniform concentrations of dissolved oxygen to the bottom waters. In places where enhanced wind mixing is desirable, ponds can be constructed with their long axis parallel to the direction of the prevailing wind. Wind-induced currents can resuspend sediment particles to create excessive turbidity and they can cause erosion of pond embankments. At sites where strong winds are common, vegetative barriers may be planted perpendicular to prevailing winds to provide wind-breaks. Moreover, stone or plastic liners may be installed along embankments to minimize wave erosion. Grass cover should be established on above-water portions of earthworks to protect against erosion by wind and rains (Boyd, 1999; Boyd et al., 2003).

When water in aquaculture ponds is still because of windless conditions, surface water often becomes highly supersaturated with dissolved oxygen. On bright, calm days, concentrations may exceed 200 per cent saturation (Boyd et al., 1994). Life stages of culture species or natural organisms that cannot move into deeper water to escape the excessive gas pressure near the surface may be stressed or killed by gas bubble trauma.

Strong winds or the combination of strong winds and heavy rainfall also may cause thermal destratification of ponds and lakes during summer. The hypolimnion of eutrophic lakes and ponds is depleted of dissolved oxygen and has high concentrations of dissolved and particulate organic matter, reduced iron and manganese, and other reduced inorganic and organic substances. When sudden destratification occurs, anaerobic hypolimnetic water dilutes the dissolved oxygen in the water with which it mixes. Oxygenation of reduced substances from the hypolimnion increases the oxygen demand. Cold fronts from the north-west sometimes pass through the south-eastern United States in summer. These fronts travel quickly and result in strong winds and cold rain. Lakes and ponds in the region are typically stratified in summer and the mixing action of the wind and rain often causes destratification (FAO, 1968). Low dissolved oxygen concentration may occur in fertilized sport fish ponds and in commercial channel catfish ponds common in the region, and fish kills may result.

Cage culture operations commonly are placed in natural lakes or in reservoirs. These water bodies may thermally stratify, and the contribution of

wastes from cage culture operations will contribute to the oxygen demand in the hypolimnion. Sudden thermal destratification or overturns of lakes with cage culture operations can lead to dissolved oxygen depletion and massive fish mortality. For example, a large tilapia cage culture operation is located in El Cajon Reservoir in Honduras. In 2003, an unusually strong cold front with heavy rain caused destratification of the reservoir. Dissolved oxygen concentrations declined to less than 0.5 mg l^{-1} in cages and there was a complete loss of the tilapia – the mortality was estimated at 1 500 tonnes of fish. An unknown quantity of wild fish in the reservoir also died. Similar mass mortalities of fish resulting from thermal overturns of lakes with cage culture operations have also been reported in Indonesia, the Philippines, China and other countries (Schmittou, 1993).

Ponds for shrimp farming and other types of coastal aquaculture are especially susceptible to storm damage. There have been numerous cases in which ponds have been overtopped by storm surges and embankments have been breached. One of the most disastrous examples was the impact of Hurricane *Mitch* on shrimp farms along the Gulf of Fonseca in Honduras and Nicaragua in 1998. Heavy rainfall from the hurricane caused extensive flooding that overtopped and breached embankments and left deep layers of sediment in riverbeds, canals and ponds. Mangroves provide considerable protection from waves and storm surges. In some locations, the likelihood of storm damage has been exacerbated by the removal of mangrove forest for constructing ponds. Shrimp and other aquaculture farms should be constructed behind mangrove areas with the mangrove habitats left undisturbed (Phillips, 1995).

In regions where hurricanes are frequent, farms should be designed to minimize damage by taking into account probable storm surge height and wind velocities. These precautions are seldom considered, but farm managers usually lower water levels in ponds so that rain falling into ponds does not cause water to overtop embankments.

Aquaculture cages are especially susceptible to heavy waves. There have been numerous instances of escapes of culture species as a result of cage failure in storms (FAO, 1984). Such events are obviously economically damaging to producers, but there are also environmental concerns related to escapes. Some scientists think that farmed fish are genetically inferior to wild stocks, and massive escapes from cages or other facilities could damage the gene pools of local populations of the same species. Cages should be installed in areas that are less susceptible

to heavy waves. Recent advances in cage technology have reduced the probability of cage failure. Some cages are even installed several metres below the surface to minimize the influence of heavy seas.

13.5.7 Barometric pressure

Dissolved oxygen concentration is probably the single most important variable in aquaculture. This parameter is frequently measured in ponds for research and commercial aquaculture. The usual method of measurement is a polarographic dissolved oxygen meter. In order to properly calibrate a dissolved oxygen meter or to estimate the dissolved oxygen concentration at saturation in a body of water, the barometric pressure must be known. The most common source of barometric pressure information is a weather station at the nearest airport. Individuals using such data should be aware that barometric pressure readings at these stations usually have been adjusted to the equivalent pressure at sea level. The station barometric pressure is needed for calibrating dissolved oxygen meters or estimating dissolved oxygen concentration at saturation. Boyd (1990) provided instructions and tabular data needed for correcting sea-level-adjusted barometric pressure readings to station barometric pressures.

Data for dissolved oxygen concentration at saturation (Table 13.4) are for sea level. These values can be adjusted to station barometric pressure with the following equation:

$$DO_{ss} = DO_{ssl} \times \frac{760}{BP} \quad (13.16)$$

where DO_{ss} = dissolved oxygen saturation at station (mg l^{-1}); DO_{ssl} = dissolved oxygen saturation at sea level (mg l^{-1}); BP = station barometric pressure (mm hg).

If barometric pressure cannot be measured but station elevation is known, the barometric pressure can be estimated by the following equation (Colt, 1984):

$$\log_{10} BP = 2.880\,814 - \frac{\text{Station elevation (m)}}{19\,748.2} \quad (13.17)$$

13.6 RESEARCH NEEDS

There needs to be a more organized effort to define relationships between agrometeorological data and fisheries and aquacultural production. In fisheries, the greatest priority probably should be given to predicting the influence that global climate change will have on production. Of course, a better understanding of the influence of meteorological

variables on the structure and function of natural aquatic ecosystems should also be a long-term goal. Better methods for predicting the forces, paths and conditions of storms and enhanced communications for warning fishermen of impending danger could save many lives.

In aquaculture, the emphasis should be placed on developing a greater knowledge of the relationships among agrometeorological variables, water quality and production. Some particularly important issues include the effects of wind-induced circulation on water quality, phytoplankton and off-flavour in ponds; refinement of dissolved oxygen models to incorporate weather forecast information and newer technologies for measuring phytoplankton biomass, such as satellite images and hand-held spectral reflectometers; predictive models of fish feeding behaviour based on weather and water quality data; and effects of weekly or shorter variations in water temperature on the growth of culture species.

Much of the inland aquaculture in developing nations is done in ponds without the option for mechanical aeration. Sites with good exposure to the wind are favoured, and periods of calm, hot weather are potentially dangerous to fish populations. In areas with a high probability of calm weather, production levels should be lowered so that phytoplankton blooms do not become excessive and cause chronically low night-time dissolved oxygen concentrations.

There are millions of hectares of aquaculture ponds in the world, and most of them are concentrated in Asia. Compared to natural aquatic ecosystems, large amounts of nutrients are applied to these ponds, and organic matter accumulates in pond bottoms (Boyd and Tucker, 1998). Decomposition of organic matter in sediment of aquaculture ponds produces carbon dioxide and methane that enter the atmosphere. It would be interesting to determine the contribution of world aquaculture to greenhouse gases.

Global warming will affect aquaculture production. Because aquaculture will eventually be the main source of fisheries products, it seems imperative to assess the possible negative impacts of global warming on the major types of aquaculture.

13.7 APPLICATION OF AGROMETEOROLOGY

Existing meteorological and climatological data should be more fully used in fisheries and

aquaculture. Aquaculturists need to be aware of local conditions relating to normal patterns in air temperature, solar radiation, cloud cover, evaporation and wind velocity. A knowledge of the frequency of excessive rainfall and floods, droughts, air temperatures that are lower or higher than normal, and destructive storms would also be beneficial. Armed with this information, aquaculturists would be able to plan and conduct operations in harmony with local climatic conditions. Aquaculturists could use local weather forecasts to prepare for adverse weather and decrease the likelihood of weather-related losses.

Aquaculture is a major activity in many nations, and it is expected to expand in the future. Because of increasing environmental awareness and the need to conserve natural resources, environmental impact analysis (EIA) often is required for new commercial aquaculture projects (Boyd and Tucker, 1998). An EIA should include an evaluation of local climate and adverse weather conditions that could affect the project. The size of the project should be in accordance with the availability of water and facilities should be designed to protect against drought, flooding, wind and water erosion, and storms.

Conservation of freshwater is a major issue worldwide. It is particularly important to design aquaculture facilities so that water can be used efficiently (Boyd, 2005). An effort should be made in major aquaculture regions to provide the aquaculture sector with records of rainfall (to include frequency–intensity–duration relationships for use in the design of facilities) and evaporation.

13.8 EDUCATION NEEDS

The major obstacle to the use of agrometeorological data in fisheries and aquaculture is the lack of familiarity with the topic by those who work in the sector. The training of aquaculture scientists does not

usually include coursework in this area. The importance of water temperature is included in courses about aquaculture production, but the relationship of water temperature to other agrometeorological data is usually not emphasized. Even less attention is given to precipitation, evaporation, wind and other meteorological variables in the training of aquaculture scientists. This is a strange situation and is probably the result of the development of aquaculture curricula within fisheries or biology programmes, where the emphasis has been on natural systems that are not managed intensively. In agronomy, all students are required to take at least one basic soil science course that includes information on the interaction of climatic factors with soils and their productivity. A similar class in water science should be provided to students of fisheries and aquaculture. This kind of class is currently being taught at Auburn University in the United States. It includes information on meteorology, hydrology and water quality, with emphasis on how these topics are related to fisheries and aquaculture.

Nations with large aquaculture sectors have extension programmes to provide technical assistance to producers. Governmental fisheries agencies in these countries usually are in close contact with international development organizations such as FAO, the World Bank and the Asian Development Bank, and foreign aid programmes from Australia, Canada, the European Union, Japan and the United States. These development organizations should be made aware of the importance of agrometeorological data in aquaculture and fisheries so that they can initiate training efforts and provide data to producers. The most effective way of promoting the use of agrometeorological data in aquaculture is to convince the future generation of fisheries and aquacultural scientists that these data are useful and to train them to use the data. They will then begin to conduct research on the topic and include information about agrometeorology in their extension programmes. As a result, those who work in the private sector as managers will apply agrometeorological data to farm operations.

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CHAPTER 14

AGROMETEOROLOGICAL ASPECTS OF DESERTIFICATION

14.1 INTRODUCTION: DESERTIFICATION AND WMO

Desertification is a highly complex set of events that poses serious threats to the environment and to the socio-economic well-being of people in various parts of the world, and climate can be a contributing factor to this process. In a general sense, the term “desertification” refers to land degradation in the Earth’s dry zones. In the process of land degradation, dryland areas become much less biologically productive. Desertification can be caused by multiple interacting factors of climatic, socio-economic and ecological origin that play out through a myriad of pathways in different locales. As such, it has been difficult to precisely define the term, and over 100 formal definitions exist (Geist, 2005). The most commonly accepted definition today is that given by the United Nations Convention to Combat Desertification (UNCCD): “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities” (UNEP, 1994). Land degradation can occur in any climate, however, and some authorities call for a modified definition that encompasses all climates or better accounts for the role of plant/soil relationships in measures of aridity (for example, Riábchikov, 1976; Instituto de Meteorología, 1999; Rivero et al., 1999).

Natural oscillations in the extent of existing deserts should not be confused with desertification (UNEP, 1992). Expansion and contraction of deserts along their margins may occur over time due to inter-annual variations in precipitation, and are part of the natural spatial variability of most deserts. On the other hand, remote patches of land in dry zones sometimes hundreds of miles from deserts may become degraded and ultimately coalesce to form larger areas of desertified land. Physical attributes of such degraded land are numerous and include reductions in:

- (a) perennial plant biomass;
- (b) biological productivity;
- (c) ecosystem biodiversity;
- (d) soil fertility;
- (e) stored plant and animal litter;
- (f) soil organic matter;
- (g) protection of soil from wind and water erosion;

- (h) soil water-holding capacity, sometimes with salinization of soils or groundwater.

The resulting transformations may benefit some organisms over others, and generally result in reduced livelihood opportunities for humans, especially for the production of crops and livestock. Reduced economic output is a negative outcome from the perspective of humans. Human value judgments are at the core of the concept of desertification.

Dryland environments comprise approximately 6.1 billion ha, or about 47 per cent of all land area. Approximately 84 per cent of this area falls within the arid, semi-arid and dry sub-humid climates that are inherently susceptible to desertification (UNEP, 1997). Estimates vary widely, but about 10–20 per cent of the susceptible drylands are believed to have already undergone land degradation (Millennium Ecosystem Assessment, 2005). In 1996 the UNCCD Secretariat estimated that the livelihoods of approximately one billion people in over 100 countries are at risk from desertification, and over 250 million people are directly affected. The UNCCD notes that desertification appears to preferentially affect “the world’s poorest, most marginalized and politically weak citizens” (UNCCD, 2006). Annually across the globe, it is estimated that desertification results in the direct loss of US\$ 42 billion in foregone income from agriculture (Dregne and Chou, 1992). This figure does not include the likely higher costs associated with indirect economic and social impacts (for example, out-migration to other areas, health impacts, political instability, human suffering). Problems caused by desertification are not new, and are believed to be at the root of the collapse of a number of ancient societies, including those in the south-west Asian fertile crescent, upland steppe plateaus of northern China and the Tehuacán Valley of Mexico. The consequences of desertification may expand in the future, as a projected 2.0°C–4.5°C rise in global average temperature and an increase in land area affected by droughts are expected by the year 2100 (IPCC, 2007).

Desertification threatens the sustainability of land, and is believed to be one of the most serious global environmental problems. The World Meteorological Organization (WMO), as a United Nations specialized agency addressing human welfare in relation

to the Earth's atmosphere, climate and water resources, considers desertification issues a high priority in its operations. In efforts to combat desertification, it has been active in improving meteorological observing networks, research and prediction capabilities related to climatic drivers of desertification; drought preparedness and mitigation plans; and knowledge transfer programmes. The purpose of this chapter is to discuss climate in relation to drylands and desertification – fundamental processes, interactions, agrometeorological interventions and WMO roles – with a view towards promoting sustainable use of global drylands.

14.2 A GLOBAL SURVEY OF DESERTIFICATION AND ITS CAUSES

14.2.1 Drylands

This section draws heavily on a report on drylands by the Food and Agriculture Organization of the United Nations (FAO, 2004). Drylands prevail where water deficit occurs to some extent throughout a hydrological year, and may be classified on the basis of aridity. The aridity index is assessed on the basis of climate variables using the ratio of annual average precipitation to potential evapotranspiration (P/PET). According to the *World Atlas of Desertification* (UNEP, 1992, 1997), drylands have a P/PET ratio of less than 0.65 and precipitation of less than 600 mm per year. The aridity index uses the P/PET to classify drylands into hyper-arid, arid, semi-arid and dry sub-humid areas (Table 14.1). In the context of agrometeorology, FAO also assesses aridity based on how many days the water balance allows plant growth (the growing season). A negative balance between

precipitation and evapotranspiration usually results in a short growing season for crops (less than 120 days). Alternatively, delimitation of climate zones can also be carried out by adopting Koeppen's classification scheme or the ecological dryness index, which relates productivity of ecosystems to actual and potential evapotranspiration (AET/PET). Useful examples are available in the scientific literature with respect to crop yields (Doorenbos and Kassam, 1988) and for natural ecosystems (Riábchikov, 1976).

Although arid zones are not restricted to any particular regions, most arid land areas of the world where agriculture is of relevance are located between latitudes 20° and 35° north and south. The main semi-arid areas occupy each side of the arid zone and include both Mediterranean-type and monsoonal-type climates. Hyper-arid and arid zones extend mostly across the Saharan, Arabian and Gobi deserts; sedentary agriculture is localized around major water bodies, as in the Nile Valley and the Nile Delta, or is intensively irrigated. Another type of dryland is the cold desert, which generally occurs in high-latitude or high-altitude continental areas and is not considered further in this chapter. Overall, Africa and Asia have the largest expanse of arid zones, accounting for almost four fifths of hyper-arid and arid zones in the world (see Figure 14.1). By definition, desertification only applies to dryland regions, despite degradation of land in other climates occurring through similar processes. Hyper-arid regions are generally not considered in discussions of desertification because, as a rule, there is no crop growth unless under intensive irrigation.

Soils are an important resource of drylands for provision of food in these areas. They provide the

Table 14.1. Dryland categories according to the aridity index classification scheme

<i>P/PET</i>	<i>Rainfall (mm)</i>	<i>Classification</i>	<i>Increasing aridity</i>
<0.05	<200	Hyper-arid	
0.05 – <0.20	<200 (winter) <400 (summer)	Arid	
0.20 – <0.50	200–500 (winter) 400–600 (summer)	Semi-arid	
0.50 – <0.65	500–700 (winter) 600–800 (summer)	Dry sub-humid	

Winter – defined as the period December to February
Summer – defined as the period June to August

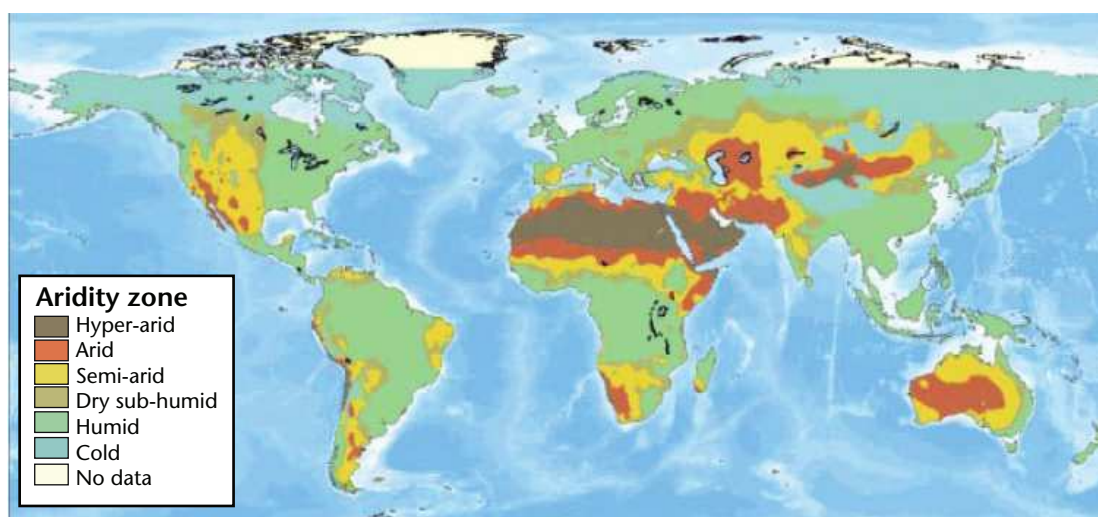


Figure 14.1. Global distribution of drylands based on the aridity index (UNEP, 1997)

medium in which plants grow and their properties determine proportions of precipitation available for plant growth. While dryland soils vary considerably, they principally comprise aridisols and entisols, along with others including alfisols, mollisols and vertisols (Dregne, 1976). Dryland soils are characterized by frequent water stress, small water-holding capacity, low organic matter content, susceptibility to erosion and low nutrient content, particularly in nitrogen (Skujins, 1991). Vegetation supported by these soils ranges from barren or sparsely vegetated desert to grassland, shrubland and savanna or dry woodlands. Forest vegetation is sparse, with species adapted to arid soils and high water use efficiency. Plants that have adapted to drylands survive irregular rainfall, high solar radiation and periods of drought. Indeed, many plants have well-adapted strategies or characteristics to cope with the overall aridity and periods of drought (which can be defined as periods – 1 to 2 years – when rainfall is below average), such as deep root systems, waxy leaf

surfaces and specific germination and life cycles. Dryland plants are also adapted to windy conditions with very low values of relative humidity. Plants also fulfil a dual role in that they protect soil surfaces from wind and water erosion and also help to stabilize mobile dune systems. Removal or loss of vegetation cover results in an increased risk of soil erosion and land degradation.

The predominant land use of drylands is agriculture, specifically pastoralism and subsistence food production. Typical crops grown under rainfed conditions are presented in Table 14.2 (FAO, 1993). A combination of meteorology (rainfall, temperature, radiation), climate and soil characteristics (water-holding capacity, organic matter content) coupled with low germination rates and high seedling mortality, results in very low plant productivity for sedentary agricultural systems in drylands. Indeed, a major constraint on agricultural development is low and highly variable

Table 14.2. Typical crops grown in drylands under rainfed conditions

<i>Classification</i>	<i>Growing season (days)</i>	<i>Typical crops</i>
Hyper-arid	0	No crop, no pasture
Arid	1–59	No crops, marginal pasture
Semi-arid	60–119	Bulrush millet, sorghum, sesame
Dry sub-humid	120–179	Maize, beans, groundnut, peas, barley, wheat

rainfall. Where natural and/or anthropogenic land degradation and desertification occurs, especially when these processes encroach onto marginal semi-arid environments, further environmental stress is added to cultivation and rangeland agricultural practices. Traditional systems of rainfed cropping that cope with low and erratic rainfall have evolved, however. In drier regions, livestock grazing, with regular seasonal movements, usually predominates. In areas where reasonable levels of rainfall occur and soils are relatively deep, rainfed agriculture is generally practised. Normally, several crops are sown in order to reduce the risk of total crop failure. Other agricultural strategies include the use of drought-resistant/adapted crop varieties, long fallow periods and soil protection by vegetation or other material (such as mulch or stones).

14.2.2 Causes of desertification

Although there is a widespread awareness that desertification threatens the livelihood of many people in the world's drylands, the causes of desertification remain controversial (Helldén, 1991; Lambin et al., 2001). The UNCCD definition of desertification emphasizes two main causative factors: climatic variations and human activity. It could be argued, however, that the real cause of land degradation in drylands is the removal of the natural vegetation cover. Dryland vegetation is important for maintenance of soil fertility and moisture, and for protection of the soil against destructive forces of wind and rainfall. But why does the vegetation cover become degraded? Many factors can contribute to the removal of vegetation cover. Traditionally, drought, overgrazing by livestock and exploitive use of vegetation have been blamed for dryland degradation (Dregne et al., 1991). Other factors linked to desertification include poor irrigation practices that result in soil salinization or waterlogging, overcultivation of soils, excessive pumping of groundwater and spread of bush fires.

Drought is an intrinsic feature of the world's drylands. Drought refers to a period with below-average rainfall, which can occur within a year, but multiple years may have abnormally low rainfall as well. In drylands, the natural vegetation is adapted to periods of water scarcity, and usually vegetation will quickly recover after a drought period (ecosystem resilience). In the case of a multiple-year drought (like the one during the 1970s in the Sahel), the recovery is much slower. Trees and shrubs may have died, and it may take years for the vegetation to recover. It does not necessarily follow, however, that drought per se will give rise to or cause

desertification in drylands (Darkoh, 1998). Much depends on the land management practices, which either weaken or improve the resilience of the soils and natural vegetation.

In the 1970s, Charney (1975) related the Sahelian drought to a positive climate–land cover change feedback mechanism. He speculated that overgrazing causes less vegetation cover, which increases the surface albedo. Less solar radiation is absorbed and the Earth's surface becomes cooler, leading to less precipitation and a further decline in vegetation cover. In a recent study, however, Giannini et al. (2003) showed that oceanic forcing played an important role in the Sahelian drought. Sahelian rainfall is closely related to a tropical sea surface temperature anomaly pattern that spans the Pacific, Atlantic and Indian oceans. This is not to say that sea surface temperatures are the whole story. There could be additional land–atmosphere feedback mechanisms that enhance drought conditions initiated by sea surface temperature anomalies (Zeng, 2003). But at this point the role played by changes in land use and vegetation cover in climate variability and change is poorly understood and will require more research.

Global climate change could result in more frequent and prolonged droughts in the world's drylands. But it remains unclear what the exact impact of global climate change will be in the drylands (WMO, 2003a). This obviously may differ from region to region, and could result in more favourable conditions in some places and worse conditions in other areas. For example, recent model predictions for Sahelian Africa range from increasing precipitation (Haarsma et al., 2005) to more dry conditions (Held et al., 2005). Despite such contradictory model predictions, most climatologists seem to agree that weather will become more extreme, with higher temperatures, stronger winds and more erratic rainfall patterns (WMO, 2003a). If drought increases in a certain region, this could result in shifts of entire vegetation zones. If the number of people relying on the land in those areas remains the same, drought will enhance the risk of desertification, and adapted land management that reduces vulnerability to more erratic rainfall and drought will be needed.

Livestock keeping is traditionally an important economic activity in many dryland areas. When the land is non-degraded, grazing can be sustainable as long as livestock numbers are relatively low. But in many of the world's drylands, rural populations have grown substantially over the last decades, leading to increased livestock numbers. At the same

time, much former rangeland was converted into cropland. When populations and land pressure increase, grazing may lead to degradation of the rangeland vegetation, and soils can become prone to wind and water erosion processes. Overgrazing often occurs around wells or other places where the herds gather for drinking. This somewhat negative view of livestock grazing as a cause of serious vegetation degradation was reconsidered during a conference on soil fertility management in West Africa (Renard et al., 1998). The meeting concluded that “livestock are no longer described as agents of destruction but instead as agents of positive change. Rather, livestock is a crucial and integral part of the soil fertility cycle; principal vectors of nutrient redistribution across the landscape” (Webb, 1998). Hence, in many cases livestock grazing should not be blamed for causing desertification. Livestock keeping is an integral part of the land use in drylands, and only contributes to land degradation if the animal numbers exceed the threshold for sustainable use of the land. The latter may vary from location to location, depending on soils, climate and land management practices, and it is therefore difficult to determine when and where overgrazing is a serious problem.

Another factor that has been blamed for causing desertification is the removal of natural vegetation by local communities. Wood is needed for construction and for fuel, and growing population numbers increase the demand for wood. Also, the expansion of cropland has often caused clearance of trees and shrubs. But again, the destruction of natural vegetation by local communities is a more complicated issue than previously thought. While deforestation for fuelwood and charcoal production can have serious effects, recent research has shown that these effects are usually confined to densely populated settlement areas (Darkoh, 1998). Little evidence exists to suggest that rural household energy consumption is responsible for large-scale deforestation. Instead, it is the urban demand, usually for charcoal, that is responsible for deforestation of large rural areas. The economic value of charcoal makes it an interesting commodity for entrepreneurs who can derive income from its production and distribution (Darkoh, 1994).

It is tempting to conclude that an expanding rural population is the ultimate driving force behind vegetation degradation and desertification. The dependence of more people on the resources in an area exerts more pressure on those resources. Sometimes the pressure is indirect, such as in the case of a high demand for charcoal in urban areas. But the causes of desertification are complex, and

the relationship between population growth and desertification is not clear-cut (UNCCD, 2005). Other factors can be of equal importance. For instance, poverty prevents people from investing in improved land management and rehabilitation, often resulting in soil-mining practices. Also, national policies may be more oriented towards cash crop production than towards maintaining the self-sufficiency of agricultural production systems in many dryland zones. Other human factors may also contribute to desertification problems. Examples are unfavourable land tenure arrangements, which may lead to insufficient investments in the land, or war zones, which can cause large-scale migration and the establishment of refugee camps, such as in Darfur, western Sudan, where thousands of people fled the country and settled in refugee camps in neighbouring Chad. Such concentration of many people in a small area places great pressure on the surrounding land, especially when wood is collected for fuel and construction material.

Basically, the human causes of desertification are not fully understood. Changing paradigms and varying views among researchers mean that there is no consensus yet on how human factors play a role in desertification (Darkoh, 1998). According to Geist and Lambin (2004), a limited suite of recurrent core variables, of which the most prominent are climatic factors, economic factors, institutions, national policies, population growth and remote influences, drive desertification. These factors give rise to cropland expansion, overgrazing and infrastructure extension. For each location, a set of causal factors, in combination with feedback mechanisms and regional land use, make up specific pathways of land change that could trigger desertification.

Desertification can be considered and studied at different spatial scales, varying from arable fields (microscale) to the scale of entire nations (macroscale). When studying desertification at those different spatial scales, several processes may act as the causative factors driving desertification. In addition, indicators of desertification may depend on the scale that is considered. Table 14.3 summarizes major causes and indicators of desertification at three different spatial scales.

14.2.3 **Distribution of areas affected by desertification and relative importance of causes**

Arid zones occupy a diverse range of regions on Earth and are not restricted by latitude, longitude

Table 14.3. Desertification causes and indicators at different spatial scales

<i>Spatial scale</i>	<i>Desertification</i>		
	<i>Natural causes</i>	<i>Human causes</i>	<i>Indicators</i>
Macroscale (2 000–10 000 km)	Global climate change Increasing drought Shift of vegetation zones	Large-scale migration Population increase	Land use changes Reduced vegetation cover
Mesoscale (2–2 000 km)	Local climate change Disturbed rainfall patterns Increasing temperatures	Population increase Forced migration Settlement of herders Deforestation Urbanization	Reduction in forest cover Decrease in grasslands Increase in cropland Declining yield statistics Sediment load in rivers Duststorm frequency
Microscale (<2 km)	Erratic rainfall pattern Increased temperatures More extreme events Disturbed water balances Increased erosion	Poor land management Bad irrigation practices Soil nutrient depletion Tree removal Overgrazing	Poor vegetation cover Low crop yields Water erosion features Wind erosion features Crusted soils Bare soils

or elevation (see Figure 14.1). For example, China has both the highest desert, the Qaidam Depression at an altitude of 2 600 m, and one of the lowest deserts, the Turpan Depression, at 150 m below sea level. This ubiquitous distribution of arid regions indicates potential widespread vulnerability of environments to desertification processes from various human and natural factors. Figure 14.2 provides at least some indication of the potential vulnerability of areas to desertification and its global pattern

(after USDA-NRCS, 1998). There are many uncertainties regarding the extent, causes and seriousness of desertification, however. For example, in terms of desertification vulnerability, what criteria should be used to identify vulnerability to desertification? Emphasis, for the environmental scientist, is usually centred on physical processes, such as potential for wind erosion, water erosion or changes in vegetation cover. For social scientists investigating desertification, however, human factors such as

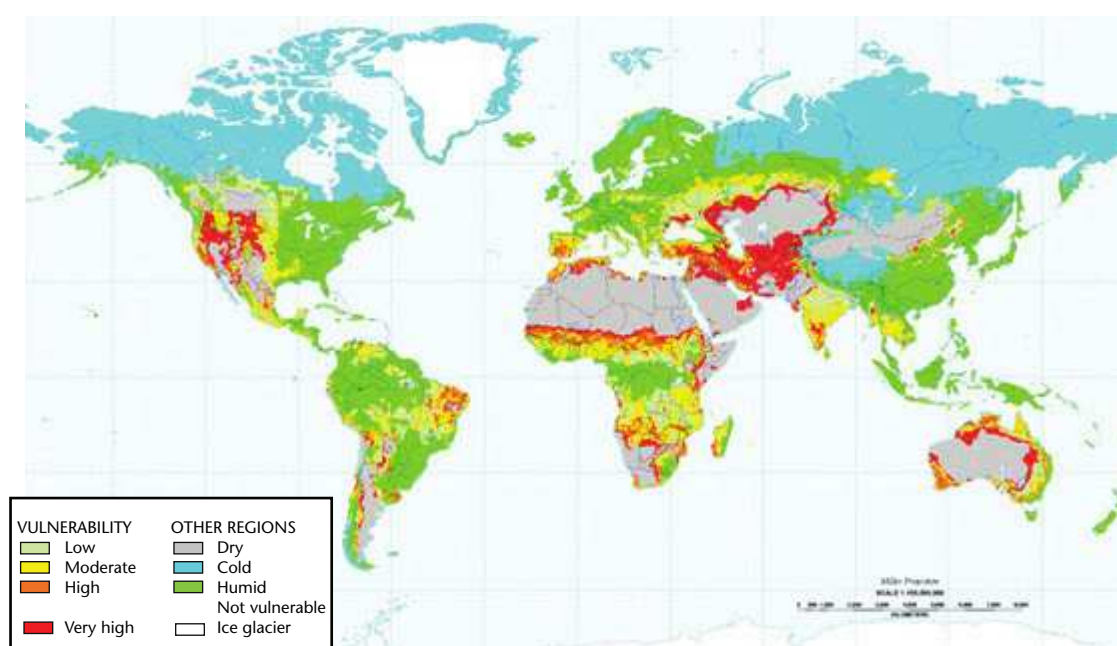


Figure 14.2. Global distribution of desertification vulnerability based on reclassification of the global soil–climate map and global soil map (USDA–NRCS, 1998)

political stability, demographics, poverty, market and trade systems, and technological utilization also affect processes of desertification and are normally absent from maps of desertification vulnerability. Indeed, despite large global assessments and international policies that have been initiated and developed in response to desertification (for instance, the Global Assessment of Human-Induced Soil Degradation (GLASOD), the United Nations Environment Programme (UNEP) and UNCCD), the phenomenon is still poorly documented and largely unmeasured. The extent and severity of desertification, vulnerable locations and the dynamics of desertification under future climate change scenarios are poorly understood at the global scale (Dregne, 2002). Furthermore, previous global assessments have been restricted to a large extent by disagreement over the definition and criteria for scientific investigation of desertification. A lack of synthesis among scientific disciplines regarding the complexity of causes and effects of desertification has also limited understanding of desertification, in terms of both natural and anthropogenic factors. Such institutional and scientific limitations have hampered policy development and planning for mitigation in areas experiencing desertification, and measures to reduce desertification risk in locations vulnerable to land degradation. A more recent global programme on land cover change – the Millennium Ecosystem Assessment (MEA) – has attempted to provide a more focused assessment of land cover change to meet the needs of decision-makers, government bodies and the public. The MEA has been charged with providing scientific and practical information for the sustainable management of ecosystems for human well-being. Its approach differs in many respects from previous global programmes in that it is performing multiscale and diverse assessments of land cover change, from the village level to a global scale. In addition, findings conducted at a given scale are informed by the assessments at other scales, which further emphasizes the diverse range of causes associated with land degradation.

While the causes of desertification are numerous and complex, one can conclude that desertification is driven by a limited group of core variables, which are above all climatic, technological, political (both institutional and policy-based) and economic factors. While drylands exist naturally because of background environmental conditions (such as atmospheric circulation patterns or sea surface temperatures), additional influences of human-induced land degradation (including deforestation, overgrazing, and salinization in irrigated areas) or changes in climate encourage desertification

through expansion of dryland ecosystems in marginal areas. Therefore, the relative importance of these natural and anthropogenic factors in affecting the global distribution of desertification can vary and is dependent upon pressures faced by people and agricultural systems in a particular location. To highlight this, two examples of the relative importance of different factors influencing the distribution of desertification in different areas of the Earth (Southern Africa and northern China) are described below:

- (a) Southern Africa: Relative impacts of changes in aridity, temperature and rainfall can alter the extent and seriousness of desertification. Arid regions are principally formed as a result of atmospheric circulation, through development of semi-permanent high-pressure systems formed by cool descending air from the poleward flow of air from the Equator (around 30° north and south latitude). In the context of climate change, changes in patterns of atmospheric circulation may intensify and broaden desert areas, resulting in an expansion of desert-type conditions. For example, episodes of aridity and changes in rainfall variability on the African continent linked to fluctuations in large African desert basins (such as the Kalahari and Namib deserts) have been shown to be connected with changes in sea surface temperatures, influencing both atmospheric moisture content and the strength of the African monsoon (Stokes et al., 1997; Washington et al., 2003). Such changes in aridity driven by sea surface temperatures in the tropical Atlantic have been identified with large-scale changes in African vegetation and episodes of desertification (Scheffuss et al., 2003). Therefore, relative changes in sea surface temperatures as a result of future climate change or variability may affect arid regions controlled by such teleconnection mechanisms, and result in changes to vegetation cover and aridity for agricultural systems.
- (b) Northern China: From the point of view of desertification in the arid and semi-arid regions of northern China, population pressure, intensive agriculture and industrialization, combined with natural processes of wind and water erosion, have affected spatial distributions of desertification (Yuxiang and Yihua, 1993; Zhenda and Wang, 1993). Research by Zhenda and Wang (1993) indicates that since the mid-1980s annual spread rates of desertified land have varied between 2 and 10 per cent of the total area of dry farmland areas and grasslands in northern China. Agropastoral regions, desert steppes and marginal zones (such as oases and

inland rivers) have experienced expanding desert conditions with up to 40.5 per cent of the land area classified as desertified. In particular, open coal mining has aided extreme and rapid desertification of the Shenfu region, with the total area of desertified land in the Shenfu coalfield estimated at 62 per cent.

Further examples of the distribution of desertification and the relative importance of its causes can be seen in salinization in the Middle East (for example, Sombroek and Sayegh, 1992) and in the anthropogenic and natural effects in the Sahel region of Africa (for example, DECARP, 1976; Kassas, 1991; Hulme, 2001).

14.3 **DRYLAND SURFACE CLIMATE AND AGROMETEOROLOGICAL PRACTICE**

14.3.1 **Understanding the dryland surface climate**

Desertification involves actions that occur at the Earth's surface. The surface climate is an integral component of the surface environment that both shapes and is shaped by land degradation (Williams and Balling, 1996; WMO, 2005). Surface climates are largely characterized by exchanges of moisture or water, energy and momentum (for instance, wind) occurring at or near the Earth's surface. These events play key roles in the physical processes of desertification.

14.3.1.1 **Water in the surface environment**

Water movement within the near-surface dryland environment can be described by the terms of the water balance equation (see 14.2.3) (WMO and UNEP, 1983; Mather, 1984; WMO, 1992; Thompson, 1999). Rainfall is the chief form of precipitation in drylands, although moisture from fog (Seely, 1978) and dew (Evernari, 1985) can be a significant source in some areas. Precipitation variability is high in many dry environments and episodes of drought alternate with periods of normal and above-normal precipitation. Some drylands are even subject to seasonal flooding. The result of these factors is that vegetation and the accompanying erosion-thwarting leaf litter tend to be sparse. With little organic matter added to the soil, humus is largely unavailable to maximize soil moisture retention or to promote binding of individual soil particles into aggregates that more fully resist erosion. In addition, low levels of soil aggregation reduce the proportion of large pores in soil that aid water infiltration and

prevent erosive overland flow. Thus, the erosion potential of drylands is high. Any actions by humans that reduce the vegetation cover or compact the soil decrease water infiltration and increase overland flow, thus raising the susceptibility to land degradation.

Rainfall, especially the high-intensity rainfall that may occur in drylands during severe thunderstorms, is the most important contributor to erosion (WMO, 2005). Heavy rainfall has a greater impact at the start of the growing season, when less protective vegetation is present. The force of heavy rainfall may act to dislodge soil particles, which then may be carried away in overland flow. Small, light soil particles are more easily moved, and when transported in sufficient quantities in storm events, may later act to seal the soil surface. In this process, fine-grained clay and silt particles clog the surface. A surface crust then develops as the soil dries (Farres, 1978; WMO, 2003b). This process further reduces infiltration of water into the soil. High rates of erosion reduce the soil profile depth, in turn reducing the total amount of soil moisture that can be stored. This means that the land becomes more prone to drought and floods.

Land degradation can occur either during drought or wet periods. Drought may result in increased wind and water erosion as a result of vegetation loss, even as agricultural and other economic demands on the land remain. Pressure on better-watered land may increase during drought, causing land degradation that may become highly apparent when drier times return. During wetter periods, high rainfall can erode poorly vegetated or damaged soils. The tendency is to increase agricultural production during wetter periods, again with consequences that manifest themselves when rainfall declines (Gonzalez Loyarte, 1996).

Surface evaporation from dryland soils may result in soil salinization – the accumulation of salts at the soil surface and in the root zone. Dryland soils are naturally high in salt content due to low amounts of percolating soil water available to leach the salts out of the soil layer. Human-caused salinization may occur due to (Szabolcs, 1976):

- (a) Introduction of additional salts to the soil layer through irrigation water;
- (b) An increase in the height of groundwater, which then permits transport of salts from deeper soil layers to the root zone through the upward motion of groundwater under capillary suction;

- (c) Ineffective drainage of irrigated soils, which impedes loss of soil salts through leaching.

The consequence of salt build-up is the loss of protective vegetation and agricultural production. Salinization of water supplies and soils along coastal areas, particularly for small islands, may become problematic with a potential climate warming and sea-level rise.

14.3.1.2 Energy in the surface environment

Energy interactions in the surface environment can best be summarized through the energy balance equation for the Earth's surface,

$$(Q + q)(1 - \alpha) - (I_u - I_d) - H - LE - G = 0 \quad (14.1)$$

where Q and q are the direct and diffuse portions, respectively, of short-wave radiation reaching the Earth's surface; α is the surface albedo (fraction of incoming short-wave energy reflected from the surface); I_u is long-wave radiation emitted by the Earth's surface towards the overlying atmosphere; and I_d represents long-wave radiation emitted from the overlying atmosphere towards the Earth's surface. The balance of these radiative terms (net radiation) determines the amount of energy available at the surface for heating and evapotranspiration. Thus, H represents the sensible heat flow between surface and atmosphere, LE represents latent heat flow (incorporating the energy involved in evapotranspiration and condensation) between surface and atmosphere, and G is the ground heat flow. Positive terms represent energy directed towards the Earth's surface. Photosynthesis is assumed to be negligible.

Direct and diffuse radiation together are typically high in most drylands due to the low cloudiness of such environments. Net radiation is also high, even though albedos for desert soils are higher than for most other vegetated surfaces (Oke, 1988). The high dryland albedo is partially attributed to the lack of a well-developed vegetation canopy, the structure of which contributes to particularly effective interception of incident short-wave radiation.

High net radiation values mean more energy for work at the surface, such as heating and evapotranspiration. Evapotranspiration rates are usually low, however, owing to the limited environmental moisture. What little water exists is rapidly evaporated, leaving less stored soil moisture for plant use. Due to limited water availability, most

energy is partitioned into heating of air and soil. High surface soil temperatures may result in cracking of clayey soils, leaving both soil surface and subsurface open to erosive forces.

Human use of drylands may result in a modification of the surface energy balance. A significant change of albedo may occur due to changes in land use, removal of vegetation, or degradation of soil. Irrigation is used to enhance soil moisture for agriculture, resulting in increased evapotranspiration and lower surface temperatures. Agriculture, soil degradation, loss of vegetation cover and burning of various fuels release carbon dioxide and other trace gases into the atmosphere, which may intensify incoming long-wave radiation from the atmosphere. Various activities that promote wind erosion can result in a substantial load of wind-blown dust, with implications for stability of the lower atmosphere (Williams and Balling, 1996; WMO, 2005). Remotely sensed imagery has revealed that Saharan dust is sometimes blown across the Atlantic Ocean to the Caribbean Islands, where it has been linked to human illnesses, algal blooms and the decline of the coral reefs. Thus, impacts of desertification may extend beyond the source region with important global ramifications.

14.3.1.3 Momentum in the surface environment

The mean wind speed at the near surface can be described as

$$U(z) = (u_*/k) \ln(z/z_0) \quad (14.2)$$

where $U(z)$ is the mean wind speed at height z , k is von Kármán's constant (about 0.4), and z_0 is the roughness parameter, a measure of the aerodynamic roughness of the surface. The value u_* represents the friction velocity, which is equal to the square root of the sheering stress divided by the air density.

Surface winds may act as a surface erosive force or modifier of the terms of the energy balance. With vegetation removal, changes to the surface roughness may result in enhanced wind speeds or mechanical turbulence, each of which could act to increase transport of sensible and latent heat into the overlying atmosphere. In addition, advection (horizontal transport) of hot air over irrigated fields in drylands may create an oasis effect in which downward transport of energy can result in a considerable evaporation of irrigation water from fields. Finally, wind can act

as an erosive force, carrying soil and dust into the overlying atmosphere. Wind-generated dust storms can significantly block incoming solar radiation to the surface, resulting in a significant drop-off of net radiation available for heating and evapotranspiration. The lighter soil fractions (such as clay and silt) are preferentially eroded, leaving behind a coarse-textured soil (high in sands and pebbles) that has a smaller soil moisture-holding capacity.

14.3.2 Application of agrometeorological practices to the surface environment

Combating the root causes of desertification often requires addressing interrelationships among climate and economic, political and social drivers of land degradation. While amelioration of problems of a socio-political or socio-economic nature may require long-term efforts, a variety of readily available agrometeorological methods to address the biophysical concerns of desertification at the farm and local levels are possible and are discussed in the present publication. Other strategies that are implemented on regional to international scales, including drought preparedness, early warning and agroclimatic mapping, are covered in 14.4, 14.6.5 and 14.6.6.

The aim of agrometeorological practice as applied to the surface environment is to maintain the

surface climate within a range of conditions to promote:

- Protection of the soil surface through maintenance of good soil structure and resistance to erosion;
- Efficient use of available rainwater and snow-melt, with consideration given to the advisability of surplus water storage;
- The success of natural plant and crop productivity;
- High carbon and nutrient maintenance within the plant biomass, leaf litter and soil matrix;
- Ecosystem stability and biodiversity.

As implied in these objectives, prevention of land deterioration is preferable to reversal of already-degraded land. Desertified land may be resistant to treatment measures. Furthermore, the costs of desertification are high, considering the expense of rehabilitation efforts and loss of ecosystem services and economic productivity (Millennium Ecosystem Assessment, 2005). A variety of agrometeorological techniques may be applied to prevent and treat soil erosion, improve water use efficiency and make appropriate land-use choices (Table 14.4). Optimal interventions for particular places must take into account local needs, traditions and environmental knowledge, and involve recipient communities in the decision-making process. In such an approach, the agrometeorologist is seen as more of a facilitator than a prescriber of solutions (Scoones, 1997).

Table 14.4. Examples of mitigation strategies employed over various scales

<i>Macroscale (2 000–10 000 km)</i> <i>International strategies</i>	<i>Mesoscale (2–2 000 km)</i> <i>National/ regional strategies</i>	<i>Microscale (<2 km) Practices of</i> <i>communities or individual farmers</i>
United Nations Convention to Combat Desertification (UNCCD): International cooperation in research, education and combating desertification	National action programmes: National long-term strategies and practical measures to support UNCCD	No-till farming
Inter-Agency Task Force on Disaster Reduction: Statement on short-term climate variability/ climate extremes	Vegetation policies: Laws prohibiting the cutting of vegetation in northern Burkina Faso	Crop rotation
European Commission Thematic Strategy for Soil Protection: Measures for combating soil erosion and policy options for prevention and remediation	Windbreak schemes: Shelter belts of scattered trees and grasses over a large area to settle wind-blown sand in central Sudan (Stigter et al., 2005b)	Cover crops/legume fallows
	Reforestation schemes: Development of forest reservations and roadside avenues in Israel on degraded lands	Agroforestry schemes: In Kenya's Laikipia District, <i>Grevillea robusta</i> trees and <i>Coleus</i> hedges, providing shade, wind protection and increased water infiltration, were grown with maize and beans (Stigter et al., 2005b)
	Crop/livestock policies: Prohibition in Syria of barley production where rainfall is less than 200 mm; restriction of numbers of grazing livestock	Local water resource projects: When removal of gravel from Malir River, Pakistan, resulted in decreased groundwater recharge and crop productivity, public awareness was promoted and a traditional water reserve expanded

Soil conservation techniques can substantially reduce water erosion. Details of the procedures can be found in WMO (1992), Toy et al. (2002), Troeh et al. (2003) and Morgan (2005). Water harvesting, contour farming, terracing and strip cropping act to reduce the speed of surface runoff and thus erosional forces on slopes, while increasing soil moisture infiltration and storage. A variation of these techniques using local knowledge by farmers in western Africa involves placing branches and stones on fields to slow runoff and increase infiltration. In South-East Asia, hedges of tall, deep-rooted perennial grasses are planted to create a living wall on slopes. Erosional forces and rain-drop impact can be reduced through the accumulation of crop residues on the soil surface, and this is one aim of reduced or no-till agriculture. In South America, the dibble stick is used to punch holes into the ground for planting seeds, leaving the rest of the surface cover undisturbed. Organic matter on the surface means increased soil humus content, fertility, and soil moisture infiltration and holding capacity.

Maintenance of soil fertility is important in providing an ample vegetation cover to protect the soil surface. While organic fertilizers have the benefit of providing both nutrition and organic matter for good soil structure, they are sometimes difficult to obtain in drylands. Integrated soil fertility management supports combined use of organic and inorganic fertilization, as well as policies that promote successful economic environments and conservation incentives for the farmer (Breman and van Reuler, 2000). Mixed farming based on both crop and livestock production promotes soil fertility through easy application of livestock manure to nearby cropland. Crop rotation prevents depletion of key soil nutrients and may even replace some lost soil nutrients.

Farmlands in windy regions may be protected from wind erosion by tree shelterbelts or other windbreaks made from grasses and other natural materials. Wind speed reductions to the lee of the structure are established over larger areas when the windbreak is taller and porous. Soil moisture is conserved as a result of reduced surface evapotranspiration (Rosenberg et al., 1983; Oke, 1988). Even scattered trees may arrest erosional processes contributing to desertification (Stigter et al., 2003, 2005a). Design rules for success of protective shelterbelts have been determined by Al-Amin et al. (2005). Windbreaks of various forms can also stabilize moving sand dunes, as have boulders, sand fences made from crop residues, and straw grids. Where irrigation water is

available, shrubs can be planted on the dune's lower windward side, reducing wind speeds and blowing sand. Higher wind speeds at the dune top will produce a flat surface on which trees can be planted for stabilization (Walker, 1996). Stigter et al. (2002) have reported on the use of vegetation in local solutions to a variety of problems caused by wind. Careful consideration should be given to the selection of tree, shrub and grass species that can withstand drifting sand in deserts; a comparison of the performance of various types is provided in Al-Amin et al. (2006). Elephant grass (*Pennisetum purpureum*) has been planted on hillsides of East Africa, providing both forage and protection of soils.

New and traditional programmes of establishing vegetation to support soil quality, ecosystem services, raw material availability and diverse livelihoods have been employed, especially in Africa. Renewed interest in agroforestry means that trees are increasingly left or planted in fields where they are managed along with crops and livestock for their various resources. One tree species that is particularly valuable is the *Acacia albida*, which returns nitrogen to the soil and provides shading, moisture, browse and fruit. The shea butter tree (*Vitellaria paradoxa* ssp. *nilotica*) protects soils, while the seeds are used in making oil for cooking, cosmetics and chocolate (McIntosh, 2004). The Eden Foundation promotes the cultivation of perennial drought-tolerant, edible plants in Niger through a voluntary seeding programme (Eden Foundation, 1999). A Global Environment Facility–United Nations Development Programme project advances community-based integrated ecosystem management (IEM), incorporating community co-management of protected areas and community nature reserves in Senegal (Global Environment Facility, 2002). Salt- and drought-resistant crops and native vegetation with wide genetic variation provide good soil cover under numerous environmental conditions. Legumes restore soil nitrogen. Agroclimatic mapping assures that planted crops are likely to withstand prevailing climatic conditions. Loss of existing vegetation can be prevented through the promotion of careful land-use management and the use of alternative fuels, construction materials and livelihoods.

Careful management of water resources in drylands goes hand in hand with protection of soil and vegetation. Drip irrigation systems may reduce erosion from the spread of irrigation water, while reducing evaporative losses. Rainwater harvesting (Mather, 1984; Hatibu and Mahoo, 2000; Lancaster, 2006, 2007), surface and subsurface water storage

(Ludwig, 2005), floodwater spreading and fog collection maximize available water supplies. Revegetated upstream areas promote groundwater storage and streamflow during drier times. Irrigation applications should be carefully planned to avoid salinization and waterlogging. Water budgeting techniques that track soil moisture content may be useful for determining the need for and appropriate amounts of irrigation applications (Mather, 1978; CIMIS, 2009). Planting of deep-rooted trees may arrest salinization associated with rising water tables caused by excessive irrigation or vegetation removal. Subsurface drainage of waterlogged soils may be appropriate in other situations.

Agricultural techniques aimed at effective energy management through manipulation of the surface energy balance are sometimes applied to desertifying lands. Such methods as albedo control and mulching can reduce energy income and surface evapotranspiration. More detailed discussion is available in Rosenberg et al. (1983) and Lowry (1988).

Conservation agriculture (CA) is another approach to long-term protection of agricultural yields that is not focused on particular technologies per se, but on a series of conservation objectives. CA seeks to optimize, rather than maximize, yields and profits in order to “achieve a balance of agricultural, economic and environmental benefits” (Dumanski et al., 2006). This approach to sustainable agriculture combines modern technology that maintains or enhances the ecological integrity of the soil with traditional knowledge to enable adjustment to local areas and changing conditions. In general, CA promotes zero tillage, careful management of farm residues and wastes, integrated pest management, crop rotations, cover crops, balanced and precision applications of farm chemicals, legume fallows and agroforestry. Benefits include a reduction in water/soil pollution, external inputs, fossil fuel costs and soil erosion, with an enhanced soil water economy and soil biological health. Such an approach works effectively against forces of desertification.

14.4 **RANGELAND MANAGEMENT**

The material in this section has been drawn largely from the work of Sombroek and Sene (1993) and FAO (2004). Based on the classification of farming systems in developing regions specified by FAO/World Bank (2001), most of the farming systems in drylands fall into the category of rainfed farming systems in dry, low-potential areas. These may be characterized by

mixed crop–livestock and pastoral systems that merge into sparse and often dispersed systems with low productivity or potential because of extreme aridity. Rangelands are predominantly pastoral systems, of which the main types in drylands are:

- (a) Nomadic/transhumance pastoral systems: Nomadic systems involve more or less the continuous movement of livestock with no set pattern. Herding is with drought-hardy livestock, such as camels, goats and sheep, and in some cases a few cattle. Transhumance is typified by the movement of livestock along more predetermined routes leading from wet-season grazing in arid zones to fallow lands in semi-arid areas in the dry season.
- (b) Sedentary livestock systems: Farmers who are mainly concerned with rainfed sedentary cropping in semi-arid areas practice this system of agriculture. Livestock are grazed on fallow or communal land close to the village and these areas can be intensively grazed.
- (c) Ranching: Ranching is typical of highly commercial, market-based pastoral systems in the drylands of developed nations, such as the United States and Australia, though not exclusively. The development of lucrative markets in countries such as Argentina, Brazil and Nigeria has encouraged full-scale ranching systems and trails to established ranches in the savanna zone.

In the last 50 years, traditional agricultural practices in rangelands have been either overwhelmed or discouraged in favour of non-traditional, large-scale, capital-intensive agricultural systems (such as ranching) originally developed for more humid or temperate climates. In addition to their exposure to the effects of rapid population growth, rangelands have come under increased pressure from new systems of agricultural practice, leading to rangeland degradation and desertification. An assessment undertaken by UNEP in 1990/1991 indicated that the largest area of degraded rangelands lay in Asia and Africa. Overall, estimates indicate that 3.333 million hectares, or about 73 per cent of the total area of rangelands in the world's drylands, are affected by degradation, mainly through vegetation removal accompanied by soil erosion processes. The continuing and accelerating course of degradation in rangelands shows many common features, including:

- (a) Deterioration in quantity, quality and persistence of native pasture (for example, diminution of plant cover, invasion of shrubs of low pastoral value and reduced germination rates);
- (b) Structural changes in plant cover (for example, the loss of shrubs and trees through collection of fuelwood and agricultural deforestation);

- (c) Changes in soil surface conditions (such as soil compaction, reduced organic matter, deterioration of soil-plant-water relationships);
- (d) Additional processes of sand drift (such as dune migration and deflation, leading to further destruction of vegetation).

The two main causes of rangeland degradation in drylands are overgrazing and encroachment of rainfed sedentary agriculture or ranching, aggravated by climate factors (rainfall and temperature). Other factors such as government policies and new technology are important, too, usually heightening the impact of overgrazing and increasing sedentary agriculture on rangelands. For example, overgrazing occurs when livestock density becomes excessive and too many animals are allowed to graze on the same area of rangeland. As plant cover is degraded, soil erosion becomes increasingly serious. Livestock density can increase in a number of ways. First, herd sizes grow too large during wet years to be sustained during drier periods, or they may expand as a result of improved veterinary care or heavily subsidized feed prices. Second, the area available for grazing decreases as nomads are displaced by sedentary farmers owing to pressures such as expanding rural populations or government policy, which can include resettlement schemes that result in the concentration of livestock around certain features such as villages, or the sinking of permanent boreholes. Finally, traditional controls on grazing break down due to growing urban populations, economic development and market-oriented agriculture. Furthermore, many of these social, economic and political pressures contributing to rangeland degradation may be exacerbated through natural factors such as frequent drought, periods of prolonged desiccation and climate change.

Control of desertification by means of proper rangeland management is a priority. Both management of rangelands and rehabilitation of degraded rangelands should rely on sound ecological and integrated management of natural resources, using both indigenous knowledge of the ecosystem and sensitive scientific applications. Adapted technology, economic planning, and legal and financial measures should also support management of degraded rangelands, underpinned with improved institutional policy and planning. Agrometeorology applications for rangeland management play an important role through the provision of localized and international expertise, with an emphasis on local practices using favourable microclimates, which can be created by simple and inexpensive devices. Conservation agriculture (such as that

advocated by the European Conservation Agriculture Federation, for instance) can play an important role in protecting rangelands.

At the local level, practical advice for management of rangelands parallels that provided in 14.3.2. Techniques addressing domestic and stock water supplies, runoff use (ponding, berms), flood irrigation schemes (syphoning), wind erosion reduction (afforestation, mulching), and grassland and savanna management (seed collection, sowing, planting, protection) should be provided in conjunction with local knowledge. For example, in parts of Niger, soil fertility is viewed much more holistically by farmers than by agronomists, who disaggregate influences on crop productivity into factors such as water supply, water intake, wind stress, individual nutrients and soil structure (Osbahe and Allen, 2002). Local farmers are aware that productivity of different soils is determined by a combination of factors, but do not rationalize it in the same way as an agronomist. Hence, in a wet year, clay-rich soils in depressions may be waterlogged and unproductive, while sandy soils, where managed adequately, yield acceptable crop returns. Clay-rich soils at better-drained sites may be very productive and responsive to inputs of manure or fertilizer. The maintenance of appropriate livestock densities and rotational grazing systems also prevent overgrazing and consequent soil erosion.

At an international level, agrometeorology can provide support for evaluating, forecasting and predicting current, near-future and future changes in natural conditions, and this helps furnish information that is used to target rangeland degradation through a number of different management techniques. From a meteorological point of view, drylands have long been undergoing continual transformation in response to environmental changes (for example, Washington et al., 2003), and traditional forms of agriculture have responded. Dryland environments are now widely recognized and accepted as having a complex history of change, based on event-driven non-equilibrium dynamics rather than gradual, linear change (Scoones 2001; Sorbo, 2003). Therefore, such scientific evaluations and information should provide for event-driven policies (Reenberg, 2001), as planning in such an environment will be challenging. Instead of simplified, standardized approaches and predefined technical solutions, rangeland management will need to offer an array of technological and management options from which farmers can choose according to their needs.

Specific agrometeorological techniques are available for the management of dryland livestock rangelands. Many agrometeorological applications for sustainable management of rangeland farming systems are contained in a recent WMO publication (WMO, 2004). Many of the applications remain simple indicators for assessing and monitoring the current status of rangelands, but these simple techniques for evaluation become more powerful when combined with quantitative mathematical models and Geographical Information Systems (GIS).

Evaluation of the water and wind erosion hazard in rangelands can be undertaken using simple soil erosion relationships that incorporate major soil loss factors. The application of the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1994) may be undertaken in order to understand soil erosion for agricultural application using the following equation:

$$A = R K L S C P \quad (14.3)$$

where A is the soil loss per year (t/ha/yr), R represents the rainfall-runoff erosivity factor, K is the soil erodibility factor, L represents the slope length, S is the slope steepness, C is the cover management and P denotes the supporting practices factor.

14.5 MEASURES OF DESERTIFICATION AND RELATED TECHNIQUES

In 1977, the United Nations Conference on Desertification (UNCOD) gave legitimacy to the term desertification as a synonym for dryland degradation. Since then, four attempts to assess the global extent and severity of desertification have been made (Dregne, 2002). The first World Map of Desertification was prepared for UNCOD by FAO, the United Nations Educational, Scientific and Cultural Organization (UNESCO), and WMO. This map was basically a vulnerability map and did not show severity of actual land degradation. This initial desertification map was improved upon three times in succession. The fourth attempt by UNEP was an analysis of human-induced soil degradation (but not vegetation degradation) for arid and humid regions (Oldeman et al., 1990). It was based on expert knowledge from soil scientists around the world, and not on actual data of soil degradation status. This Global Assessment of Soil Degradation map has been much criticized, but it is by far the best representation of global soil degradation (Dregne, 2002). It also provided the basic data for

the UNEP World Atlas of Desertification (UNEP, 1992). The second edition of this atlas (UNEP, 1997) was improved by shifting the attention from soil degradation alone to include vegetation degradation as well.

A general problem with these assessment studies is the lack of high-quality data and a poor definition of desertification indicators. Many dryland areas are (and have always been) subject to degradation processes such as wind and water erosion. Hence, an observation of wind erosion in a certain area is not sufficient to conclude that the area is experiencing desertification. Only when the frequency of duststorms rises and the magnitude of the storms increases is there a clear indication of ongoing land degradation. Obviously, such analysis requires detailed data on the frequency and size of duststorms, but these data are rarely available. A different indicator that has been used to identify land degradation is crop yield data. In the Sahel, for instance, shrinking yields of pearl millet have been used to indicate soil degradation. But the data encompassed a decline in rainfall during more or less the same period and were perhaps more reflective of moisture shortages than soil degradation status. Also, decreasing yields could have been caused by a lack of fertilizer use, and thus the yield data did not necessarily indicate desertification.

The best possible indicator for desertification is probably the vegetation cover in an area. When persistent changes in vegetation cover are observed and more and more areas become barren, there is an indication of desertification. This indicator should be treated cautiously, however. The seasonality and variability of rainfall in drylands will also cause variability in vegetation cover. Timing of the vegetation observations is of crucial importance and should be done during the growth period, when vegetation cover is at its maximum. Observations should be related to the annual rainfall, as a drought year may have less vegetation cover than other, more normal years. Finally, it is important to compare the observed vegetation cover in a certain area with historic vegetation cover, which cannot always be done due to a lack of information.

Before the introduction of remote-sensing satellites, the assessment of land use, land cover, landscape features, soil characteristics and land degradation features was performed with the help of aerial photographs for the most part. These studies were usually complemented by detailed field observations to verify the different classes and their

distribution as derived from the photographs. Multiple sets of aerial photographs always were and in fact still are very useful to monitor land degradation problems in a given area, because of the generally high resolution of the photographs. Land degradation features such as gullies and barren, crusted patches are easily distinguished. The disadvantage of aerial photographs is the relatively small spatial extent the photographs cover, and the relatively high cost of ordering sets of good-quality photographs. Usually, people rely on whatever sets of photographs are available for an area, irrespective of the times at which the photographs were taken.

Since the early 1970s a great number of remote-sensing satellites have been launched with many different sensors and resolutions. The sensors can be divided into two classes. Optical systems measure the reflection of sunlight in the visible and infrared parts of the electromagnetic spectrum, as well as thermal infrared radiance. Radar imaging systems actively transmit microwave pulses and record the received signal (backscatter) (Vrieling, 2006). Optical remote-sensing systems have most frequently been applied in studies of land degradation. Depending on the type of study and the spatial scale, a choice has to be made from the many optical satellite systems. Some systems, like IKONOS and QUICKBIRD, have very high spatial resolutions (on the order of 1 m), but cover relatively small areas, albeit with much detail. Other systems, such as the LANDSAT 7 Enhanced Thematic Mapper (ETM) and SPOT 4, have lower spatial resolutions (on the order of 10–30 m), but cover much larger areas. Vrieling (2006) provides a thorough review of the available satellite remote-sensing sensors and how these different sensors have been used for water erosion assessment.

Satellite data can be used to directly detect land degradation features, such as duststorms (Figure 14.3), or the consequences of land degradation, such as polluted surface waters resulting from high sediment contents. Other features that can be detected from satellite images are (Lantieri, 2006):

- (a) Salinization patterns in irrigation schemes (salt appears as white patches);
- (b) Overgrazing features, such as low-cover grasslands around animal paths, for example;
- (c) Water erosion patterns of great size and over large areas (primarily gully erosion);
- (d) Burned areas or areas subject to bush fires.

In addition, it is possible to detect bare surfaces and land-use changes (through multitemporal analysis)

that may help to assess land degradation problems in a particular area.

Satellite remote-sensing imagery is especially useful for classification of vegetation cover. The most common index used for vegetation cover is the normalized difference vegetation index (NDVI), which is defined as the near-infrared reflection minus red reflection divided by the sum of the two (Tucker, 1979). When vegetation cover maps are created for different years, it is possible to determine the changes in land cover, which may indicate desertification. It is important that the maps be created for more or less the same time of the year, however, preferably in the late growing season, when vegetation cover is at its maximum. Also, it should be verified that moisture conditions at the times the various satellite images were taken were not widely divergent. A comparison of vegetation cover between a wet year and a dry year may lead to wrong conclusions about vegetation changes and possible desertification. This straightforward method of using vegetation cover maps to assess desertification is robust and rather accurate, but remains restricted to a physical state assessment of desertification. It does not look at driving forces, and therefore it identifies the problem, and may



Figure 14.3. Dust cloud moving over the Atlantic Ocean off the coast of Morocco (NASA Earth Observatory; image taken from the Terra-MODIS satellite on 25 July 2004)

assess its intensity, but does not provide guidance as to its solution (Lantieri, 2006).

Usually studies of land degradation combine satellite remote-sensing information with other spatial data, such as topography, soils and land use, into a Geographical Information System. A GIS enables analysis of combinations of different data layers, which may result in a better understanding of land degradation problems, causes and consequences. Also, within a GIS, modelling with relatively simple empirical and semi-empirical models can be done to determine the risk of land degradation in an area. For instance, Okoth (2003) used a simple logit regression equation that combines the parameters of slope and ground cover to determine water erosion risk in Kiambu District of Kenya. The ground cover and slope data were derived from remote-sensing imagery, while the erosion data for the regression analysis came from field studies. In the GIS, the regression model was used to determine the erosion risk in the entire area. A similar approach was used by Vrieling et al. (2002) to determine water erosion risk in the Colombian Eastern Plains. Instead of a simple erosion model, they used a decision tree for erosion classification. The decision tree combined relevant information on soils, slopes and vegetation cover, and was derived from expert knowledge.

14.6 **ACTIVITIES RELATING TO DROUGHT AND DESERTIFICATION**

14.6.1 **International activities: the role of WMO in the UNCCD and the United Nations International Strategy for Disaster Reduction**

Widespread international concern over the consequences of desertification came to the forefront in the late 1960s and early 1970s with the spread of the Sahelian drought. By the 1980s a significant area of sub-Saharan Africa had suffered enormous environmental, economic and social impacts. As a result, a United Nations Conference on Desertification was held in Nairobi in 1977. Products of the conference included the gathering and synthesis of the state of knowledge related to desertification, resulting in the paper “Desertification: An Overview” (UNCOD, 1977), and global and regional desertification maps of varying quality. A Plan of Action to Combat Desertification was adopted to “prevent and to arrest the advance of desertification and, where possible, to reclaim desertified land for productive use” (UNCOD, 1978). The

approach was one of “adaptation and application of existing knowledge”, using education in mitigation techniques and training programmes to address desertification. UNCOD was beset by funding and political issues, however (MacDonald, 1986). In 1991 the United Nations Environment Programme found that complications from desertification had increased since the implementation of the UNCOD Plan of Action.

The United Nations Conference on Environment and Development (UNCED), which took place in Rio de Janeiro in 1992, promoted a new holistic, integrated approach to the prevention of land degradation in susceptible drylands by encouraging sustainable development. As a result of the efforts initiated at this conference, an intergovernmental committee was established to create a legally binding treaty to address desertification. The United Nations Convention to Combat Desertification was adopted in Paris in 1994 and went into effect in 1996 with the signature of the fiftieth country. The heart of the UNCCD (<http://www.unccd.int/main.php>) is the development and implementation of National Action Programmes (NAPs). NAPs specify long-term strategies and practical measures to engage governments and local communities in combating desertification, to promote sustainable development and to reduce poverty in drylands.

Today, WMO supports the UNCCD through the application of the meteorological and hydrological sciences to agriculture and other human activities related to desertification. As such, WMO facilitates the “systematic observation, collection, analysis and exchange of meteorological, climatological and hydrological data and information; drought planning, preparedness and management; research on climatic variations and climate predictions; and capacity-building and transfer of knowledge and technology” (WMO, 2005). WMO’s Agricultural Meteorology Programme (AGMP) (http://www.wmo.int/pages/prog/wcp/agm/agmp_en.html) and Hydrology and Water Resources Programme (HWRP) (http://www.wmo.int/pages/prog/hwrrp/index_en.html) have been particularly involved in these efforts.

WMO is also a member of the Inter-Agency Task Force on Disaster Reduction (IATF/DR) for the International Strategy for Disaster Reduction (<http://www.unisdr.org/isdrindex.htm>). Composed of 25 United Nations, international, regional and other organizations, IATF/DR is the lead body responsible for creation of disaster reduction policy. Working Group 1 on Climate and Disasters is

chaired by WMO, and has chosen drought as a focus to promote working group interactions.

14.6.2 **Meteorological observing networks and monitoring of drought and desertification**

WMO is a specialized agency of the United Nations whose main role is to promote international cooperation in the provision and rapid exchange of information on weather, water and climate. WMO engages National Meteorological and Hydrological Services (NMHSs) in the development of long-term strategies for systematic weather, climate, hydrological and water resource observation; the exchange and analysis of data; and enhanced drought monitoring. These activities support Article 16 of the UNCCD, which stresses the importance of collection and coordination of relevant, timely data to further the monitoring, assessment and understanding of drought and desertification.

WMO coordinates a global network of meteorological observing platforms under the Global Observing System (GOS) of the World Weather Watch Programme. The network integrates some 10 000 land-based stations, 1 000 stations performing upper-level observations, 3 000 aircraft, 7 000 sea vessels and about 1 200 buoys and fixed marine platforms. The resulting 150 000 daily observations are enhanced with the addition of observations of 16 meteorological and environmental satellites. The newly formed WMO Space Programme has already improved satellite data access, utilization and products across WMO and its supported programmes. In parallel with the objectives of GOS, the World Hydrological Cycle Observing System (WHYCOS) (http://www.whycos.org/rubrique.php3?id_rubrique=2) focuses on measurement and collection of hydrological parameters through existing national/regional meteorological and hydrological stations. Additional specialized observations are made for atmospheric chemical constituents and various ocean and circulation measures through other specialized programmes. The Global Climate Observing System (GCOS) (<http://www.wmo.int/pages/prog/gcos/>), sponsored in part by WMO, seeks to provide the comprehensive observations required for monitoring, research and assessment of the climate system.

14.6.3 **Research**

WMO supports research by universities and international and national organizations related to

causes of climatic variations, interactions between climate and land degradation, and advances in climate prediction. Since the 1970s, Sahelian droughts have been studied to determine the possible causes, such as the impact of human modifications of the land surface and atmosphere on the energy balance of local and regional climates. Numerical model simulations of these interactions have been carried out for a large number of drylands across the globe. Many of these same objectives are being carried out at present under the Global Energy and Water Cycle Experiment (GEWEX) (<http://www.gewex.org>) of the WMO World Climate Research Programme (WCRP) (<http://wcrp.wmo.int/wcrp-index.html>; Sivakumar, 2005).

Drought conditions often appear in relation to variations in strength or displacements in the location of a number of large-scale features of the general circulation of the atmosphere. Accordingly, a number of WMO programmes advance the understanding and prediction of climate variability over seasonal to interannual timescales. Adequate representation in models of the processes that guide climate permits better decision-making by NMHSs across the globe in regard to the prevention of, response to, and recovery from drought and desertification impacts. Better understanding of El Niño–Southern Oscillation events is beginning to enable advance warning of drought on the order of seasons to over one year.

Two WMO activities in particular address climate variability and prediction. Climate Variability and Predictability (CLIVAR) (<http://www.clivar.org>) within WCRP hosts a number of projects related to drought, including evaluation of temporal and spatial precipitation patterns from general circulation models, causes of droughts and floods, and climatic feedback processes (Sivakumar, 2005). The Working Group on Tropical Meteorology Research of the WMO World Weather Research Programme (http://www.wmo.int/pages/prog/arep/wwrp/new/tropical_meteorology.html) seeks better understanding and prediction of tropical monsoons and droughts, and of the meteorology of semi-arid regions and rain-bearing tropical systems, as well as enhanced use of model tropical forecasts.

The Intergovernmental Panel on Climate Change (IPCC) (<http://www.ipcc.ch/>), established jointly by WMO and UNEP, evaluates peer-reviewed, published literature in assessing the risk of human-induced climatic change, and potential impacts and adaptation/mitigation strategies. According to the IPCC

Fourth Assessment Report (IPCC, 2007*a*, 2007*b*), the warming of the climate system is unequivocal. Eleven of the last 12 years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature. The 100-year trend (1906–2005) is 0.74°C. The linear warming trend over the last 50 years (0.13°C per decade) is nearly twice that for the last 100 years. At continental, regional and ocean-basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heatwaves and the intensity of tropical cyclones. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.

Projected warming in the twenty-first century is expected to be greatest over land and at the highest northern latitudes. For the next two decades a warming of about 0.2°C per decade is projected. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions. Drought-affected areas will likely increase in extent. It is very likely that hot extremes, heatwaves and heavy precipitation events will continue to become more frequent. Given these projections of future climate change, there will be increased land degradation owing to droughts and increased soil erosion owing to heavy rainfall events.

Carbon dioxide-induced climate change and desertification remain inextricably linked because of feedbacks between land degradation and precipitation. Water resources are bound inseparably to climate. Annual average river runoff and water availability are projected to increase by 10–40 per cent at high latitudes and in some wet tropical areas, and to decrease by 10–30 per cent over some dry regions at mid-latitudes and in the dry tropics. Soils exposed to degradation as a result of poor land management could become infertile as a result of climate change.

Climate change may exacerbate desertification through alteration of spatial and temporal patterns in temperature, rainfall, solar radiation and winds. The impacts can be described as follows:

- (a) Soil properties and processes, including organic matter decomposition, leaching and soil water regimes, will be influenced by temperature increase.
- (b) At lower latitudes, especially seasonally dry and tropical regions, crop productivity is

projected to decrease with even small local temperature increases (1°C–2°C).

- (c) Agricultural production in many African regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease.
- (d) In the drier areas of Latin America, climate change is expected to lead to salinization and desertification of agricultural land.
- (e) In Southern Europe, higher temperatures and more frequent drought are expected to reduce water availability, hydropower potential and crop productivity in general.

14.6.4 **Capacity-building and transfer of knowledge and technology**

WMO believes that advances in scientific understanding of the atmosphere should be in support of sustainable development and social and economic decision-making of communities around the world. Enhancing understanding and capabilities in accessing, adapting and applying advances in climate science and prediction, remote-sensing and Geographical Information Systems can substantially improve the fight against drought and desertification. To these ends, WMO has sponsored a number of programmes aimed at the dissemination and successful use of research achievements. The Climate Information and Prediction Services project (CLIPS) (<http://www.wmo.int/pages/prog/wcp/wcasp/CLIPSIntroduction.html>) was created by the Twelfth World Meteorological Congress for this purpose. Efforts are made to ensure that NMHSs have access to global and regional monitoring products and that the staff are sufficiently trained to provide climate-based decision-making to local communities. Other programme activities have included demonstration/pilot projects, various training opportunities and liaisons between research programmes. For example, to promote capacity-building associated with the UNCCD National Action Plans, WMO sponsored Roving Seminars on the Application of Climatic Data for Desertification Control, Drought Preparedness and Management of Sustainable Agriculture in Beijing, China, in May 2001 and in Antigua and Barbuda in April 2004.

Regional Climate Outlook Forums were organized by WMO to assist advanced climate prediction centres around the world in developing consensus forecasts and other climate prediction products, along with appropriate users' guides. The resulting interaction among the agencies was effective in the transfer and

discussion of the current knowledge and limitations of climate prediction, which ultimately led to an improved consensus forecast product.

WMO has sponsored the preparation and distribution of publications relating to climate and desertification, including *Interactions of Desertification and Climate* (Williams and Balling, 1996) and *Agrometeorology Related to Extreme Events* (WMO, 2003b). *Climate and Land Degradation* (WMO, 2005) was prepared for the seventh session of the Conference of the Parties (COP-7) of the UNCCD in October 2005, and a corresponding International Workshop on Climate and Land Degradation was held in Arusha, Tanzania, in December 2006 (http://www.wmo.int/pages/prog/wcp/agm/meetings/wocald06/wocald06_en.html).

14.6.5 **Application of agrometeorological science and methods**

The WMO Agricultural Meteorology Programme has played a leading role in the application of meteorological and hydrological sciences to agriculture through the delivery of various agrometeorological services and through the provision of assistance to farmers in the application of agrometeorological methods. The scope of such applications includes practices relating to the manipulation of the microclimate to favour the growth of crops and other vegetation (see 14.3.2). Afforestation programmes and land-use planning practices can combat desertification both on and off farm fields. The Commission for Agricultural Meteorology (CAgM) (http://www.wmo.ch/pages/prog/wcp/agm/cagm/cagm_en.html) has been active since the 1970s in recommending agrometeorological approaches to drought. The commission has promoted development of indices for drought assessment, drought probability maps, national and regional drought management plans, assessments of the economic impacts of drought, and improvements in agrometeorological bulletins and methodologies for advising farmers. The commission collaborates with the International Society for Agricultural Meteorology (INSAM) (<http://www.agrometeorology.org/>) to promote networking among agrometeorologists all over the world in support of better agrometeorological practice. The WMO WHYCOS Programme (http://www.whycos.org/rubrique.php?id_rubrique=2) promotes detailed monitoring, assessment and management of water resources in support of drought mitigation and other goals.

Successful drought and desertification intervention requires not only mitigation, response and remedial action, but also preparedness. As such, WMO

promotes the use and establishment of partnerships in drought-preparedness strategies, risk management applications and hazard vulnerability assessment. Temporal comparisons of 10-year mean isohyet maps enable easy detection of areas undergoing continued desiccation and in which rainfed agricultural operations should be avoided. Proper agroclimatic zoning is an important element in minimizing climatic risks to agriculture by identifying appropriate crops for an area using an array of relevant climatic elements. Similarly, the mapping of climatic hazards permits integration of numerous biophysical variables for spatial assessments of hazard likelihood and magnitude for land-use and preparedness planning. Remote-sensing products have multiplied the quantity of information available for such analyses, while Geographical Information Systems have enabled the rapid manipulation and evaluation of the many data layer components. Hazard and agroclimatic mapping products may play an integral role in government and resource management decision support systems. The continuing efforts by WMO in encouraging the quality and quantity of systematic observation across meteorological networks are imperative for such projects.

14.6.6 **Drought preparedness and early warning systems**

Drought is a normal part of the climate system and occurs virtually in all regions of the world (Wilhite, 1992). Drought may be classified broadly into several main types – meteorological, hydrological, socio-economic and agricultural – though a precise and universally accepted definition of drought is largely absent (Wilhite and Glantz, 1985). Meteorological drought occurs when there is a prolonged absence or marked deficiency of precipitation. Hydrological drought occurs when there is sustained and extensive occurrence of below-average natural water availability, in the form of rainfall, river runoff or groundwater. Agricultural drought is defined as a deficit of rainfall in respect to the long-term mean, affecting a large area for one or several seasons or years, which drastically reduces primary production in natural ecosystems and rainfed agriculture (WMO, 1975). Socio-economic drought occurs when water supply is insufficient to meet water consumption for human activities such as agricultural production, industrial output, urban water supply, and so forth (Heathcote, 1974; WMO, 1975).

While these definitions of drought may be meaningful for scientists, however, in most cases a lack of

consideration as to how other disciplines or policy-makers will eventually need to apply the definition to actual drought situations is problematic. Other types of drought definitions may be more specific. For example, an agricultural drought describes a situation in which rainfall amounts and distribution over a wide region combine with evaporation losses, soil water reserves and surface or subsurface water resources to markedly diminish crop or livestock yields. Therefore, a strict meteorological definition of drought conditions may be insufficient for agricultural purposes. A working definition is needed in order to facilitate drought-preparedness planning through the linking of environmental considerations involving drought (that is, meteorological, hydrological and ecological factors) to specific impacts in key socio-economic sectors (agriculture, tourism, poverty, nutrition, and so on).

Overall, drought plans and the use of early warning systems (EWSs) have become widely accepted tools for governments at all levels to apply in order to reduce the exposure of agricultural activities to risks of future drought events. Effective drought EWSs play an integral part in efforts to improve drought preparedness, with timely and reliable data and information the cornerstone of effective drought policies and plans for rainfed agriculture and pastoral systems of farming. Notable examples include the United States monitoring tool – Drought Monitor – developed in 1999, and the inception of the Australian National Drought Policy in 1992. Without a doubt, the core principle of “self-reliance” moved Australia’s drought policy away from a crisis-driven approach to one that treated drought as a normal part of the Australian farming environment (WMO, 2000a). Most progress in the preparation and development of drought plans, however, is in developed countries (for instance, Australia and United States), and while many developing countries have some type of drought plan and early warning system, these systems are not always comprehensive and have limited use.

14.6.6.1 **Role of WMO and drought preparedness**

In addition to providing meteorological data services, WMO promotes preparedness for drought through the establishment of national drought plans, drought risk assessments and data input to EWSs. Based on a clear definition, drought preparedness should contain three basic components (after WMO, 2000b), which include:

- (a) Monitoring and early warning;
- (b) Risk assessment;
- (c) Mitigation and response.

WMO activities in the field of drought are focused primarily on these components and encompass four phases: mitigation/prevention; preparedness; response; and recovery. These phases are primarily organized through the various scientific and technical programmes of WMO and include:

- (a) World Weather Watch (http://www.wmo.int/pages/prog/www/index_en.html);
- (b) World Climate Programme (http://www.wmo.int/pages/prog/wcp/index_en.html);
- (c) World Weather Information Service (<http://www.worldweather.org>);
- (d) Severe Weather Information Service (<http://severe.worldweather.wmo.int/>);
- (e) Hydrology and Water Resources Programme (http://www.wmo.int/pages/prog/hwrp/index_en.html).

Increasingly, society is recognizing the impacts that climate has on human activities, whether from long-term climate change or climate variability. These Websites are designed to provide a single and centralized source of climate and meteorological information on the Internet for a wide range of stakeholders, such as the public, scientists, regulators, non-governmental organizations, governments, policymakers and business, so as to limit potential negative impacts to agriculture of climatic hazards and enhance agricultural planning activities through the developing capacity of climate science. Therefore, the Websites combine different functions that work closely with and aid NMHSs in the provision and exchange of climate data and services. Broadly, these functions include:

- (a) Information and forecasting services (World Weather Information Service);
- (b) Database and data management services (World Weather Watch);
- (c) Technical support and implementation of climate services (World Climate Programme/CLIPS).

14.6.6.2 **Early warning systems**

As a consequence of drought and associated famine in West and East Africa during the late 1970s and early 1980s, the affected areas and international agencies were faced with the need to provide appropriate tools to facilitate preparedness for reoccurring droughts. Although they are still in the development and evolutionary stages, EWSs are being introduced as a means of integrated management to bring drought preparedness to agricultural systems, and to aid in the prevention of famine and in the prediction of drought. Table 14.5 provides a summary of current EWSs and agrometeorological models

used for forecasting drought and anticipating food crises. From a meteorological perspective, more developed and extensive recording stations, coupled with deeper knowledge and dissemination of climate processes (such as teleconnections and their effects) through WMO programmes, have permitted the collection and use of data that underpin EWS schemes.

Agrometeorological monitoring for EWS schemes consists primarily of various data and information that can affect the outcome of agricultural production. It combines observational data as well as satellite data and model outputs. For seasonal forecasting, outputs of ocean–atmosphere dynamic models, coupled with outputs of national statistical models, are used to delineate zones for which forecasts are made. Seasonal forecasts for agricultural production purposes are usually made up of the probabilities of July–August–September rainfall or maximum river flow, which are combined with specific agrometeorological models (such as the ZAR, or Zones à Risque, model). Most information is based on monitoring of the cropping season and determining risk zones, however, and is addressed to policymakers at the government or international aid agency level. Several agrometeorological indicators are used throughout the rainy season to assess crop and livestock conditions. Indicators include, among others:

- (a) Rainfall amounts (10-day and cumulative);
- (b) Potential evaporation;
- (c) Air temperature and radiation levels;
- (d) Surface water level and flow;
- (e) Crop and overall biomass yield estimates;

- (f) Crop water requirements;
- (g) Cropping season start;
- (h) Natural vegetation status;
- (i) Disease status.

Early warning is an art, not a science, however, and EWSs are used to make predictions based on an analysis of available information and, inevitably, an element of judgement (WMO, 2000c). Long-range forecasts of drought are not yet operationally possible despite improvement of best practices and methodologies of current EWS schemes (for example, the Global Information and Early Warning System, or GIEWS; Système Intégré de Suivi et Prévision, or SISP; and ZAR). Indeed, a feature of EWSs is that data are never as comprehensive and accurate as practitioners would like, and the earlier the warning, the less certain a forecast will be. This issue of long-range uncertainty in EWS forecasts sits at odds with the usually risk-adverse, quantifiable decision-making of many governments and donor agencies that usually look for evidence before responding (Thomson et al., 1998). Increasing gains are being made in developing EWSs for the forecast of droughts and their potential effect on crop and livestock production, however, by using multidisciplinary technical structures and inter-agency committees for the development of EWSs and drought plans (Martini et al., 2004). Recognition of the need to define methods to optimize the use and integration of available data and administrative structures has aided, and will further aid, the ongoing development of EWS schemes.

Table 14.5. Examples of early warning systems and agrometeorological models used for decision-making by governments and international agencies in the area of food security

<i>Early warning system</i>	<i>Organization</i>	<i>Output</i>
GIEWS	FAO	Monitoring of world food prices, estimates of global food production and supply
FEWS	United States Agency for International Development	Compilation of hazard information: hazard, shock factors and risk analysis
WFP–VAM	World Food Programme	Vulnerability analysis: identification of important income sources for population groups and analysis of risk related to productive activities and coping capacity to provide vulnerability conditions
SISP	Agrhymet	Seasonal monitoring, crop growth assessment, yield forecasting
ZAR	Agrhymet	Identification of successful sowing dates, areas of failed sowing, potential duration of growing season
DHC–CP	Agrhymet	Identification of first and successful sowing dates

14.6.7 **WMO, desertification and the future**

Since its inception, WMO has been committed to improving global meteorological and hydrological monitoring networks and strategies for systematic observation. In a new era when a potential rise in global temperature, increased climate variability and growing population pressure may place increased stresses on the land, the need for accurate and systematic climatic data observations in assessing interactions between climate and desertification is apparent. While greater information on rainfall intensity is needed in particular, strengthened systems of meteorological and land degradation monitoring allow for better spatio-temporal evaluation of the role of individual climatic elements in desertification processes. In addition, there is an enhanced ability to develop accurate seasonal climate forecasts for improved dryland decision-making.

In future efforts to combat desertification, WMO will promote:

- (a) Use of appropriate instruments and statistical processing for meteorological data in support of effective drought early warning systems;
- (b) Continued efforts towards effective provision and communication of drought warnings and long-term predictions from drought monitoring centres to farmers through extension agents and non-traditional methods such as rural radios, facsimile, e-mail, Internet, mobile telephones and wireless access. Local people should be involved in a collaborative process with applicable community, regional, national and international organizations and research entities for the purpose of the production, exchange and dissemination of such information;
- (c) Strengthening drought prevention, preparedness, management and contingency plans across multiple geographic scales, based on coordinated efforts by the relevant government authorities, extension agents, local citizens and economic sectors;
- (d) Inclusion of geographic assessment tools such as multi-indicator drought monitoring

maps, agroclimatic zonation, temporal isohyet analysis, remote-sensing products, and climatic hazard and vulnerability mapping in effective decision-making related to land use;

- (e) Creation of global databases on the frequency, intensity, onset, spread and duration of meteorological and hydrological drought, and the related impacts on agriculture, livestock and forestry;
- (f) Full and improved application of agricultural meteorological practices and hydrologic management in combating drought and desertification, with associated capacity-building and education efforts;
- (g) Continuation of research in climate variability and drought processes, including the role of large-scale global atmospheric circulation and improved seasonal forecasting.

Drought and desertification are insidious processes with manifold environmental, social and economic repercussions, but progress is being made. The past decade has seen an explosion in remote-sensing and geospatial technologies for enhanced dryland monitoring and decision-making, and expanded communication and education capacities through greatly improved access to microcomputers, the Internet, mobile phones and e-mail. Advances in the climate science in relation to El Niño–Southern Oscillation phenomena are beginning to make possible climate prediction on the order of a few seasons. Yet the challenges in addressing a potential climate change and increasing climate extremes with a global population that is expected to reach 8.2 billion by 2020 loom large. With nearly one in six people worldwide presently at risk from the impacts of land degradation, much work remains in terms of monitoring and preventing desertification, understanding causal interactions, and education. Through its outreach efforts in these areas, WMO stands to play a significant role in maintaining the sustainability of drylands and the well-being of the millions of people who are dependent on them.

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CHAPTER 15

AEROBIOLOGY

15.1 INTRODUCTION

This chapter deals with practical aspects of aerobiology relating to agricultural meteorology and presents an interdisciplinary approach to the properties and airborne movement of biota that are significant to plants, animals, pests and diseases. Owing to the recent expansion of Internet access to weather, climate, pest, plant and animal data, models and management guidelines, it was considered that updating specific parts of this chapter on aerobiology would be of benefit to readers and meteorological services users.

Aerobiology is a scientific discipline that deals with the transport of organisms and biologically significant materials through the atmosphere (Isard and Gage, 2001). Aerobiology also encompasses the generation, uptake, translocation, dispersion, viability, deposition and infection/infestation of seeds, viruses, fungi, bacteria and other agents, including insects such as aphids and mosquitoes, which act as virus vectors. Finally, this discipline deals with agriculturally significant insects such as locusts, bush flies and moths.

Any movement of biota, particles or gases through the atmosphere that may have an adverse effect on vegetation or animal life must concern the agricultural meteorologist. Particles less than 0.1 μm in size, which include viruses, are in permanent suspension in the atmosphere and are subject to Brownian movements. The most important disease organisms that affect agriculture vary in size from 0.1 to 100 μm . These airborne particles are in a transitory state, each with a specific fall speed. Particles above 100 μm cannot be sustained in the atmosphere for any significant time by strong winds, unless powered flight is a factor, such as for insects, birds and bats. Allergy is also of concern to the aerobiologist, who can provide warnings of pollen episodes that may cause allergic reactions, thus allowing for the timely use of preventive medications.

A common procedure adopted by agricultural meteorologists is to use seasonal meteorological indicators to signify the last stage, namely, the infection episode, rather than proceeding from the first phase, that is, the generation. When considering the end phase per se, the inoculum is assumed

to be present, unless a plant pathologist provides information to the contrary. An index such as degree-days or heat units is sometimes used to indicate the phase during which infection would probably occur given the presence of a suitable pathogen.

For specific purposes, an index such as the product of temperature and wetness duration is used to signify a potential infection period (Mills and Laplante, 1951). Products of 140, 200 and 300 degree-wetness hours correspond approximately to light, moderate and heavy infections of apple or pear scab for optimum temperatures ranging from 18°C to 24°C. This approach can also be applied to brown rot in peaches and can be used to indicate fungal infection on grass leading to facial eczema in sheep. Various combinations of meteorological elements are used for other diseases.

While these established routines will continue to play an important role in the field of agrometeorology, the widespread use of aerobiology promises to improve the service. Pedgley (1982) provides a broad survey of airborne dispersal of plant pathogens, human allergens, livestock diseases, and pest insects and other organisms. Aerobiological techniques have already been used successfully in some areas. These include practices such as tracking the spread of foot-and-mouth disease (Moutou and Durand, 1994), locusts and bush flies. The interdisciplinary approach to aerobiology incorporates the sampling routines and instrumental observations of entomologists, plant pathologists and other biologists, together with real-time weather or climatic data of meteorologists, for use in models specifically designed to simulate certain disease infections or insect infestations. In addition, the aerobiological techniques may include monitoring and modelling of airborne movement of beneficial biota and their impact on pest populations.

Agronomic management must maintain environmental quality at an acceptable level when applying countermeasures to deal with pests and diseases. Judicious use of chemical sprays and biological control tactics are needed to reduce environmental risk and maintain the long-term effectiveness of pesticides and biological control tactics for pest management.

15.2 TYPES OF SERVICE TO BE PROVIDED TO USERS

The ecological systems approach to aerobiology (Edmonds and Benninghoff, 1973) describes potential products that could be delivered to users. An interdisciplinary team, comprising a plant pathologist, entomologist, agronomist, animal scientist, and an air pollution chemist, meteorologist and systems mathematician, could form the nucleus of an aerobiology unit that could offer:

- (a) A research unit to investigate airborne biota, in particular the generation, release, dispersion, viability, deposition and infection stages;
- (b) A specific programme to assess the magnitude of problems involving aerial transport of economically important diseases and pests of crops and forests, as well as the need for aerobiological surveys to improve understanding of the problems and the need for monitoring to assist in control measures (to deal with leafhoppers, cereal rusts, corn blight, fire blight, fusiform rust, white pine blister rust, gypsy moth and Douglas-fir tussock moth, for example);
- (c) Investigations into the contribution that aerobiological techniques could make to various methods of biological control of pests and diseases;
- (d) A focus for the development and implementation of a programme for progressive improvement in the estimation of crop losses due to diseases and pests utilizing the appropriate methods from aerobiology and aerobiological models;
- (e) Encouragement for further simulation modelling of aerobiological phenomena in the context of ecosystems.

Once an interdisciplinary body is established, its ultimate challenge is to provide the right information to the right farm, nursery, forest, and so on, in the right form at the right time. The host-pathogen relationship is determined mainly by the microclimate and is thus related to weather as modified by the crop. The agricultural meteorologist is the obvious person to monitor the weather continuously and feed the data collected into an approved model. The meteorologist also has an excellent communication link with farmers who rely on weather information.

Criteria for the successful implementation of specific pest and disease management systems have also been given by Johnson (1987) as follows:

- (a) A serious pest or disease problem must exist for which low-cost solutions, such as host resistance, are unavailable and unreliable;

- (b) It should be possible to explain efficiently and predict accurately the variations in the incidence of problems by means of a model;
- (c) Facilities must exist for communication of model predictions so that timely control measures can be taken;
- (d) Control measures must be available that are effective, economically justified and non-hazardous to the environment.

A study of the modelling of disease epidemics (WMO, 1989*a*) mentions strategic methods, such as host resistance, crop rotation and fertilizer practices, along with tactical methods, such as the application of pesticides or fungicides, in response to model indications of infections or epidemics. The aim of these methods is to achieve prevention rather than containment of damage. The EPIPRE system (Djurle and Jonsson, 1985), among other models, considers the cost of application of a mixture of pesticides and fungicides in a single operation, while the BLITECAST model (Krause et al., 1975) provides a model for early disease control. Models used for aerobiological investigation could profit from adoption of the principles outlined by Johnson (1987).

15.3 DATA AND MODELS AVAILABLE FOR USE BY AEROBIOLOGISTS

Climatic data are useful in the development of computer models to simulate outbreaks of pest and disease infection. The introduction of a new crop and its susceptibility to disease infection or pest infestation can be tested using a simulation model (Waggoner and Horsfall, 1969). Real-time weather reports are vital during operational investigations. Real-time weather data and climatic data are widely available for free access on the Internet (for instance, from <http://lwf.ncdc.noaa.gov/oa/ncdc.html>). Increasingly, weather data are being generated by parameterization of remotely sensed data (for example, radar reflectivity and Doppler radar radial velocity).

Wind data at all heights are quite important. Wind shear and gustiness at the surface of plants can assist in spore release, uptake, dispersal and deposition. Tromp (1980) reported long-range transport by wind of yellow rust spores over 1 000 km. The temporal distribution of wind direction at specific locations can provide valuable information regarding the state of the atmosphere. If R is the range of extreme wind direction values over a given period, then $R/6$ is a good approximation of the standard deviation of the wind direction. Values of the

standard deviation of wind directions of 2.5, 10 and 25 degrees represent very stable, neutral and unstable atmospheric conditions, respectively. An alternative system to deduce the state of the atmosphere is shown in Table 15.1.

Wind analyses using constant altitude, isothermal, isentropic or isobaric surfaces, or the three-dimensional sigma model can be used to obtain trajectories at the higher latitudes, while in the tropics streamline analyses are preferable to pressure–height contours.

Temperature is a vitally important element for agriculture. Degree-day indices can be used to indicate critical phases for pests and diseases, thus enabling the timely application of cultural or chemical treatments. The temperature lapse rate, besides indicating the state of the atmosphere, is also used to estimate the mixing height, or the height to which all particles and gases are dispersed during the day. High surface temperatures can trigger the release of spores and seeds and set limits to fungal activity.

Precipitation, including dew and fog deposition, is an important factor in disease propagation and the microclimatic humidity conditions must be consistently monitored. Precipitation results in the wetting of vegetation and also the release of spores from plants. In the presence of rainfall, nearly all of the airborne particles can be washed out. Spores washed out by rain may be significant in the initiation of disease (Rowell and Romig, 1966).

Radiation, both visible (380–780 nm) and ultraviolet (UV) (190–380 nm), may have epidemiological significance. The germination of spores of blister blight is favoured by faint light; *Phytophthora* sporulates germinate overnight with favourable

humidity. While small doses of UV stimulate germination, large doses minimize infectivity. According to Aylor (1986), the combined effects of temperature, relative humidity and UV light found at the top of the mixing layer may be particularly lethal to spores. Ultraviolet radiation at wavelengths greater than 290 nm reaches the ground with sufficient intensity on sunny summer days to kill sensitive spores in a few hours (Bashi and Aylor, 1983). The sensitivity of spores to UV radiation is enhanced when spores are wet (Rotem et al., 1985) or when maintained at high relative humidity. This effect may be greater at the lower temperatures near the top of the mixing layer because of the less efficient repair by photo-reactivation of their DNA (Maddison and Mannings, 1973).

15.3.1 Remote-sensing data

Radar can register rainfall, rainfall washout of biota, and also the aerial movement of many pest and beneficial organisms. Further, Doppler radars can also measure the speed and displacement direction of airflow, and consequently movement of airborne biota (Westbrook and Eyster, 2003). Satellite imagery can provide cloud and rainfall patterns, along with vertical profiles of temperature and moisture, which are useful in the analysis of charts and the establishment of trajectories. Cloud-top temperatures have been well correlated with rainfall probability. Satellite-derived vegetation indices (such as the normalized difference vegetation index (NDVI)) can be used to locate host vegetation for pests and diseases, thus enabling the application of preventive actions (for example, sprays or cultural practices) after ground truth verification. Further, much activity is underway to use aerial imagery of vegetation to generate prescription maps for precision application of pesticides.

Table 15.1. Stability categories

Surface wind speed at 10 m (m s ⁻¹)	Day			Night	
	Incoming solar radiation			Thinly overcast or	
	Strong	Moderate	Slight	≥4/8 Low Cloud	<3/8 Cloud
<2	A	A–B	B		
2–3	A–B		C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

Note: A, B, C, D, and E are stability indicators. The neutral class, D, should be assumed for overcast conditions day or night.

15.3.2 Vertical mixing and dispersion models

Many of the problems of dispersion depend on the mixing height, which is the atmospheric layer in which the bulk of material is distributed. If the mixing height is low, the materials are highly concentrated in a relatively small volume, and vice versa.

An aerological sounding can be analysed to establish a mixing level. The dry adiabatic lapse rate ($-9.8^{\circ}\text{C km}^{-1}$) is followed from the surface temperature and pressure until it intersects with the environmental lapse rate, and the intersection point determines the mixing height. If a rural trace is used in a built-up area, 5°C is often added to the morning temperature to allow for the heat island effect (Figure 15.1). The product of the mixing height and the mean wind speed is a measure of the ventilation rate.

Predetermined results from Gaussian-type equations can be obtained for given wind speed and atmospheric stability for point, line or area release of a unit source from ground level or from a given height. Solutions to potential problems such as these can be prepared for a variety of likely combinations of wind speed and stability for distribution to workers in the field for their information and experiment.

Computer models involving various forms of the Gaussian equations are available, such as Slade (1968), Turner (1967), Pasquill (1962) and Sutton (1953). The additional data required to use these equations are the standard deviations S_y and S_z , which are dispersal coefficients in the horizontal and vertical, respectively, as shown in Figures 15.2 and 15.3 The

atmospheric stability indicators after Pasquill (1961) are shown in Table 15.1. The mixing height usually reaches a maximum during the afternoon and a minimum in the early hours of the morning.

The Gaussian equations make many simplifying assumptions, which include the following:

- There is continuous or instantaneous emission from a source.
- There is an absence of rain (washout).
- Theory is constrained to a flat, featureless terrain (grasslands) because the dispersion coefficients in Figures 15.2 and 15.3 were measured under such conditions.
- Once an atmospheric stability class is selected (from Table 15.1) it must remain fixed, in other words, there is no allowance for a change in turbulent structure.
- Once selected, the mean wind velocity cannot change and thereafter remains constant with height.
- In view of the above assumptions, the Gaussian plume model is strictly valid only for a region close to the source and for a period during which no significant change in any important parameter occurs. An example in which those limitations have been overcome to some extent is the Roberts model (Roberts et al., 1972), where a trajectory-diffusive model replaces a purely diffusive model.

The Web-based Real-time Environmental Applications and Display sYstem (READY) allows users to access meteorological data and run atmospheric trajectory and dispersion models (<http://www.arl.noaa.gov/ready.php>). READY can be used to model the transport of any airborne

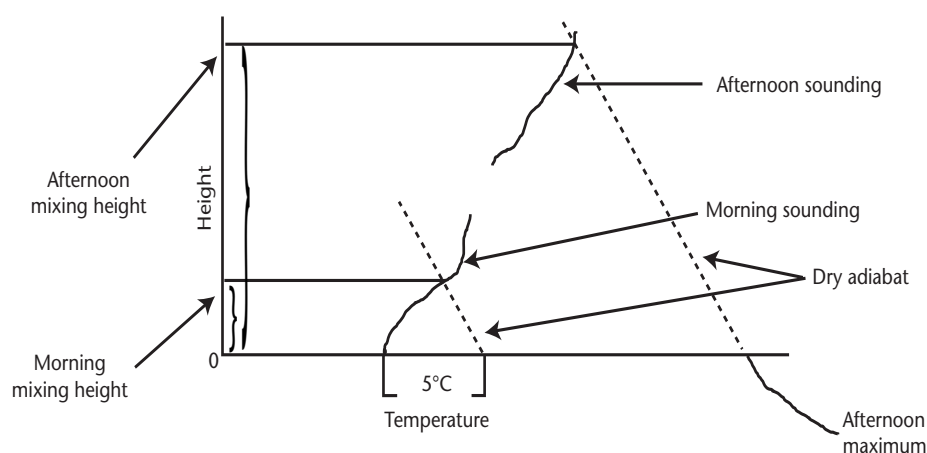


Figure 15.1. Determination of mixing height from soundings (after Edmonds and Benninghoff, 1973)

material, including spores, insects and air pollutants. READY allows users to access archived meteorological data and run the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model to generate customized georeferenced maps of atmospheric trajectories and dispersion concentrations. Use of READY or similar systems that integrate database access and modelling software will advance the capabilities of aerobiologists by drastically reducing the data-processing burden and by providing efficient and accurate analytical results.

15.3.3 Additional data required

Sampling data collected by entomologists involve instrumentation such as insect nets attached to manned aircraft, radio-controlled aircraft, tethered balloons and kites. Other data come from suction traps, light traps and traps baited with sex-specific pheromones, aggregation pheromones or feeding attractants placed in the vicinity of crops. Captured insects are identified and analysed and contribute to the essential aerobiological database.

Information provided by plant pathologists results from field observations of lesions and infection levels in crops, together with quantitative identifications and analyses of information from

spore traps. Chemical analyses of air samples can be carried out as required. Air pollution data may also be necessary because of the possibility of an adverse impact on spore viability and plant health.

Plant simulation models, such as that created by Waggoner and Horsfall (1969), isolated single steps in the life of a pathogen, which were recreated in a laboratory. The effect of varying the weather, one element at a time, was investigated and documented. Eventually, a computer model or simulation was created that incorporated the complete system of host, pathogen and environment. Five years of climatic data were used to parallel the behaviour of the fungal disease *Alternaria solani* in the simulated computer program.

The resultant simulator permitted exploration of extreme values of weather, pathogen and host. Slowing the sporulation process had little effect on an epidemic; shortening wetness duration decreased the incidence of disease, but the interruption of wet periods with dry episodes simply decimated the disease. Irrigation turned out to have little effect on the incidence of the disease, while dew formation on the foliage caused an explosive epidemic with the set of data used.

The trial with a simulator demonstrated that a lifetime of experiments in weather modification with a

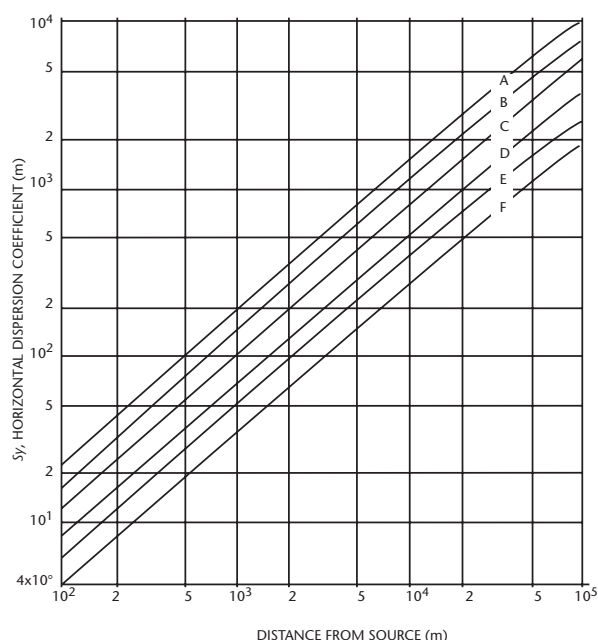


Figure 15.2. Lateral dispersion vs. downwind distance from point source. A = extremely unstable; B = moderately unstable; C = slightly unstable; D = neutral; E = slightly stable; F = moderately stable (after Slade, 1968)

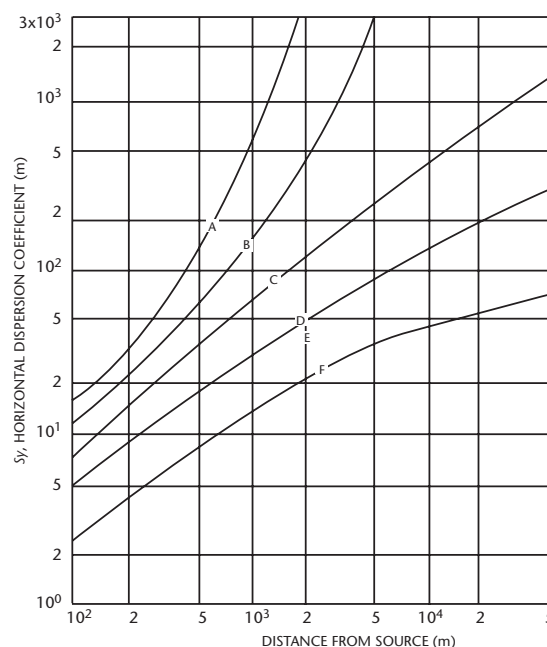


Figure 15.3. Vertical dispersion vs. downwind distance from point source. A = extremely unstable; B = moderately unstable; C = slightly unstable; D = neutral; E = slightly stable; F = moderately stable (after Slade, 1968)

view to investigating plant disease can be carried out in a matter of hours. Waggoner et al. (1972) also created a simulation of Southern corn leaf blight. There is a compelling need for more computer simulator models for the important diseases and pests that cause epidemics or plagues of economic significance, however. Models like SIRATAC (Hearn and Brook, 1983; Ives et al., 1984) and BLITECAST (Krause et al., 1975) and the EPIPRE system (Djurle and Jonsson, 1985) are good prototypes.

15.4 SCALES ON WHICH TO CONSIDER AEROBIOLOGICAL PROBLEMS

Scientists must determine the temporal and spatial scales that are relevant to their specific aerobiological problems. For example, Gage et al. (1999) discussed issues of ecological scaling that are important for vegetative development and aerobiological processes over the landscape. Intra- and interannual patterns of plant development form the foundation for atmospheric transport of pollen, spores and other organisms associated with plant health. Meteorological scaling appropriate for particular aerobiological systems was summarized by Westbrook and Isard (1999). Aerobiological dispersal remains incompletely incorporated into integrated pest management systems, however (Jeger, 1999).

15.4.1 Microscale transport

A systems approach that integrates biological, chemical and cultural practices involved with the ecosystem containing the host, crop, pest and disease is suited to this type of transport. Getz and Gutierrez (1982) have reviewed pest-modelling approaches on this scale and classified them by simulation, analytical and operations-research approaches. A study of the modelling of pest outbreaks (WMO, 1989b) pointed out that there may be no significant meteorological component when pest dynamics are dependent on specific field conditions, for example, rice paddies. An example of a pest management system that does employ weather, however, is the SIRATAC system (Hearn and Brook, 1983; Ives et al., 1984), which is applicable to the control of the tobacco cluster grub; this pest almost wiped out the irrigated cotton-growing industry in the warm temperate regions of Australia.

Examples in which aerobiology is useful on this scale can be found. A human disease and allergy group (Edmonds and Benninghoff, 1973) investigated the dispersion of algae cells downwind from a

eutrophied lake. The concentration of algae in the lake was a function of nutrients, temperature and light, following work by Blanchard and Syzdek (1972). Taking the algal population as 2×10^3 cells ml^{-1} (Labine and Wilson, 1973), the rate of algal emission from the lake becomes 0.2267 algae cells $\text{sec}^{-1} \text{ cm}^{-2}$ of lake surface. The dimensions of the lake were 100 m $\times$ 100 m, or 10^8 cm^2 , and hence the emission rate $Q = 0.2267 \times 10^8$ algae cells sec^{-1} . Turner (1970) allowed for an area source to be treated as a point source by taking the initial standard deviation of the plume in the cross-wind direction $S_y O = s/4.3$, where s is the dimension of one side of the square (100 m). Hence $S_y O$ (the value at the virtual point source) = 100 m/4.3 = 23.3 m. From Table 15.1, stability class B was selected for strong incoming radiation. Since $S_y O = 23.3$ m, from Figure 15.2 the virtual distance X_y back to the virtual point source was found to be 125 m. Thus, the algae concentration can be determined 1 m above the surface at distances of 200, 400, 600, 800 and 1 000 m from the centre of the lake at 100 m and 200 m from the plume centre line.

Wind speed was taken as 10 m s^{-1} and the deposition velocity of algae as 0.01 m s^{-1} . Values for S_y were found using $x + X_y$ in Figure 15.2, and values for S_z were derived from x in Figure 15.3, which then provided the values in Table 15.2.

These values were used in a Gaussian formula (Turner, 1970) to obtain the predicted isopleths of algae concentration 1 m above the surface, downwind from the source, on a 1 000 m $\times$ 400 m grid. The results shown in Figure 15.4 are compatible with values measured by various investigators.

Another problem treated in a similar fashion was that of the airborne dispersal of gypsy moth larvae (*Porthetria dispar* L.), which cause severe leaf defoliation to shade and orchard trees in the north-eastern United States. A dispersion pattern shown in Figure 15.5 was obtained for a source release height of 20 m and a sampling height at 1 m above the surface. Although concentrations are extremely small, the pattern was used to estimate potential defoliation. Using similar techniques, the concentration of spray from an aircraft or ground source can be assessed by substituting appropriate values

Table 15.2. Horizontal (S_y) and vertical (S_z) dispersion coefficients

x (m)	200	400	600	800	1 000
S_y (m)	55	88	115	145	180
S_z (m)	20	40	70	90	125

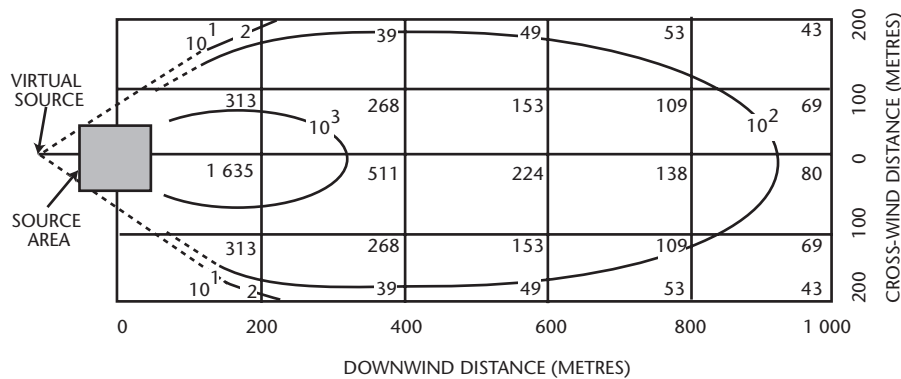


Figure 15.4. Predicted isopleths of algal concentration per cubic metre 1 m above the surface downwind from a 100 m × 100 m lake on a day with strong incoming radiation and a wind speed of 4 m s⁻¹ (from Edmonds and Benninghoff, 1973)

of stability and fall velocity of the drops. The solution for the gypsy moth could also be applied to fire blight, a bacterial disease affecting pears and apples.

15.4.2 Mesoscale transport

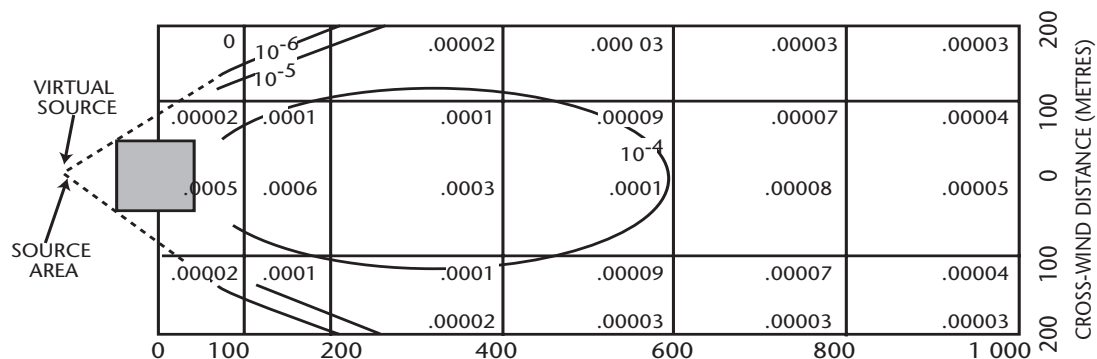
A framework for examining interregional transport of spores has been provided by Aylor (1986), and it will be followed in 15.5 below because it is an example that spans the meso- and macroscales. Aylor (1986) sought to gauge the effect on a hypothetical New England (United States) target tobacco crop from a 500 ha source infected with the downy mildew *P. tabacina*, or blue mould disease of tobacco. The infected field was located 700 km south of the target area. For comparison, a small patch of abandoned tobacco plants diseased to the same level as the larger field, but at only a 2 km distance from the target area, was considered for infection capacity

(Figure 15.6). Aylor (1986) considered five stages in solving the problem, as described in 15.5.

15.4.3 Macroscale transport

For very large- or global-scale transport at a high altitude, say 6–12 km, where the wind flow tends toward simple meandering patterns, the wavelengths are of the order of continental scale and wind speeds may vary from 150 km h⁻¹ to over 200 km h⁻¹. Wind flows at these upper levels have been studied using the Global Horizontal Sounding Technique (GHOST) balloon programme (Lally and Lichfield, 1969). Macroscale transport can be very important.

Super-pressure balloons are designed to rise to a selected isentropic level and remain at that level. One balloon at the 20 kPa isobaric level was tracked around the world for 102 d, while it made ten circumnavigations (Figure 15.7). An interesting fact



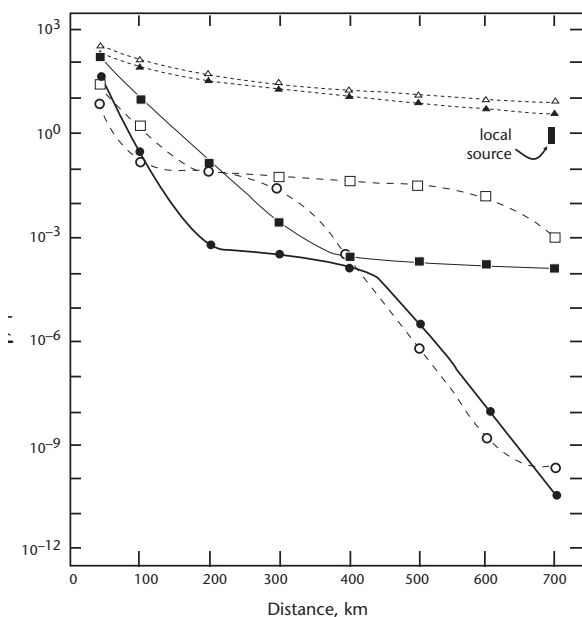


Figure 15.6. Calculated transport of sporangia. Deposition, D_T (spores m^{-2}), of sporangia on the ground versus distance (km) from 500 ha of tobacco diseased with blue mould at severity $X = 0.1$. Also shown (solid bar at 700 km) is the D_T expected from spores released from 0.01 ha of similarly diseased tobacco located only 2 km away.

The top two curves (triangles) are for spores leaving the source at 10 a.m. and travelling at speed U (solid triangles, 20 $km\ h^{-1}$; open triangles 40 $km\ h^{-1}$) during overcast conditions. The two solid lines marked by solid circles and solid squares are for spores leaving the source at 10 a.m. and travelling at U (circle, 20 $km\ h^{-1}$; square, 40 $km\ h^{-1}$) during clear sky conditions. The two dashed lines marked by open circles and open squares are for spores leaving the source at 3 p.m. and travelling at U (circle, 20 $km\ h^{-1}$; square, 40 $km\ h^{-1}$) during clear sky conditions. The number of spores, Q_0 , injected into the air at the source is $P \times E \times \text{FRACT}$, which was set equal to 3.2×10^{12} for spores leaving at 10 a.m. and 0.5×10^{12} for spores leaving at 3 p.m. (Aylor, 1986).

about the average lifetime of these balloons is that it is similar to that of small particles, in spite of the very large difference in size.

The lifetime at 50 kPa (about 5.48 km) is about 7 to 10 days, while at 10 kPa (16.76 km) the lifetime varies from 1 to 1.5 months. Volcanic dust injected high into the atmosphere distributes around the globe in a manner similar to that of the super-pressure balloon. An extreme amount of volcanic dust, say five or six major eruptions per year for two or three years, would form a dust veil over the globe and screen global radiation to such an extent that significant cooling could occur.

15.5

EXAMPLES OF AEROBIOLOGICAL MODELLING – SPORE TRANSPORT

Isard et al. (2005) adopted the general aerobiological process model (Figure 15.8) identified by Edmonds (1979) and conceived a specific aerobiological process model for soybean rust (*Phakopsora pachyrhizi*) (Figure 15.9). The Soybean Rust Aerobiology Prediction System (SRAPS), an aerobiological process model for soybean rust, was developed using the Integrated Aerobiology Modeling System (IAMS) (Figure 15.10). The IAMS model incorporates multidisciplinary data sources, biological and atmospheric models, and computer analysis to prepare pest management advisories for scientists and non-scientific users on continental and intercontinental scales. SRAPS was used to predict deposition patterns of hypothetical cohorts of soybean rust spores released from South America and arriving in the south-eastern United States. Subsequently, the SRAPS-predicted deposition patterns (Figure 15.11) were found to represent the region of soybean infections when validated by polymerase chain reaction (PCR) tests of soybean plants in the south-eastern United States. Isard et al. (2005) note that IAMS can be used with other biological data sets to create a specific process model for other biota. The five aerobiological components used by Aylor (1986) in a spore transport model are described below.

15.5.1 Production (P) of spores

For a given level of disease, the spore production, P , per ha of source is obtained from the product of:

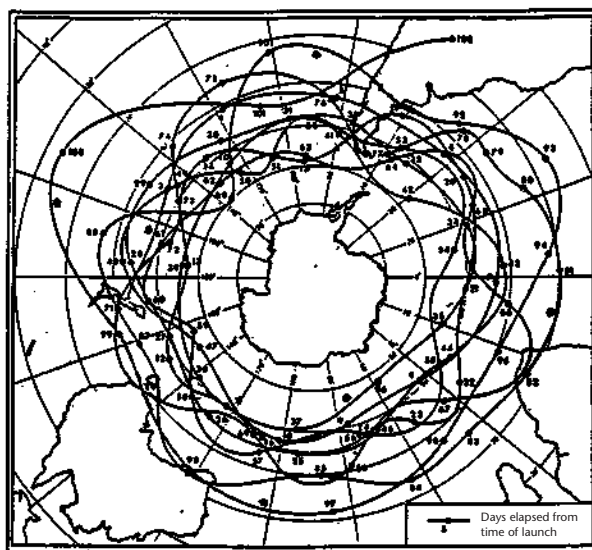


Figure 15.7. Complete flight trajectory for Balloon No. 79R, launched from Christchurch, New Zealand. Flight level 20 kPa (from Lally and Lichfield, 1969).

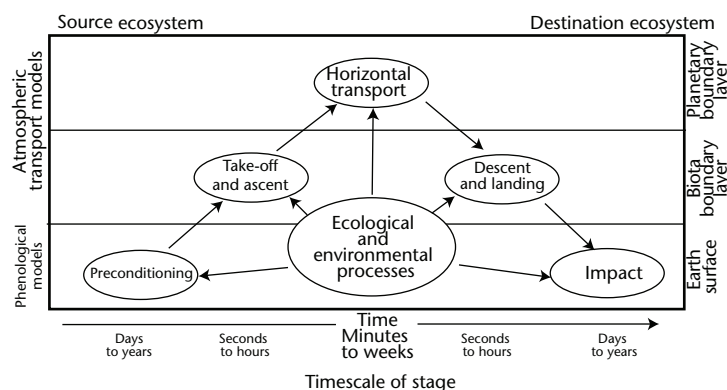


Figure 15.8. General aerobiological process diagram (Isard et al., 2005).
Copyright: American Institute of Biological Sciences.

spores lesion⁻¹ day⁻¹ = 2×10^4 ; the lesions cm⁻² of leaf area index = 2.8; and finally, a conversion factor to ha of 10^8 . For 500 ha, the total spore production is $P = 6.44 \times 10^{13}$ spores day⁻¹. Estimates such as these can be obtained from a direct survey or by a computer simulation of disease after Waggoner and Horsfall (1969) or Waggoner et al. (1972).

15.5.2 Escape (E) of spores from the canopy

The escape factor E depends considerably on the canopy architecture and the vertical distribution of spore release in the canopy. It also depends, to an important but lesser extent, on the exact functional form used to describe wind speed and eddy diffusivity in the canopy. Although the eddy diffusivity theory gives estimates that seem

reasonable, it does not hold when gusts of wind penetrate from above to deep within a canopy, where local sources cause the aerial spore concentration to vary rapidly with height.

There is a diurnal variation in the release of spores due partly to spore maturity and partly to diurnal variation in solar irradiance, wind speed, turbulence and relative humidity. The time of peak spore release is correlated well with the time that the ambient relative humidity falls below about 70 per cent (Aylor and Taylor, 1983). The fraction (FRACT) of spores released at 10 a.m. is taken as 0.33, and FRACT at 3 p.m. is taken as 0.05 using local time. Hence the number of spores injected into the air at 10 a.m. = $6.44 \times 10^{13} \times 0.15 \times 0.33 = 3.2 \times 10^{12}$, and the number of spores leaving the crop at 3 p.m. becomes $6.4 \times 10^{13} \times 0.15 \times 0.05 = 0.5 \times 10^{12}$. Here the escape factor E was taken as 0.15.

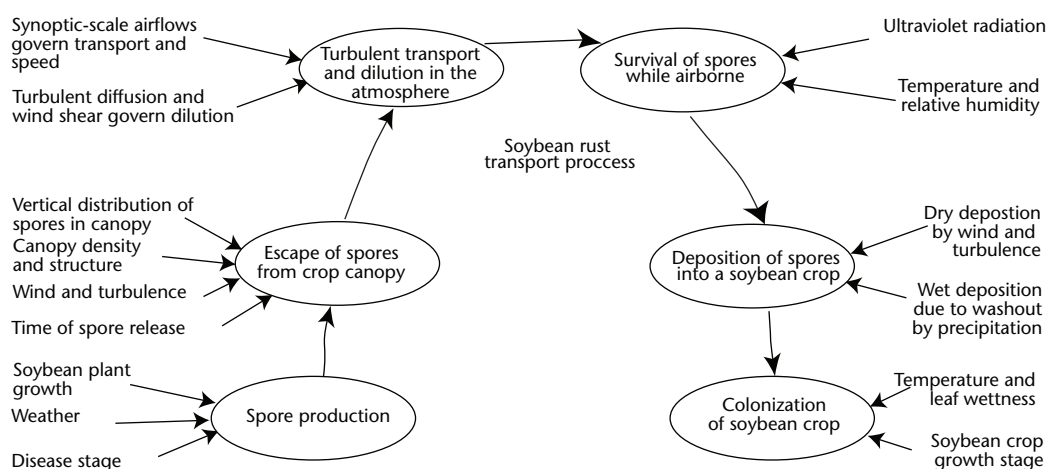


Figure 15.9. Aerobiological process diagram for soybean rust (Isard et al., 2005).
Copyright: American Institute of Biological Sciences.

15.5.3 Turbulent transport (T) and dilution

The methodology of Aylor (1986) is meant to be used for calculating the probability of successful spore transfer and not necessarily to prove that a particular transport was responsible for starting an epidemic. A combination of the spore transport model with an air parcel trajectory between source and receptor was advocated to develop a climatology

of disease spread. The extent of the vertical dispersion coefficient S_z is limited by the mixing height, H , which in turn is often limited by a temperature inversion. Thereafter, concentration becomes approximately uniform with height and the subsequent spread is largely two-dimensional.

The dilution of spores in the air by wind shear, turbulent diffusion, ground deposition and loss of spore viability all increase with travel time between source

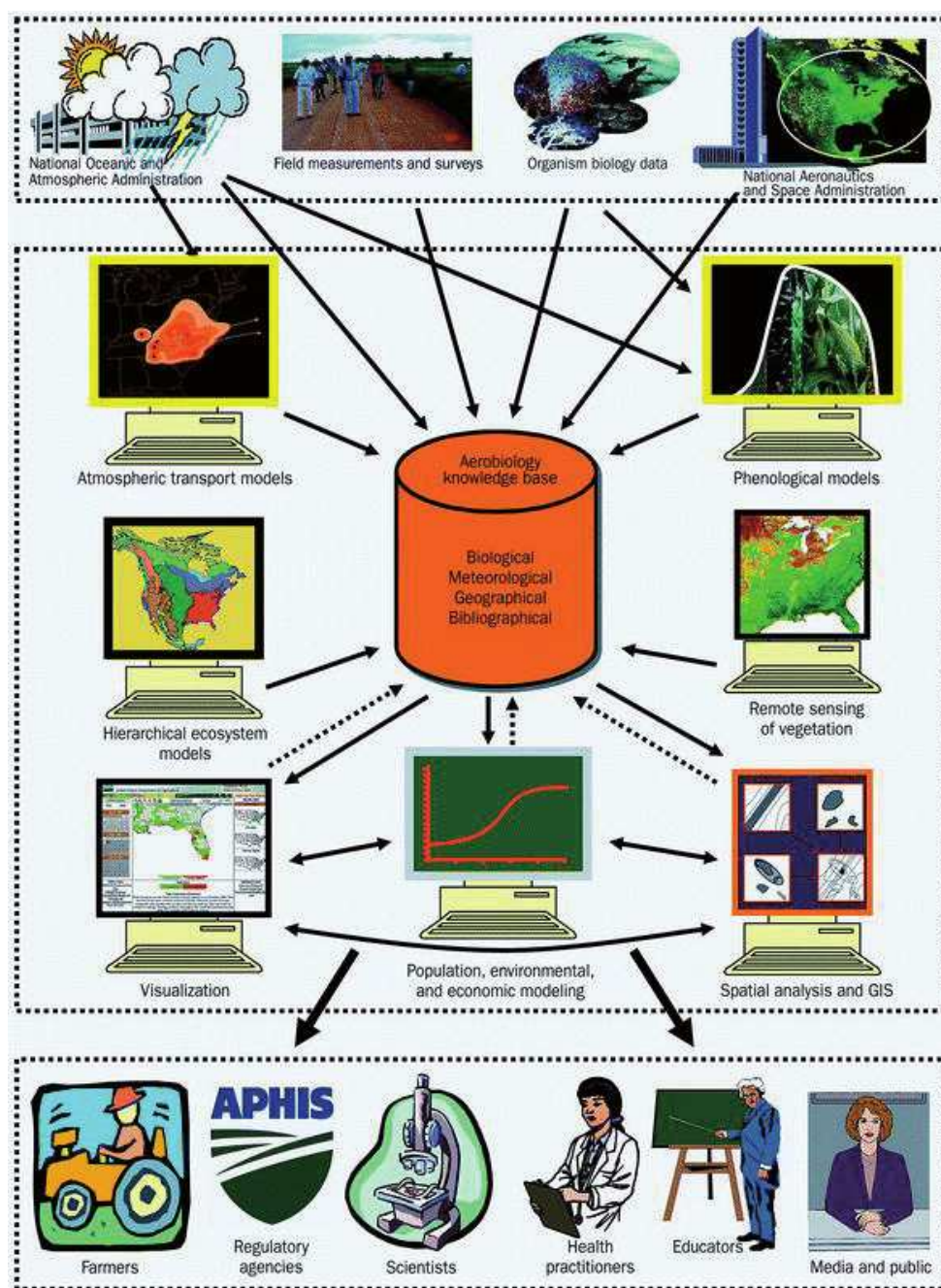


Figure 15.10. Integrated Aerobiology Modeling System (IAMS) diagram (Isard et al., 2005).
Copyright: American Institute of Biological Sciences.

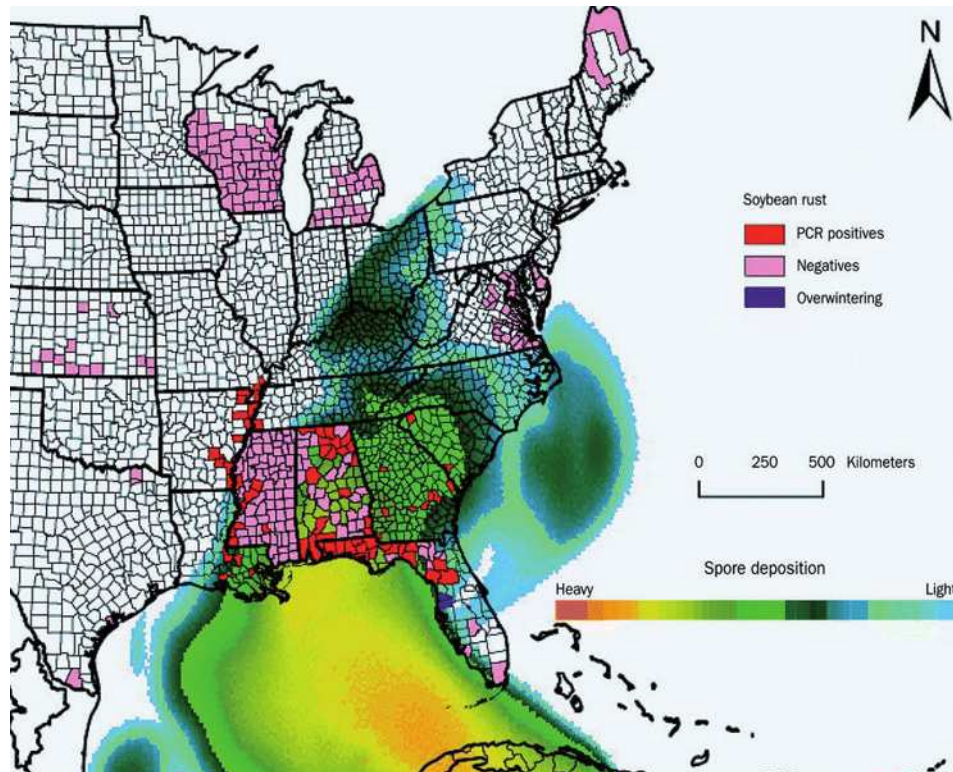


Figure 15.11. Predicted deposition pattern for Soybean Rust Aerobiology Prediction System (SRAPS) simulation using hypothetical cohorts of spores released from the Rio Cauca source area on 7, 8, and 9 September 2004 (Isard et al., 2005). Copyright: American Institute of Biological Sciences.

and receptor. Both Turner (1970) and Heffter (1980) assume the equality of standard deviations S_x and S_y ; the dilution of a spore cloud that has grown until limited by the mixing height is proportional to $1/(S_y^2 H)$ and on the average $S_y = 0.5t$ after Heffter (1965), where S_y is in metres and travel time, t , in seconds.

A number of spores released instantaneously at a source should become diluted in a volume of about HS_y^2 . Thus for $H = 3\,000$ metres and time $t = 30$ hours the number of spores should be diluted by a factor of about 10^{13} . This dilution is comparable to spore production, P ; hence spore survival becomes highly significant in determining the likelihood of success of long-distance transport. In the case of dry deposition, the number of spores remaining airborne is approximately one tenth of the original number and hence dry deposition is insignificant compared with the dilution factor 10^{13} . Transport should be a function of time of day and, although not adopted in this example, could be described in an Eulerian frame after Eliassen (1980), which allows a change in mixing height to be treated more accurately than does the chosen Lagrangian frame of reference.

15.5.4 Survival (S) of spores

Along with temperature and relative humidity, the UV component of solar radiation, which is the most lethal, controls survival of spores in the atmosphere. Most spores, which will be transported through the atmosphere and deposited within a few hundred kilometres of the source, remain with the mixed layer of the atmosphere (Clarke et al., 1983) and generally reach altitudes of only 1 to 3 km. Although these spores do not normally encounter temperatures or relative humidities that can be lethal, the combination of temperature, relative humidity and UV radiation found at the top of the mixing layer can be fatal to such spores. The irradiance to which spores are exposed in the atmosphere may result in zero germination in a sample of 500 spores, yet there is still a 50 per cent probability that germination of spores drawn from the entire population can be as high as 1.385×10^3 (Fisher and Yates, 1948). Thus, if 10^5 spores were exposed to the same irradiation, about 139 spores would probably be seen to germinate.

15.5.5 Deposition (*D*) of spores onto plants

Deposition mechanisms can be either dry or wet. Most wet deposition occurs as a result of washout by rain. The efficiency of raindrops to capture spores depends on the size of the spores and the raindrops, the rate and duration of rainfall, as well as the depth of precipitation and spore layers.

Wet and dry depositions are closer in number than has been suggested by their relative deposition rates because there are many more dry hours than wet hours. Spores delivered during rain will be more likely to initiate disease because leaves will be wet and infection can begin immediately. The uncertainty in estimating the rate of wet deposition is large and it is difficult to ascribe to this mechanism a representative role (Smith, 1981). Calculations using this model have been carried out considering only dry deposition.

A solution to the problem of the total number of spores deposited during the total transport event is shown in Figure 15.6. The problem was solved for two wind speeds, 20 km h⁻¹ and 40 km h⁻¹, and for two sky conditions, sunny and overcast. The solution in Figure 15.6 shows the overwhelming importance of spore survival. The danger of infection from the small, potentially unnoticed local source, plotted in Figure 15.6 as a solid bar at 700 km, 2 km away from the location of the target area, might be considerably more serious on a sunny day than the massive source 700 km away, or a comparable danger on a cloudy day. Transport speed is very important during sunny weather, as doubling the speed increased by a factor of about 10⁷ the number of spores deposited after travelling 700 km. The time that the spore cloud leaves the

source is important on clear days. Although fewer spores leave at 3 p.m. (dashed line and open square) compared with the 10 a.m. release (solid line and solid square), the spores released at 3 p.m. are exposed to less sunlight and soon exceed the greater number of spores released at 10 a.m., which are exposed to greater hours of sunshine. At 700 km downwind there is a difference factor of about 10¹² in the calculated spores deposited, depending on sky conditions and transport speed. The calculations in this model are subject to large uncertainties and are discussed in Aylor (1986). The methodology should provide pathologists with reasonable estimates of the likelihood that viable spores from distant sources will reach susceptible crops by aerial spore transport. Aylor (1986) expressed the various uncertainties in his model in Table 15.3.

Synoptic models can be associated with specific trajectories. Investigation of the potential carriage of small particles, such as spores, from the Australian continent to Macquarie Island, about 1 500 km south of continental Australia, was carried out by Pierrehumbert et al. (1984) by investigating 85 kPa temperatures and selecting abnormally high values that were up to three standard deviations above the average. The high temperatures were ascribed to advection of continental air to Macquarie Island, rather than vertical advection due to subsidence. Trajectories were drawn for occasions when 85 kPa temperatures were two and three standard deviations above the mean. These trajectories were drawn from Macquarie Island and invariably arrived back to the Australian continent. A synoptic model was deduced, which required the rear edge of an anticyclone to remain quasi-stationary over the area for several days. Such a model must assume the availability of particulate matter to be transported beneath a subsidence inversion and can only establish a possible means of transport.

Table 15.3. Uncertainties in estimates of transport factors

<i>Process</i>	<i>Factor</i>
<i>P</i>	100–1 000?
Simulation	
Survey	
<i>T</i>	2–5
Mixed layer (ML)	10–20
Escape from ML	?
<i>S</i>	
>1%	2–5
<0.1%	?
Dry deposition velocity	2–5
Wet deposition velocity	?

15.6 AIR POLLUTION

Although not strictly aerobiological quantities, gaseous and particulate pollutants can be spread from source regions through the atmosphere to affect regions of sensitive biota, including airborne spores. Major atmospheric pollutants include ozone, nitric oxides, volatile organic compounds and sulphur dioxide, mostly generated by the burning of fossil fuels. Ozone is formed by the reaction of nitric oxides (NO_x) and volatile organic compounds (VOCs) in the presence of heat and sunlight. Ozone disrupts plant physiological processes, which leads to poor

plant health and susceptibility to disease, pests and environmental stresses; ozone also leads to reduced yields. Sulphur dioxide combines with atmospheric water vapour to create sulphuric acid, which precipitates as acid rain that can acidify rivers and lakes, and damage crops, trees and other plants. Government environmental protection agencies establish and enforce allowable limits for air pollutants to prevent health hazards such as eye irritation, asthma and other ailments.

15.7 **SPECIAL CONSIDERATIONS FOR FLYING ORGANISMS**

Inanimate airborne objects were the predominant topic of discussion in preceding sections because similar physical processes may be applied to them. The impact of organism flight is also important to agricultural production systems, however. Such organisms include numerous species of insects, birds and bats. Aerobiological transport models presented in 15.5 can be readily modified for use with flying organisms.

The flight ability of pest insects allows them to evade natural enemies and seek new habitats in search of mates, nutrition and oviposition sites. Knowledge of insect biology is essential to the development of aerobiological process models and agricultural management strategies. For example, one should know when to expect insects to attain the adult stage capable of flight, and under what atmospheric and other environmental conditions they are likely to do so. Web-based models are

available to calculate pest development based on degree-day accumulations (for instance, <http://www.ipm.ucdavis.edu/general/tools.html>). Bio-physical factors, including vertical distribution of airborne insects, flight speed, flight heading, lateral spacing among organisms in flight and flight duration, must also be considered when investigating movement of pest insects. Empirical data are often difficult and expensive to acquire – as a result, agricultural meteorologists may need to apply aerobiological factors among similar organisms (such as moths from caterpillar pests). For example, Wolf et al. (1990) tracked a broad dispersing cloud of insects for a distance of 400 km using aircraft-mounted radar and determined dispersal characteristics that can be applied to other biota flying in the nocturnal boundary layer.

It is important to stress that beneficial organisms also disperse in the atmosphere. Insect parasites and predators have been captured in aerial nets, revealing that these natural enemies also disperse but generally not as fast as moderate or fast-flying pest insects. For the agriculturist, natural predators are commonly considered to be other insect species. Birds and bats also consume large quantities of insects, however. Migratory species of predators coincidentally appear to migrate along the same aerobiological pathways used by crop pest insects (Westbrook et al., 1995). For example, large populations of Brazilian free-tailed bats migrate from Mexico into central Texas and are known to consume a diverse diet of insects, including major migratory insect pests of corn, cotton and vegetable crops (McCracken and Westbrook, 2002).

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APPLICATIONS OF CLIMATIC RESOURCES IN MOUNTAINOUS REGIONS

16.1 INTRODUCTION

As stated in the document on mountains that was endorsed in 1992 by the Earth Summit in Rio de Janeiro (Agenda 21, Chapter 13, Managing Fragile Ecosystems: Sustainable Mountain Development), "Mountains are an important source of water, energy and biological diversity. Furthermore, they are a source of such key resources as minerals, forest products and agricultural products and of recreation. As a major ecosystem representing the complex and interrelated ecology of our planet, mountain environments are essential to the survival of the global ecosystem."

Although they are usually viewed as "badlands" in most developed countries, mountainous regions are home to around 270 million rural mountain people in developing and transition countries. According to FAO (2003), 78 per cent of the world's mountain areas are considered marginally suited or unsuited for arable agriculture and only 7 per cent are currently classified as cropland. Meanwhile, rainfed agriculture constitutes around 83 per cent of global agriculture (Borlaug and Dowsell, 2000). When considering resource-poor farmers in mountainous areas, virtually all of the agriculture is rainfed.

Mountains are responsible for delivering water and sediment distribution to lowlands. Fertile and deep soil profiles in lowland valleys are usually formed at the expense of soils eroded from hillsides, leaving behind erosional features and shallow soil (Romero et al., 2007b). An estimated 80 per cent of human

freshwater consumption comes from rainfall and melting glaciers in mountainous areas (Schreier et al., 2002). Moreover, 12 per cent of the global population is directly supported by mountain resources, while 50 per cent of the population is indirectly affected by mountains. Many of the world's most impoverished and food-insecure people live in these regions (United Nations, 2003).

Most of the abiotic risk in mountainous regions is associated with the influence of the interannual climatic variability that severely affects the fragile mountain environment. The high climatic variability affects all human activities in mountains. The aim of this chapter is to document the climatic impacts on resources in mountains with an emphasis on small-scale issues. At the same time, ideas related to how people can adapt to these climatic conditions and manage the climatic resources in these regions will be explored. First, however, the effects of mountains on the general atmospheric circulation patterns need to be described and the implications these actions have for decision-making processes at the regional and farm levels need to be discussed.

16.2 WHY IS THE CLIMATE DIFFERENT IN MOUNTAINOUS REGIONS?

The primary and most evident difference between mountain climate and the climate in other regions is altitude (Figure 16.1). The atmospheric density over

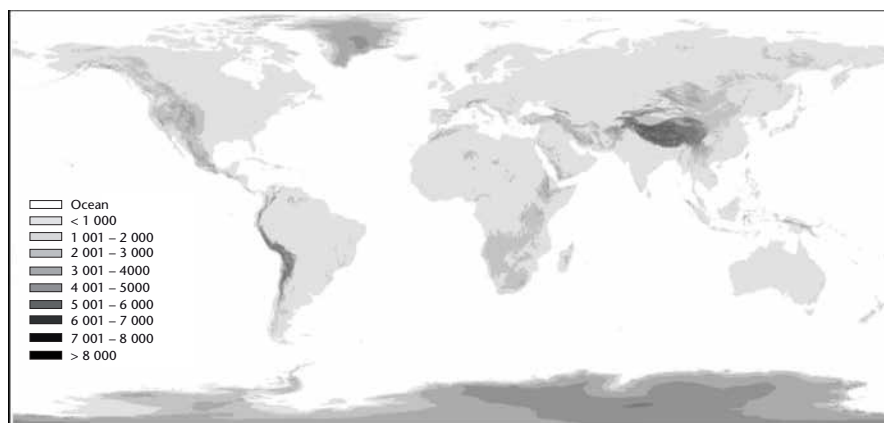


Figure 16.1. Mountainous regions in the world
(based on data from United States Geological Survey's EROS Data Center, 1996)

the mountains is reduced and this increases atmospheric transmissivity (16.3.1.2 below; Baigorria et al., 2004; Whiteman, 2000). Incoming solar radiation at the surface of the Earth is equivalent to the extraterrestrial solar radiation (which depends on the relative position of the Earth and Sun and the latitude) multiplied by the filtering coefficient of atmospheric transmissivity. In mountainous areas, these filtering coefficients are commonly greater than 0.75 on an average monthly basis during the dry season (clear skies) and daily atmospheric transmissivity coefficients can reach values up to 0.95 (Baigorria, 2005; Lee, 1978; SENAMHI-MEM, 2003).

Mountains are also generally dominated by complex topography, which is a major factor of climate in mountainous regions, but this is not always the case. For example, in the Andean High Plateau (14° S latitude, 71° W longitude, to 20° S latitude, 67° W longitude), which ranges from 3 600 to 5 000 m above sea level (Figure 16.2), the mean

slope angle is 2 degrees. The first impression is that this 135 910 km² plateau should be a desert in terms of human presence; however, agriculture and livestock activities have been performed in many areas for centuries and continue to this day, owing to certain special climatic characteristics, which will be discussed in 16.3.2.3 below.

In mountainous areas, topography is a major factor that determines the amount of incoming solar energy received at the surface. Variability in elevation, slope, aspect (angle formed by the geographic north and the mountain hillside) and shade can create strong local gradients in the incoming solar radiation that directly and indirectly affect such biophysical processes as air and soil heating, energy and water balances, and primary production (Dubayah and Rich, 1995).

Altitude has been used as the main factor affecting the spatial distribution of rainfall and temperature.

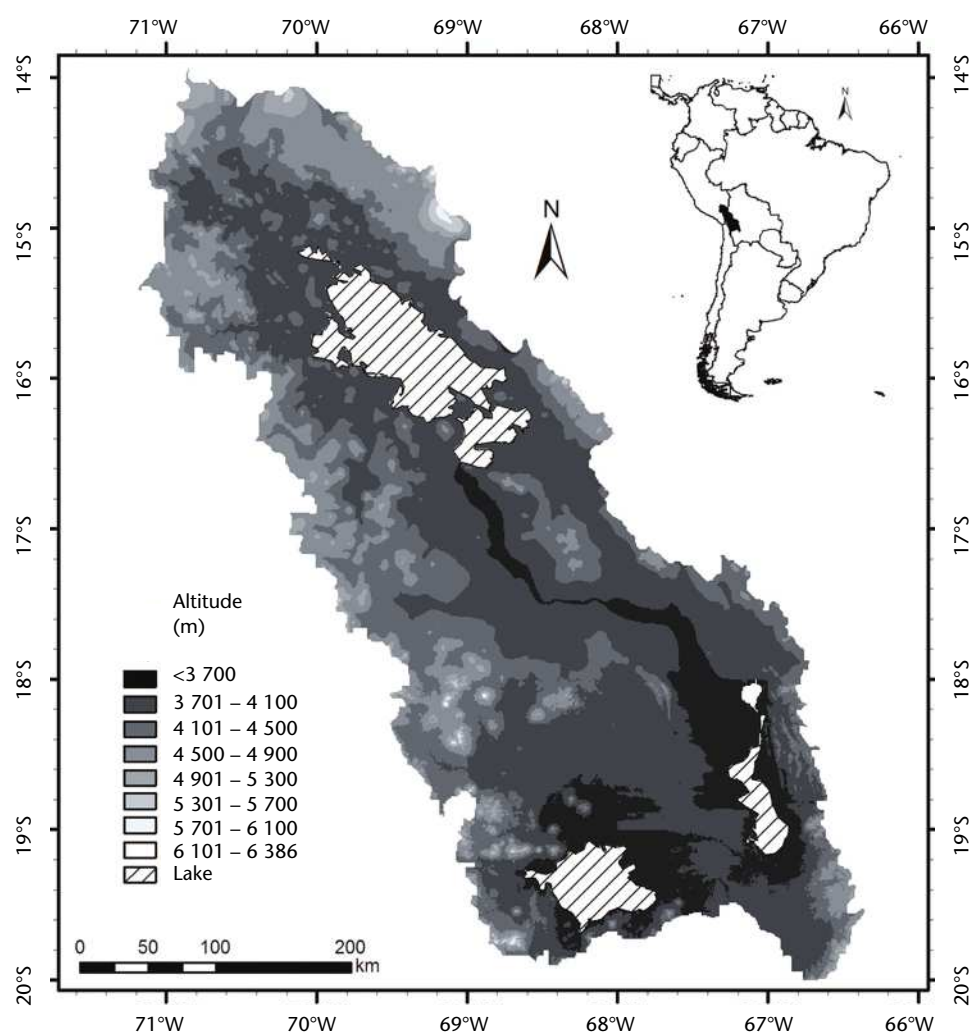


Figure 16.2. Location and altitude maps of the Andean High Plateau

Most of the time, however, the combined factors of topography and wind circulation are the principal elements responsible for rainfall distribution, whereas temperature variation is mainly explained by these variables, plus altitude and the low water vapour content in the atmosphere.

Global circulation models (GCMs) are usually unaffected by the high elevation gradient (Figueroa et al., 1995). A cumulonimbus cloud could reach a height of 15 km (Whiteman, 2000), while Mount Everest has an elevation of 8 846 m (Fellman et al., 1992). Mountain chains and peaks cause the air to lift, however, and then condensation processes in the lower troposphere occur, which, under certain atmospheric humidity conditions, causes small-scale cloud formations and even rainfall. These movements affect the condensation level not only of the mountain, but also areas far away that are parallel to the lee side of mountains, owing to the formation of atmospheric waves.

Water vapour constitutes around 4 per cent of the atmosphere by volume close to land surface (and 3 per cent in terms of weight), and it is almost absent above an altitude of 10 km. Water vapour is available to the atmosphere through evaporation from water and land surfaces and through transpiration by plants, which rises by virtue of air turbulence. According to the Clausius–Clapeyron equation, saturation vapour pressure depends on air temperature: because air temperature decreases with altitude, water vapour content in the atmosphere decreases inversely to altitude (Barry and Chorley, 1998). Water vapour content is another important characteristic in mountainous areas, since it is responsible for the sensible heat level that is directly related to the daily temperature range. Water in mountainous areas is not only important for crop requirements, but also as a thermoregulating agent. As will be discussed, the presence of water bodies affects the spatial distribution of temperature, especially in mountainous areas.

16.3 METEOROLOGICAL VARIABLES IN MOUNTAINOUS REGIONS

16.3.1 Incoming solar radiation

The present section will deal with the interactions between incoming solar radiation and hillside orientation and the effects of altitude in the optical thickness of the atmosphere. In particular, the effects of global circulation patterns in the

atmospheric transmissivity in mountainous regions will be reviewed, along with the relationships between the spatial and temporal variability of incoming solar radiation and crops and crop pests and diseases.

16.3.1.1 Facing the sun

An important factor in the climate of mountains is the orientation of the mountain chain. Hillsides oriented to the east receive direct and diffuse incoming solar radiation during the morning, whereas hillsides oriented to the west receive diffuse and part-time direct incoming solar radiation later in the morning (part (a) in Figure 16.3). The process reverses during the afternoon. Warming of land during the morning, however, produces convective (vertical) movements that form convective clouds. The albedo of these clouds reflects part of the direct incoming solar radiation into space, which acts as a filter. Therefore, during the afternoon, the amount and quality of incoming solar radiation decreases in comparison with that received in the morning (part (b) in Figure 16.3). As a result, west-oriented hillsides receive less of the total daily incoming solar radiation than do east-oriented hillsides. This is especially true for deep and narrow mountain passes, gorges and canyons.

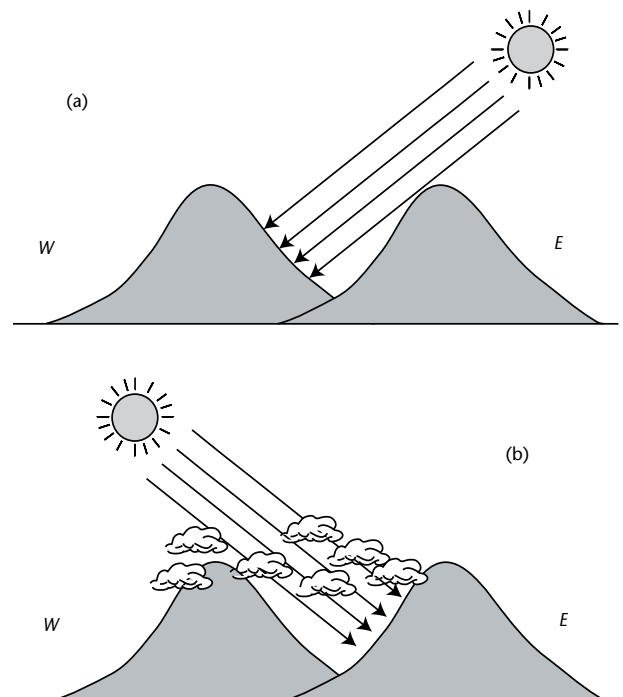


Figure 16.3. Effect of the hillside orientation in receiving incoming solar radiation. Figure (a) depicts the morning and (b) the afternoon

Hillsides oriented towards the Equator receive more total annual incoming solar radiation than those oriented to the polar regions. The higher the latitude, the larger the difference observed. This difference increases when crossing the 23.45° N and 23.45° S latitudes, which are the extreme latitudes where the relative movement of the sun reaches the Tropics of Cancer and Capricorn, respectively, during the solstices. As an historical example of the hillside orientation effects, one can cite the ancient Middle Eastern city of Shechem, which was located between the vegetated north-facing slope of Mount Gerizim and the arid south-facing slope of Mount Ebal. This ecological difference was the result of an evaporative rate on the south-facing slope of Mount Ebal that was almost double the rate on the other slope because of the direct incoming solar radiation (Hillel, 2006).

This geographical orientation creates climatic differences that are especially important in mountain chains like the Himalayas, which follow an east–west direction, in contrast to the Andes, which run north to south. Owing to differences in the radiative budget, latitudinal changes generate more climate variability than longitudinal changes. This creates a combination of climates and micro-climates that differ among the mountain chains that dissect the Earth's surface. This also results in such extremes as desert lands in the southern Andes of Chile and Argentina, and rainforests in the northern Andes of Colombia and Venezuela. Geographical orientation at local scales also has a significant influence on climate, as will be shown in 16.3.2 to 16.3.4 below.

16.3.1.2 Atmospheric transmissivity

Most of the energy available in the environment is due to the amount of incoming solar radiation. Gases, aerosols and other particulates in the atmosphere filter some of the energy available in the top of the atmosphere before it reaches the Earth's surface. The percentage of energy that goes across this filter on its way to the surface of the ground is called atmospheric transmissivity (τ), which is calculated as shown in Equation 16.1. Transmissivity has temporal and spatial variations; however, because mountains reduce the optical thickness of the atmosphere, under clear sky conditions, τ can reach values as high as 95 per cent (Lee, 1978).

$$\tau = \frac{H}{H_o} \times 100 \quad (16.1)$$

where H and H_o ($\text{MJ m}^{-2} \text{d}^{-1}$) are the measured and extraterrestrial incoming solar radiation, respectively.

Baigorria et al. (2004) found a gradient of τ parallel to the Andes, as a result of altitude and orographic barrier effects over clouds and aerosols in the atmosphere. Thus, mountains are major topographic barriers to weather systems and airflow below an altitude of 2 500 m, preventing the regular exchange of airmasses – in case of the Andes, between the Pacific and Atlantic oceans.

High altitudes do not always mean high τ , as shown in Figure 16.4. Interactions between climatic controls and atmospheric circulation patterns create unique seasonality effects like those of the Andean High Plateau (Figure 16.2). In this area, precipitation is concentrated over the two- to three-month wet season during the austral summer, which is associated with the development of convective clouds over the Central Andes and the southwestern part of the Amazon Basin (Horel et al., 1989). As a result, during these wet episodes, around 50 per cent of the area is covered by clouds in the afternoons, whereas convective clouds are almost non-existent during the dry episodes (Garreaud, 1999). These observations explain both the occurrence of monthly average τ values that are lower than 65 per cent in the winter and the occurrence of rainfall in the summer, even though the altitude exceeds 4 000 m in some areas. Nevertheless, monthly average τ values higher than 75 per cent can be reached in spring, owing to the position of the Sun over the southern hemisphere and the fact that cloud systems are not yet formed. In conclusion, one can say that it is not τ , but the potential of higher τ values that increases with elevation.

16.3.1.3 Beneficial use of knowledge on incoming solar radiation in mountains

Due to the potentially high transmissivity levels of the atmosphere at high altitudes (Baigorria et al., 2004; Lee, 1978), incoming solar radiation at the crop surface exceeds the maximum threshold of photosynthetically active radiation (PAR) needed for photosynthesis. This is especially true when receiving direct incoming solar radiation. As explained in 16.3.1.1, hillsides oriented to the north and to the south receive incoming solar radiation of medium to high quality during the morning, but medium to low quality during the afternoon, which is related to weather conditions. Changes in ratios of PAR to H with altitude have been reported in the range of +3.6 per cent per km under cloudless weather and –1.8 per cent per km under cloudy weather in the first 1 500 m of altitude in the Naeba Mountains of Japan (Wang et al., 2007). Thus, daily

integration of incoming solar radiation for crops is higher on hillsides oriented to the north and to the south, followed by hillsides oriented to the east; those oriented to the west have the lowest integration.

This information is important for crop zoning. If the interest is in fruits, for which markets favour colour appearance and sugar concentration levels ($^{\circ}\text{Brix}$), as is the case with apples (Merzlyak et al., 2002; Reay and Lancaster, 2001), grapes (Kliewer, 1977; Kliewer et al., 1967), peaches (Erez and Flore,

1986; Layne et al., 2001) and so on, then east-oriented hillsides are recommended. Extreme conditions of incoming solar radiation cause sunburn or sunscald, however. (Merzlyak et al., 2002; Piskolczy et al., 2004). Therefore, crop and cultivar selection, especially in fruit plantations with several years before the first harvest, is one of the most important factors to consider before planting in mountainous regions.

Planting at higher densities than normal can be favourable under conditions of high incoming solar

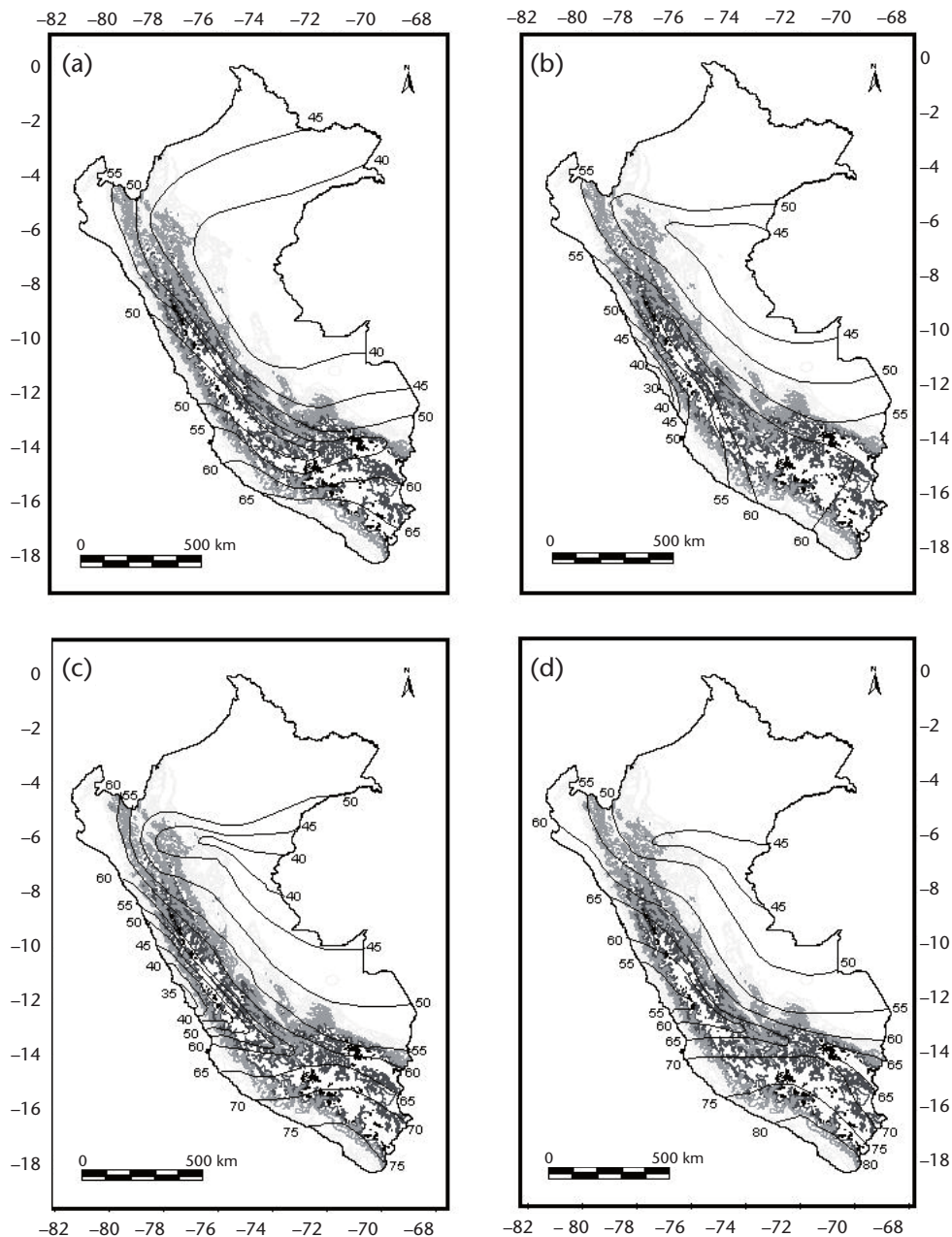


Figure 16.4. Climate maps of atmospheric transmissivity (%) in different seasons in Peru: (a) March, (b) June, (c) September and (d) December (adapted from Baigorria et al., 2004)

radiation (Dosio et al., 2000). If the interest is focused on yield with C₄ crops, (maize, sorghum, and so forth), then hillsides oriented to the north and to the south are recommended. Finally, because under low water vapour contents (commonly found at high altitudes) incoming solar radiation is directly related to temperature, crops like potato, native roots, tubers and pastures, as well as green or yellow fruit cultivars, are suitable for these conditions.

This zoning approach is based only on quantity and quality of incoming solar radiation. This aspect must be combined with other variables, especially rainfall regimes or water availability, for a better crop selection.

Another beneficial use of potentially high levels of incoming solar radiation in mountainous regions is the control of pests and diseases. As for crops, the majority of pests and diseases are affected by constraints on growth and development caused by climatic conditions. This means that the most important pests and diseases in the lowlands hardly survive under the climatic conditions in high mountainous regions. For example, incoming solar radiation has a detrimental effect on the germination of *Phytophthora infestans* sporangia (Jaime-Garcia et al., 1999; Mizubuti et al., 2000; Rotem and Aust, 1991; Rotem et al., 1985), which are responsible for the late potato blight, a major constraint to potato production worldwide (Forbes et al., 2001).

A good example is the district of Huasahuasi, Junín Region, Peru (14°23' S latitude, 71°19' W longitude, 4 046 m altitude), which is located in the climatic boundary area where commercial potato varieties can be cultivated but where almost no pest and disease can survive. There, high-quality asexual potato seeds are produced for highly productive fields in the lowlands, with low needs for pesticides, fungicides and nematicides (Bentley et al., 2001; Moreno, 1985). Some changes in climate have been affecting this region in recent years, however, slightly increasing the incidence of pests and diseases there.

16.3.2 Temperature

16.3.2.1 Temperature versus altitude

When unsaturated air (relative humidity less than 100 per cent) is lifted, it cools at the thermodynamic rate of 9.8°C per 1 km altitude, which is called dry adiabatic lapse rate. This happens in a free atmosphere, however, far away from the ground surface effect and in the absence of

temperature inversions.¹ The direct relationship between temperature and altitude is shown only when the vertical structure of the atmosphere is analysed, but not necessarily when topography and land characteristics are taken into account. For example, Tang and Fang (2006) reported different temperature lapse rates at different hillslope orientations in Mount Taibai (Qinling Mountains, China). South-oriented hillslopes registered a temperature lapse rate of $0.34 \pm 0.05^\circ\text{C}/100 \text{ m}$, whereas north-oriented hillslopes recorded $0.50 \pm 0.02^\circ\text{C}/100 \text{ m}$. These values showed a large seasonal difference within a maximum range of 59 per cent and 42 per cent for the southern and northern hillslopes, respectively. François et al. (1999) reported higher temperatures on the hillsides of mountains and volcanoes in comparison with the flat lower areas of the Andean High Plateau. Thus, this theoretical relationship between altitude and temperature is far from linear, especially when observed in large mountain areas, due to the effect oceans and continents have on the atmosphere, an effect that diminishes with height (Baigorria, 2005; Peixoto and Oort, 1992).

This dry adiabatic lapse rate is usually misunderstood and applied to mountains in the wrong way. Many highland valleys above 2 500 m of altitude have higher temperatures than their neighbours in adjacent valleys at the same altitude. These are usually fertile valleys supporting a high density of livestock and intensive agriculture. These important areas are exceptions to the rule of the inverse relationship between altitude and temperature.

At local scales, spatial variations of minimum temperatures are closely related to the terrain type, owing to cold air accumulation. Thus, frost occurs most frequently in narrow valleys and concave locations, whereas peaks and convex areas are found to have very few radiative frost events (Lindkvist et al., 2000). This is why the spatial and temporal distribution of temperature in mountainous areas will be described in more detail.

16.3.2.2 Frost events

The importance of the high levels of atmospheric transmissivity in mountainous regions and how these are related to high values of incoming solar radiation have already been described. All bodies with temperatures above 0° Kelvin generate

¹ Layers in which temperature increases with height instead of decreasing (Whiteman, 2000)

radiation in a wavelength inverse to the body's temperature (Peixoto and Oort, 1992). Because the Earth's temperature is higher than 0°K (it is assumed to have a temperature of 255°K), it generates the maximum emission in the infrared (thermic) range (~10 µm). In mountainous regions, due to the low atmospheric optical thickness and the lack of water vapour in the atmosphere (which captures the long-wave radiation and maintains the sensible heat), the downward long-wave radiation is reduced and the Earth's radiation disperses over space under cloudless weather nights. This loss of energy diminishes surface temperature, which can reach temperatures below 0°C, depending on other atmospheric and land characteristics. This is called radiative frost and often occurs during night-time clear skies, including occurrences in the most equatorial mountainous regions of the Ecuadorian Andes (Baigorria, 2005; Baigorria et al., 2007; Crissman et al., 1998). Most radiative frosts occur during the dry season when rainfed agricultural fields are usually fallow. Frost events can occur early and/or later during the cropping season, however, and this can have a serious effect on emerging crops and/or harvests, respectively. Knowledge of the frost-free period supports decision-makers in selecting planting dates, as well as in selecting from short- to long-term crops and varieties. In areas where water is available for irrigation, a combination of frost-resistant crop varieties and night-time irrigation during radiative frosts is key for a successful harvest.

Air temperature decreases gradually during radiative frost at night-time. This is not necessarily the case for advective frost, however, which occurs when low-temperature airmasses come from cooler regions through global atmospheric circulation. These advective frosts do not depend on clear sky conditions, and temperatures decrease drastically in minutes to hours, sometimes creating temperatures below 0°C. There are two important aspects of freeze events: frost and duration of the event. During radiative frosts, air temperature gradually decreases and plant cells begin to release intracellular water, trying to generate heat from the water phase change from liquid to solid (latent heat of fusion: 333 J gr⁻¹ of water). If the frost event is long enough, the plant cells die by dehydration. Irrigation under these circumstances makes extra energy from phase changes available and does not supply water to the plant. In case of a rapid temperature decrease during advective frost, temperatures fall below 0°C and the intercellular water freezes, forming ice that eventually breaks the cellular membrane. Irrigation and/or air movement does not help at all. Advective frost kills the crop and

necrotic tissues appear immediately as black-coloured patches replacing the green chlorophyll.

Again, knowledge of topography and global atmospheric circulation patterns will support decision-making when planting different kinds of crops and varieties. Several native crops and varieties are frost-resistant in some or all of their phenological stages. Usually, however, they have a low capacity for productivity, owing to their shape, size, taste or colour, which attract low market values. These native germoplasms are an asset to marginal agriculture, however, because they guarantee food security for farmers.

Examples of resistant crops are native Andean roots and tubers. One of these examples is known as maca (*Lepidium meyenii* Walp.). It is typically cultivated above the altitude of 4 400 m and grows in areas with a mean temperature of -1.5°C and a potential minimum temperature of -10°C (Quiroz and Cárdenas, 1997). Oca (*Oxalis tuberosa*) can grow at elevations of up to 4 100 m and can yield from 35 to 55 tonnes per hectare (t/ha) with adequate management (<http://www.cipotato.org/artc/artc.htm>); ulluco (*Ullucus tuberosum*) and mashua (*Tropaeolum tuberosum*) both contain up to 75 per cent of dry matter in their tubers, as well as high levels of isothiocyanates known for their insecticidal, nematicidal and bactericidal properties. They can tolerate temperatures from -2°C to -4°C (Romero et al., 1989). Native grains such as quinoa (*Chenopodium quinoa* Willd.) survive in temperatures as low as -8°C, and canihua (*Chenopodium pallidicaule*) can survive in temperatures down to -10°C (FAO, 1994).

Some cultivated bitter potatoes, such as *Solanum juzepczukii*, *Solanum ajanhuiri* and *Solanum tuberosum andigenum*, tolerate lower temperatures than commercial varieties. Such bitter varieties are cultivated in high mountainous niches where commercial varieties cannot grow. Figure 16.5 shows simulated differences in the distribution and yields between a commercial variety (Mariva) and bitter potato variety (Imilla Negra). Some native bitter potato varieties resist temperatures as low as -4°C (*Solanum chomatophilum*, *Solanum multidissectum*) and even -12°C (*Solanum comersonii*) (Chen et al., 1976). These species are used as the genetic source for frost tolerance of commercial potato varieties (Baudo et al., 1996; Cardi et al., 1993; van Swaaij et al., 1987; Wallis et al., 1997). These germoplasms are considered a major asset to societies and fortunately most of them are under care of local and international study and selection efforts.

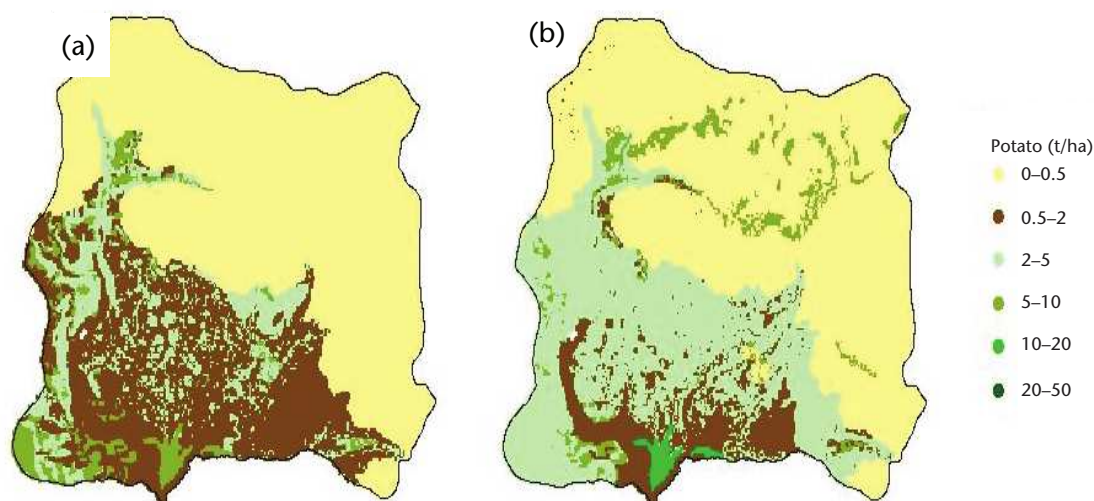


Figure 16.5. Comparison of simulated potato yield distribution between two subspecies of *Solanum* under rainfed conditions and low N fertilization rates. La Encañada, Peru. (a) *Solanum tuberosum* L. subsp. *tuberosum* var. Mariva, and (b) *Solanum tuberosum* L. subsp. *andigenum* var. Imilla Negra.

16.3.2.3 Daily temperature range and thermoregulating agents

Water vapour in the atmosphere stores the sensible heat flux, which is directly reflected in the air temperature. Because of the low level of water vapour at high altitudes and in deserts, the variations in air temperature mainly depend on the incoming solar radiation. Low water vapour content combined with high atmospheric transmissivity gives rise to a wide daily temperature range.

Air temperature is measured at a meteorological station. The same body (with the same albedo), however, will record large differences in temperatures depending on whether or not it is exposed to direct sunlight. A typical example is observed in towns located in mountainous areas; people walking on footpaths in the shade of houses are usually wearing coats, while people across the street and under direct sunlight conditions are wearing T-shirts. According to Toudert and Mayer (2007), a study of thermal comfort in a street canyon with an east-west orientation under hot summer conditions in Freiburg (Germany) showed that there was a small increase in air temperature in the irradiated surfaces of the street canyon. This was due to the direct impact of the incoming solar radiation and the heat gained because of the geometry and orientation of the canyon. According to this study, thermal stress was mostly attributed to solar exposure, and on average, a standing body absorbed 74 per cent and 26 per cent of heat in the form of long- and short-wave irradiance, respectively. In mountainous regions with low water vapour content, temperatures are

higher under direct solar exposure than under shaded surfaces.

Plant metabolism is affected by daily temperature range and not by mean temperatures. If the goal is agricultural production, then one must focus on temporal and spatial analysis of maximum and minimum temperatures. In mountainous regions, plants are subject to much wider daily temperature ranges than at lower elevations. Maximum temperatures can be managed by plants depending on their type of metabolism (C_3 , C_4 or CAM). Plants regulate their internal temperature accordingly, but for most of them, 40°C is the threshold at which protein (enzyme) denaturalization starts.

Crop areas in mountains are more affected by a low temperature threshold than by a high temperature threshold. The presence of water bodies in mountainous regions is important not only as a source for irrigation, but at high altitudes bodies of water modify the daily temperature range by increasing the atmospheric water vapour content and capturing energy across the water body profile.

Because of water's transparency, sunbeams penetrate deeper in water than in soils. As a result, more solar energy is stored in water than in an equivalent area of soil. Large water bodies absorb large amounts of energy, which in mountainous regions is released into the atmosphere during the night, thereby avoiding extreme minimum temperatures and diminishing occurrences of radiative frost. To demonstrate the thermoregulatory effect, an analysis was conducted of annual maximum and minimum temperatures from 16 weather stations

around Lake Titicaca, on the border between Peru and Bolivia (Andean High Plateau, Figure 16.2) (SENAMHI-MEM, 2003). To diminish the altitudinal effect, all temperatures were standardized to the lake level by using the dry adiabatic lapse rate ($+9.8^{\circ}\text{C km}$). Distances from each weather station to the lake were estimated using a Geographical Information System (GIS). Figure 16.6 shows the scatter plots and the coefficient of determination between minimum temperatures, temperature range and maximum temperatures versus distance. Minimum temperatures decrease linearly with distance to the lake, whereas temperature range and maximum temperature increase. Distance from Lake Titicaca explains 73.9 per cent, 72.9 per cent and 54.7 per cent of the spatial variability of each variable, respectively, up to a distance of 120 km. Therefore, land no more than 5 km from Lake Titicaca can be used for agricultural purposes (François et al., 1999).

In the case of shallow water bodies, the volume of mass where the solar energy is stored may be

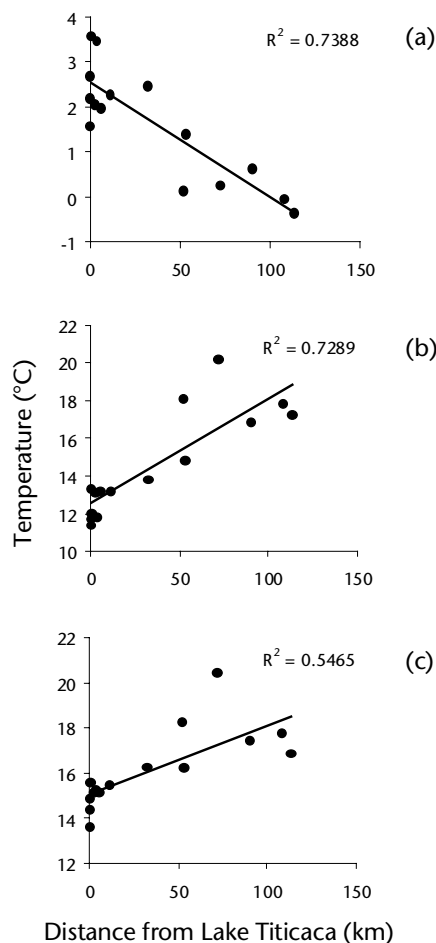


Figure 16.6. Thermoregulatory effect of Lake Titicaca at: (a) minimum temperature; (b) temperature range; (c) maximum temperature

relatively small; before temperatures drop below 0°C , however, the change in the state of water from liquid to solid provides a buffer effect against low minimum temperatures owing to the energy released during the process (333 J g^{-1} of water).

16.3.2.4 Beneficial use of knowledge on mountain temperature

Knowledge of these facts allows for the design of solutions to the challenge of food production. Some agricultural management practices make use of the thermoregulatory and buffer effects provided by water. Raised field systems (Figure 16.7) in a series of elevated soil platforms (up to 1.2 m high and

2–20 m wide) surrounded by canals (1.6–4.5 m wide) flooded with water have been utilized in the Lake Titicaca area for centuries (Kolata and Ortloff, 1989; Sánchez de Lozada et al., 1998). These constructions are known as *camellones* in Spanish, *waru-warus* in Quechua and *suka kollo* in Aymara (native languages). They are used to take advantage of the thermoregulatory effect of Lake Titicaca. This technique has been applied to cultivate potato among other native roots and tubers at an elevation between 3 800 and 4 000 m (de la Torre and Burga, 1986). The crop temperature is always 1°C to 2°C higher on the platforms of the raised fields compared with crop temperatures in the plains, owing not only to the thermoregulatory effect of water, but also to the higher relative humidity in the air around the canopy (Lhomme and Vacher, 2002; Sánchez de Lozada et al., 1998). Another similar technology is named *cocha*, a natural or artificial land depression with a depth of between 0.5 and 5 m and an area of up to 3 000 m^2 (de la Torre and Burga, 1986). This land depression is used for storing water for crop irrigation, but its

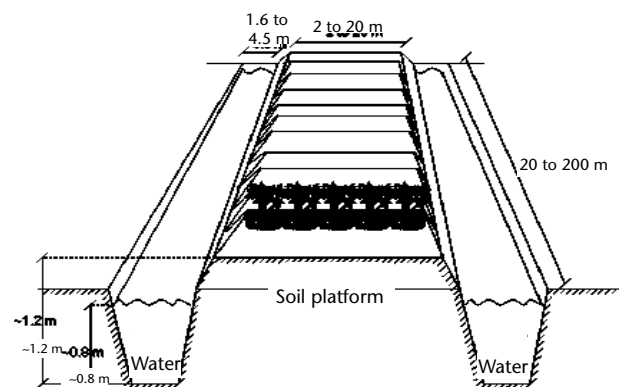


Figure 16.7. Outline of the raised field system (*camellón*). Measurements from Sánchez de Lozada et al. (1998) and Lhomme and Vacher (2003).

main function is to reduce the effects of minimum temperatures on crops.

Another possibility for diminishing the effect of low temperature in mountainous regions is to increase plant density. Weak plants will die first, delivering available water from their necrotic tissues, creating the desirable water change-of-state buffer effect. This practice creates an inter-plant competition for soil nutrients, but increases the possibility of plant survival, which increases food security. Together with these practices, it is common to mix commercial varieties that are usually susceptible to frost but take up nutrients efficiently, with native frost-resistant varieties that have low productivity. Under good seasonal climate conditions, commercial varieties will take up most of the soil nutrients and because they grow fast, they will intercept most of the sunlight. On the other hand, in a cold seasonal climate the commercial varieties will not survive, but native varieties will assure crop yields. Intercropping is another possibility in those areas where good seasonal climatic conditions exist.

Knowing the differences in the thermal capacity, conductivity and diffusivity among soils and rocks (Clauser and Huenges, 1995; Sass et al., 1971; Vosteen and Schellschmidt, 2003) allows farmers to increase the capacity to store more energy and to deliver it at night. This delivered energy creates a microclimate around the plant that is capable of attenuating frost effects. Nobel et al. (1992) reported the effect of rocks on soil temperature and soil water potential, and its relationship with rooting patterns in a desert region. In mountainous areas where rocks are available, these are placed at the side of commercial plants. The thermoregulatory effects of the rocks can also be used in stone terraces known as *anden*, which were built by the Incas. On these bench terraces, plants grow more vigorously close to the rock wall compared with ones planted on the opposite side. All kinds of terraces with and without stone walls create favourable microclimates close to walls, however, by increasing the area where incoming solar radiation is stored, delivering the energy during the night.

Rocks are also used to build windbreak walls that allow one to avoid excessive evapotranspiration by breaking the leaf boundary limit. Small areas surrounded by short rock barriers are used to protect crops from wind and low temperatures (Schreier et al., 2002). Highly valuable commercial crops are usually planted in these small farmyards.

A major strategy against frost events is to use topoclimatology. This can be achieved on two different spatial scales: at the regional scale by mapping frost risk, and at the local and field scale by estimating potential cold air accumulation.

To help in planning a large-scale frost protection campaign at the regional level, it is necessary to use a method that combines long historical records of weather station data with spatially extended data, usually with poor temporal coverage. A simple method to accomplish this is to obtain algorithms relating point data (measured at a weather station) with the grid cell data (extracted from satellite or radar images) at the same location. Next, the algorithms can be applied to the entire grid in the images, finally obtaining the minimum temperature maps. With the resulting maps, a reclassification can be performed based on temperature thresholds in order to find the areas affected by frost events of different intensities (François et al., 1999).

An important issue to bear in mind at the local and field scale is that air is considered a fluid. Movement of high-density cold air close to the ground affects crops in the form of frosts. Topographic depressions are susceptible to filling by cold air moving over complex orography.² After a frost event, it is common to find crop parcels highly affected by the low temperatures, whereas metres away, unaffected parcels with the same crops and varieties continue growing. In most of the cases, these highly affected parcels are surrounded by rock, mud or shrub barriers up to 1 m high. These walls transform the parcel into a swimming pool where cold air is captured, thus exposing the crops to low temperatures for longer periods. Under these circumstances, a cold-air drainage placed in the lower boundary will allow the cold air to move downslope without negative consequences.

Lindkvist et al. (2000) described the use of land attributes (plane and profile curvature) calculated from Digital Elevation Models (DEMs) to define zones highly susceptible to frost events. In their study, which was performed in Scandinavia's Scandes mountain range, they found very low frost risk in convex terrain and exposed upper slopes, whereas high frost risk was found in broad concave areas, mainly those that were part of large "U-shaped" valley bottoms. "V-shaped" concavities were highly affected by frost events owing to the high degree of wind shelter and accumulation of cold air. In the case of mountainous plateaus

² Orography is the study of the physical geography of mountains and ranges.

surrounded by elevations, air tends to be colder in the open flat areas than on the hillslopes, since dense cold air flows downwards and is accumulated in the lower areas (Collier et al., 1989).

Mapping frost risk zones based on potential cold air accumulation will support decision-making with regard to where to plant, from watershed level to farm level. Availability of high-resolution DEMs allows for the location of areas where plants are potentially overexposed to cold air for longer periods. Figure 16.8 shows an example of terrain analysis based on a DEM, used for detecting fluxes and accumulation of cold air. A more refined methodology is presented by Chung et al. (2006). Use of differential Global Positioning Systems opens up the opportunity to combine this methodology with precision agricultural practices.

16.3.3 Rainfall

Rainfall has one of the highest spatio-temporal variabilities of all climatic variables. This is especially true in mountainous regions, but there is usually a lack of reliable data to cover large heterogeneous areas. In this section the main physical processes involved in rainfall formation and distribution in

mountains will be addressed, with emphasis on convective and orographic rainfall. These have special characteristics that change from local to regional scales. The rule-of-thumb relationship between rainfall and altitude will also be discussed, together with some ideas on how to construct a weather station network in mountains with a view to increasing its representativeness.

16.3.3.1 Rainfall processes in mountainous regions

There are three main processes responsible for the development of rainfall in mountainous areas: advection, convection and orographic lifting. The first two are also present in non-mountainous areas. Advective rainfall is related to weather fronts travelling across large regions owing to natural air mass movement around the planet through the general atmospheric circulation process. These fronts occur when at least two air masses face each other and then produce air lifting, water condensation and rainfall. Convective rainfall, which usually occurs in summer, is formed by the lifting of air after this air mass has been warmed over a warm land surface. Convective rainfall events are locally formed and their formation has a high

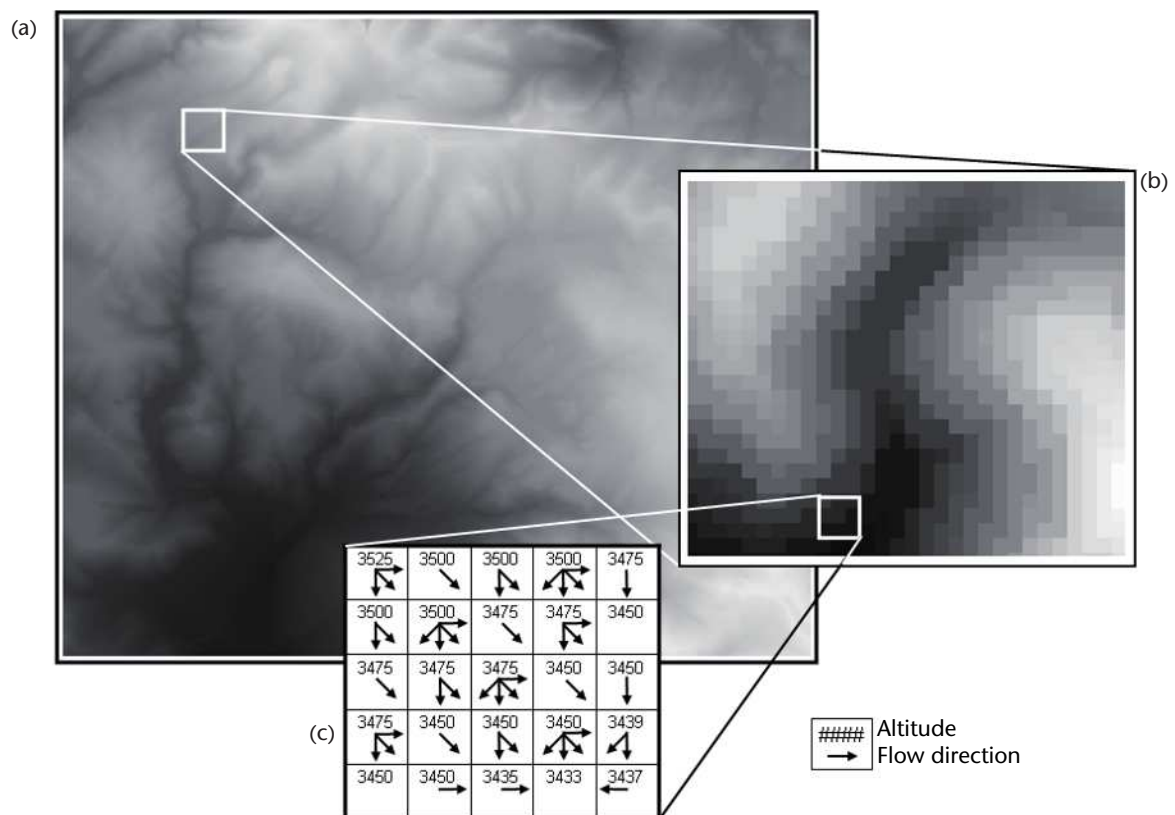


Figure 16.8. Flow direction determined by grid cell analysis: (a) DEM; (b) DEM zoom; (c) numerical analysis of a grid cell subset indicating divergence and convergence of cold air. The number of flow direction arrows at each cell is inversely proportional to the frost risk potential in the cell.

spatial variability. Surface warming is more efficient on flat terrain than on complex topography; this is due to the rugosity of the terrain, which increases the surface area in which incoming solar radiation is stored. Hence, energy storage capacity on flat areas is lower than on those that present rugosity. On flat terrain, excess energy warms the lower atmosphere, raises the temperature of the air, diminishes air density and initiates the air lifting process faster than on rough terrain. Convective rainfall in plateau regions is formed at large scale, as in the Andean High Plateau (Horel et al., 1989; Garreaud, 1999), and at the local scale (Romero et al., 2007a). Large-scale convection in plateau areas can affect the general atmospheric circulation patterns, which is the case with the so-called “Bolivian High”. This warm-cored thermal anticyclone that occurs in the austral summer arises from the intense heating of the Andean High Plateau as a result of incoming solar radiation coupled with high atmospheric transmissivity (Baigorria et al., 2004). This high-altitude anticyclone modifies rainfall regimens from the southern Amazon basin to the Central and Southern Andes (Garreaud, 1999). Local-scale convective rainfall events in mountainous regions are highly erosive and, in combination with steep slopes and erodible soils, can accelerate the soil erosion rate (Baigorria and Romero, 2007; Romero et al., 2007a, 2007b). These types of events have large interannual variability and, depending on the geographical location, are related to El Niño–Southern Oscillation (ENSO) phases.

Orographic rainfall events are generated when an air mass is forced to lift when it faces elevation. A Pacific island is a typical example of this phenomenon: an island featuring a paradise beach in the middle of the ocean with a high volcano in its centre and a big cloud surrounding the volcano’s peak. The lee side of the volcano, which is usually dry due to the foehn effect, will be described in 16.3.4. There are two possibilities for the formation of orographic rainfall: a single peak (usually of volcanic origin) surrounded by a plain, such as Mount Kilimanjaro and most of the mountains in East Africa; and a mountain chain formed by tectonic plates, such as the Himalayas in Asia and the Andes in South America. The big difference between these two situations is that in the first, the air mass has the possibility of moving partially around the mountain, whereas for mountain chains, the air mass is forced to cross over the mountain formation. This latter air mass is uplifted as it encounters the mountain chain and produces rainfall on the windward side of the mountain that is parallel to the mountain chain.

Airmasses crossing mountain chains not only generate cloud formation and rainfall in the mountains, but also mountain waves parallel to the lee side of the chain. When an air mass crosses a mountain chain, air is forced to rise in order to pass this obstacle, becoming cooler and denser than the surrounding air, and under the influence of gravity, it sinks on the lee side of the barrier. The air then overshoots, and oscillates around its equilibrium level, forming mountain waves (Barry and Chorley, 1998; Whiteman, 2000). During the lifting process, water vapour condenses at the crests of the waves, thus forming clouds across and downwind from the mountain barrier. The amplitude of the waves depends on the initial displacement of the flow above its equilibrium position on the windward side of the mountain and is directly proportional to the height of the barrier (Queney, 1948). Wavelength is proportional to wind velocity and rises when air stability decreases.

It should be noted that rain formation is different from rainfall distribution. Rainfall formation processes have been well studied. While raindrops are falling to the land surface they are affected by wind fluxes, which are especially turbulent in mountainous areas. Rainfall distribution is affected not only by terrain height (Hevesi et al., 1992), but also by proximity to moisture sources, terrain relief and the direction of the approaching wind (Blocken et al., 2005; Daly et al., 1994; Marquinez et al., 2003; Mellor, 1996; Whiteman, 2000). Hence, maps based on low station density that depict rainfall distribution in mountainous regions are of limited value when detailed information about a particular site is needed, as for modelling processes involving crop growth or soil erosion. Therefore, it is necessary to include additional information such as orography and atmospheric circulation patterns when creating more detailed maps (Baigorria, 2005).

16.3.3.2 Rainfall, altitude and orography

Many studies, especially those related to rainfall interpolation, underscore the hypothetical relationship between rainfall and altitude. These kinds of studies are often used as an alternative when there is a lack of information. Generalization of rainfall values, indices and/or coefficients to large areas without taking into account climatic controls, orography and other factors can significantly affect end results. The lack of insight in the use of these studies does not mean that they can be ignored: “The absence of evidence is not the evidence of absence” (Sagan, 1997). Nevertheless, environmental sciences tend to use relationships observed over large areas and implement them in small areas at

the watershed or even farm level. This may result in major errors, especially in relation to complex mountainous terrain.

All this does not mean that empirical approaches do not work or that process-based models perform better than empirical ones. It rather means that before applying any method, it is necessary to calibrate, validate and if possible perform an uncertainty analysis of the models, as well as the effect of the data resolution. From a scientific point of view, process-based models are more appreciated than empirical ones. Process-based models are complex to develop, however, and they usually require detailed inputs and have inherent problems in their operation related to their complexity. Although they contribute to the cumulative process of scientific understanding, they do not always perform better than simple empirical procedures. Perhaps the best approach is to disaggregate the empirical analysis into components with a biophysical significance (Baigorria, 2005).

In terms of mesoscale analyses, when normalized difference vegetation index (NDVI) images (Sellers et al., 1994) around mountain chains like the Andes and the Himalayas are analysed, relationships between altitude and rainfall are not directly apparent. In a comparison of two opposite hillsides on the same mountain, one on the windward side and the other on the lee side, at the same altitude and distance from the peak, the NDVI values detected in the windward direction are larger than the ones in the lee.

Soil development is due to interaction of the well-known soil-forming factors (Jenny, 1941). The presence of different rainfall regimes on the two mountain hillsides influences the moisture regimes of the soil and affects the soil formation rate. Parent materials in extremely dry areas in which water and vegetation are scarce may inhibit soil formation. On the other hand, parent materials under moist conditions in warm climates favour the redistribution of soluble materials, which results in a well-defined soil profile. As an example, the World Soil Resources Map (USDA-NRCS, 2005; scale 1:130 000 000) shows highly weathered soils (Ultisols and Oxisols) in the windward eastern Andes of Peru; the lee western hillside contains young soils such as Entisols, however, and in some areas rocky lands are present. A similar picture arises in the Himalayas, where incipient to well-developed soils, such as Inceptisols and Ultisols, are found on the windward southern hillside, whereas a vast area of young Gelisols lies on the lee northern hillside. Both the Andean and Himalayan windward areas are subject to wet winds coming

from the Atlantic and Indian oceans, respectively. As these mountain chains act as natural barriers, orographic rainfall is limited to the windward side of the mountain.

According to Barry and Chorley (1998), the relationship between altitude and rainfall is present only in certain elevations of the same mountainous hillside. These authors reported differences in the altitude at which the maximum precipitation is found and in how the relationship changes in different regions. In tropical and subtropical zones for example, maximum precipitation is found below the summit, and after this point, precipitation decreases with altitude. In conclusion, simple linear relationships between rainfall and altitude might perhaps be valid on the same hillsides facing the wind, but only at mesoscale level (Baigorria, 2005).

In terms of regional and local analyses, however, being on the same hillside of a mountain chain does not mean that the altitude-rainfall relationship can be applied at higher resolutions. Table 16.1 shows rainfall data collected during one month by a network of nine automatic weather stations in a northern Andean highland watershed in Peru. Distances between weather stations ranged from 0.8 to 10.3 km, and as expected, the rainfall spatial variability is not explained by altitude. At daily scale, for example, weather stations at the same altitude (Paulino and Calvario) recorded 21.8 and 0 mm, respectively. In another event, the lowest weather station (Manzanas) recorded 14.4 mm and the highest (La Toma) recorded 3.8 mm. For the closest weather stations (Chagmapampa and Usnio), located at 800 m, the maximum differences of 7.1 mm were registered. From these data, no relationship can be established between amount of rainfall and altitude at high resolutions. Spatial rainfall variability can be explained by the complexity of terrain in mountainous areas (Romero et al., 2007a; Whiteman, 2000).

Orographic details are important because the steeper the underlying terrain, the higher the precipitation rate when air is forced directly up the slope (Whiteman, 2000). Models based on the estimation of orographically forced vertical motions and advection to simulate orographic precipitation (Barros and Lettenmaier, 1993; Pandey et al., 2000; Sinclair, 1994; Smith, 2003) better describe processes of this kind on a small scale. Furthermore, airflow acceleration over the crest of a barrier with steep and narrow upwind faces may displace the precipitation maximum to the lee side of the crest (Daly et al., 1994). From the rain formation point of view, however,

orography must not be seen as a direct effect of changes in the terrain height, but as changes in the cloud's path. For instance, air crossing a deep narrow pass transversally will not follow the orography, falling slope downward to finally climb on the opposite side and produce water condensation and rainfall. Otherwise, the airmass would "jump" from side to side, dissipating the orography effect. Air crossing along the narrow pass will move up or down the path following the orography, however. Figure 16.9 shows the same watershed affected by different wind directions, and how the interaction between orography and wind direction affects the wind flux over the area, and hence the air lifting and formation of orographic rainfall.

It is important to note the difference between wind direction at the surface and at cloud levels. Wind direction measured at weather station level is strongly influenced by the roughness and complexity of the terrain. Whiteman (2000) provides a compilation of the most important changes in wind fluxes due to mountains. In this instance, for orographic rainfall, the focus is more

on the wind direction at cloud altitude, which can be obtained from data that has been reanalysed (Kalnay et al., 1996), or from a sequence of hourly geostationary satellite images (Baigorria, 2005).

16.3.3.3 Monitoring rainfall in mountainous regions

In general, according to Linsley et al. (1977), sample errors in relation to rainfall amounts tend to rise when the average rainfall over an area is increased and tend to decrease when the network density, rainfall duration and area size are increased. According to the *Guide to Hydrometeorological Practices* (WMO, 1970), for hydrometeorological purposes, one weather station is recommended for an area between 100 and 250 km² in the tropical Mediterranean mountain regions. According to data shown in Table 16.1, however, the values recommended are too low for this complex terrain. Moreover, in other applications such as dynamical crop modelling (Jones et al., 2003) or soil erosion modelling (Nearing et al., 1989), not only is the amount of rainfall important, but also its

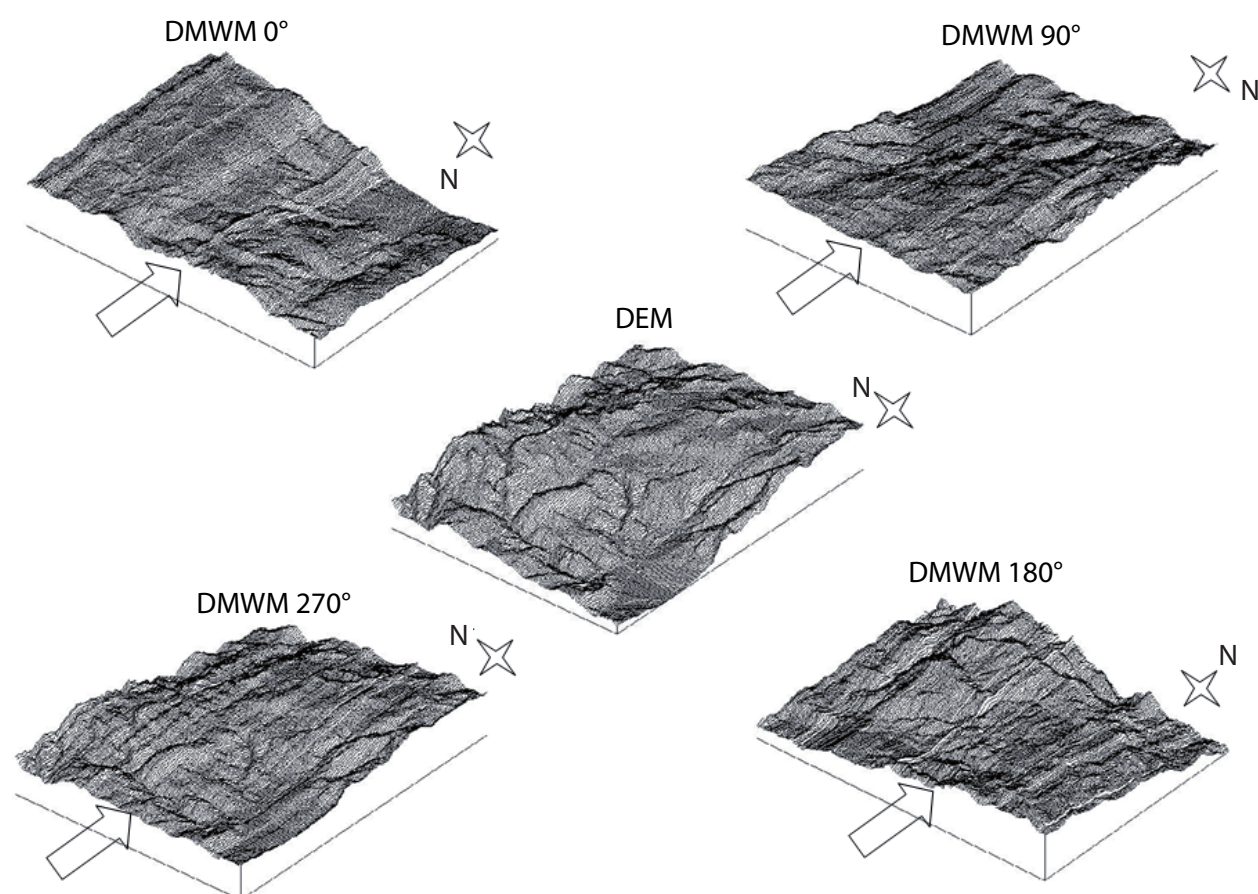


Figure 16.9. Digital Elevation Model (DEM) and four simulated digital mountain wave models (DMWM) corresponding to main wind directions: north (0°), east (90°), south (180°) and west (270°) (adapted from Baigorria, 2005)

Table 16.1. Total rainfall received between 4 December 1998 and 4 January 1999 at nine different weather stations in the La Encañada watershed, northern Peru (adapted from Romero, 2005)

ID	Weather station	Altitude (m)	Rainfall (mm)	Distance between weather stations (km)							
				B	C	D	E	F	G	H	I
A	La Toma	3 590	203	3.7	2.8	7.5	5.4	4.8	5.7	7.2	6.9
B	San José	3 550	27		6.3	10.3	7.2	6.5	8.2	9.5	6.9
C	Quinuamayo	3 500	298			5.0	4.2	3.9	3.7	5.2	6.9
D	Sogorón	3 400	99				3.6	4.2	2.1	1.7	6.8
E	Chagmapampa	3 300	99					0.8	1.7	2.3	3.4
F	Usnio	3 260	117						2.1	3.0	3.3
G	Paulino	3 250	29							1.5	5.1
H	Calvario	3 250	166								5.2
I	Manzanas	3 020	107								

distribution in time and space. The accuracy of rainfall data and the representativeness of the weather station network are extremely important owing to the impact of the raw data used in the model on the model results obtained.

In order to gather rainfall data across the area of interest, the ideal methodology entails on-site collection of near-surface meteorological data. As the size of the target area increases, however, this approach becomes prohibitively expensive (Thornton et al., 1997). The use of methodologies based on satellite and radar images facilitates the understanding of spatial variability of the rainfall. So far, however, the current development of algorithms that take into account the orography of the terrain does not allow one to make full use of these methodologies for mountainous regions.

There are other alternatives for estimating the spatial distribution of precipitation, including geostatistical techniques and atmospheric modeling. Over the past few decades, geostatisticians have developed different interpolation techniques based on the spatial correlation between observations and have used correlations with different terrain attributes (Hevesi, 1992; Kyriakidis et al., 2001; Marquez et al., 2003). For mountainous regions with a lack of weather stations and spatial representativeness, however, errors in the application of these techniques are frequent, due to the inability of the point data to capture the high variability of the rainfall.

The use of atmospheric models based on physical and dynamic processes are another option. General circulation models (GCMs) operating at large grid scales are limited in terms of resolving small-scale

distribution of orographic precipitation (Baigorria, 2005). Mesoscale models and models that include orographically induced dynamics (Barros and Lettenmaier, 1993; Sinclair, 1994; Smith, 2003) need to be initialized from a large-scale numerical model, radiosonde data, radar data and/or surface observation. These models require substantial amounts of input data, and even in developed countries where meteorological networks exist, the applications are not detailed enough to support decision-making for watersheds and farms.

All the methods that are used to estimate the spatial variability of rainfall are calibrated and validated based on the raw data measured at weather stations; for mountainous regions it is necessary to increase the representativeness of the data by planning the network according to certain principles. If the interaction between wind direction and the mountain hillside aspect is the main source of spatial variation, then transects parallel to the wind direction are recommended. Weather stations should follow wind direction and not necessarily altitudes.

If one is interested in measuring the potential rainfall in the windward hillside, the range where the condensation level is located during the season of interest should be found. The weather station must be located at this point.

In addition, weather stations must be located in areas of high interannual variability, for instance within the boundaries of climatological cyclones and anticyclones. This is because small changes in the position of the core or its intensity change the wind direction in the region, carrying different airmasses from different regions, which finally will produce orographic precipitation. If possible and

when resources are available, the weather station density across the region needs to be increased. With the new advances in technology, relatively cheap portable data loggers that measure specific variables are now available. Using this easy-to-install equipment in a secondary network that supports the main weather station network would be most beneficial. The extra information obtained, which can be temporary and floating, will contribute to an understanding of the spatial variability of rainfall in the study areas and create the capability to resolve the non-random rainfall occurrence.

16.3.3.4 Beneficial use of knowledge of rainfall in mountainous regions

In places such as Xinjiang Province (China), where optimal temperatures seldom overlap with the optimal rainfall regime, a deep irrigation is performed after harvesting at the end of the cropping season. Then, at temperatures below zero, the soil water freezes and is thus stored until the next cropping season. At the beginning of the next cropping season, when temperatures rise, rainfall events are rare, but the water soil content is at optimum condition for planting and plants can grow until

rainfall events arrive. When they do, rainfed agriculture is usually performed. Rainfall water is then stored for irrigation at the end of the cropping season to increase the soil water content for the next cropping season. Some frost-resistant roots and tubers that can be planted using non-sexual seeds are planted at the end of the cropping season, before soils freeze. Seeds, together with the water and soil, stay in a frozen state for several months during the low-temperature season. In the next cropping season, these roots and tubers begin to grow as soon as the stored soil water melts.

Many traditional weather forecast indicators (based on meteorological, astronomical and biological observations) used by farmers around the world include observation of wind and cloud direction (Baigorria, 2006; Valdivia et al., 2002). These observations are directly related to seasonal changes in the general atmospheric circulation due to the energy balance. For mountainous regions, these changes cause the different airmasses to rise and generate orographic rainfall on different hillsides at different times of the year, producing different climatic regimes around the mountain. As shown in Figure 16.10, the heaviest rainfall events are

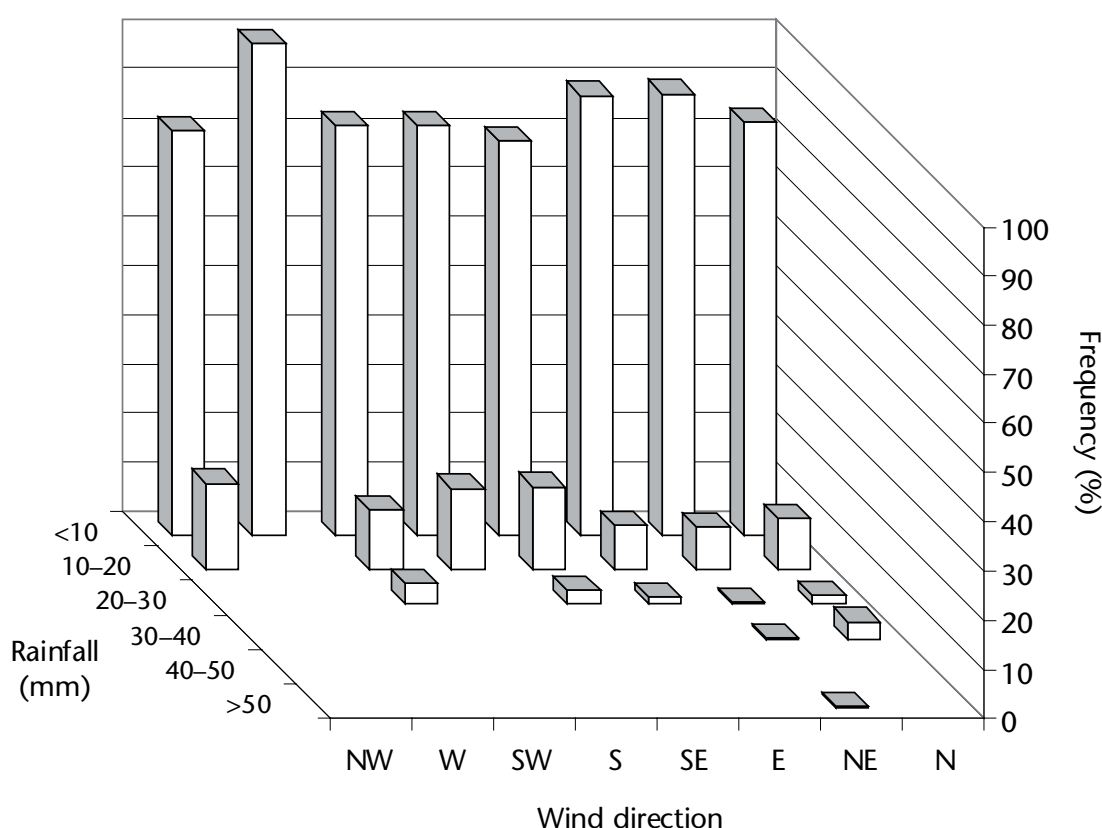


Figure 16.10. Frequency analysis of rainfall according to wind direction. Watersheds of Chitán and San Gabriel (Carchi, Ecuador).

generated when wind blows from the north-east, which occurs mostly during winter and spring as shown in Figure 16.11. This makes hillslopes facing south-west more vulnerable to soil erosion, but also creates a different ecosystem by affecting rainfall regimes and soil-forming processes (see 16.4 below). To different degrees, the remaining hillslopes in this area are mostly affected by non-erosive rainfall events with comparatively lower amounts of water occurring mostly during summer and fall (Figure 16.11). This last combination tends to create drier ecosystems with a relatively slow soil-forming process (Baigorria, 2005). Farmers at San José de Llanga, Province of Aroma (in Bolivia at 17°22' S latitude, 67°50' W longitude and an altitude of 3 750 m) in the Andean High Plateau, know that winds coming from the north are related to dry years, while winds from the east are related to rainy years with good yields. These farmers are climatologically located at the boundaries of the

Bolivian High (Horel et al., 1989; Garreaud, 1999) and the winds they observe correspond to 700 hPa, the altitudinal range in which they live. What they observe is the relative position of the Bolivian High (Valdivia et al., 2002). In so doing, they forecast incoming airmasses from the dry northern Andes or from the wet Amazon basin, respectively. Of course, this kind of empirical observation transmitted from generation to generation takes time; however, application of the principle of knowing where the study area is located in relation to some important climatic control gives the observer a head start in the forecasting process.

16.3.4 Atmospheric humidity and foehn effect

When unsaturated air ascends (or descends), it cools (or warms) at the thermodynamically determined rate of 9.8°C per 1 km altitude; this is called

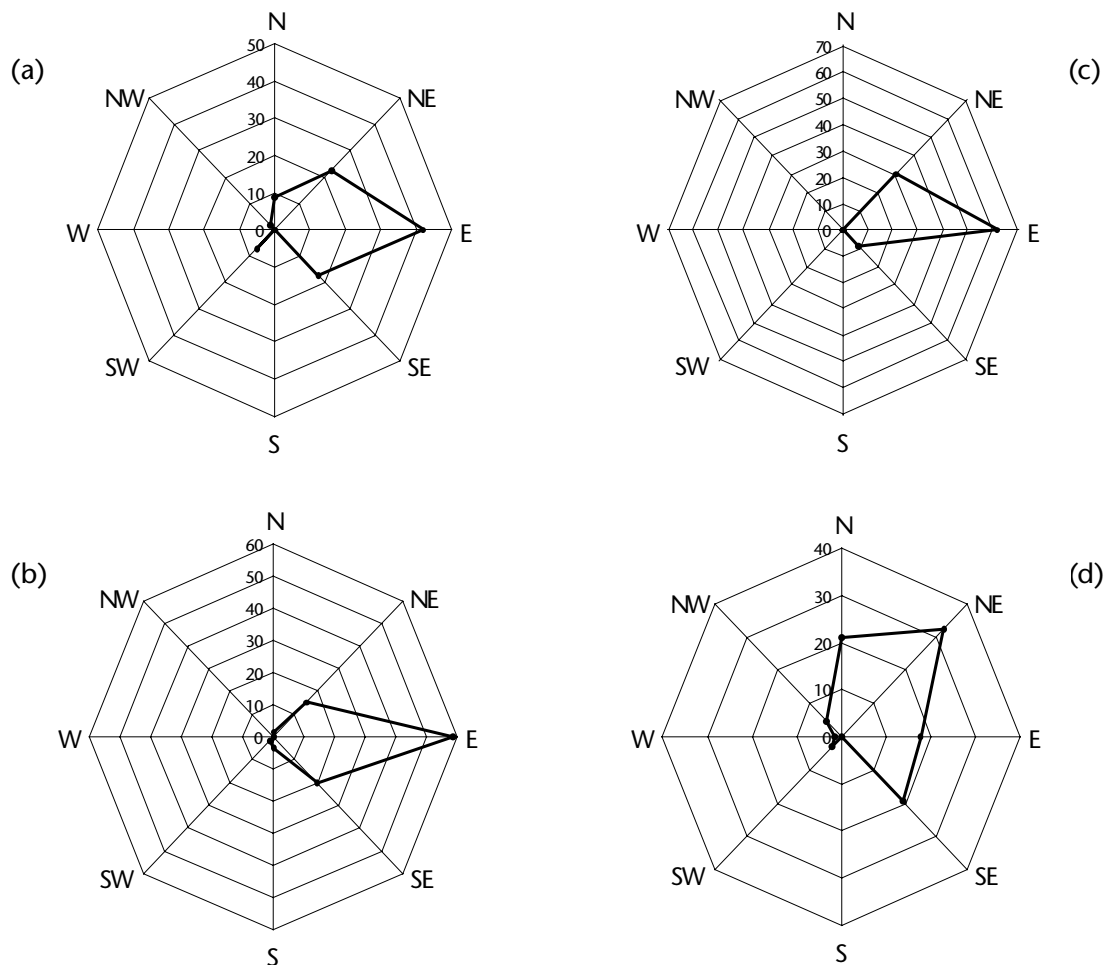


Figure 16.11. Seasonal frequency analysis of wind direction: (a) summer, (b) fall, (c) winter, (d) spring

the dry adiabatic lapse rate (γ_d). This dynamic adiabatic cooling (warming) is caused by the increase (decrease) in the volume of the airmass due to pressure changes in relation to the altitude. Once the air becomes sufficiently cold while ascending, it can no longer maintain water as a vapour, and the vapour condenses, forming cloud droplets. The altitude at which the change of water state occurs is called the condensation level. The process releases the latent heat of condensation, which is defined as the heat gained by the air when water vapour changes into a liquid ($2\,500\text{ J g}^{-1}$ of water); this adds to the buoyancy of the air, causing it to rise more rapidly. From the condensation level, because the air is now saturated (air temperature equals dewpoint), it cools at a slower rate, and this is referred to as the saturated adiabatic lapse rate (γ_s). If the airmass is still rising, air temperature as well as dewpoint decrease together following γ_s , which, unlike γ_d , is not constant and varies according to the pressure and air temperatures. During all the upward movement, rainfall is produced if the water drop weight is greater than the ascending forces of the wind. When the crest of a mountain is crossed, and depending upon atmospheric stability, the airmass begins to go downslope on the lee side of the mountain owing to gravitational forces. Then the airmass begins to increase its temperature according to the γ_d ; the dewpoint remains without change, however, because there is no moisture gain during the process. This loss of moisture while the air ascends, followed by the adiabatic compression and warming as air descends the slope on the leeward side of a mountain range, is designated as the föhn or foehn effect (Figure 16.12).

The föhn effect divides the two sides of the mountain into two different temperature and moisture regimens: the leeward side is warmer and drier than

the windward side, which is subject to the effects of the orographic rainfall as well. A typical example takes place in the Central Andes, where rainfall forest is found on the windward east hillside, while desert lies on the leeward west hillside. Table 16.2 shows two transversal transects across the Andes where the differences in precipitation can be observed. Of course, the South Pacific anticyclone and the cold Humboldt Current, which modify the air temperature, also influence this area (Baigorria et al., 2004).

At smaller scales, dry and warm airmasses on the leeward side of mountains increase crop water requirements because the vapour pressure deficit rises and thereby increases crop evapotranspiration. Again, crop zoning is the best approach for agriculture in these conditions and depends on the intensity of the föhn effect. The higher the orographic barrier, the higher the adiabatic compression. Similarly, moisture and temperature regimen differences on both sides depend on the altitude of the condensation level relative to the summit. If the condensation level is not reached, moisture and temperatures on both sides will remain unchanged. If water is needed but the condensation level is poorly reached because of the formation of fog only (clouds at ground level), water can be obtained by capturing the fog using condensation surfaces. These surfaces act as filters for moisture, allowing water vapour to condense at the surface or to aggregate small weightless water drops that cannot fall over the ground. These condensation surfaces are usually dense nets placed at a perpendicular angle to the wind path as parallel walls in order to filter as much moisture as possible. In the desert coasts of Chile and Peru, under the presence of cold water currents, water from fog is naturally captured by rocks located in low hillslopes facing the wind. This captured water maintains

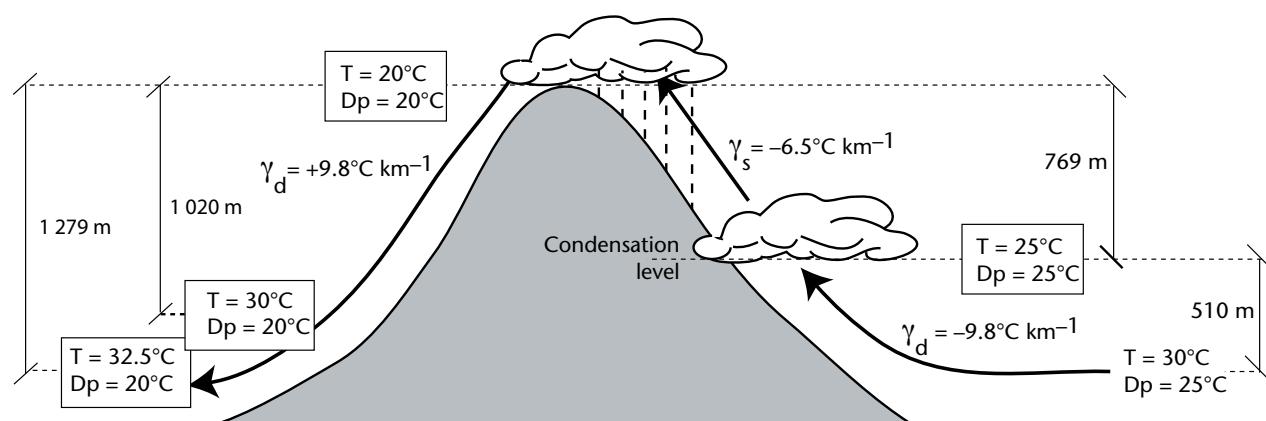


Figure 16.12. Hypothetical example of föhn effect

Table 16.2. Two transversal transects across the Andes showing changes in rainfall patterns as the airmasses cross from west to east

<i>Weather station</i>	<i>Latitude (South)</i>	<i>Longitude (West)</i>	<i>Altitude (m)</i>	<i>Rainfall (mm)</i>
San Ramón – Junín	11°08′	75°20′	800	2 050
Huancayo	12°02′	75°19′	3 308	765
Cosmos	12°09′	75°34′	4 575	1 047
A. von Humboldt	12°05′	76°56′	238	16
El Porvenir	6°35′	76°19′	230	1 041
San Ramón – San Martín	5°56′	76°05′	184	2 158
Bambamarca	6°40′	78°31′	2 536	737
Chiclayo	6°47′	79°50′	31	37

natural forests locally called *lomas*, which can include certain salt-tolerant trees and shrubs.

16.4 APPLICATION OF KNOWLEDGE ABOUT SPATIO-TEMPORAL CLIMATE VARIABILITY IN MOUNTAINOUS REGIONS

Two case studies in mountainous regions where the knowledge of spatio-temporal climate variability is linked to knowledge provided by other scientific studies will be instructive. The first example allows one to investigate the role of climate in the formation of soils derived from volcanic ash. The second investigates the spatial variability of soil erosion and runoff in a mountainous watershed, a process that seriously affects sustainable agriculture in these areas.

16.4.1 Influence of climate on soil formation: A case study

Many studies have shown the importance of altitude zoning when explaining differences in the rate at which pedogenesis proceeds (Zehetner et al., 2003; Vacca et al., 2003). Other studies have confirmed the general importance of rainfall as a primary factor regulating soil development pathways in volcanic materials (Parfitt et al., 1985; Nizeyimana et al., 1997; Ugolini and Dahlgren, 2002), but few have analysed the climatic parameters and their relationship with soil characteristics (Chatwick et al., 2003).

The five main soil-forming factors, which are parent material, topography, climate, organisms and time (Jenny, 1941), influence the type of process (physical, chemical and biological), the duration, and the rate of soil development at a given location (van Breemen and Buurman, 1998).

Parent material and topography define the initial state in which climate and organisms begin the physical, chemical and biological soil-forming process in the current pedon. In this conceptual model of soil formation, climate is an important driving factor because it influences weathering rates both directly and indirectly through the type and quantity of plants and organisms affecting the dynamics of organic matter in the soil (Baldwin et al., 1938; Zehetner et al., 2003; Ugolini and Dahlgren, 2002).

Digital soil mapping uses reproducible, quantitative methods that make extensive use of auxiliary information to provide spatial predictions of soil properties (Scull et al., 2003; McBratney et al., 2003). Several methods are rapidly being developed, ranging from geostatistical techniques, Geographical Information Systems, topographic analysis and remote-sensing (Bell et al., 2000; Mueller and Pierce, 2003; Scull et al., 2003; McBratney et al., 2003; Nanni and Demattê, 2006). Nevertheless, high-resolution input data remain a serious constraint for many cases and this is why little attention has been directed to climate variability as a driving factor behind soil variability (McKenzie and Ryan, 1999; King et al., 1999; Ryan et al., 2000; Guo et al., 2006). Process-based interpolated maps (Baigorria et al., 2001; Baigorria, 2005) provide a new basis for digital soil mapping using climatic variability. Climate as a soil-forming factor can now be studied at higher resolution and may enable values of soil properties at a particular site to be predicted by disaggregating soil mapping units and incorporating secondary climate information.

This case study explores the predictability of the spatial variation of soil organic matter (SOM) in a mountainous region as a function of topography and climate variables. The study area is located in the Ecuadorian Andes between 0°42′ N, 78°30′ W and 0°32′ N, 77°30′ W in the Province of Carchi

(Figure 16.13). The area includes the Chitán and San Gabriel watersheds with an altitude ranging from 2 700 to 3 840 m. The study area is highly suitable for a first exploration of the relations between soil properties and short-distance variability because of the importance of climatic variability in soil genesis.

Four automatic weather stations recording maximum and minimum temperatures, rainfall and incoming solar radiation were installed in the study area and operated for three years. During the same period, sequences of infrared images from the geostationary operational environmental satellite (GOES) system were used to derive the main wind direction at the altitude of cloud formations using daily time steps (based on cloud movement every 15 minutes). These data were used to produce daily maps of maximum and minimum temperatures, rainfall and incoming solar radiation. From these maps, monthly and yearly aggregations yielded high-resolution maps (Figure 16.14) used as predictors of SOM (Figure 16.15).

From the study area, 190 georeferenced soil samples were taken across all the soil units. Values were extracted from topographic and climatic GIS layers at the soil sample points, forming a database containing SOM, topographic and climatic data. The database was stratified on the basis of the five main soil units. For each soil unit, one linear regression was performed to predict SOM as a predictor altitude. In addition, two sets of stepwise multiple regression models were generated with these databases. The first regression analysis was between SOM and topographic variables, whereas the second was between SOM and topographic and climatic variables. A stepwise procedure was carried out for sequentially entering and/or removing independent variables one at a time into/from a regression equation in an order that improves the regression equation's predictive ability. This method is particularly useful for screening datasets that consist of many independent variables from which it is possible to identify a smaller subset of variables that determine the value of a dependent variable. Results in Table 16.3 show the extra value gained by using

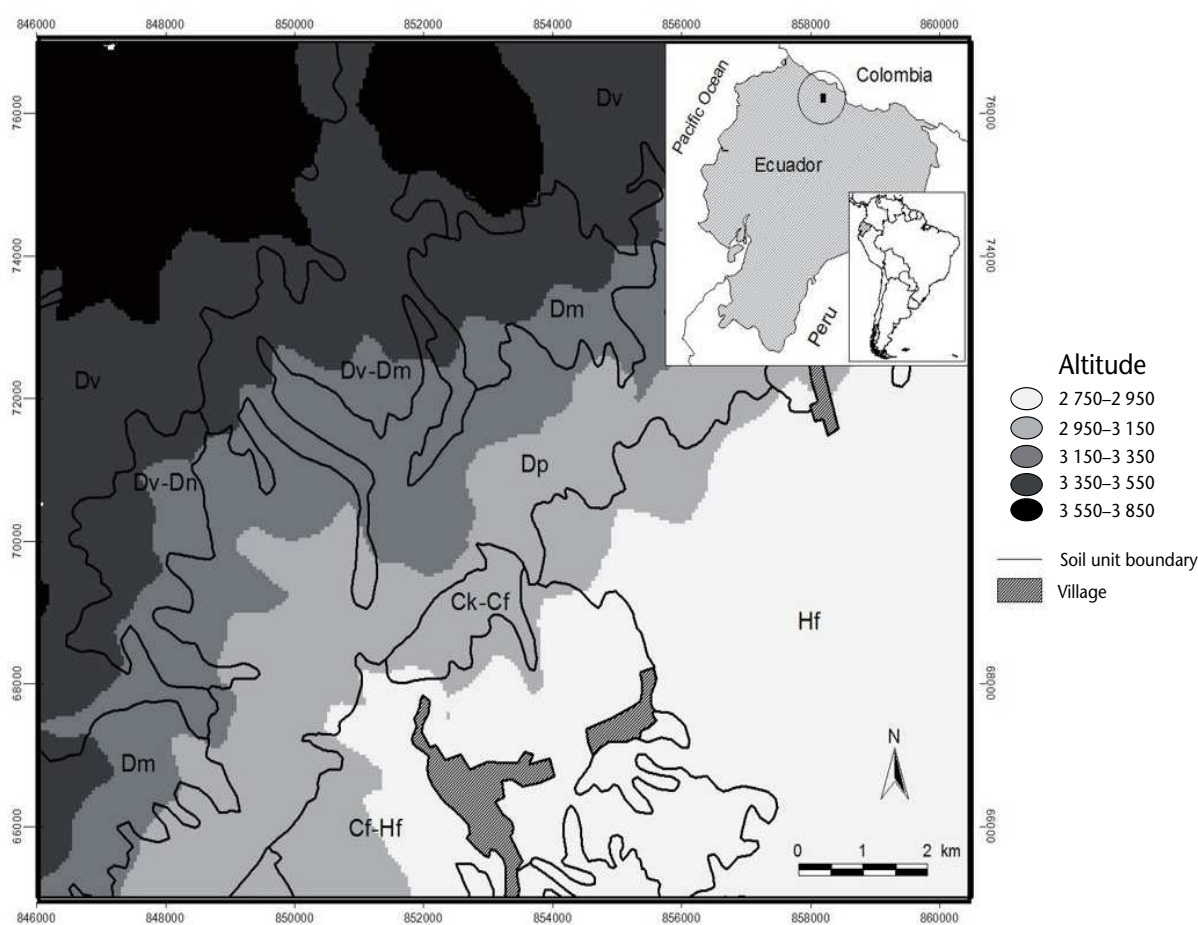


Figure 16.13. Map of Carchi, Ecuador, including altitudes and soil units (adapted from Baigorria, 2005). The soil units shown are: Duriudoll (Cf, Ck), Andic Argiudoll (Hf), Typic Dystrandept (Dp, Dm), Typic Hydrandept (Dv).

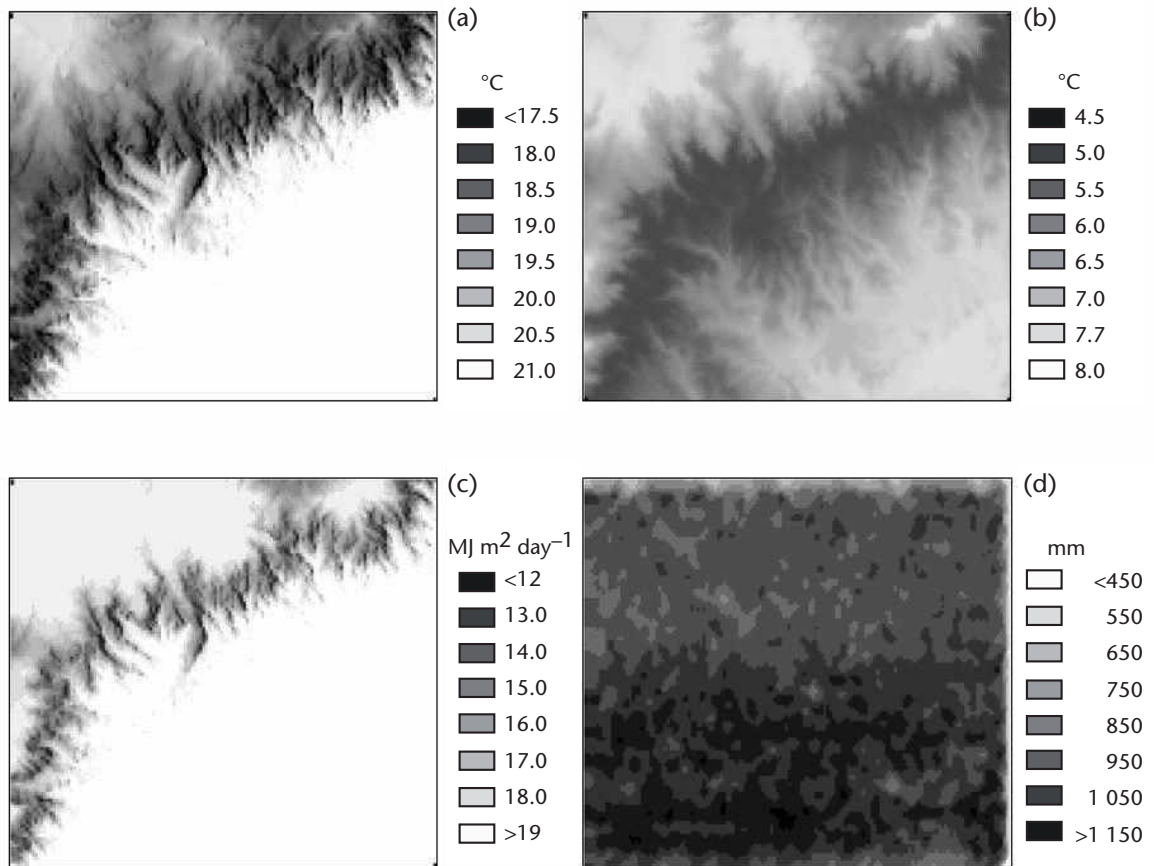


Figure 16.14. Interpolated climate maps: (a) annual average of maximum temperature, (b) annual average of minimum temperature, (c) annual average of incoming solar radiation, (d) total annual rainfall (adapted from Baigorria, 2005)

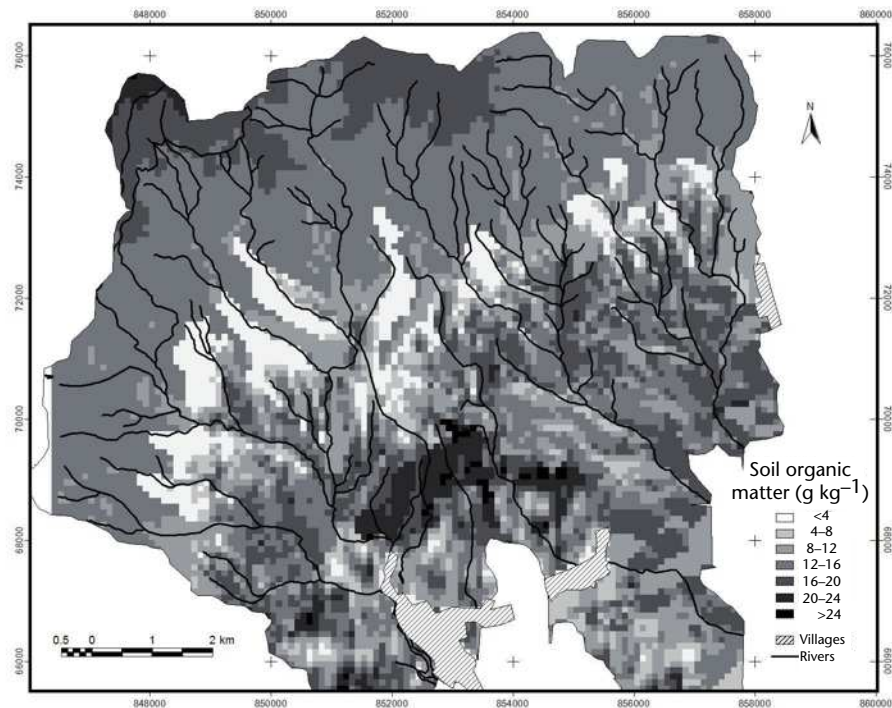


Figure 16.15. Map of soil organic matter obtained by means of stratified multiple regression models using climatic and topographic variables as predictors (adapted from Baigorria, 2005)

topographic and climatic variables as predictors for SOM at each soil unit, whereas Figure 16.15 shows the final SOM map. Other soil characteristics were also analysed as a function of topography and climate, and these are described in more detail in Baigorria (2005) and Baigorria et al. (2007).

From the results obtained, one can conclude that there is an added value in explaining the variability within soil units by using climatic variables as predictors of soils derived from volcanic ash. The use of these secondary data supports the refinement of the altitude–temperature or altitude–rainfall relationships that are usually applied. Rainfall and minimum temperatures are the climatic variables frequently used to explain spatial variation of soil characteristics. Incoming solar radiation and maximum temperature become important variables in soil units where steep slopes are found, however. Weights given to each climatic variable change across soil units, possibly because different physical, chemical and biological processes are involved. Seasonal/monthly disaggregated climate information significantly improves the spatial predictability of SOM. Monthly climatic predictors must be seen as the upper and/or lower bounds where physical, chemical and biological processes are promoted or restricted. Finally, it should be underscored that this mountainous area is an ideal case in which climate is likely to govern soil variation at short distances. In other regions, other soil-forming factors may prevail. Nonetheless, in mountainous areas, orography represents an advantage for this kind of application.

16.4.2 Soil erosion in mountains: a case study

Soil erosion caused by water has been a problem ever since land was first cultivated (Morgan, 1995). This is especially true in mountainous regions, where steep slopes add extra potential energy to the

process. It is known that soil loss is related to rainfall erosivity, soil erodibility, slope of the land and the nature of the plant cover. Erosion occurs partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff; rainfall intensity is considered the most important characteristic that influences particle detachment and splash (Hillel, 1998; Morgan, 1995). In mountainous regions of the humid tropics, erosion is expected to be more pronounced with a rise in slope steepness and length, and with the resulting increases in the speed and volume of surface runoff. Due to population pressures in these areas, farmers, often unwisely, till more marginal lands, which further increases the risk of soil erosion (Kessler and Stroosnijder, 2005).

Rainfall data are of interest for land-use planning because rainfall characteristics such as duration, frequency and intensity affect the soil erosion process (Schwab et al., 1993; Whiteman, 2000). Rainfall can be characterized in many ways, varying from total precipitation in a year, season or other period, to daily rainfall or totals per rainfall event (Hoogmoed, 1999). Often a shortage of water for farming is not the consequence of low annual rainfall, however, but of poor seasonal distribution (Sivakumar and Wallace, 1991). The response of soil to rainfall in terms of soil loss can be variable. Dramatic erosion processes can be observed during a rainy season, when heavy but not extreme precipitation intensities coincide with infrequent high soil moisture conditions in the watershed (Romero et al., 2007a).

The second case study is related to soil erosion assessment in the Andes, from small plots to watershed-level scale (Romero, 2005). The analysis of rainfall and soil characteristics, as well as other factors that affect erosion, are important and constitute the basic requirement for erosion quantification and qualification. Generally

Table 16.3. Changes in the coefficient of determination according to the independent variables used to predict the spatial distribution of SOM

<i>Soil Unit</i>	<i>Altitude</i>	<i>Topographic^a</i>	<i>Topographic and Climatic^a</i>
Cf – Hf	0.047 ^{ns}	0.288 ^b	0.606 ^b
Ck – Cf	0.005 ^{ns}	0.454 ^b	0.898 ^b
Dp	0.283 ^b	0.283 ^b	0.936 ^b
Dv – Dm	0.004 ^{ns}	0.004 ^{ns}	0.772 ^b
Hf	0.046 ^{ns}	0.091 ^c	0.939 ^b

^a adjusted R2

^{b, c} significant at the 0.05 and 0.01 probability levels

^{ns} non-significant

speaking, studies of this kind are carried out in one location at a time, because the installation of runoff plots is often expensive and time-consuming, and does not always represent the regional spatial variability. Applying erosion models may become important for the analysis of hillslope and watershed processes and their interactions, and for the development and assessment of watershed management scenarios (He, 2003).

The study area was located in the La Encañada watershed in the northern Andes of Peru (Figure 16.16), which received between 500 and 1 000 mm of rainfall per year between 1995 and 2000. Three weather stations in the area were used: La Toma, Usnio and Manzanillas (Table 16.4). In the period considered, the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA) in the United States established that the conditions in the tropical Pacific

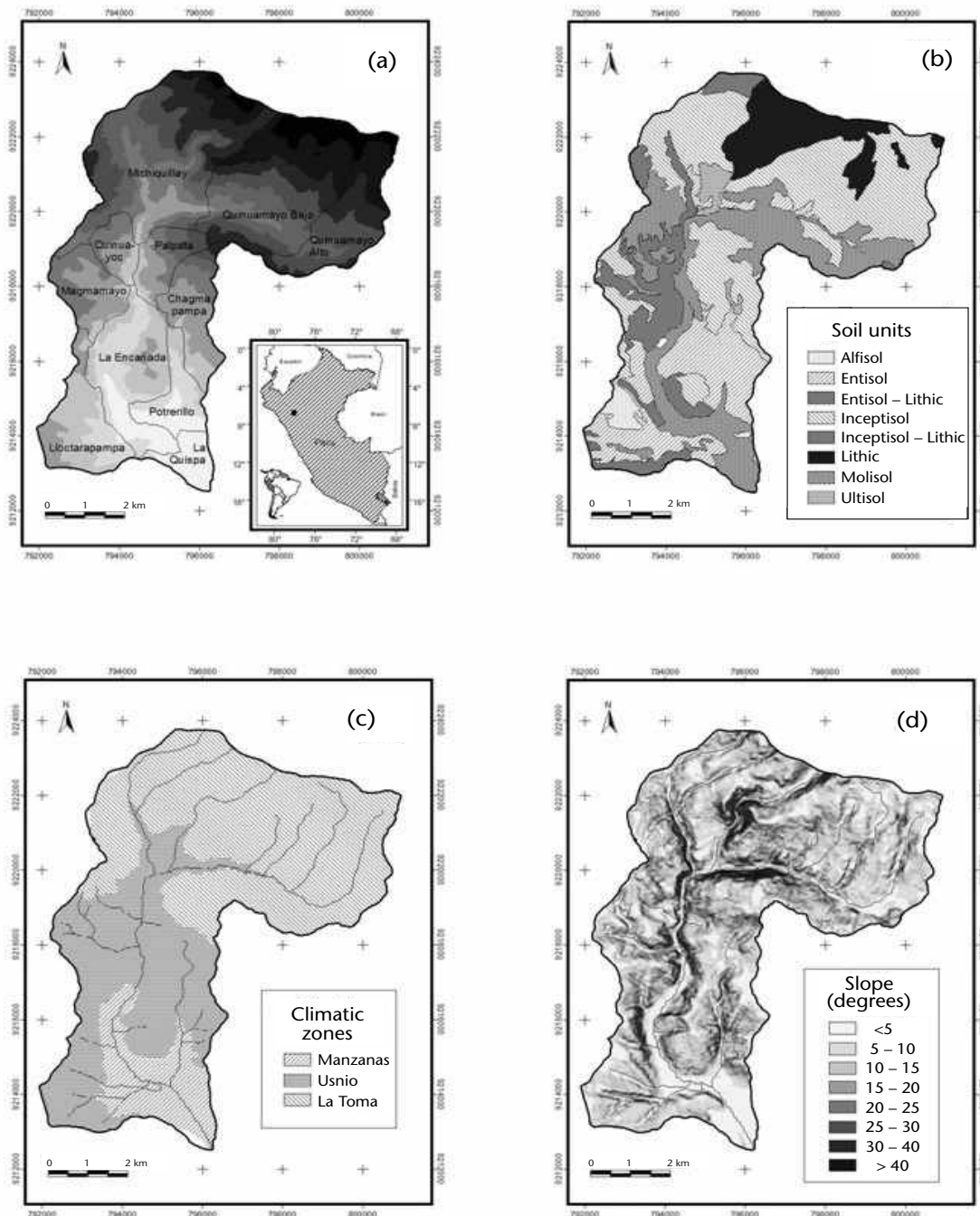


Figure 16.16. Spatial information for the La Encañada watershed, northern Peru: (a) location map, (b) soil map, (c) climate map, (d) slope map (adapted from Baigorria and Romero, 2007)

area were neutral for 1995 and 1996, with a weak incidence of La Niña at the end of 1995. CPC recorded a strong El Niño occurrence from the end of 1997 to the beginning of 1998, and a weak episode followed by a strong episode of La Niña during the end of 1998 and beginning of 1999, with a replication of this pattern from the end of 1999 to the beginning of 2000, respectively (NOAA, 2006). The main results of the study showed that almost 80 per cent of these rainfall events had an average intensity below 2.5 mm h^{-1} and that 4 per cent had an average intensity above 7.5 mm h^{-1} , with a maximum value of 156.3 mm h^{-1} . During the year of the El Niño occurrence, the high-intensity events increased in comparison with the La Niña events and neutral years (Table 16.4). The La Niña events were characterized by a large total

rainfall, however, albeit with low rainfall intensities. Detailed information can be obtained in Romero et al. (2007a).

The soil parent material consisted mainly of limestone, sandstone, siltstone and shale and, as shown in Figure 16.16, the dominant soils in the area were classified under the United States Taxonomic Classification System as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) (INRENA, 2002). The most common soil texture was sandy loam and the organic matter content was medium to high (over 2 per cent). According to these characteristics, the interrill (*Ki*) and rill (*Kr*) erodibility values measured were low in the area (Romero et al., 2007b), the most erodible soils being those with the greatest

Table 16.4. Frequency analysis of rainfall intensity classes for neutral/El Niño/La Niña years at different locations in the La Encañada watershed in northern Peru

Neutral years (1995 and 1996)

	$<2.5 \text{ mm h}^{-1}$	$2.5\text{--}7.5 \text{ mm h}^{-1}$	$>7.5 \text{ mm h}^{-1}$
La Toma			
No. of events	163	63	23
% of total	65.5	25.3	9.2
Usnio			
No. of events	130	78	16
% of total	58.1	34.8	7.1
Manzanas			
No. of events	179	63	15
% of total	69.6	24.5	5.8

El Niño year (1997)

	$<2.5 \text{ mm h}^{-1}$	$2.5\text{--}7.5 \text{ mm h}^{-1}$	$>7.5 \text{ mm h}^{-1}$
La Toma			
No. of events	151	55	7
% of total	70.9	25.8	3.3
Usnio			
No. of events	99	42	2
% of total	69.2	29.4	1.4
Manzanas			
No. of events	72	19	20
% of total	64.8	17.1	18.0

La Niña years (1998 and 1999)

	$<2.5 \text{ mm h}^{-1}$	$2.5\text{--}7.5 \text{ mm h}^{-1}$	$>7.5 \text{ mm h}^{-1}$
La Toma			
No. of events	355	37	0
% of total	90.6	9.4	0
Usnio			
No. of events	289	21	2
% of total	92.6	6.7	0.6
Manzanas			
No. of events	370	27	5
% of total	92.0	6.7	1.2

amount of silt and very fine sands, and the most resistant being the clayey soils.

Once the climatic and soil data were collected and analysed all around the watershed, “flying erosion plots systems” (Romero, 2005; Romero and Stroosnijder, 2002; Stroosnijder, 2003) were installed at four locations within the watershed to evaluate runoff and soil loss from natural rainfall events. Flying plots consist of a set of portable low-cost materials to delineate and monitor a series of Wischmeier-type plots. With flying plots only a few measurements are used to validate prediction technology, and they can be reinstalled several times during one rainy season, for instance, to measure the effect of different land cover, soil types, climates and topographies. Then, the slope angle and soil management were evaluated at each flying plot. With all the collected data, the hillside version of the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) was validated and calibrated for the study area. The soil-loss process at watershed level was assessed by using a tool that integrates GIS with WEPP (Baigorria and Romero, 2007). Using this interface, the authors of the study generated runoff and soil-loss maps under different land-use scenarios consistent with the current land use (Figure 16.17).

Generation of these maps facilitated the visualization of the erosion process at spatial and temporal scales according to the actual land use of the watershed. Areas at risk of runoff and soil loss can be identified from the maps. Although the map does not give the soil loss at watershed level, it can be used to identify “hot spots”, thus helping decision-makers to formulate recommendations for soil and water conservation.

Water coming from rainfall or melting ice can have different effects on mountain environments. It can provide sustenance for human life and vegetation if it is well distributed in a watershed. Soil acts as a “sponge” that is able to store water for a limited time and for different uses (consumption, evaporation, transpiration, percolation). But sometimes extreme rainfall events are poorly distributed in time and space, as they can be concentrated over a few days in a year in one specific location. The excess water can be negative for living species as well as for non-living resources, such as soils. If rainfall intensity, for example, exceeds the infiltration capacity of the soil, runoff will be produced and water and nutrients can be lost. There may be a need to reduce erosion to control the loss of nutrients and water from agricultural lands to prevent not only pollution of water bodies, but also

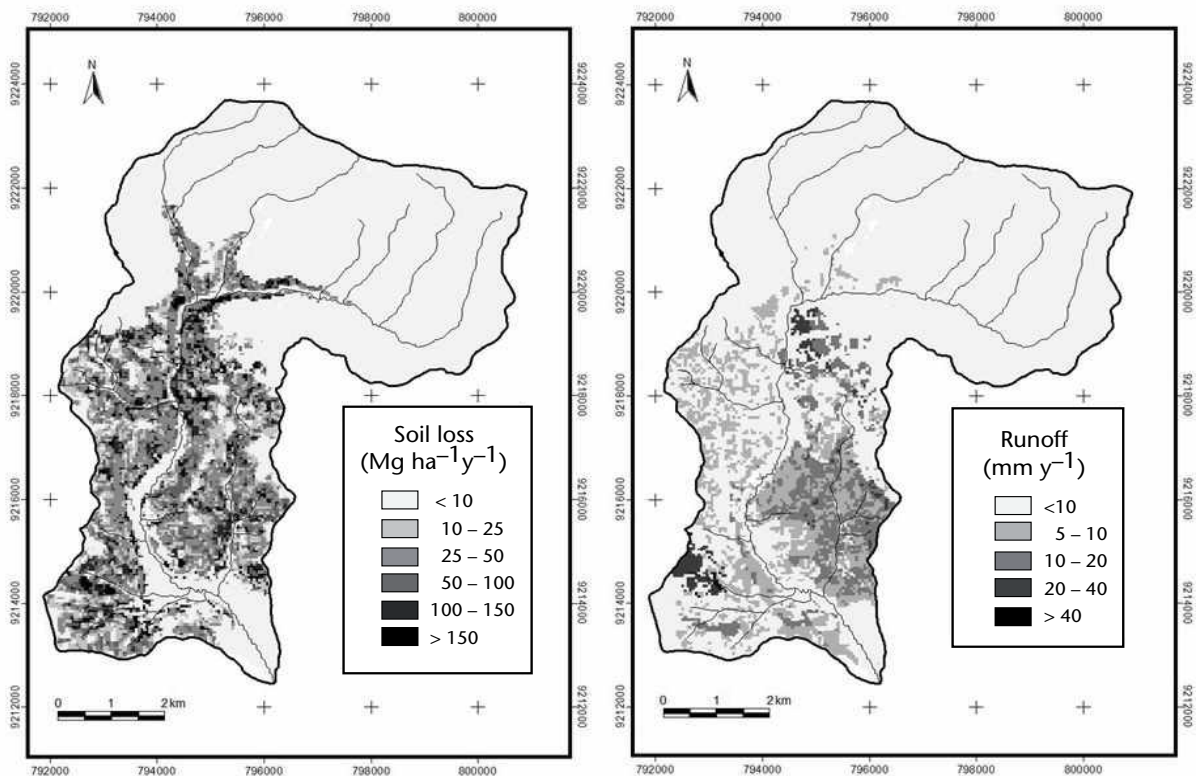


Figure 16.17. Simulated soil-loss and runoff maps of the La Encañada watershed (adapted from Baigorria and Romero, 2007)

to assure agriculture sustainability for farmers living in the highlands.

As shown previously, soil conservation design follows a sequence of events. Using tools like modeling and GIS to identify vulnerable areas in a watershed, erosion can be reduced to an acceptable rate by implementing some recommended conservation strategies (Morgan, 1995). For example, the farming of slopes that are too steep, which is a common practice in developing countries, accelerates the erosion process. To prevent this condition, rapid establishment of vegetation is recommended before the first highly erosive rainfall event hits the area. The challenge is to render this vegetation cover productive in the short term, in order to meet the immediate needs of the farmers and people living in the affected area.

Mechanical field practices are used to control the movement of water and wind over the soil surface (Morgan, 1995). For example, bench terraces consist of a series of alternating shelves and risers and are employed where steep slopes, with inclinations up to 30°, need to be cultivated. The riser is vulnerable to erosion and is protected by a vegetation cover and sometimes protected with stone or concrete. These structures appear to be reasonably satisfactory as a conservation measure under a wide range of conditions, although they may require high labour input for construction and maintenance. Case studies of the effectiveness of bench terraces have been reported in the loess areas of China (Fang et al., 1981), in clay loam soils of Jamaica used in banana cultivation (Sheng, 1981), and in the Uluguru Mountains in Tanzania (Temple, 1972). Since the time of the Incas, farmers have built bench terraces with great success in the Andean highlands of Peru and Bolivia in order to catch more water from rainfall and to avoid runoff. An alternative conservation practice is the so-called slow-forming terraces, which are more common in slopes with inclinations up to 14° (Baigorria et al., 2002). They are made by constructing soil embankments across the slope, which are supported by a wall of stones (slope >14°) or protected by grasses or bushes (slope <14°). The main function of slow-forming terraces is to intercept soil particles and organic matter carried away by runoff. Other type of terraces are diversion and retention terraces, which are designed to intercept runoff and preserve water by storing it on the hillside, although they are only useful for slope inclinations up to 7°.

The contouring of rows is another recommended mechanical practice that prevents erosion and improves water retention in the soil. Its effectiveness

varies with the length and steepness of the slope, but usually it cannot be used on slopes with inclinations higher than 8°. Contoured rows need to have a slight grade across the slope. Another instance to be avoided is the accumulation of rainfall around crops, which saturates the soil and thereby promotes fungus diseases such as potato late blight. Finally, waterways are another conservation system that collects runoff at a non-erosive velocity and delivers it to a suitable disposal point.

16.5 RISK ASSOCIATED WITH MOUNTAIN CLIMATIC RESOURCES

In the context of environmental vulnerability (EV) analysis, the environment is understood as the combination and interaction of natural and human systems, whereas vulnerability is defined as the degree to which a system is sensitive to and unable to cope with adverse impacts of external stresses and shocks. An EV analysis should thus include identification of the external stress factors and how the system responds and interacts to reduce its exposure, and a search for options to enhance its adaptive capacity to the stress factor (R. Quiroz, personal communication).

This section presents an EV analysis in a watershed located in the northern Andean Highlands of Peru to illustrate the process that can be used in different mountainous regions. The EV analysis used agricultural intensification as the stress factor; it assessed the magnitude by which this factor affected the potato- and cereal-producing areas. The vulnerability of current potato–cereal systems in this Andean watershed was assessed based on how the system responds to management scenarios. The vulnerability indicators included yield and yield variability, soil erosion, runoff and nitrogen leaching.

Several processes were modelled in order to generate the geospatial data required to assess the environmental vulnerability of potato-, wheat- and barley-growing areas in the watershed. The SUBSTOR-Potato (Ritchie et al., 1995) and CERES-Cereal (Ritchie et al., 1998) models from the Decision Support System for Agrotechnology Transfer (DSSAT) family of models (Jones et al., 2003) were used to simulate yields and nitrogen leaching for potato, wheat and barley, respectively. The WEPP model (Flanagan and Nearing, 1995) was used to simulate soil erosion and runoff. The DSSAT and WEPP models had previously been calibrated for the study area by Bowen et al. (1999) and Romero

(2005). Using the same approach as described in 16.4.2 (Baigorria and Romero, 2007), maps of all the mentioned variables were produced under two different management scenarios: the base scenario that mimics the current conditions, consisting of rainfed agriculture and no external inputs (Sánchez, 2005), and the intensification scenario that considers an N fertilization of 200 kg ha^{-1} and enough irrigation to supplement rainfall in order to reach field capacity. The purpose of this scenario was to evaluate, using external inputs, the expected environmental cost of agricultural intensification in this mountainous region.

Optimal planting dates for each crop varied according to the location within the watershed and the crop. The methodology to obtain the optimal planting dates used in this case study can be found at Baigorria (2006). After simulating both

scenarios for each grid cell and crop in the study area, yearly grids of yields, soil erosion and NO_3 leaching were obtained. The average and standard deviation for each grid cell across the 20 years of historical record were calculated, obtaining, as a result, average and standard deviation grids of crop yields, soil erosion (Figure 16.17) and NO_3 leaching. To assess the EV analysis, averaged grids from the base scenario were subtracted from the intensification scenario. Therefore, yield differences were obtained for each crop due to differences in agricultural management (Figure 16.18(a)). Then, grids on soil erosion change and NO_3 leaching were divided by the corresponding yield-change grid. Thus, grids were obtained of the soil erosion change per unit of crop-yield difference for each crop (Figure 16.18(b)), along with grids of NO_3 leaching change per unit of crop yield difference (Figure 16.18(c)).

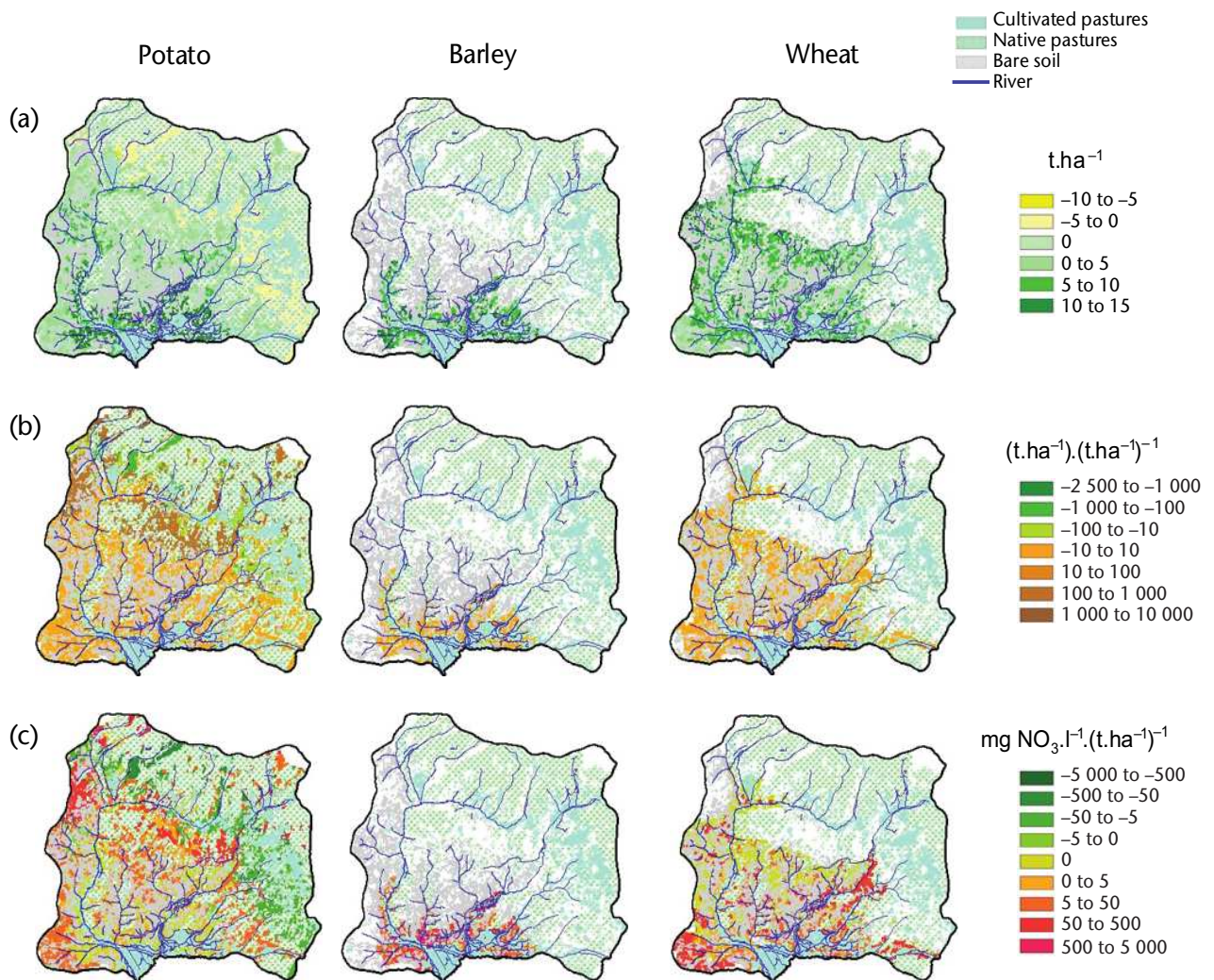


Figure 16.18. Environmental vulnerability maps for potato, barley and wheat in the La Encañada watershed under optimal planting dates for each crop and location: (a) represents the yield difference among scenarios, (b) the soil erosion change per unit of yield increase/decrease and (c) NO_3 pollution change per unit of yield increase/decrease (adapted from Sánchez, 2005).

Due to the high spatial variability, not only in climate and soils, but also in the management of mountainous regions, it is unrealistic that EV maps will be derived that show large areas with the same results. Because making decisions in these highly fractionated areas is difficult, it is most important in these regions to use this spatial information to find vulnerable areas where degradation occurs. In mountainous regions, soil erosion and pollution (among other environmental factors) can occur under certain combinations of climate, topography, soils and management. As shown in Figure 16.19, some areas increase productivity by increasing external inputs; in other areas, however, this will not occur. Depending on the location, some increases in productivity will increase or decrease soil erosion and/or NO_3 pollution. Hence, thresholds can be established in order to locate these vulnerable areas and to spatially focus practices to preserve the environment within certain limits of degradation or to turn the process around. Crop zoning in areas with high spatial variation, such as mountains, must be focused not only on increasing productivity, but should also take environmental conditions into account. In highly vulnerable regions like these, risks associated with small sources can easily spread to larger areas. Mudslides can occur under extreme climate events in areas vulnerable to runoff. Intensification of external inputs like N fertilizers in specific vulnerable areas can contaminate large water bodies that are used not just for agriculture, but also for other purposes. Bearing these aspects in mind, risk analysis in mountainous regions must take into account as much resolution as possible, owing to the potential

major implications that can arise from a few small sources.

16.6 CONCLUSIONS

Mountainous regions are highly sensitive to climate events and management practices need to take into account the importance of climate in order to assure food security for the farmers who occupy mountain regions.

The best way to apply climate knowledge in mountainous regions is to know the general atmospheric circulation patterns in relation to the topographic conditions and the orientation of the mountain hillside. Many factors influence climatic and weather conditions. An analysis of the advantages and disadvantages of using topographic and climatic variables is essential if the problems facing these areas are to be addressed. In this chapter, examples and approaches have been presented on how to determine climatically induced hazards and how to adopt management practices that help to moderate climatic factors. Some of the examples provided can be used as recipes, whereas others only give ideas about how to use the agrometeorological knowledge more effectively in mountainous areas to adjust cultivation to climate, improve food production and minimize degradation. Mountains are complex environments and there is no single solution, but if the predictability of climatic variables can be improved, there will be better opportunities to improve the livelihood of farmers in the mountains.

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COMMUNICATING AGROCLIMATOLOGICAL INFORMATION, INCLUDING FORECASTS, FOR AGRICULTURAL DECISIONS

17.1 INTRODUCTION

While the seasonal variability of weather is a major source of production risks (Fraisie et al., 2006), significant benefits have arisen from the use of seasonal climate forecasts. Nonetheless, it is now widely accepted that the existence of predictable climate variability and impacts is necessary but not sufficient to achieve effective use of seasonal forecasts (Podesta et al., 2002). The realization of such benefits has been shown to require deliberate efforts to design and implement effective mechanisms for using climate information in the service of society. Several empirical studies have identified theoretical and practical obstacles to the use of climate information and forecasts (for example, Mjelde et al., 1998; Stern and Easterling, 1999; Agrawala et al., 2001; Patt and Gwata, 2002). The obstacles are diverse, ranging from limitations in modelling the climate system's complexities (for example, forecasts have coarse spatial and temporal resolution, not all relevant variables can be predicted, the skill of forecasts is not well characterized or understood, and contradictory predictions may coexist), to procedural, institutional, and cognitive difficulties in receiving or understanding climatic information. The capacity and willingness of decision-makers to modify actions may also play a limiting role.

There are many communities of potential users, including farmers, agribusiness, transportation entities, persons who are interested in reducing the off-farm impacts of agriculture, and so forth. Rijks et al. (2000) note that different groups of potential clients may exist within the same community, such as those who are aware of information and have access to it, but may need guidance on use; those who might know information exists but may need improved access; and those who may not be aware of existing information and the potential benefits of its use. Climate information is not yet widely used by farmers who make routine decisions about production in existing farming systems (Jones, 2003). This is partly due to the complexity of agricultural systems. In addition, there may be insufficient consideration of the actual conditions of the livelihood of farmers and thus of local adaptive strategies (WMO, 2003). In such cases, the result is usually development of inappropriate support systems (WMO, 2004a).

Several place-based studies have highlighted communication as a key weakness in the ability of the climate information system to serve the agricultural sector. This weakness has been well documented for some time in the forecast applications literature, yet remains of critical importance.

Farmers face many challenges, including uncertain prices, access to needed inputs, governmental policies, marketing, pests and diseases, soil degradation and extreme weather. A common strategy is to employ surveys among farmers working with a particular crop or commodity, asking the respondents to list and prioritize the problems they face in production. During and after the 1997–1998 El Niño–Southern Oscillation (ENSO) events, many pilot projects were developed in which stakeholders were and are being engaged in dialogues with researchers and extension personnel on climate variability and the use of uncertain climate forecasts (Buizer et al., 2000). Vehicles for the communication of new information in agriculture include the media, agrometeorological bulletins, extension services, and the like. Significant work still remains before climate forecast information is routinely used throughout agriculture for making decisions aimed at reducing climate-related risks. This chapter reviews the challenges of effective communication and offers recommendations for bridging identified gaps. This is not simply a problem of rural underdeveloped areas. As Fraisie et al. (2006) note, even in more technologically advanced areas there is still the need for face-to-face, multidirectional communication and training among the extension agents.

This discussion focuses primarily on the communication of climate information for on-farm planning. Many of the concepts are applicable to supporting off-farm activities as well, however. Livestock planning and management are not addressed explicitly.

17.2 USE OF CLIMATE INFORMATION IN AGRICULTURE: FRAMING THE DECISION PROBLEM

It is widely accepted that researchers, information providers and practitioners (in this case farmers and agribusinesses) frame problems differently (Schon

and Rein, 1984). "Framing" refers to the way a particular problem is presented or viewed. Frames are shaped by knowledge and underlying views of the world. This is related to the organization of knowledge that people have about their world in the light of their underlying attitudes towards key values, their notions of agency and responsibility, and their judgments about reliability, relevance, and weight of competing knowledge (Jasanoff and Wynne, 1998). Researchers, policymakers and practitioners (public and private) operate on different timelines, use different languages, and respond to different incentive systems. These frames lead to different definitions of what constitutes the critical components of a problem, different approaches to problem-solving, decidedly different recommendations for action and differing criteria for appraisal. The most important learning involves the basic "framing" of issues in terms of the relevance and importance of particular conditioning outcomes.

The degree of acceptability of information and trust in the providers dictate the context of communicating climate information. The following questions frame effective communication (Jones, 2003; Pulwarty et al., 2003):

- (a) Is the information relevant for decisions in the particular agricultural system?
- (b) Are the sources/providers of information credible to the intended user?
- (c) Are farmers receptive to the information and to research?
- (d) Is the research accessible to the policymaker or decision-maker?
- (e) Is the information compatible with existing decision models and farming practice?
- (f) Do decision-makers have the capacity to use information?

All studies to date show that rainfall distribution over a season is the key variable for all farmers throughout the tropics (Phillips et al., 2001). This information translates into the following key information needs, depending on the particular crop being cultivated: adequacy of rainfall amounts and deficits and excesses, as the case may be; and "early warnings" of potentially poor seasons to inform key actions for general planning questions, such as when to start planting, knowing how much to diversify, knowing which crops to plant, and the likelihood of meeting or failing to meet quotas.

This calls for a much closer inter-institutional collaboration among national meteorological and hydrological services and agencies that directly intervene in rural areas, such as extension services,

development projects, and community-based organizations and non-governmental organizations (NGOs).

Farmers and information providers should be able to evaluate the outcomes of alternative actions (Hammer et al., 2000; Meinke et al., 2001). Crop models and simulation approaches provide means to explore the consequences of a broad range of decisions. Simulation studies have shown associations between El Niño phases and yields of peanuts in Australia (Meinke et al., 1996), corn in Zimbabwe (Phillips et al., 1998) and Argentina (Ferreira et al., 2001), as well as mixed crops (Messina et al., 1999; Hansen et al., 2001; Fontana and Camargo, 2002). Crop models are the preferred choice of analysis because of their ability to simulate yield response to alternate management conditions, such as planting date, row spacing, plant population, irrigation and cultivar choice, over many years of historical weather records (Boote et al., 1996, 1998; Meinke and Hammer, 1995). The traditional ENSO forecasts still lack the capability to characterize intraseasonal rainfall variability, and without knowing the rainfall distribution, it is difficult to correctly forecast crop yields (S. Jagtap, personal communication, 2006). Idealized estimates of the economic value of information (including forecasts) form difficult benchmarks to achieve in practice. It is important to complement the use of such models with an understanding of the impacts of previous climatic and other events (for example, different types of ENSOs) on farming practice, and favourable or poor outcomes depending on the crop being considered. To enable effective responses, farmers should have tools such as access to extension advice, inputs, markets and credits to allow them to make farm investments, and a functioning communication infrastructure (accessible roads, markets and extension advice).

Creating a favourable environment for the effective use of climate information requires asking the question, "What conditions must be in place before farmers can benefit from seasonal climate forecasts?" (Hansen, 2002). The vulnerability and capacity assessment literature provides a useful typology for structuring capacity to respond to climatic risks (Pulwarty and Riebsame, 1997):

- (a) Physical/material resources: What physical climate risks, social skills and productive resources exist?
- (b) Social/organizational capacity: What are the relations and organizations among information providers and users?
- (c) Behavioural incentives: How does the community view its ability to create change?

There has been a growing emphasis on devolution of risk management to the community level and greater recognition of varying degrees of effectiveness of community-based management. This requires that the information management community develop and legitimize innovative approaches for the application of emerging communication technologies in agricultural management. Differing goals, problem criticality, institutional barriers, basis for decisions, usability and capacity, appropriate entry points for information, and experience or tradition shape the use of existing climate information, including forecasts, in the context of other issues affecting productivity.

Benefits arise when prediction of climate fluctuations leads to decisions that reduce vulnerability to impacts of climate variability. It is increasingly recognized that improved decisions depend on communication and that the process depends on institutional support in an appropriate policy environment. Hansen (2002) proposed five preconditions for successful forecast application:

- (a) Decision-maker vulnerability and motivation. Forecast information is useful only when it addresses a need that is real and perceived. Decision-makers must be aware of climate risk and its impacts and motivated to use forecasts to manage this risk.
- (b) Viable forecast-sensitive decision options. Benefits are conditioned upon the existence and understanding of decision options that are sensitive to incremental information in forecasts, and compatible with goals and constraints.
- (c) Predictability of climate fluctuations. Relevant components of climate variability must be predictable in relevant periods, at an appropriate scale, with sufficient skill and lead time for decisions.
- (d) Communication. Use of climate forecasts requires that the right audience receives, understands and correctly interprets the right information at the right time, in a form that can be applied to the problem(s) that require a decision.
- (e) Institutions and policy. Sustained operational use of forecasts requires institutional commitment to provide forecast information and other support, and policies that support provision and use of climate forecasts.

17.2.1 **Communication channels**

In addition to the nature of forecasts themselves, the research community has identified several impact

aspects of forecast communication, such as communication channels, stakeholder awareness, key relationships, and language and terminology. There is a significant disparity in communication infrastructure across countries and across different kinds of agricultural user groups. While among the scientific and technical community there is a great deal of enthusiasm to make use of emerging communications technologies to share real-time information, as well as local knowledge and experiences, extension agents most responsible for managing farmer linkages have to rely on rather conventional means of communication. Low bandwidth and poor computing infrastructure impose serious constraints. On a national and regional level, this calls for conscious integration of emerging and conventional communication technologies. While disparities in communication infrastructure do exist, there are significant local innovations that need to be harnessed and integrated with new technologies. The use of local cable television for Internet access and of phone booths for Internet kiosks in India, as well as wireless Internet access in Laos, are some examples of local innovation that can be exploited for communications in disasters. In some areas, farmers have identified local-language radio programmes as credible and accessible mechanisms to deliver forecasts if they need to be issued, along with follow-up meetings with extension agents or other intermediaries (Konneh, 2006). Radio broadcasting could ensure widespread and timely coverage, while follow-up meetings would enable farmers to ask questions and receive technical advice. This latter point of following up is non-trivial and merits special attention, as discussed below.

One illustrative assessment of follow-up needs (see Ziervogel, 2004) and several examples from Southern Africa outline the limitations of the present modalities for the communication and dissemination of climate information. Country-identified limitations include:

- (a) Zambia: Dissemination of climate information to outlying farming areas is weak.
- (b) Namibia: Communication strategies of the climate information system do not serve the communal farming sector.
- (c) Lesotho: The flow information from the meteorological service through extension to the farmers is poor.
- (d) Swaziland: There is excessive reliance on radio as a tool of dissemination; this "one-way" modality for communication is thought to be inadequate for agricultural applications (for example, farmers are not able to ask further questions regarding the information provided).

- (e) Mauritius: The provision of forecasts is restricted. More intensive use of the Mauritian media would be needed so that climate information can reach the entire population.
- (f) Mozambique: At present the forecast is provided too late for planting decisions in parts of southern Mozambique.

Several countries (Lesotho, Mozambique and Swaziland) found that timely issuance remains a key weakness in climate information systems, especially for communication passed on to the National Early Warning Units (NEWUs).

Channels of communication typically take the form of (WMO, 2004b):

- (a) Workshops and meetings (shared scenario construction, shared model building);
- (b) Presentations and briefings (including locally organized events, for example, hearings);
- (c) One-on-one technical assistance;
- (d) Coordination with other ongoing projects;
- (e) Work with the local media;
- (f) Website development and maintenance;
- (g) Courses on climate impacts and adaptation (see below);
- (h) Media (mass media and information, tele-novelas (soap operas) and the like).

Successful interactions rely on open decision-making processes that recognize multiple interests, community-based initiatives, and integrative science, in addition to traditional science. Weaknesses and gaps identified by earlier and concurrent diagnoses of forecasts and early warning and/or climate information systems still persist. All of the above issues point towards the need for increased training and use of extension staff as tools for communication and dissemination, and the need to improve relations with the print media. Such stakeholder interactions should concentrate on the incorporation of new knowledge or experience into existing models and decision processes, and also on media representation.

17.2.2 **Capacity development for effective communication**

Several countries (for example, Argentina, Brazil, Ethiopia, Peru, South Africa and Zimbabwe) have ongoing programmes within either their meteorological institutions or agricultural research systems that support the use of forecasts by agricultural decision-makers. Other programmes have targeted particular countries as well as groups of countries in a manner that allows comparison across countries. A sampling of some of the

programmes and projects that have a strong research approach to user applications is given below:

- (a) In Australia, there is a strong network of institutions that support agricultural application of seasonal forecasts. The Agricultural Production Systems Research Unit (APSRU) and the Queensland Centre for Climate Applications (QCCA) are the best known.
- (b) The Florida Consortium, now called the Southeast Climate Consortium (University of Florida, Florida State University and University of Miami), first worked in Argentina, then in the south-eastern United States, leading to the development of a programme in the state of Florida on climate applications cooperatively implemented through Florida's agricultural extension service.
- (c) Climate Prediction for Agriculture (CLIMAG)-West Africa is a consortium of institutions in West Africa and Europe that explore seasonal forecasts for early warning applications at the farm level and are focused on the prevention of food insecurity in Mali through a project entitled "Climate Prediction for Mitigation of Global Change Impacts on Agroecosystems in Sudano-Sahelian West Africa".
- (d) Climate Forecasting for Agricultural Resources (CFAR) is a joint project of the University of Georgia and Tufts University (both in the United States) that targets smallholder farmers in Burkina Faso.
- (e) CLIMAG-Asia. The initial project, entitled "Management Responses to Seasonal Climate Forecasts in Cropping Systems of South Asia's Semi-arid Tropics", was carried out in India and Pakistan with participants from Australia and the United States. The next phase, "Applying Climate Information to Enhance the Resilience of Farming Systems Exposed to Climatic Risk in South and Southeast Asia", extended this project to Indonesia.
- (f) The Advanced Training Institute on Climate Variability and Food Security, implemented by the International Research Institute for Climate and Society (IRI) and co-sponsored by the Global Change System for Analysis, Research, and Training (START), was designed to equip young agricultural and food security professionals in developing countries to apply advances in seasonal climate forecasting to the ongoing efforts of their home institutions. Participants in 14 countries are now managing projects that involve exploration or application of seasonal forecasting.
- (g) The Agrometeorological Information Center (CIIAGRO)-Brazil. In 1998 CIIAGRO was

created in the state of São Paulo, Brazil, as a joint initiative by the Office of Agriculture and Supply and the Office for Science and Technology. A key activity is the operational use of agrometeorological models for estimation of water needs of main crops and related productivity, as well as estimation of the potential frequency of pests and crop diseases (Fontana and Camargo, 2002).

- (h) Regional Climate Outlook Forums (COFs). COFs are international frameworks in which climate analysis, assessment and data are synthesized by various regional forecasting groups to arrive at consensus regional forecasts for a particular upcoming rainfall season. Policymakers and decision-makers are active participants in this effort. The Office of Global Programs under the National Oceanic and Atmospheric Administration (NOAA) in the United States initiated this process (Buizer et al., 2000).

Many countries highlight the need for extension training (using rural training centres, for example) to include the use of tailored forecasts. For example, Lesotho instituted awareness-raising campaigns aimed at farmers (and the larger community) regarding the importance of climate information and its distribution, and user education programmes to raise consciousness about the usefulness of forecasts in communal areas. Lesotho also organized an annual workshop aimed at extension training in various agricultural risk management directorates. In South Africa, this training included recommendations for the interpretation of the South African Weather Service's training manual specifically for the agricultural sector. Lessons from these workshops and similar projects funded by NOAA and other agencies are summarized in Table 17.1.

17.3 EXPERIENCE FROM EXTENSION SERVICES: KEY LESSONS

Quantitative, computer-based analytical tools can be combined effectively with participatory approaches to facilitate farmer discussion and foster mutual learning.

Climate information is likely to have the greatest value if it is communicated through advisors whom farmers already know and trust. Any initiative must either work through existing institutions and advisory networks or invest considerable time and effort to establish trust and credibility.

Different factors determine farmers' ability to change decisions in response to forecasts. Many apparent barriers can be overcome by taking a holistic approach and engaging all relevant stakeholders in the process. As has been shown, such activities entail considerable personnel (and personal) effort and resources applied over long periods. As agricultural applications of seasonal climate prediction move increasingly beyond exploratory efforts of the climate

Table 17.1. Key lessons from international experience with agricultural application of seasonal forecasts (Konneh, 2006)

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- Climate information is likely to have value if it is communicated through extension agents or contacts whom farmers already know and trust. Seasonal forecast communication, therefore, needs to flow through existing trusted institutions (Hansen, 2003; Jones, 2003; Walker et al., 2003).
 - Communicating the right information to farmers at the right time is one of the greatest challenges in the application of seasonal climate information in farmer decision-making. This study suggests that current information needs to include additional details, such as technological options that can be applied given the forecast. For instance, if the forecast changes during the season, how can users respond?
 - The availability of the right type of seasonal climate information does not guarantee that it will be used. The method of presenting the information and understanding the decision contexts of different user groups, such as the seed growers, livestock managers and seed suppliers, are equally critical to effectively communicating seasonal climate forecast for the benefit of users (Kirshen et al., 2003).
 - Future resource allocations and policy priorities should focus on both technology transfer and programmes, such as microcredit financing, that would create an enabling environment for the application of technology, especially in developing regions, such as Africa, Latin America and South-East Asia.
 - Decision-makers continue to resort to crisis management in climate-related disasters largely owing to the low confidence they have in the current seasonal climate forecasts (Baethgen, 2003). The low level of use of current seasonal forecasts is due in particular to their minimal ability to accurately inform decision-makers about upcoming climatic conditions.
 - User perception of climate vulnerability (for example, exposure to recent extreme events) and understanding user decision contexts are critical factors that can influence forecast use (Yarnal et al., 2003).
 - The value of ENSO forecasts depends to a great extent on the identification of flexible mitigation options and the desire and ability of agricultural stakeholders to adopt alternative farm management practices.
-

community into mainstream agricultural research, credible demonstration of farmer use and benefit becomes increasingly important (Ziervogel, 2004).

Three key areas of concern relating to communication can be distilled from these efforts (for instance, Ziervogel and Downing, 2004):

- (a) Language/terminology: Challenges of language and terminology were specifically highlighted by 10 of the responding country teams. A range of responding countries called for the translation of forecast terms into a language understandable to the agricultural user. Zambia, for example, specifically stated that the language is too technical.
- (b) Awareness and training for providers/users/stakeholders: User/stakeholder training and awareness are critical weaknesses. In addition, providers need to be educated about the needs and decision-making processes that the farmers employ. Strategies to improve user and stakeholder awareness of climate information and its potential applications are described below.
- (c) Characteristics of climate forecasts: The spatial distribution of forecasts is of particular concern for several countries and locations. Agroecologically specific forecasts are of key importance (for instance, statements from Lesotho, southern Mozambique and Mauritius). Several country teams analysed forecasts currently provided for different timescales and raised the following criticisms:
 - (i) Seasonal: provides probability of rainfall amounts, but does not address distribution;
 - (ii) Monthly: provides probability of rainfall amounts, but is too general and probabilistic;
 - (iii) Dekadal: addresses rainfall distribution, but in general provides no daily rainfall amounts or relative humidity projections;
 - (iv) Daily: addresses rainfall distribution, but is generally deficient in providing rainfall amount and relative humidity parameters.

That forecasts can be too general (spatially and in other aspects) to be of use to the agricultural sector echoes findings of other assessments. Farmers and extension agents also point to the limited utility of the above-normal, normal and below-normal categories regularly presented in Climate Outlook Forums for decision-making. Thus, determining

the level of acceptability of risk for particular negative outcomes is key.

Given the limited familiarity with concepts of climate across timescales (from extremes to change), efforts simply to provide awareness of the role of climate in the lives of farmers and agribusiness need to be developed and understood by information providers, including extension agents themselves (see 17.3.2 on training the trainers). One such effort is the "Climate Field School". While the lessons from the field school concept are slowly emerging, it is worth outlining the approach for the purpose of supporting effective communication channels.

17.3.1 **The Climate Field School concept: setting the context for effective communication**

The concept of the Climate Field School is adopted from the Farmer Field School designed for Integrated Pest Management (see Gallagher, 1999; Birkhaeuser, 1991). The Climate Field School (CFS) is intended to increase farmers' knowledge of climate and their ability to anticipate extreme climate events for particular farming activities; assist farmers in observing climatic parameters and facilitate their use in support of farming activities; and aid farmers in translating the climate (forecast) information to support farming activities, in particular in the areas of planting decisions and cropping strategy (see the Annex to this chapter for an illustrative case). The procedure for the dissemination of climate information to farmers should follow the process used to introduce new technology. Farmers should be convinced from their own experiences that the use of climate forecast information will be to their benefit and enhance the resilience of their systems to extreme climate events. The activities of the Climate Field School are conducted in the form of simulation processes and interactive discussion on climate between a field facilitator and farmers, and through group dynamics. Training materials in field schools should cover the following aspects:

- (a) Basic concepts of climate prediction (probability concept, terminology used in climate prediction, and so on), climate forecast products, and explanation of seasonal forecasts on shifting probabilities for crop yields, marketing trends, likely pest outbreaks, and so forth;
- (b) The use of historical agriculture data (such as drought/flood data, planting data, frost, harvesting data and agriculture production data) to assess the impact of climate

variability/extreme events on agriculture, and simple water balance analysis, technology for harvesting rain, and so on;

- (c) The use of climate forecast information for setting up a cropping strategy (cropping patterns, crop rotation, intercropping, and so forth).

As discussed by Feder et al. (2003), there is merit in continually reviewing the curriculum and focusing training on topics with the highest priority, while simplifying the presentation of the information. The simplification of the programme's content will make it more effective, as this will improve the performance of graduates and increase the likelihood and speed of diffusion of new knowledge among other farmers. Diffusion can also be enhanced (and made more cost-effective) by employing mass media and other dissemination approaches for key aspects of the knowledge (for example, safety rules regarding the use of pesticides). This would require additional efforts to ensure that the media (print, television) are familiar with concepts such as ENSO and the associated forecast uncertainties. They may themselves be seen as recipients of extension services. The narrowing and prioritizing of the curriculum will also shorten the length of the training and reduce programme costs. Increasing the extent of simple decision rules in the training will make the programme less dependent on trainer quality and more amenable to scaling up.

17.3.2 **The necessity of training the trainers**

Information providers should themselves be clear as to the nature and limitations of the information being provided. Extension agents can themselves benefit from Climate Field Schools, which would build additional trust among users. In addition to developing a critical acceptance, the key emphases should be identifying appropriate entry points and application of jointly produced information at those points of decision-making (Pulwarty et al., 2003). This requires a technically strong facilitator. A major problem is that the providers of climate information are communicating probability information in deterministic ways. Seasonal forecasts must be communicated and understood in probabilistic terms. It is, however, difficult to communicate that the climate forecasts are a spread of possible outcomes (with some probability of an outcome of "dry" conditions in a forecast that is wetter than normal) and not a single prediction. The

expectation of a deterministic forecast that will turn out to be either "correct" or "false" is especially damaging in situations when the decision-maker will experience post-decisional regret after believing that he or she acted on a "false" forecast.

Overconfidence due to miscommunication or distortion of uncertainty can negate the value of forecast use, leading farmers to make decisions that are inconsistent with their risk tolerance. Better understanding of the outcome variables that matter to farmers provides guidelines on whether and how best to "translate" climate forecasts. If, for example, crop yields or the costs of production input require particular attention, it becomes necessary to "translate" a climate forecast into the agronomic yield, income and/or cost implications that it holds.

Various researchers have found that communicating the nature of seasonal forecasts is critical for changing user behaviour with regard to utilizing seasonal forecasts. The researchers agree that agricultural extension agents are among the best vehicles to communicate forecast information to users in the agricultural sector. Many extension agents, however, lack basic climate education to enable them to "package" the probabilistic climate information into flexible and operational formats for users (Hansen, 2002; Jones, 2003; Walker et al., 2003.) As discussed, workshops and participatory discussions, which actively engage decision-makers, are effective for communicating seasonal forecast information (Kirshen et al., 2003; Patt and Gwata, 2002; Orlove and Tosteson, 1999). This conclusion is especially true for rural communities in developing regions of Africa, Latin America and the Caribbean, and South-East Asia, where opportunities for Internet access are low and the use of print media is minimal due to low literacy levels. As noted above, however, even in more technologically advanced areas, there is still the need for face-to-face, multidirectional communication and training.

There are many other issues that undermine the effectiveness of agricultural extension agents, especially in developing regions such as Africa. Extension services in many countries (for example, Burkina Faso) are being severely impaired by cuts in government spending, so that agents do not even have the means of transport to reach farmers; low pay and poor work conditions result in a lack of motivation and absenteeism. In other cases (such as Uganda), "modernization" policies support the hiring of university graduates as agricultural

extension agents, but the latter have no experience with farming, can often show too little respect for farmers and rarely visit the areas they are supposed to cover (Roncoli, 2006). Against this backdrop, WMO should collaborate with Radio and Internet for the Communication of Hydro-meteorological Information for Rural Development (RANET), the NOAA climate education programme, IRI, the NOAA Regional Integrated Sciences and Assessments (RISA) through the Southeast Climate Consortium (SECC), and regional institutions in Africa, Latin America and the Caribbean, South-East Asia and the South Pacific, to develop a training and reporting scheme that would enable the extension agents, regional journalists and users to understand the basics of seasonal forecasting, and how climate affects the agricultural sector. The instruction should focus on how the trainees use the knowledge to optimize production and minimize climate-related losses in the agricultural sector (Konneh, 2006).

17.3.3 **Off-farm planning and decision-making**

Climate variability is also associated with other sources of production risks such as pest and disease incidence; for their part, market plans require analyses of supply and demand projections throughout the cropping season and post-season storage and transportation. In addition to on-farm users (farmers), a broader typology of agricultural “users” or “stakeholders” would include:

- (a) Information providers;
- (b) Owners and suppliers of inputs (seeds, fertilizers);
- (c) Buyers and market intermediaries;
- (d) Sources and developers of technology;
- (e) Financiers of technology transfer;
- (f) Local, regional and national governments.

While studies have identified barriers related to resource availability, few have attempted to involve relevant actors sufficiently, such as suppliers of agricultural inputs or credit, to address the barriers (Hansen, 2002). Few attempts at forecast interventions have allowed sufficient time for farmer learning, often due to the constraints of project funding cycles. There are not many clear, well-documented examples of forecast use, particularly by resource-poor farmers in less-developed countries (see Archer, 2003). Marketers now examine seasonal forecasts in developing marketing and shipping plans, and harvest operators and farmers have identified different harvesting strategies that can be employed for different climate outlooks. In addition, they

have identified how seasonal climatic forecasts can be used to assist with herbicide and fertilizer management. The ex post analysis of forecast use and utility should facilitate an ongoing process of social learning.

17.3.4 **Linking the decision-making calendar to the agroclimatic calendar: seasonality of climate, practices and decision-making inputs**

Decision-makers in numerous domains, including research, have been shown to have limited insight into their own decision processes and goals and objectives. Employing simple elicitations such as “What do you need and when do you need it?” might be in fact misleading since a high degree of prior knowledge is presumed. Successful information development and use is a learning process. Many researchers and mediators have argued for consensus in judgemental forecasts, for example, combining regional-scale dynamic forecasts with local insight. Without consensus validity, scientific consistency and generalizability may be lost (Arkes, 2001). Such processes can also lead to “groupthink”, with domination by particular individuals. A more careful structuring of feedback within partnerships developed between providers and users (or representatives of users) needs to be established.

The concept of the decision calendar was introduced in Pulwarty and Melis (2001) as a means of obtaining and cooperatively mapping decision-making characteristics, perceptions and information inputs as they co-evolve with the hydroclimatic, or in the present context, the agroclimatic calendar. This simple tool, employed as a joint product among farmers, resource providers (for instance, of seeds, fertilizer, and so forth) and information providers, is a means of co-producing knowledge about the key timing of inputs to generate particular outcomes. In addition to the benefits of the “annual round”, it can also indicate potential off-farm interactions (for example, at the ENSO level, in the market, or relating to the globalization of farm inputs) as they affect on-farm activities. Table 17.2 (Walker et al., 2003) shows one example of an agroclimate decision calendar. Added to this could be information on how ENSO affects the seasonality of precipitation during key activity periods and what climate information would be needed at which critical points in time to be included in decision-making, as shown in Table 17.3 (Pulwarty et al., 2001). It helps an information provider structure his or her interaction while allowing for stakeholder inputs for planning, resource gathering, implementation, harvest,

Table 17.2. Various decisions taken by farmers in the low and adequate rainfall agroclimatic regions of the central Rift Valley of Ethiopia (Walker et al., 2003)

Agroclimate zone	Crops			Order of choice	Date of sowing	Variety preference	Land preparation	Labour preparation	Harvest date
	Dominant	Secondary	Cash						
S3 Single growing period low rainfall areas: Melkassa and Mieso	Maize		Maize	3	Early April to early May	Medium duration	3 times	Medium	Starts in early Oct.
			Beans	1			2 times	Least	
		Sorghum		4			3 times	Medium	
	Beans	Teff	Teff	2	Late June to early July	Short duration	4 times	Greatest	Late Oct to Nov.
			Teff		Late July	No choice	4 times		
D3 Double growing period, adequate rainfall: Awassa and Arsi Negelle	Wheat		Wheat		Early to late April	No choice, long duration		Medium	Nov. & Dec. for long duration
	Maize						3 times	Medium	
	Barley		Barley						
		Teff	Teff			Medium	4 times	High	
		Sorghum							
			Potatoes		June, July & August	Replanting if failure		High	
			Onion					High	
			Tomatoes					High	

Table 17.3. Key issues in linking the decision-making calendar to the agroclimatic calendar for assessing and responding to potential ENSO impacts (Pulwarty et al., 2001)

- What are the sources of climate variability and controls on yields and operations?
- What are the critical months that influence the crop quality in the following harvest?
- How do rainfall and temperature (solar radiation, and so forth) affect these critical months?
- What is the critical period (which seasons) for ENSO impacts on yield predictability?
- How do different “warm” (El Niño) and “cold” (La Niña) events and their evolution phase affect yield?
- What is the present degree and evolving use of climate information?
- Where are the entry points for climate information into the annual cycle of operation decisions and into longer-term planning?
- What types of information (forecast characteristics) are identified as important and when, where and how should this information be provided?
- What other factors determine vulnerability? What practices and policies give rise to failures and to successes in the use of scientific information? What changes in the physical and management environments have affected sugar production on an annual basis (pest outbreaks, worker strikes and factory breakdowns)?
- What management actions can be taken with given probabilities and lead times? What capacity-building measures are needed within the industry?

storage, processing and transportation as forecasts change or verify. It also offers a means of facilitating knowledge development among providers at different scales (such as on-farm, regional forecast providers) and farmers (or managers).

Table 17.3 provides a sequential list of questions that may be cooperatively answered by providers and stakeholders over the period of interest (for instance, planting through harvesting), linking the key inputs (for instance, how an ENSO event modifies the climatological averages and exceedance probabilities, and how this in turn affects practice).

17.4 CONCLUSIONS

Few studies that have taken a holistic approach have been designed explicitly to evaluate information adoption, impact and refinement. Podesta et al. (2002) and other authors outline the following key supporting activities in the effective communication of climate information for agricultural decisions:

- (a) There is need to develop procedures to convert raw climate information and forecasts into likely outcomes of alternative decisions in climate-sensitive sectors of society. Mapping practical pathways to different outcomes can be carried out as a co-production strategy among research, extension and farmer communities.

- (b) Efforts to foster effective use of climate information and forecasts must be grounded in a firm understanding of the goals, objectives and constraints of farmers and agribusinesses in the target system.
- (c) Existing stakeholders' networks and organizations may provide effective ways to disseminate and assess climate information and forecasts.
- (d) Research, teaching and outreach on the environmental and societal implications of climate variability and change require a broad spectrum of talents and participants. Yet our understanding of factors leading to the development and sustained operation of successful interdisciplinary research and outreach teams is still quite limited.

Wherever resources allow, a holistic approach that attempts to put the necessary conditions in place and concerted efforts to demonstrate and quantify use and benefits will serve the cause of seasonal forecast applications and the farmers. The following framework for researchers and practitioners cooperatively engaging in the use of climate information, including forecasts, in the agricultural sector can be proposed:

- (a) Integrate an understanding of local contexts and contending perspectives with an understanding of how new information becomes framed and socialized into farming practice;
- (b) Assess impediments to and opportunities for the flow of information, including issues of credibility, legitimacy, compatibility (appropriate scale, content, match with existing practice) and acceptability.

Baseline work with farmers and other agricultural stakeholders includes the following steps:

- (a) Describe the agroclimatic decision calendar/annual cycle of decisions of different processes (planning, information gathering, forecasting, decision-making, implementation, evaluation, and so on) to identify entry points for relevant climatic information and competing pressures at different stages;
- (b) Clearly document single past events of significance and evaluate the contexts within which decision-making occurred, including lessons learned and incorporated;
- (c) Refine Climate Field School material in the context of other field schools. Key emphasis should be on analyses of the role of antecedent events and decisions in constraining or enabling alternatives recommended during rapidly developing events;

- (d) Evaluate decisions and outcome scenarios within the context of longer-term climate variations such as decadal-scale wetter and drier periods. This includes evaluating the cumulative impacts of shorter multi-year variations (such as extended dry periods) and antecedent physical conditions (such as high precipitation during key germination periods or high temperatures during flowering).

From the perspective of forecasting, the tasks outlined below involve actions to clarify both the acceptability of information and the context in which this information is going to be used (Fischhoff, 2001; Pulwarty and Melis, 2001).

Before making forecasts:

- (a) Meet with recipients or representatives to determine which measures they would find most useful;
- (b) Independently analyse the problems that stakeholders face in order to obtain a complementary perspective;
- (c) Empirically test formats for communication in order to ensure that stakeholders understand the information as intended;
- (d) Seek users' explicit agreement on appropriate formats;
- (e) Develop decision calendars cooperatively with stakeholders to determine key entry points for different kinds of information.

While making forecasts:

- (a) Make the nature of links to decision calendars and the forecast as explicit as possible, including alternate possible outcomes;
- (b) Document the assumptions underlying forecasts, including how changes in seasonal development would change the forecast (how the forecast is verifying).

When evaluating the use of forecasts:

- (a) Do post-season farmer workshops;
- (b) Review what was predicted and what assumptions were made;
- (c) Construct explanations not only for what actually happened, but what could have happened as a way of retrieving uncertainties at the time of predictions;
- (d) Evaluate what new information was learned about the process producing the event predicted as well as the event itself.

For climate information and forecasts to be used to their considerable potential, four general requirements are identified: (1) stakeholders (or intermediaries) must be able to obtain information

(from forecasts or existing information) on factors or variables of direct interest to them and at lead times that allow for planning; (2) paths to decisions, using this information, must be clear and practical; (3) stakeholders must be able to critically question the provided information to assess appropriateness; (4) stakeholders must be convinced that such information, when used effectively, will indeed make them better off than before.

Through mechanisms such as the Climate Field School (even an abbreviated version) and the co-production of agroclimate decision calendars, information providers should treat the development, communication and use of climate (and other scientific) information as a process in which symmetrical learning takes place among providers

of scientific information and farmers and agricultural stakeholders over time. Researchers, through ongoing dialogue and joint studies, should engage practitioners as full partners in uncovering issues of mutual significance, and explicitly address uncertainties and known barriers to information. The goals are to have better matches among what is needed, what is provided and what actions may be undertaken that increase flexibility in decision-making. The recommendations above are made from years of empirical studies that show what has worked based on experience. The approaches require considerable transaction costs in terms of human resources and time. Realizing the potential of climate information, including forecasts, requires support for personnel to maintain sustained communication pathways as outlined above.

ANNEX

Key modules being developed in the first phase of the Climate Field School programme (adapted from Boer et al., 2003)

1. Knowledge about elements of weather and climate	Introduce element of weather and climate
2. Process of rain formation	Build ability to differentiate between weather and climate Study the process of rainfall formation
3. Developing understanding of terminologies and indices used in seasonal climate forecast	Develop better understanding of the importance of forest in retaining water Develop capacity to understand the meaning of averages and deviations from average
4. Developing understanding of probability concept (forecast error history)	Develop capacity to translate the seasonal climate forecast used by the Bureau of Meteorology and Geophysics (BMG) to local conditions (on their farms) considering the trend in rainfall data measured by the farmers Develop better understanding of probability concept and skill of forecast in climate forecasting and its relation to decision-making
Types of seasonal variability: ENSO-related and non-ENSO-related: Effects of ENSO–precipitation relationship in critical periods	Impacts on previous years and seasonality Also for non-ENSO-related precipitation impacts
5. Introduction to measuring tools for weather/climate, weather measurement equipment and ways of calibrating data	Introduce instruments used for measuring weather/climate elements Learn factors affecting the accuracy of data measured by non-standard instruments Learn how to calibrate data that are not measured using standard method
6. Learning about water balance concept and its use to assess irrigation water requirement and flood risk	Develop better understanding of the meaning of rainfall deficit from evapotranspiration Develop better capacity for estimating irrigation water requirement based on simple water balance
7. Using climate forecast information for setting up field management and planting strategies	Assess risk of flood from water balance analysis Develop better understanding of how extreme climate events will affect the crop (e.g., effect of cropping rotation and planting time on level of damage) – Site selection – Pest control and fertilizer applications Develop better capacity for using seasonal climate forecast in setting up cropping strategies (to avoid or minimize effect of floods and drought) Vegetation conditions for livestock.
8. Assessing the economic value of climate forecast information	Develop better capacity to quantify the economic benefit of using climate forecast information Market impacts

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APPENDIX I

BIBLIOGRAPHY OF LITERATURE ON AGRICULTURAL METEOROLOGY

A. List of recommended handbooks, textbooks and other relevant publications

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B. Selected WMO Publications

(a) Technical Notes

<i>Technical note No.</i>	<i>WMO No.</i>	<i>Title</i>
10	42	The forecasting from weather data of potato blight and other plant diseases and pests. By a WG of CAgM. 1955,48 pp. E, summary F, R, S. o/p
11	42	The standardization of the measurement of evaporation as a climatic factor. By G. W. Robertson. 1955, 10 pp. E, summary F, R, S. o/p.
17	63	Notes on the problems of cargo ventilation. By W . F . McDonald. 1957, 38 pp. E, summary F, R, S
20	72	The climatological investigation of soil temperature. By Milton L. Blanc. 1958, 18 pp. E, summary F, R, S. O/p
21	72	Measurement of evaporation; humidity in the biosphere and soil moisture. By a WG of CIMO. 1958,49 pp. E, summary F, R, S. O/p
22	73	Preparing climatic data for the user. By H. E. Landsberg. 1958, 19 pp. E, summary F, R, S. O/p
26	82	Techniques for surveying surface-water resources. By Ray K. Linsley. 1958,41 pp. E, summary F, R, S. alp
32	96	Meteorological service for aircraft employed in agriculture and forestry. Bya WGofCAGM.1960,x+ 32pp. E,summmaryE, F,R, S. alp
41	110	Climatic aspects of the possible establishment of the Japanese beetle in Europe. By P. Austin-Bourke. 1961, x+ 9 pp., E, summary E, F, R, S.
42	110	Forecasting for forest fire services. By a WG of CAgM. 1961 , xiii + 56 pp. E, summary E, F, R, S.
50	132	The problem of the professional training of meteorological personnel of all grades in the less-developed countries. By J. Van Mieghem. 1963, x + 75 pp. E -F, summary E, F, R, S. o/p
51	133	Protection against frost damage .By a WG of CAgM.1963, x+ 62 pp.; illus. E, summary E, F, R, S.
53	137	The effect of weather and climate upon the keeping quality of fruit. Bya WG ofCAGM. 1963 , xxii + 180 pp. E, summary E, F, R, S.
54	138	Meteorology and the migration of Desert Locusts. By C. Rainey and C. I. H.Aspliden. 1963,x+ 17pp; illus. E, summary E, F,R, S.
55	140	The influence of weather conditions on the occurrence of apple scab. By a WG of CAgM.1963, xi+ 41pp. E, summary E, F,R,S.

<i>Technical note No.</i>	<i>WMO No.</i>	<i>Title</i>
56	141	A study of agroclimatology in semi-arid and arid zones of the Near East. 1963 , xv + 64 pp; illus. E -F, summary E, F, R, S.
59	147	Windbreaks and shelterbelts, By a WG of CAgM. 1964, xv+ 188 pp. E, summary E, F, R, S. alp.
69	171	Meteorology and the Desert Locust. 1965, 310 pp; illus. E or F, summary E , F, R, S. alp.
71	178	Statistical analysis and prognosis in meteorology. 1966, xii + 197 pp. E or F, summary E, F, R, S. o/p.
76	191	Instruments and measurements in hydrometeorology. 1966,56 pp.; illus. E or F, summary E, o/p.
79	195	Climatic change. by a WG of CCI. 1966,79pp.E,summary E,F, R, S.
81	199	Some methods of climatological analysis. By H. C. S. Thorn. 1966, xii+ 54pp.E -F, summary E, F, R, S. alp .
83	201	Measurement and estimation of evaporation and evapotranspiration. By a WG of CIMO. 1966, xv + 120 pp; figures. E, summary E, F, R, S. alp.
86	210	An agroclimatological survey of a semi-arid area in Africa south of the Sahara. By J. Cocherne and P. Franquin. 1967, xxv + 136 pp. mus. E-F
96	234	Air pollutants, meteorology and plant injury. By a WG of CAgM. 1969, x + 73 pp. E, summary E, F, R, S.
97	235	Practical soil moisture problems in agriculture. By a W G of CAgM. 1969, xv + 69 pp. E, summary E, F, R, S. o/p.
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100	242	Data processing for climatological purposes. Proceedings of WMO Symposium, Asheville, U.S.A., 1968. 1969, xvi + 132 pp.; illus. E or F, introduction E, F, R, S.
101	243	Meteorology and grain storage. By C. V. Smith. 1969, xvi + 65 pp.; figures. E, summary E, F, R, S.
106	251	Meteorological aspects of air pollution. 1970,69 pp.; illus. E or F. o/p.
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114	274	Meteorological factors of air pollution. By A. G. Forsdyke. 1970, x + 32 pp.; illus. E, summary E, F, R, S.

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116	279	Investigation on the climatic conditions of the advancement of the Tunisian Sahara. By H. Flohn. 1971, vii + 30 pp. E, F.
118	281	Protection of plants against adverse weather. By G. W. Hurst and R P. Rumney. 1971, x + 64 pp. E, summary E, F, R, S.
119	298	The application of micrometeorology to agricultural problems. Edited by L. P. Smith. 1972, xiv + 74 pp. E, summary E, F, R, S.
121	319	Dispersion and forecasting of air pollution. By a WG of CAS. 1972, x + 116 pp. E, summary E, F, R, S.
122	325	Some environmental problems of livestock housing. By C. V. Smith. 1972, 98 pp. E, summary E, F, R, S.
125	339	A study of the agroclimatology of the highlands of eastern Africa. By L. H. Brown and J. Cocheme. 1973, xvi + 198 pp. E, summary E, F, R, S.
126	354	Comparison between pan and lake evaporation. By C. E. Hounam. 1973, x + 54 pp. E, summary E, F, R, S. o/p.
131	373	Climate under glass. By Dr. J. Seeman. 1973, x + 40 pp. E, summary E, F, R, S.
132	375	Applications of meteorology to economic and social development. By R. Schneider, J. D. McQuigg, L. L. Means and N. K. Klyukin. 1974, x + 130 pp. E, summary E, F, R, S.
133	378	An introduction to agrotopoclimatology. By L. B. MacHattie and F. Schnelle. 1974, xii + 132 pp. E, summary E, F, R, S. o/p.
136	388	Mulching effects on plant climate and yield. By J. W. Davies. 1975, xii + 118 pp. E, summary E, F, R, S.
137	391	Meteorology and the Colorado potato beetle. By G. W. Hurst. 1975, x + 52 pp. E, summary E, F, R, S.
138	392	Drought and agriculture. Report of the Working Group on the Assessment of Drought of the Commission for Agricultural Meteorology. 1975, xviii + 128 pp. E, summary E, F, R, S.
139	393	Climatological aspects of the composition and pollution of the atmosphere. By G. C. Holzworth. 1975, x + 44 pp. E, summary E, F, R, S. D/p.
143	415	Sur l'analyse statistique des series d'observations. Par R. Sneyers. 1975, xx + 192 pp. F, summary E, F, R, S.
144	423	Rice and weather. By G. W. Robertson. 1975, viii + 40 pp. E, summary E, F, R, S.
145	424	Economic benefits of climatological services. By Dr. R. Berggren. 1975, xiv + 44 pp. E, summary E, F, R, S.

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146	426	Cost and structure of meteorological services with special reference to the problem of developing countries. By E. A. Bernard. 1975, xiv + 52 pp. E, summary E, F, R, S.
147	431	Review of present knowledge of plant injury by air pollution. By E. 1. Mukammal. 1976, xi + 27 pp. E, summary E, F, R, S.
148	436	Controlled climate and plant research. By J. Downs and H. Hellmers, CAgM Rapporteurs on Controlled Climates. 1976, x + 60 pp. E, summary E, F, R, S.
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157	487	Techniques of frost prediction and methods of frost and cold protection. By A. Bagdonas, J. C. Georg and J. F. Gerber. 1978, x + 101 pp. E, summary E, F, R, S.
159	497	Weather and parasitic animal disease. Edited by T. E. Gibson. 1978, viii + 174 pp. E, summary E, F, R, S.
160	498	Soya bean and weather. By F. S. da Mota. 1978, xvi + 64 pp. E, summary E, F, R, S.
161	506	Estudio agroclimatologico de la zona andina. By M . Frere, J. Q. Rijks and J. Rea . 1978, Liii + 297 pp. S, summary S, F, E, R.
164	526	The economic value of agrometeorological information and advice. By M. H. Omar. 1980, xv + 52 pp. E, summary E, F, R, S.
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168	536	The role of agrorneteorology in agricultural development and investment projects. By G. W. Robertson. 1980, viii + 85 pp. E, summary E, F, R, S.
172	557	Meteorological Aspects of the Utilization of Solar Radiation as an Energy Source. 1981. 298 pp. E Annex: World Maps of Relative Global Radiation. 20 pp. E.
173	562	Weather and Airborne Organisms. By D.E. Pedgley. 1980. 91 pp E
174	566	The Effect of Meteorological Factors on Crop Yields and Methods of Forecasting the Yield. Based on a report by the CAgM Working Group on the Effect of Agrometeorological Factors on Crop Yields and Methods of Forecasting the Yield. 1982. 54 pp.
175	575	Meteorological Aspects of the Utilization of Wind as an Energy Source. 1981. 180 pp. E

<i>Technical note No.</i>	<i>WMO No.</i>	<i>Title</i>
178	591	Meteorological Aspects of Certain Processes Affecting Soil Degradation - Especially Erosion. Report of the CAgM Working Group on Meteorological Factors Associated with Certain Aspects of Soil Degradation and Erosion. 1983. 149 pp.
179	597	A Study of the Agroclimatology of the Humid Tropics of South-East Asia. By L.R. Olderman and M. Frère. 1982. 229 pp.
180	620	Weather-Based Mathematical Models for Estimating Development and Ripening of Crops. By G.W. Robertson. 1983. 86 pp.
182	629	The Analysis of Data Collected from International Experiments on Lucerne. (Report of the CAgM Working Group on International Experiments for the Acquisition of Lucerne/Weather Data). 1986. 133 pp.
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196	802	Climate Variability, Agriculture and Forestry. Report of the CAgM-IX Working Group on the study of Climate Effects on Agriculture including Forests, and of the Effects of Agriculture and Forest on Climate. 1994. 152 pp.
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199	841	Climate Variability, Agriculture and Forestry: An Update. By M.J. Salinger, R. Desjardins, M.B. Jones, M.V.K. Sivakumar, N.D. Strommen, S. Veerasamy, and W. Lianhai. 1997. 51 pp.
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(b) Scientific and technical publications

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5	Composition of the WMO. Quarterly, loose-leaf. E/F.
8	Guide to meteorological instrument and observing practices. 4th edition, 197 I, loose-leaf. E-F.
100	Guide to climatological practices. 1960, loose-leaf, E-F-S. O/p
113	Weather and food. By L. P. Smith. 1962, 80 pp. E-F-S. (S o/p).
117	Climatological normals (CLINO) for CLIMAT and CLIMAT SHIP stations for the period 193 I-I 960. 197 I edition, loose-leaf. E/F.
143	Weather and man -The role of meteorology in economic development. 1964, 80 pp . E-F-S . (E-S o/p).
168	Guide to hydrometeorological practices. 1970, loose-leaf, E-F-S. o/p. Guide to hydrological practices. 1974 (3rd edition), loose-leaf.
174	Catalogue of meteorological data for research. (Part I) 1965, loose-leaf. E. (Part II) 1970, loose-leaf. E/F. (Part III) 1972, loose-leaf. E. (Part IV) 1979, loose-leaf. E.
182	International meteorological vocabulary. 1966, xv + 276 pp. E/F/R/S. O/p.
202	Syllabi for instruction in agricultural meteorology. 1966, v + 44 pp. E.O/p.

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204	Weather and water. 1966, 27 pp. E-F-R-S. O/p.
220	Harvest from weather. By Gwenda Mathews. 1967, 48 pp., illus. EF-R-S.
240	Compendium of meteorological training facilities. 5th ed., 1977, vii + 365 pp. E-F.
257	How to become a meteorologist. 1970, 16 pp., illus. E-F-R-S.
258	Guidelines for the education and training of personnel in meteorology and operational hydrology. Second edition. 1977, xxviii + 236 pp. E-F.
266	Compendium of lecture notes for training Class IV meteorological personnel. Volume I -Earth Science. 1970 xii + 179 pp. E-F-S. (F-S o/p). Volume II-Meteorology. 1970 xv + 435 pp. E-F-S. (FS o/p)
276	Selected bibliography on urban climate. 1970, 383 pp. E.
291	Compendium of lecture notes for training Class III meteorological personnel. 1971, xvii + 380 pp. E-F-S. (E o/p).
307	WMO helps the developing countries. 1971, 86 pp. E-F-S. O/p.
309	Radiation processes in the atmosphere. By K. Ya. Kondratyev. 1972, xxxiv + 220 pp. E, summary E, F, R, S.
310	Agricultural meteorology. Proceedings of the WMO Seminar on Agricultural Meteorology, with special reference to tropical areas of Regions III and IV (Barbados, November 1970). 1972, xviii + 358 pp. E.
313	Meteorology and the human environment. 1971, 40 pp. E-F-S. S o/p.
314	La función de los servicios meteorológicos en el desarrollo económico de América Latina (The role of meteorological services in economic development in Latin America). 1972 viii + 356 pp. S. alp.
317	Proceedings of the Regional Seminar on Modern Methods and Equipment for Data Processing for Climatological Purposes in Africa (Cairo, January 1970). 1972, viii + 328 pp. E. alp.
327	Compendium of lecture notes in climatology for Class IV meteorological personnel. Prepared by Professor W. Lowry. 1972. vi + 154 pp. E.
335	Compendium of lecture notes in climatology for Class III meteorological personnel. Prepared by Professor W. Lowry. 1972, vi + 154 pp. E-F.
338	Twenty years of WMO assistance. 1972, 188 pp. illus. E-F.
340	Agroclimatology in the semi-arid areas south of the Sahara Proceedings of the Regional Technical Conference, Dakar, 8-20 February 1971. 1973, xxxii + 254 pp. E or F.
345	One hundred years of international co-operation in meteorology (1873-1973). A historical review. 1973. vi + 60 pp. E-F-S.

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364	Compendium of meteorology for use by Class I and Class II meteorological personnel. Edited by A. Wiin-Nielsen. Volume I, Part 1 -Dynamic meteorology. Prepared by A. Wiin-Nielsen, 1973 , vi + 334pp.E-S.Volume I, Part 2-Physicalmeteorology. Prepared by B. J. Retallack. 1973, vi + 212 pp. E-S. Volume 1. Part 3 -Synoptic meteorology. Prepared by F. Defant with H. T. Mörrth. 1978, xiv + 276 pp. E.
379	A survey of meteorological and hydrological data available in six Sahelian countries of West Africa. A survey of studies in meteorology in the Sudano-Sahelian zone of West Africa. By E. G. Davy. 1974. vi + 120 pp. E/F.
389	Agroclimatology of the highlands of eastern Africa. Proceedings of the Technical Conference, Nairobi, 1-5 October 1973. 1974, xxvi + 242 pp. E.
396	Agrometeorology of the wheat crop. Proceedings of the WMO Symposium, Brunswick, 22-27 October 1973 .1974, viii + 242 pp. E.O/p
410	WMO -The achievement and the challenge. By H. Daniel, 1976, 48 pp. E-F-S.
432	Proceedings of the WMO/IAMAP Symposium on Education and Training in Meteorology and Meteorological Aspects of Environmental Problems (Caracas, February 1975). 1975, xii + 322 pp. E.
440	<i>History of the Commission for Agricultural Meteorology of the WMO.</i> Prepared by W. Baier, I.G. Gringof and N.D. Strommen (Task Force on Historical Perspectives of CAgM. 1991
463	Weather and water. 1977, 24 pp., E-F-S.
496	<i>Systems for Evaluating and Predicting the Effects of Weather and Climate on Wildland Fires.</i> W.E. Reifsnyder and B. Albers, 1994, x + 34 pp.; Summary E,F,R,S
551	Lecture notes for training agricultural meteorological personnel. By J. Wieringa and J Lomas, 2001, x + 196 pp. E.
593	Lecture notes for training Class IV agricultural meteorological personnel. By A.V. Todorov, 1982, x + 154 pp., E-F-S.
635	Casebook on operational assessment of areal evaporation. OHR No. 22., xvii + 196 pp., E, Summary E-F-R-S.
646	Intercomparison of models of snowmelt runoff. OHR No. 23. xxxii + 440 pp., E-F-R-S.
721	Forty years of progress and achievement - A historical review of WMO. Edited by Sir Arthur Davies. 1990, vii + 205 pp., E.
733	Economic and social benefits of Meteorological and Hydrological Services - Proceedings of the Technical Conference (Geneva, 26-30 March 1990) . 1990. xxx + 461 pp., E.
749	Snow cover measurements and areal assessment of precipitation and soil moisture. Edited by B. Sevruck. OHR No. 35., xxviii + 283 pp. Summary E-F-R-S.

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887	Precipitation estimation and forecasting. By C.G. Collins. OHR NO. 46. xi + 83 pp., E, Summary E-F-R-S.
1034	Secure and Sustainable Living - The Findings of the International Conference on Secure and Sustainable Living: Social and Economic Benefits of Weather, Climate and Water Services. 2009. 100 pp., E-F-R-S.
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<i>Brochures</i>	
624	Meteorology aids food production. 1984. 35 pp., E-F-S.
653	Climatic variations, drought and desertification. By F.K. Hare, revised by L.A.J. Ogallo (Second edition), vi + 45 pp., E-S.
729	The WMO achievement (40 years in the service of international meteorology and hydrology). 1990. 44 pp., F, E (O/P).
760	WMO and UNCED-1992: Protecting the atmosphere, oceans and water resources: Sustainable use of natural resources. 1991. 14 pp., E-F-R-S.
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1051	60 years of service for your safety and well-being. 2010. 24 pp., E-F-S.
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(c) CAgM Reports

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1	--	Measurements of Minimum Temperature near the Surface. By M.M. El Bakry. 1977, 69 pp. E.
2	--	Guide to the Acquisition of Crop - Weather Data for International Experiments. By S.N. Edey, Chairman of a Working Group of CAgM. 1978, 18 pp. E.
3	--	Application of Minimum Temperature near the Surface. By S.E. Taylor and R. Davis. 1979, 22 pp. E.
4	--	The Education and Training of Agricultural Meteorology Personnel in the WMO Member Countries. By V.V. Popova. 1980, 18 pp. E.
5	--	Meteorological Factors and their Influence on the Epidemiology of the Cassava Mites. By Z.M. Nyiira. 1980, 22 pp. E. printed in 1987)
6	--	Report on Water Requirements of Agricultural Crops Under Arid and Semi-arid Conditions. By M.H. Omar. 1981, 71 pp. E.
7	--	Groupe de travail sur les Aspects Météorologiques de l'Agriculture dans les zones Tropicales Humides et sub-humides- Rapport Final. By C. Riou, Chairman of CAgM Working Group. 1982, 122 pp. F
8	--	The Role of Forests in the Global and Regional Water and Energy Balances. By W.E. Reifsnnyder, Chairman of CAgM Working Group. 1982, 33 pp. E.
9	--	Recent Developments in Research on Air Pollution and Plant Injury. By H.H. Neumann, 1982, 24 pp. E.
10	--	Wildland Fires Particularly in Tropical Regions. By A.B.Oguntala. 1982, 39 pp. E.
11	--	Report of the Working Group on Analysis of Wheat/Whether Data. By K. Heger, Chairman of CAgM Working Group. 1982, 35 pp. E.
12	--	Part I: Use of Remote Sensing for Obtaining Agrometeorological Information. By A.D. Kleschenko. 1983, 59 pp. E. Part II: Remote Sensing and Agricultural Meteorology: An Annotated Bibliography. By J.C. Harlan. 17 pp. E.
13	--	Development and Application of Dynamic Simulation Models in Agrometeorology. By O.D. Sirotenko. 1983, 45 pp. E.
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15	--	Weather-Based Mathematical Models of Estimating Development and Ripening of Crops. By G.W. Robertson. 1983, 115 pp. E.

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16	--	Requirements for the Standardization of Instruments and Methods of Observation in the Field of Agricultural Meteorology. By V.N. Strashny. 1983, 24 pp. E.
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18	--	Lectures presented at the eighth session of CAGM. 1983, 95 pp. - Solve Agroclimatic Constraints in the Humid Tropics at the Ground. By M.W. Baradas (Philippines). E. - Meteorological Aspects of Desertification. By I.G. Gringof (U.S.S.R.). E. - Satellite Remote Sensing Applications Development for International Desert Locust Survey and Forecasting. By J. Hielkema, (FAO). E. - Application of Models. By H. van Keulen (Netherlands). E. - Use of Remote Sensing in Agrometeorology. By A.D. Kleschenko (U.S.S.R.). E. - Météorologie et Ennemis des Plantes. C. Samie, C. (INRA, France). E.
19	--	Guidance Material for Agrometeorological Services to Rice Farmers. B.S. Lomotan and M.W. Baradas. 1983, 139 pp. E.
20	--	Glossary of Terms Used in Agrometeorology (Enlarged Edition). 1984, 244 pp. E
21	--	Glossary of Terms Used in Agrometeorology (Provisional Simplified Edition). 1984, 134 pp. E.
22	--	Agrometeorological Services in Developing Countries. By J. Lomas, Chairman of a Working Group of CAGM. 1984, 35 pp. E.
23	--	Agroclimatic Mapping of the Continents. By Z.A. Mischenko. 1984, 131 pp. E.
24	207	Drought Probability Maps. By G.A. Rao. 1987, 46 pp. E.
25	228	Microclimate Management and Manipulation in Traditional Farming. Gestion et Manipulation du Microclimat dans l'agriculture traditionnelle. By C.J. Stigter, Chairman of a Working Group of CAGM. 1988, 77 pp. E; 91 pp. F.
26	206	(Practical Manual Series No. 1). Babau, M.C. 1987. Rain, its Intensity and Energy. 51 pp. (English) (Serie Manuels Pratiques No. 1). Babau, M.C. 1987. La pluie, son intensite, son energie. 51 pp. (French)
27	212	Economic Benefits of Agrometeorological Services. By T. Keane, P.O. Harsmar, and E. Jung. 1986, 66 pp. E.
28	236	Recent Developments in Agrometeorological Research on Groundnut Crop and Agroclimatological Aspects of Groundnut Production in Asia. By W. Yongqin. 1988, 26 pp. E.

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29	207	Agrometeorology of the Banana Crop. By P.S.N. Sastry. 1988, 85 pp. E.
30	238	Agroclimatic Zoning. By O.P. Bishnoi. 1989, 147 pp. E.
31	239	Report of the RA VI Working Group. 1988, 151 pp. E. Part I: Agrometeorology of the Potato Crop. Part II: Survey of Available Information and Techniques on Operational Agro-meteorological Services for Plant Protection. Part III: Crop Protection Models.
32	285	Drought and Desertification in Asia. By K. Noohi. 1988, 62 pp. E.
33A	248	Simulation of Primary Production. By the Centre for Agrobiological Research (CABO) and TPE, Wageningen. 1990, 149 pp. E.
33B	249	Manual on Use of PC, MS-DOS, Edit and CSMP for Simulation of Primary Production of Natural Pastures. By the Centre for Agrobiological Research (CABO), and TPE, Wageningen.. Practical Manual Series No. 2. 1990, 30 pp. E.
34	297	Climate Applications Referral System - Desertification (Cars-Desertification). 1989. 98 pp. E.
35	381	Report of the RA VI Working Group on Agricultural Meteorology. Chairman J. Hrbek. 1990. 246 pp. Part I: Survey of the Operational Methods in Use for Agrometeorological Services for Potato Crop Production. E. Part II-A. Study on Requirements to be Met by an Agrometeorological Services in Countries with Highly Developed Industries. E. Part II-B. Requirements in Agricultural Meteorology in the Highly Industrialized Areas with Developed Agriculture. E. Part III: Agrometeorological Data Bank. E. Part IV-A: Influence due temps et du climat sur la qualité des récoltes. F. Part IV-B: Information on the study of weather and climatic impacts on the quality of grain crops. E.
36	404	Meteorology for Locust Control. La météorologie au service de la lutte anti-acridienne. By National Meteorological Services. 1991. 90 pp. F, E.
37	347	Climate Applications Referral System - FOOD CARS-FOOD, Part II. 1990, 74 pp. E.
38	478	Report of the Measurement of Leaf Wetness. By R.R. Getz. 1992, 10 pp. E.
39	480	Part I - Report on Drought and Desertification. Rapport sur la lutte contre la secheresse et la desertification. By L.E. Akeh. 1992, 29 pp. E, F. Part II - Report on Locust and Crop Pests. Rapport sur la lutte contre les acridiens et autres ennemis des cultures. By O. Sadi. 1992, 25 pp. E, F.

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40	391	Glossary of Terms Used in Agrometeorology. Glossaire des termes utilisés en agrometeorologie. Glosario de terminos usados en la agrometeorologia. 1990, 223 pp. E, F, S.
41	481	Aspects agrometeorologiques de la protection operationnelle des recoltes. By N. Thompson, Rapport du groupe de travail de la CMAg. 1992, 186 pp. F.
42A	484	Meteorologie et viticulture. By A. Carbonneau. 1992, 72 pp. F.
42B	500	Report on the Effect of Agrometeorological Parameters on Viticulture in Countries of Eastern Europe. By T.I. Turmanidze. 1992, 48 pp. E.
43	499	Application of Microclimate Management and Manipulation Techniques in Low External Input Agriculture. By C.J. Stigter, P.H. Karing, W. Chen, and G.C. Wilken. 1992, 192 pp. E.
44	501	Development of Agrometeorological Services in Developing Countries. By N.N. Khambete. 1992, 75 pp. E.
45	502	Part A: New Specialized Agrometeorological Services in Countries with Highly Developed Industries. By M.A. Stroganova. 1992, 42 pp. E ; 57 pp. R. Part B: Study on Requirements to be met by an Agrometeorological Service in Countries With Highly Developed Industries. By H. Dommermuth. 1990, 31 pp. E.
46	503	Part I - Meteorological Aspects of Transport of Agricultural Produce. By A. Chowdhury. 1992, 35 pp. E. Part II - Meteorological Aspects of the Storage and Transport of Animal produce. By A. Porteous. 27 pp. E.
47	505	Monitoring, Assessment and Combat of Drought and Desertification. Surveillance permanente, évaluation et mesures de controle de la sécheresse et de la désertification. By R. Motha, Chairman of CAGM IX Working Group. 1992, 111 pp. E, A, F.
48	506	The Influence of Climatic Factors on Pests and Diseases Attacking Citrus Crop. Influencia de los factores climaticos sobre las plagas y enfermedades de los criticos. By R. Ramon Coscolla. 1992, 35 pp. E, S.
49	507	Part I: Agrometeorology of the Chickpea Crop. By A.R. Subramaniam. 1992, 29 pp. E. Part II: Agrometeorology and Ecophysiology of Cassava. By I.C. Onwueme.

<i>CAGM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
50	508	Part 1: Operational Remote Sensing Systems in Agriculture. By E.T. Kanemasu, and I.D. Flitcroft. 1992, 19 pp. Part II - Applications des satellites en agrométéorologie developments technologiques pour la période 1985-1989. Satellite applications to Agrometeorology - technological developments for the period 1985-1989. By B. Seguin. 26 pp. F, E. Part III - The use of satellite information in agricultural meteorology. By A.D. Kleschenko. 35 pp.
51	514	Scientific Lectures Presented at the Tenth Session of the Commission for Agricultural Meteorology. 1992, 77 pp. E.
52	524	Report of the RA II Working Group on Agricultural Meteorology. 1993, 198 pp. E.
53	527	La meteorologie service de la lutte anti-acridienne. Contribution d'un service météorologique national. Par Météorologie algérienne. 1992, 39 pp. F.
54	542	Aerobiology. By A. Powell. 1993, 48 pp. E.
55	556	Assessment of Air Pollution Effects on Plants. By D.W. Heck. 1993, 59 pp. E.
56	566	L'Agrometeorologie du mil. (Pennisetum glaucum (L) Leake). By G. Marrachi. 1993, 124 pp. F.
57	614	Agrometeorology of Grass and Grasslands in Tropical and Sub-tropical Regions. By J. Ruiz-Vega. 1994, 39 pp. E.
58	615	Agrometeorology of the Coffee Crop. By A.P. Paes de Camargo and A.R. Pereira. 1994, 95 pp. E.
59	616	Agrometeorology of Grasslands for Middle Latitudes. By A.J. Brereton, S.A. Danielov, and D. Scott. 1994, 98 pp. E.
60	629	Practical use of agrometeorological data and information for planning and operational activities in agriculture. By J.F. Villalpando, B.C. Biswas, R. Cáceres Mariscal, A. Coulibaly, Z. Gat, R. Gommès, C. Jacquart, B.S. Lomoton, K.B. Perry, E.S. Ulanova, and A. Ussher. 1994, 113 pp. E.
61	676	Report of the RA VI Working Group on Agricultural Meteorology. By K. Heger. 1995, 156 pp. E.
62	726	Practical Applications of Micro-climatic Knowledge and Information to Agriculture. By P. Karing. 1995, 61 pp. E.

<i>CAGM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
63	727	L'Information agrometeorologique requise pour l'exploitation des sols et des cultures irrigues. Agrometeorological information required of the management of irrigated soils and crops. By C. Riou and G. Zipoli. 1995, 125 pp. F.
64	728	Part I: Definition of Agrometeorological Information Required for Forest Management and Exploitation in Humid Tropical Regions - A. A Case Study from Indonesia. By E. Retnowati. 23 pp. E. - B. Specific Management Decisions that Require Agrometeorological Data. By T. Deanna de Abreu Sá. 21 pp. E. Part II: Meteorological Needs for Temperate and Boreal Forest Management. By M.A. Fosberg. 1995, 13 pp. E. Part III. Meteorological Information Required for Managing forests in Arid and Semi-arid Regions. By J.L. Clayton and M. Elosmani. 1997, 7 pp. E.
65	748	Agrometeorological Data Management. By R.P. Motha, H.H. Hayhoe, A.D. Kleschenko, I.A. Igue, C.E. Gay, and R. Gommès. 1996, 84 pp. E.
66	746	Agrometeorology of the Pearl Millet. By V. Mahalakshmi. 1996, 16 pp. E.
67	747	Agroclimatic Factors and Cocoa Production. By E. Owusu-Manu. 1996, 31 pp. E.
68	750	Agroclimatology of the Apple Crop. By A.S. Porteous. 1996, 48 pp. E.
69	751	Definition of Agroclimatological Information Required for Pasture and Livestock Production in Cold Climate Regions. By S.A. Danielov, I.G. Gringof, and M.T. Germogenov. 1996, 51 pp. E.
70	757	Definition of Agrometeorological Information Required for Field and Bush Crops. By S. Al-Hazim, B.C. Biswas, K.G. Hubbard, and P.S.N. Sastry. 1996, 97 pp. E.
71	809	The Definition of Agrometeorological Information Required for Pasture and Livestock Production in Temperate Regions. By A.J. Brereton, and C.J. Korte. 1997, 51 pp. E.
72	817	Relationships between Weather and Sustainable Agricultural Production and Protection for Groundnuts. By S.M. Vimami. 1997, 26 pp. E.
73	836	Extreme Agrometeorological Events. By G.J. Bedson, D. Dambe, T. Darnhofer, R. Gommès, G.N. Mwongela, D.E. Pedgley, and V. Pérarnaud. 1997, 182 pp. E.
74	838	Weather/Climate and Sustainable Agricultural Production and Protection. By A. Brunetti, P.B. Ford, E.T. Kanemasu, W.N. Lablans, P.F. Mills, R. Mulder, O.D. Sirotenko, and F. Wang. 1997, 112 pp. E.

<i>CAGM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
75	866	Definition of Agrometeorological Information Required for Vegetable Crops. By H.P. Das. 1997, 110 pp. E.
76	885	Training in Agrometeorology. Formación profesional en meteorología agrícola. By E. Sequeira. 1998, 11 pp. E, S.
77	988	UNCED follow-up. By W. Baier. 1998, 43 pp. E.
77B	1029	Contributions from Members on Operational Applications in Agrometeorology in the International Workshop: "Agrometeorology in the 21st Century, Needs and Perspectives". 2001, 175 pp. E.
78	990	Education and Training in Agrometeorology. By J. Collins, S. Gachara, J. Lomas, and S. Mukhopadhyay. 2000, 36 pp. E.
79	989	Weather and Climate Related to Pasture and Livestock Production in Arid and Semi-Arid Regions. By D. Dagvadorj. 2000. 26 pp. E.
80	997	Validation of Information Requirements on Irrigated Soils and Crops. By A.K. Abdullaev and R.P. Samui. 2000, 107 pp. E.
81	1015	Agrometeorological Data Management. By M. Bernard, H. Hayhoe, D. Kleschenko, B.L. Lee, L. Leskinen, R.P. Motha and O. Virchenko. 2000, 98 pp. E.
82	1022	Report of the RA VI Working Group on Agricultural Meteorology. By A. Bussay, R. da Mata Reis, H. Dommermuth, Z. Dunkel, B. Gozzini, M. Hunká, T. Keane, L. Leskinen, J. Lomas, G. Maracchi, M. Molendijk, S. Orlandini, D. Rijks, L. Seghi and J. Valter. 2000, 274 pp. E.
83	1033	WMO/CAGM-Related Achievements in Agricultural Meteorology. By W. Baier. 2000, 27 pp. E.
84	1050	Report of the RA I Working Group on Agricultural Meteorology. By A.L. du Pisani, G. Goroza, J.G. Kabira, M.V. Laing, R. Lekhal, M.F. Lukando, A. Makarau and E. Mersha. 2000, 54 pp. E.
85	1030	Agrometeorological Information Needs in Agricultural Production, by P.D. Jamieson, A.D. Agbangla, P. Diemer, S.S. Jagtap, F. Lansigan, J.F. Strand, V.N. Strashny and S. Wang. 2001, 89 pp. E.
86	1134	Validation of Information Requirements on Livestock and Pasture Production in Arid and Semi-Arid Regions, by O.L. Babushkin and L.V. Lebed. 2002, 76 pp. E.
87	1079	Report of the CAGM Working Group on Weather and Climate related to Agricultural Production. By V.Pérarnaud, A.K. Chan, M.A.A. Dawod, S.K. Shaha and O. Sirotenko. 2001, 113 pp. E.

<i>CAGM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
88	1111	Report of the RA II Working Group on Agricultural Meteorology, by G.A. Kamali, A.K. Abdulaev, K.M. Abdulaev, O.L. Babushkin, D. Dagvadorj, H.P. Das, B.L. Lee, K. Noohi, W. Shili, O.D. Sirotenko, A.I. Strashnaya and N. Van Viet. 2003, 244 pp. E.
89	1113	Report of the RA VI Working Group on Agricultural Meteorology. By Z. Dunkel, V. Alexandrov, O. Braslavskaya, H. Friesland, Z. Gat, R. Guerreiro, A. Kleschenko, and Y. Ozalp. 2002, 216 pp. E.
90	1158	Agrometeorological Aspects of Organic Agriculture, Urban Agriculture, Indoor Agriculture and Precision Agriculture. By N.M. Holden and M.C. Otiz. 2003, 101 pp. E.
91	1166	Interactions Between Climate and Biological Diversity. By M.P. Bah, S. Korsakova, V. Gringoryan, O. Hendrickson, and W. Baier. 2003, 105 pp. E.
92	1175	The Impacts of Agrometeorological Application for Sustainable Management of Farming, Forestry and Livestock. By A. Kleschenko, L. Grom, M. Ndiaye, and R. Stefanski. 2003, 70 pp.
93	1202	Experts for Collection of Case Studies of Economically Beneficial Agrometeorological Applications and Services and Other Success Stories in Agrometeorology for Policy Matters. By W. Baier. 2004, 89 pp.
94	1213	Contribution from Members on Operational Applications in Agrometeorology and from Discussants of the Papers Presented at the International Workshop: "Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change". Many Authors. 2004, 94 pp. E.
95	1230	User Requirements for Satellite and Other Remote-Sensing Information in the Field of Agricultural Meteorology. By P.C. Doraiswamy G.B. Diagne M. Labo S.K. Shaha O. Virchenko. 2004, 11 pp. E.
96	1229	Impact of Agrometeorological Information on Rangeland and Pasture Ecology and Management. By L.V. Lebed, Y. Gandega, D. Rijks. 2004, 24 pp. E.
97	1254	Working Group on the Communication of Agricultural Information. By V. Perarnaud, A. Bootsma, P. Isabyrie, B.-L. Lee. 2004, 133 pp. E.
98	1222	Informe Del Grupo Trabajo Sobre Meteorología Agrícola de la AR IV. By O. Solano, R. Villalobos, y A. Albañil. 2004, 364 pp. S.
99	839	Fire in Forests, Rangelands and Agricultural Systems. By A. R. Riebau and D. G. Fox. 2006, 27 pp. E.
100	1342	Impact of the Use of Meteorological and Climatological Data on Fisheries and Aquaculture. By Ngo Sy Gai and Paul Taylor. 2006, 32 pp. E.

<i>CAGM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
101	1343	Impacts of Desertification and Drought and Other Extreme Meteorological Events. By S. Gathara, I.G. Gringof, E. Mersha, K.C. Sinha Ray, and P. Spasov. 2006, 85 pp. E.
102	1344	Use Of Seasonal Forecasts And Climate Prediction In Operational Agriculture. By M. Harrison, A. Kanga., G.O. Magrin, G. Hugo, I. Tarakidzwa, C. Mullen, H. Meinke. 2007. 81 pp. E

(d) Proceedings (AGM Reports)

<i>AgM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
--	--	Drought Preparedness and management for Western African countries. (Proceedings of the Workshop held in Banjul, Gambia, 1995).
--	--	Prévention et gestion des situations de sécheresse dans les pays de l'Afrique du Nord. (Proceedings of the workshop held in Casablanca, Morocco, 24 to 28 June 1996).
--	--	Wind Erosion in Africa – Problems and Control Strategies. (Proceedings of the Expert Group Meeting held in Cairo, Egypt, 22 –25 April 1997).
--	--	Atelier régional sur la gestion des données agrométéorologiques et leur utilisation pour les services agricoles., Bamako, Mali, 24-28 novembre 1997.
--	--	Técnicas agrometeorológicas en la agricultura operativa de América Latina. (Proceedings of the Regional Workshop / Expert Meeting held in Paipa, Colombia, 17– 21 March 1997). WMO, Geneva, December 1997.
--	--	Encuesta agrometeorológica de las tierras bajas de los trópicos húmedos de América del Sur. FAO – WMO – UNESCO – UNEP Interagencies Working Group on Agricultural Biometeorology. WMO, Geneva, June 1998.
--	--	User Requirements for Agrometeorological Services. (Proceedings of the International Workshop held in Pune, India, 10-14 November 1997), India Meteorological Department, Pune, India 1998.
--	--	Sivakumar, M.V.K., C.J. Stigter and D. Rijks (Eds.). 2000. Agrometeorology in the 21st Century: Needs and Perspectives. Papers from the International Workshop on Agrometeorology in the 21st Century: Needs and Perspectives, 15-17 February 1999, Accra, Ghana. Special Issue, Agricultural and Forest Meteorology, Volume 103, Nos. 1-2, June 2000. 227 pp.
--	--	Reunión de expertos de las Asociaciones Regionales III y IV sobre fenómenos adversos. (Actas de la reunión celebrada, 12-14 julio 1999, Caracas, Venezuela). Geneva, Switzerland: World Meteorological Organization, 2000. 254 pp.

<i>AgM No.</i>	<i>WMO/TD No.</i>	<i>Title</i>
--	--	Sivakumar, M.V.K. (ed.). 2000. Climate Prediction and Agriculture. Proceedings of the START/WMO International Workshop, 27-29 September 1999, Geneva, Switzerland. Washington DC, USA: International START Secretariat. 322 pp.
1	1035	Coping with Drought in Sub-Saharan Africa: Better Use of Climate Information. 2000.
2	1037	Wilhite, D.A., M.V.K. Sivakumar and D.A. Wood. 2000. Early Warning Systems for Drought Preparedness and Drought Management. WMO. 185 pp.
3	1074	Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives. 2001. Proceedings of an International Workshop held in Lincoln, Nebraska, USA, 6-10 March 2000. Edited by Kenneth G. Hubbard and M.V.K. Sivakumar. Lincoln, Nebraska: High Plains Climate Center and Geneva, Switzerland: WMO.
4	1075	Software for Agroclimatic Data Management. 2001. Proceedings of an Expert Group Meeting, 16-20 October 2000, Washington DC, USA. Edited by R.P. Motha and M.V.K. Sivakumar. Washington DC, USA: United States Department of Agriculture and Geneva, Switzerland: WMO.
5	1108	Improving Agrometeorological Bulletins. 2004. Proceedings of the Inter-Regional Workshop. 15-19 October 2001, Bridgetown, Barbados. Edited by M.V.K. Sivakumar.
6/WCAC-2	1234	Servicios de Información y Predicción del Clima (SIPC) y Aplicaciones Agrometeorológicas para los Países Andinos: Actas de la Reunión Técnica. 2004. del 8 al 12 de diciembre de 2003, Guayaquil, Ecuador. Ginebra, Suiza: OMM. S.
7/WCAC-2	1123	Applications of Climate Forecasts for Agriculture. 2004. Proceedings of an Expert Group Meeting for Regional Association I - Africa. 9-13 December 2002, Banjul, Gambia. Edited by M.V.K. Sivakumar.
8	1182	Satellite Remote Sensing and GIS Applications in Agricultural Meteorology. 2004. Proceedings of the Training Workshop, 7-11 July 2003, Dehradun, India. Edited by M.V.K. Sivakumar, P.S. Roy, K. Harmsen, and S.K. Saha.
9	1277	Strengthening Operational Agrometeorological Services at the National Level. 2006. Proceedings of the Inter-Regional Workshop, 22-26 March 2004, Manila, Philippines. Edited by R. Motha, M.V.K. Sivakumar, and M. Bernardi.

(e) Books

Natural Disasters and Extreme Events in Agriculture: Impacts and Mitigation. 2005. Proceeding from a CAgM Expert Team Meeting, 16–20 February 2004, Beijing, China. Edited by M.V.K. Sivakumar, R.P.Motha, and H.P. Das. Springer. 367p.

Increasing Climate Variability and Change: Reducing the Vulnerability of Agriculture and Forestry. 2005. Edited by James Salinger, M.V.K. Sivakumar and Raymond P. Motha. Reprinted from *Climatic Change*, Volume 70, Nos. 1–2, 2005. Springer. 362 pages.

Climate Prediction and Agriculture: Advances and Challenges. 2007. Edited by M.V.K. Sivakumar and James Hansen. Proceedings from the International Workshop on Climate Prediction and Agriculture and Synthesis Workshop on Climatic Variability and Food Security. Several papers reprinted from *Climate Research* Vol 30, No. 1. Springer. 306 pages.

Climate and Land Degradation. 2007. Edited by M.V.K. Sivakumar and Ndegwa Ndiang'ui. Proceedings from the International Workshop on Climate and Land Degradation held in Arusha, Tanzania, 11–15 December 2006. Springer. 623 pages.

Managing Weather and Climate Risks in Agriculture. 2007. Edited by M.V.K. Sivakumar and Raymond P. Motha. Proceedings from the International Workshop on Agrometeorological Risk Management held in New Delhi, India, 25–27 October 2006. Springer. 503 pages.

(f) Selected WMO Brochures

WMO No.	Title
849	Food Security – The climate factor. 1996, 12 pp. E, S, F.
869	Climate, Drought and Desertification. 1997, 12 pp. E, S, F.
906	Early Warning Systems for Drought and Desertification: Role of National Meteorological and Hydrological Services. 2000, 12 pp. E, S, F.
933	Weather, Climate and Food Security. 2001, 24 pp. E, S, F.
989	Climate and Land Degradation. 2005, 32 pp. E, F, S.
999	Commission for Agricultural Meteorology (CAgM): the First Fifty Years. 2006. 44 pp. E, S, F.
1006	Drought Monitoring and Early Warning: Concepts, Progress, and Future Challenges. 2006. 24 pp. E, S, F.
--	Climate Change and Desertification. 2007. Poster and Brochure. E, S, F.

(g) WMO Congress Reports and Proceedings

<i>WMO No.</i>	<i>Title</i>
292	Sixth World Meteorological Congress: Abridged report with resolutions. 1971, xxiv + 229 pp. E-F-R-S. O/p..
293	Sixth World Meteorological Congress: Proceedings. 1972, xxi + 214 pp. E-F. O/p.
416	Seventh World Meteorological Congress: Abridged report with resolutions. 1975, xxvii + 256 pp, E-F-R-S. F-R-S o/p.
428	Seventh World Meteorological Congress: Proceedings. 1975, xxxvii + 230 pp. E-F. O/p.
533	Eighth World Meteorological Congress: Abridged report with resolutions. 1979, xxvii + 253 pp. E-F-R-S.
547	Eighth World Meteorological Congress: Proceedings. 1980, xxxiii + 261 pp. E-F
615	Ninth World Meteorological Congress: Abridged report with resolutions. 1983, xxxiii + 293 pp. E-F-R-S.
645	Ninth World Meteorological Congress: Proceedings. 1985, xxxi + 136 pp. E-F
681	Tenth World Meteorological Congress: Abridged report with resolutions. 1987, xxx + 212 pp. E-F-R-S.
698	Tenth World Meteorological Congress: Proceedings. 1988, xxx + 118 pp. E-F
756	Eleventh World Meteorological Congress: Abridged report with resolutions. 1991, vi + 141 pp. E-F-R-S.
757	Eleventh World Meteorological Congress: Proceedings. 1993, xx + 100 pp. E-F
827	Twelfth World Meteorological Congress: Abridged report with resolutions. 1995, vi + 162 pp. E-F-R-S.
880	Twelfth World Meteorological Congress: Proceedings. 1998, xxiii + 90 pp. E-F
902	Thirteenth World Meteorological Congress: Abridged report with resolutions. 1999, vi + 163 pp. E-F-R-S.
932	Thirteenth World Meteorological Congress: Proceedings. 2001, xxv + 94 pp. E-F
960	Fourteenth World Meteorological Congress: Abridged report with resolutions. 2003, vii + 223 pp. E-F-R-S.
972	Fourteenth World Meteorological Congress: Proceedings. 2004, xxiv + 77 pp. E-F

(h) Reports of sessions of the Commission for Agricultural Meteorology

<i>Date</i>	<i>Session No..</i>	
1953	CAGM-I	WMO-No.27, 1954 , 64 pp. E-F. o/p.
1958	CAGM-II	WMO-No. 83, 1958, 54 pp, E-F. O/p.
1962	CAGM-III	WMO-No. 125, 1962, x + 55 pp. E-F. O/p
1967	CAGM-IV	WMO-No. 221, 1968, ix + 47 pp. E-F-R-S. O/p.
1971	CAGM-V	WMO-No. 318, 1972, xii + 70 pp. E-F-R-S. O/p.
1974	CAGM-VI	WMO-No. 402, 1974 xii + 80 pp. E-R-S o/p.
1979	CAGM-VII	WMO-No. 546 , 1980, xii + 65 pp. E-F-R-S.
1983	CAGM-VIII	WMO-No. 612, 1983, xiv + 82 pp. E-F-R-S.
1986	CAGM-IX	WMO-No. 677, 1987, xvi + 89 pp. E-F-R-S.
1991	CAGM-X	WMO-No. 775, 1992, v + 46 pp. E-F-R-S.
1995	CAGM-XI	WMO-No. 825, 1995, vi + 50 pp. E-F-R-S.
1999	CAGM-XII	WMO-No. 900, 1980, xii + 65 pp. E-F-R-S.
2002	CAGM-XIII	WMO-No. 951, 1980, xii + 65 pp. E-F-R-S.
2006	CAGM-XIV	WMO-No. 546, 1980, xii + 65 pp. E-F-R-S.
2010	CAGM-XV	WMO-No. 1059, 2011

(i) Basic Documents

- No. 1 Basic Documents (excluding the Technical Regulations). 1975 edition (WMO-No. 15), 177 pp. E-F-R-S.

(j) Various (unnumbered)

The Role of Meteorological Services in economic development in Africa. Proceedings of the ECA Seminar. Ibadan (Nigeria), September 1968. 1969, viii + 145 pp. E-F.

Meteoro-pathological forecasting diseases of livestock. By M. Crawford.

Climatic Atlas of Europe, Volume I: Maps of mean temperature and precipitation. 1971. E-F-R-S (published jointly by WM O, Unesco, Cartographia).

Climatic Atlas of South America, Volume 1: Maps of mean temperature and precipitation. E-F-S- Portugese (published jointly by WMO, Unesco, Cartographia).

(WMO publications available for sale are listed in the catalogue of publications of the World Meteorological Organization Requests/or the catalogue should be addressed to: WMO, PO. Box No.5, CH-1211 Geneva 20, S witzerland.)

- No. 1 A brief survey of the activities of WMO relating to human environment. 1970 ,22 pp., E-F-R-S
- No. 5 Drought. Lectures presented at the twenty-fifth session of the WMO Executive Committee. (WMO-No. 403), 1975 . E or F, summaries E, F, R, S.
- No. 9 An evaluation of climate and water resources for development of agriculture in the Sudano-Sahelian zone of West Africa. (WMONo. 459), 1976, xv + 289 pp. E-F.
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APPENDIX II

List of periodicals of interest to agricultural meteorologists

The list below is divided into sections by country, and each section is subdivided into the following classes of publications: "meteorological" (or "meteorological/climatological"), "agricultural" (or "agricultural/agrometeorological") and "general scientific". Most of the information is presented as provided by the individual countries. Many countries provide agrometeorological forecasts and products that can be found at the World AgroMeteorological Information Service website (www.wamis.org). (NOTE: "Bimonthly" is understood herein to mean six times per year.)

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Albania		
Meteorological		
<i>Buletini Agrometeorologjik</i> (Agrometeorological Bulletin)	Instituti Hidrometeorologjik i Shqipërisë (Hydrometeorological Institute - IHM of Albania) Address: Rr. Durrësit, P.O. Box 1544 Tirana Email: agrometeoalb@yahoo.com Website: http://www.wamis.org/countries/albania.php	Every 10 days
<i>AJNTS – Albanian Journal of Natural and Technical Sciences</i> (in English)	Akademia e Shkencave të Shqipërië (Academy of Sciences of Albania)	Quarterly
Agricultural		
<i>Revista Shqiptare e Shkencave Bujqësore</i> (Albanian Journal of Agricultural Sciences)	Universiteti Bujqësor i Tiranës (Agricultural University of Tirana) Kamez	Quarterly
<i>Bujqësia dhe Ekologjia</i> (Agriculture and Ecology)	Shoqata e Bujqësisë Organike (Association of Organic Agriculture) Address: Rr. A. Frashëri, P. 10, Sh. 1, Ap. 6 Tirana Email: organic@icc-al.org	Bimonthly
General scientific		
<i>Gjeomatika</i> (Geomatics)	Instituti Gjeografik Ushtarak i Shqipërisë (Military Geographic Institute of Albania) Tirana Email: itu@albmail.com	Periodically

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Buletini Shkencor</i> (Scientific Bulletin)	Seria e Shkencave Natyrore (Natural Sciences Series) Luigj Gurakuqi University of Shkodra Shkoder	Quarterly
Algeria		
<i>Bulletin décadaire d'informations climatologiques et agro-climatologiques</i>	Office National de la Meteorologie Centre Climatologique National BP 153 Dar El Beida, 16011	36 times per year
<i>Bulletin mensuel d'informations climatologiques</i>		Monthly
<i>Résumé Annuel du temps en Algérie - Analyse et Cartes</i>		Annually
<i>Résumé Annuel du temps en Algérie - Données de base</i>		Annually
Argentina		
Meteorological/ Agrometeorological		
<i>Revista Argentina de Agrometeorologia</i>	Asociación Argentina de Agrometeorologia http://www.aada.com.ar/	Annually
<i>Revista del Centro Argentino de Meteorólogos</i>	Centro Argentino de Meteorólogos http://www.cenamet.org.ar/	Annually
Agricultural		
<i>Revista de Investigaciones Agropecuarias</i>	Instituto Nacional de Tecnología Agropecuarias (INTA) http://www.inta.gov.ar/ediciones/ria/	Two or three times per year
<i>AgriScientia</i>	Facultad de Ciencias Agropecuarias, Universidad Nacional de Cordoba http://www.agriscientia.unc.edu.ar	Biannually
<i>Revista de la Facultad de Ciencias Agrarias y Forestales</i>	Facultad de Ciencias Agrarias y Forestales Universidad Nacional de La Plata http://www.agro.unlp.edu.ar/	Irregularly
<i>Revista de la Asociación Argentina de Producción Animal</i>	Asociación Argentina de Producción Animal aapa@ balcarce.inta.gov.ar	Bimonthly
<i>Revista de la Facultad de Agronomía</i>	Facultad de Agronomía, Universidad Nacional de La Pampa http://www.agro.unlpam.edu.ar	Biannually
<i>Revista de la Facultad de Ciencias Agrarias</i>	Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo http://www.fca.uncu.edu.ar	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Revista de Investigaciones de la Facultad de Ciencias Agrarias</i>	Facultad de Ciencias Agrarias, Universidad Nacional de Rosario http://www.fcagr.unr.edu.ar/investigaciones/rev2	Irregularly
General scientific		
<i>Boletín de la Sociedad Argentina de Botánica</i>	Sociedad Argentina de Botánica http://fai.unne.edu.ar/SAB	Two to four issues per year
<i>Anales de la Academia Nacional de Agronomía y Veterinaria</i>	Academia Nacional de Agronomía y Veterinaria http://www.anav.org.ar/	Annually
<i>Anales de la Academia Nacional de Ciencias Exactas, Físicas y Naturales</i>	Academia Nacional de Ciencias Exactas, Físicas y Naturales http://www.ancefn.org.ar	Annually
Armenia		
Meteorological/Climatological		
Meteorological bulletins		
Agrometeorological bulletins	Armenian State Hydrometeorological and Monitoring Service (Armstatehydromet) 54 Leo Street, 375002 Yerevan http://www.meteo.am	Daily/every 10 days/monthly Every 10 days/monthly Monthly Biannually Annually
Monthly meteorological survey		Monthly
Seasonal meteorological survey		Biannually
Annual review of dangerous hydrometeorological phenomena		Annually
Agricultural		
<i>Hask</i> (official newspaper of Armenian Agricultural Academy) <i>Bulletin of the Armenian Agricultural Academy</i> (international scientific journal)	Armenian Agricultural Academy Publishing House, 74 Teryan Street 375009 Yerevan http://www.armagroacad.am	Once every 20 days Quarterly
<i>Agrolratu</i> (newspaper)	Ministry of Agriculture, Agricultural Support Republican Centre 39a Mamikonyants Street 375051 Yerevan http://arm.agrowebcac.org/asrc/agrolratu.php	Every 10 days
<i>Agrogitutyun</i> (scientific journal)	Ministry of Agriculture, National Agricultural Support Centre 39a Mamikonyants Street 375051 Yerevan http://arm.agrowebcac.org/asrc/journal.php	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General scientific		
<i>Journal of Natural Sciences</i> (new electronic publication)	National Academy of Science 24 Marshall Baghramian Avenue 375019 Yerevan http://ejns.sci.am http://www.epnet.com	
<i>Problems of Ecology and Environmental Protection</i> (annotated scientific transactions)	Centre for Ecological Noosphere Studies 68 Abovian Street 375025 Yerevan	Annually
Electronic catalog of the Scientific Library of the State Engineering University of Armenia	State Engineering University of Armenia (SEUA) 105 Teryan Street 375009 Yerevan http://www.seua.am/rus/library/elcat.htm http://www.armunicat.am:4505/ALEPH	
<i>Bnaget</i> (scientific popular journal of the Ministry of Education and Yerevan State University)	Yerevan State University 1 Alex Manoogian Street 375049 Yerevan	Four to six times per year
<i>Banber</i> (official newspaper of Yerevan State University)	http://www.ysu.am/	Every 10 days
<i>Bnakan tegekagir/Uchenie Zapiski</i> (scientific notes Yerevan State University)		Three times per year
Australia		
Meteorological/Climatological		
<i>Australian Meteorological and Oceanographic Journal</i> (formerly <i>Australian Meteorological Magazine</i>) Climag (newsletter) http://www.managingclimate.gov.au/publications/climag-archive/	Bureau of Meteorology Melbourne	Quarterly
	Grains, Rural Industries and Sugar Research and Development Corporations; the Australian Government through the Department of Agriculture, Fisheries and Forestry; Dairy Australia; Meat & Livestock Australia; and Land & Water Australia	Biannually
Agricultural		
<i>Australasian Plant Pathology</i> http://www.publish.csiro.au/nid/39.htm	Commonwealth Scientific and Industrial Research Organization for the Australasian Plant Pathology Society Adelaide	Bimonthly
<i>Australian Journal of Botany</i> http://www.publish.csiro.au/nid/65.htm	Commonwealth Scientific and Industrial Research Organization Melbourne	Eight times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Australian Journal of Soil Research</i> http://www.publish.csiro.au/nid/84.htm	Commonwealth Scientific and Industrial Research Organization Melbourne	Eight times per year
<i>Australian Journal of Agricultural and Resource Economics</i> http://www.blackwellpublishing.com/journal.asp?ref=1364-985X&site=1	Blackwell Publishers, Oxford, for the Australian Agricultural and Resource Economics Society	Quarterly
<i>Agfacts</i> http://www.dpi.nsw.gov.au/aboutus/resources/factsheets/agfacts_and_agnotes	New South Wales Department of Primary Industries Sydney	
Austria		
Agricultural		
<i>Die Bodenkultur</i> (Austrian Journal of Agricultural Research) http://www.boku.ac.at/bokujournal/index.html	Institut für Agrarökonomik Peter Jordanstr. 82 Vienna	Quarterly
<i>Agrarische Rundschau</i> http://www.agrarverlag.at	Agrarverlag Zeitschriften Achauerstrasse 49 a 2335 Leopoldsdorf bei Wien	Bimonthly
<i>Der Pflanzenarzt</i> http://www.agrarverlag.at	Agrarverlag Zeitschriften Achauerstrasse 49 a 2335 Leopoldsdorf bei Wien	Eight times per year
<i>Besseres Obst</i> http://www.agrarverlag.at	Agrarverlag Zeitschriften Achauerstrasse 49 a 2335 Leopoldsdorf bei Wien	Monthly
<i>Der Winzer</i> http://www.agrarverlag.at	Agrarverlag Zeitschriften Achauerstrasse 49 a 2335 Leopoldsdorf bei Wien	Monthly
<i>Pflanzenschutzberichte</i> http://www7.ages.at/service/publikationen/pflschbe/bericht.htm	Bundesamt und Forschungszentrum für Landwirtschaft Institut für Phytomedizin Spargelfeldstrasse 191 Vienna	Irregularly
General scientific		
<i>Ländlicher Raum</i> http://www.laendlicher-raum.at/	Bundesministerium für Land- und Forstwirtschaft Umwelt und Wasserwirtschaft, Abt. II 5 Stubenring 1 Vienna	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Belgium		
Meteorological		
Metagri Bulletins (in French & Dutch)	Royal Meteorological Institute of Belgium Ringlaan 3 Avenue Circulaire 1180 Brussels http://www.meteo.oma.be	Daily except public holidays and weekends
Climatological Bulletins	Royal Meteorological Institute of Belgium Ringlaan 3 Avenue Circulaire 1180 Brussels http://www.meteo.oma.be	Monthly
<i>B-CGMS Agrometeorological Bulletin</i>	Belgium Crop Growth Monitoring System (B-CGMS) CRA-W, ULg-Arlon and VITO Consortium Rue de Liroux 9 5030 Gembloux http://b-cgms.cra.wallonie.be	Monthly from May to November (since April 2002)
Agricultural		
<i>B-CGMS Agrometeorological Bulletin</i>	Belgium Crop Growth Monitoring System (B-CGMS) CRA-W, ULg-Arlon and VITO Consortium Rue de Liroux 9 5030 Gembloux http://b-cgms.cra.wallonie.be	Monthly from May to November (since April 2002)
Publications	Walloon Agricultural Research Centre (CRA-W) - Ministry of the Walloon Region Rue de Liroux 9 5030 Gembloux http://cra.wallonie.be	Irregularly / annually
Publications	Agricultural Research Centre (CLO) - Ministry of the Flemish Community Burg. Van Gansberghelaan 96 9820 Merelbeke http://www.clo.fgov.be/	Irregularly / annually
Portail Agriculture and official statistics	Federal Public Service - Economy, SMEs, Self-employed and Energy http://statbel.fgov.be/en/portals/statport/index.jsp	Irregularly / annually
General scientific		
Publications	Belgian Federal Science Policy Office Rue de la Science 8 Wetenschapsstraat 1000 Brussels http://www.belspo.be/	Irregularly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Publications	Earth Observation Help Desk, Federal Science Policy Office http://telsat.belspo.be	Irregularly
Publications	Université de Liège (ULg) Avenue de Longwy, 185 6700 Arlon http://www.ful.ac.be/	Irregularly
Publications	Faculté Universitaire des Sciences Agronomiques de Gembloux (FUSAGx) Passage des Déportés, 2 5030 GEMBLOUX http://www.fsagx.ac.be/	Irregularly
Publications	Faculty of Bio-engineering, Agronomy and Environment (UCL) http://www.ucl.ac.be/en/faculties/agro.html	Irregularly
Publications	Vrije Universiteit Brussel (ULB) http://www.vub.ac.be/	Irregularly
Publications	Katholieke Universiteit Leuven (KUL) http://www.biw.kuleuven.be/	Irregularly
Publications	Université Libre de Bruxelles (ULB) http://www.ulb.ac.be/	Irregularly
Publications	Rijksuniversiteit Gent (RUG) http://www.ugent.be/portal/la	Irregularly
Benin		
Agrometeorological/ Meteorological		
<i>Bulletin Agrométéorologique Décadaire</i> (10-day Agrometeorological Bulletin)	Service Meteorologique National 01 BP 96 and 01 BP 379 Cotonou	Every 10 days
<i>Bulletin Climatologique mensuel</i>	Email : meteo@leland.bj	Monthly
Agricultural		
<i>Annales des Sciences Agronomiques</i>	01 BP 526 Cotonou	Biannually
Brazil		
Meteorology/Agrometeorology		
<i>Revista Brasileira de Agrometeorologia</i> (RBAgro)	Sociedade Brasileira de Agrometeorologia (www.sbagro.org.br/rbagro) – online since 1993	Three times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Revista Brasileira de Meteorologia (RBMet)</i>	Sociedade Brasileira de Meteorologia (www.sbmet.org.br/internas/publicacoes/revista) – online since 2004	Three times per year
Agriculture and Forestry		
<i>Pesquisa Agropecuária Brasileira (PAB)</i>	Empresa Brasileira de Pesquisa Agropecuária (www.spi.embrapa.br/pab) - online at www.scielo.br since 1999	Monthly
<i>Bragantia</i>	Instituto Agronômico de Campinas (www.iac.sp.gov.br/bragantia) - online at www.scielo.br since 1997	Quarterly
<i>Horticultura Brasileira (Hort Bras)</i>	Sociedade de Olericultura do Brasil - online at www.scielo.br since 2001	Quarterly
<i>Pesquisa Agropecuária Gaúcha (PAG)</i>	Fundação Estadual de Pesquisa Agropecuária do RS (www.fepagro.rs.gov.br)	Biannually
<i>Scientia Agricola</i>	Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo (www.esalq.usp.br/scientia/index.html) - online at www.scielo.br since 1992	Bimonthly
<i>Ciência Rural</i>	Universidade Federal de Santa Maria (www.ufsm/ccr/revista) - online at www.scielo.br since 2001	Bimonthly
<i>Acta Amazônica</i>	Instituto Nacional de Pesquisas da Amazônia (www.inpa.gov.br) - online at www.scielo.br since 2004	Quarterly
<i>Revista Brasileira de Fruticultura (RBF)</i>	Sociedade Brasileira de Fruticultura (www.ufpel.tche.br/sbfruti) - online at www.scielo.br since 2001	Three times per year
<i>Revista Árvore</i>	Sociedade de Investigações Florestais / Universidade Federal de Viçosa (www.sif.org.br/arvore/arvore.asp) - online at www.scielo.br since 2002	Bimonthly
<i>Scientia Florestalis</i>	Instituto de Pesquisas Florestais (www.ipef.br/publicacoes/scientia) - online since 1970	Biannually
<i>Revista Engenharia Agrícola (REA)</i>	Sociedade Brasileira de Engenharia Agrícola (www.sbea.org.br/rea/index.htm) - online at www.scielo.br since 2004	Three times per year
General scientific		
<i>Revista Brasileira de Engenharia Agrícola e Ambiental (Agriambi)</i>	Universidade Federal de Campina Grande (www.agriambi.com.br) – online since 1997	Three times per year
<i>Brazilian Journal of Plant Physiology</i>	Sociedade Brasileira de Fisiologia Vegetal (www.cpa.unicamp.br/sbfv) - online at www.scielo.br since 2000	Three times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Fitopatologia Brasileira</i>	Sociedade Brasileira de Fitopatologia (www.sbfito.com.br) - online at www.scielo.br since 2001	Bimonthly
<i>Revista Brasileira de Ciência do Solo</i>	Sociedade Brasileira de Ciência do Solo (www.sbc.org.br/por/revista.jsp) - online at www.scielo.br since 2003	Bimonthly
<i>Revista Irriga</i>	Universidade Estadual Paulista (www.fca.unesp.br/irriga/volumes.php) - online since 2001	Three times per year
<i>Revista Energia</i>	Universidade Estadual Paulista (www.fca.unesp.br/revistaenergia/index.htm) - online since 2005	Three times per year
<i>Revista Engenharia na Agricultura</i>	Universidade Federal de Viçosa (www.ufv.br/dea/reveng) - online since 2002	Quarterly
Bulgaria		
Agrometeorological		
<i>Bulgarian Journal of Meteorology and Hydrology</i>	NIMH-BAS 66 Tsarigradsko shausse Sofia 1784 www.meteo.bg	Quarterly
<i>Mesechen buletin na NIMH</i> (Monthly Bulletin of NIMH)	NIMH-BAS 66 Tsarigradsko shausse Sofia 1784 www.meteo.bg	Monthly
Agriculture		
<i>Pochvoznanie, agrochimia i ekologiya</i> (Soil Science, Agrochemistry and Ecology)	Agency Europress 125 Tsarigradsko shausse, Bl.1 Sofia 1113 www.europressbg.net	Bimonthly
<i>Rastenievadni naouki</i> (Plant Science)	Agency Europress 125 Tsarigradsko shausse, Bl.1 Sofia 1113 www.europressbg.net	Bimonthly
<i>Bulgarian Journal of Agricultural Science</i>	Agency Europress 125 Tsarigradsko shausse, Bl.1 Sofia 1113 www.europressbg.net	Bimonthly
<i>General and Applied Plant Physiology</i> (formerly <i>Bulgarian Journal of Plant Physiology</i>)	Institute of Plant Physiology Acad. G. Bonchev Street, Bl. 21 Sofia 1113 http://www.bio21.bas.bg/ipp/	Quarterly
<i>Agronom</i> (Agronomist)	Rick Lover Private Publishing House P.O.Box 1148 Sofia 1000	10 times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Zelen ray</i> (Green Paradise)	Private Publishing House Press P.O. Box 25 Sofia 1784	24 times per year
General scientific		
<i>Bulgarian Geophysical Journal</i>	Bolid Publishing House Acad. G. Bonchev Street, Bl. 3 Sofia 1113	Quarterly
<i>Dokladi na BAN</i> (Comptes rendus de l'Academie Bulgare des Sciences)	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Monthly
<i>Matematika Balkanica</i>	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Quarterly
<i>Nauka za gorata</i> (Forest Science)	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Quarterly
<i>Problemi na Geografiata</i> (Problems of Geography)	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Quarterly
<i>Spisanie na BAN</i> (Journal of the Bulgarian Academy of Sciences)	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Bimonthly
<i>Silva Balkanica</i>	Prof. Marin Drinov Academic Publishing House Acad. G. Bonchev Street, Bl. 5 Sofia 1113	Quarterly
<i>Computer</i>	New Technik Publishing Ltd. Panaiot Volov 11 Sofia 1257 www.newteck.bg	Monthly
Burkina Faso		
Agrometeorological		
<i>Bulletin Agrométéorologique Décadaire</i> (10-day Agrometeorological Bulletin)	Direction de la Météorologie 01 BP 576 Ouagadougou 01 http://www.wamis.org/countries/burkina.php	Every 10 days

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Canada		
Meteorological/Climatological		
<i>Atmosphere-Ocean CMOS Bulletin SCMO</i>	Canadian Meteorological and Oceanographic Society http://www.cmos.ca/index.htm	Quarterly Bimonthly
<i>CSAFM Newsletter</i>	Canadian Society of Agricultural and Forest Meteorology http://www.uoguelph.ca/~csafm/	Two to three times per year
<i>Canadian Journal of Soil Science</i>	Agricultural Institute of Canada http://www.aic.ca/index.cfm	Quarterly
Agricultural		
<i>Canadian Journal of Plant Science</i>	Agricultural Institute of Canada http://www.aic.ca/index.cfm	Quarterly
<i>Canadian Journal of Animal Science</i>		Quarterly
<i>The Biology of Canadian Weeds</i>	Canadian Phytopathological Society http://www.cps-scp.ca/index.html	Occasionally
<i>Canadian Journal of Plant Pathology</i>		Quarterly
<i>Canadian Plant Disease Survey</i>	National Research Council Canada http://pubs.nrc-cnrc.gc.ca/rp2_home_e.html Canadian Society for Bioengineering (CSBE) http://www.engr.usask.ca/societies/csae/journal.html	Annually
<i>Canadian Journal of Botany</i>		Monthly
<i>Canadian Biosystems Engineering</i>		Annually
General scientific		
<i>The Canadian Geographer</i>	Canadian Association of Geographers http://www.cag-acg.ca/en/index.html	Quarterly
<i>Canadian Journal of Earth Science</i>	National Research Council Canada http://pubs.nrc-cnrc.gc.ca/rp2_home_e.html	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
China		
Meteorological		
<i>Chinese Journal of Agrometeorology</i> (中国农业气象)	中国农业科学院农业气象研究所 http://zgny.chinajournal.net.cn 中科院大气物理研究所	Quarterly
<i>Chinese Journal of Atmospheric Sciences</i> (大气科学)	http://dqxk.chinajournal.net.cn/	Bimonthly
<i>Acta Meteorologica Sinica</i> (气象学报)	中国气象学会 http://qxzb.chinajournal.net.cn/ 中国科学院寒区与旱区环境与工程研究所	Bimonthly
<i>Plateau Meteorology</i> (高原气象)	http://gyqx.chinajournal.net.cn/	Quarterly
<i>Journal of Applied Meteorological Science</i> (应用气象学报)	中国气象科学研究院 http://yyqx.chinajournal.net.cn/	Bimonthly
<i>Meteorological Monthly</i> (气象)	中国气象局	Monthly
<i>Journal of Nanjing Institute of Meteorology</i> (南京气象学院学报)	南京气象学院 http://njqx.chinajournal.net.cn/	Quarterly
<i>Climatic and Environmental Research</i> (气候与环境研究)	中科院大气物理研究所 http://qhyh.chinajournal.net.cn/	Quarterly
<i>Journal of Tropical Meteorology</i> (热带气象学报)	广州热带海洋气象研究所 http://rqxb.chinajournal.net.cn	Quarterly
<i>Arid Meteorology</i> (干旱气象)	中国气象局兰州干旱气象研究所、中国气象学会干旱气象学委员会 http://gsqx.chinajournal.net.cn/	Quarterly
<i>Meteorological Science and Technology</i> (气象科技)	中国气象科学研究院情报所 http://qxkj.chinajournal.net.cn/	Quarterly
Agricultural		
<i>Agricultural Sciences in China</i> (中国农业科学)	中国农业科学院 http://www.ChinaAgriSci.com	Monthly
<i>Acta Agronomica Sinica</i> (作物学报)	中国作物学会 http://xbzw.chinajournal.net.cn	Monthly
<i>Transactions of the Chinese Society of Agricultural Engineering</i> (农业工程学报)	中国农业工程学会 http://nygu.chinajournal.net.cn ; http://www.tcsae.org	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Acta Botanica Boreali-occidentalia Sinica</i> (西北植物学报)	陕西省科学院、陕西省植物学会 http://dnyx.chinajournal.net.cn/	Bimonthly
<i>Chinese Bulletin of Botany</i> (植物学通报)	中国科学院植物研究所 中国植物学会 http://zwxt.chinajournal.net.cn/	Bimonthly
<i>Acta Botanica Sinica</i> (植物学报)	中科院植物研究所 中国植物学会 http://zwxh.chinajournal.net.cn/	Monthly
<i>Acta Ecologica Sinica</i> (生态学报)	中国生态学学会 http://stxb.chinajournal.net.cn/	Monthly
<i>Acta Geographica Sinica</i> (地理学报)	中国地理学会 中国科学院地理研究所 http://dlxb.chinajournal.net.cn	Bimonthly
<i>Acta Pedologica Sinica</i> (土壤学报)	中国土壤学会 http://trxb.chinajournal.net.cn/	Bimonthly
<i>Chinese Journal of Applied Ecology</i> (应用生态学报)	中国科学院沈阳应用生态研究所 http://yysb.chinajournal.net.cn/	Monthly
<i>Acta Phytocologica Sinica</i> (植物生态学报)	中国植物学会 http://zwsb.chinajournal.net.cn/	Bimonthly
<i>Journal of Soil and Water Conservation</i> (水土保持学报)	中国科学院水利部水土保持研究所 http://trqs.chinajournal.net.cn/	Quarterly
<i>Chinese Journal of Ecology</i> (生态学杂志)	中国生态学会 http://stxz.chinajournal.net.cn/	Bimonthly
<i>Scientia Geographica Sinica</i> (地理科学)	中科院长春地理研究所 http://dlkx.chinajournal.net.cn/	Bimonthly
<i>Journal of Natural Resources</i> (自然资源学报)	中国自然资源学会 http://zrzx.chinajournal.net.cn/	Bimonthly
<i>Chinese Journal of Soil Science</i> (土壤通报)	中国土壤学会 http://trtb.chinajournal.net.cn/	Bimonthly
<i>Resource Science</i> (资源科学)	中国科学院地理科学与资源研究所 http://zrzy.chinajournal.net.cn/	Bimonthly
<i>Journal of Natural Disasters</i> (自然灾害学报)	中国灾害防御协会 中国地震局工程力学所 http://zrzx.chinajournal.net.cn/	Quarterly
<i>Bulletin of Soil and Water Conservation</i> (水土保持通报)	中科院水利部水土保持研究所 http://sttb.chinajournal.net.cn/	Bimonthly
<i>Journal of Remote Sensing</i> (遥感学报)	中国地理学会环境遥感分会 中国科学院遥感应用研究所 http://ygxb.chinajournal.net.cn/	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Côte d'Ivoire		
Agrometeorological		
<i>Bulletin Agrométéorologique Décadaire</i> (10-day Agrometeorological Bulletin)	Direction de la Météorologie Nationale 15 BP 990 Abidjan 15 Côte d'Ivoire http://www.wamis.org/countries/cdivoire.php	Every 10 days
Agricultural		
<i>Agronomie Africaine</i>	Association Ivoirienne des Sciences Agronomiques (AISA) 20 BP 703 Abidjan 20 Côte d'Ivoire	Three times per year
Croatia		
Meteorological		
Croatian Meteorological Journal	Croatian Meteorological Society (Hrvatsko meteorološko društvo) Grič 3, 10000 Zagreb	Irregularly
Czech Republic		
Agrometeorological/Meteorological		
Agrometeorologický zpravodaj (Agrometeorological bulletin)	Czech Hydrometeorological Institute Na Šabatce 17 143 06 Praha 4 www.chmi.cz	Weekly (April to September) monthly (October)
Meteorologické zprávy	Czech Hydrometeorological Institute Na Šabatce 17 143 06 Praha 4 ISSN: 0026-1173 www.chmi.cz/reditel/sis/casmetzp.html	Bimonthly
Mesíční přehled počasí	Czech Hydrometeorological Institute Na Šabatce 17 143 06 Praha 4 ISSN: 0862-0172	Monthly
Agricultural		
<i>Plant, Soil and Environment</i>	Czech Academy of Agricultural Sciences Tešnov 17 117 05 Praha 1 ISSN 1214-1178 http://www.cazv.cz/	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Scientia Agriculturae Bohemica</i>	Czech Agricultural University Prague 165 21 Praha 6 – Suchbátův ISSN: 1211-3174 www2.czu.cz/home/scientia.php	Quarterly
<i>Acta Universitatis agriculturae et silviculturae Mendelianae Brunensis</i>	Mendel University of Agriculture and Forestry Zemědělská 1 613 00 Brno ISSN: 1211-8516 http://old.mendelu.cz/veda/acta/	Irregularly
Collection of Scientific Papers	University of South Bohemia, Faculty of Agriculture Studentská 13 370 05 České Budejovice ISSN 1212-0731 www.zf.jcu.cz/veda_a_vyzkum/vedecky_casopis/index.php	Biannually
<i>Horticultural Science</i>	Czech Academy of Agricultural Sciences Tešnov 17 117 05 Praha 1 ISSN 0862-867X http://www.cazv.cz/	Quarterly
<i>Journal of Forest Science</i>	Czech Academy of Agricultural Sciences Tešnov 17, 117 05 Praha 1 ISSN 1212-4834 http://www.cazv.cz/	Monthly
<i>Zemědělec</i>	Profi Press Drtinova 8/557 150 00 Praha 5 www.agroweb.cz/projekt/casopis.asp?cid=zem	Weekly
<i>Úroda</i>	Profi Press Drtinova 8/557 150 00 Praha 5 ISSN: 0139-6013 www.agroweb.cz/projekt/casopis.asp?cid=uro	Monthly
<i>Lesnická práce</i>	Lesnická práce, s. r. o., Zámek 1 PO Box 25, 281 63 Kostelec n. C. l. ISSN: 0322-9254 http://lesprace.silvarium.cz/	Monthly
<i>Zemědělský týdeník</i>	Vydavatelství ZT Konevova 3 130 00 Praha 3, ISSN 1214-2298	Weekly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Pedologie a meliorace</i>	Ústav vedeckotechnických informací pro zemědělství Slezská 7 (ÚVTIZ), 120 56 Praha 2 ISSN: 0036-5386	Biannually
Farmár	Profi Press Drtinova 8/557, 150 00 Praha 5, ISSN: 1210-9789	Monthly
General Scientific		
<i>Studia geophysica et geodaetica</i>	Geophysical Institute, Czech Academy of Science Bocní II/1401 141 31 Praha 4, ISSN: 0039-3169 http://seis.ig.cas.cz/studia/studia.php	Quarterly
<i>Pokroky matematiky, fyziky a astronomie</i>	Jednota českých matematiku a fyziku, Stavební fakulta CVUT, Thákurova 7 166 29 Praha 6 ISSN 0032-2423 http://mat.fsv.cvut.cz/ppjcmf/rejstrikPMFA/clanky.html	Quarterly
<i>Acta Universitatis Carolinae Environmentalica</i>	Charles University in Prague Nakladatelství Karolinum Ovocný trh 3/5 116 36 Praha 1 ISSN: 0862-6529	Biannually
<i>Acta Universitatis Carolinae Mathematica et Physica</i>	Charles University in Prague Nakladatelství Karolinum Ovocný trh 3/5 116 36 Praha 1 ISSN: 0001-7140	Biannually
Cuba		
Meteorological/Agrometeorological		
<i>Revista Cubana de Meteorología</i>	Instituto de Meteorología. Ministerio de Ciencia, Tecnología y Medio Ambiente (CITMA). ISSN 0-864-151-X Apartado Postal No. 17032 Havana 17	Annually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Institute of Meteorology Web Site	http://www.insmet.cu	Continuously and containing other links
Agricultural – forest and environment		
<i>Agricultura Orgánica</i>	Asociación Cubana de Técnicos Agrícolas y Forestales (ACTAF) ISSN 1028-2130 Conill y Avenida Independencia Plaza de la Revolución Havana Email: actafnac@actaf.co.cu	Quarterly
<i>Revista de la ACPA</i>	Asociación Cubana de Producción Animal ISSN 0138-6247 Calle 10 No. 351 e/ 15 and 17, vedado, Havana	Quarterly
<i>Voluntad Hidráulica</i>	Instituto Nacional de Recursos Hidráulicos ISSN 0505-9461 Calle Humboldt No. 106 Havana Email: thic@ceniai.inf.cu and minerva@hidro.cu	Annually
<i>Revista Forestal Baracoa</i>	Instituto Cubano de Investigaciones Forestales (IIF) ISSN: 0138-6441 Calle 174 No. 1723 e/ 17B y 17C, Rpto. Siboney Playa Havana direccion@forestales.co.cu	Annually
General Scientific		
<i>Ciencia, Innovación y Desarrollo</i>	Ministerio de Ciencia, Tecnología y Medio Ambiente Capitolio de La Habana, 4to. piso Industria y San José Havana ISSN 1023-1722 Fax 60961. Email: palcien@ceniai.inf.cu	Irregularly/ annually
<i>Energía y tú</i>	Sociedad Cubana para la Promoción de las Fuentes Renovables de Energía y el Respeto Ambiental (CUBASOLAR) ISSN 1028-9925 http://www.cubasolar.cu	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>EcoSolar Electronic Journal</i>	Sociedad Cubana para la Promoción de las Fuentes Renovables de Energía y el Respeto Ambiental (CUBASOLAR) http://www.cubasolar.cu	---
Denmark		
Meteorological		
Publications	Danish Meteorological Institute Lyngbyvej 100 2100 Lyngby http://www.dmi.dk	Irregularly
Bulletins	http://www.dmi.dk	Hourly/daily/ weekly/monthly
Agricultural		
Publications i.e. "Weather in the growing season"	Danish Institute of Agricultural Sciences Research Centre Foulum P.O. Box 50 8830 Tjele http://www.agrsci.dk	Irregularly/ annually
Publications	The Royal Vet. and Agricultural University Højbakkegård Allé 30 2630 Tåstrup http://www.kvl.dk	Irregularly
PlanteInfo	http://www.planteinfo.dk	Three hourly/ daily/ irregularly
Publications	Danish Agricultural Advisory Service Udkærvej 15, Skejby 8200 Århus N http://www.lr.dk	Irregularly
Dominican Republic		
Agrometeorological/Meteorological		
<i>Perspectica Agrometeorologica Semanal</i> (Weekly Agrometeorological Perspective)	Instituto Dominicano De Aviación Civil Oficina Nacional de Meteorología – ONAMET (National Office of Meteorology of the Dominican Republic) Departamento De Meteorológica Operativa Division De Agrometeorologia Santo Domingo, Estei http://www.onamet.gov.do	Weekly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Resumen Agrometeorológico</i> (Monthly Agroclimate Summary)	Idem http://www.onamet.gov.do/?s=web&p=1048	Monthly
<i>Incidencia de las Condiciones Climaticas el la Agricultura</i> (Monthly Effects of Climatic Conditions on Agriculture)	Idem http://www.onamet.gov.do/?s=web&p=1037	Monthly
<i>Agroclima Mensual</i> (Monthly Agroclimate Outlook)	Idem http://www.onamet.gov.do/?s=web&p=1036	Monthly
<i>Desviación Precipitaciones</i> (Precipitation Anomalies)	Idem http://www.onamet.gov.do/?s=web&p=1043	Monthly
<i>Perspectiva Climatica Mensual</i> (Monthly Climate Perspective)	Instituto De Aviación Civil Dominicano Oficina Nacional De Meteorología Sub-Direccion Tecnica	Monthly
Ecuador		
Meteorological		
<i>Climatic Bulletin</i>	Instituto Nacional de meteorología e Hidrologia – INAMHI Estudios e investigaciones meteorologicas www.inamhi.gov.ec	Every 10 days Monthly
<i>Agroclimatic Bulletin</i>	Instituto Nacional de meteorología e Hidrologia – INAMHI Estudios e investigaciones meteorologicas www.inamhi.gov.ec	Every 10 days Monthly
<i>CPPS Climatic Outlook Bulletin</i>	Comision Permanente del Pacifico Sur . CPPS (Chile, Colombia, Ecuador, y Peru) www.cpps-int.org	Monthly
<i>CIIFEN Bulletin</i>	Centro Internacional para la Investigación del Fenómeno “El Nino” – CIIFEN www.ciiifen-int.org	Monthly
<i>Climate – Agricultural Risk Index</i>	Idem	Monthly
<i>Seasonal Forecast</i>	Idem	Quarterly
Agricultural		
<i>Bulletin CORPEI</i>	Corporacion para la Promocion de las Exportaciones e Inversiones (CORPEI) www.corpei.org	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Floricultural Information</i>	Exportadores de Flores del Ecuador (EXPOFLORES) www.expoflores.com	Monthly
<i>Cocoa Production</i>	Asociación Nacional de Exportadores de Cacao (ANECACAO) www.anecacao.com	Monthly
<i>Banana News</i>	Corporación Nacional de Bananeros (CONABAN) www.conabanecuador.com	Monthly
Agricultural News Letters	Camera de Agricultura de la Primeria Zona www.agroecuador.com	Monthly
General Scientific		
<i>Cenaim Bulletin</i> (Shrimp and other sea products research)	Escuela Politecnica del Litoral – ESPOL Centro Nacional de Investigaciones Marinas (CENAIM) www.cenaim.espol.edu.ec	Monthly
Fundacyt News	Fundacion para la Ciencia y la Tecnologia (FUNDACYT) www.fundacyt.org	Monthly
El Salvador		
Agrometeorological		
<i>Boletín Agrometeorológico Decádico</i> (10 day Agrometeorological Bulletin)	Servicio Nacional de Estudios Territoriales (National Service of Territorial Studies) Km. 5 ½ Carretera a Nueva San Salvador Avenida Las Mercedes El Salvador http://www.snet.gob.sv/ver/meteorologia/clima/agrometeorologico/	Every 10 days
Ethiopia		
Agrometeorological/Meteorological		
<i>Ten-Day Agrometeorological Bulletin</i>	National Meteorological Services Agency P.O. Box 1090 Addis Ababa Email: nmsa@ethionet.et http://www.wamis.org/countries/ethiopia.php	Every 10 days

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General Scientific		
<i>SINET: Ethiopian Journal of Science</i>	SINET Faculty of Science Addis Ababa University P.O. Box 31226 Addis Ababa, Ethiopia ISSN: 0379-2897	Biannually
<i>Momona Ethiopian Journal of Science</i>	College of Natural and Computational Sciences P.O. Box. 3037 Mekelle University Mekelle	Biannually
Fiji		
Agrometeorological		
Fiji Islands Sugar Cane Rainfall Outlook	Fiji Meteorological Service Private Mail Bag (NAP 0351) Nadi Airport, Fiji. Email: climate@met.gov.fj http://www.met.gov.fj	Two to four times per year
Meteorological/Climatological		
Fiji Islands Climate Outlook	Idem	Monthly
Fiji Islands Climate Summary	Idem	Monthly
ENSO Update	Idem	Periodically
Annual Climate Summary	Idem	Annually
Finland		
Meteorological		
Finnish Meteorological Institute Contributions	Finnish Meteorological Institute / Library P.O. Box 503 00101 Helsinki http://www.fmi.fi/kirjasto/julkaisut_14.html	Irregularly
<i>Ilmastokatsaus</i> <i>Climate Review</i> (in Finnish only)	Idem	Monthly
Meteorological publications and reports	Idem	Irregularly
Agricultural		
<i>Agricultural and Food Science</i>	MTT Agrifood Research Finland 31600 Jokioinen http://www.mtt.fi/afs/	Irregularly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Silva Fennica</i>	Finnish Society of Forest Science Unioninkatu 40 A 00170 Helsinki http://www.metla.fi/silvafennica	Quarterly
Finnish Forest Research Institute Working Papers	Finnish Forest Research Institute Unioninkatu 40 A, FI-00170 HELSINKI, Finland http://www.metla.fi/julkaisut/workingpapers/	Irregularly
Annual Reports	The Ministry of Agriculture and Forestry PL 30, 00023 Valtioneuvosto http://www.mmm.fi/english/publications	Annually
Statistics and other publications	The Ministry of Agriculture and Forestry PL 30, 00023 Valtioneuvosto	Irregularly
General Scientific		
<i>Fennia International Journal of Geography</i>	Department of Geography, 20014 University of Turku http://www.helsinki.fi/maantiede/geofi/fennia/	Irregularly
France		
Meteorological		
<i>Météo</i>	Météo-France 1, quai Branly 75340 Paris cedex 07 www.meteofrance.com Email : meteomagazine@meteo.fr ISSN : 1961-9200	Three times per year
<i>La Météorologie</i>	Société météorologique de France (SMF) 1, quai Branly 75340 Paris cedex 07 lameteorologie@meteo.fr www.smf.asso.fr/lameteo.html irevues.inist-fr/la-meteorologie	Three times per year
Agricultural		
<i>Agronomy for Sustainable Development</i> (formerly Agronomie)	EDP Sciences 17, Avenue du Hoggar Parc d'Activité de Courtabœuf BP 112 91944 Les Ulis cedex A Email: editorial@edpsciences.org ISSN (Print Edition): 1774-0746	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Annals of Forest Science</i>	EDP Sciences 17, Avenue du Hoggar Parc d'Activité de Courtabœuf BP 112 91944 Les Ulis cedex A Email: editorial@edpsciences.org Tel.: +33 (0) www.afs-journal.org	Eight times per year
Apidologie (Bee Science)	Institut National de la Recherche Agronomique (INRA) and Deutschen Imkerbundes e.V. (D.I.B.) 17 avenue du Hoggar Parc d'activités de Courtaboeuf BP 112 91944 Les Ulis cedex A www.edpsciences.org	Bimonthly
General Scientific		
<i>La Recherche</i>	Société d'Editions Scientifiques 74, Avenue du Maine 75014 Paris Email : courrier@larecherche.fr	Monthly
<i>Sciences au sud</i>	l'Institut de Recherche pour le Développement 44, bd de Dunkerque CS 90009 13572 Marseille cedex 02 Email : sciences.au.sud@ird.fr	Five times per year
<i>Natures Sciences Sociétés</i>	INRA-SAD UPIC BP 52627 31326 Castanet-Tolosan cedex Email : nss@toulouse.inra.fr ISSN (Print Edition): 1240-1307	Quarterly
<i>Annales de Limnologie - International Journal of Limnology</i>	118 route de Narbonne 31062 Toulouse cedex 9 Email: cereghin@cict.fr ISSN: 0003-4088 EISSN: 2100-000X www.limnology-journal.org	Quarterly
Gambia		
Agrometeorological		
<i>Early Warning Bulletin For Food Security In The Gambia</i>	Multidisciplinary Working Group of the AGRHYMET Regional Programme Department of Water Resources Email: dwr@mofwrnam.gov.gm www.mofwrnam.gov.gm	Every 10 days during the growing season (May to October)

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Germany		
Meteorological		
<i>International Journal of Biometeorology</i>	Springer Berlin/Heidelberg; Springer Science+Business Media Corporate Communications Heidelberger Platz 3 14197 Berlin http://www.springer.com/sgw/cda	Approx. six times per year
<i>Meteorologische Zeitschrift</i>	E. Schweizerbart Science Publishers Johannesstr. 3A 70176 Stuttgart http://www.schweizerbart.de/	Bimonthly
<i>Climate Dynamics</i>	Springer Berlin/Heidelberg; Springer Science+Business Media Corporate Communications Heidelberger Platz 3 14197 Berlin http://www.springer.com/sgw/cda	Monthly
Berichte zur Erdsystemforschung (Reports on Earth System Science)	Max-Planck-Institut für Meteorologie Bundesstrasse 55 20146 Hamburg http://www.mpimet.mpg.de/	Irregularly
Klimastatusbericht (Climate Status Report)	Deutscher Wetterdienst Referat Satellitengestütztes Klimamonitoring Kaiserleistr. 29/35 63067 Offenbach am Main http://www.dwd.de/en/FundE/Klima/KLIS/prod/KSB/index.html	Annually
Statusberichte (status reports)	Deutsches Klimarechenzentrum GmbH Bundesstrasse 55 20146 Hamburg http://www.dkrz.de/	Irregularly
<i>Wetterfax für die Landwirtschaft</i> (Fax and online)	Deutscher Wetterdienst Abt. Agrarmeteorologie, regional offices Schleswig, Leipzig, Geisenheim, Weihenstephan http://www.dwd.de/de/wir/Geschaefsfelder/Landwirtschaft/Wir_aus/	Six times per week
<i>Wetterfax für den Weinbau</i> (Fax and online)	Deutscher Wetterdienst Abt. Agrarmeteorologie, regional office Geisenheim http://www.dwd.de/de/wir/Geschaefsfelder/Landwirtschaft/Wir_aus/	Six times per week

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agrowetter Prognose (online)	Deutscher Wetterdienst Kaiserleistr. 42 63067 Offenbach am Main http://www2.dwd-shop.de	Daily (four updates)
Wöchentlicher Witterungsbericht 2006 für ... [different federal states of Germany] [weekly weather report] (online)	Deutscher Wetterdienst Kaiserleistr. 42 63067 Offenbach am Main http://www2.dwd-shop.de	Weekly
Agrarmeteorologischer Wochenbericht für Schleswig-Holstein, Hamburg, Nieder-sachsen, Bremen und Mecklenburg-Vorpommern (online)	Deutscher Wetterdienst Abt. Agrarmeteorologie Aussenstelle Schleswig Regenpfeiferweg 9 24837 Schleswig http://www.agrowetter.de/produkte/berichte/wosgtext.htm	Weekly
Agrarmeteorologischer Wochenbericht für Sachsen-Anhalt, Brandenburg, Sachsen und Thüringen (online)	Deutscher Wetterdienst Abt. Agrarmeteorologie Aussenstelle Leipzig Kärnerstr. 68 04288 Leipzig http://www.agrowetter.de/produkte/berichte/wohktext.htm	Weekly
Agrarmeteorologischer Wochenbericht für Braunschweig (online)	Deutscher Wetterdienst Agrarmeteorologische Forschung Braunschweig Bundesallee 50 38116 Braunschweig http://www.agrowetter.de/produkte/berichte/wobgtext.htm	Weekly
Agrarmeteorologischer Monatsbericht für Nordbayern (online) same für Südbayern (online)	Deutscher Wetterdienst Abt. Agrarmeteorologie Aussenstelle Weihestephane Alte Akademie Nr. 16 Weihestephane Berg 85354 Freising http://www.agrowetter.de/produkte/berichte/mowntext.htm	Monthly
Wochenvorhersage für die Landwirtschaft (online)	Deutscher Wetterdienst Abt. Agrarmeteorologie from the different regional offices http://www2.dwd-shop.de	Daily
Welt-Klima-Rückblick/Global Climate Review (online)	Deutscher Wetterdienst Kaiserleistr. 42 63067 Offenbach am Main http://www2.dwd-shop.de	Monthly
Europäischer Wetter-bericht/ European Meteorological Bulletin (online)		Daily

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
promet, Meteorologische Fortbildung	Selbstverlag des Deutschen Wetterdienstes Kaiserleistr. 42	Quarterly
<i>Annalen der Meteorologie</i>	63067 Offenbach am Main	Irregularly
Berichte des Deutschen Wetterdienstes	http://www.dmg-ev.de/gesellschaft/publikationen/promet.htm	Irregularly
PIK Reports	Potsdam-Institut für Klimafolgenforschung (PIK) Potsdam Institute for Climate Impact Research Telegrafenberg A 31 14473 Potsdam http://www.pik-potsdam.de/publications	Irregularly
Institutsreports	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) Institut für Physik der Atmosphäre Oberpfaffenhofen 82234 Wessling http://www.dlr.de/ipa	Irregularly
Ergebnisbericht ueber Forschung und Entwicklung	Forschungszentrum Karlsruhe GmbH Institut für Meteorologie und Klimaforschung Hermann-von-Helmholtz-Platz 1 76344 Eggenstein-Leopoldshafen http://www-imk.fzk.de	Irregularly
Berliner Wetterkarte	Berliner Wetterkarte e.V. Carl-Heinrich-Becker-Weg 6-10 12165 Berlin http://wkserv.met.fu-berlin.de/	Nearly daily
WETTERmagazin. Klima, Forschung, Technik, Mensch	Deutsche Meteorologische Verlagsgesellschaft mbH Magdeburger Strasse 17 20457 Hamburg http://www.wettermagazin.de	Monthly
Geschichte der Meteorologie in Deutschland	Selbstverlag des Deutschen Wetterdienstes Kaiserleistr. 42 63067 Offenbach am Main http://www.dwd.de/en/wir/Veroeffentlichungen/Publikationen.htm	Irregularly
Various report series	Meteorological institutes of universities	Irregularly
Agricultural		
Landbauforschung Völkenrode – FAL Agricultural Research	Bundesforschungsanstalt für Landwirtschaft (FAL) Federal Agricultural Research Centre (FAL) Bundesallee 50 38116 Braunschweig www.fal.de	Quarterly + special issues

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Mitteilungen aus der Biologischen Bundesanstalt für Land- und Forstwirtschaft	Biologische Bundesanstalt für Land- und Forstwirtschaft (BBA), Berlin und Braunschweig Messeweg 11/12 38104 Braunschweig www.bba.de	Irregularly
<i>Zeitschrift für Pflanzenernährung und Bodenkunde / Journal of Plant Nutrition and Soil Science</i>	WILEY-VCH Verlag GmbH & Co. KGaA, Boschstrasse 12 69469 Weinheim http://www3.interscience.wiley.com/cgi-bin/jhome/10008342	Bimonthly
<i>Irrigation Science</i>	Springer Berlin / Heidelberg; Springer Science+Business Media Corporate Communications Heidelberger Platz 3 14197 Berlin http://www.springer.com/sgw/cda	Quarterly
Various publications	Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF) e. V. Eberswalder Strasse 84 15374 Müncheberg http://www.zalf.de/	Irregularly
<i>European Journal of Forest Research</i>	Springer Berlin / Heidelberg; Springer Science+Business Media Corporate Communications Heidelberger Platz 3 14197 Berlin http://www.springer.com/sgw/cda	Quarterly
General scientific		
<i>Bild der Wissenschaft</i>	Konradin Medien GmbH Ernst-Mey-Strasse 8 70771 Leinfelden-Echterdingen http://bdw.wissenschaft.de	Monthly
<i>Fraunhofer Magazin. Zeitschrift für Forschung, Technik und Innovation</i>	Fraunhofer-Gesellschaft Hansastr. 27c 80686 München http://www.fraunhofer.de/fhg/publications/index.jsp	Quarterly
Forschungs Report	Geschäftsstelle des Senats der Bundesforschungsanstalten c/o BBA Messeweg 11/12 38104 Braunschweig http://www.bmvel-forschung.de	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Naturwissenschaften</i>	Springer Berlin/Heidelberg; Springer Science+Business Media Corporate Communications Heidelberger Platz 3 14197 Berlin http://www.springer.com/sgw/cda/	Monthly
<i>Spektrum der Wissenschaft</i>	Spektrum der Wissenschaft Verlagsgesellschaft mbH Postfach 10 48 40 69038 Heidelberg http://www.wissenschaft-online.de/blatt/d_sdw_home	Monthly

Ghana

Agricultural

<i>Agricultural and Food Science Journal of Ghana</i>	Council for Scientific and Industrial Research P O Box M32 Accra	Annually
<i>Ghana Journal of Agricultural Science</i>	idem	
<i>Ghana Journal of Forestry</i>	Forestry Research Institute of Ghana University PO Box 63 Kumasi ISSN 0855-1707	Biannually

Hungary

Meteorological

Idojaras (Weather, in English)	Országos Meteorológiai Szolgálat 1024 Budapest, Kitaibel Pal u. 1.	Four to five times per year
Idojaras felhavi előrejelzése (Prognosis for 2 weeks)	Idem	Bimonthly
Idojaras napijelentes (Daily weather prognosis)	Idem	Daily
Meteorológiai előrejelzés 6 hónapra (Prognosis for 6 months)	Idem	Biannually
Meteorológiai előrejelzés 10 hónapra (Prognosis for 10 months)	Idem	Annually
Legkor (The Atmosphere)	Idem	Bimonthly

Agricultural

<i>Acta Agronomica Academiae Scientiarum Hungaricae</i> (in English)	Akademiai Kiado 1519 Budapest, Pf. 245 Email: journals@akkr.hu	Two to four times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Agrokémia és Talajtan</i> (Agrochemistry and the Soil)	Idem	Three to four times per year
<i>Allattenyésztes és Takarmányozás</i> (Animal Husbandry and Breeding)	Allattenyésztes és Takarmányozási Kutatóintézet 2053 Herceghalom, Gesztenyes u. 1 Email: szerk@atk.hu	Three to four times per year
<i>Novénytermes</i> (Plant Growing)	Agroinform Kiadó 1149 Budapest, Angol u. 34 Email: kiado@agroinform.axelero.hu	Three to four times per year
<i>Novényvédelem</i> (Plant Protection)	Idem	Bimonthly
<i>Kertészet és szőlészet</i> (Horticulture and Viticulture)	Magyar Posta Rt. Sajtómenedzser Bt. 1147 Budapest, Pf. 560.	Weekly
<i>Öntözési gazdálkodás</i> (Irrigation Management)	Öntözési Kutató Intézet 5540 Szarvas, Szabadság u. 2.	Biannually
<i>Acta Botanica Academiae Scientiarum Hungaricae</i> (in English)	Akademiai Kiadó 1519 Budapest, Pf. 245 Email: journals@akkrt.hu	Biannually
General Scientific		
<i>Hidrologiai Közlemények</i> (New in Hydrology)	Magyar Hidrológiai Társaság 1027 Budapest, Fő u. 68	Monthly
<i>Acta Universitatis Debreceniensis</i>	Debreceni Egyetem 4032 Debrecen, Egyetem tér 1	Annually
<i>Acta Biologica Academiae Scientiarum Hungaricae</i> (in English)	Akademiai Kiadó 1519 Budapest, Pf. 245 Email: journals@akkrt.hu	Quarterly
<i>Acta Oecologica Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly
<i>Acta Physica Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly
<i>Acta Physiologica Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly
<i>Acta Phytopathologica Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly
<i>Acta Veterinaria Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Acta Zoologica Academiae Scientiarum Hungaricae</i> (in English)	Idem	Quarterly
<i>Gazdalkodas</i> (Management)	Karoly Robert Kutato-Oktato Kht. 3200 Gyongyos, Matrai u. 36	Monthly
<i>Georgikon for Agriculture</i> (in English)	University of Veszprem Faculty of Agronomy P.O. Box 71 8361 Keszthely	Biannually
India		
Meteorological /Agrometeorological		
<i>Journal of Agrometeorology</i>	Association of Agrometeorologists Anand Agricultural University, Anand 388 110 www.agrimetassociation.com pandey04@yahoo.com	Triannually
<i>Mausam</i> (Formerly Indian Journal of Meteorology Hydrology and Geophysics)	India Meteorological Department Lodi Road, New Delhi 110 003 mausamps@imd.ernet.in bmukho@imd.ernet.in	Quarterly
Agricultural		
<i>Indian Journal of Agricultural Sciences</i>	Indian Council of Agricultural Research, Krishi Anusandhan Bhavan II Pusa New Delhi 110 012 bmicar@kab.delhi.nic.in	Monthly
<i>Indian Journal of Agronomy</i>	Indian Society of Agronomy Indian Agricultural Research Institute Pusa New Delhi – 110 012 snagarajan@iari.res.in	Quarterly
<i>Indian Farming</i>	Indian Council of Agricultural Research, Krishi Anusandhan Bhavan I I, Pusa New Delhi – 110 012 bmicar@kab.delhi.nic.in	Monthly
<i>Progressive Farming</i>	Punjab Agricultural University Ludhiana	Monthly
<i>Indian Journal of Entomology</i>	Entomological Society of India Division of Entomology IARI New Delhi 110 012	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Indian Phytopathology</i>	Indian Phytopathological Society Division of Mycology and Plant Pathology IARI, New Delhi – 110 012, INDIA	Quarterly
<i>Indian Journal of Horticulture</i>	Horticulture society of India 255, Upper Palace Orchards Banglore 560 006	Quarterly
<i>Journal of Indian society of soil science</i>	Indian Society of Soil Science Division of Soil Science and Agricultural Chemistry IARI, New Delhi 110 012	Quarterly
<i>Journal of Soil and Water Conservation</i>	Soil Conservation Society of India IARI, New Delhi 110 012	Quarterly
<i>Indian Journal of Ecology</i>	Indian Ecological Society College of Agriculture, Panjab Agricultural University Ludhiana	Biannually
<i>Madras Agricultural Journal</i>	Tamil Nadu Agricultural University Campus Coimbatore 641 003	Monthly
<i>Andhra Agricultural Journal</i>	Andhra Agricultural Union, Agricultural College Baptla (Andra Pradesh)	Bimonthly
<i>Research Journal of Mahatma Phule Agricultural University</i>	Mahatma Phule Agricultural University College of Agriculture Pune 410 005	Biannually
<i>Advances in Agricultural Research in India</i>	International Book Distributors 9/3, Raipur Road Dehra Dun 248 001 www.ibdbooks.com	Biannually
<i>Agricultural Reviews</i>	The Business Manager. Agricultural Research Communication Center 1130, Sadar Bazaar Karnal 132 001	Quarterly
<i>Agricultural Economics Review</i>	Agricultural Economics Research Association (India) Division of Agricultural Economics IARI, New Delhi 110 012	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Agriculture Today</i>	Center for Agriculture and Rural Development C-17, Lajpat Nagar – I IIIrd Floor New Delhi 110 024 agricult@del3.vsnl.net.in	Monthly
<i>Agricultural Science Digest- A Research Journal</i>	The Business Manager. Agricultural Research Communication Center 1130, Sadar Bazaar Karnal- 132 001	Quarterly
<i>Legume Research</i> (An International Journal)	The Business Manager. Agricultural Research Communication Center 1130, Sadar Bazaar Karnal- 132 001	Quarterly
<i>Indian Journal of Agricultural Research</i>	Idem	Quarterly
<i>Crop Research- An International Journal</i>	The Society of Agricultural Research Information Centre Hisar 125 004 Haryana arcmd@hotmail.com www.cropresearch.org.net.in	Bimonthly
<i>Indian Farmers Digest</i>	Director Communication Center G. B. Pant University of Agriculture and Technology Pantnagar 263 145 Uttaranchal	Monthly
<i>Gujarat Agricultural University Research journal</i>	Director of Extension Education Anand Agricultural University Anand 388 110	Biannually
<i>Indian Agriculturist</i>	The Agricultural Society of India, 35 Ballygunge Circular Road, Kolkata 700 019 agrisocietyindia_57@rediffmail.com	Quarterly
<i>Indian Journal of Forestry</i>	23-A, Connaught Place P.O. Box No. 137 Dehra Dun 248 001	Quarterly
<i>Indian Journal of Animal Sciences</i>	Indian Council of Agricultural Research, Krishibhavan, New Delhi – 110001	Monthly
<i>Indian Journal of Animal Health</i>	61/4, Belgachioa Road, Culcutta 700037	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General Scientific		
<i>International Journal of Ecology and Environmental Sciences</i>	International Scientific Publications 50-B, Pocket C, Siddharth Extension New Delhi 110 014	Quarterly
<i>Annals of Arid Zone</i>	Arid zone Research Association of India, CAZRI, Jodhpur, Rajasthan	Quarterly
<i>Current Science</i>	Current Science Association Bangalore- 560 006,	Fortnightly
<i>Proceedings of the Indian Academy of the sciences, Section A &B</i>	Indian Academy of sciences Hebbal P O Bangalore 560 006	Monthly
<i>Science and Culture</i>	Indian Science News association, 92, Acharya Prafullachandra Road, Kolkata 700 009	Monthly
Iran (Islamic Republic of)		
Meteorological		
<i>Journal of Agricultural Aridity and drought (Persian)</i>	www.IRcADM.com	Seasonal
<i>Nivar (scientific and technical journal of IRIMO)</i>	Islamic Republic of Iran Meteorological Organization (IRIMO)	Monthly
Agricultural		
<i>Jangal va marta</i>	Jangal va marta-may@FRW.Org.ir	Quarterly
<i>Agricultural and Natural Resources Engineering Regulation</i>	Seasonal@agri.eng.org natural www.agri-eng.org	Seasonal
<i>Sustainable Agriculture</i>		Seasonal
<i>Journal of Agricultural Engineering Research</i>	AERI@ABDNET.com	Quarterly
Agricultural Science		
<i>Journal of Agricultural Science</i>	JaGRIC@lib.scu.ac.ir	Quarterly
<i>Journal of Agricultural Technology and Natural resources</i>	Jasanr@cc.Iut.ac.ir	Seasonal
<i>Iran natural resources</i>	ijnr@nrt.ut.ac.ir	Seasonal

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Iran Agricultural Research	info@aiiri.com www.aiiri.com	Quarterly
Insurance and Agriculture		Seasonal
General Scientific		
Geographical Research	Geodept@iramirkq ir.com	Seasonal
Earth and Space Physics (Farsi and English)	Igtu-jnl@ut.ac.ir	Biannually
Researches in Geography	Geog-ins@ut.ac.ir www.geophysics.ut.ac.ir	Seasonal
Iraq		
Agrometeorological		
<i>Agrometeorology monthly Bulletin</i> - Climate brief of the previous month, daily meteorological parameters recorded by the stations in both tabulated and graphical forms	Directory of Agriculture Ministry of Agriculture Erbil-Kurdistan	Monthly
Agricultural		
<i>The Iraqi Journal of Agriculture Science</i> (research papers related to agriculture in all aspects)	College of Agriculture University of Baghdad Baghdad	Bianually
<i>Journal of Rafiddain of Agriculture</i> (scientific research papers related to agriculture in all aspects)	College of Agriculture University of Mosul Mosul	Biannually
General Scientific		
Zanco - Journal of Pure and Applied Science, (including agriculture in all aspects)	University of Salahaddin Erbil	Biannually
Ireland		
Meteorological/Climatological		
<i>Monthly Weather Bulletin</i>	Met Éireann Glasnevin Hill Dublin 4 http://www.met.ie/climate	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural (and agri-environmental)		
<i>Irish Journal of Agriculture & Food Research</i>	Teagasc Johnstown Castle Research Centre Wexford http://www.teagasc.ie/research/journal.htm	Biannually
<i>Farm & Food Research & Development Digest</i>	http://www.teagasc.ie/research/journal.htm	Quarterly
<i>Irish Forestry</i>	Society of Irish Foresters Enterprise Centre Ballintogher Co. Sligo http://societyofirishforesters.ie/irishforestryjournal.shtml	Biannually
<i>Tearmann: Irish Journal of Agri-Environmental Research</i>	Dept. of Environmental Resource Management Faculty of Agri-Food & The Environment University College Dublin Belfield Dublin 4 http://www.ucd.ie/agri/html/homepage/faculty.htm	Annually
<i>Biology and Environment: Proceedings of Royal Irish Academy</i>	Royal Irish Academy Dawson Street Dublin 2 http://www.ria.ie	Three times per year
<i>Irish Geography</i> <i>The International Journal of the Geography of Ireland</i>	Geographical Society of Ireland Dept. of Geography University College Dublin Belfield Dublin 4 http://www.geographical-society-ireland.org	Annually
General scientific		
<i>Technology Ireland</i>	Enterprise Ireland Glasnevin Dublin 9 http://www.enterprise-ireland.com/	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Israel		
General scientific		
<i>Israel Environment Bulletin</i>	Israel Ministry of Environmental Protection P.O. Box 34033 Jerusalem 95464 Email: shoshana@environment.gov.il www.environment.gov.il/english	Quarterly
Italy		
Agrometeorological		
<i>Italian Journal of Agrometeorology</i>	Associazione Italiana di Agrometeorologia Via Caproni 8 50144 Firenze www.agrometeorologia.it	Three times per year
Bulletins	http://www.politicheagricole.it/ucea/ban/filecomuni.htm http://www.arpa.emr.it/smr/pagine/agrometeo/bollettino/ http://www.sar.sardegna.it/mainpubblicazioni.html http://www.lamma.rete.toscana.it/previ/ita/bollmet.html http://www.arpa.veneto.it/bollettini/htm/in_evidenza.asp http://www.arssa.abruzzo.it/car/ http://www.csa.fvg.it/priagro.htm http://www.meteotrentino.it/aspweb/index	Daily/weekly/ monthly
Environmental		
<i>Alberi e Territorio</i> (previously <i>Monti e Boschi</i>)	Il Sole 24 ore Edagricole http://www.edagricole.it/	Eight times per year
<i>Forest@ - Rivista di Selvicoltura ed Ecologia Forestale</i>	Bollettino della Società Italiana di Selvicoltura ed Ecologia Forestale http://www.sisef.it/forest@/bull.php	Monthly
Agricultural		
<i>Frutticoltura</i>	Il Sole 24 ore Edagricole http://www.edagricole.it/	Monthly
<i>Genio Rurale</i>		Irregularly/ annually
<i>Alberi e Territorio</i> (previously <i>Monti e Boschi</i>)	Il Sole 24 ore Edagricole http://www.edagricole.it/	Eight times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Italian Journal of Agronomy</i>	Official Journal of Italian Society of Agronomy Printed by Forum Editrice Universitaria Udinese http://www.agr.unipi.it/gtta/IJA/IJA-HomePage.html	Quarterly
<i>Vigne e Vini</i>	Il Sole 24 ore Edagricole http://www.edagricole.it/	10 times per year
<i>Informatore Agrario</i>	Edizioni l'Informatore agrario Verona http://www.informatoreagrario.it/	Weekly
General scientific		
<i>Il Nuovo Cimento</i>	Italian Society of Physics Bologna http://www.sif.it/journals.php	Monthly
Japan		
Agrometeorological / Meteorological		
<i>Journal of Agricultural Meteorology</i>	Society of Agricultural Meteorology of Japan (SAMJ) 113-0033 5-chome, Hongo, Bunkyo-ku Tokyo 30-15 Email: nogyo-kisho@yokendo.co.jp ISSN:0021-858 http://www.jstage.jst.go.jp/browse/agrmet	Quarterly
<i>Climate in Biosphere</i>	Idem http://www.soc.nii.ac.jp/agrmet/Climate_Biosphere.html ISSN : 2185-7954	Annually
<i>Journal of the Meteorological Society of Japan</i>	Meteorological Society of Japan 1-3-4, Ote-machi Chiyoda-ku Tokyo 100-004 Japan Email: jmsj@metSOC.jp www.soc.nii.ac.jp/msj/index-e.html	Biannually
<i>Journal of Meteorological Research</i>	Idem	Monthly
Papers in Meteorology and Geophysics	Meteorological Research Institute Japan Meteorological Agency 1-3-4 Otemachi, Chiyoda-ku Tokyo 100-8122	Annually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
<i>Bulletin of National Institute for Agro-Environmental Sciences</i>	National Institute for Agro-Environmental Sciences 3-1-3 Kannondai Tsukuba, 305-8604 Email: www@niaes.affrc.go.jp ISSN 0911-9450 http://www.niaes.affrc.go.jp/sinfo/publish/bullet_e.html	Annually
<i>Japanese Journal of Crop Science</i>	Crop Science Society of Japan Tokyo Secretariat	Quarterly
<i>Plant Production Science</i>	2F, Shin-Kyoritsu Building Shinkawa 2-22-4, Chuo-ku Tokyo, 104-0033 Email: cssj-jim@bridge.ocn.ne.jp	Quarterly
Kenya		
Agrometeorological/Meteorological		
<i>Dekadal Agrometeorological Bulletin</i>	Kenya Meteorological Department Agrometeorological Advisory Services Division Dagoretti Corner, Ngong Road P.O. Box 30259 00100 Nairobi Email: agromet@meteo.go.ke ;	Every 10 days
<i>Journal of the Kenya Meteorological Society (JKMS)</i>	Kenya Meteorological Society IMTR Library Dagoretti Corner Ngong Road P.O. Box 41959 00100 Nairobi	
Agricultural		
<i>Bulletin of Animal Health and Production in Africa</i>	African Union –Interafrican Bureau For Animal Resources (AU-IBAR) P.O. Box 30786 00100 Nairobi www.au-ibar.org	Quarterly
Lesotho		
Agrometeorological		
<i>Ten-Day Agrometeorological Bulletin</i>	Lesotho Meteorological Services Agrometeorological Section P.O. Box 14515 Maseru 100 Email: agrometeorology@lesmet.org.ls http://www.lesmet.org.ls	Every 10 days

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Malawi		
Agrometeorological		
<i>Malawi 10-Day Rainfall & Agrometeorological Bulletin</i>	Department of Climate Change and Meteorological Services P.O. Box 1808 Blantyre Email: metdept@metmalawi.com http://www.metmalawi.com/bulletins/bulletins.php	Every 10 days during the growing season (October to April)
Malaysia		
Agrometeorological		
<i>10-Day Agrometeorological Bulletin</i>	Malaysian Meteorological Department Jalan Sultan, 46667 Petaling Jaya Selangor Darul Ehsan Indonesia http://www.met.gov.my/index.php?option=com_content&task=view&id=2615&Itemid=1787	Every 10 days
Mali		
Agrometeorological		
<i>Bulletin d'Information Agro-Hydro-Météorologique Décadaire</i> (10-Day Agro-Hydro-Meteorological Information Bulletins)	Multidisciplinary Working Group of Meteorological Assistance Direction Nationale de la Météorologie route de l'aéroport BP 237 Bamako Senou	Every 10 days
Mexico		
Meteorological/Climatological		
<i>Atmósfera</i>	http://www.ejournal.unam.mx/cuadros2.php?r=1	Quarterly
Agricultural		
<i>Agrociencia Journal</i>	http://www.colpos.mx/agrocien/agrociencia.htm	Eight times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Mozambique		
Agrometeorological		
<i>Boletim Meteorológico para a agricultura</i>	Instituto Nacional de Meteorologia Rua de Mukumbura, 164 C.P. 256, Maputo Email:mozmet@inam.gov.mz http://www.inam.gov.mz	Every 10 days
Namibia		
Agrometeorological		
<i>WHOT Bulletin</i>	Namibian Meteorological Service Private Bag 13224 Windhoek	Three times per month
Agricultural		
<i>Agricola</i>	Director Agricultural Research and Training Ministry of Agriculture, Water and Forestry Private Bag 13184 Windhoek	Annually
General scientific		
<i>Journal of the Scientific Society of Namibia</i>	Scientific Society of Namibia Windhoek	Annually
<i>Dinteria</i>	Scientific Society of Namibia Windhoek	Annually
<i>Cimbebasia</i>	National Museum of Namibia	Annually/ Biennially
New Zealand		
Meteorological / Climatological		
<i>New Zealand Climate Update</i>	National Institute of Water and Atmospheric Research (NIWA) 41 Market Place Viaduct Harbour Auckland Central 1010 Private Bag 99940 Newmarket, Auckland 1149 http://www.niwa.co.nz/news-and-publications/publications/all/cu	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
<i>New Zealand Journal of Agricultural Research</i>	The Royal Society of New Zealand 4 Halswell Street Thorndon	Quarterly
<i>New Zealand Journal of Botany</i>	Wellington 6011 P.O. Box 597 Wellington 6140 Email: publish@royalsociety.org.nz	Quarterly
<i>New Zealand Journal of Crop and Horticultural Science</i>		Quarterly
General Scientific		
<i>New Zealand Journal of Geology and Geophysics</i>	Idem	Quarterly
Netherlands		
Agrometeorological / Meteorological		
<i>Agricultural and Forest Meteorology</i>	Elsevier B.V. (Corporate Office) Radarweg 29 Amsterdam 1043	Monthly
Agricultural		
<i>Agriculture, Ecosystems & Environment</i>	Elsevier B.V. (Corporate Office) Radarweg 29 Amsterdam 1043	Monthly
<i>Netherlands Journal of Agricultural Science (NJAS) - Wageningen Journal of Life Sciences</i>	office.klv@wur.nl P.O. Box 79 6700 AB Wageningen The Netherlands http://library.wur.nl/ojs/index.php/njas/index	Annually
Niger		
Agrometeorological		
<i>Bulletins Agro-Hydro-Meteorologiques Decadaires</i> (10 day Agro-Hydrometeorological Bulletins)	Multi-disciplinary Working Group of Niger Lead Group : Direction de la Météorologie Nationale du Niger BP 218 Niamey Email: dmn@intnet.ne	Every 10 days during the growing season (May to October)

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Nigeria		
Agrometeorological/ Meteorological		
<i>Agromet Bulletin</i>	Nigerian Meteorological Agency Plot 507 Pope John Paul Crescent	Every 10 days
<i>Climate Bulletin</i>	Maitama District Abuja	Monthly
Nigeria Climate Review Bulletin		Annually
Agricultural		
<i>Agro-Science</i>	Professor M. I. Uguru Editor-in-chief Dept. of Crop Science University of Nigeria Nsukka Email: chiefeditor@agrosiencejournal.com	Biannually
<i>Journal of Agricultural Extension</i>	Department of Agricultural Extension, University of Nigeria Nsukka Email: madukwemichael@yahoo.com	Biannually
<i>Nigeria Agricultural Journal</i>	Prof. A. C. Nwosu College of Agricultural Economics Rural Sociology and Extension Michael Okpara University of Agriculture Umudike Abia State	Annually
Norway		
Meteorological		
<i>Meteorologiske data for Ås</i>	Universitet for miljø og biovitenskap	Annually
Bulletins	Meteorologisk institutt: http://met.no/index.shtml http://met.no/observasjoner/	Daily monthly
	Storm weather centre: http://www2.storm.no	Daily
Agrometeorological		
Bulletin	Bioforsk (Agrometeorological service): http://lmt.bioforsk.no/	Daily

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
Bulletin	Bioforsk (warning pests and diseases): http://www.vips-landbruk.no/index.jsp	Daily
Environmental		
Vann	Norsk Vannforening Forening for Vassdragspleie og Vannhygiene	Quarterly
Pakistan		
Meteorological/Climatological		
<i>Pakistan Journal of Meteorology</i>	Pakistan Meteorological Department P.O. Box 1214, Sector H-8/2 Islamabad	Biannually
Agricultural		
<i>Pakistan Journal of Agricultural Sciences</i>	Editorial Office Pakistan Journal of Agricultural Sciences Institute of Soil and Environmental Sciences University of Agriculture Faisalabad 38040	Quarterly
<i>Sarhad Journal of Agriculture (SJA)</i>	Agricultural University Peshawar http://www.aup.edu.pk/sarhad_journal.php	Quarterly
<i>Pakistan Entomologist</i>	Pakistan Entomological Society University of Agriculture Faisalabad 38040 http://www.pakentomol.com/	Biannually
<i>Soil and Environment</i>	Soil Science Society of Pakistan Institute of Soil and Environmental Sciences University of Agriculture Faisalabad 38040 http://www.sss-pakistan.org/Soil and Environment/journal.htm	Biannually
<i>Journal of Agricultural Research</i>	Directorate of Agricultural Information, Punjab 21 Sir Agha Khan III Road, Lahore or Research Information Unit, AARI Campus, Jhang Road, Faisalabad, Punjab http://www.jar.com.pk/	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Pakistan Journal of Agricultural Research</i>	Editor: Sabiha Amin, Plot 20 G 5/1 P.O. Box 1031 Pakistan Agricultural Research Council Islamabad http://www.parc.gov.pk/Pjar/Journal-17-2.html	Quarterly
<i>Journal of Agronomy</i>	Asian Network for Scientific Information (ANSINET) 308-Lasani Town, Sargodha Rd Faisalabad 38090	Quarterly
<i>Zaraat Nama</i>	Directorate of Agricultural Information Punjab 21, Sir Agha Khan III Road Lahore	Fortnightly
<i>Asian Journal of Plant Sciences</i>	Asian Network for Scientific Information (ANSINET) 308-Lasani Town, Sargodha Rd Faisalabad 38090 http://www.ansinet.com/current.php?issn=1682-3974	Quarterly
<i>Pakistan Journal of Biological Sciences</i>	Asian Network for Scientific Information (ANSINET) 308-Lasani Town, Sargodha Rd Faisalabad 38090 http://www.ansinet.com/current.php?issn=1727-3048	Quarterly
<i>Plant Pathology Journal</i>	Asian Network for Scientific Information (ANSINET) 308-Lasani Town, Sargodha Rd Faisalabad 38090 http://www.ansinet.com/current.php?issn=1812-5387	Quarterly
<i>Pakistan Journal of Weed Science Research</i>	Weed Science Society of Pakistan Dept. of Weed Science NWFP Agricultural University Peshawar http://www.wssp.org.pk/article.htm	Quarterly
<i>Pakistan Journal of Phytopathology</i>	Department of Plant Pathology University of Agriculture Faisalabad 38040 E-Mail: mushroomking041@yahoo.com	Biannually
<i>Pakistan Veterinary Journal</i>	Faculty of Veterinary Science University of Agriculture Faisalabad 38040 http://pvj.com.pk/default.htm	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>International Journal of Agriculture and Biology</i>	Dr. Zafar I. Randhawa, Editor-in-chief Dept. of Veterinary Parasitology University of Agriculture Faisalabad 38040 http://www.fspublishers.org/ijab/index_ijab.jsp	Quarterly
<i>Pakistan Journal of Life and Social Sciences</i>	704 Amin Town P.O. Nishatabad Faisalabad 38600 email: elitescientificforum@gmail.com	Biannually
<i>Journal of Animal and Plant Sciences</i>	Dr. Hafiz Muhammad Abdullah Faculty of Animal Production and Technology University of Veterinary and Animal Sciences Lahore	Quarterly
<i>Biologia</i>	The Biological Society of Pakistan Biological Laboratories Government College University Lahore	Biannually
<i>Pakistan Journal of Marine Sciences</i>	Quddusi B. Kazmi, Chief Editor Marine Reference and Resource Collection Centre University Campus University of Karachi Karachi 75270 http://www.ku.edu.pk	Biannually
<i>Pakistan Journal of Marine Biology</i>	Mustafa Shameel, Editor-in-Chief Centre of Excellence in Marine Biology University of Karachi http://www.ku.edu.pk/research/cemb/	Quarterly
<i>Pakistan Journal of Botany</i>	Dr. Abdul Ghaffar, Chief Editor Dept. of Botany University of Karachi Karachi Email shaji@super.net.pk	Quarterly
<i>Pakistan Journal of Forestry</i>	Pakistan Forest Institute Peshawar 25120	Quarterly
General scientific		
<i>Pakistan Journal of Scientific and Industrial Research</i>	Editor-in-Chief, Dr. Saeed Iqbal Zafar Scientific Information Centre Saddar 39 Garden Rd Karachi 74400 http://www.pjsir.org	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Peru		
Meteorological/ agrometeorological		
<i>Boletín Meteorológico e Hidrológico del Perú</i>	Servicio Nacional de Meteorología e Hidrología http://www.senamhi.gob.pe	Monthly
<i>Boletín Agroclimático del Perú</i>		Monthly
<i>Boletín Informativo Monitoreo del Fenómeno El Niño</i>		Monthly
<i>Radiación Ultravioleta-B</i>		Monthly
<i>Boletín de Pronostico Diario del Tiempo en la Capital de la Republica del Perú</i>		Monthly
<i>Vigilancia Sinóptica de Sudamérica y su Perspectiva</i>		Monthly
<i>Seguimiento de las Condiciones Agrometeorológicas del Valle de Cañete</i>		Monthly
<i>Pronostico Agrometeorológico para el Valle del Río Mantaro</i>		Monthly
<i>Pronostico Agrometeorológico para el Valle del Urubamba</i>		Monthly
<i>Clima y Agua en la Agricultura</i>	Ministerio de Agricultura del Perú http://www.minag.gob.pe/	
<i>Perdidas y Afectaciones</i>		

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
<i>Estadística Agraria Mensual</i>	Ministerio de Agricultura del Perú http://www.minag.gob.pe/	Monthly
Informe Seguimiento Agroeconómico		Monthly
Boletines Agrícolas Regionales		Monthly
General scientific		
<i>Evaluación Hidrológica de Cuencas</i>	Servicio Nacional de Meteorología e Hidrología	Monthly
<i>Boletín Informativo Ambiental</i>	http://www.senamhi.gob.pe/	Monthly
<i>Evaluación de la Contaminación Atmosférica en la Zona Metropolitana de Lima-Callao</i>		Monthly
Cotizaciones Internacionales	Ministerio de Agricultura del Perú http://www.minag.gob.pe/	Monthly
Abastecimiento y Precios		Monthly
Informe de Coyuntura		Monthly
Philippines		
Agricultural		
<i>Philippine Agricultural Scientist</i>	College of Agriculture University of the Philippines Los Baños Laguna 4031 Email: pas@mozcom.com www.pas-uplbca.edu.ph	Quarterly
<i>Philippine Journal of Crop Science</i>	The Philippine Journal of Crop Science Crop Science Cluster College of Agriculture University of the Philippines at Los Baños College Laguna 4031 Email: pjcs.pcs@gmail.com	Quarterly
Poland		
Meteorological		
Review of Geophysics/ Przegląd Geofizyczny	Uniwersytet Warszawski – Wydział Geografii i Studiów Regionalnych ul. Krakowskie Przedmieście 30 00-927 Warszawa Email: mosowiec@uw.edu.pl	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General scientific		
Polish Geographical Review/ Przegląd Geograficzny	Instytut Geografii i Przestrzennego Zagospodarowania Im. Stanisława Leszczyckiego PAN ul. Twarda 51/55 00-818 Warszawa Tel: 22 69 78 844 Email: i.kwait@twarda.pan.pl	Quarterly
Portugal		
Agrometeorological		
<i>Boletim Meteorológico para a Agricultura</i>	Instituto de Meteorologia Rua Cao Aeroporto 1749-077 Lisboa www.meteo.pt	Three times per month
Climatological		
<i>Relatório de Acompanhamento Quinzenal da Seca 2005</i>	Av. Almirante Gago Coutinho, N°30 1049-066 Lisboa www.inag.pt	Fortnightly (when necessary)
<i>Boletim Climatológico</i>	Instituto de Meteorologia Rua C ao Aeroporto 1749-077 Lisboa www.meteo.pt	Monthly
Agricultural/Environmental		
<i>Agros</i>	Associação de Estudantes do Instituto Superior de Agronomia Tapada da Ajuda 1349-017 Lisboa	Biannually
<i>Anais do Instituto Superior de Agronomia</i>	Instituto Superior de Agronomia Tapada da Ajuda 1349-017 Lisboa	Annually
<i>Revista de Ciências Agrárias</i>	Sociedade de Ciências Agrárias de Portugal Rua da Junqueira N°299 1300-338 Lisboa http://www.scap.pt/scap_revista.asp	Quarterly
<i>Boletim Trimestral do Instituto de Financiamento e Apoio ao Desenvolvimento da Agricultura e Pescas/ Instituto Nacional de Intervenção e Garantia Agrícola</i>	R. Fernando Curado Ribeiro, 4, G 1649-034 Lisboa http://www.inga.min-agricultura.pt/index.html	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Anuário Florestal</i>	Direcção-Geral dos Recursos Florestais Av. João Crisóstomo 26-28, 1069-040 Lisboa	Annually
<i>Info Ambiente e Água</i>	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
<i>Boletim Florestal</i>	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
<i>Info Energia Renovável</i>	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
<i>Anuário Vegetal</i>	Gabinete de Planeamento e Política Agro-Alimentar Rua Padre António Vieira, 1 1099-073 Lisboa http://www.gppaa.min-agricultura.pt/pbl/Anuario_2003_Vegetal.pdf	Annually
<i>Floresta e Ambiente</i>	Revista de Divulgação Técnica Rua Camilo Álvares, 1003, 1º 2775-177 Parede	Quarterly
Agricultural		
<i>Revista Jovens Agricultores</i>	Associação dos Jovens Agricultores de Portugal, Rua do Pedro V, 108 – 2º andar 1269-128 Lisboa http://www.ajap.pt/	Quarterly
Jovens Agricultores Suplemento da Revista Jovens Agricultores de Portugal	Associação dos Jovens Agricultores de Portugal/Instituto Nacional de Intervenção e Garantia Agrícola Rua do Pedro V, 108 – 2º andar 1269-128 Lisboa	Annually
<i>Info Azeite</i>	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
AJAP Objectiva Newsletter	Associação dos Jovens Agricultores de Portugal R. D. Pedro V, 108 – 2º andar 1269-128 Lisboa http://www.ajap.pt/	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Revista Voz da Terra	Confederação Nacional da Agricultura, Rua do Brasil, Nº 155 3030-175 Coimbra	Bimonthly
Boletim Informativo da Confederação Nacional da Agricultura	http://www.cna.pt/	Bimonthly
Guia do Jovem Agricultor	Confederação Nacional dos Jovens Agricultores de Portugal Rua do Castilho 36-1º 1250-070 Lisboa	Annually
Revista Nova Agricultura	http://www.cnjap.pt/	Quarterly
Catálogo Nacional de Variedades	Direcção Geral de Protecção das Culturas Quinta do Marquês 2780-155 Oeiras	Annually
Revista – Protecção da Produção Agrícola		Annually
Boletim do Registo de Variedades Protegidas		Annually
Revista do Agricultor	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
Notícias da Confederação dos Agricultores de Portugal	http://www.cap.iweb.pt/SAPPortal/	Fortnightly
Info Estruturas		Monthly
Info Pecuária		Monthly
Info Frutos e Produtos Hortícolas		Monthly
Info Vinho		Monthly
Info Culturas Arvenses, Tabaco em Rama e Beterraba Sacarina	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
Info Associativismo	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
Info União Europeia	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly
Info CESE	Confederação dos Agricultores de Portugal Av. Colégio Militar, Lote 1786 1549-012 Lisboa	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Espaço Rural</i>	Confederação das Cooperativas Agrícolas e do Crédito Agrícola de Portugal R. Maria Andrade, 13 1199-013 Lisboa http://www.confagri.pt/Publicacoes/EspacoRural/	Bimonthly
<i>Anuário Pecuário</i>	Gabinete de Planeamento e Política Agro-Alimentar Rua do Padre António Vieira, 1 1099-073 Lisboa	Annually
<i>Principais Indicadores</i>	Gabinete de Planeamento e Política Agro-Alimentar, R. Padre António Vieira, 1 1099-073 Lisboa http://www.gppaa.min-agricultura.pt/pbl/Princ.Indic-02.pdf	Annually
<i>Panorama Agricultura</i>	Gabinete de Planeamento e Política Agro-Alimentar R. Padre António Vieira, 1 1099-073 Lisboa http://www.gppaa.min-agricultura.pt/pbl/Pan2000/Indice.html	Annually
<i>Gazeta das Aldeias</i>	Adubos de Portugal, S.A. Estrada Nacional 10 Salgados da Póvoa Apartado 88 2616-907 Alverca do Ribatejo	Quarterly
Republic of Korea		
Meteorological		
<i>Asia-Pacific Journal of Atmospheric Sciences</i>	Korean Meteorological Society Youngdungpo-gu, Shingil-dong 508 Ciwon Bldg 704 Seoul, 150-050 komes@komes.or.kr	Quarterly
Agricultural		
<i>Journal of Crop Science and Biotechnology</i>	Han-Yong Kim Chonnam National University, (Rice Science, Climate Change Agronomy) http://www.springer.com/life+sciences/plant+sciences/journal/12892	Quarterly
<i>Journal of the Korean Forestry Society</i>	Korean Forestry Society ISSN: 0445-4650	

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Russian Federation		
Meteorological		
<i>Meteorology and Hydrology</i> (<i>Meteorologiya i gidrologiya</i>) ISSN 0130-2906 (Russian) ISSN 1068-3739 (English)	Zhurnal "Meteorologiya i gidrologiya" Novovagankovsky per., 12 Moscow, 123242 Email mig@mecom.ru http://mig.mecom.ru	Monthly
<i>Proceedings of the Russian Academy of Sciences. Physics of Atmosphere and Ocean</i> (<i>Izvestija Akademii Nauk. Fizika atmosfery i okeana</i>) ISSN 0002-3515	Institute of Atmospheric Physics Pyzhevsky per., 3 Moscow 119017 Email japho@omega.ifaran.ru	Bimonthly
<i>Atmospheric and Oceanic Optics</i> <i>Optika Atmosfery i Okeana</i> ISSN 0869-5695 (Russian) ISSN 0235-6880 (English)	Email psb@iao.ru http://ao.iao.ru	Monthly
<i>Bulletin of Russian Academy of Sciences. Geographic Series</i> <i>Izvestija Akademii Nauk. Serija Geograficeskaja</i> ISSN 0373-2444	Zhurnal "Izvestija Akademii" Nauk. Serija Geograficeskaja Staromonetny per., 29 Moscow, 119017	Bimonthly
<i>Proceedings of the Russian Geographical Society</i> <i>Izvestiia Russkogo geograficheskogo obshchestva</i>	Zhurnal "Izvestiia Russkogo geograficheskogo obshchestva" Mendeleevskaya linia, 1 St.Petersburg 199034	Bimonthly
<i>Earth Cryosphere / Kriosfera Zemli</i>	Zhurnal "Kriosfera Zemli" ul. Fersmana, 11, korpus 2 kv. 68, Moscow, 117312 Email krioziem@online.ru http://www-psb.ad-sbras.nsc.ru/kriosw.htm	Quarterly
<i>Oceanology, Hydrology of Lands, Glaciology</i> <i>Okeanologia. Gidrologia sushi. Glaciologia</i>	Zhurnal "Okeanologia. Gidrologia sushi. Glaciologia" ul. Usievicha 20 Moscow 125315 Email market@viniti.msk.su http://www.viniti.msk.su	Monthly
<i>Water Resources/ Vodnye Resursy</i> [Russian and English] ISSN 0321-0596	Zhurnal "Vodnye Resursy", ul. Gubkina, 3, GSP-1 Moscow 119333 Email martin@wapr.msk.su	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Oceanology/</i> <i>Okeanologiya</i> [Russian and English] ISSN 0030-1574	Institut okeanologii Nakhimovsky pr., 36 Moscow, 117218 http://www.maik.rssi.ru/win/journals/ocean	Bimonthly
<i>Aeromechanics & Gasdynamics/</i> <i>Aeromekhanika i gazovaya dinamika</i> [Russian and English] ISSN 1681-5173 (English)	Scientific-Editorial Center of Mechanics Michurinsky prospect, 1, Moscow 119192 Email amgd@amgd.ru http://www.amgd.ru	Quarterly
Agricultural		
<i>Achievements of Agricultural</i> <i>Science and Engineering/</i> <i>Dostizhenia nauki i tekhniki APK</i> ISSN 0235-2451	Zhurnal "Dostizhenia nauki i tekhniki APK" Sadovaya-Spasskaya, 18, GSP-6, Moscow	Bimonthly
<i>Agrarian journal/</i> <i>Agrarny zhurnal</i>	Zhurnal "Agrarny zhurnal", of. 113, Orlikov per. 3, korpus 3 Moscow 107139	Monthly
<i>Agricultural Biology</i> <i>Selskokhoziaystvennaya biologia</i>	Zhurnal "Selskokhoziaystvennaya biologia" ul. Krzhizhanovskogo, 15, korp. 2, Moscow 117218	Bimonthly
<i>Agricultural Chemistry/</i> <i>Agrokimiya</i> ISSN 0002-1881	Zhurnal "Agrokimiya" Maronovsky per., 26 Moscow 119049	Monthly
<i>Agricultural Machinery and</i> <i>Equipment/Tekhnika v selskom</i> <i>khoziaystve</i>	Zhurnal "Tekhnika v selskom khoziaystve" ul. Krzhizhanovskogo, 15, korp. 2 Moscow 117218 http://press.aris.ru/JOURNAL/JOURNAL/tehn.html	Bimonthly
<i>Agricultural News/Selskokhoziaystvennye</i> <i>vesti</i>	Zhurnal "Selskokhoziaystvennye" P.O. Box 105, St.Petersburg 193312 Email abc@iac.spb.ru , agri_news@iac.spb.ru	Quarterly
<i>Agricultural Produce Storage and</i> <i>Processing/</i> <i>Khranenie i pererabotka</i> <i>selkhozsyrya</i>	http://www.foodprom.ru/rus/magaz.php?file=xips	Monthly
<i>Agricultural Science/</i> <i>Agrarnaya nauka</i>	Zhurnal "Agrarnaya nauka" Sadovaya-Spasskaya 18 GSP-6, Moscow	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Agriculture / Zemledelie</i>	Zhurnal "Zemledelie" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/zemlja.html	Bimonthly
<i>AIC (Agro-Industrial Complex) - Economy and management/ APK - ekonomika, upravlenie</i>	Zhurnal "APK - ekonomika, upravlenie" Sadovaya-Spasskaya, 18 GSP-6, Moscow,	Monthly
<i>Animal Science / Zootechnia</i>	Zhurnal "Zootechnia" Sadovaya-Spasskaya, 18 GSP-6, Moscow	Monthly
<i>Beekeeping/ Pchelovodstvo</i>	Zhurnal "Pchelovodstvo", Sadovaya-Spasskaya, 18 GSP-6 Moscow Email beekeeping@orc.ru http://www.beekeeping.orc.ru	10 times per year
<i>Cereal Crops (Zernovye kultury)</i>	Zhurnal "Zernovye kultury" Sadovaya-Spasskaya, 18 GSP-6 Moscow http://press.aris.ru/JOURNAL/JOURNAL/zerno.html	Bimonthly
<i>Economics of Agricultural and Produce-processing Enterprises / Ekonomika sel'skokhoziaystvennykh i pererabatyvayushchikh predpriyatiy</i>	Zhurnal "Ekonomika sel'skokhoziaystvennykh i pererabatyvayushchikh predpriyatiy" Sadovaya-Spasskaya, 18, GSP-6, Moscow Email eshipp@awax.ru http://www.reason.ru/economy/home.htm	Monthly
<i>Eurasian Soil Science/ Pochvovedenie</i> [Russian and English] ISSN 1064-2293 (English)	Zhurnal "Pochvovedenie" Pyzhevskii per., 7 Moscow, 109017	
<i>Feed Production / Kormoproizvodstvo</i>	Zhurnal "Kormoproizvodstvo" Sadovaya-Spasskaya, 18 GSP-6 Moscow http://press.aris.ru/JOURNAL/JOURNAL/korm.html	Monthly
<i>Flora Price/ Flora Prays</i>	Zhurnal "Flora Price" of. 227A ul. Marshala Govorova 52 St.Petersburg 198095 Email flora@floraprice.ru http://www.floraprice.ru	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Horticulture and Viticulture/ Sadovodstvo i vinogradarstvo</i>	Zhurnal "Sadovodstvo i vinogradarstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/sadov.html	Bimonthly
<i>International Agricultural Journal / Mezhdunarodny selskokhozyaystvenny zhurnal</i>	Zhurnal "Zemelnye otnoshenia i zemleustroystvo" ("Mezhdunarodny selskokhozyaystvenny zhurnal") Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/msj.html	Bimonthly
<i>Melioration and Water Management / Melioratsiya i vodnoye khozyaystvo ISSN 0235-2524</i>	Zhurnal "Melioratsiya i vodnoye khozyaystvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/melior.html	Bimonthly
<i>Mixed Feeds/ Kombikorma</i>	Zhurnal "Kombikorma" Sadovaya-Spasskaya, 18 GSP-6, Moscow	Monthly
<i>New Agriculture / Novoe selskoe khozyaystvo</i>	Zhurnal "DLV Agrodelo" Editorial office, of. 16 ul., Degununskaya ul., 10a Moscow 127486 Email info@nsh.ru http://nsh.ru	Bimonthly
<i>New Gardener and Farmer / Novy sadovod i fermer</i>	Email sad.farm@g23.relcom.ru http://www.sadfarm.ru	Bimonthly
<i>Pig Breeding / Svinovodstvo</i>	Zhurnal "Svinovodstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/svinovod.html	Bimonthly
<i>Potatoes and Vegetables / Kartofel i ovoshchi ISSN 0022-9148</i>	Zhurnal "Kartofel i ovoshchi", Sadovaya-Spasskaya, 18 GSP-6, Moscow http://www.kartofel.org	Eight times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Poultry farming / Ptitsevodstvo</i>	Zhurnal "Ptitsevodstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/ptic.html	Bimonthly
<i>Protection and Quarantine of Plants (Zashchita i karantin rasteniy)</i>	Zhurnal "Zashchita i karantin rasteniy" Sadovaya-Spasskaya, 18 GSP-6, Moscow Email fitopress@ropnet.ru http://press.aris.ru/JOURNAL/JOURNAL/karantin.html	Monthly
<i>Rabbit and Fur Farming / Krolikovodstvo i zverovodstvo</i> ISSN 0023-4885	Zhurnal "Krolikovodstvo i zverovodstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/zverovod.html	Bimonthly
Reports of Russian Academy of Agricultural Sciences / Doklady Rossiyskoy akademii sel'skokhoziaystvennykh nauk	Zhurnal "Doklady RASKhN" ul. Krzhizhanovskogo, 15, korp. 2 Moscow 117218	Bimonthly
<i>Selection and Seed Breeding / (Selektsia i semenovodstvo)</i>	Zhurnal "Selektsia i semenovodstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/semena.html	Quarterly
<i>Sheeps. Goats. Wool-producing / Ovtzy, kozy, sherstianoe delo</i>	Zhurnal Ovtzy, kozy, "sherstianoe delo" Pasechnaya ul., 4 Moscow 127550 http://www.fadr.msu.ru/rin/sheep/	Quarterly
Soil Fertility / Plodorodie	Zhurnal "Plodorodie" ul. Prianishnikova, 31a, Moscow 127550 Email cinao.oit@g23.relcom.ru	Bimonthly
<i>Sugar Beet / Sakharnaya svekla</i>	Zhurnal "Sakharnaya svekla", Sadovaya-Spasskaya, 18 GSP-6, Moscow Email info@sugarbeet.ru http://www.sugarbeet.ru	Monthly
Winemaking and Viticulture / Vinodelije i vinogradarstvo	Zhurnal "Vinodelije i vinogradarstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow Email grape_and_wine@mail.ru , beerprom@ropnet http://www.foodprom.ru	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General Scientific		
<i>Achievements in Modern Biology / Uspekhi sovremennoy biologii</i> ISSN 0042-1324	Zhurnal "Uspekhi sovremennoy biologii" Maronovsky per., 26 GSP-1, Moscow 119049 http://www.maik.rssi.ru/win/journals/uspbio	Bimonthly
<i>Achievements in Physiological Sciences / Uspekhi fiziologicheskikh nauk</i> ISSN 0301-1798	Zhurnal "Uspekhi fiziologicheskikh nauk" of. 106, Maronovsky per., 26, GSP-1, Moscow 119049 http://www.maik.rssi.ru/win/journals/uspfiz	Quarterly
<i>Applied Biochemistry and Microbiology / Prikladnaya biokhimiya i mikrobiologia</i> [Russian and English] ISSN 0555-1099	Zhurnal "Leninskiy" pr., 33 Moscow 119071 http://www.maik.ru/win/journals/prikbio	Bimonthly
<i>Biochemistry Moscow / Biokhimiya</i> [Russian and English] ISSN 0320-9725	Zhurnal "Biokhimiya", of. 133, 137 Maronovsky per., 26 Moscow Email biochem@maik.ru ; ozrina@bio.chem.msu.ru http://www.maik.ru/win/journals/biokhimmsc	Bimonthly
<i>Biophysics / Biofizika</i> [Russian and English] ISSN 0006-3029	Zhurnal "Biofizika", of. 235 Maronovsky per., 26 GSP-1, Moscow 119049	Bimonthly
<i>Botanical Journal / Botanicheskiy zhurnal</i>	"Botanicheskiy zhurnal", RBO ul. Professora Popova, 2 St.Petersburg 197022 http://rbo.nm.ru/bj.htm	Monthly
<i>Chemistry and Life - 21/ Khimia i zhizn</i>	Lefortovsky per., 8, Moscow, 105005 Russia Phone +7-095-2675418; Fax +7-095-2675418 Email redaktor@hij.ru http://www.hij.ru	Monthly
<i>Chemistry for Sustainable Development / Khimiya v interesah ustoichivogo razvitiya</i> [Russian and English]	Zhurnal "Khimiya v interesah ustoichivogo razvitiya" Morskoy pr., 2 Novosibirsk 630090 Email csd@ad-sbras.nsc.ru http://www-psb.ad-sbras.nsc.ru/csdw.htm (Russian), http://www-psb.ad-sbras.nsc.ru/English/CSDE.HTM (English)	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Chemistry of Plant Raw Materials / Khimiya rastitelnogo syrya</i> ISSN 1029-5151 (printed) ISSN 1029-5143 (on-line)	Redaktsia zhurnala "Khimiya rastitelnogo syrya" pr. Lenina, 61 Barnaul, 656015 Email journal@chemwood.dcn-asu.ru http://www.nioch.nsc.ru/mirrors/press/chemwood/	Quarterly
<i>Ecological Examination and Environmental Impacts Evaluation / Ekologicheskaya ekspertiza i otsenka vozdeystvia na okruzhayushchuyu sredu</i>	Email ngrishin@online.ru http://www.priroda.ru	
<i>Economics and Mathematical Methods / Ekonomika i matematicheskie metody</i> ISSN 0424-7388	Zhurnal "Ekonomika i matematicheskie metody", of. 305 Nakhimovsky pr., 47 Moscow, 177418 http://www.maik.rssi.ru/win/journals/matmet	Quarterly
<i>Russian Journal of Bioorganic Chemistry / Bioorganicheskaya khimiya</i> [Russian and English] ISSN 0132-3423	Zhurnal "Bioorganicheskaya khimiya", of. 509, ul. Miklukho-Maklaya, 16/10, korp. 32 GSP-7, Moscow 117997 Email rjbc@ibch.ru http://rjbc.siobc.ras.ru	Five times per year
<i>Entomological Review / Entomologicheskoye obozrenie</i> ISSN 0367-1445 (Russian) ISSN 0013-8738 (English)	Zhurnal "Entomologicheskoye obozrenie" Mendeleevskaya linia, 1 St. Petersburg 199034 http://www.zin.ru/journals/entrev/ (Russian), http://www.maik.rssi.ru/journals/enteng.htm (English)	Quarterly
<i>Fish-farming and Fishing / Rybovodstvo i rybolovstvo</i>	Zhurnal "Rybovodstvo i rybolovstvo" Sadovaya-Spasskaya, 18 GSP-6, Moscow Email romal@mx.iki.rssi.ru http://press.aris.ru/JOURNAL/JOURNAL/ribovod.html	Quarterly
<i>Geochemistry International/ Geokhimiya</i> ISSN 0016-7525 (Russian) ISSN 0016-7029 (English)	Zhurnal "Geokhimiya" ul. Kosygina, 19 Moscow 117586	Monthly
<i>Geomagnetism and Aeronomy / Geomagnetizm i Aeronomija</i> ISSN 0016-7940 (Russian) ISSN 0016-7932 (English)	Zhurnal "Geomagnetizm i Aeronomiya" Maronovskii per. 26 Moscow 119991 Email Oleg@or6074.spb.edu	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Hydraulic Engineering / Gidrotekhnicheskoye stroitelstvo</i>	Zhurnal "Gidrotekhnicheskoye stroitelstvo", of. 710 Podkolokolny per., 13/5 Moscow, 109028 Email pni@mail.magelan.ru http://www.energy-journals.ru/gts	Monthly
<i>Industrial Laboratory (Statistics, Experimental Design, etc) / Zavodskaya Laboratoria [Russian and English] ISSN 0019-8447 (English)</i>	IMET im. A.A.Baykova Leninsky prosp., 49 Moscow 119334 Email zavlabor@ultra.imet.ac.ru http://phase.imet.ac.ru/zavlabor/	
<i>Instruments and Experimental Techniques / Pribory i tekhnika eksperimenta ISSN 0032-8162 (Russian) ISSN 0020-4412 (English)</i>	Zhurnal "Pribory i tekhnika eksperimenta", of. 428, ul. Profsoyuznaya 90, B-485, Moscow, 117485 Email instr@maik.ru	Bimonthly
<i>Izvestiya, Physics of the Solid Earth / Fizika Zemli [Russian and English] ISSN 0002-3337</i>	Zhurnal "Fizika Zemli" ul. Bolshaya Gruzinskaya, 10, D-242 Moscow 123242 Email journal@uipe-ras.scgis.ru http://www.maik.ru/win/journals/fizzemli	Monthly
<i>Journal of Evolutionary Biochemistry and Physiology / Zhurnal evolyutsionnoi biokhimii i fiziologii ISSN 0022-0930</i>	"Zhurnal evolyutsionnoi biokhimii i fiziologii", pr. Morisa Toreza, 44 St. Petersburg 194223 Email Duke@iephb.ru http://www.evol.nw.ru/journr.htm	
<i>Physics-Uspekhi / Uspekhi Fizicheskikh Nauk ISSN 0042-1294 (Russian) ISSN 1063-7869 (English)</i>	Zhurnal "Uspekhi Fizicheskikh Nauk" Leninsky pr., 15, B-71 Moscow 119071 Email ufn@ufn.ru http://www.ufn.ru	Monthly
<i>Plant Resources/Rastitelnye resursy</i>	Zhurnal "Rastitelnye resursy" Mendeleevskaya linia, 1 St. Petersburg 199034	
<i>Population / Narodonaselenie ISSN 1561-7785</i>	Zhurnal "Narodonaselenie" Nakhimovskiy pr., 32 Moscow 117218 http://www.narodonaselenie.ru	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Problems of the Far East (Problemy Dalnego Vostoka) ISSN 0131-2812	Zhurnal "Problemy Dalnego Vostoka" Nakhimovsky pr., 32 Moscow 117218 Email pdv@ifes-ras.ru http://www.ifes-ras.ru/pdv/ (Russian), http://www.eastview.com (English)	Bimonthly
<i>Radiation Biology. Radioecology / Radiatsionnaya biologiya. Radioekologiya</i> ISSN 0869-8031	Zhurnal "Radiatsionnaya biologiya. Radioekologiya" Maronovsky per., 26 Moscow 119049 http://www.maik.rssi.ru/win/journals/radbio	
<i>Risk management / Upravlenie riskom</i>	Zhurnal "Upravlenie riskom" of. 23 Elizavetinsky per., 6, korp. 1 Moscow 105005 Email ankil@caravan.ru http://www.ankil.com	Quarterly
<i>Russian Journal of Cell Biology / Tsitologiya</i> ISSN 0041-3771	Zhurnal "Tsitologiya" Mendelevskaya linia, 1 St. Petersburg 199034 Email cytology@mail.cytspb.rssi.ru http://www.tsitologiya.cytspb.rssi.ru/index_ru.htm	Monthly
<i>Russian Journal of Marine Biology / Biologiya morya</i> ISSN 0134-3475 (Russian) ISSN 1063-0740 (English)	Institute of Marine Biology ul. Palchevskogo 17 Vladivostok 690041 Email biolm@mail.primorye.ru http://bm.dvo.ru	Bimonthly
<i>Russian Journal of Plant Physiology/ Fiziologiya rastenii</i> ISSN 0015-3303 (Russian) ISSN 1021-4437 (English)	Zhurnal "Fiziologiya rastenii" ul. Botanicheskaya, 35, Moscow, 127276 Email journal@ippras.ru http://www.rusplant.ru	Bimonthly
<i>Siberian Ecological Journal / Sibirsky ekologichesky zhurnal</i> ISSN 0869-8619	"Sibirsky ekologichesky zhurnal", of. 341 ul. Sovetskaya 18, Novosibirsk, 630099 Email phsb@ad-sbras.nsc.ru http://www-psb.ad-sbras.nsc.ru/secjw.htm	Bimonthly
<i>Vegetation of Russia/ Rastitelnost Rossii</i>	Zhurnal "Rastitelnost Rossii", RBO ul. Professora Popova, 2 St.Petersburg 197022 Email veget@vh5238.spb.edu http://rbo.nm.ru/veg.htm	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Veterinary Science / Veterinaria</i>	Zhurnal "Veterinaria" Sadovaya-Spasskaya, 18 GSP-6, Moscow http://press.aris.ru/JOURNAL/JOURNAL/veterin.html	
<i>Water and Ecology: Problems and Solutions / Voda i ekologiya: problemy i reshenia</i>	Zhurnal "Voda i ekologiya: problemy i reshenia" ul. Kronshtadtskaya, 8 St. Petersburg 198096 Email vodoproekt@mail.admiral.ru http://www.waterandecology.ru	Quarterly
Slovakia		
Meteorological		
<i>Meteorologický časopis / Meteorological Journal</i>	Editorial Board of the Meteorological Journal Slovak Hydrometeorological Institute P.O. Box 15 833 15 Bratislava 37 ISSN: 1335-399X	Quarterly
Slovenia		
Meteorological		
<i>Mesečni Biltin/Monthly Bulletin</i>	Agencija RS za okolje (Environmental Agency of Slovenia) Vojkova 1b 1000 Ljubljana gp.arso@gov.si	Monthly
<i>Mesečni Biltin/Monthly Bulletin</i>	Agencija RS za okolje (Environmental Agency of Slovenia) Vojkova 1b 1000 Ljubljana gp.arso@gov.si	Monthly
South Africa		
Meteorological/Climatological		
Climate of South Africa	South African Weather Service Private Bag X097 Pretoria 0001	Irregularly
Climate Summary of Southern Africa	http://www.weathersa.co.za	Monthly
Daily Weather Bulletin		Monthly
Technical Paper		Irregularly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
<i>African Journal of Range and Forage Science</i>	NISC P.O. Box 377, Grahamstown 6140 http://www.nisc.co.za/Journals/Range%20and%20forage%20JoRangeJ.htm	Triannually
<i>African Plant Protection</i>	Agricultural Research Council P.O. Box 8783 Pretoria 0001	Biannually
<i>Agrekon</i>	Private Bag X1311 Silverton 0127 http://www.aeasa.org.za	Quarterly
<i>AgriNews</i>	DOA: Dir. Agricultural Information Services Private Bag X144 Pretoria 0001	Monthly
<i>Agri Review / Agri Oorsig</i>	Standard Bank P.O. Box 6702 Johannesburg 2000	Quarterly
<i>Bulletin of the Grassland Society of Southern Africa</i>	P.O. Box 626 Dundee 3000	Quarterly
<i>Farmers Weekly</i>	P.O. Box 1797 Pinegowrie 2123,	Weekly
<i>FSSA Journal</i>	Fertilizer Society of SA P.O. Box 75510 Lynwoodrif 0400	Annually
<i>Landbouweekblad</i>	P.O. Box 1802, Cape Town 8000	Weekly
<i>Noordwesfokus / North West Focus</i>	Private Bag X804 Potchefstroom 2520	Biannually
<i>OTKaner</i>	P.O. Box 2779 Brooklyn Square 0075	Bimonthly
<i>SA Co-Op / SA Koöp</i>	Mediakom, P.O. Box 20250 Noordbrug 2522	Monthly
<i>SA Dry Beans / SA Droëbone</i>	P.O. Box 26269 Arcadia 0007	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Southern African Forestry Journal</i>	Southern African Institute of Forestry, Postnet Suit3 329 Private Bag X4 Menlo Park 0102	Quarterly
<i>SA Fruit Journal / SA Vrugte Joernaal</i>	P.O. Box 163 Paarl 7622	Bimonthly
<i>SA Graan/SA Grain</i>	Grain South-Africa P.O. Box 88 Bothaville 9660 http://www.graansa.co.za	Monthly
<i>South African Irrigation</i>	Shorten Publications 18 7th Avenue Highlands North 2192	Bimonthly
<i>South African Journal of Agricultural Extension / Suid-Afrikaanse Tydskrif vir Landbouvoortligting</i>	South African Society for Agricultural Extension (SASAE) Department of Agriculture, Economics, Extension and Rural Development University of Pretoria 0002	Annually
<i>South African Journal of Animal Science</i>	Department of Animal & Wildlife Sciences P.O. Box 13884 Hatfield 0028 http://sasas.co.za	Quarterly
<i>South African Journal of Plant and Soil / Suid-Afrikaanse Tydskrif vir Plant en Grond</i>	Forum Press International P.O. Box 72589 Lynnwood Ridge 0040	Quarterly
<i>SA Vegetables & Fruit / SA Groente & Vrugte</i>	P.O. Box 20250 Noordbrug 2522	Bimonthly
<i>Undercover Farming</i>	P.O. Box 759 Montana Park 0159	Bimonthly
<i>Wheat Focus / Koring fokus</i>	Mediakom P.O. Box 20250 Noordbrug 2522	Bimonthly
General scientific		
<i>Journal of Energy in Southern Africa</i>	Energy Research Institute University of Cape Town Rondebosch 7701 http://www.eri.uct.ac.za/eri.html	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Science in Africa</i>	P.O. Box 186 Grahamstown 6140 http://www.scienceinafrica.co.za	Monthly
<i>South African Geographical Journal</i>	Dept. of Environmental and Geographical Science University of Cape Town Rondebosch 7700 http://www.egs.uct.ac.za	Biannually
<i>South African Journal for Science and Technology / Suid-Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie</i>	South African Academy for Science and Arts P.O. Box 538 Pretoria 0001 http://www.akademie.co.za/	Quarterly
<i>South African Journal of Science</i> http://www.sajs.co.za/	National Research Foundation P.O. Box 2600 Pretoria, 0001 http://www.nrf.ac.za/	Monthly
<i>Water SA</i>	Water Research Commission Private Bag X03 Gezina 0031 http://www.wrc.org.za	Quarterly
<i>Water Wheel</i>	Water Research Commission Private Bag X03 Gezina 0031 http://www.wrc.org.za	Bimonthly

Spain

Agricultural

<i>Spanish Journal of Agricultural Research</i>	Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (Spanish National Institute for Agricultural and Food Research and Technology) (INIA). Autopista A-6, km 7.5 Madrid	Quarterly

Sudan

Meteorological

<i>Sudan Meteorological Authority (in Arabic)</i>	Meteorological Authority Khartoum	Biannually
<i>Agrometeorological Bulletin</i>		Irregularly
<i>Weather Bulletin</i>		Every 10 days
<i>Rainfall Performance</i>		Irregularly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Agricultural		
<i>Current Climate</i>		Monthly
<i>Journal of Agricultural Science</i>	Faculty of Agriculture University of Khartoum	Quarterly
<i>Sudan Silva</i>	Sudanese Society for Forestry University of Khartoum	Biannually
<i>Sudan Journal of Agricultural Research</i>	Agricultural Research Corporation Wad Medani	Annually
<i>Gezira Journal of Agricultural Science</i>	Deanship of Graduate Studies and Scientific Research University of Gezira Wad Medani	Annually
<i>Marawi Dam</i>	Ministry of Irrigation	Irregularly
<i>Agriculture</i>	Agricultural Bank Khartoum	Irregularly
<i>Forestry and Environment</i>	Forestry Public Society Ministry of Agriculture Khartoum	Annually
<i>Agricultural Technology</i>	Ministry of Agriculture Khartoum	Monthly
Scientific Research Summaries	National Center for Research Ministry of Science and Technology Khartoum	Biannually
Research	National Center for Research Ministry of Science and Technology Khartoum	Biannually
Sweden		
Meteorological		
<i>Tellus</i> - Series A: Dynamic Meteorology and Oceanography	National Meteorological Institute in Stockholm Arrhenius Laboratory S-10691 Stockholm tellusa@misu.su.se	Five times per year
<i>Tellus</i> - Series B: Chemical and physical Meteorology		Five times per year

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General scientific		
<i>AMBIO – A journal of the Human Environment</i>	Royal Swedish Academy of Sciences Box 50005 s-104 05 Stockholm www.ambio.kva.se	Eight times per year
Switzerland		
Agrometeorological		
<i>Rapports ART</i> (formerly <i>Rapports FAT</i>)	Institut de recherche Agroscope Reckenholz-Tänikon ART Tänikon 8356 Ettenhausen www.art.admin.ch	Irregularly (about 20 editions per year)
Meteorological		
<i>Annales de MétéoSuisse</i>	Office fédéral de météorologie et de climatologie MétéoSuisse Krähbühlstrasse 58 Postfach 514, 8044 Zurich www.meteosuisse.ch/web/fr/climat/bulletins_actuels Annales de meteosuisse.html	Annually
Agricultural		
<i>Revue suisse d'Agriculture</i>	Pour les 2 revues :	Bimonthly
<i>Revue suisse de Viticulture, Arboriculture Horticulture</i>	Station de recherche Agroscope Changins-Wädenswil ACW Case postale 1006 1260 Nyon www.acw.admin.ch/dokumentation/	Bimonthly
<i>Schweizerische Zeitschrift für Obst- und Weinbau (SZOW)</i>	Verein Publikationen Spezialkulturen c/o Station de recherche Agroscope Changins-Wädenswil ACW Schloss Postfach 185 8820 Wädenswil www.szow.ch	Biweekly
<i>Publications</i>	Office fédéral de l'agriculture OFAG 3003 Berne www.blw.admin.ch/dokumentation/	Irregularly
<i>AGRAR Forschung</i>	Agrarforschung Agroscope Liebefeld-Posieux ALP 1725 Posieux www.agrarforschung.ch	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>“die grüne”</i>	Schweizer Agrarmedien GmbH Thunstrasse 78 Postfach 228 3000 Berne 15 http://www.bauernzeitung.ch/die-gruene/aktuelle-ausgabe/	Biweekly
General scientific		
Publications de MétéoSuisse	Office fédéral de météorologie et de climatologie MétéoSuisse Krähbühlstrasse 58 Postfach 514 8044 Zurich www.meteoswiss.ch/web/en/research/publications.html www.meteosuisse.ch/web/fr/recherche/publications.html	Irregularly
Rapports de travail de MétéoSuisse	Office fédéral de météorologie et de climatologie MétéoSuisse Krähbühlstrasse 58 Postfach 514 8044 Zurich www.meteoswiss.ch/web/en/research/publications.html www.meteosuisse.ch/web/fr/recherche/publications.html	Irregularly
The former Yugoslav Republic of Macedonia		
Agrometeorological		
<i>AGROMET Agrometeorological Bulletin</i>	Hydrometeorological Service Skupi bb 1000 Skopje	Monthly
General scientific		
<i>Macedonian Journal of Meteorology, Hydrology and Environment</i>	Hydrometeorological service of Republic of Macedonia in collaboration with the American Meteorological Society Skupi bb 1000 Skopje http://www.meteo.gov.mk	Biannually

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Almanach</i> (1999/2000/2001) (in French and English)	National Institute of Meteorology (NIM) http://www.meteo.tn/htmlen/publication/almanach.html	
<i>Climate Atlas</i> (only in Arabic)	http://www.meteo.tn/htmlen/publication/atlas.html	
Seismic-Tectonic Map (in French)	http://www.meteo.tn/htmlen/publication/seismes.html	
Agro-Climatic Data of the Cap Bon Area (in French and English)	http://www.meteo.tn/htmlen/publication/agroclimatique.html	
Frequency Analysis of Rain Episodes, in French and English	http://www.meteo.tn/htmlen/publication/frequence.html	
Rain Intensity (in French)	http://www.meteo.tn/htmlen/publication/intensites.html	
Uganda		
Meteorological/Climatological/Hydrological		
<i>Agrometeorological Bulletin</i>	Uganda Department of Meteorology P.O. Box 7025 Kampala http://www.meteo-uganda.net	Monthly
The Water Update Bulletin	Directorate of Water Development P.O. Box 20026 Kampala	Quarterly
Wet News letter	Wetlands Inspection Division Ministry of Water, Lands and Environment P.O. Box 9629 Kampala	Biannually
Agricultural		
African Crop Science Journal	African Crop Science Society Department of Crop Science Makerere University P. O. Box 7062, Kampala Email: acss@agric.mak.ac.ug acsj@agric.mak.ac.ug website: www.acsj.info/ ISSN: 1021-9730	Quarterly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Improving Rural Lives</i>	Plan for Modernisation of Agriculture Secretariat P.O. Box 5675 Kampala http://www.pma.go.ug	Quarterly
General scientific		
<i>The Forester Newsletter</i>	National Forestry Authority P.O. Box 70863 Kampala http://www.nfa.org.ug	Quarterly
<i>The Water Herald</i>	National Water and Sewerage Corporation P.O. Box 5073 Kampala	Irregularly
United Kingdom of Great Britain and Northern Ireland		
Meteorological/Climatological		
<i>Weather</i>	Royal Met Society, 104 Oxford Road, Reading	Monthly
<i>Quarterly Journal of the Royal Met Society</i>		Quarterly
<i>Meteorological Applications</i>	Cambridge University Press	Monthly
<i>Atmospheric Environment</i>	Elsevier	Monthly
<i>Global Change Biology</i>	Blackwell Synergy	Monthly
Agricultural		
<i>Biosystems Engineering</i>	Elsevier	Monthly
<i>Agricultural and Forest Meteorology</i>	Elsevier	Monthly
<i>International Journal of Biometeorology</i>	Springer	Monthly
<i>European Journal of Agronomy</i>	http://www.sciencedirect.com	Monthly
<i>Agriculture, Ecosystems & Environment</i>	http://www.sciencedirect.com	Monthly
<i>Annals of Applied Biology</i>	Blackwell Synergy	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>Journal of Agricultural Science</i>	Cambridge University Press	Bimonthly
<i>European Journal of Soil Science</i>	Blackwell Synergy	Quarterly
<i>Veterinary Record</i>	British Veterinary Association	Weekly
<i>Journal of Hydrology</i>	Elsevier	64 issues per year
<i>EPPO Bulletin</i>	Blackwell Synergy	Three times per year
<i>Hydrology and Earth System Sciences</i>	http://www.copernicus.org/EGU/hess/hess.html	Monthly
General scientific		
New Scientist	Reed Business Information	Weekly
United Republic of Tanzania		
Agrometeorological/Meteorological		
<i>Dekadal Weather Review</i>	Tanzania Meteorological Agency 3rd, 4th & 10 th Floors	Every 10 days
<i>Monthly Weather Bulletin</i>	Ubungo Plaza – Morogoro Road P.O. Box 3056 Dar es Salaam Email: met@meteo.go.tz http://www.meteo.go.tz/mwb/index.php	Monthly
United States of America		
Agrometeorological		
<i>Weekly Weather and Crop Bulletin</i>	NOAA/USDA, Joint Agricultural Weather Facility USDA South Building, Room 4443B Washington, DC 20250 http://www.usda.gov/oce/weather/pubs/Weekly/Wwcb/index.htm	Weekly
<i>U.S. Drought Monitor</i>	http://www.drought.unl.edu/dm/monitor.html	Weekly
<i>North American Drought Monitor</i>	http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Meteorological		
<i>Bulletin of the American Meteorological Society</i>	American Meteorological Society 45 Beacon Street Boston, Massachusetts 02108	Monthly
<i>Journal of Applied Meteorology and Climatology</i>		Monthly
<i>Monthly Weather Review</i>		Monthly
<i>Journal of Hydrometeorology</i>		Monthly
<i>Journal of Climate</i>		Semimonthly
<i>Journal of Atmospheric Sciences</i>		Monthly
<i>Weather and Forecasting</i>		Bimonthly
<i>Journal of Atmospheric and Oceanic Technology</i>		Monthly
<i>Earth Interactions</i>	Published jointly online by the American Geophysical Union, American Meteorological Society, Association of American Geographers http://earthinteractions.org/	
<i>Climatic Change</i>	Department of Biological Sciences Stanford University 371 Serra Mall Stanford, California 94305-5020 (Printed in the Netherlands)	16 times per year
<i>Climate Diagnostics Bulletin</i>	United States Department of Commerce National Oceanic and Atmospheric Administration	Monthly
<i>Earth System Monitor</i>	National Weather Service Room 605 5200 Auth Road Camp Springs, Maryland 20746-4303	Quarterly
<i>EOS Transactions</i>	American Geophysical Union 2000 Florida Avenue, NW Washington, DC 20009	Quarterly
<i>Global Biological Cycles</i>		Quarterly
<i>International Journal of Biometeorology</i>	The International Society of Biometeorology Dept of Geography, University of Oklahoma, 3200 Marshall Avenue, Suite 110 Norman, Oklahoma 73073	Biannually
<i>Weatherwise</i>	Heldref Publications 1319 18th Street NW Washington DC 20036-1802	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
<i>National Weather Digest</i>	NWA Publications, 228 West Millbrook Road Raleigh, North Carolina 27609-4304	Monthly
Agricultural		
<i>Agronomy Journal</i>	American Society of Agronomy 677 S. Segoe Road Madison, Wisconsin 53711	Bimonthly
<i>Crop Science</i>		Bimonthly
<i>Soil Science Society of America Proceedings</i>		Bimonthly
<i>Transactions of the American Society of Agricultural Engineers (ASAE)</i>	American Society of Agricultural Engineers (ASAE) 2950 Niles Road St. Joseph, Michigan 49085	Monthly
<i>Soil Science</i>	Williams and Wilkins Co. 428 E. Preston Street Baltimore, Maryland 21202	Monthly
<i>Plant Physiology</i>	American Society of Plant Physiologists 9650 Rockville Pike Bethesda, Maryland 20014	Monthly
<i>Journal of the Irrigation and Drainage Division</i>	American Society of Civil Engineers 3445 E. 47th Street New York, New York 10017	Monthly
<i>Proceedings of the American Society of Civil Engineers</i>		Monthly
<i>Journal of Forestry</i>	Society of American Foresters 1016 16th Street NW Washington, DC 20036	Monthly
<i>Journal of Animal Science</i>	American Society of American Scientists 113 Neil Street Champaign, Illinois 61820	Monthly
<i>Phytopathology</i>	American Society of American Scientists 3340 Pilot Knob Road St. Paul, Minnesota 55121	Monthly
<i>Plant Disease Report</i>	United States Department of Agriculture Agricultural Research Service Beltsville Agricultural Research Center Beltsville, Maryland 20705	Monthly
<i>Water Resources Research</i>	American Geophysical Union 2000 Florida Avenue NW Washington, DC 20009	Bimonthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
General scientific		
<i>Journal of Geophysical Research</i>	American Geophysical Union 2000 Florida Avenue NW Washington, DC 20009	Three times per month
<i>Review of Geophysics</i>		Quarterly
<i>American Scientist</i>	Society of the Sigma Xi Scientific Research Society of America 115 Whitney Avenue New Haven, Connecticut 06510	Bimonthly
<i>Ecology</i>	Duke University Press College Station, P.O. Box 6697 Durham, North Carolina 27708	Bimonthly
<i>American Journal of Botany</i>	Botanical Society of America 1735 Neil Avenue Columbus, Ohio 43210	Monthly
<i>Science</i>	American Association for the Advancement of Science 1515 Massachusetts Avenue NW Washington, DC 20005	Weekly
<i>Scientific American</i>	Scientific American Inc. 415 Madison Avenue New York, New York 10017	Monthly
<i>Environmental Research</i>	Academic Press 111 Fifth Avenue New York, New York 10003	Bimonthly
<i>Bioscience</i>	American Institute of Biological Sciences 1401 Wilson Blvd. Arlington, Virginia 22209	Monthly
<i>National Geographic</i>	1145 17th Street NW Washington DC 20036-4688	Monthly
<i>Natural Hazards Observer</i>	University of Colorado Boulder 482 UCB Boulder, Colorado 80309-0482	Bimonthly
<i>Proceedings of the National Academy of Sciences of the United States</i>	National Academy of Sciences 500 5th Street NW Washington, DC 20001	Weekly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Uruguay		
All relevant information on agrometeorology and agroclimatology: Novedades Clima Monitoreo de la situación agroclimática Cambio Climático Sistemas de información y teledetección Interfase anterior para antiguos usuarios Proyectos Publicaciones Testimonios Unidad de Agroclima y Sistemas de información	Grupo Agroclima y Sistemas de información Instituto Nacional de Investigación Agropecuaria http://www.inia.org.uy/gras	
Viet Nam		
Agrometeorological		
<i>Agrometeorological Bulletin</i>	Centre for Agricultural Meteorology Institute of Meteorology and Hydrology Ministry of Natural Resources and Environment Magazine 5/62 Nguyen Chi Thanh Street Lang Trung, Dong Da Hanoi	Monthly
Agricultural		
Journal of Agriculture and Rural Development	Ministry of Agriculture and Rural Development 2 Ngoc Ha Street Hanoi	Monthly
Agricultural Extension of Vietnam	Department of Agricultural Extension Ministry of Agriculture and Rural Development 2 Ngoc Ha Street Hanoi	Monthly
Hydro-Meteorological Journal	Hydro-Meteorological Service of Vietnam Ministry of Natural Resources and Environment 4 Dang Thai Than Street Hanoi	Monthly

<i>Title</i>	<i>Editorial or business office</i>	<i>Frequency of publication</i>
Ministry of Natural Resources and Environment Magazine	Ministry of Natural Resources and Environment 79 Nguyen Chi Thanh Street Dong Da Hanoi	Monthly
The Scientific Activity Review	Ministry of Science and Technology 39 Tran Hung Dao Street Hanoi	Monthly
Zimbabwe		
Agrometeorological		
UZ – AGMET Newsletter	Agricultural Meteorology Group Physics Department, University of Zimbabwe Mt Pleasant, PO Box MP 167 Harare	Biannually
Agricultural		
New Farmer	Zimbabwe Newspapers Limited	Monthly
General scientific		
<i>Journal of Applied Science in Southern Africa (JASSA)</i>	http://www.uz.ac.zw/publications	Biannually
<i>Transactions of the Zimbabwe Scientific Association</i>	Zimbabwe Scientific Association http://www.ajol.info/journal_index.php?jid=100	Annually

APPENDIX III

LIST OF INTERNATIONAL ORGANIZATIONS OF INTEREST TO AGRICULTURAL METEOROLOGISTS

Notes: The following abbreviations are used to indicate the status of the organizations listed:

UN for United Nations and/or associated agencies and institutions.

IGO for intergovernmental organizations.

NGO for non-governmental organizations.

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
African Cotton Association	ACA	IGO	P.O. Box 06 BP 2944 PK3 Cotonou Benin http://www.africancotton.org/
African Groundnut Council		IGO	10, Alhaji Ribadu Road, SW Ikoyi P.O. Box 3025 Lagos Nigeria
African Rice Center (AfricaRice) (formerly West Africa Rice Development Association)	formerly WARDA	NGO	01 B.P. 2031 Cotonou Benin http://www.warda.cgiar.org/
AGRHMET Regional Center	ARC	NGO	P.O. Box 11011 Niamey Niger www.agrhymet.ne
Asian-Pacific Weed Science Society	APWSS	NGO	Department of Agronomy Faculty of Agriculture NWFP Agriculture University Peshawar Pakistan
Association for Science and Information on Coffee	ASIC	NGO	24, ch. de la violette CH-1030 Bussigny Switzerland http://www.asic-cafe.org/index.php

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
Bioversity International		NGO	Via dei Tre Denari 472/a 00057 Maccarese (Fiumicino) Rome Italy http://www.bioversityinternational.org/
Caribbean Food and Nutrition Institute	CFNI	IGO	Jamaica Centre University of the West Indies Mona, P.O. Box 140 Kingston 7 Jamaica http://new.paho.org/cfni/
Centre for Agricultural Bioscience International	CABI	IGO	Nosworthy Way Wallingford Oxfordshire OX10 8DE UK http://www.cabi.org/
Center for International Forestry Research	CIFOR	NGO	P.O. Box 0113 BOCBD Bogor 16000 Indonesia http://www.cifor.cgiar.org/
Cocoa Producers' Alliance	COPAL	IGO	National Assembly Complex Tafawa Balewa Square 8-10 Broad Street P.O. Box 1718 Lagos Nigeria http://www.copal-cpa.org/
Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel (Permanent Inter States Committee for Drought Control in the Sahel)	CILSS	IGO	03 BP 7049 Ouagadougou 03 Burkina Faso http://www.cilss.bf/
Commonwealth Forestry Association	CFA	NGO	The Crib Dinchope Craven Arms Shropshire SY7 9JJ United Kingdom http://www.cfa-international.org

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Commission Z for the Nomenclature of Cultivated Plants	ICNCP	NGO	Drs Wilbert L. A. Hetterscheid Department of Plant Sciences Generaal Foulkesweg 37 6703 BL Wageningen The Netherlands http://www.ishs.org/sci/icraiubs.htm
Convention on Biological Diversity	CBD	UN	Secretariat of the Convention on Biological Diversity 413, Saint Jacques Street, suite 800 Montreal QC H2Y 1N9 Canada www.cbd.int
Cooperation Centre for Scientific Research Relative to Tobacco	CORESTA	NGO	11 rue du Quatre Septembre 75002 Paris France http://www.coresta.org/
Council of the International of Congresses of Entomology	CICE	NGO	Entomology Section of the International Union of Biological Sciences http://www.iubs.org/
Desert Locust Control Organization for Eastern Africa	DLCO -EA	IGO	P.O. Box 4255 Addis Ababa Ethiopia. Regional Office: P.O. Box 30023 (00100) Nairobi Kenya. http://www.dlcoea.org.et/
East African Agriculture and Forestry Research Organization	EAAFRO	IGO	c/o East African Community P.O. Box 1001 Arusha 3181 Tanzania
Economic Commission for Africa	ECA	UN	P.O. Box 3001 Addis Ababa Ethiopia http://www.uneca.org/
Economic Commission for Europe	ECE	UN	Palais des Nations CH-1211 Geneva 10 Switzerland http://www.unece.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
Economic Commission for Latin America and the Caribbean	ECLAC / CEPAL	UN	Av. Dag Hammarskjöld 3477 Vitacura, Santiago de Chile http://www.eclac.org/
Economic and Social Commission for Asia and the Pacific	ESCAP	UN	The United Nations Building Rajadamnern Nok Avenue Bangkok 10200 Thailand http://www.unescap.org/
Economic and Social Commission for Western Asia	ESCWA	UN	P.O. Box 11-8575, Riad el-Solh Square Beirut Lebanon http://www.escwa.un.org/
European and Mediterranean Plant Protection Organization	EPPO	IGO	21 Boulevard Richard Lenoir 75011 Paris France http://www.eppo.org/
European Association for Animal Production	EAAP	NGO	Via G. Tomassetti 3, A/1 Rome Italy http://www.eaap.org
European Association for Potato Research	EAPR	NGO	P.O. Box 500, 3001 Leuven 1 Belgium http://www.eapr.net/
European Association for Research on Plant Breeding	EUCAR-PIA	NGO	Agricultural Research Institute of the Hungarian Academy of Sciences 2462 Martonvásár, Brunszzvik u. 2. Hungary http://www.eucarpia.org/
European Commission for the Control of Foot and Mouth Disease	EuFMD	IGO	Secretariat: c/o FAO, Via delle Terme di Caracalla 00100 Rome Italy http://www.fao.org/ag/againfo/commissions/en/eufmd/eufmd.html

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
European Grassland Federation	EGF	NGO	Secretariat Agroscope Reckenholz-Tänikon Research Station ART Reckenholzstrasse 191 CH- 8046 Zürich Switzerland http://www.europeangrassland.org/
European Weed Research Society	EWRS	NGO	EWRS Membership Office c/o drs Ben Post Postbus 28 NL-6865 ZG Doorwerth The Netherlands E-mail: membership@ewrs.org http://www.ewrs.org/
Food and Agriculture Organization of the United Nations	FAO	UN	Via delle Terme di Caracalla 00100 Rome Italy http://www.fao.org/
InterAfrican Coffee Organization	IACO/ OIAAC	IGO	Secretary General: BPV 210 Abidjan Côte d'Ivoire http://www.iaco-oiac.org/index.php
Inter-American Committee for Agricultural Development	CIDA		1725 Street NW, Room 414 Washington, DC 20006 USA
Intergovernmental Authority on Development in Eastern Africa	IGAD	IGO	IGAD Secretariat Avenue Georges Clemenceau P.O. Box 2653 Djibouti Republic of Djibouti http://igad.int/
International Association of Agricultural Economists	IAAE	NGO	555 East Wells Street, Suite 1100 Milwaukee, WI 53202 USA http://www.iaae-agecon.org/
International Association for Cereal Science and Technology	ICC	NGO	Marxergasse 2 1030 Vienna Austria http://www.icc.or.at/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Association for Plant Physiology	IAPP	NGO	Secretary / Treasurer Nagoya University Extension Yurigaoka D-103 Ida-cho, Owari-Asahi Aichi 488-0024 Japan
International Association for the Plant Protection Sciences	IAPPS	NGO	E. A. Heinrichs Dept. of Entomology University of Nebraska Lincoln, NE 68583-0816 USA www.plantprotection.org
International Association for Vegetation Science	IAVS	NGO	Wes Beekhuizenweg 3 NL-6871 VJ Renkum The Netherlands http://www.iavs.org/
International Association of Hydrological Sciences	IAHS	NGO	Secretary General : Dr Pierre Hubert IAHS/AISH SG, UMR Sisyphe, Université Pierre & Marie Curie Case 105, 4 Place Jussieu, 75252 Paris Cedex 05 France http://www.iahs.info/
International Association of Meteorology and Atmospheric Sciences	IAMAS	NGO	General Secretariat Deutsches Zentrum fuer Luft und Raumfahrt e.V. (DLR) Institut fuer Physik der Atmosphaere (IPA) Muenchner Strasse 20 D-82234 Oberpfaffenhofen Germany http://www.iamas.org
International Bee Research Association	IBRA	NGO	16 North Road Cardiff CF10 3DY United Kingdom http://www.ibra.org.uk/
International Biometric Society	IBS	NGO	1444 I Street NW, Suite 700 Washington, DC 20005 USA Email: ibs@tibs.org http://www.tibs.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Center for Agricultural Research in the Dry Areas	ICARDA	NGO	P.O. Box 5466 Aleppo Syrian Arab Republic http://www.icarda.cgiar.org
International Center of Tropical Agriculture	CIAT	NGO	Km 17, Recta Cali-Palmira Apartado Aéreo 6713 Cali Colombia http://www.ciat.cgiar.org
International Coffee Organization	ICO	IGO	22 Berners Street London W1T 3DD England http://www.ico.org
International Commission for Agricultural and Food Industries	ICAI-CIIA	IGO	42 rue Scheffer 75116 Paris France http://www.cii-a-c.com/ENG_index.html
International Commission of Agricultural and Biosystems Engineering	CIGR	NGO	Research Group of Bioproduction Engineering, Research Faculty of Agriculture, Hokkaido University, N-9, W-9, Kita-ku, Sapporo, Hokkaido, 060-8589, Japan http://www.cigr.org/
International Commission on Irrigation and Drainage	ICID	NGO	48 Nyaya Marg Chanakyapuri New Delhi 110021 India http://www.icid.org/
International Committee of Plastics in Agriculture	CIPA	NGO	Coslada, 18 28028 Madrid Spain http://www.plasticulture.com/
International Confederation of European Beet Growers	CIBE	NGO	Boulevard Anspach 111 B-1000 Brussels Belgium http://www.cibe-europe.eu/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Council of Scientific Unions	ICSU	NGO	5 rue Auguste Vacquerie 75116 Paris France http://www.icsu.org/
International Crops Research Institute for the Semi-Arid Tropics	ICRISAT	NGO	Patancheru 502324 Andhra Pradesh India http://www.icrisat.org
International Dairy Federation	IDF / FIL	NGO	70/B, Boulevard Auguste Reyers 1030 Brussels Belgium www.fil-idf.org
International Federation of Beekeepers' Associations	APIMONDIA	NGO	101, Corso Vittorio Emanuele 00186 Rome Italy http://www.apimondia.com
International Food Policy Research Institute	IFPRI	NGO	2033 K Street NW Washington, DC 20006-1002 USA http://www.ifpri.org
International Fund for Agricultural Development	IFAD	UN	Via Paolo di Dono, 44 00142 Rome Italy www.ifad.org
International Geographical Union	IGU	NGO	Secretary-General and Treasurer: Michael Meadows Department of Environmental & Geographical Science, South Lane University of Cape Town Rondebosch, 7701 Cape Town South Africa http://www.igu-online.org
International Grains Council	IGC	IGO	1 Canada Square Canary Wharf London E14 5AE United Kingdom

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Hop Growers Convention	IHGC	NGO	Malgajeva 18 SI-3000 Celje Slovenia http://www.hmelj-giz.si/ihgc/
International Institute for Sugar Beet Research	IIRB	NGO	40, Rue Washington B-1050 Brussels Belgium http://www.iirb.org/
International Livestock Research Institute	ILRI	NGO	P.O. Box 30709 Nairobi 00100 Kenya http://www.ilri.org/
International Institute of Tropical Agriculture	IITA	NGO	IITA PMB 5320, Ibadan Oyo State Nigeria http://www.iita.org
International Maize and Wheat Improvement Center (Centro Internacional de Mejoramiento de Maíz y Trigo.)	CIMMYT	NGO	Apdo. Postal 6-641 06600 Mexico, D.F. Mexico http://www.cimmyt.org
International Olive Council	IOC	NGO	Executive Secretariat C/ Príncipe de Vergara, 154 – 28002 Madrid Spain http://www.internationaloliveoil.org/
International Organization for Biological Control of Noxious Animals and Plants	IOBC	NGO	General Secretary Laboratory of Entomology Wageningen University P.O.Box 8031 6700 EH Wageningen THE NETHERLANDS http://www.iobc-global.org
International Organization for Succulent Plant Study	IOS	NGO	Dr David Hunt The Manse, Chapel Lane Milborne Port, Sherborne, DT9 5DL United Kingdom http://www.iosweb.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Organization of Citrus Virologists	IOCV	NGO	Secretary-Treasurer Department of Plant Pathology University of California Riverside, CA 92521 USA http://www.ivia.es/iocv/
International Organisation of Vine and Wine	OIV	IGO	Director 18 Rue D'aguesseau 75008 Paris France http://www.oiv.int/
International Poplar Commission	IPC	IGO	Secretariat Forest Management Team Forestry Department, FAO Viale delle Terme di Caracalla 00153 Rome Italy http://www.fao.org/forestry/ipc/en/
International Potato Center (Centro Internacional de la Papa)	CIP	NGO	Avenida La Molina 1895 La Molina Apartado Postal 1558 Lima Peru http://www.cipotato.org/
International Red Locust Control Organisation for Central and Southern Africa	IRLCO CSA	IGO	P.O. Box 240252 Ndola Zambia http://sadbiz.com/countries/zambia/categories/science/adverts/red_locust/index.htm
International Rice Commission	IRC	IGO	AGPC/FAO, Viale delle Terme di Caracalla, 00100 Rome Italy http://www.fao.org/ag/agp/agpc/doc/field/commrice/index_en.htm
International Rice Research Institute	IRRI	NGO	DAPO Box 7777 Metro Manila 1301 Philippines http://irri.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
Regional International Organization for Health in Agricultural	OIRSA	IGO	Calle Ramón Bellosó, Final Passage Isolde Colonia Escalón San Salvador El Salvador http://www.oirsa.org
International Seed Testing Association	ISTA	NGO	Zürichstrasse 50 CH-8303 Bassersdorf Switzerland http://www.seedtest.org
International Sericultural Commission	ISC	NGO	26 rue Bellecordière 69002 Lyon France http://www.inserco.org/
International Society for Horticultural Science	ISHS	NGO	ISHS Secretariat PO Box 500 3001 Leuven 1 Belgium http://www.ishs.org/
International Society for Plant Pathology	ISPP	NGO	Secretary-General Dr Greg I Johnson PO Box 412, Jamison ACT 2612 Australia http://www.isppweb.org/
International Society for Tropical Ecology	ISTE	NGO	Secretary: Department of Botany Banaras Hindu University Varanasi 221 005 India http://www.tropecol.com/
International Society of Biometeorology	ISB	NGO	Secretary: Department of Geography, Bolton 410 P.O. Box 413 University of Wisconsin-Milwaukee Milwaukee, WI 53201-0413 http://biometeorology.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Society of Sugar Cane Technologists	ISSCT	NGO	97 Georgetown Bldg St Jean Road Quatre-Bornes Mauritius http://issct.intnet.mu/
International Union of Soil Sciences	IUSS	NGO	Secretary General ISRIC - World Soil Information PO Box 353 6700 AJ Wageningen The Netherlands http://www.iuss.org/
International Sugar Organization	ISO	NGO	1 Canada Square Canary Wharf London E14 5AA United Kingdom http://www.isosugar.org/
International Tea Committee	ITC	NGO	Secretary 1 Carlton House Terrace London, SW1Y 5DB United Kingdom http://www.inttea.com/
International Union for Conservation of Nature and Natural Resources	IUCN	NGO	Rue Mauverney 28 CH-1196 Gland Switzerland http://www.iucn.org/
International Union of Biological Sciences	IUBS	NGO	Université Paris Sud XI Bâtiment 442 91405 Orsay Cedex France http://www.iubs.org/
International Union of Forestry Research Organizations	IUFRO	NGO	Mariabrunn (BFW) Hauptstrasse 7 A-1140 Vienna Austria http://www.iufro.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
International Union of Geodesy and Geophysics	IUGG	NGO	Karlsruhe Institute of Technology Geophysical Institute Hertzstr. 16 Geb. 06.36, 76187 Karlsruhe Germany http://www.iugg.org/
International Water Association	IWA	NGO	Alliance House 12 Caxton Street London SW1H 0QS United Kingdom http://www.iwahq.org/Home/
International Water Management Institute	IWMI	NGO	P. O. Box 2075 Colombo Sri Lanka http://www.iwmi.cgiar.org/
International Weed Science Society	IWSS	NGO	IWSS Secretary Dept. of Crop, Soil, and Environmental Sciences University of Arkansas 1366 W. Altheimer Drive, Fayetteville, AR 72704 USA http://www.iwss.info/
Liaison Committee for Mediterranean Citrus Fruit Culture	CLAM	NGO	Calle Princesa No.1 Torre de Madrid Planta II No.4 Madrid 13 Spain
Nordic Association of Agricultural Scientists	NJF	NGO	General Secretariat c/o Royal Swedish Academy of Agriculture and Forestry Drottninggatan 95B P.O. Box 6806 SE-113 86 Stockholm Sweden http://www.njf.nu
Nordic Research Board	NORDFORSK	NGO	Northern Research Stensberggata 25 0170 Oslo Norway http://www.nordforsk.org

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
Organization for Economic Co-operation and Development	OECD	IGO	Secretary General: 2, rue André Pascal 75775 Paris Cedex 16 France http://www.oecd.org
Scandinavian Plant Physiology Society	SPPS	NGO	SPPS Office c/o Dept. of Biosciences Plant Biology P.O.Box 65 Viikinkaari 1 FI-00014 University of Helsinki Finland http://www.spps.fi/cgi-bin/SPPS.pl
Secretariat of the Pacific Community	SPC	IGO	B.P. D5 Noumea Cedex 98848 New Caledonia
Southern Africa Development Community	SADC	IGO	SADC Headquarters Plot No. 54385 Central Business District Private Bag 0095 Gaborone Botswana http://www.sadc.int/
United Nations Convention to Combat Desertification	UNCCD	UN	UNCCD Secretariat P.O. Box 260129 D-53153 Bonn Germany www.unccd.int
United Nations Development Programme	UNDP	UN	Administrator One United Nations Plaza New York, NY 10017 USA http://www.undp.org/
United Nations Environment Programme	UNEP	UN	Executive Director P.O. Box 30552 Nairobi Kenya http://www.unep.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
United Nations Educational, Scientific and Cultural Organization	UNESCO	UN	Director General Place de Fontenoy 75700 Paris France http://www.unesco.org
United Nations Framework Convention on Climate Change	UNFCCC	UN	UNFCCC secretariat P.O. Box 260124 D-53153 Bonn Germany Web: http://unfccc.int
United Nations Geographical Information Working Group	UNGIWG	UN	http://www.ungiwg.org/
United Nations International Strategy for Disaster Reduction	UN-ISDR	UN	9-11 Rue de Varembe CH-1202 Geneva Switzerland http://www.unisdr.org/
World Agroforestry Centre (formerly International Center for Research in Agroforestry)	(IGRAF prior to 2002)	NGO	United Nations Avenue, Gigiri PO Box 30677 Nairobi 00100 Kenya http://www.worldagroforestrycentre.org/
World Association for Animal Protection	WAAP	NGO	EAAP Secretariat Via G. Tomassetti 3 - 1/A 00161 Rome Italy http://www.waap.it/
World Association for Buiatrics	WAB	NGO	Secretary General Szent István University Faculty of Veterinary Sciences P.O. Box 2 H-1400 Budapest Hungary http://www.buiatrics.com/
World Association for the Advancement of Veterinary Parasitology	WAAVP	NGO	Secretary/Treasurer Massey University Palmerston North New Zealand http://www.waavp.org/

<i>Title</i>	<i>Initials</i>	<i>Status</i>	<i>Address</i>
WorldFish Center		NGO	P.O. Box 500, GPO 10670, Penang Malaysia http://www.worldfishcenter.org
World Food Programme	WFP	UN	Via C.G.Viola 68 Parco dei Medici 00148 Rome Italy http://www.wfp.org/
World Organisation for Animal Health (formerly International Office of Epizootics)	OIE	IGO	12, rue de Prony 75017 Paris France www.oie.int
World Poultry Science Association	WPSA	NGO	PO Box 31 NL-7360 AA Beekbergen The Netherlands http://www.wpsa.com/
World Veterinary Association	WVA	NGO	Rue Defacqz 1 1000 Brussels Belgium http://www.worldvet.org/

APPENDIX IV

LIST OF AGRICULTURAL METEOROLOGICAL SOCIETIES

INTERNATIONAL

The International Society of Agricultural Meteorology (INSAM)
Website: <http://www.agrometeorology.org/>

ARGENTINA

Argentina Association of Agrometeorology (AADA)
(La Asociación Argentina de Agrometeorología)
Cátedra de Agrometeorología
Fac. de Ciencias Agropecuarias de la UN de Córdoba
Avenida Valparaíso s/n - Ciudad Universitaria
5000 Cordoba, Argentina
Tel.: 54 351 433 41 16/7, ext. 307 (Agrometeorología)
Fax: 54 351 433 41 14
E-mail: aada.arg@gmail.com
Website: <http://www.aada.com.ar/>

BRAZIL

Brazilian Society of Agrometeorology
(Sociedade Brasileira de Agrometeorologia)
Rodovia MG 424, S/N - Zona Rural
Sete Laogas
Minas Gerais, Brazil
Tel.: 55 31 3027 13 32
Fax: 55 31 3027 11 88
E-mail: secretaria@sbagro.org.br
Website: <http://www.sbagro.org.br>

CANADA

Canadian Society of Agricultural and Forest Meteorology (CSAFM)
E-mail: CSAFM-SCMAF-L@www.agr.gc.ca
Website: <http://www.uoguelph.ca/~csafm/English/>

GERMANY

German Meteorological Society (DMG)
(Deutsche Meteorologische Gesellschaft)
Technical Committee on Biometeorology
German Weather Service
Centre for Agricultural Meteorology Research
Bundesallee 50
38116 Braunschweig, Germany
E-mail: Franz-Josef.Loepmeier@dwd.de
Website: http://www.dmg-ev.de/fachausschuesse/Biomet/biomet_index.htm

INDIA

Association of Agrometeorologists in India
B.A. College of Agriculture
Anand Agricultural University
Anand 388 110
Gujarat, India
Tel.: 91 2692 261 426
E-mail: info@agrimetassociation.org, secretary.aam@gmail.com
Website: www.agrimetassociation.org

IRELAND

AGMET (Joint Working Group on Applied Agricultural Meteorology)
Met Éireann Headquarters
Glasnevin Hill Dublin 9, Ireland
Tel.: 353 1 806 42 00
Fax: 353 1 806 42 47
Website: <http://www.agmet.ie/>

ITALY

Italian Society Of Agrometeorology
c / o Regione Piemonte - Plant
Via Livorno, 60 - 10144
Torino, Italia
Tel.: 39 11 432 47 70, 39 11 432 37 06
Fax: 39 11 432 37 10
E-mail: segreteria@agrometeorologia.it
presidenza@agrometeorologia.it
Website: <http://www.agrometeorologia.it/>

JAPAN

The Society of Agricultural Meteorology of Japan
5-16-9 Honkomagome
Bunkyo-ku, Tokyo 113-8622, Japan
Tel.: 81 3 581 45 801
Fax: 81 3 581 45 820
E-mail: [nogyo-kisho\(at\)yokendo.co.jp](mailto:nogyo-kisho(at)yokendo.co.jp)
Website: <http://www.soc.nii.ac.jp/agromet> (Japanese only)

REPUBLIC OF KOREA

The Korean Society of Agricultural and Forest Meteorology
Kyung Hee University College of Life Sciences
Seocheon dong 212, Republic of Korea
Tel.: 82 31 201 2651
Fax: 82 31 204 3640
E-mail: ksafm1@gmail.com
Website: <http://www.ksafm.org/> (Korean only)

UNITED STATES OF AMERICA

American Society of Agronomy
Agroclimatology and Agronomic Modeling Community

Presiding Leader

Judy Tolk

Term: 5 Jan. 2011 – 31 Dec. 2012

USDA-ARS

P.O. Drawer 10

Bushland, TX 79012, USA

Tel.: 806 356 57 36

E-mail: Judy.Tolk@ars.usda.gov

Vice Leader

Steven Evett

Term: 5 Jan. 2011 – 31 Dec. 2012

USDA-ARS

P.O. Drawer 10

Bushland, TX 79012, USA

Tel.: 806 356 57 75

E-mail: Steve.Evett@ars.usda.gov

Website: <https://www.agronomy.org/about-society/committees/A014.4/members/>

VENEZUELA

Society of Agrometeorology (Svagromet)

(Sociedad Venezolana de Agrometeorología)

INIA anzoátegui

Vía El Tigre - Soledad Km 5

Estado Anzoátegui, Venezuela

Tel.: 58 283 235 03 52; 58 416 297 66 16

Website: <http://www.svagromet.com.ve/>
