WORLD METEOROLOGICAL ORGANIZATION

SPECIAL TOPICS ON CLIMATE

Lectures presented at the forty-second session

of the WMO Executive Council

WMO-No. 771

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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ISBN: 92-63-10771-8

NOTE

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FOREWORD

The subject selected for the scientific lectures presented during the forty-second session of the Executive Council was "Special topics on climate". This was a particularly topical subject for a session of the Council held approximately mid-way between the Second World Climate Conference and the United Nations Conference on Environment and Development.

The topic was addressed by three distinguished scientists who presented the following lectures:

- Dr J. T. Houghton (UK) — A discussion of uncertainty in climate models
- Mr T. Karl (USA) — Detecting climate change: Issues of special concern
- Dr G. Golitsyn (USSR) — Present knowledge of minor atmospheric constituents playing a major role in the radiation balance

These excellent lectures raised a great deal of interest and were much appreciated by the Executive Council. Sincere thanks are therefore expressed to the lecturers for their valuable . contributions.

(G. O. P. Obasi)
Secretary-General

A DISCUSSION OF UNCERTAINTY IN CLIMATE MODELS

by

Dr J. T. Houghton

Meteorological Office, Bracknell, Berkshire, UK

The material used in the presentation to the forty-second session of the Executive Council was subsequently incorporated into the "Bakerian Lecture" delivered by Dr J. T. Houghton to the Royal Society in London in March 1991. The same material was updated and used in Dr Houghton's scientific lecture to the Eleventh World Meteorological Congress in May 1991. For these reasons, Dr Houghton's lecture is not included in the present volume but will be contained in the WMO publication *Scientific lectures presented at the Eleventh World Meteorological Congress.*

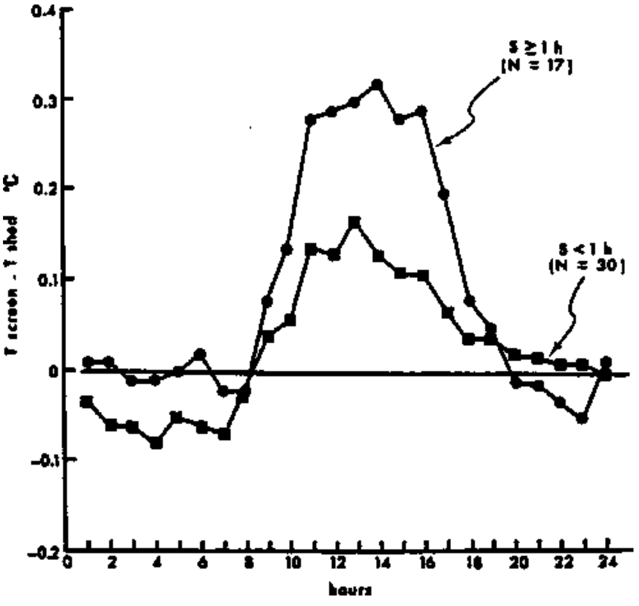


Figure 3 Mean differences of air temperatures between a thermometer screen and a thatched shed with different durations of bright sunshine from January 3, 1978 to June 4,1978 *(from Chen, 1979).*

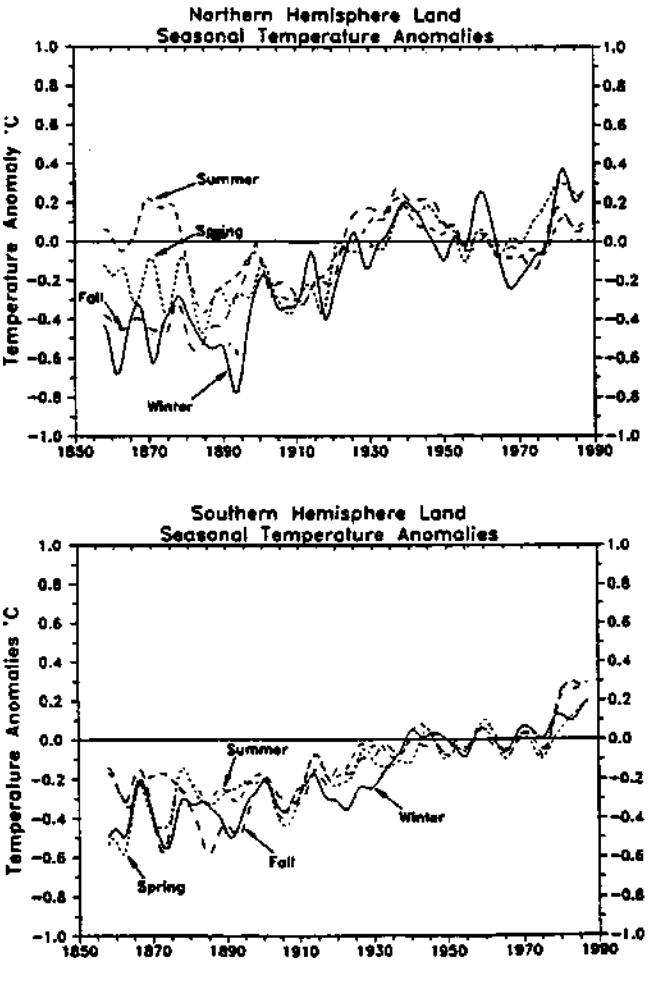


Figure 4 Smoothed seasonal land surface temperature anomalies, relative to 1951-1980 *(from chapter 7 IPCC, WG-1).*

dependent. For example, the differences between a thermometer in a Stevenson screen compared with one in a thatched shed for a station located in Hong Kong is given in Figure 3, but Table 1 indicates that for a similar comparison in Sri Lanka the differences are of opposite sign. This makes corrections for the biases extremely difficult It is likely that biases due to instrument exposure have indeed contaminated the global temperature record. Figure 4 depicts very warm Northern Hemisphere summer temperatures during the late nineteenth century, however, it is likely that the direct and indirect effects of insolation have biased the record. Unshielded north facing thermometers were common in many areas at this time; Parker (1990) examines these issues in more detail. At present, many countries are now or have already, switched from the Stevenson screen to new shelters suitable for automatic readings. It is imperative that side-by-side comparisons of new and old technology be initiated prior to the removal of the old equipment if we hope to avoid the problems of the past in the future.

Often an unavoidable change in a station's location must be made. The impact of these changes in the thermometric record is illustrated through several examples. Figure 5 shows the non-climatic induced cooling at Binghamton, New York by a station relocation from the a city to a more rural airport location. The airport was located several hundred

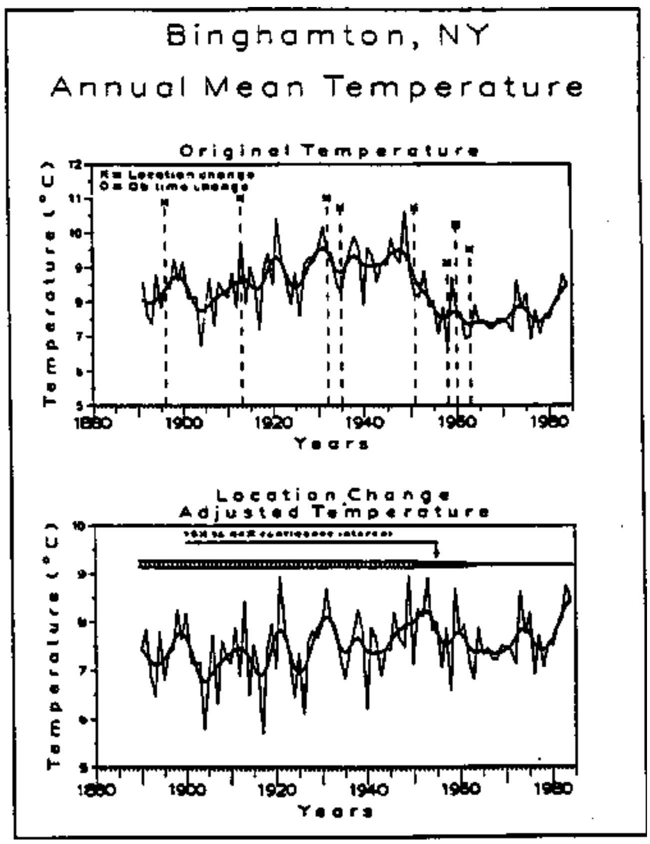


Figure 5 Original and adjusted mean annual temperatures. Smooth curve is a nine-point binomial filter. The width of the confidence intervals of the adjustments are shown relative to the 1984 location of the station *(from Karl and Williams, 1987).*

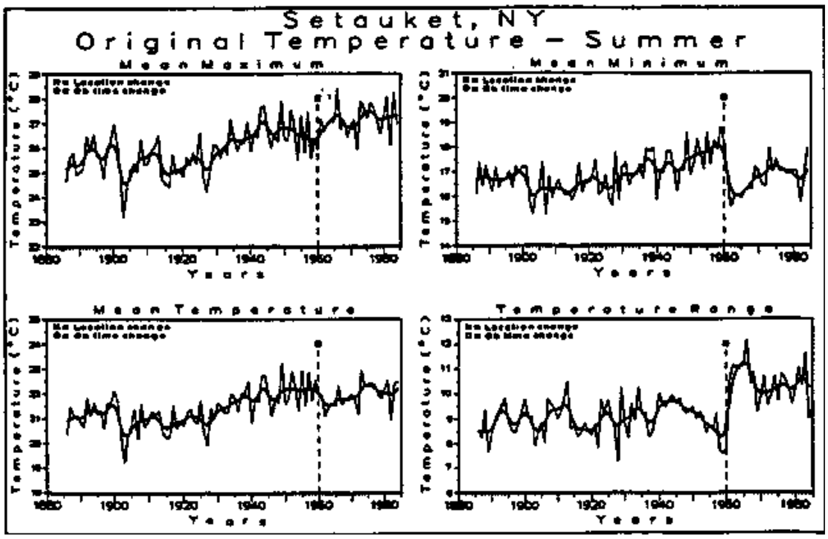


Figure 6 Same as Figure 5 except tor summer mean maximum, minimum, average and the diurnal temperature range *(from Karl and Williams, 1987).*

meters higher in elevation. The data can be adjusted for this discontinuity, and the adjusted time series in Figure 5 is derived by a statistical technique which relies on neighboring station'data (Karl and Williams, 1987). Nonetheless, no matter how well the technique performs, it is disconcerting to adjust time series more than the net change in the entire record. Figure 6 depicts the large impact on the thermometric record (especially the minimum temperature) of just one small site relocation of a thermometer housed in a ‘window box’ shelter attached to the north wall of an unheated room to a Stevenson type of instrument shelter 50 meters away. Similarly, the Washington, DC, station used in WWR and MCDW had a relocation from the city office to the urban airport (Figure 7); its associated discontinuity in the thermometric record is quite apparent as well as the gradual warming of the Washington, DC record after the relocation. The recent gradual warming is not characteristic of nearby, less urbanized, stations, and it is generally recognized to be the result of another bias, the urban heat island bias.

Fortunately, some of the errors and biases introduced by these inhomogeneities seem to have cancelled on a global basis. Karl and Jones (1990) provide evidence for this with respect to the urban warming issue and the systematic change of stations from the city to more rural airport locations. Figure 8 shows how the urban warming bias at stations like Chicago and Des Moines have been masked by relocations to

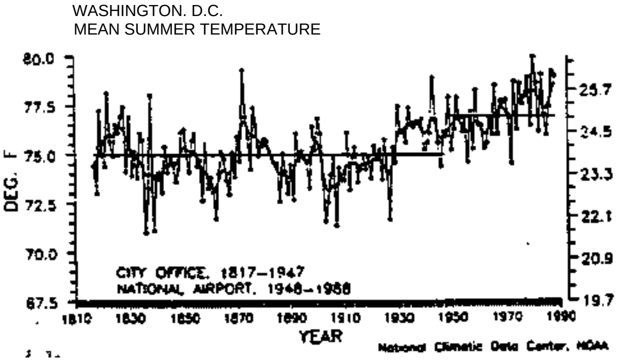


Figure 7 Time series of the mean annual temperature at Washington, DC at its city office and urban airport locations.

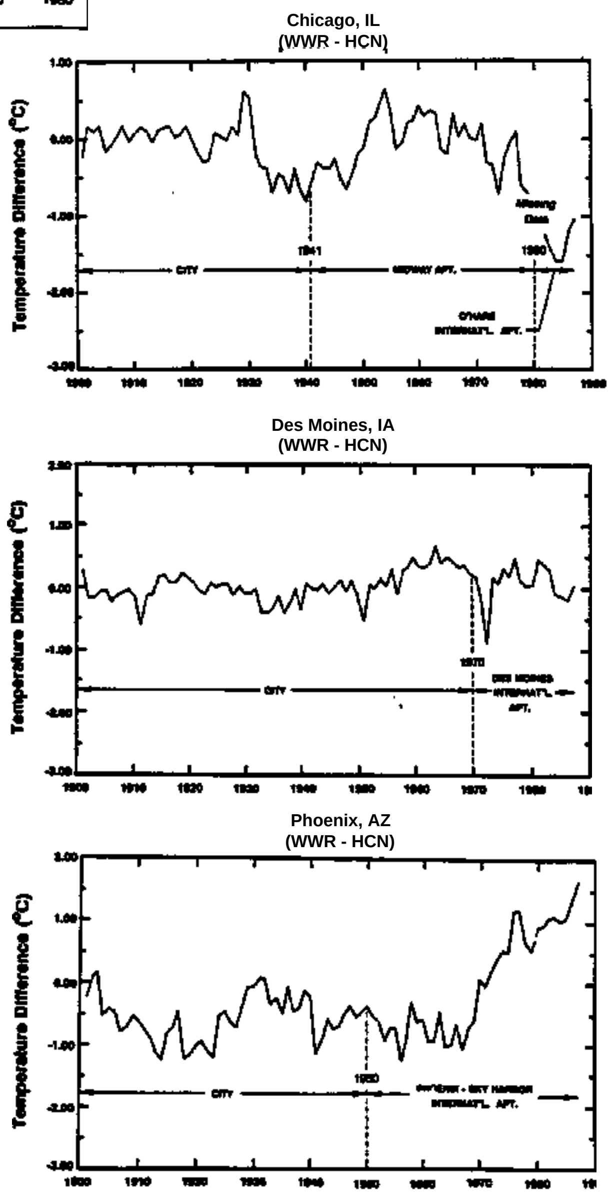


Figure 8 For selected stations, the difference of temperature between the data from *World Weather Records* and *Monthly Climate Data of the World* and the nearest two rural U.S. Historical Climate Network stations. The change from city to airport (APT) locations is denoted *(from Karl and Jones, 1990).*

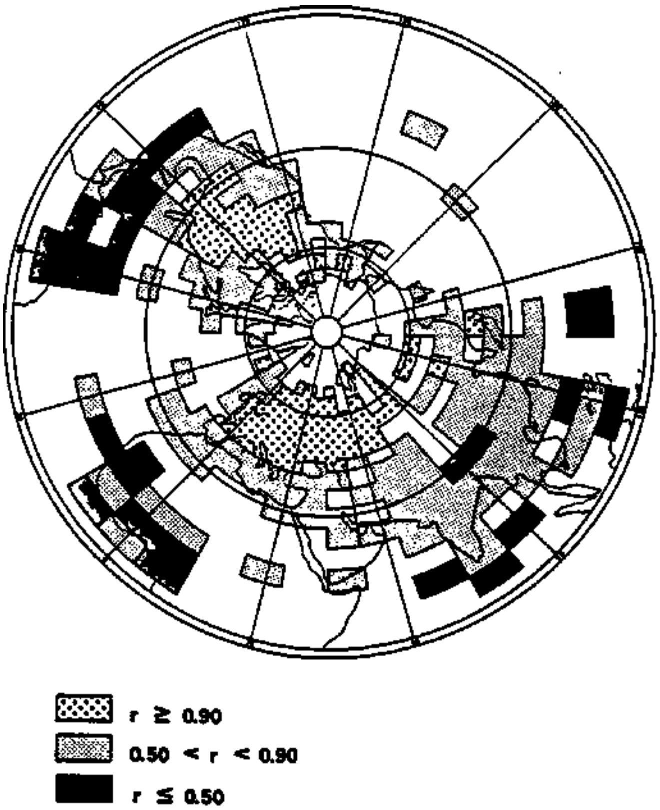


Figure 9 The correlation of mean monthly temperature anomalies of the Jones et al. (1986a, b) data set with an updated hemispheric land based data set described by Kleschchenko et al. (1988). Unshaded areas represent missing data.

the airport. This has, to a significant degree, offset the urban induced wanning at locations like Phoenix, Arizona (Figure 8) and elsewhere to such an extent that the urban bias in the current global records is not large (< 0.1 °C per century). Jones et al. (1990) also infer a similar scenario with respect to the urban warming bias in China.

Although we may have been fortunate up to now in this rather haphazard approach to global temperature monitoring, it would be unwise to imply that we can continue to take such an indifferent attitude about homogeneous observations in the future. Cancellation of errors is not an appropriate quality control mechanism to build scientific databases. Today it is very difficult to reconstruct reliable time series of regional and local climate variations from the thermometric record. Such information however, is essential to understand the impacts associated with climate change. As an example, Kleschchenko et al. (1988) calculate (Figure 9) the correlation of the temperature anomalies from a hemispheric thermometric data set they developed with those derived from the data of Jones et al. (1986a, b). Many areas of the Northern Hemisphere have poor agreement between the two data sets, especially outside of North America, eastern Asia, and Europe. Based on this analysis, and others, it is clear that our global data sets cannot adequately resolve regional and local-scale climate anomalies.

Many of the inhomogeneities that have arisen in our climate records over the past few decades are attributable to the fact that observations have primarily been made for weather forecasting, where the reliability and the uniformity of the network is more important than the long-term homogeneity from specific locations. Furthermore, in the first half of the instrumental record, adequate observing techniques were still being developed with numerous changes in instrument shelters being introduced, often in poorly documented ways. As long as the National Weather Services of the World continue to be the primary source of information for climate change and variations this problem will not be resolved unless there is a commitment to long-term homogeneous networks by the National Weather Services throughout the world. The World's National Weather Services must consider the impact of cost-saving measures and new automation changes in their weather observing networks before implementation. This may for example, require a period of side-by-side monitoring of new observing systems to establish their differences before discontinuing measurements from the system being replaced.

Recently, the WMO has taken some positive steps in this direction associated with the Climate Change Detection Project, the Climate Reference Network, and the Global Climate Baseline Data Set. An important word of caution however, is needed with respect to the Climate Reference Network. We should not delude ourselves into thinking that even a Reference Network will remain totally free of inhomogeneities. It will be impossible to assure that a large network of stations will never undergo significant sources of biases. It is essential that we maintain a dense network of supporting stations that can be used to adjust for inhomogeneities which will inevitably occur at these stations. In addition, climatological supporting stations can better define the spatial patterns of climate variation and change so necessary for understanding biophysical and socio-economic impacts of climate change.

It cannot be overemphasized that it is extremely important that adequate documentation of instruments, environmental changes, observing schedules, and data processing methods accompany the basic data. In the absence of such metadata, assessments regarding the longterm homogeneity of the observations is much more tentative. Unfortunately, this metadata is often overlooked, or hastily compiled, thereby needlessly degrading the value of the original observations for the detection of climate change.

(ii) Oceans

The oceans comprise about 61% of the Northern Hemisphere and about 81% of the Southern Hemisphere. Their thermometric changes cannot be ignored, and in fact they may hold the key to understanding the atmosphere's spatial and temporal response to greenhouse gas emissions. At the present time global estimates of ocean temperature deviations have been derived from two basic data sets. This includes the Comprehensive Ocean Atmosphere Data Set (COADS) compiled by the USA National Oceanic and Atmospheric Administration (NOAA) and the UK Meteorological Office's data seL These data sets consist of millions of observations from commercial ships, supplemented with observations from drifting and moored buoys as well as weather ships. Unfortunately, when these data are used to reconstruct ocean

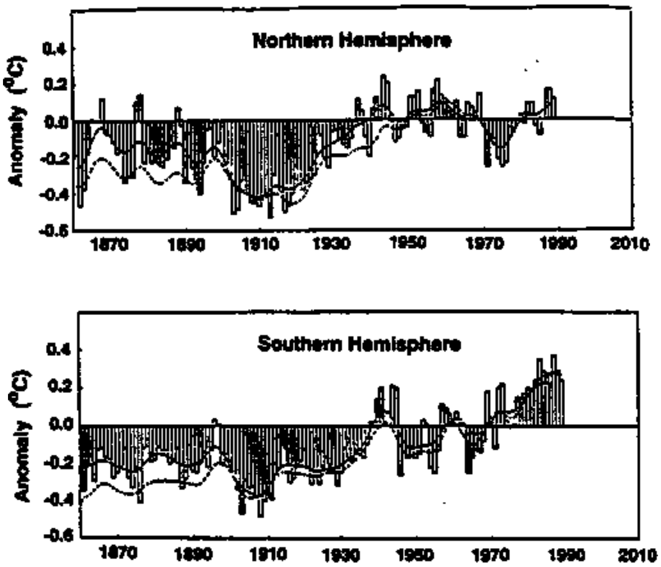


Figure 10 Sea-surface temperature anomalies 1861 -1889, relative to 1951-80. Smoothed curves are 15-term binomial filters, — dashed from Farmer *etal.* (1989), smoothed from the UK Meteorological Office *(Updates from Folland, 1990 prepared for IPCC WG-1, Chapter* 7).

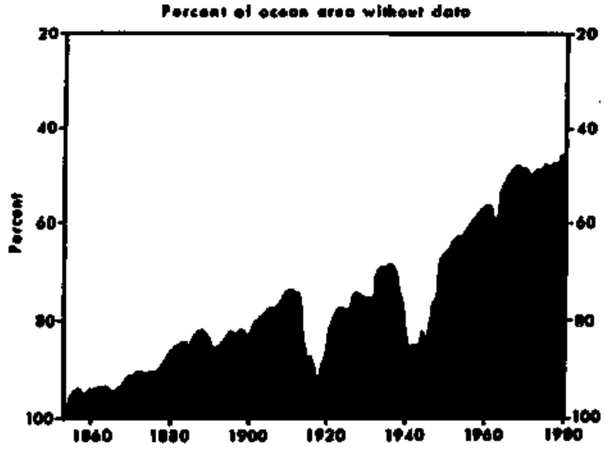
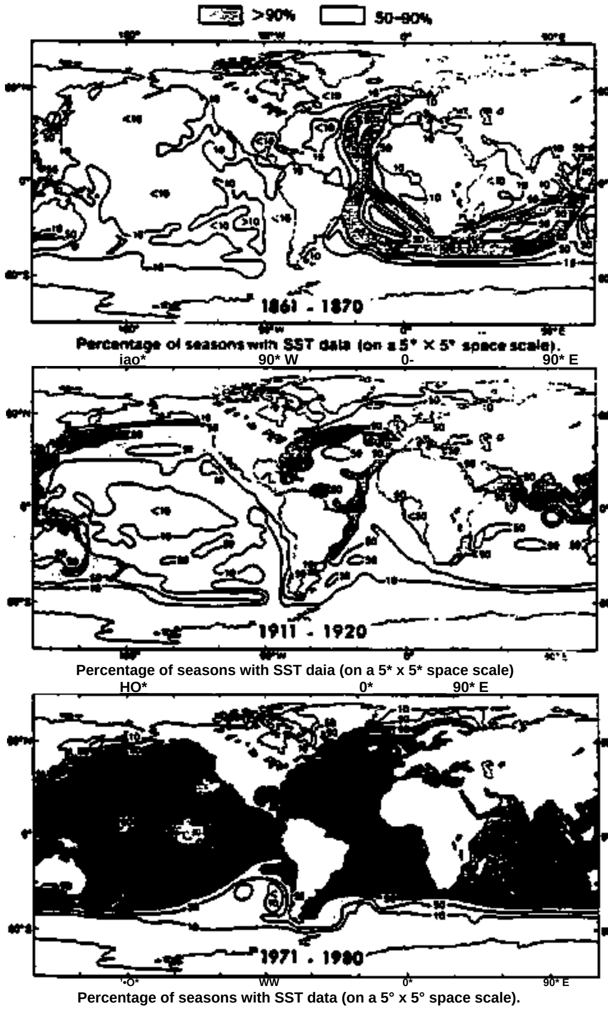


Figure 11 a Percent of ocean area with at least one observation per year in a 2°x2° box *(from Karletal., 1989}.*



from Bottomley ot al.

Figure 11 b Percent of seasons with at least one observation on a 5°x5° space scale *(from UK Meteorological Office database as given in Karl et al., 1989).*

temperatures back to the Nineteenth Century the biases in the data set (due to changing methods of observing air and sea surface temperatures) are as large as the observed warming of the land based observations (Figure 1). Depending upon the assumptions used to adjust these data, small, but significant, differences in the rates of global ocean warming result (Figure 10).

Since the differences in Figure 10 are primarily due to the assumptions made regarding the observing methods used (canvas versus wooden buckets) they do not represent the potential bias that may result due to incomplete and changing global coverage. Even today, there are large portions of the globe without adequate measurements (Figure 11). Permanently moored and well-maintained buoys or Ocean Weather Ships, especially in the Southern Hemisphere, could help alleviate this problem. Space-based observations will also aid considerably. At present, satellite measurements alone will not be sufficient because of unresolved problems associated with instrument drift and unknown, unpredictable, and varying compositions and concentrations of tropospheric and stratospheric atmospheric aerosols which interfere with the normal radiative atmospheric windows.

(b) Precipitation

In many portions of the globe variations of precipitation are even more critical than temperature, but unfortunately there exists many problems associated with the measurement and homogeneity of even this basic element Point observations of precipitation collected in a raingage are still considered the most accurate measurements. Unfortunately, these measurements typically underestimate the true rainfall (Sevruk; 1979,1986). There is no universally accepted raingage, and there, have been many studies to compare the efficiencies of

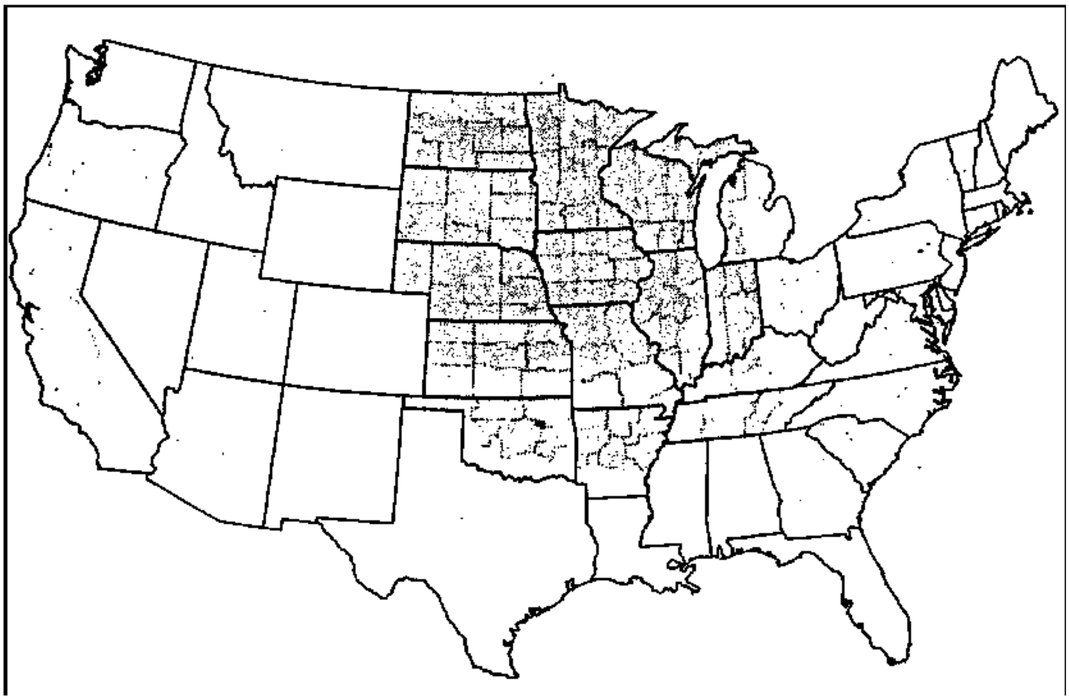


Figure 12a
Area of anticipated increases of winter precipitation and decreases of summer precipitation in an enhanced greenhouse world.

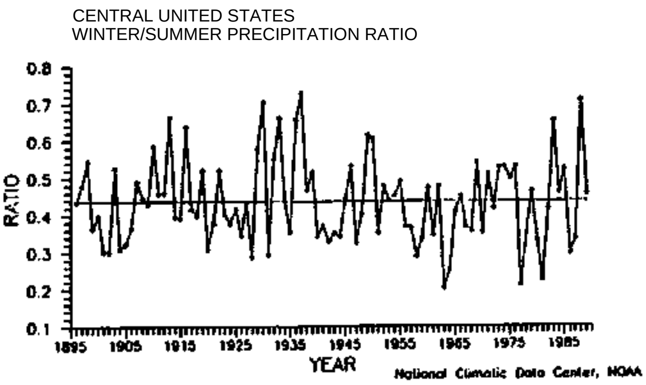


Figure 12b Changes in the rates of winter to subsequent summer precipitation since the turn of the century.

various gage designs (Rodda, 1971, Sevruk, 1982, 1986, 1987; Folland 1988). This has been recognized by many National Weather Services, and they have often strived to implement new methods of collection efficiency, often in ways which are either poorly documented or have difficult accessibility, introducing biases of unknown magnitude into the climate record. Such changes are often driven by the needs of weather observing programs as opposed to climate programs.

In addition to the systematic underestimate of precipitation due to evaporation, wetting losses, and aerodynamic affects, recent work by Willmott and Leagates (1990) demonstrates that in many studies the gridding procedures used to convert the point observations of precipitation to area averages can result in biases in the opposite direction. These biases are a function of the density of stations in the network. The question of the appropriate number of stations to use is not new, and it has been grappled with for many decades (Gandin, 1970; WMO 1985). There is no universally applicable solution to this problem, since topographic variations and climatological processes play a role. Because precipitation is historically more variable than temperature, a denser network of recording stations is required. Recent investigations of changes in global precipitation (Bradley et al., 1987; Diaz et al., 1989; Vinnikov et al., 1990) have used as many stations as possible (usually a few thousand land stations); but this is woefully inadequate for regional or local assessments of climate change, and, as Willmott and Leagates (1990) demonstrate even for global assessments. Fortunately, there are nearly 200 000 regular reporting precipitation stations on a global basis. Unfortunately, most of these data are not exchanged between countries on a routine basis. This is an important topic, one in which the World Meteorological Organization can be of substantial benefit, both in terms of the spatial coverage and consideration of homogeneous observations free from systematic bias.

The importance of these data sets cannot be overemphasized both in terms of comparing climate trends and variations with model projections and climate change impact assessments. For example, they can be used to check the veracity of our General Circulation Climate model projections associated with enhanced greenhouse gas concentrations, such as the reduction of summertime precipitation and the increase of wintertime precipitation in the central portion of North America (Figure 12). They are absolutely essential if we are to understand the spatial variability of precipitation on an annual basis, let alone its change over longer time periods. Even on an annual basis over the flat piedmont of central North Carolina (USA) annual errors of precipitation estimation of nearly 400 mm (25%) can occur based on the use of observations from the synoptic network alone (Figure 13).

(c) Aerological variables

(i) Temperature

Observational studies of tropospheric and stratospheric changes of temperature are important for comparisons with

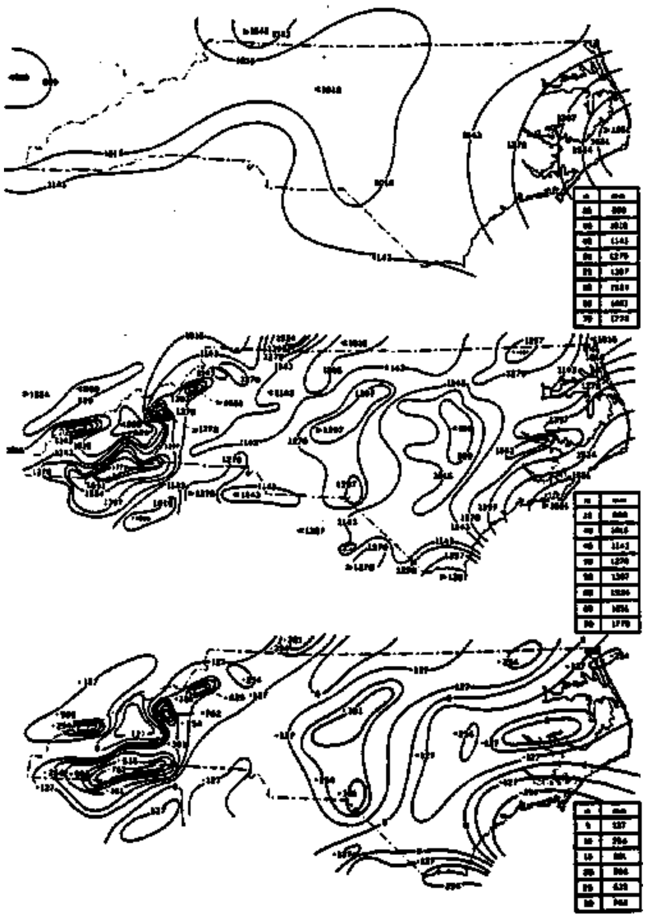


Figure 13 North Carolina's (USA) annual precipitation from the synoptic network and the denser climatological co-operative network for 1985; and the co-operative network minus the synoptic network *(from Karl and Quayle, 1980).*

model projections. They have been completed by many researchers (Parker, 1980; Parker, 1985; Oehlert, 1986; Barnett, 1986; Karoly, 1987; Barnett and Schlesinger, 1987; Sellers and Liu, 1988; Angell, 1988; Karoly, 1989). These studies have used temperatures derived from radiosondes which are also subject to instrumental biases, such as radiation shielding problems, time of observation biases, etc. These biases have not been assessed in any of the above mentioned studies. Part of the reason for this is the difficulty in obtaining adequate station history operation procedures and instrument packages used by the various National Weather Services. Again the World Meteorological Organization has a role to play with respect to international comparisons of radiosondes and ensuring consistency and completeness of observations. The WMO Commission for Instruments and Methods of Observation (CIMO) has taken some initiative to help clarify the existing disarray of information on station histories. Nonetheless, the World's National Weather Services must make a commitment to climate monitoring as well as weather prediction if we are ever going to achieve significant improvements in our ability to produce homogeneous observations.

Despite the potential biases in the aerological data, some encouraging results have recently emerged from a

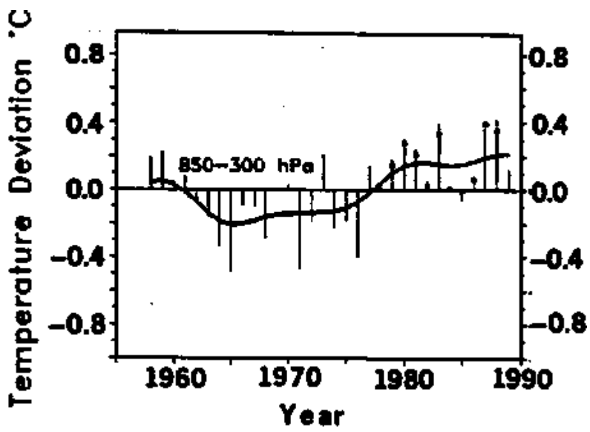


Figure 14 Annual global averages of 850 to 300 hPa temperature anomalies from Angell (1988) and from brightness temperatures (dots) derived from NOAA-7 and 8 Microwave Sounding Unit (MSU) measurements as calculated by Spencer and Christy (1990), *(from IPCC-WG1, Chapter 7).*

comparison of thermometric data derived from 63 global aerological stations with the space-based measurements assembled by Spencer and Christy (1990) from the Microwave Sounding Unit (MSU) aboard the NOAA series of satellites. Figure 14 depicts the time series of global average temperatures from Angell's (1988) network of 63 stations and those from the MSU data. The MSU data are brightness temperatures which correspond best to an integrated mid-tropospheric temperature. Over the period 1979 to 1988 the root mean square of the difference of the annual anomalies (forced to the same reference) between the two data sets is 0.02°C and the correlation is nearly 0.98.

(ii) Moisture

An enhanced hydrological cycle with increased atmospheric moisture content is projected by every GCM with enhanced concentrations of greenhouse gases. This alone makes the observations of atmospheric moisture important, but in addition it is one of the key components to understanding the linkages of heat and moisture in the climate system. Obviously, this is an important climatological element Again, the daily observations of radiosondes are the primary source of data. Recent work by Elliot (1988) and Hense et al. (1988) suggest that there has been a significant increase in the water vapor content of the mid-troposphere in the last decade or so. Unfortunately, the uncertainties associated with atmospheric moisture monitoring are large. As with thermometric observations, corrections for biases have been hampered because of the difficulty in obtaining global station histories.

(iii) Winds

Changes in circulation patterns can be derived from geopotential heights. The importance of these patterns has been recently illustrated by Flohn et al. (1990). They argue that it is unwise to decouple natural climate variability and anthropogenic climate change as demonstrated by some recent changes in circulation over the North Atlantic and Pacific.

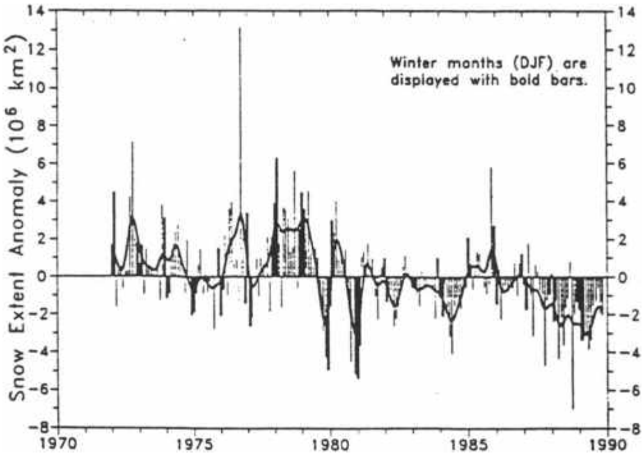


Figure 15a Northern Hemisphere snow cover anomalies *(from IPCC-WG 1 Chapter 7).*

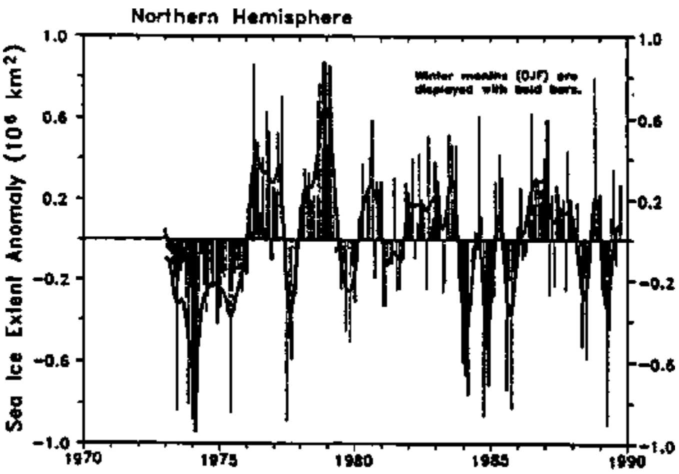


Figure 15b Northern Hemisphere sea-ice anomalies *(from IPCC-WG 1 Chapter 7).*

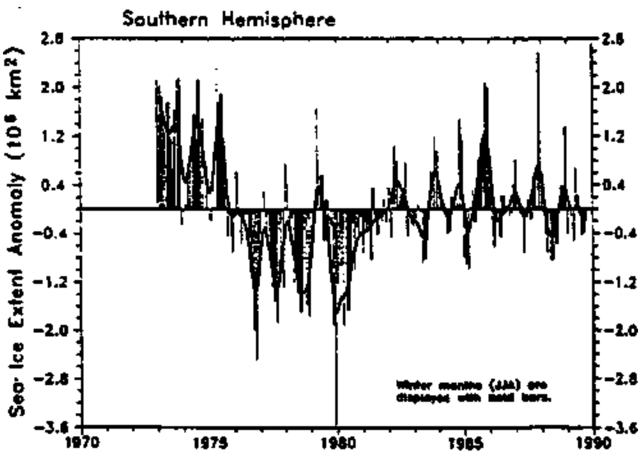


Figure 15c Southern Hemisphere sea-ice anomalies *(from IPCC-WG 1 Chapter 7).*

Changes in frequency and types of circulation patterns over the North Pacific have also been pointed out in a recent study by Trenberth (1990). Since these studies depend on accurate geopotential heights and statcompressures it is important that station histories adequately reflect instrument packages and instrument heights over the course of a station's lifetime.

(d) Other surface variables

(i) Vegetation

Increasingly, climatologists are giving more attention to the interaction between the biota and the climate (Schwartz and Karl, 1990; Segal, et al., 1989). Not only does the plant community respond to climate, but changes in plant transpiration and albedo have feedback effects which influence local and regional climate. The International Geosphere Biosphere Program (IGBP) was developed in part to help address these concerns. There is now beginning to be a recognition that long-term monitoring of changes in vegetation is essential for a true understanding of the interaction of surface processes and the climate. This ranges from the chlorophyll measurements made at sea by various researchers to the space-based measurements of active photosynthesis such as the Normalized Difference Vegetation Index (NDVI) as described by Malingreau (1986) and Justice (1986) and the intensive set of land-surface measurements made in the First ISLSCP* Field Experiment (FIFE) (Sellers et al., 1988). The land surface provides an important feedback with the climate system that is critical for a detailed understanding of climate change. Programs such as the IGBP's core project the Global Change and Terrestrial Ecosystems (GCTE) will be extremely valuable for a better understanding of the ways in which the atmosphere and the land surface interact. But it is not clear that these programs will be able to support long-term measurements. Observations for a better understanding of vegetation and climate interaction and model physics are extremely important, but so are long-term measurements if we ever expect to assess the impact of climate change and long-term feedbacks.

(ii) Snow and sea ice

Variations of snow and ice are key surface parameters which play a major role in the exchange of heat, moisture, momentum, and long/short wave radiation between the Earth's surface and the atmosphere. This makes their long-term monitoring of special importance. Global coverage of changes in snow and ice cover have recently been derived from space-based observations (Figure 15). On a regional basis, observations of snow depth are available, but these are only stored in national centers and are often unorganized or poorly documented (Robinson, 1989).

The USA NOAA prepares weekly snow/no snow information for 7921 grid boxes in the Northern Hemisphere. They are compiled from visible and near-infrared satellite imagery. These data have been compiled since 1966, but the

♦ International Satellite Land Surface Climatology Project quality of the earlier data is questionable due to a variety of factors including low or no solar illumination in the polar winter, persistent cloudiness, omission of the Himalayan region in early years, and a too coarse grid resolution in some mountain areas (but this latter bias has not changed with time). Since the early 1970s however, it is generally believed that these data are reasonably homogeneous. Consistent with the surface temperature records a significant jump in the hemispheric snow cover is detected around 1980 (Figures 1 and 15a).

Unfortunately, there has been little work on changes in snow depth/cover from long-term *in situ* observations of snow. Few studies have dealt with long-term trends or low-frequency fluctuations of snow depth over even small regions (Arakawa, 1957; Manley, 1969; Jackson, 1978; Pfister, 1985; Robinson, 1987).

Observations of sea ice are made from shore stations, ships, aircraft, and satellites. The first three are quite limited in scope compared to satellite observations. Barry (1986) indicates that early *in situ* observations of sea ice present many problems of interpretation. This is because of inadequate metadata. For the more recent times, however, the USA NOAA produces digitized maps of sea-ice (Figures 15 b and c). These charts are produced by all four types of information listed above including visible, infrared, and microwave satellite sensors. Data quality has been consistent in time, but the digitization of sea ice concentration switched in 1980 from eighths to tenths. This does not, however, coincide with the jumps (of opposite sign) in ice coverage that occurred around 1975 (Figures 15 b and c).

Gloersen and Campbell (1988) point out the difficulty in interpreting changes in ice coverage. Using Nimbus 7 micro wave data they indicate that during the years 1978 to 1987, despite the fact there was little overall change in global ice coverage, the amount of open water within the ice increased significantly.

It is essential that these types of satellite measurements continue on an operational basis as they have for the past two decades. Unfortunately, the *in situ* observations of snow cover/depth are not being utilized to their full extent.

(iii) Soil moisture

An important variable that has been shown to be of considerable importance with respect to understanding local and regional climate anomalies is the soil moisture content It has been shown to effect the changes in the surface boundary layer conditions during droughts, and their relationship with surface temperature, precipitation, and feedbacks to the atmospheric circulation (Segal, et al. 1989; Karl, 1986; Rind 1982; Walsh et al. 1985; Van den Dool 1984; Yeh et al. 1984; Rowntree and Bolton 1983; Sawyer 1964; Namias 1952, 1962). Unfortunately, actual measurements of soil moisture are often not even taken by National Weather Services. This should be changed in light of the importance both to the agricultural community and the climate community. A long-term measurement program should be established in nations where such measurements do not exist, and where such measurements have been made better documentation and access to these data are needed.

(e) Clouds

Clouds modify both shortwave (solar) and longwave (terrestrial) radiation, the former by reflection and the latter by absorption. Therefore they may cause a net warming or cooling of global temperature, depending on their type, distribution, coverage, and radiative characteristics (Charlock, 1982; Webster and Stephens, 1984; Sommerville and Remer, 1984; Roeckner et al, 1987; Cess and Potter, 1987). Ramanathan et al (1989) show that with today's distribution and composition of clouds, their overall effect is to cool the earth. Changes in cloudiness are therefore very important for understanding global climate change. Furthermore, local and regional climate variations can be strongly influenced by the presence or absence of low, middle, and high clouds (Figure 16).

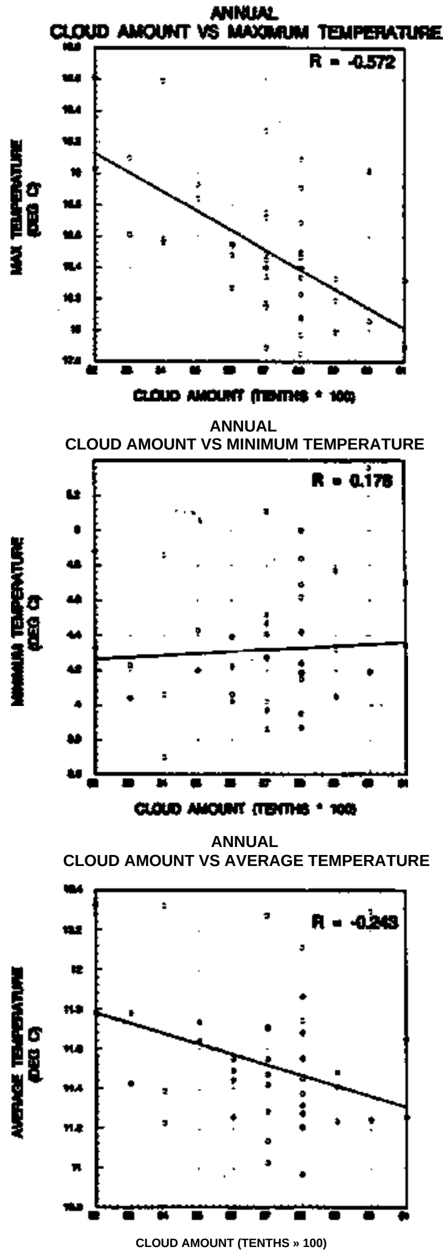


Figure 16 Correlation of mean annual cloud cover over the United States versus mean annual temperature *(from Plantico et al., 1990).*

Observations of cloudiness can be made from the Earth's surface by a trained observer from land stations or ocean vessels, or by an automated system. Above the Earth's surface, aircraft or space platforms are used (de Bary and Moller 1963; Rossow, 1989; McGuffie and Henderson-Sellers, 1989a). Surface-based observations of cloudiness give closely similar results to space-based observations. Careful and detailed intercomparisons, undertaken as a preliminary part of the International Satellite Cloud Climatology Project (ISCCP) by Seze et al. (1986), have unequivocally demonstrated that surface and space-based observations are highly correlated. Presently, space-based observations of cloudiness from major international programs, such as ISCCP, are not yet available for periods of sufficient duration to detect long-term changes, and it is not clear that such projects will provide us with long-term homogeneous measurements. Nonetheless, a 25-year data set of global cloud cover now exists which consists of visual and infrared images from the "Meteor" satellite system (Matreev, 1986). These data are now of sufficient length that they can and should be compared to surface-based observations.

(i) Land

Henderson-Sellers (1986a,b, 1989) and McGuffie and Henderson-Sellers (1989a) have analyzed changes in total cloud cover over North America and Europe during the twentieth century. Both continents give an increase of annual cloudiness. Preliminary analyses by Henderson-Sellers (1990) for Australia and the Indian sub-continent also give increases in cloudiness. The increases are substantial: 7% of initial cloudiness/50 years over India, 6%/80 years over Europe, 8%/80 years for Australia, and about 10%/90 years for North America.

These changes are very large, but once again it is not certain how much of the increase is due to changes in observing practices and in the subsequent processing of cloud data. For example, the large increase in cloudiness observed in many areas during the 1940s and 1950s occurred at a time (about 1949 or later, depending on the country) when the synoptic meteorological code underwent a major change (but not in the USA, USSR, and Canada). Observers began recording cloud cover in "oktas" (eighths) instead of in

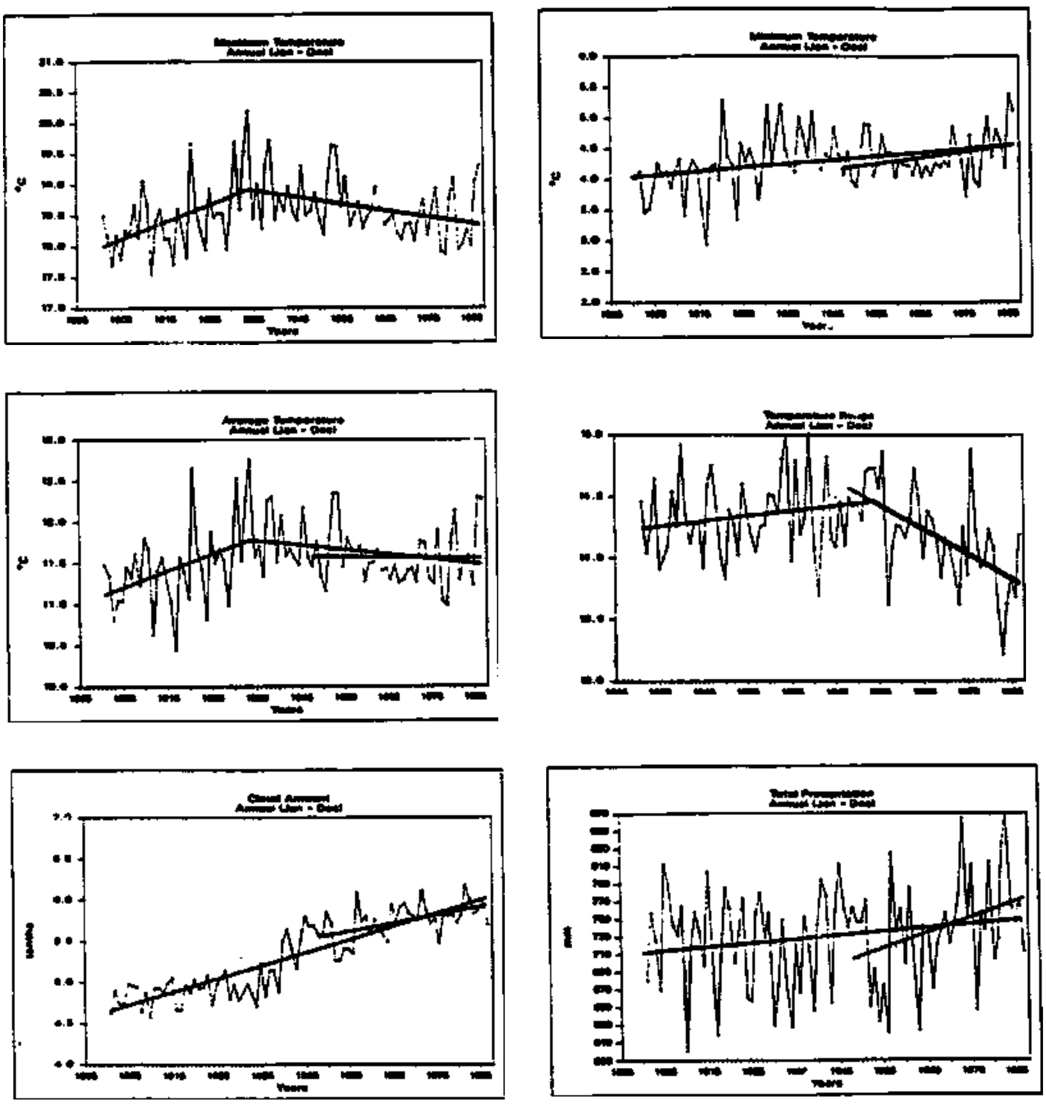


Figure 17
Time series of annual temperature, cloudiness, and precipitation across the United States for the period 1900-1987. Trend lines are linear for the last 40 years and with one inflection point possible (if statistically significant) for the full period of record *(from Plantico et al., 1990).*

tenths. When skies were partly cloudy it is possible that some observers who had been used to making observations in the decimal system converted to the same number of oktas, thereby overestimating cloud cover.

Recently, Karl and Steurer (1990) have compared daytime cloudiness statistics over the USA with data from automated sunshine recorders. They attribute the large increase of cloudiness during the 1940s to the inclusion of the obscuring effects of smoke, haze, dust, and fog in cloud cover reports (there being no change in the recording practice from tenths to oktas in the USA). Nonetheless, they argue that the increase in cloudiness after 1950 may be real as the increase is consistent with a decrease in the diurnal temperature range and an increase of precipitation in the USA (Figure 17).

Observed land-based changes in cloudiness are difficult to assess. Notwithstanding, total cloud amount appears to have increased in some continental regions, a fact supported by significant changes in the character of regional-scale temperature. Cloudiness records are difficult to interpret reliably, primarily because of the inadequate metadata describing how measurements and the processing of these measurements have changed over time. Comparisons of the more recent 25 years of *in situ* surfaced-based data can, and should, be made with the Meteor satellite data set to help assess homogeneity issues in each of these data sets.

(ii) Oceans

Ocean-based observations of changes in cloud cover have been compiled by Warren et al (1988) since 1930. The data are derived from maritime synoptic weather observations. The number of observations varies between 100,000 and 2,000,000 each year, increasing over time. The data indicate that a relatively large increase in marine cloudiness occurred from the 1940s to the 1950s exceeding one percent in total sky covered. This increase is not reflected in the number of completely clear sky observations, nor is it observed in the number of completely overcast conditions. The largest increases are in stratocumulus clouds in mid Northern Hemisphere latitudes and in cumulonimbus in the tropics. Since 1930, mean Northern Hemisphere values have increased by 3-4 percent of total sky covered and by about half this value in the Southern Hemisphere. Fixed ocean weather ships, placed after 1945 in parts of the North Atlantic and North Pacific with well trained observers, however, show no trends in cloudiness between the 1940s and 1950s when other ship data from nearby locations showed relatively large increases. It is clearly not possible to be confident about the increases but these comparisons point out the value of many different sources of data.

3. INTEGRATION OF SPACE-BASED OBSERVATIONS, NEW OBSERVING SYSTEMS, AND *IN SITU* DATA

Spaced-based observations of important parameters are not yet long enough on their own to document climate variations and change. In order for these data to be most useful, it is very important that they be analyzed and interpreted with existing *in situ* data. This can be in the form of a rigorous cross validation of these data; the proper interpretation of remote sensing information for climate purposes is often dependent on such comparisons. The comparison of the MSU derived brightness temperatures with the radiosonde derived temperatures (Spencer and Christy, 1990) or the comparison of *in situ* and spaced-based observations of snow cover are good examples where such comparisons are essential. Even more valuable however, is the blending or integration of spaced-based and *in situ* data sets in such a way as to build on the strengths of each type of data. The development of blended long-term data sets should have a high priority. Sufficient space-based data already exist for some variables so that it would be very feasible to increase the veracity of long-term historical data sets by blending both *in situ* and space-based observations. This includes, but is not limited to *in situ* data sets such as:

(1) snow cover/depth for some large land areas of the globe,

(2) global sea-surface temperature measurements,

(3) vegetation indices and historical measures of drought intensity,

(4) temperatures both over the land, ocean, and throughout the atmosphere, and

(5) cloud cover.

For example, it would be very useful if *in situ* snow cover/depth data were related to space-based derived information to both increase the information content of the modem data and establish the required density of stations needed to capture most of the seasonal and year-to-year variance of continental snow cover of the *in situ* instrumental record. In this manner records could be extended backward in time with more consistency and knowledge of their spatial biases. Similarly, the comparison of space-based ocean temperatures with *in situ* observations could help establish the effects of inadequate sampling in the historical observations and also improve the more recent satellite products (Reynolds, 1988).

Since a long-term commitment to observing and producing homogeneous data sets is needed to document changes in climate, our best hope to fulfill this need from satellite systems is to build databases from operational systems. They provide the necessary commitment of resources to produce long-term data sets. In addition to the commitment for long-term data sets however, all instruments aboard the satellite should be calibrated both prior to launch and in flight. One of the most reliable methods to check the veracity of the data is to fly redundant instruments on two satellites. Although this may be more costly, the uncertainty about instrument drift can make the observations useless for documenting climate change and variations. For those instruments now in operation, where none of the above procedures are possible, techniques should be developed to prevent or help detect instrument drift. Similarly, when new algorithms to process data are introduced, the entire data collection should be reprocessed to prevent discontinuities. In planning new space-based observations for long-term climate monitor-

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СОСТОЯНИЕ ЗНАНИЙ О ПАРНИКОВЫХ ГАЗАХ В АТМОСФЕРЕ, ОПРЕДЕЛЯЮЩИХ РАДИАЦИОННЫЙ БАЛАНС ЗЕМЛИ*

Г.С. ГОЛИЦЫН

ИНСТИТУТ ФИЗИКИ АТМОСФЕРЫ АН СССР, МОСКВА

ВВЕДЕНИЕ

Атмосфера состоит из двух типов компонентов: один меняется очень мало на временных масштабах порядка тысячелетий и другой, который может меняться на временах порядка столетия, или даже много меньших. Первая часть составляет около 99,6% по объему и состоит из азота, кислорода, аргона (и других благородных газов в существенно меньших количествах) в пропорциях 78:21:1.

Эти компоненты действительно менялись в пропорциях на временных масштабах порядка миллионов лет в течение истории Земли [2], особенно кислород, концентрация которого менялась в несколько раз. Самое присутствие кислорода в атмосфере нашей планеты является следствием появления жизни на нашей планете и условием ее развития, по крайней мере на суше. Масса и состав атмосферы - результат деликатного баланса между выделением газов из недр Земли, процессов на ее поверхности, включая океан, диссипации атмосферы в космическое пространство и т.д. В результате Земля имеет атмосферу массой $5{,}15.10^{15}$ тонн с 99,6% состава, как указано выше.

Остаток около 0,4% состоит в основном из водяного пара с концентрацией около 3200 млн$^{-1}$ (частей на миллион молекул воздуха по объему), если взять глобальную среднюю концентрацию водяного пара, соответствующую слою в 2 см осажденной воды. Следует отметить, что водяной пар является одним из наиболее переменных в пространстве и времени компонентов атмосферы благодаря изменчивости его источников, фазовым переходам и осадкам. На порядок меньше концентрация углекислого газа. Эти два компонента - основные малые примеси, которые обеспечивают основную часть парникового эффекта. Другими существенными парниковыми газами являются метан, CH_4, закись азота, M_2O, тропосферный озон и хлорфторуглероды - фреоны. Без наличия парниковых газов в атмосфере средняя по земному шару температура ее поверхности была бы около 255 К = -18°С, т.е. на 33°С меньше, чем теперь. Поэтому без парниковых газов жизнь на Земле едва ли была бы возможна.

Существо парникового эффекта состоит в том, что эти газы поглощают меньшую долю солнечного излучения, чем это они делают в отношении теплового излучения земной поверхности и самой атмосферы. В результате часть тепловой радиации переизлучается назад к поверхности, тем самым увеличивая количество энергии, приходящей к поверхности, и нагревая ее дополнительно.

На других планетах Солнечной системы, имеющих атмосферы, парниковый эффект также наблюдается. Наиболее разительным примером является Венера, чья атмосфера примерно в 100 раз более массивна, чем у нас, и состоит в основном из CO_2. Это вызывает эффект порядка 500 К вместо примерно 30 К у нас. Другим достаточно хорошо изученным примером является Марс с массой атмосферного столба в 60 раз меньше, чем у нас, но поскольку главный компонент его атмосферы снова углекислый газ, результирующий парниковый эффект несколько больше 10 К. Марс также дает пример так называемого антипарникового эффекта, когда температура поверхности может охладиться до температур, несколько ниже, чем те, которые получаются из простых оценок по балансу между солнечной радиацией, достигающей планету, и термической радиацией, излучаемой планетой в космическое пространство.

На Марсе антипарниковый эффект имеет место во время пыльных бурь, которые могут достигать глобальных масштабов. Пылевой аэрозоль поглощает солнечную радиацию лучше, чем тепловую, поэтому при уменьшенном количестве солнечной радиации у поверхности и недостаточном количестве тепловой радиации, переизлученной назад атмосферой к поверхности, последняя охлаждается до величин меньших, чем в обычных условиях. В случае Марса это охлаждение может достигать 15-20 К по сравнению с нормой [3,4]. Эти процессы лежат в основе явления ядерной зимы и, поскольку их сущность стала четко понятной в начале 70-х годов, они явились отправной точкой для формулировки гипотезы о ядерной зиме [5-8].

ОБЩИЕ ХАРАКТЕРИСТИКИ ПАРНИКОВОГО ЭФФЕКТА И СВЯЗАННЫЕ С НИМИ НЕОПРЕДЕЛЕННОСТИ

Количества пропущенной солнечной и поглощенной термической радиации зависят от спектрального поглощения в атмосфере. Природа поглощения зависит от газа

* Текст лекции, прочитанной на 42-й сессии Исполнительного Совета Всемирной Метеорологической Организации в Женеве 22 июня 1990 г. Большую часть материала, изложенного здесь, и с большими деталями читатель может найти в [1] - докладе I рабочей группы МПКИ, также появившемся в июне 1990 г.

и формируется спектральными линиями и молекулярными полосами, которые могут быть насыщенными и ненасыщенными. Поглощательная способность зависит также от температуры, давления, присутствия других газов, перекрытия полос и тд. Количественное значение этих основных свойств получается путем длительных и дорогих лабораторных измерений и численных расчетов. Точность, с которой известны все эти свойства и зависимости, порядка 10% или хуже (см. [1]).

Удобной мерой величины парникового эффекта является изменение радиационного баланса тропосферы, осредненного по пространству (глобально) и времени (год) при удвоении концентрации CO_2 в атмосфере. Обозначим эту величину 6 ($2CO_2$), или просто 8_2. Еще недавно [9] всюду использовалось 8_2 = 4.0 Вт/м^2, затем [10] рекомендовалось 8_2 = 4,62 Вт/м^2, и в [1] (лето 1990 г.) рекомендуется 8_2 = 4,35 Вт/м^2, как можно вычислить по данным таблицы 2.2 из [1]. Разброс в этих цифрах хорошо иллюстрирует состояние знаний в данном вопросе.

Все приведенные значения 8_2 вычислялись для так называемых нормальных или средних условий в отношении температуры, давления, содержания водяного пара, молекулярные полосы которого перекрываются с таковыми для CO_2. В действительности, все эти параметры зависят от сезона, географических координат, вертикальных профилей термодинамических переменных, количества облаков и т.п. Работа по расчетам величины 3_2 для этих разных условий и по ее последующему осреднению не производилась. Величина 8_2 при этом может меняться в пределах от 2,5 до 6 Вт/м^2 [11,12]. При этом могут возникать неопределенности порядка 20%.

Другие парниковые газы в отношении их поглощательных свойств и зависимостей последних от вышеуказанных параметров пользовались гораздо меньшим вниманием исследователей, чем углекислый газ. Тщательная и обширная работа должна быть проведена в этом направлении, поскольку их суммарный парниковый эффект практически такой же, как от CO_2.

Большой научный и практический интерес представляет вопрос - как величина парникового эффекта зависит от количества данного газа в атмосфере. Это определяется, в первую очередь, природой поглощения в ИК-области спектра (детали см. в таблице 2.2 из [1]). Для углекислого газа основное поглощение дает молекулярная полоса с центром 15 мкм. Эта полоса уже насыщена, т.е. уже при теперешнем содержании CO_2 тепловое излучение полностью поглощается атмосферой в центральных частях полосы. Любые добавления CO_2 в атмосферу увеличивают поглощение, 8, лишь в крыльях этой полосы. Эго приводит к логарифмической зависимости поглощения от концентрации С: 8 а 1пС.

Для метана и закиси азота ситуация другая. Их концентрации на два или три порядка меньше, чем у CO_2, и поэтому их основные поглощательные полосы ненасыщены, но линии в этих полосах насыщены. Поэтому увеличение концентрации CH_2 и X_2O ведет к заполнению промежутков между линиями в полосе. В результате 8 а $C^{1/2}$.

Наконец, фреоны и озон в тропосфере обладают основными линиями поглощения в окне прозрачности 8-12 мкм. Линии не насыщены и поэтому величина 8 прямо пропорциональна их концентрациям. В результате эти компоненты наиболее эффективны в поглощении тепловой радиации. В расчете на одну молекулу данные газы примерно на три порядка более эффективны, чем метан, который, в свою очередь, примерно в 20 раз более эффективен, чем молекула (дополнительная) углекислого газа в атмосфере.

ИЗМЕНЕНИЯ ВО ВРЕМЕНИ РАЗЛИЧНЫХ ПАРНИКОВЫХ ГАЗОВ

В доиндустриальную эпоху любые изменения состава атмосферы были очень медленными по сравнению с таковыми за последнее столетие или два. Весьма точные инструментальные реконструкции состава атмосферы в отношении углекислого газа и метана были выполнены недавно группой французских и советских ученых [13,14], которые проанализировали состав пузырьков воздуха ледяных кернов со станции Восток, имеющих возраст до 160 тысяч лет (Кл). Оги данные показывают очень тесную корреляцию содержания CO_2 и CH_4 с температурными вариациями: в предыдущий интергляциал и в нынешний концентрации CO_2 были в пределах 280-300 млн-^{1}, а в период максимума оледенения (18 Кл) они были в пределах 180-200 млн-^{1}. Примерно вдвое разнятся соответствующие цифры для метана - 700 и 350 млрд-^{1} для теплых и холодных периодов. Не говоря прямо нам, что является причиной чего и какова чувствительность климата на временных масштабах порядка тысяч лет (а мы интересуемся временными масштабами порядка десятилетий), тесная корреляция между средней температурой поверхности и концентрацией парниковых газов в атмосфере вне всякого сомнения.

Очень медленные вариации концентраций малых примесей атмосферы означают, что источники и стоки для этих газов очень хорошо балансируют друг друга. Гораздо более быстрые вариации, а именно, увеличение концентраций в атмосфере многих малых примесей за последние десятилетия, означают, что естественные стоки для данного газа не могут справиться с усилившимися источниками и накопление этих газов в атмосфере и означает рост их концентрации. Понять изменения в интенсивностях источников и стоков - является одной из главных задач Международной геосферно-биосферной программы, или Программы глобальных изменений. Оценить и предсказать антропогенную часть источников - это относительно хорошо поставленная задача, которая требует инвентаризации источников, связанных с деятельностью человека, т.е. производство за год, время хранений и время употребления продукта и т.д. Естественная часть источника и все стоки, которые все натурального происхождения, являют собой наиболее трудную часть проблемы, поскольку они требуют знания многих физических, химических, биологических процессов в атмосфере и на земной поверхности, в почве, на границе раздела атмосфера-океан, внутри океана и т.д. Большинство из этих процессов известны лишь очень худо и многие из них ожидают своего уточнения, или даже открытия.

Все рассматриваемые малые примеси выявляют, помимо трендов, специфические распределения с широтой и высотой, которые, в свою очередь, определяются локализацией в пространстве и времени источников и стоков. Мониторинг этих газов из космоса, с самолета и на наземных базовых станциях абсолютно необходим для описания и понимания проблемы источников и стоков, времени жизни молекул газа в атмосфере, его перемешивания и их реакций внутри атмосферы и на земной поверхности. Без понимания всех этих процессов и явлений мы не сможем надежно предсказывать будущие концентрации этих газов и, следовательно, будущий климат. Теперь обсудим основные малые примеси и состояние нашего понимания этих газов.

Водяной пар

Водяной пар - главный парниковый газ естественного происхождения. Любые дополнения к его содержанию в атмосфере благодаря, скажем, большим новым водохранилищам, существенны, в лучшем случае, на региональном уровне, однако их вклад в глобальную величину весьма мал. Основной источник влаги в атмосфере - испарение с поверхности океана, затем - испарение с почв, особенно путем эвалотранспирации, что влияет на региональные содержания водяного пара и осадки. Среднеглобальное содержание водяного пара около 2 г/см^2 (3200 млн-^{1})» но локально оно сильно изменяется в пространстве и времени. Среднее время жизни молекулы H_2O в атмосфере оценивается в 10 дней.

Благодаря уравнению Клапейрона-Клаузиуса, чем теплее атмосфера, тем больше пара она может содержать. Это определяет основную положительную обратную связь в климатической системе, примерно удваивая эффект второго по значению парникового газа в атмосфере - углекислого газа. Благодаря большой изменчивости водяного пара в атмосфере не существует систематического мониторинга его содержания, что жалко, поскольку иначе мы смогли бы понять многие важные особенности нашей климатической системы. Особенно важно это могло бы оказаться для стратосферы, где водяной пар вступает во многие важные химические реакции, связанные с метаном, озоном и другими субстанциями. Он также является источником образования радикала гидроксила, ОН, главного очистного агента атмосферы. Некоторые отдельные измерения дают основания предположить, что количество водяного пара в стратосфере могло за последние десять лет увеличиться примерно на 30%, однако эти результаты, благодаря их важности для химии стратосферы, нуждаются в систематических подтверждениях, т.е. в мониторинге. Это увеличение могло бы дать несколько процентов в увеличение роста температуры за последнюю декаду.

Со спектроскопической точки зрения проблема континуума поглощения в окне прозрачности 8-13 мкм все еще ожидает уточнения в зависимости от температуры, давления и концентрации H_2O. Поскольку можно ожидать, что в более теплом климате континуум будет сильнее, это дает еще одну положительную обратную связь в климатической системе.

Углекислый газ

Двуокись углерода - основа фотосинтеза и без него жизнь не существовала бы на земле. Этот газ пренебрежимо мало поглощает солнечную радиацию и очень сильно - тепловую радиацию, в основном в полосе 13-17 мкм. Точность нашего знания поглощения была описана выше. В настоящее время CO_2 дает около 55% суммарного эффекта всех парниковых газов, если исключить водяной пар. Годовой поток CO_2 между атмосферой и биосферой оценивается в 17% от полного его содержания в атмосфере, а между атмосферой и океаном - в 12%. Время жизни молекулы CO_2 порядка пяти лет, но, учитывая взаимодействие с океаном и его дном, это время возрастает до 150 лет [1]. Интенсивность антропогенного источника CO_2 порядка 0,8% в год, из чего порядка 20% обязано биологическим источникам (сжигание биомассы, обезлесивание, деградация гумуса и т.п.). Более точное определение интенсивности биологического источника ожидает своего осуществления.

Регулярные измерения концентрации CO_2 начались в 1958 г. на Мауна Лоа, о. Гавайи, затем они были дополнены станциями на Южном полюсе, Самоа, мысе Барроу, на Аляске и рядом других. В 1980 г. регулярные измерения начались на озере Иссык-Куль в Киргизии [15]. Все эти данные выявляют постоянное увеличение среднегодовых значений приблизительно на 0,5% в год Данные Южного полюса запаздывают по уровню CO_2 по сравнению с Мауна Лоа примерно на один год. Все станции проявляют сезонный ход, который максимален - свыше 20 млн^1 - для внутриконтинентальных станций средних широт (Иссык-Куль) и невелик - лишь несколько млн'^{1} - для станции на тропическом о. Самоа и на Южном полюсе и для всего южного полушария, поскольку оно в основном - океан. Максимум концентрации наблюдается в конце зимы-начале весны, а минимум - в конце лета-начале осени. Эго связано с усилением биологической активности в теплый период, что ведет к увеличению использования двуокиси углерода растениями. Обзор сезонно-широтного распределения CO_2 в глобальном масштабе можно найти в [16].

Иногда спрашивают, что если потоки CO_2 между атмосферой, океаном и биосферой, известные лишь с точностью порядка 10%, почти на два порядка больше, чем потоки CO_2 от сжигания ископаемого топлива (более или менее хорошо установленные путем инвентаризации), то почему мы уверены, что увеличение содержания CO_2 в атмосфере вызвано именью деятельностью человека?

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