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Drought

Lectures presented at the twenty-sixth session of the WMO Executive Committee

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NOTE

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the World Meteorological Organization concerning the legal status of any country or territory or of its authorities, or concerning the delimitation of its frontiers.

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(Summaries in English, French, Russian and Spanish are provided with each lecture)

FOREWORD

At each session of the WMO Executive Committee a theme is chosen for a scientific discussion which takes the form of previously prepared lectures delivered by acknowledged experts in the chosen theme followed by a general discussion.

In view of the disastrous droughts which have occurred in recent years in many countries, particularly in Africa and Asia, the Organization is now giving greatly increased attention to this subject. Among the steps taken to this end was the decision of the Executive Committee to select "Drought" as the theme for the scientific discussions at its twenty-sixth session (1974). The present publication contains the full texts of the three papers presented on that occasion.

The first paper, entitled "Drought - its definition, delineation and effects", was prepared by Dr. W. J. Gibbs (Australia) and was presented on his behalf by Dr. J. W. Zillman. The second, entitled "Drought, a recurrent element of climate", was presented by Professor H. E. Landsberg (U.S.A.). The third paper, entitled "Aperçu sur les données hydrologiques de la sécheresse de la période 1970-1973 en Afrique tropicale", was presented by Mr. J. A. Rodier (France).

I am pleased to have this opportunity of expressing to the scientists concerned the sincere appreciation of the World Meteorological Organization for the time and effort they have devoted to the preparation of these valuable papers.

D. A. Davies
Secretary-General

DROUGHT - ITS DEFINITION, DELINEATION AND EFFECTS

by

W. J. Gibbs
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SUMMARY

The lecture sought to answer four questions:

1. What is drought?

2. Is drought the result of a change in climate?

3. Is it possible to ameliorate drought by artificial modification of climate?

4. Can a world-wide strategy be developed to combat the effects of drought?

Although drought is difficult to define precisely, in general terms it can be regarded as the condition where there is "lack of sufficient water to meet requirements", the requirements being dependent upon the distribution of plant, animal and human populations, their life-style and their use of the land. The problem of drought is thus an integral part of the larger problem of the management and use of the worlds limited resources.

In examining the occurrence and attempting to delineate the extent of drought, the most useful single index of water supply is rainfall. However, the non-Gaussian distribution of rainfall occurrence suggests the need for statistical description of parameters other than the mean and standard deviation. Gibbs and Maher in 1967 advocated the use of a system which was based on the limits of each ten per cent (or decile) of the distribution. The fifth decile or median is the rainfall amount not exceeded by 50 per cent of occasions. The decile ranges span the values between deciles; some examples were given for various Australian climatic régimes. In particular, attention was drawn to discrepancies between mean and median monthly rainfalls. Maps were also shown depicting the distribution of annual decile ranges over Australia during two of the most severe drought periods since rainfall records began. The occurrence of the first decile range corresponds well with drought areas delineated on the basis of other conditions. Examination of decile values for shorter than annual periods has been used in Australia since 1965 for a drought alerting service.

Preliminary results of an application of the Gibbs-Maher approach to world rainfall data by Lee and Maher were discussed. Maps of the world distribution of decile ranges for the years 1965, 1968, 1969 and 1970 show the considerable spatial variability of the decile values of annual rainfall and indicate the beginnings of the drought in the Sudano-Sahelian regions of Africa. More detailed examination of the African regions for the years 1971-1973 showed the spread of the first decile range over the Sahelian zone during this period.

The question as to whether drought is the result of climatic change is difficult to answer. Particularly in arid and marginal lands, differences between successive 30-year "normals" may be due to no more than sampling effects. It is important to distinguish between drought and aridity. In the marginal lands bounding arid zones the "normal" variability of rainfall means that drought must be regarded as a normal climatic occurrence.

With the present state of scientific knowledge and technology there appears little hope of ameliorating drought by the artificial modification of weather or climate as drought periods are usually characterized by large-scale subsidence and cloud-free skies.

Australian experience has shown that the effect of drought is lessened when farmers and government authorities are aware of its nature and extent and therefore can make appropriate plans. It is believed that the Australian experience could have an application on a world-wide scale. In the context of global plans for dealing with natural disasters, consideration might be given to a world-wide drought and alerting service, possibly with a centre operating in each continent and reporting to some central position such as the WMO Secretariat or the Secretariat of the United Nations.

RESUME

Le conférencier s'est efforcé de répondre aux quatre questions suivantes :

1. Qu'est-ce que la sécheresse ?
2. La sécheresse est-elle le résultat d'un changement de climat ?
3. Est-il possible de pallier la sécheresse en modifiant artificiellement le climat ?
4. Est-il possible de mettre au point une stratégie mondiale pour combattre les effets de la sécheresse ?

Bien qu'il soit difficile de définir avec précision ce qu'est la sécheresse, on peut estimer généralement qu'il y a sécheresse lorsqu'"il n'y a pas suffisamment d'eau pour satisfaire aux besoins", ceux-ci étant fonction de la distribution de la flore, de la faune et de la population humaine, de leurs modes de vie et de l'usage qu'elles font du sol. Le problème de la sécheresse fait donc partie intégrante du problème plus vaste de la gestion et de l'exploitation des ressources limitées de la Terre.

Lorsque, pour étudier les cas de sécheresse et essayer de déterminer l'extension de celle-ci, on utilise un seul indice des apports d'eau, le plus utile est la hauteur des précipitations. Toutefois, du fait que les jours de précipitations ne sont pas distribués selon la loi de Gauss, il est nécessaire, pour les besoins de la description statistique, d'utiliser d'autres paramètres que la moyenne et l'écart type. En 1967, Gibbs et Maher ont préconisé l'utilisation d'un système fondé sur les limites déciles de chaque tranche de 10% de la distribution. Le cinquième décile (ou médiane) est égal à la hauteur des précipitations qui n'est dépassée que dans 50% des cas. Les <u>écarts</u> interdéciles correspondent aux intervalles entre déciles successifs; des exemples ont été fournis pour divers régimes climatiques de l'Australie. En particulier, l'auteur a attiré l'attention sur les différences qui existent entre la moyenne et la médiane des précipitations mensuelles. Il a également présenté des cartes montrant la distribution des écarts interdéciles au-dessus de l'Australie durant deux des plus rigoureuses sécheresses enregistrées depuis que l'on dispose de relevés pluviométriques. Les zones où la hauteur des précipitations est inférieure au premier décile correspondent bien avec les zones de sécheresse délimitées sur la base d'autres critères. En Australie, depuis 1965, on suit l'évolution des valeurs des déciles établies pour des périodes plus courtes que l'année, afin de pouvoir lancer des alertes de sécheresse.

L'auteur a analysé les premiers résultats que Lee et Maher ont obtenus en appliquant aux données pluviométriques mondiales le système élaboré par Gibbs-Maher. Des cartes de la distribution mondiale des écarts interdéciles pour les années 1965, 1968, 1969 et 1970 montrent la variabilité spatiale considérable des valeurs des

déciles de la hauteur des précipitations annuelles et révèlent l'apparition de la sécheresse dans les régions soudano-sahéliennes de l'Afrique. Un examen plus détaillé des régions africaines en ce qui concerne les années 1971-1973 a révélé l'extension des hauteurs de précipitations inférieures au premier décile à l'ensemble de la zone sahélienne au cours de cette période.

Il est difficile de répondre à la question de savoir si la sécheresse est le résultat d'un changement de climat. En particulier dans les zones arides et semi-arides, les différences constatées entre les "normales" trentenaires successives peuvent être simplement dues à des différences dans l'échantillonnage. Il importe de bien distinguer la sécheresse de l'aridité. Dans les zones semi-arides, en bordure des zones arides, la variabilité "normale" de la hauteur des précipitations impose de considérer la sécheresse comme éventualité climatique normale.

Dans l'état actuel des connaissances scientifiques et de la technologie on ne peut guère, en période de sécheresse, escompter améliorer la situation en recourant à la modification artificielle du temps ou du climat, étant donné que durant ces périodes il règne généralement de la subsidence au-dessus de vastes territoires, ce qui entraîne une absence totale de nuages.

L'expérience australienne montre que les conséquences de la sécheresse sont minimisées lorsque les agriculteurs et les autorités gouvernementales sont informés de la nature et de l'étendue du phénomène et peuvent ainsi prendre des dispositions appropriées. L'auteur estime que l'expérience australienne pourrait avoir des applications à l'échelle mondiale. Dans le cadre des plans mondiaux destinés à faire face aux calamités naturelles, on pourrait envisager d'établir un service d'alerte mondial pour la sécheresse comprenant un certains nombre de centres, éventuellement un dans chaque continent, qui feraient rapport à un organisme central tel que le Secrétariat de l'OMM ou le Secrétariat de l'Organisation des Nations Unies.

РЕЗЮМЕ

В лекции делается попытка ответить на четыре вопроса:

1. Что такое засуха?

2. Является ли засуха результатом изменения климата?

3. Можно ли избежать засухи путем искусственного воздействия на климат?

4. Можно ли разработать мировую стратегию по борьбе с влиянием засухи?

Хотя точно определить засуху трудно, в общих чертах ее можно считать условием, когда "воды недостаточно для удовлетворения потребностей"; потребности зависят от распределения растительности, животных и населения, их образа жизни и использования земли. Таким образом, проблема засухи является составной частью более крупной проблемы управления ограниченными мировыми ресурсами и их использования.

При изучении возникновения засухи и при попытках описания ее размеров наиболее полезным <u>единичным</u> индексом водоснабжения являются дождевые осадки. Однако распределение осадков, не поддающееся закону Гаусса, приводит к необходимости статистического описания параметров, помимо средних и стандартных отклонений. Гиббс и Махер в 1967 г. защищали применение системы, имеющей в качестве пределов каждые десять процентов (или дециль) распределения. Пятой децилью, или медианой, является количество осадков, не превышающее 50% случаев. Границы децилей перекрывают значения между децилями. Были даны некоторые примеры различных климатических режимов Австралии. В частности, обращалось внимание на несоответствие между средним месячным количеством осадков и медианой. Были также показаны карты, демонстрирующие распределение по Австралии годовых диапазонов децилей во время двух наиболее суровых периодов засухи, наблюдающихся со времени начала регистрации количества осадков. Размещение границ

первой децили хорошо соответствует районам засухи, очерченным на основе других условий. Изучение значений децилей для периодов короче одного года проводилось в Австралии с 1965 г. службой предупреждения о засухе.

Обсуждались предварительные результаты подхода Гиббса-Махера, примененного Ли и Махером к мировым данным об осадках. Карты мирового распределения диапазонов децили за 1965, 1968, 1969 и 1970 гг. свидетельствуют о значительной пространственной изменчивости значений децили для годовых осадков и отмечают начало засухи в Судано-Сахельском районе Африки. Более подробное изучение африканских районов за 1971 -1973 гг. показало, что в течение этого периода границы децили распространились на Сахельскую зону.

На вопрос о том, является ли засуха результатом климатических изменений; ответить трудно. В частности, на засушливых и пограничных с ними землях разница между последовательными 30-летними "нормами" могут не превышать влияния отбора. Важно проводить различие между засухой и засушливостью. В районах, граничащих с засушливыми зонами, изменчивость "нормального" количества осадков означает, что засуху следует рассматривать как результат обычной климатической повторяемости.

При нынешнем уровне научных знаний и техники нет особых надежд на преодоление засухи путем искусственных воздействий на погоду или климат, поскольку периоды засухи обычно характеризуются крупномасштабным оседанием воздушных масс и безоблачным небом.

Опыт Австралии показал, что влияние засухи уменьшается, когда фермеры и правительственные органы информированы о ее характере и масштабах для выработки соответствующих планов. Мы полагаем, что опыт Австралии может быть применен во всемирном масштабе. В глобальных планах по борьбе со стихийными бедствиями следует уделить должное внимание всемирной службе предупреждения о засухе, возможно, с центром, действующим на каждом континенте и направляющим данные в некоторый главный центр, например, в Секретариат ВМО или в Секретариат Организации Объединенных Наций.

RESUMEN

En esta conferencia se trató de responder a las cuatro preguntas siguientes:

1. ¿Qué es sequía?

2. ¿La sequía, es el resultado de un cambio de clima?

3. ¿Es posible reducir la sequía mediante la modificación artificial del clima?

4. ¿Se pueden crear sistemas mundiales para combatir los efectos de la sequía?

Aunque es difícil definir con precisión la sequía, en general se puede considerar que constituye una situación en la cual existe "falta de agua suficiente para satisfacer las necesidades". Estas necesidades dependen de la distribución de las poblaciones de plantas, animales y seres humanos, de su modo de vida y del aprovechamiento de las tierras. El problema de la sequía constituye pues parte integrante de otro problema mayor que es el aprovechamiento y uso de los limitados recursos mundiales.

Para estudiar la ocurrencia de las sequías y tratar de delimitar su extensión, el índice único más útil del suministro de agua es la lluvia. Sin embargo, el hecho de que la distribución de la ocurrencia de la lluvia no responde al tipo de Gauss, hace pensar en la necesidad de describir de manera estadística todos los parámetros, con excepción de la media y de la desviación típica. Gibbs y Maher en 1967 preconizaron la utilización de un sistema que se fundaba en los límites de cada decila de la distribución. La quinta decila o mediana es la cantidad de lluvia que no excede en el 50% de las ocasiones. Las amplitudes de la decila separan los valores entre las decilas. Se dieron algunos ejemplos de distintos regímenes climáticos en Australia. En particular se hicieron resaltar las discrepancias entre la media y la mediana mensual de la lluvia. Se mostraron mapas que describían la distribución de las amplitudes anuales de la decila en Australia durante dos de los períodos más fuertes de sequía, desde que se comenzaron hacer registros de la lluvia. La ocurrencia de la amplitud de la primera decila corresponde bien a las zonas de sequía delimitadas fundándose en otras condiciones. El estudio de los valores de la decila correspondientes a períodos más cortos de un año ha sido utilizado en Australia desde 1965 por el servicio de aviso de sequías.

Se discutieron los resultados preliminares de la aplicación hecha por Lee y Maher del método Gibbs-Maher a los datos mundiales de lluvia. Los mapas de la distribución mundial de las amplitudes de las decilas correspondientes a los años 1965, 1968, 1969 y 1970 mostraron la considerable variabilidad espacial de los valores de la decila correspondientes a la lluvia anual e indicaron los principios de la sequía que se produjo en la región Sudano-Saheliana de Africa. El estudio más detallado de las regiones africanas correspondientes a los años 1971-1973 demostró la extensión de la amplitud uno de la decila en la zona Saheliana durante dicho período.

Es difícil responder a la pregunta de si la sequía es el resultado de un cambio climático. Especialmente en las tierras áridas e improductivas, la diferencia entre las normales sucesivas de 30 años quizás no sean debidas más que a efectos de muestreo. Es importante distinguir entre sequía y aridez. En las tierras improductivas que limitan las zonas áridas, la variabilidad "normal" de la lluvia significa que la sequía debe ser considerada como una ocurrencia climática normal.

Teniendo presente los actuales conocimientos científicos y tecnológicos que se poseen, parece que existe poca esperanza de mejorar las sequías mediante la modificación artificial del tiempo o el clima ya que los períodos de sequía se caracterizan habitualmente por una subsidencia en gran escala y por la existencia de cielo despejado.

La experiencia australiana ha demostrado que el efecto de la sequía queda disminuido cuando los agricultores y las autoridades gubernamentales conocen su naturaleza y extensión lo cual les permite establecer los planes oportunos. Se cree que la experiencia australiana podría ser aplicada a escala mundial. Dentro de los planes mundiales establecidos para luchar contra las catástrofes naturales se podría estudiar la posibilidad de incluir un servicio mundial de aviso de sequías, posiblemente contando con una oficina principal en cada continente que transmitiese la información a otro organismo central tal como la Secretaría de la OMM o la Secretaría de las Naciones Unidas.

DROUGHT - ITS DEFINITION, DELINEATION AND EFFECTS

This paper seeks to answer four questions:

1. What is drought?
2. Is drought the result of a change in climate?
3. Is it possible to ameliorate drought by artificial modification of climate?
4. Can a world-wide strategy be developed to combat the effects of drought?

WHAT IS DROUGHT?

Definitions of drought are almost as numerous as the number of publications dealing with the subject. A comprehensive list of such definitions is included in a forthcoming WMO Technical Note prepared by a working group of the WMO Commission for Agricultural Meteorology. A most important factor in understanding drought, often not included in definitions, is that it is a "supply and demand" phenomenon. A definition which does not include reference to water requirement or "demand" must be regarded as inadequate. "Lack of sufficient water to meet requirements" is a definition probably as satisfactory as any other.

If the "demand" factor is included in the definition it follows that delineation of drought occurrence depends on the nature of the water need. Conditions which a vegetable farmer may regard as drought may cause a sheep farmer no concern. In other words, drought occurrence depends on the density and distribution of plant, animal and human populations, their life-style and their use of the land as much as on rainfall deficiency.

There has been a recent upsurge of interest in the management and use of the world's limited resources in relation to the exponential growth of world population and the way in which this will affect the quality of life of the world community in the future. Interest in this subject is apparent in the Specialised Agencies and the General Assembly of the United Nations and in bodies such as the Club of Rome. This body has commissioned a study by an MIT group, the results of which, in the publication "The limits of growth" (1972), include models linking the interaction between resource use, population growth and the quality of life.

Few such studies appear to give sufficient emphasis to the importance of water resources. Treatment of subjects such as rainfall occurrence, water storage and desalination is usually superficial.

Drought in the Sudano-Sahelian region of Africa in recent years has highlighted a more general and long-standing problem regarding the efficient use of water resources. Although the problem is as old as man himself, communities and nations seem particularly ill-equipped to cope with natural disasters, such as droughts, when these occur rarely. Expediency in dealing with more frequent and more immediate national and international problems pushes the need to plan for amelioration of such rare disasters into the background of man's consciousness. It is only when beset by such disasters that, often too late, he seeks remedial measures.

The exponential growth of world population and the finite nature of world resources demand that more attention be given to this problem in the immediate future.

DROUGHT INDICATORS

The definition of drought as "the situation when demand for water exceeds supply" obviously needs amplification. Reduced availability of water may result in a modification of demand. Consider the example of a particular grain crop which has a basic water requirement to avoid wilting before harvest and a larger optimum requirement necessary to produce maximum yield.

Rainfall which produces zero crop yield obviously results in drought but the amount below which a crop is considered to be drought-stricken depends on the degree to which a reduced yield can be tolerated. Usually the criterion will depend on economic factors. The limit may be set at that which reduces yield to a quarter, or one half or three-quarters the "optimum" yield. Obviously there is no unique criterion.

Urban communities and industrial activities also have a demand for water, the acceptable minimum of which might be that necessary to maintain essential industry, and to meet those requirements necessary for personal health and survival. The amount of water considered to be the optimum for urban and industrial requirements depends very much on the standard of living and the life-style of the community and the nature and extent of its agricultural and industrial activities.

Although many factors are involved in considering availability of water, for example run-off, river systems, evaporation, the most useful single index of water supply is rainfall.

Because rainfall, unlike many other meteorological elements, for example, temperature and pressure, is non-continuous in time and space, its statistical description is quite complex.

The best known and most commonly used rainfall statistic is the mean (often called "average" or "normal"), which in the case of a normal or "gaussian" distribution is the same as the median - the value exceeded by half of the occurrences. In the case of a normal distribution the mean, together with some measure of the dispersion, such as the variance or standard deviation, completely describe the distribution and with these two parameters it is possible to calculate the probability of occurrence of values within any given range.

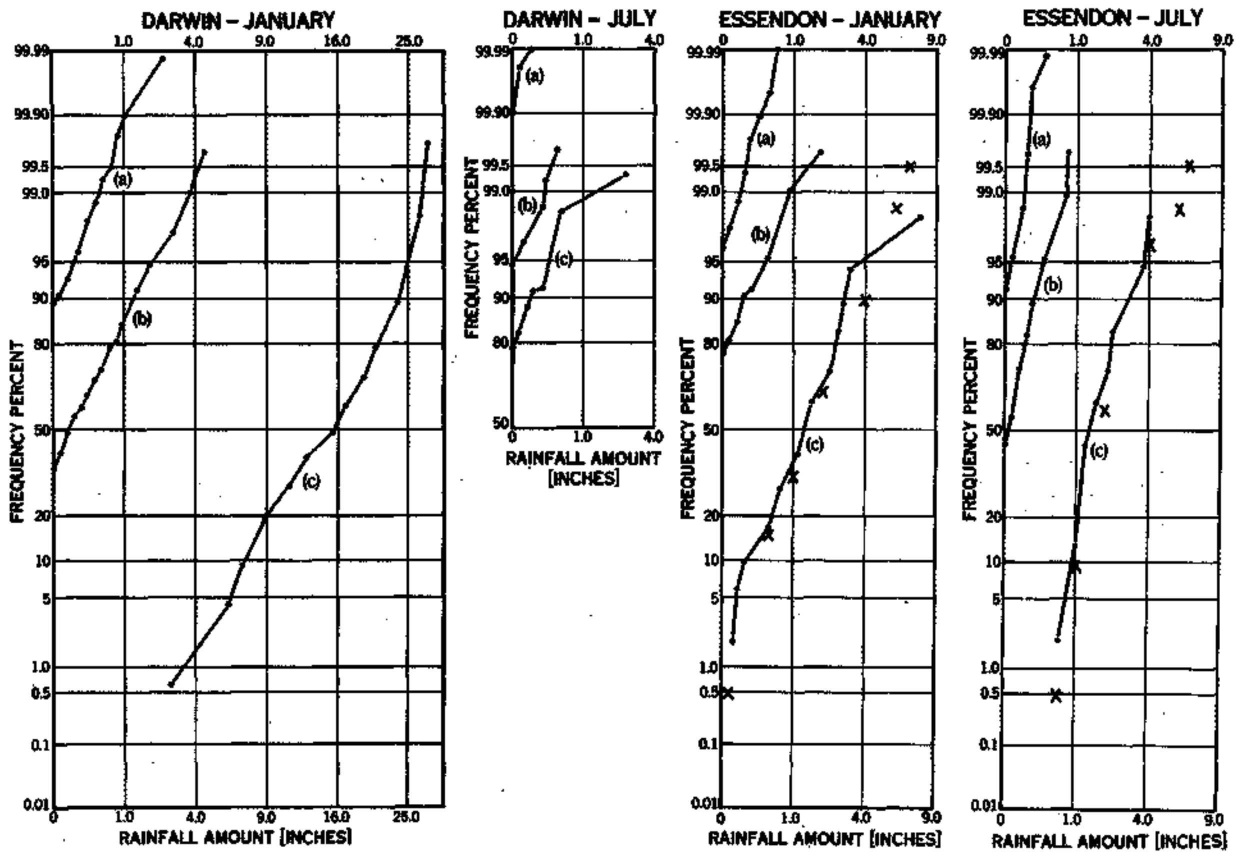

Figure 1 - Cumulative frequency distribution of (a) hourly, (b) daily, (c) monthly, rainfall amounts for Darwin and Essendon for the months January and July. Monthly data for Melbourne are indicated by X. Lengths of records are:

Darwin	(a) 3720 hours	(b) 155 days	(c) 82 months
Essendon	(a) 3720 hours	(b) 155 days	(c) 17 months
Melbourne			(c) 102 months

The abscissa on these figures plots rainfall on a square root scale and the ordinate of frequency is such that a normal distribution will be represented as a straight line

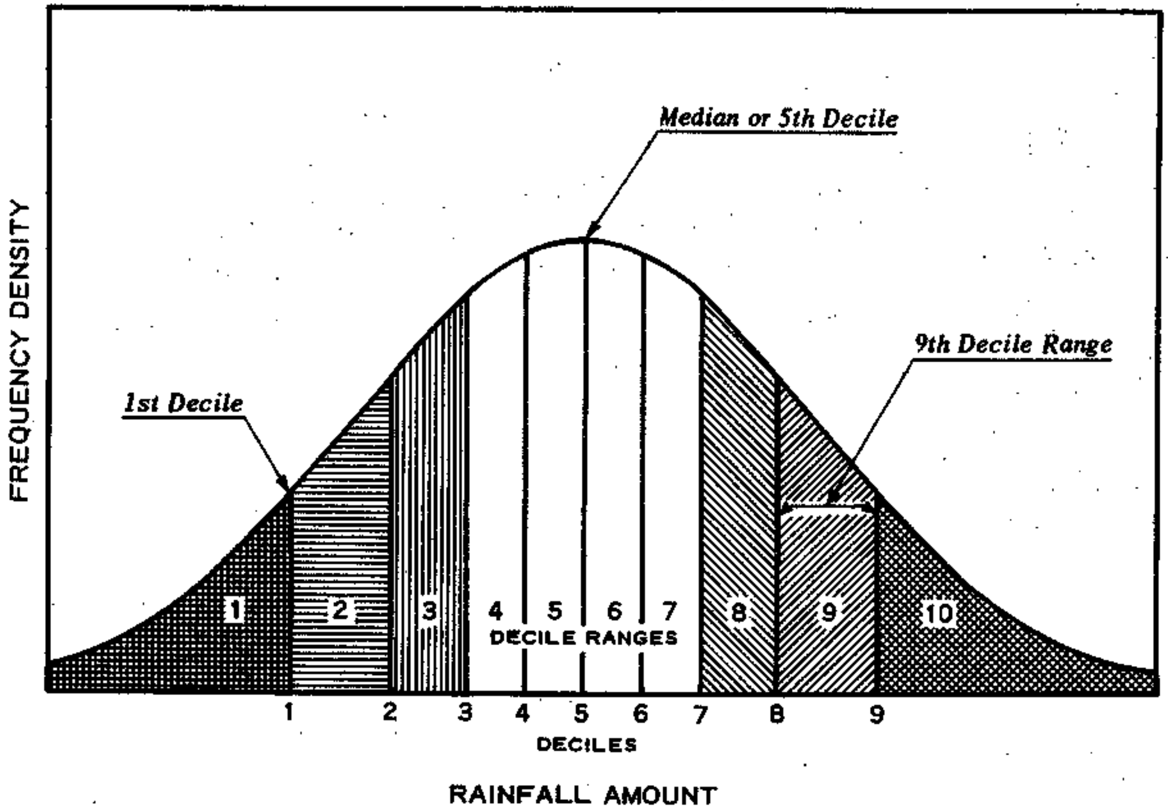

Figure 2 - Illustrating use of deciles and decile ranges. Normally the square root of rainfall will be plotted on the abscissa. The area under the curve for any given range of rainfall indicates the frequency or probability of occurrence within that range: thus there is an equal probability of rainfall falling in any decile range and the number of the decile range indicates "dryness" or "wetness" with respect to "normal"

However, it is rare for rainfall totals to be normally distributed - the distribution of many annual totals is not significantly different from normal but most monthly and all daily totals show a marked departure from the normal curve.

For this reason the common statistical measures of the mean and standard deviation are often poor indicators of the probability of rainfall occurrence. Gibbs (1964) has pointed out that the square roots of daily, monthly and even annual rainfall amounts for many Australian localities appear to be close to normally distributed, as illustrated in Figure 1, and the mean and standard deviation of the square roots enable a more accurate description of the distribution.

But whatever the nature of the statistical distribution a more attractive method of describing rainfall is one which is non-parametric, for example the use of percentile values.

Gibbs and Maher (1967) advocated a system which uses the limits of each ten per cent (or decile) of the distribution. Thus the first decile is that rainfall amount which is not exceeded by ten per cent of totals, and so on. The fifth decile or median is the amount not exceeded on 50 per cent of occasions. The decile ranges are the ranges of values between deciles. Thus the first decile range is that below the first decile, the eighth decile range between deciles seven and eight and the tenth decile range above decile nine. Figure 2 illustrates this concept.

Decile values give a good description of rainfall at a particular station. The decile range in which a particular rainfall occurs gives a useful indication of its departure from "average". Thus decile range one suggests abnormally dry and decile range ten abnormally wet conditions.

In drier climates decile values of monthly rainfall are frequently zero, as illustrated by the figures in Table I for Alice Springs, Halls Creek and Mardie. By contrast the figures for Darwin illustrate a case of tropical wet season month. The January and July figures for Melbourne are interesting in that whilst there is no significant difference in the January and July mean rainfall, there is a considerable difference in the median values (decile 5) which are 36 mm and 46 mm respectively. It might be noted that all decile values up to decile 8 for July at Halls Creek are below the mean value. Similarly at Mardie in October all up to decile 9 are below the mean.

TABLE I

Rainfall data for selected stations (mm)

	DARWIN	MELBOURNE		ALICE SPRINGS	HALLS CREEK	MARDIE
	Jan.	Jan.	July	Jan.	July	Oct.
Lowest	68	0.2	14	0	0	0
Decile 1	175	8	26	0	0	0
" 2	221	16	30	3	0	0
" 3	260	25	37	5	0	0
" 4	349	32	41	11	0	0
" 5	401	36	47	15	0	0
Mean	391	48	49	39	6	0.8

TABLE I (contd.)

	DARWIN	MELBOURNE		ALICE SPRINGS	HALLS CREEK	MARDIE
	Jan.	Jan.	July	Jan.	July	Oct.
Decile 6	443	46	53	33	0	0
" 7	487	60	57	44	0.5	0
" 8	526	76	62	71	3	0
" 9	595	106	73	95	23	0.3
Highest	708	176	178	280	80	24

Darwin	12° 24'S 130° 48'E	1873-1941, 1948-1964
Melbourne	37° 49'S 144° 58'E	1856-1964
Alice Springs	23° 36'S 133° 36'E	1874-1964
Halls Creek	18° 14'S 127° 40'E	1891-1964
Mardie	21° 12'S 115° 57'E	1891-1964

DROUGHT IN AUSTRALIA

Two major publications of the Australian Bureau of Meteorology are devoted to the question of drought in Australia. Gibbs and Maher (1967) proposed the use of deciles of annual rainfall as drought indicators and point out that the occurrence of the first decile range of rainfall during the period 1885 to 1965 corresponds rather well with droughts listed by Foley (1957) on the basis of newspaper and other reports of effects on crop yield and livestock populations.

The occurrence of the first decile range on the Gibbs and Maher maps of annual decile values corresponds well with droughts listed by Foley. Examination reveals that the most damaging droughts in Australia have coincided with the occurrence of large areas of the first decile range over successive years.

Figures 3, 4 and 5 show maps for 1900, 1901 and 1902. These were years usually regarded as experiencing one of the worst droughts on record. In New South Wales the average wheat harvest in 1903 was 1.2 bushels per acre (against a normal yield of ten bushels per acre) and the number of sheep in that State dropped from 42 million in 1901 to 27 million in 1902.

Figures 6-9 show maps for 1912-1915. In 1914 the wheat yield was two bushels per acre in Western Australia and 1.4 bushels per acre in South Australia and Victoria and there were heavy stock losses in Queensland, New South Wales and Victoria.

Figures 10, 11 and 12 show maps for 1965-1967. In Queensland, New South Wales and Victoria this period is regarded with 1902 as experiencing one of the most severe droughts on record. This drought resulted in a drop of about 40 per cent in

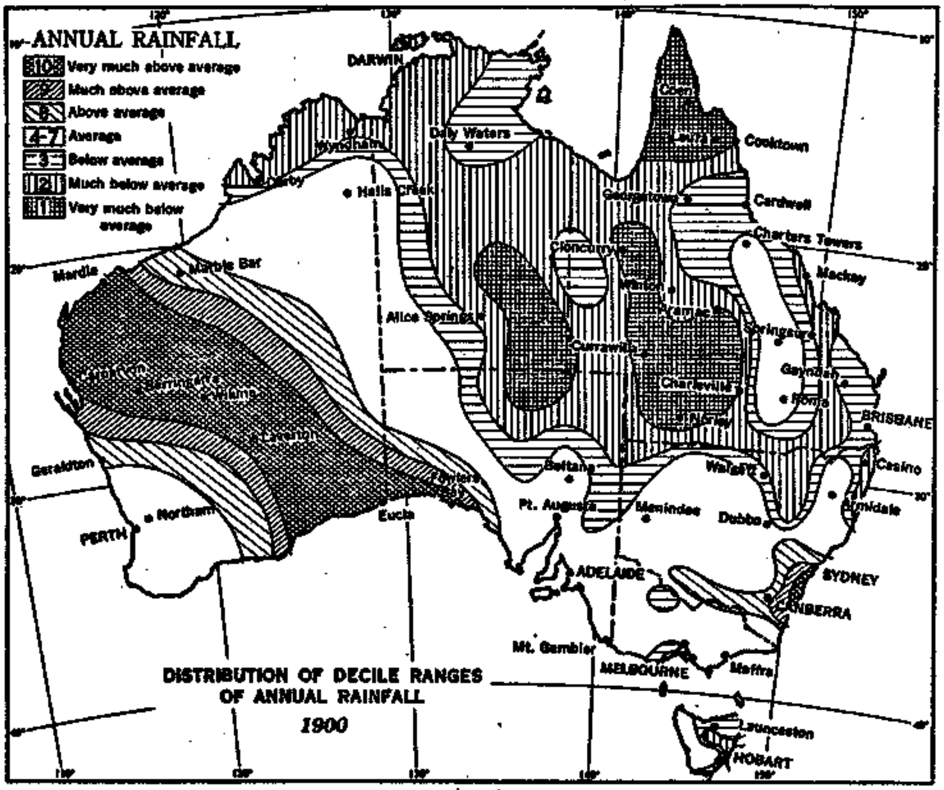

Figure 3

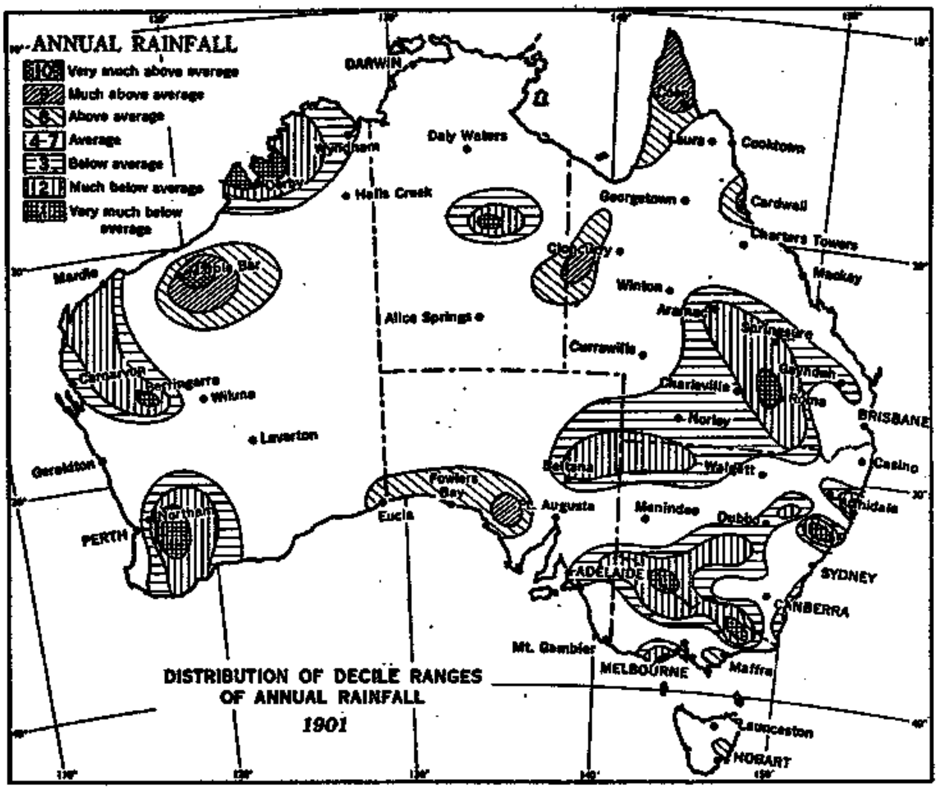

Figure 4

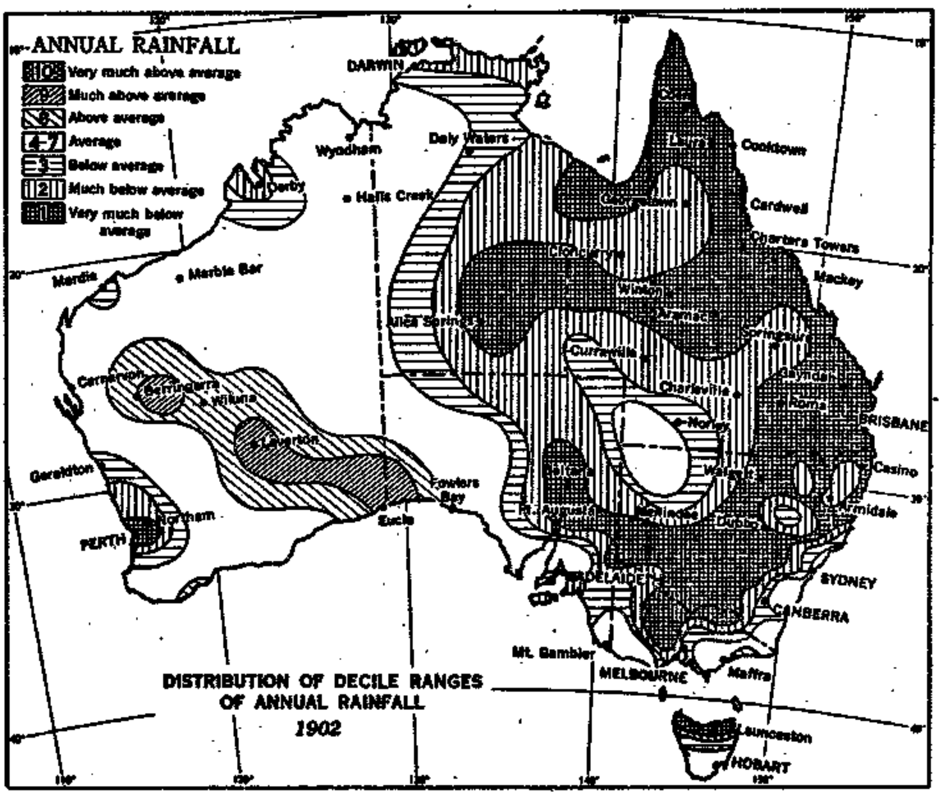

Figure 5

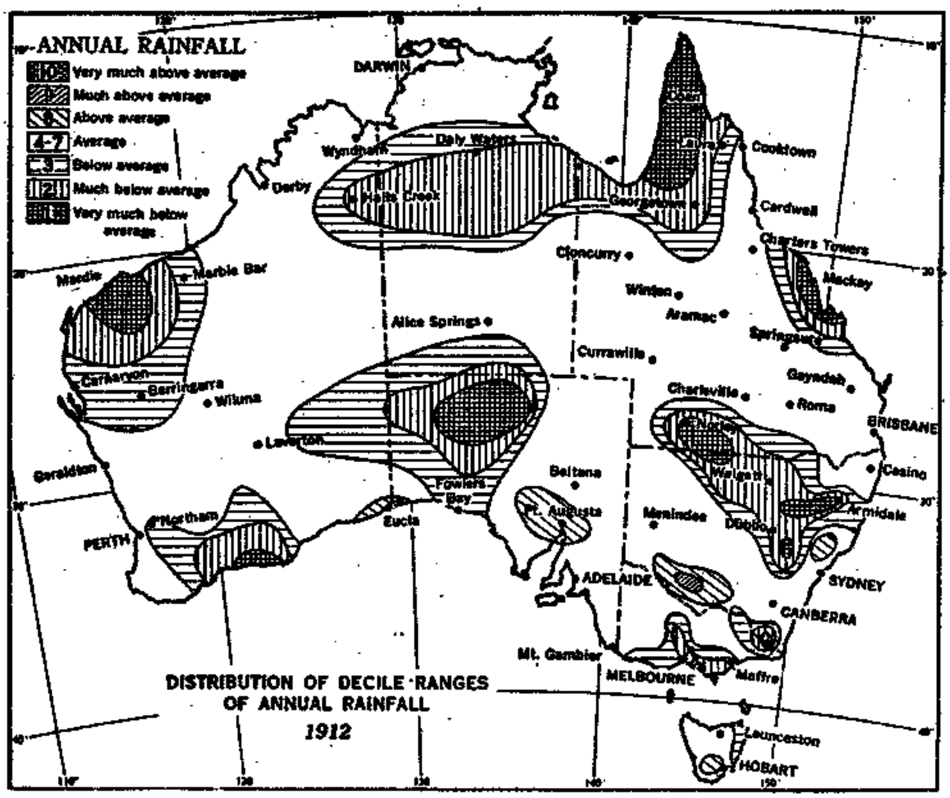

Figure 6

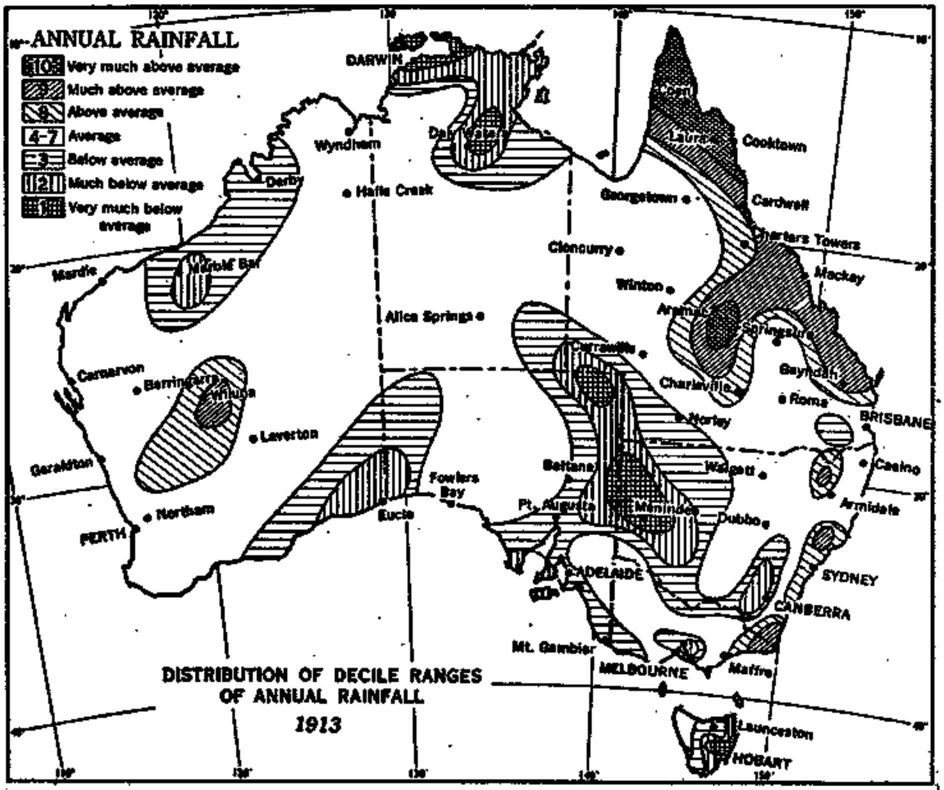

Figure 7

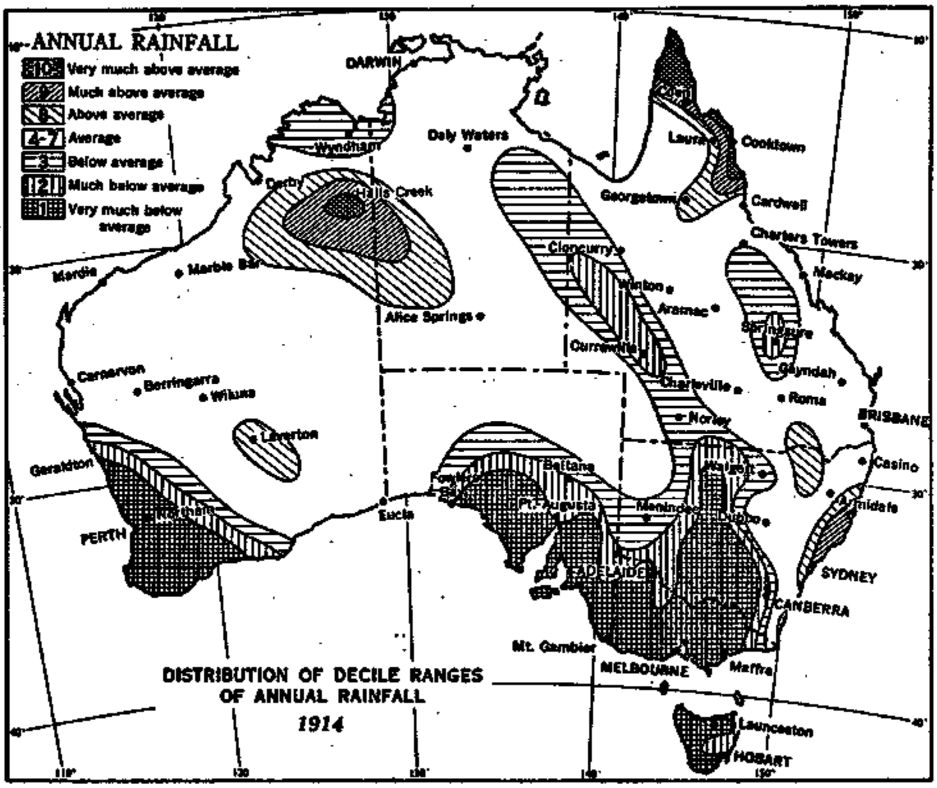

Figure 8

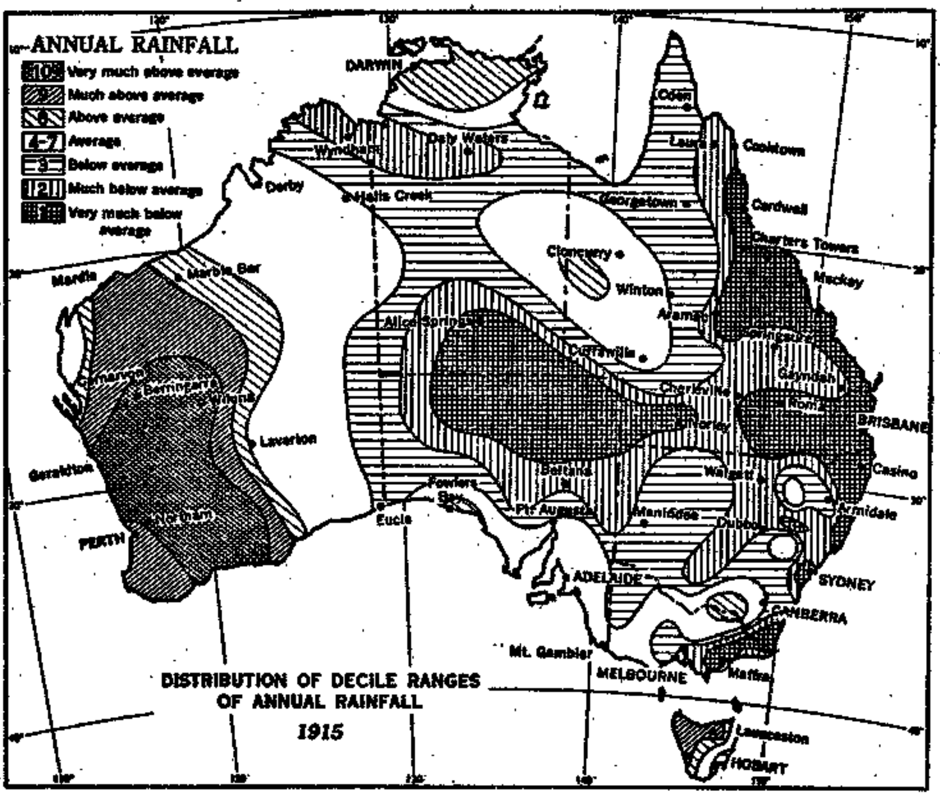

Figure 9

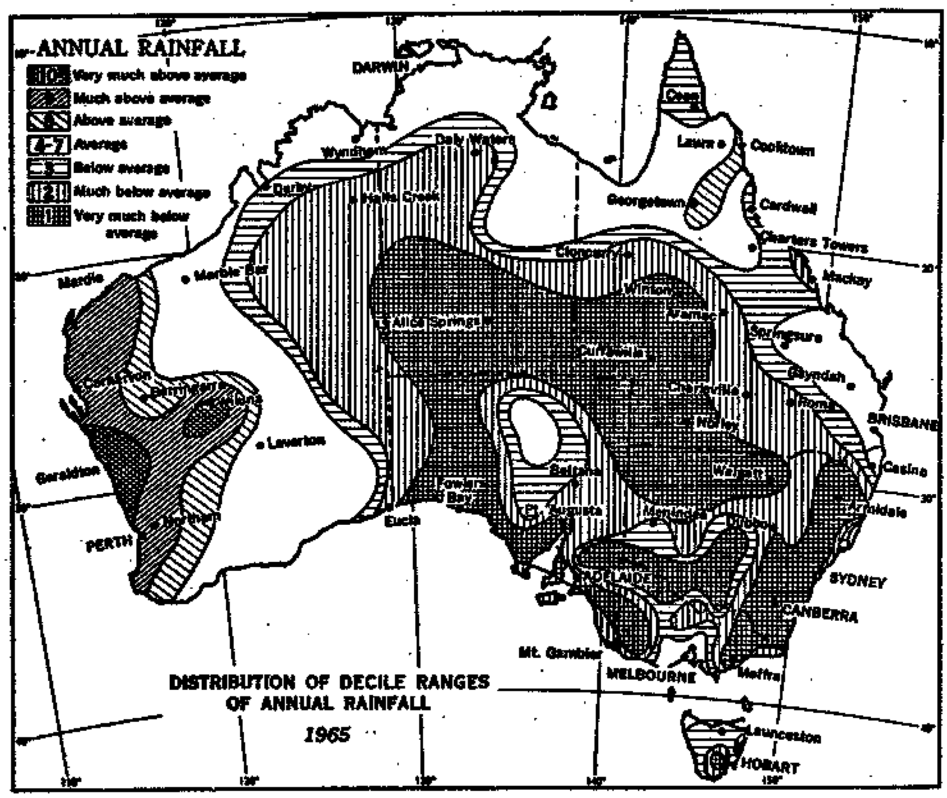

Figure 10

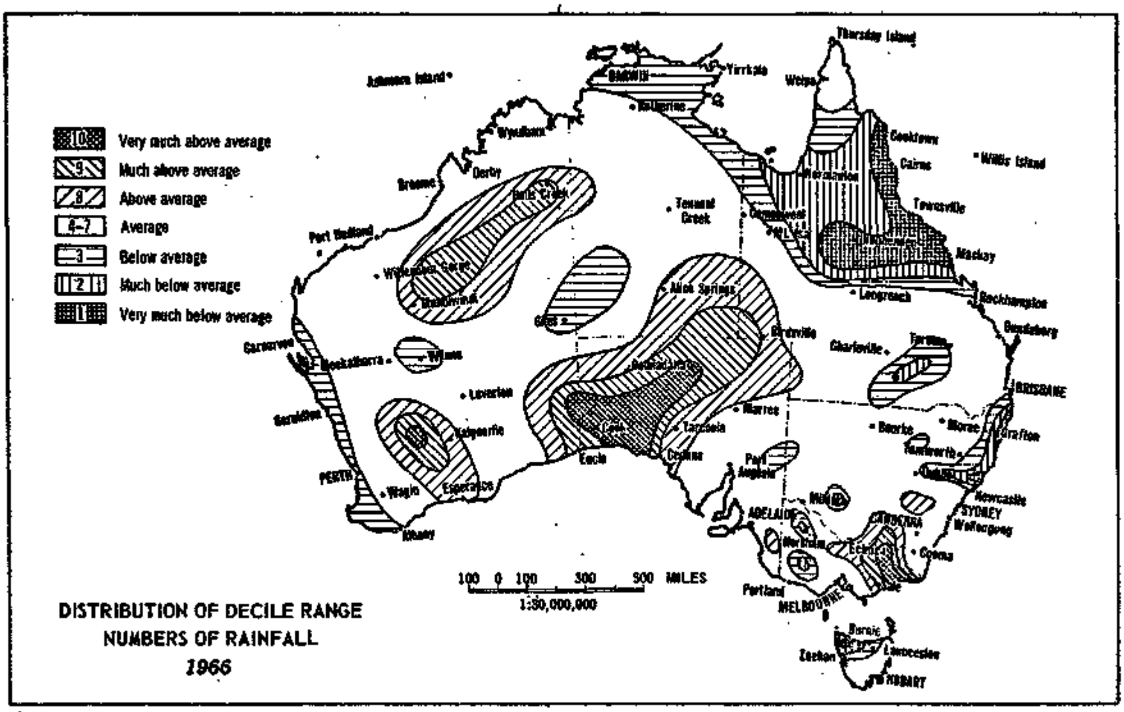

Figure 11

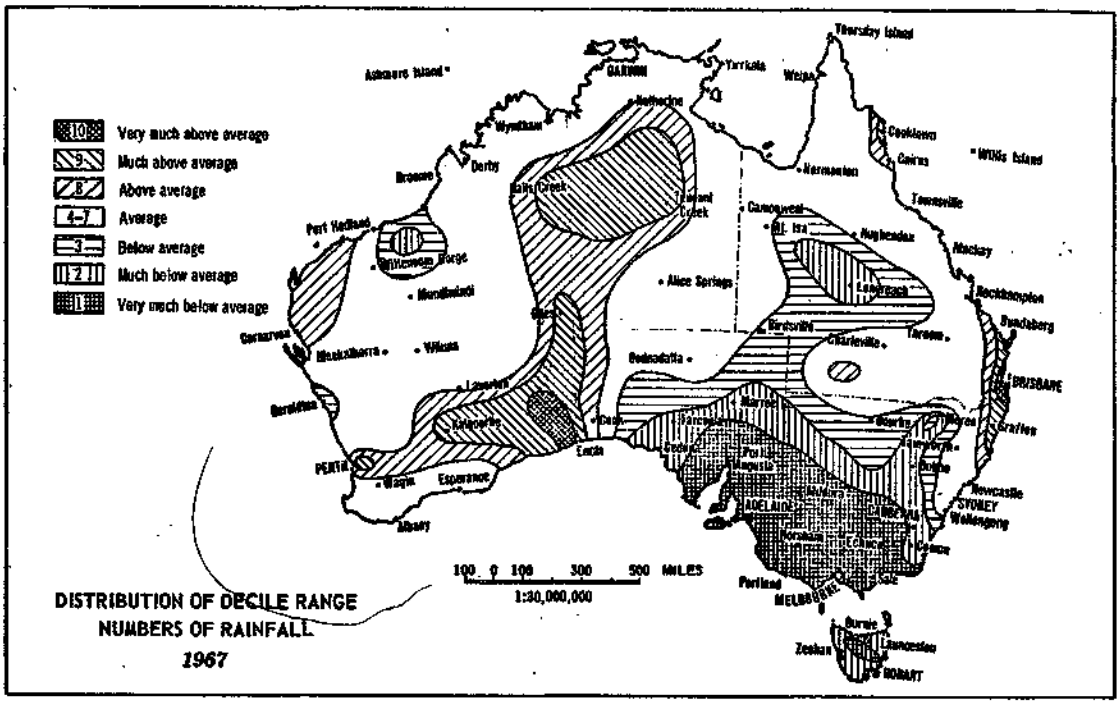

Figure 12

the wheat harvest and 60 per cent, 30 per cent and 15 per cent in oats, barley and rice crops respectively. Sheep population in the eastern States was reduced by over 20 million. Farm incomes decreased between $300 and $500 million with a very considerable chain reaction to other industries. In particular, manufacturers of farm machinery were hard hit and the New South Wales railways deficit of $10 million during the period was largely attributed to lack of revenue from transport of farm produce. Another serious effect of the drought was the heavy and sometimes complete depletion of large water storages leading to severe rationing of water in irrigation areas which might otherwise have helped ameliorate drought effects.

From their analysis of maps of decile values of annual rainfall from 1885 to 1965, Gibbs and Maher derived a table indicating the frequency with which the first decile range covered given areas of individual States and the continent as a whole. This is reproduced in Table II which gives frequency (in per cent) with which the first decile range occurred over given percentages of the areas of each of the Australian States 1885-1965.

TABLE II

STATE	PER CENT OF AREA										
	91-100	81-90	71-80	61-70	51-60	41-50	31-40	21-30	11-20	1-10	NIL
Western Australia	0	0	0	1	5	2	3	4	7	32	46
Northern Territory	0	1	1	0	2	6	2	3	6	14	65
South Australia	0	0	0	3	1	2	5	5	9	19	56
Queensland	0	0	0	2	1	4	2	10	7	25	49
New South Wales	0	1	1	1	4	2	2	2	2	32	53
Victoria	1	1	0	3	1	1	1	1	6	26	59
Tasmania	0	2	0	2	2	2	1	5	4	9	73
Australia	0	0	0	0	0	2	5	11	19	41	22

From this they deduced that the continent should be completely drought-free in 22 years out of 100 and that it was most unlikely that more than 50 per cent of the continent would be drought-stricken in any one year, whilst the frequency of completely drought-free conditions in a given State range from 46 years in 100 in Western Australia to 73 years in 100 in Tasmania.

While it must be admitted that the occurrence of the first decile range of rainfall is a very coarse indicator of droughts, particularly if taken over a period of a calendar year, Gibbs and Maher have shown that it is a useful index in Australia for a general assessment of drought occurrence.

DROUGHT ALERTS

With the onset of dry conditions in 1965 after 20 years without a major drought in eastern and southern Australia, the Bureau of Meteorology decided to commence an alerting service. The aim of this service is to alert farmers and government authorities to conditions which could lead to a major drought.

"Serious drought" was defined as the situation when the rainfall total over a period of three months or more fell between the fifth and tenth percentile, "severe drought" when the total fell below the fifth percentile. Since 1965 official "drought statements" have been issued by the Bureau of Meteorology at monthly intervals whenever such conditions exist. Aggregate rainfall totals are maintained from the beginning of the "drought" and maps of the extent of area covered by the tenth and fifth percentiles, corresponding with "serious" and "severe" drought, are issued monthly. The drought statement issued 5 January 1972 and appended to this paper gives an idea of the format of the statements.

These drought statements have been found useful by the farming community and government authorities because they provide an objective assessment of rainfall deficiency and are useful in determining the need for government assistance.

WORLD DROUGHT SURVEY

Lee and Maher of the Australian Bureau of Meteorology are conducting a study of world rainfall for the years 1950-1970. Such a survey is possible only if a suitable data set is obtainable and can be processed by computer. Inquiries to the Administrator of the National Oceanic and Atmospheric Administration in the United States (Dr. R. M. White) resulted in the acquisition of a set of world monthly surface climatological data which had been prepared by Spangler and Jenne of the National Centre for Atmospheric Research. This data set of four magnetic tapes is based on data published in the Monthly Climatic Data for the World augmented by data from Clayton's Weather Records and other sources.

Computer programmes were written to transform these data to a format compatible with standard programmes currently used by the Australian Bureau of Meteorology for rainfall analysis. Some 70 000 station years of monthly and yearly rainfall data have been analysed to produce decile values of rainfall for a world-wide network of stations.

Because of the current concern for the Sahelian zone of Africa, the Secretary-General of the World Meteorological Organization was also requested to provide additional rainfall data for Africa for the period 1971-1973. At short notice rainfall data were provided for about 70 stations for the rainy season June-October and deciles for these months were calculated.

The study by Lee and Maher is currently in progress but already some interesting results are emerging. The outstanding feature of their maps of annual rainfall is the considerable spatial variability of the decile values.

The annual decile distribution for 1965, a year in which major drought occurred in parts of south eastern Australia, reveals areas in the first decile range in northern India, east Iran, southern Africa, the east central states of north America and isolated locations in Brazil and Chile. Decile distributions for 1968, 1969 and 1970 indicate the beginnings of drought in the Sudano-Sahelian region of Africa and the distribution of decile values over northern Africa for the years 1971, 1972 and 1973 show the persistent occurrence of the first decile range over the Sudano-Sahelian region.

One sometimes gains the impression from reports over the news media that there may be a significant correlation between droughts in southern hemisphere countries and in recent months floods in Australia and South America have hit the news headlines. Lee and Maher are examining whether such an impression has any basis in fact or whether it is simply the result of uncorrelated random occurrences.

Preliminary examination of 20 sets of annual rainfalls observed at stations in separate continents but having similar climatic régimes revealed no significant correlation. This is in line with the finding of Maher (1973) in which he showed that over Australia, correlation of monthly and annual falls decreased repidly with distance.

DROUGHT AND CLIMATIC CHANGE

Whether drought is the result of climatic change must remain indeterminate unless the magnitude or sequence of the occurrence of the rainfall deficiency is such as to lie outside the possibility of expectation based on previous climatic records. As climatic change is likely to be a gradual and insidious process its detection will be extremely difficult, particularly if, as in the case of rainfall, the natural variability of the element is considerable. In arid and marginal lands rainfall distribution is such that a very lengthy record is required to establish the form of the distribution. A 30-year "normal" in rainfall can be dangerously misleading because differences between successive 30-year "normals", particularly in arid and marginal regions, are likely to be no more than sampling effects.

Since the middle of the last century meteorologists, including those in Australia, have attempted to develop methods for long-range drought prediction. Statistical studies have revealed little in the way of variability in annual rainfall other than that which would be expected by chance. Some evidence of periodicity has been found, for example O'Mahony's spectral analysis (1961) which indicated that some Australian rainfalls appear to show a two- to three-year periodicity. O'Mahony also found some evidence of a "break" in rainfall records in some areas in Australia in 1895. However a recent study by Kemp and Armstrong (1973) shows that siting and observational procedure can introduce fictitious anomalies in temperature records. Presumably similar effects must be investigated in studying rainfall anomalies. In arid and marginal lands there seems little conclusive evidence of a climatic change during the period of existing rainfall records.

A remark by Troup on the subject of periodicity (1965) is relevant. Troup says:

> "Thus, although in individual studies there may be strongly suggestive evidence for a particular regularity (for instance the conservatism in phase of the 2.86-yr harmonic period in the 911-yr Nile flood records, analysed by Brooks) the situation is that examination of the records by statistical methods give no convincing evidence that any do exist. It would be quite reasonable to consider, on the available evidence, that what regularities appear are the outcome of sampling fluctuations in random series, or in random series with persistence."

It is possible that a gradual change in climate is occurring but as in the case of analysis of many cloud seeding activities, the natural variability of the rainfall means that the verdict in the case must remain "not proven".

It is also important to distinguish between drought and aridity. Aridity is lack of rainfall in the climatic sense and arid areas (which may be arbitrarily defined as those with an annual rainfall of less than 250 mm) are often characterized by extreme rainfall variability. For example Woodbrook and Muyie, in the arid zone of Western Australia, have experienced long periods without rain. In the case of the former station, no rain fell between July 1923 and December 1924 and in the case of the latter, no rain fell during the calendar year 1924. Whim Creek, which is also in the arid zone in Western Australia, recorded only 4 mm in 1924 yet has recorded over 600 mm in 24 hours.

The question of the occurrence of drought in arid zones is thus one of considerable subjectivity. An arid zone may be considered to be a region of almost continuous lack of rainfall broken by occasional rainfall events sometimes of considerable magnitude, so that "drought" is the rule rather than the exception.

The boundaries of arid zones fluctuate with "normal" rainfall variability and the surrounding marginal lands are also subject to periods when they could be classified as arid. It does not follow that the occurrence of drought in marginal lands is the result of climatic change. Drought should rather be regarded as a normal climatic occurrence in such areas.

DROUGHT AMELIORATION BY ARTIFICIAL MODIFICATION OF CLIMATE

Existing scientific knowledge and technology offers little hope of ameliorating drought by artificial modification of weather or climate. Drought is usually characterized by long periods of large-scale subsidence in the atmosphere and the absence of clouds which might respond to seeding. The elimination of rainfall deficiencies requires modification of major circulation patterns which would require changes in large-scale energy budgets, techniques for which are not readily apparent. And if it were possible artificially to induce such changes great care would be necessary to ensure that the elimination of deficiencies in one region did not induce them in another.

Technology is more likely to produce alternative solutions to the problem of water shortages, the desalination process being one example.

A WORLD STRATEGY TO COMBAT DROUGHT

In Australia it has been found that two factors help to lessen the effect of drought:

(a) An awareness of farmers and government authorities of the nature of drought and the need to plan for these occurrences;

(b) Effective transport to move assets (livestock) from drought-affected to drought-free areas or to move fodder from drought-free to drought-affected areas.

Australia, because of its relatively small population and vast areas, does not have a problem in feeding its human population. Apart from the early years of European settlement, yield of its cereal crops together with its grain storage has never fallen short of domestic requirements. Drought is nevertheless a serious problem because of its effects on the national economy.

Australian strategy in dealing with drought may well have global applications. In Australia where there is a Federation of six sovereign States, the Federal government and the six State governments combine without great political difficulty to combat the effects of drought. On the international scene the political difficulties may well be greater. Adequate air, rail, road and sea transport systems in Australia have helped to overcome the drought problem despite considerable difficulties arising from the vastness of the continent. The transport of livestock and fodder at times of drought has played a vital role in drought amelioration. The use of these systems largely depends on benefit/cost considerations.

On the international scene the difficulties are likely to be greater. Differences in currency, political arrangements and transport systems suggest that a well-planned world-wide system of drought amelioration, with its focus somewhere in the United Nations Organization is necessary if these difficulties are to be overcome.

Recent press reports in Australia indicate that the Secretary-General of the United Nations is contemplating the establishment of a task force for dealing with major natural disasters. The task force will no doubt give consideration to a world-wide drought-alerting service having a centre operating in each continent and reporting to some central secretariat located within the United Nations Organization.

ACKNOWLEDGEMENT

I am grateful for the assistance of Mr. J. V. Maher and other officers of the Bureau of Meteorology in the preparation of this paper.

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Appendix to DROUGHT - ITS DEFINITION, DELINEATION AND EFFECTS BY W. J. GIBBS

BUREAU OF METEOROLOGY

Department of Science

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5 January 1973

STATEMENT ON DROUGHT ISSUED BY THE DIRECTOR OF METEOROLOGY, 5 JANUARY 1973

The Director of Meteorology, Dr. W. J. Gibbs, said today that by the end of 1972 severe or serious rainfall deficiencies were evident over the whole of Australia except for north-east New South Wales, south-east Queensland and south-west Tasmania. In the hard core of the area, the central and southern part of Victoria and areas of southern New South Wales, drought conditions were becoming worse. Similar deterioration has occurred over the east of South Australia, the western division of New South Wales and the south-west corner of Queensland.

In Western Australia, the effects of deficiencies of winter and spring rainfall continue in the central and south-east districts of the south-west. The persistent low rainfall over the past four years in the southern interior of that state has continued through yet another month.

Summer rains so far in Queensland and the Northern Territory have generally been deficient. Some areas have never had a poorer start to the wet season and good rains in January and February are necessary if drought conditions are to be avoided.

Temperatures in drought-affected areas have been higher than normal resulting in greater evaporation rates from the already parched land. During the coming two months high rates of evaporation will continue so that even more rain will be needed to alleviate drought conditions.

The rainfall needed to break the drought depends on many local factors and the attached charts give an indication of the chances of alleviation by the end of March 1973. Maps 1-3 show the extent of rainfall deficiencies to the end of 1972. Maps 4-6 show the chances of rainfall for the quarter January to March 1973 based on past experience. The tables set out figures for places selected because of their long records in and near the affected areas.

WESTERN AUSTRALIA

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS PERIOD COMMENCING 1 MARCH DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
CENTRAL COAST					
Perth	96	10	70	24.04	8 occasions
SOUTH COAST					
Albany	95	2	67	23.94	1881
NORTH CENTRAL					
Cunderdin	58	33	85	11.52	19 occasions
SOUTH CENTRAL					
Katanning	81	16	80	14.37	12 occasions
Lake Grace	57	3	63	8.09	1957
		RAINFALL 4 YEARS 1 JAN. '69 - 31 DECEMBER '72			DRIER 4 YEARS PERIOD COMMENCING 1 JAN. 1969 DRIEST LISTED FIRST
SOUTHEAST					
Kalgoorlie	76	1	57	22.21	Non prev. lowest 26.44 in 1944
Leonora	74	1	49	15.96	nil, prev. 15.74 in 1934
Sandstone	67		63	22.94	
Norseman	68	8	84	36.56	1944, 1954, 1910, 1909, 1911
MURCHISON					
Meekatharra	73	3	73	24.75	1943
Mt. Magnet	78	11	78	26.74	7 lower
EUCLA					
Rawlinna	56	2	60	16.60	nil previously lowest 16.60 in 1969
NORTHEAST					
Wiluna	72	1	58	21.98	nil, previously 22.50 in 1935

SOUTH AUSTRALIA

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
NORTHEAST					
Yunta	84	5	37	2.73	1905, 1967, 1897
MURRAY MALLEE					
Pinnaroo	66	9	60	7.15	1967, 1938, 1914, 1957, 1959
Sandalwood	57	5	55	6.54	1967, 1959
ADELAIDE	134	10	73	14.01	12 periods

QUEENSLAND

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH-31 DECEMBER 1972			DRIER 10 MONTHS MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
FAR SOUTHWEST					
Kyabra	61	7	42	3.39	1965, 1929, 1951
Thargomindah	93	13	45	3.50	12 periods
WARREGO					
Charleville	98	19	61	8.53	18 periods
Cunnamulla	93	5	39	4.08	1937, 1946, 1919

NEW SOUTH WALES

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS PERIOD MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
FAR NORTHWEST					
Tibooburra	86	1	13	0.80	nil, prev. lowest 1.18 in 1888.
White Cliffs	71	1	28	1.99	nil, prev. lowest 2.51 in 1938
LOWER DARLING					
Menindee	93	4	44	3.27	1888, 1944, 1940
Wentworth	103	2	39	3.74	1967
UPPER DARLING					
Bourke	91	4	39	3.46	1957, 1888, 1937
Cobar	84	2	37	4.26	1937
SOUTHWEST PLAINS					
Mosgiel	78	11	56	5.16	8 periods
CENTRAL WESTERN PLAINS					
Condoblin	91	11	59	8.28	9 lower
Tottenham	85	6	51	7.30	1941, 1967, 1937, 1947
Coonamble	93	24		11.43	22 periods
Nyngan	93	3	43	5.56	1888, 1957
NORTH WEST PLAINS					
Boomi	64	65		17.98	40 plus occasions
Walgett	94	4	50	6.82	1902, 1888
CENTRAL TABLELANDS					
Mudgee	102	11		13.54	10 periods
Cassilis	101	20		13.32	19 periods
Bathurst	114	9	48	12.32	9 periods
Orange	98	4	56	16.41	1944, 1888, 1957

NEW SOUTH WALES CONT.

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS PERIOD MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
CENTRAL WESTERN SLOPES					
Coonabarabun	92	34		18.39	31 periods
Dunedoo	60	8	60	11.05	1918, 1922, 1944, 1957
CENTRAL WESTERN SLOPES					
Forbes	96	8	62	10.42	1957, 1944, 1946, 1895, 1898, 1941
Parkes	82	6	58	10.63	1944, 1957, 1902, 1941
SOUTHERN TABLELANDS					
Cooma	114	3	56	8.70	1895, 1941
Goulburn	110	5	57	12.17	1895, 1944, 1883, 1962, 1907
Adaminaby	86	1	41	9.71	nil, prev. lowest 10.95 in 1904
Kiandra	85	1	34	18.80	nil

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VICTORIA

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
NORTH					
Echuca	113	2	45	6.71	1914
Kerang	91	5	54	6.83	1938, 1914, 1943, 1967
Bendigo	110	2	53	9.48	1938
Shepparton	94	2	52	9.10	1938
NORTHEAST					
Corryong	80	6	60	15.52	1967, 1938, 1941, 1902
Bright	90	3	57	21.86	1938, 1914
Omeo	92	1	57	12.34	nil, prev. lowest 12.42 in 1948
CENTRAL					
Melbourne	118	1	53	11.78	nil, prev. lowest 12.11 in 1967
Lilydale	80	4	66	20.49	1925, 1938
Bacchus Marsh	93	3	60	10.26	1967, 1938
Geelong	100	4	64	11.88	1904, 1967, 1884
GIPPSLAND					
Bonang	85	1	54	17.02	nil, prev. lowest 18.96 in 1917
Orbost	89	2	57	16.01	1915
Maffra	83	1	54	10.18	nil, prev. lowest 10.34 in 1908.
Warragul	84	5	67	24.90	1938, 1902, 1925
CENTRAL					
Kyneton	97	9	69	18.19	8 occasions
Seymour	91	3	56	11.51	1938, 1914

TASMANIA

DISTRICT STATION	YEARS OF RECORD	RAINFALL 10 MONTHS 1 MARCH - 31 DECEMBER 1972			DRIER 10 MONTHS MARCH THROUGH DECEMBER DRIEST LISTED FIRST
		PERCENTILE RANKING	% OF NORMAL	AMOUNT INCHES	
NORTHERN					
Burnie	88	3	63	22.07	1902, 1888
Launceston	47	2	56	14.01	nil, prev. lowest 14.74 in 1961
Stanley	104	5	69	22.61	1902, 1940, 1897, 1868
EAST COAST					
St. Helens	84	5	53	13.98	1904, 1908, 1897
Swansea	86	3	50	10.62	1908, 1945
MIDLANDS					
Oatlands	89	2	59	10.66	1945
SOUTHEAST					
Hobart	89	3	65	13.75	1945, 1963
DERWENT VALLEY					
Bothwell	56	28	82	15.14	15 periods

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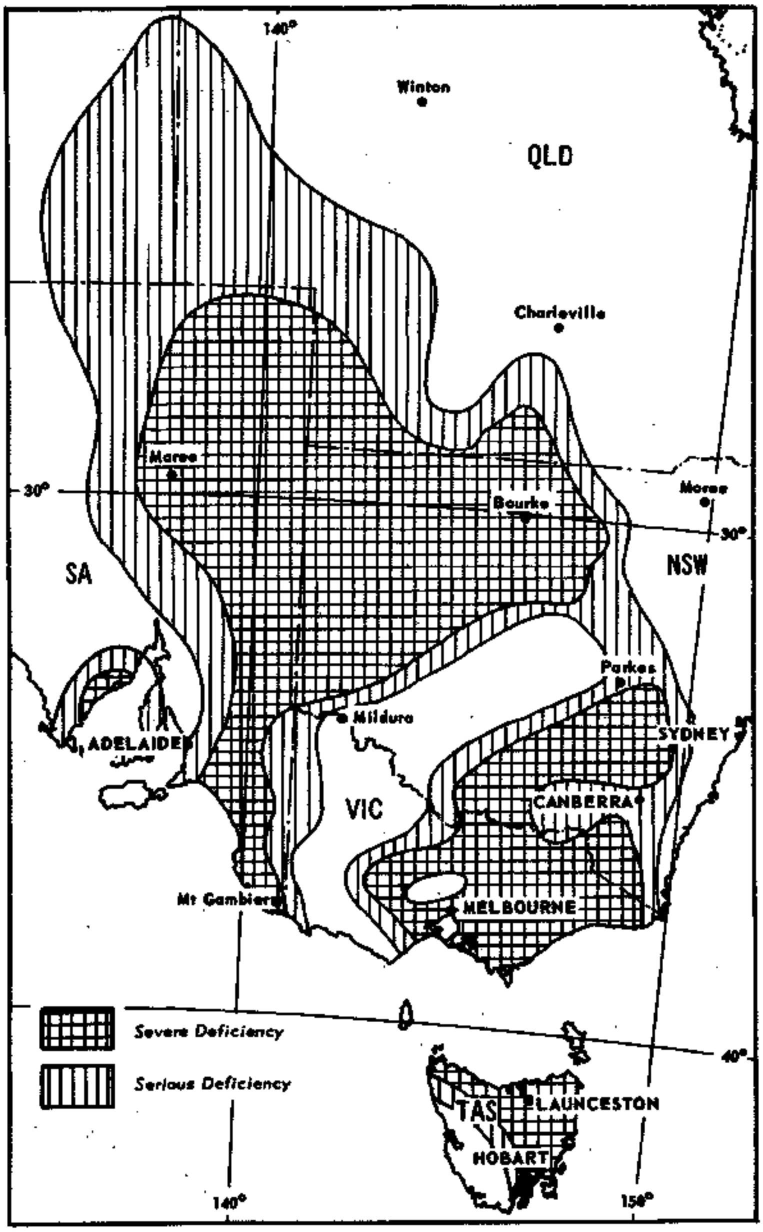
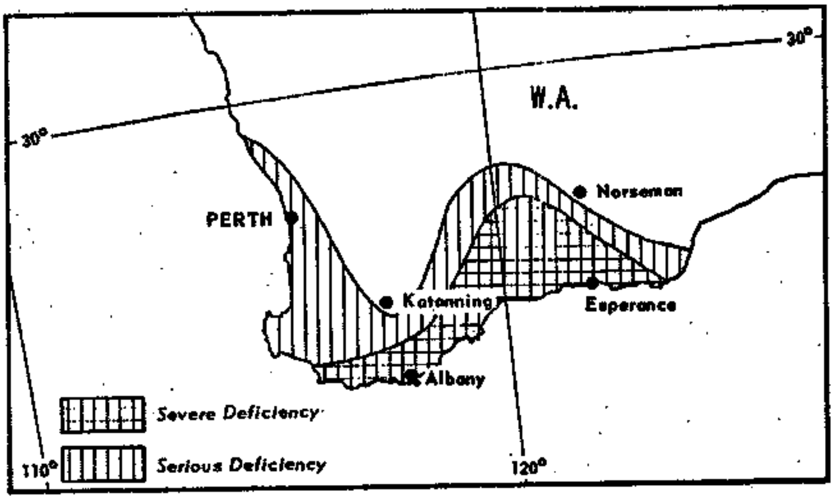
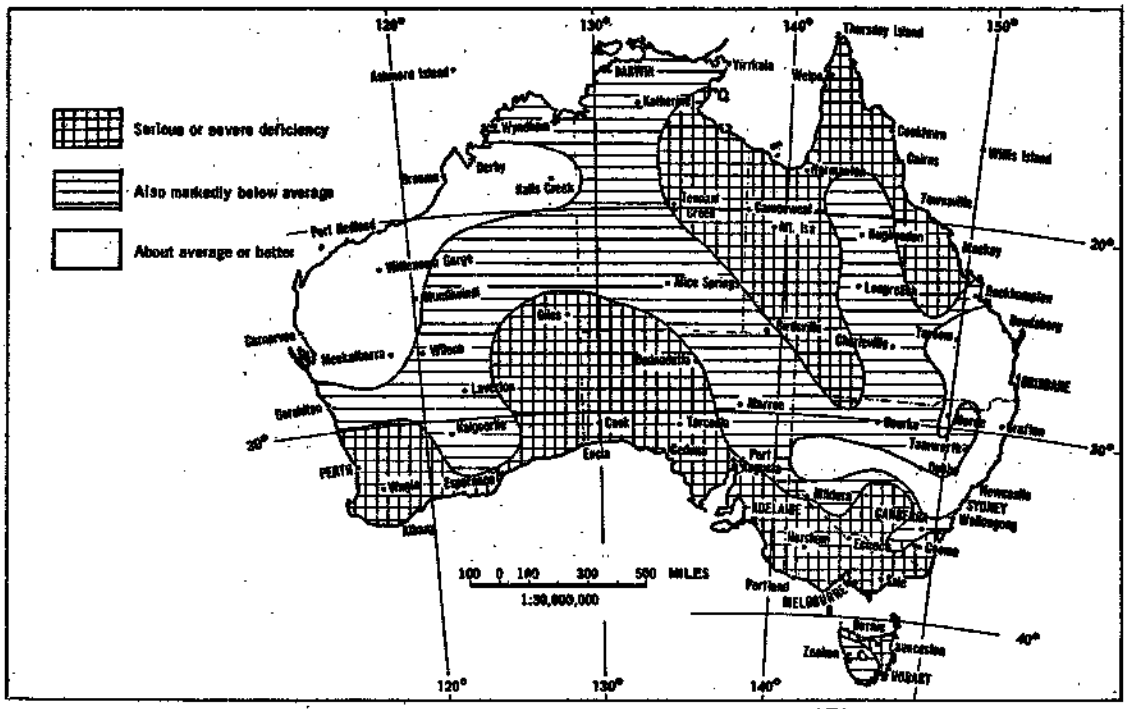


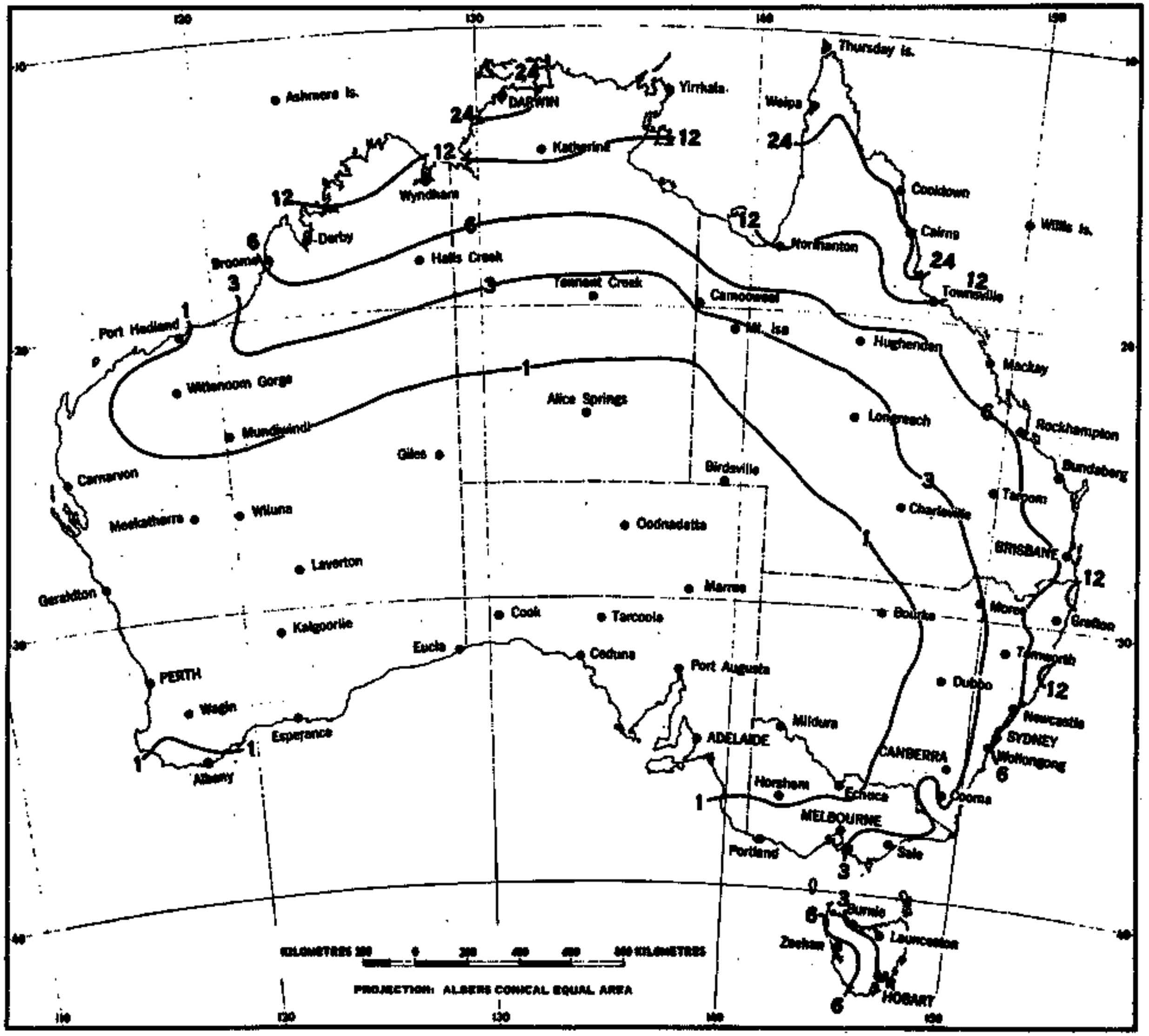
MAP 1 - Rainfall deficiencies, south-east and central Australia 1 March 1972 to 31 December 1972



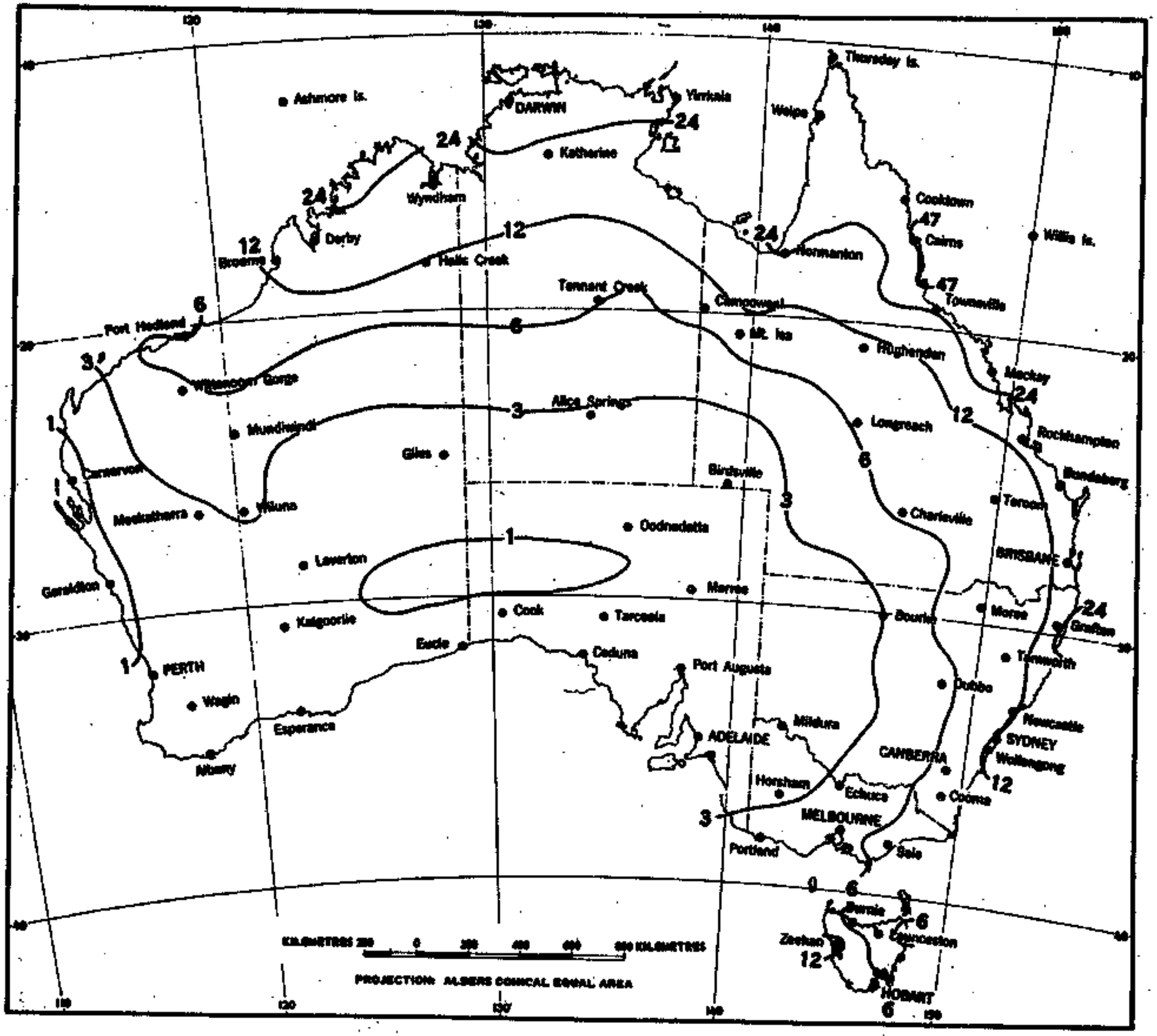
MAP 2 - Rainfall deficiencies, Western Australia
1 March 1972 to 31 December 1972



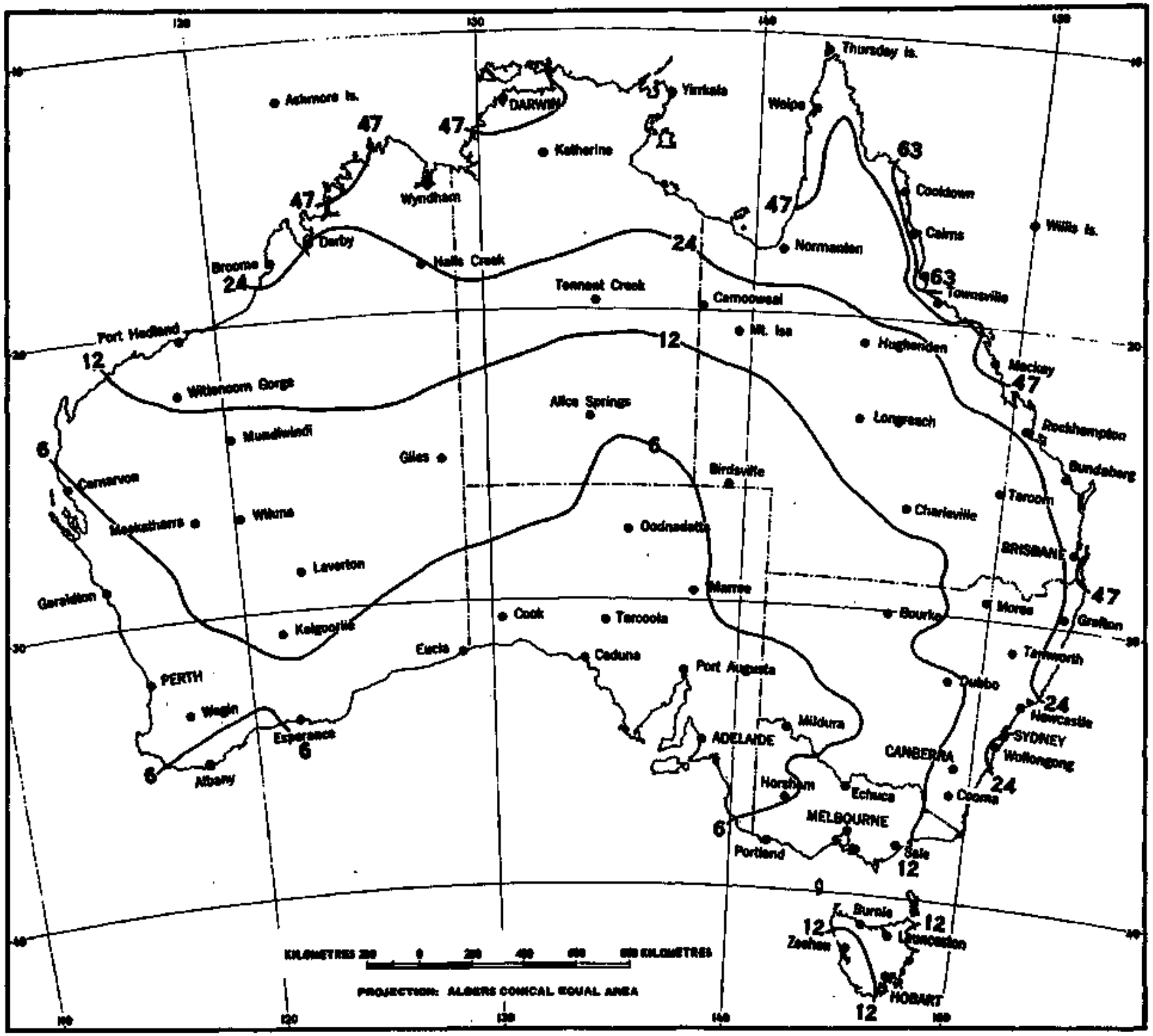
MAP 3 - Rainfall 1 September to 31 December 1972



MAP 4 - There are nine chances in ten that the January-March rainfall will be more than the amounts indicated on the map (isohyets in inches)



MAP 5 - There is an even chance that the January-March rainfall will be more than the amounts indicated on the map (isohyets in inches)



MAP 6 - There is one chance in ten that the January-March rainfall will be more than the amounts indicated on the map (isohyets in inches)

DROUGHT, A RECURRENT ELEMENT OF CLIMATE

by

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SUMMARY

Drought is experienced, with greater or lesser frequency, in all climatic areas which ordinarily have adequate precipitation for agriculture and water supplies. But the fewer the average number of days of precipitation, the greater is the variability from year to year. This number greatly depends on the prevailing large-scale atmospheric circulation. In marginal areas, especially those at the edges of the large sub-tropical high-pressure cells, this leads not infrequently to lack of rainfall, with disastrous results for the local economy. The shifts in the general circulation causing precipitation deficits that lead to drought also affect other weather elements such as clouds, with the unfortunate result that in drought-stricken areas usually no clouds suitable for possible modification attempts exist.

Data analysis of long records of precipitation in various parts of the world does not indicate any radical one-sided trends but rather fluctuations which may persist for several years. Spectral analysis reveals no well-defined cycles of rainfall anywhere but a widespread irregular rhythm of two to three years is in evidence. The analysis at the same time does not preclude entirely the presence of a weak rhythm in the 11- to 13-year spectral band which one might identify with the solar cycle. This point requires further exploration.

Lands close to the arid zones are most affected by frequency and severity of drought. Their vegetation is an ecologically fragile ensemble and their agriculture precarious. Unless cultivation is practised with utmost care, desert encroachment is an ever-present danger.

The Sahelian drought of 1971-1973 has not been entirely unprecedented and there is good evidence that it has been connected with changes in the large circulation patterns over the North Atlantic space. Only in recent years has there been a sufficient data base to investigate these anomalies but pursuit of this line of research holds some promise for early recognition of adverse conditions. In the meantime, the use of the statistical properties of precipitation series should be exploited for the assessment of drought risk in various areas.

RESUME

La sécheresse sévit plus ou moins fréquemment dans toutes les zones climatiques qui ont généralement des précipitations suffisantes pour l'agriculture et l'alimentation en eau. Mais plus le nombre moyen de jours de précipitations est faible, plus grande est la variabilité des précipitations d'une années à l'autre. Le nombre de jours de précipitations dépend énormément des caractéristiques dominantes de la circulation atmosphérique à grande échelle. Dans les zones marginales, particulièrement celles qui se trouvent en bordure des cellules anticycloniques subtropicales, il n'est pas rare d'en arriver à un manque de précipitations, avec des résultats désastreux pour l'économie locale. Les changements de la circulation générale qui sont à l'origine des déficits de précipitations conduisant à la sécheresse agissent aussi sur d'autres éléments météorologiques tels que les nuages, ce qui a malheureusement pour résultat que, dans les zones où sévit la sécheresse, il n'existe généralement pas de nuages pouvant donner lieu à des tentatives de modification artificielle du temps.

L'analyse des relevés pluviométriques portant sur de longues périodes disponibles dans diverses parties du monde ne permet pas de mettre en évidence de tendances nettement orientées mais plutôt des fluctuations qui peuvent persister plusieurs années. L'analyse spectrale ne révèle pas de cycles bien définis des précipitations, en quelque endroit que ce soit, mais décèle un rythme irrégulier de deux à trois ans qui se fait sentir sur de vastes étendues. Simultanément, cette analyse n'exclut pas complètement l'existence, dans la bande spectrale de onze à treize ans, d'un faible rythme que l'on pourrait identifier avec le cycle solaire. Ce point mérite d'être étudié plus avant.

Les territoires les plus proches des zones arides sont les plus fréquemment et les plus sévèrement touchés par la sécheresse. Leur végétation constitue un ensemble écologiquement fragile et leur agriculture est précaire. A moins que l'agriculture n'y soit pratiquée avec le maximum de précautions, la désertification reste un danger permanent.

La sécheresse de 1971-1973 dans le Sahel n'est pas absolument la première du genre et l'on a de bonnes raisons de croire qu'elle découle de modifications survenues dans les régimes de la circulation à grande échelle au-dessus de l'Atlantique Nord. Ce n'est que depuis ces dernières années qu'on dispose d'une base de données suffisante pour étudier ces anomalies et l'on a tout lieu d'espérer qu'en poursuivant les recherches dans cette direction on parviendra à déceler très tôt les conditions défavorables. En attendant, il conviendrait d'exploiter au mieux les propriétés statistiques des séries chronologiques d'observations pluviométriques afin d'évaluer le risque de sécheresse dans diverses zones.

РЕЗЮМЕ

Засуха возникает с большей или меньшей частотой во всех климатических районах, которые обычно имеют достаточное количество осадков для сельского хозяйства и водоснабжения. Но чем меньше среднее количество дней с осадками, тем больше их изменчивость от года к году. Это количество в большой степени зависит от превалирующей крупномасштабной атмосферной циркуляции. В критических районах, особенно в районах, находящихся на границах крупных субтропических ячеек высокого давления, это нередко приводит к отсутствию дождя с бедственными результатами для местной экономики. Сдвиги общей циркуляции вызывают дефицит осадков, что приводит к тому, что засуха влияет также и на другие метеорологические элементы, например облака, в результате чего в районах, подверженных засухе, обычно нет облаков, на которые можно было бы попытаться воздействовать с помощью существующих методов.

Анализ данных об осадках в различных частях мира за длительные периоды не указывает на какие-либо радикальные односторонние тенденции, на отмечает лишь отклонения, которые могут существовать в течение нескольких лет. Спектральный анализ нигде не выявляет никаких явных циклов осадков, кроме наличия широко распространенного неправильного ритма в 2-3 года. Одновременно анализ не отвергает полностью слабого ритма в 11-13-летнем спектральном диапазоне, который можно поставить в соответствие с солнечным циклом. Этот вопрос требует дальнейшего исследования.

Земли, близкие к засушливым зонам, наиболее всего подвержены частым и суровым засухам. Их растительность является экологически хрупкой, а сельское хозяйство - ненадежным. Если не проводить культивацию со всевозможной тщательностью, то постоянно присутствует опасность наступления пустыни.

Сахельская засуха 1971-1973 гг. не явилась целиком беспрецедентной, и есть основания полагать, что она была связана с изменениями в структуре крупномасштабной циркуляции над Северной Атлантикой. Только за последние годы создалась достаточная основа данных для исследования этих аномалий, а проведение таких исследований содержит некоторые перспективы заблаговременного распознавания неблагоприятных условий. Тем временем должно быть изучено использование статистических свойств серии осадков для оценки опасности засухи в различных районах.

RESUMEN

La sequía aparece con mayor o menor frecuencia en todas las regiones climáticas que ordinariamente disponen de precipitación adecuada para la agricultura y suministro de agua. Sin embargo, cuanto menor sea el número medio de días de precipitación, mayor será la variabilidad de un año a otro. Este número depende en gran medida de la circulación atmosférica en gran escala. En las regiones improductivas, especialmente en las que están situadas al borde de los grandes centros subtropicales de alta presión, esta dependencia motiva con alguna frecuencia la falta de lluvia, con desastroso resultado para la economía local. Los cambios de la circulación general causan déficit de precipitación y tienen como consecuencia el que la sequía afecte también a otros elementos meteorológicos tales como las nubes con el catastrófico resultado de que regiones afectadas por dichas sequías tampoco disponen habitualmente de sistemas nubosos adecuados para una posible modificación artificial.

El análisis de los datos de los largos registros de precipitación en distintas partes del mundo no indica ninguna tendencia radical única sino solamente fluctuaciones que pueden persistir durante varios años. El análisis espectral revela ciclos no bien definidos de lluvia en cualquier lugar aunque se aprecia un ritmo irregularmente distribuido de dos o tres años de duración. Al mismo tiempo, el análisis no impide completamente la presencia de un débil ritmo en la banda espectral comprendida entre el onceavo y el treceavo año, que podría quizás identificarse con el ciclo solar. Esta cuestión requiere ser investigada con más amplitud.

Las tierras situadas en las proximidades de las zonas áridas son las más afectadas por la frecuencia e intensidad de las sequías. Su vegetación constituye un conjunto ecológicamente frágil y su agricultura es precaria. A menos que la tierra se cultive con mucho cuidado, la desertificación constituye un peligro permanente.

La sequía que se produjo en la región del Sahel en 1971-1973 parece que ha tenido ya precedente y existen pruebas de que está relacionada con los cambios de la circulación atmosférica en gran escala sobre el Atlántico Norte. Sólo en los últimos años se ha podido disponer de datos suficientes para investigar estas anomalías y parece ofrecer buenas perspectivas la investigación de este fenómeno para poder identificar prontamente la aparición de condiciones adversas. Mientras tanto, se deben utilizar las propiedades estadísticas de las series de precipitación para la evaluación del riesgo de sequía en distintas regiones.

Drought has been a scourge of mankind throughout history. It has confronted meteorologists also for a long time. After each major drought episode descriptions and analyses appeared in the literature. A few comprehensive treatises also exist. We cite here only the book of Tannehill (1947). But the need for a clearer understanding of the drought phenomenon than heretofore, and the crying need to replace relief by forecasting and planning finds the meteorological profession still unable to cope with its share of the task (Landsberg, 1965).

It is essential to distinguish at the outset between aridity and drought. Both of them are characterized by lack of water. Aridity, however, carries the connotation of a more or less permanent climatic condition, bringing about deserts as the companion land form. Drought, on the other hand, is a temporary condition, occurring in a climatic zone where precipitation is ordinarily adequate for vegetation or agriculture, riverflow, and water supplies. There are marginal areas on the globe, often called semi-arid, that are transition zones between truly arid areas and moister regions with more reliable precipitation. These zones are those most frequented by drought. The consequences of this condition periodically focus world attention on this meteorological problem. In the most recent past the drought in the African region south of the Sahara has had world-wide attention (Davy, 1974).

It must, however, be clearly understood that no region, no matter how well blessed with water from the sky, is free from drought. And the opposite is also true that even relatively dry areas are occasionally flooded by a deluge. In the light of this it may sound incongruous that there is no precise definition of drought in the meteorological dictionary. It is simply a qualitative term for the lack of water. If the supply of the latter is inadequate for the common pursuits of the area we call it a drought. Yet there have been a very large number of attempts to come quantitatively to to grips with the occurrences of dry spells of shorter or longer duration. Our focus here shall be on the climatological aspects of the problem. In this context it may be well to recall that of all the usual elements used for representation of climate the average precipitation is often the most misleading. If used with discrimination it can, however, give geographically useful information. It usually enters as a parameter into a variety of indices used for delineation of various climatic zones. Table 1 gives a summary of a variety of aridity and drought indices which have been widely used. They range from those used for simple climatic mapping to more complex parameters which include many elements of the local hydrological balance. The most elaborate of these is the drought index of W. C. Palmer (1965). Although it includes soil factors it is still a meteorological parameter. It evolved logically from the more elementary measures of C. W. Thornthwaite (1931), whose great merits for the investigation of the water balance should not be forgotten. Added in the table are a few statistical measures that are most useful in assessing the vagaries of rainfall.

As in many other problems that can benefit from use of a climatological parameter as a basic variable (or input parameter), figures that are directly meaningful for the practical purpose on hand have begun to evolve. Thus meteorological drought has yielded to measures of agricultural drought, which is related to physiological drought for natural vegetation. The latter not infrequently is brought about by detrimental salt accumulations in soil. Effects of drought on crop yields in an affected area have certainly drawn the greatest public attention. But it would be a serious mistake to consider only the agricultural effects of drought. In populated and industrialized areas water shortages can seriously hamper production, hygiene and sanitation, and even lead to water rationing.

It is obviously inadequate to look at drought as a local phenomenon with locally observed weather elements. Even an elementary study will immediately show that drought is usually not an isolated phenomenon. It is often widespread over a large area simultaneously, like other climatic anomalies, and as such a consequence of large-scale anomalies in the atmospheric circulation patterns. These anomalies are hemispheric or even global in character (Flohn, 1973; National Science Board, 1973). And, although we can readily recognize the contemporaneous associations, very little is known about antecedent conditions and even less about how to forecast them (Namias, 1974). One can not rule out the possibility of extraterrestrial (solar) influences. We shall refer back to these broad problems again.

Yet climatological and statistical analyses do not leave us entirely helpless vis-à-vis the drought phenomenon. One clear indication these studies give is the fact that drought is a recurrent phenomenon. There is no need to invoke climatic change as a cause each time drought occurs. Quite the contrary is evident: drought is an integral, if irregular, component of climate as it exists now. Particularly exposed to this scourge are climates with low amounts of rainfall, even if they are not generally devoid of vegetation and capable of supporting some agriculture in normal and good years.

The endangered areas are readily evident in a geographical sense and closely tied to the broad patterns of the general circulation of the atmosphere. Regions at the fringes of the semi-permanent subtropical high pressure cells have notorious problems. Others, less frequently involved, but still notably affected, are parts of the world where summer monsoonal circulations are the principal rain bringers. The role of sea-surface temperatures, either influenced by cold currents or wind-induced upwelling, is also quite obvious. In many instances all three factors interact. This can be schematically seen in the spectacular rainfall gradient with respect to latitude first discussed by Lydolph (1957), (Figure 1). In a temporal sense, the variations in the general circulation are closely tied to the temperature gradient between the Equator and Pole. Korff and Flohn (1969) have demonstrated the dependence of the position of the subtropical high pressure cell in both hemispheres on upper tropospheric temperature differences (Figure 2).

Even in relatively short intervals of time shifts of the subtropical highs can affect the available precipitation amounts materially. Ganor (1963) showed this in an interesting fashion for Israel by mapping the position of the boundary of aridity. Using Thornthwaite's index value of P/E < 16 he not only demonstrated high variability from water year to water year but indicated a wobble of a degree of latitude in the time span of 20 years (Figure 3). This probably did, by no means, include the extreme positions to be expected in the present climatic era. Thornthwaite (1941b) had mapped the P/E indices for the United States for a 40-year span which included one of the major drought periods experienced over a large part of the country (Figure 4). In this region of the world the precipitation pattern is generally not governed by the latitudinal position of the subtropical high, although through monsoonal currents and development of tropical storms it is not entirely independent of it. However, the main reason for drought in the area east of the Rocky Mountains is the position of the major troughs in the tropospheric Westerlies that either permit or block influx of moist air from the Gulf of Mexico and the subtropical Atlantic Ocean. From the 40-year span the boundary of the P/E ratio < 32 (semi-arid), was derived as a statistical probability of occurrence with 1%, 50% and 99% likelihood. This shows a longitudinal difference of 18 degrees between the lowest and highest of these probabilities. One can demonstrate about the same thing by mapping the yearly position of the 400 mm annual isohyet, (Figure 5). This value, in middle latitudes, is a reasonably good indicator of the boundary below which crops can only be grown with temporary or permanent supplemental irrigation.

These simple representations are indicative of where the endangered crop areas are but further statistical analysis reveals greater detail of the precipitation values that can be expected at various levels of probability. One convenient such measure is the probability of getting between at least 75 and not more than 125 percent of the long-term average.

The relative variability is a statistic that permits, on the other hand, comparisons between areas of non-uniform synoptic régimes. Just as Biel (1929) and Conrad (1941) had already implied, many areas of small annual precipitation have the highest relative variation (Figure 6). Hershfield (1966) demonstrated this very vividly for the U. S. (Figure 7). This author also showed that the coefficient of variation has a smooth curvilinear relation to the total number of days with precipitation ($\geq$ 0.25 mm) (Figure 8). The less frequent the precipitation, the higher will be the coefficient of variation of annual totals. This is, of course, nothing but a reflection of the frequency of rain-producing synoptic weather patterns. These patterns are also those producing clouds. This is an unfortunate circumstance for only temporary dry regions where relief has been sought through rain stimulation. But cloud seeding presupposes existence of suitable clouds. Analysis of major dry spells indicates that such clouds are absent and little, if any, hope can be held out that present practices of weather modification can be gainfully employed to alleviate these droughts.

Another useful representation is a probability diagram for areas with wide divergence of rainfall amounts, because of orographic control for example, but under relatively uniform synoptic weather régimes. Such a statistical abstraction was first designed for the island of Oahu, Hawaii (Landsberg, 1951) (Figure 9). Wallén (1955) showed the applicability for

Mexico, an entirely different environment. But both areas are characterized by a wide range of average precipitation values, yet one can give a ready estimate for the risk of rainfall deficiencies of a given level for all localities in the area. The main reason for recalling these older pieces of work is to emphasize once more emphatically that drought - and often also excessive rainfall - have to be viewed in a setting of the large-scale synoptic patterns and their anomalies.

A global view of the drought problem will quickly convince anyone of its dimensions. A great deal of pertinent information has been accumulated by the, now terminated, arid zone project of UNESCO. Results were summarized in 28 monographs. One has to refer to the arid zones in this context because their margins are most endangered by drought. They are also among the densely populated areas because of their thermal suitability for settlement.

Walton (1971) has given a very good geographical overview of the dryland problems and Meigs (1953, 1957) has presented world charts of the extent of dry lands on the basis of Thornthwaite's P/E index. The vast areas concerned are clearly evident from Table II, which shows that these lands comprise 48 million square kilometers of the continents (omitting Antarctica and Greenland). As stated before, the proximity to dry land governs the overall variability of rainfall which can be clearly shown on maps previously referred to. Of the land areas only those in the zone of the mid-latitude westerlies and tropical convergence zone have reasonably reliable precipitation. Much of the major crop-producing land (excluding forest products) is in these zones (Figure 10). But almost none of these, and certainly not the riskier agricultural areas, have been spared drought of a damaging nature at least once in the past quarter century (Figure 11).

Much can be learned from careful analysis of droughts in specific regions of the world. The United States, although only 2 per cent of the earth's surface, but producing close to 20 per cent of the world's total grains, offer many lessons in the study of drought. Again, they have been a recurrent event. In the 1930's they caused a major disaster. The ground became bare in the Great Plains and the fierce winds carried millions of tons of top soil as far as the Atlantic seaboard. Farms became desolate and ten thousands of farmers and their families had to migrate from Kansas, Oklahoma, Arkansas, and other states to less affected regions in search of a livelihood. This disaster led to much research on soil conservation and on the weather factors responsible for the drought.

One result of this research was the development of an index capable of assessing the severity of drought by W. C. Palmer (1965). The index encompasses not only precipitation and evapotranspiration but also soil and climatic factors appropriate for the region. It is an accumulative parameter which not only permits gauging of present conditions but also indicates, retrospectively, the beginning and end of drought periods. The index vividly portrays the widespread character of the 1934 drought during the crop season. Although this turned out to be the drought of a century in the area affected, only 22 years later a major rain deficiency again plagued the region.

One might argue at this point that the area in which these droughts in the United States were most severe is located in the longitudinal band that showed much variability and it is, indeed, a belt with considerable agricultural risk. However, other areas are not excepted from occasional and, sometimes, persistent rainfall deficiency. This was the case in the 1960's in the northeastern part of the country. It led to severe water shortages in the densely settled and industrialized coastal belt from Maryland to Massachusetts. Cumulative deficits in 1966 had reached over750 millimeters and in some spots exceeded the total of an average year's precipitation (Russell et al., 1970). The values of such deficits for the pooled data of three long-record stations for a 96-year interval yielded a very good, statistically normal distribution (Figure 12). This analysis showed that about once in 130 years such a deficit is entirely within the realm of variability of the precipitation régime, i.e., rare but not outside of expectation.

In this particular instance, the effects on industries, which are copious consumers of water, and on water supply and sewage disposal systems of large municipalities were severe. In the agricultural sector there were also the hardships common to drought, aggravated in this area by widespread damage to ornamental and fruit-producing trees. Missing an annual crop due to drought is bad enough but a killed fruit tree has to be removed and replaced. It will take several years for a new tree to bear, long after fields and pastures have recovered from the adverse meteorological event.

Let me add here that freak dry spells, in areas otherwise blessed by adequate moisture, do occur - sometimes in relatively isolated smaller areas. These are best shown by the persistence tendency of successive dry days. The statistics of the longest such interval for each year in a longer period can be adequately represented by the Gumbel extreme value distribution. An example of this has been presented by Hershfield (1971) for part of the long, homogeneous record at Woodstock, Maryland (Figure 13). The analysis shows that the distribution does indeed fit the data well with exception of the year 1930 where one dry spell lasted 150 consecutive days. The frequency analysis would let one expect such an extraordinary event only once in 10,000 years. This occurrence is cited to show that rather singular extremes can happen and that even a century may offer only an inadequate sample of the wide range of possibilities for local anomalies in the general circulation. The fact that the much rainier conditions prevailing before 1930 were restored after this rather singular event should warn one not to jump to the hasty conclusion that a climatic change has occurred when a new extreme is recorded somewhere.

Enough long records of precipitation exist in the world, many of them preserved in that extraordinary source collection, the World Weather Records, to which WMO members contribute so commendably, that statistical evaluation is relatively easy. It turns out that longer time series of annual rainfall can be adequately represented by statistically normal distributions (Figure 14). This does not preclude temporal fluctuations in the period investigated, a theme that will be treated later. At the same time comparison of the probability distribution of various localities permits not only an assessment of precipitation risk factors (both at the high and the low end) but also makes it easy to compare various precipitation régimes. In a linear probability diagram the stations with reliable rainfall show a flat slope, those with high variability have a steep slope. We have chosen to look at some of the longest records available and at some notorious drought-plagued areas. These include the eastern United States Seaboard (centered at Philadelphia), northwestern Europe (Aberdeen) to represent humid areas; Dakar in Senegal; La Pampa in Argentina (Prohaska, 1961); Fortaleza, Brazil (Markham, 1974), a northeast Brazilian station in the tropical convergence zone, to show conditions in periodically dry regions; Seoul, Korea (Sekiguti) and Madras, India, to illustrate the Asian monsoon areas, and in addition a station at the northern edge of the Sahara still under the influence of westerlies. Three definite slope patterns show. Particularly notable is the fact that the monsoonal zones have the greatest slope - a typical feast to famine pattern. It clearly shows the wisdom of the ancient hydraulic civilization of the region with water impoundment and irrigation. It also shows, interestingly enough, the statistical similarity of the probability pattern in Dakar and the prairie climates of Western Kansas and Argentina.

Yet the probability functions, useful as they may be for assessing climatic risks, only tell a collective story. Some details can usually be gathered from a closer look at frequency histograms (Figure 15). Many of the stations analyzed show common unimodal distributions. Of those mentioned above Philadelphia (230 years) and Seoul, Korea ($\sim$ 200 years) have this form. In contrast, stand the two long-record stations in Senegal (Dakar, St. Louis). Both have nearly a century of data, unfortunately a rarity in this area under weather stress. They show that south of the Sahara a bimodal pattern for annual rainfall, which is very seasonal and restricted to the summer solstitial interval, prevails. This occurrence pattern suggests the prevalence of two régimes of rainfall. The drier of these seems to be governed by the Saharan influence and the wetter years are dominated by deep northward penetration of the Intertropical Convergence Zone. Clearly, substantial rainfall in the area will only occur when the vertical structure of the air masses permit high-reaching convection, but if the equatorial air masses are shallow, preconditions for rainfall are impaired.

The crucial role of the broad features of the large-scale circulation for the Sudano-Sahelian zone cannot be overstressed. The climatic pattern of the region (Moral, 1964) demonstrates the precarious situation in this transition zone where only five degrees of latitude separate areas of abundant rainfall from desert (Figure 16). It is a continuous battleground between dry and wet. Parenthetically one should note that the resolution of general circulation models with 5 degree grid spacing is too coarse to cope with the subtleties of such climatic patterns.

It is, of course, tempting to establish diagnostically the conditions that are associated with rainfall anomalies in the Sudano-Sahelian area. Unfortunately, the readily available synoptic material is scanty. But it seemed interesting to look at least at two recent years with widely divergent rainfall values at Dakar. In 1969 seasonal precipitation was considerably above the average and 1972 was the core of the drought period. The yearly charts issued by the Meteorologisches Institut der freien Universität Berlin supplemented by data from other sources were used for the comparison. The two years were, indeed, quite different. The rainy year in West Africa showed a weakened Atlantic circulation; both the Azoric High and the Icelandic Low were weakened and the upper-air contours showed straight zonal flow. (Figures 17-19). The temperature anomalies indicated a warm area in the Sahelian zone with a warm off-shore sector. (Figure 20). In contrast, there was an intensified North Atlantic circulation in 1972. The Azores High was stronger and the pressure in the Icelandic trough zone lowered (Figures 21, 22). In the tropospheric circulation a distinct trough is notable between 0^{o} and 10^{o} W longitude (Figure 12). There is also a marked negative temperature anomaly off West Africa (Figure 24). Although these two cases show divergent large-scale synoptic patterns they are at best suggestive for further investigations. The available data material, especially the sea-surface temperature values in critical zones adjacent to West Africa are inadequate to obtain corroborating evidence from earlier years. One should also look for further teleconnections, as suggested by Namias (1974). Diagnostic studies of this type might well furnish leads toward prognostication of anomalous events.

There is, however, no question that drought has been a recurrent phenomenon. This is reflected in the folklore and religion of all early people. We find in the pictographs and sculpture of the Mayas a rain god and a drought goddess attesting to the importance of the water problem in their culture. And one may also cite in support Chapter 41 of Genesis in the Bible. The dream of the Pharaoh of fat cattle and full ears of grain compared with lean animals and withered ears of grain, was interpreted by Joseph with a meteorological reference to the temporary prevalence of the dry east wind. We may dismiss the reference to seven good years and seven years of drought as indication of a cycle, but the passage is a definitive indication of impressive rainfall fluctuations in Egypt or the sources of the Nile River.

Year-to-year rainfall at all localities ever studied exhibits a typical noise pattern of alternating ups and downs. Despite the restlessness there are, however, nearly everywhere conspicuous intervals of shorter or longer duration when the departure from average seem to be one-sided. This feature has always been an incentive to the periodicity hunters. Yet in data universes so beset by irregularities, where it may take five decades to obtain a reasonably stable mean value, this has - by and large - been a disappointing enterprise. Actually, aside from the triviality of diurnal and annual cycles, no atmospheric element exhibits truly periodic character. There are at best irregular rhythms which can only be discerned as contributors to a particular frequency band after a long time series has been obtained. Even then, if one or the other band in the spectrum exhibits more power than others, one is always confronted with the question what model to use for tests of significance. Most work in the past has made comparisons with a white or red spectrum.

In context of droughts let me refer here to a limited material only. Mitchell (1968) has, for example, calculated a power spectrum for the Palmer drought index during the summer months for the long rainfall series at Central Park, New York (Figure 25). This spectrum shows a number of peaks. Quite significant seems to be one around 3 years; others around 8, 13, and 40 years are prominent but do not reach the 95 per cent confidence limit. This is not untypical of results in humid regions.

A similar attempt for the 86-year rainfall series at Dakar (El-Sayed and Landsberg, 1973) indicates two prominent peaks (Figure 26). One is around three years, with a minor 2.2 year peak before, the other at close to 11 years. Both of them are close to statistical significance. There is no serial correlation. It is also important in our context to stress that the statistical analysis of the Dakar data shows absence of a trend. This is important because of the many statements to the effect that the Sudano-Sahelian drought of recent years is a result of a climatic change.

The intriguing peak at 11 years, so close to the sunspot rhythm, makes it difficult to dismiss a possible solar influence on rainfall out of hand. The appearance of a rhythm approximating the double sunspot cycle in the droughts of the Great Plains in the United States induce further reflection. The study of Jagannathan and Parthasarathy (1973) of the rainfall in India also contains pertinent information. The longest series in that analysis represents the Madras observations since 1813. It is the same series of over 150 years we used to represent the probability function of the Indian monsoon. The data show no significant trend either, but a statistically significant spectral band between 2.4-2.8 years and another one between 11.7-13.5 years, although not entirely secured statistically. The Fortaleza, Brazil (Markham, 1974) power spectrum of annual precipitation showed a strong peak at 13 years, also close to the solar cycle, and one of the double length. The power in the 2-3 year interval is also high.

It may well be coincidence that four series, widely separated geographically, show a spectral peak near the frequency of the sunspot rhythm. This seems to keep the question of solar influence at least open until longer series become available or a convincing physical model can be adduced. On the other hand, the irregular 2- to 3-year pulse is so firmly established in these and other meteorological time series that it must be regarded as a fundamental oscillation of the ocean-atmosphere system even though all current explanations of this phenomenon are implausible and will remain so until the part the oceans play in the system becomes more clarified than heretofore.

It remains now to inquire lastly into the possible role man plays, other than as a victim, in the drama of drought. As we have already seen, drought is a particular menace in the areas marginal to the truly arid or desert zones.

There is no doubt that these are ecologically very fragile. Human interference with the natural vegetation can have far-reaching local consequences. They do not change the climate but they do seriously affect the micro-and meso-climate locally. There is ample documentation for this, much of it from observation of deforestation, where it takes heroic measures and great patience to re-establish a forest once it has been completely removed. The hydro-biologist Liebmann (1973) expressed the well-founded view that deforestation did not only destroy large parts of the ecology of the Mediterranean space but transformed wast areas of China to steppe and was a contributary cause for erosion forcing the Mayas to abandon their towns.

In the U. S. we had within living memory a vivid demonstration of the truism of man's detrimental effect on an ecosystem, (Thornthwaite, 1941a). The ploughing and bringing into cultivation of the Great Plains, in the period of World War I and the 1920's led, during the disastrous drought of the mid-thirtieth to massive wind erosion, and only strenuous efforts by soil conservation practices permitted a partial recovery from that catastrophe.

In other places, and the Sahel and parts of North Africa (Flohn, 1971) are examples, overgrazing has caused similar destruction of the native vegetation. Poor practices have been excused by the allegation that this was an encroachment of the desert. But the desert or the precipitation pattern is not to blame. Misuse has added territory to the desert and it is primarily man's fault. A reversal is not impossible, but it will be a costly, tedious, and drawn-out process.

In conclusion let me state that drought is part and parcel of the climatic pattern in all parts of the world. It is just as much a piece of the present-day climate as are flood-producing excessive rains. These events at the wings of the frequency distribution are consequences of the oscillations of the general atmospheric circulation, a broad band of which is accommodated in the climate that has governed the planet since the end of the Pleistocene. Unfortunately, the marginal zones of high rainfall variability will always take the brunt of the fluctuations as will the thermally disadvantaged belts near the polar regions (Butzer, 1961). Where in the past nomadism and migration were the way out of the dilemma, population pressures and political aspects now aggravate the problem. The only answer is anticipation and here the meteorologist can as yet give only inadequate help. This re-emphasizes the urgency and scope of the task to furnish extended outlooks on global weather prospects.

Acknowledgements

The writer is indebted to Mrs. J. Albert for help in the statistical analyses and Mr. Harry Rector for preparing the illustrative material. Some support for our work was furnished by the National Science Foundation under Grant GA-29304X.

TABLE I

HISTORICAL SELECTIVE SURVEY OF DROUGHT INDICES

R. Lang (1915) Rain Factor Index $\frac{P}{T}$ (<40 arid)

E. de Martonne (1926) Index of Aridity $\frac{P}{T+10}$ (<5"desert")

C. W. Thornthwaite (1931) P/E index $P/E = \sum_{I}^{XII} 1.65 \left(\frac{P_i}{t_i+12.2}\right)^{9/10}$ $P/E \leq 31$ semiarid, $P/E \leq 16$ arid

J. A. Prescott (1949) effective rainfall $= 0.54\ E^{0.7}$

R. Capot-Rey (1951) Improved aridity index $\frac{1}{2}\left(\frac{P}{T+10} + \frac{12p_i}{t_i+10}\right)$

H. P. Bailey (1958) $PE = P/1.025^{T+x}$ (< 4.6 semi-arid boundary)

P. Moral (1964) monthly aridity boundary $p_i = \frac{t_i^{\,2}}{1.0} - t + 20$

W. C. Palmer (1965) Drought Severity Index $X_i = \sum_{\tau=1}^{i} \frac{P-\hat{P}}{(\bar{P}\bar{E}+\bar{R})/(\bar{P}+L)} / (0.31\tau+2.69)$

A. Y. M. Yao (1969) Moisture stress index $MSI = E/PE$

$ET = S_\Delta + P \qquad S_\Delta \propto S_o$

Simple indices: meteorological 250 mm isohyet border of aridity
400 mm isohyet border of semi-aridity

agricultural < 90% of average crop yield

Statistical measures: (Conrad, 1941) absolute average variability $v_a = \frac{\Sigma_i^n \varepsilon_i}{n}$; $\varepsilon_i = p_i - \bar{p}$

relative variability $v_r = \frac{100 v_a}{\bar{p}}$

Coefficient of variation $C_v = \frac{100\ \sigma}{\bar{p}}$

Symbols

P or $\bar{p}$	Mean Annual precipitation [mm]	T	Mean annual Temperature °C
E	Actual annual evaporation or evapotranspiration [mm]	PE	Annual potential evapotranspiration [mm]
p_i	Individual monthly precipitation [mm]	t_i	Individual monthly temperature [°C]
$\hat{P}$	Climatically appropriate water balance for existing conditions	τ	Number of months
		L	Loss [mm]
x	Empirical coefficient	S_o	Antecedent soil moisture [mm]
R	Recharge [mm]	σ	Standard deviation
S_Δ	Soil moisture loss [mm]		

TABLE 2

DRY LANDS BY CONTINENT (ADAPTED FROM MEIGS, 1957)

CONTINENT	DRY AREA (MILLIONS OF SQ. KM.)	% OF TOTAL
AFRICA	18	64
ASIA	16	39
AUSTRALIA	6	81
N. AMERICA	4	17
S. AMERICA	3	16
EUROPE	1	1

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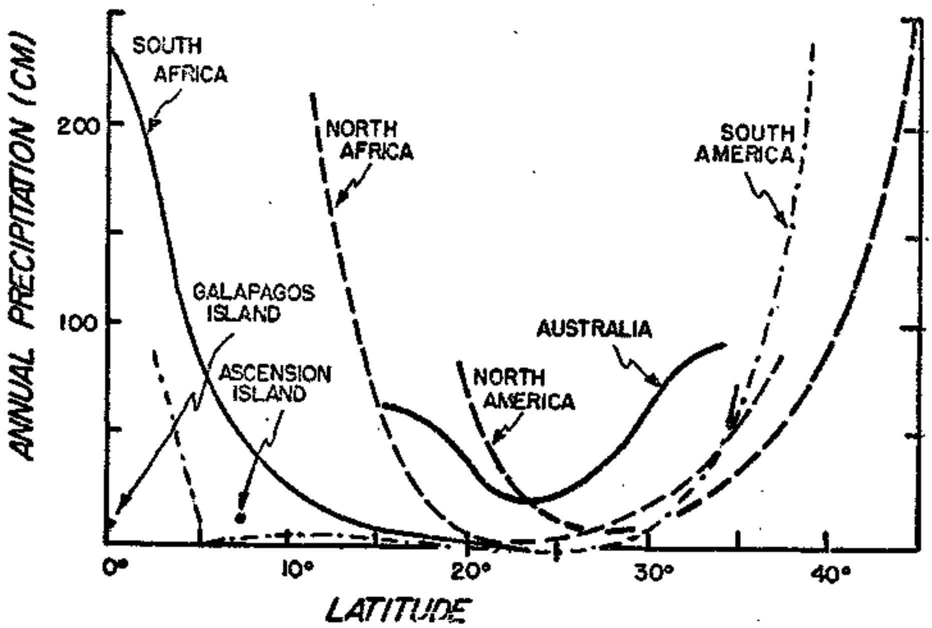


Figure 1 - Latitudinal gradient of precipitation near coastal deserts (after Lydolph, 1957)

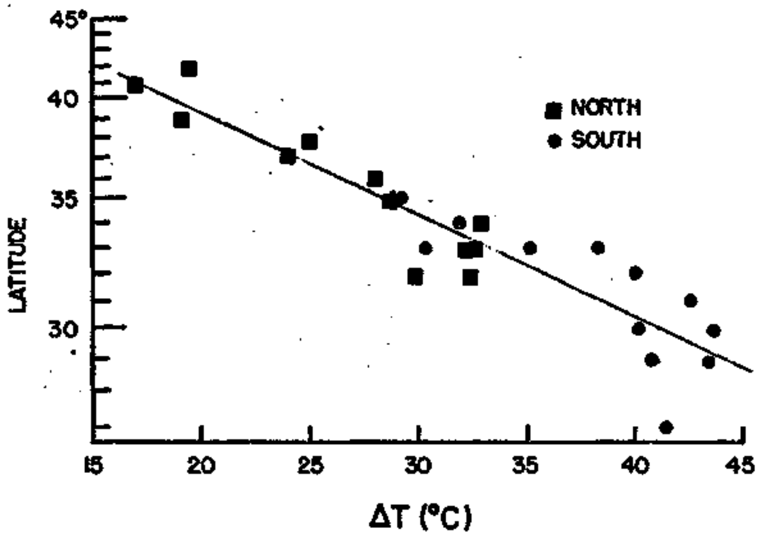


Figure 2 - Latitudinal position of subtropical High vs. tropospheric temperature gradient pole-equator (after Korff and Flohn, 1969)

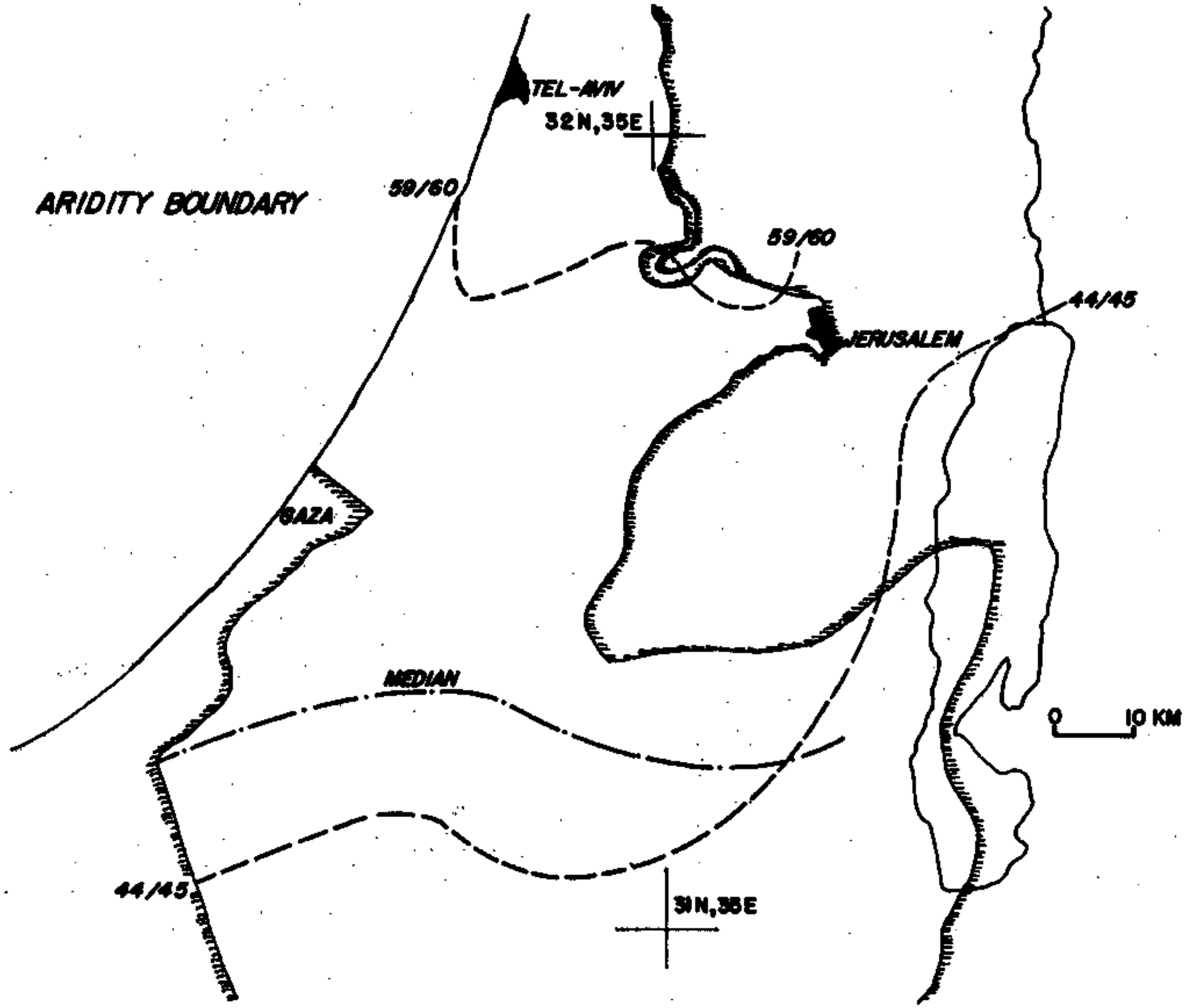


Figure 3 - Average and extreme positions of P/E index <16 boundary in Israel - 1940/1941 to 1959/1960 (after Ganor, 1963)

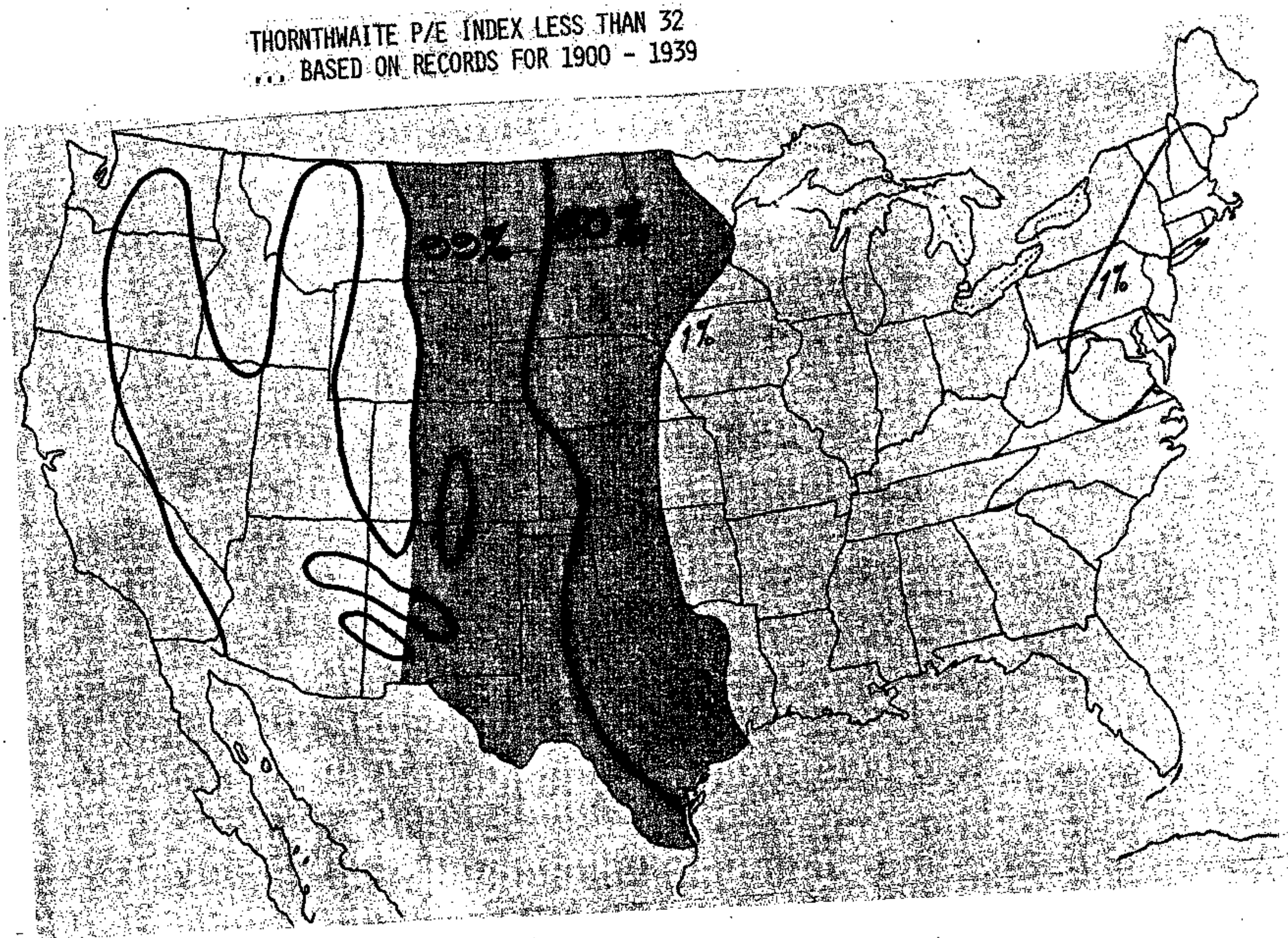


Figure 4 - Central U.S. P/E index < 32; 99%, 50%, 1% probability, 1900-1939 (after Thornthwaite, 1941)

GENERALIZED MEAN AND EXTREME POSITIONS OF THE 400 MM ISOHYET
1951 - 1973

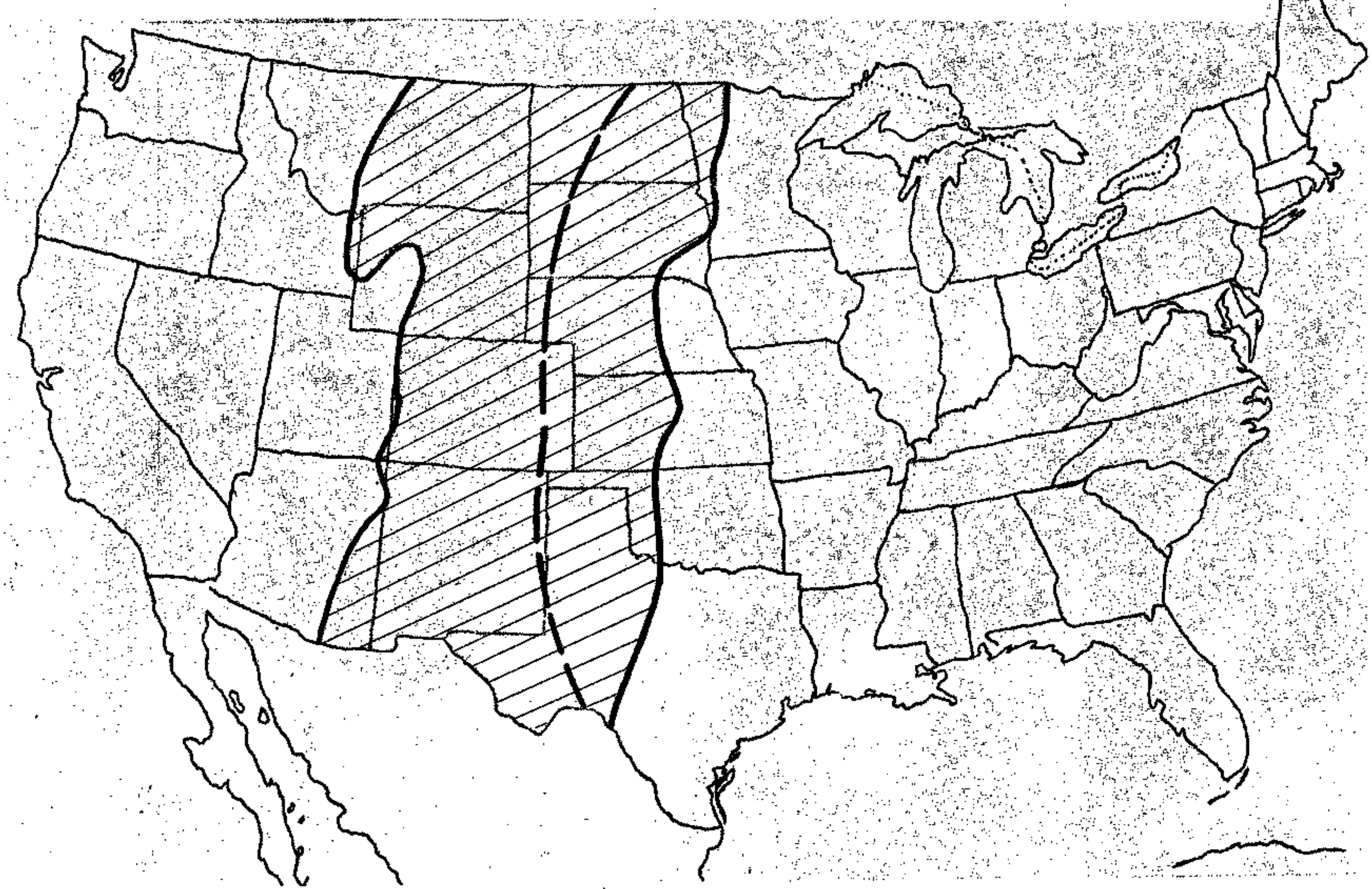


Figure 5 - Mean and extreme positions of 400 mm annual isohyet, Central U.S., 1951-1973

VARIABILITY OF RAINFALL – % DEPARTURE FROM NORMAL

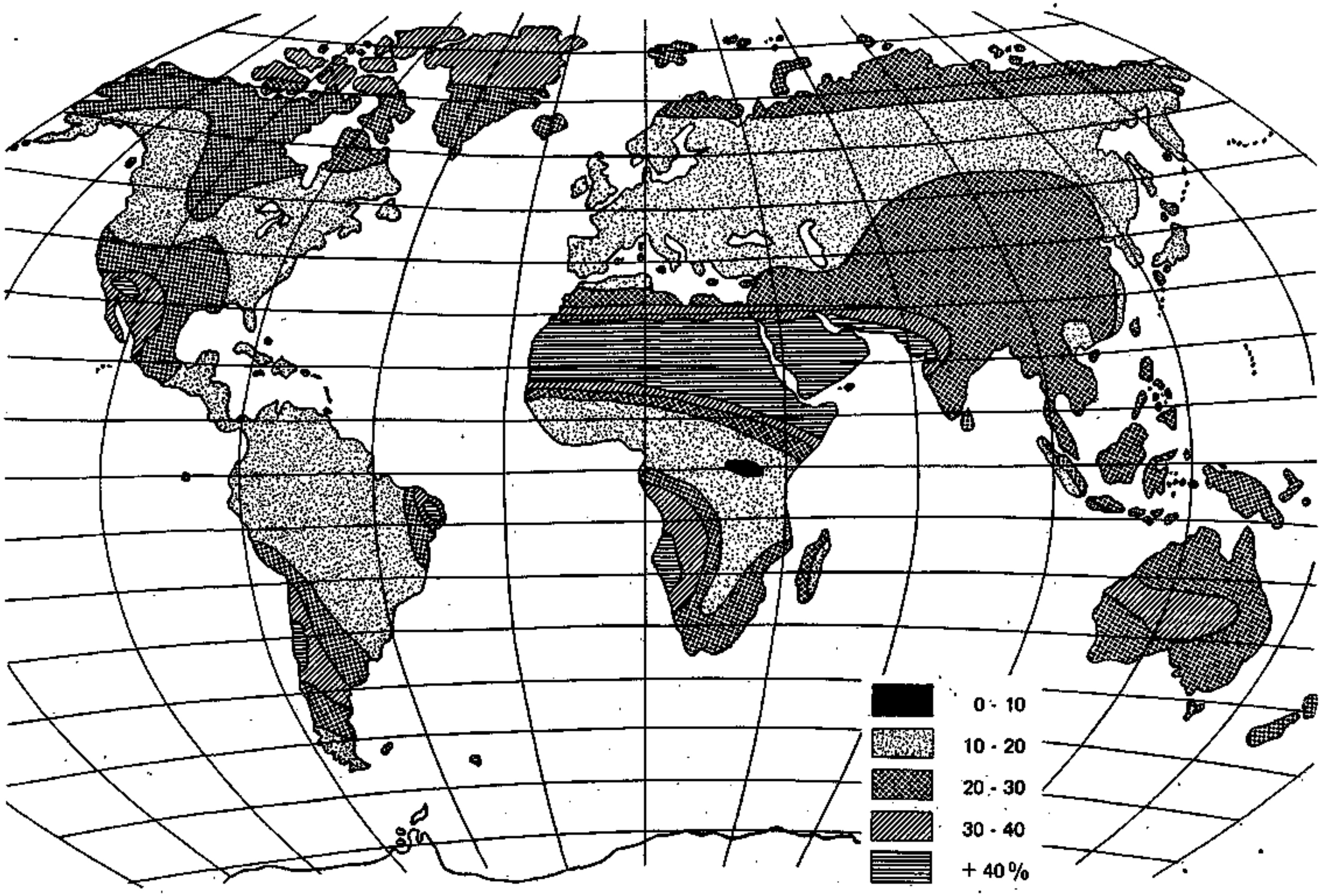


Figure 6 – Variability of annual precipitation on earth (after Conrad, 1941)

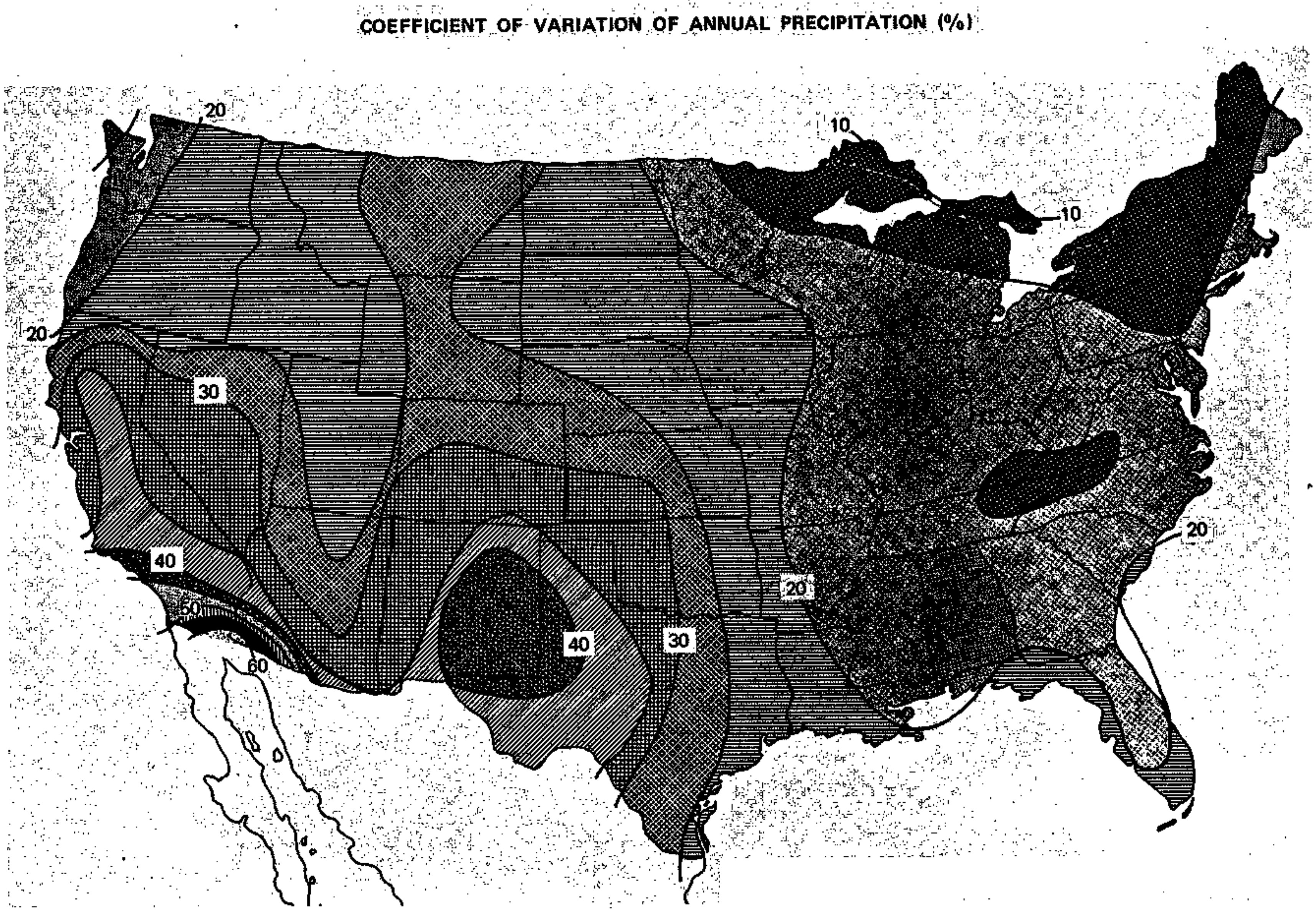


Figure 7 - Coefficient of variation of annual precipitation in the U.S. (after Hershfield, 1966)

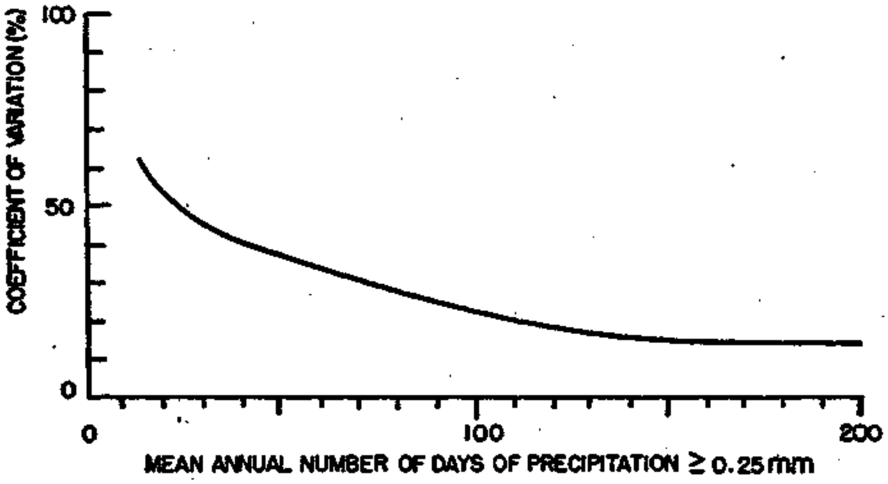


Figure 8 - Coefficient of variation of mean annual precipitation at U.S. stations vs. mean annual number of days with precipitation ≥ 0.25 mm

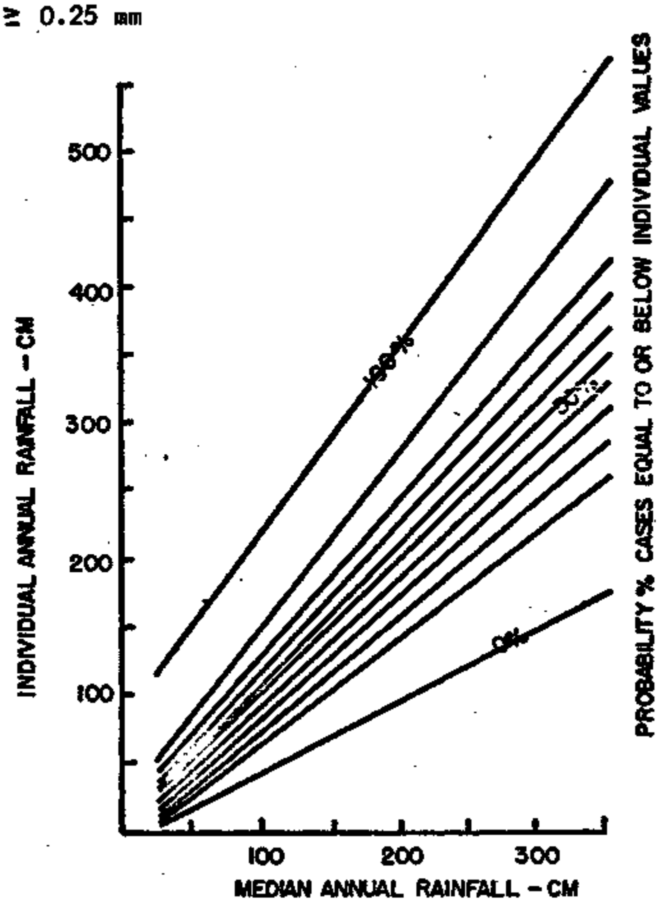


Figure 9 - Probability functions of annual rainfall vs. mean annual rainfall in an area of uniform synoptic régime, Oahu, Hawaii (after Landsberg, 1951)

MAJOR CROP PRODUCING AREAS

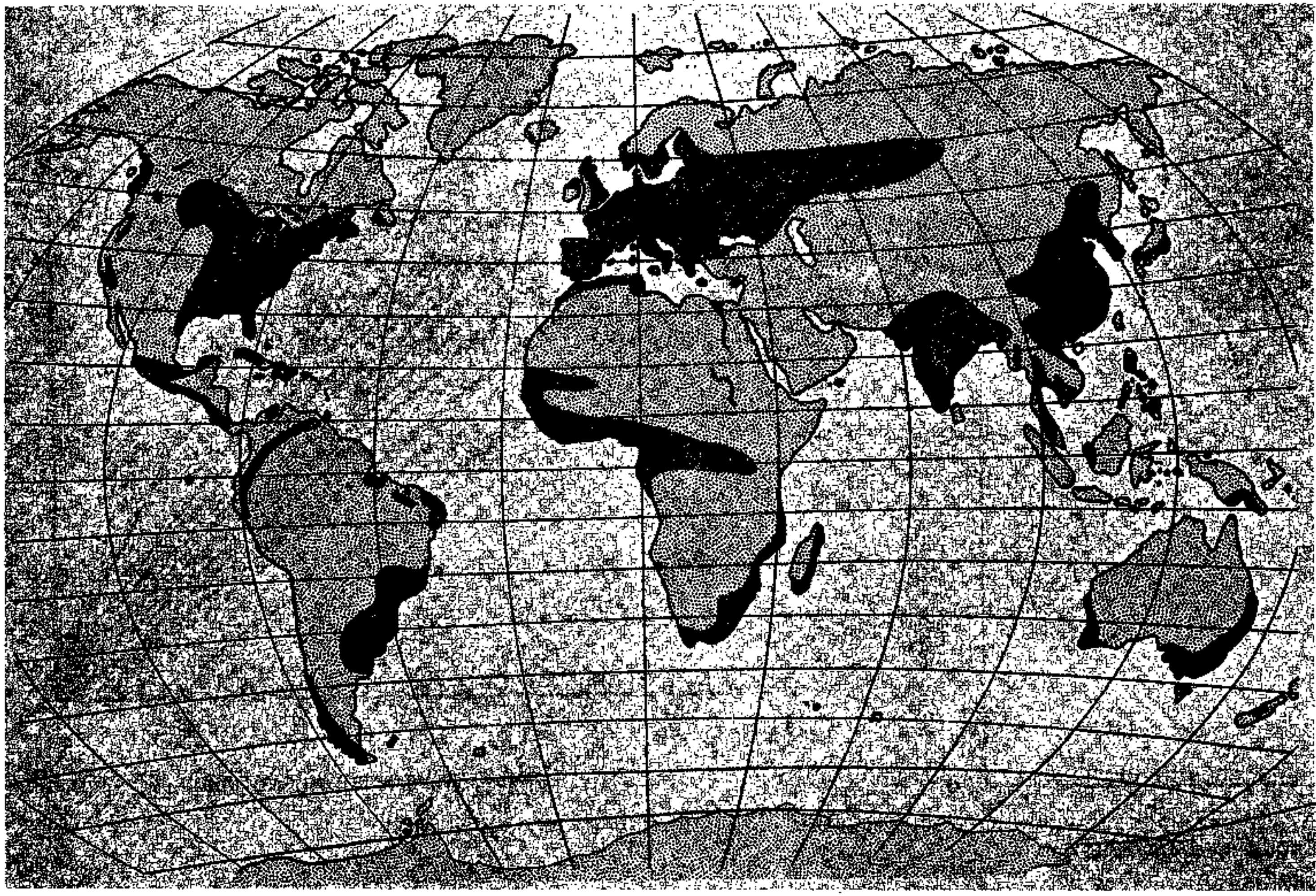


Figure 10 - Major crop producing areas on Earth

AREAS EXPERIENCING AT LEAST ONE MAJOR CROP DAMAGING DROUGHT IN 25 YEARS
(1948 - 1973)

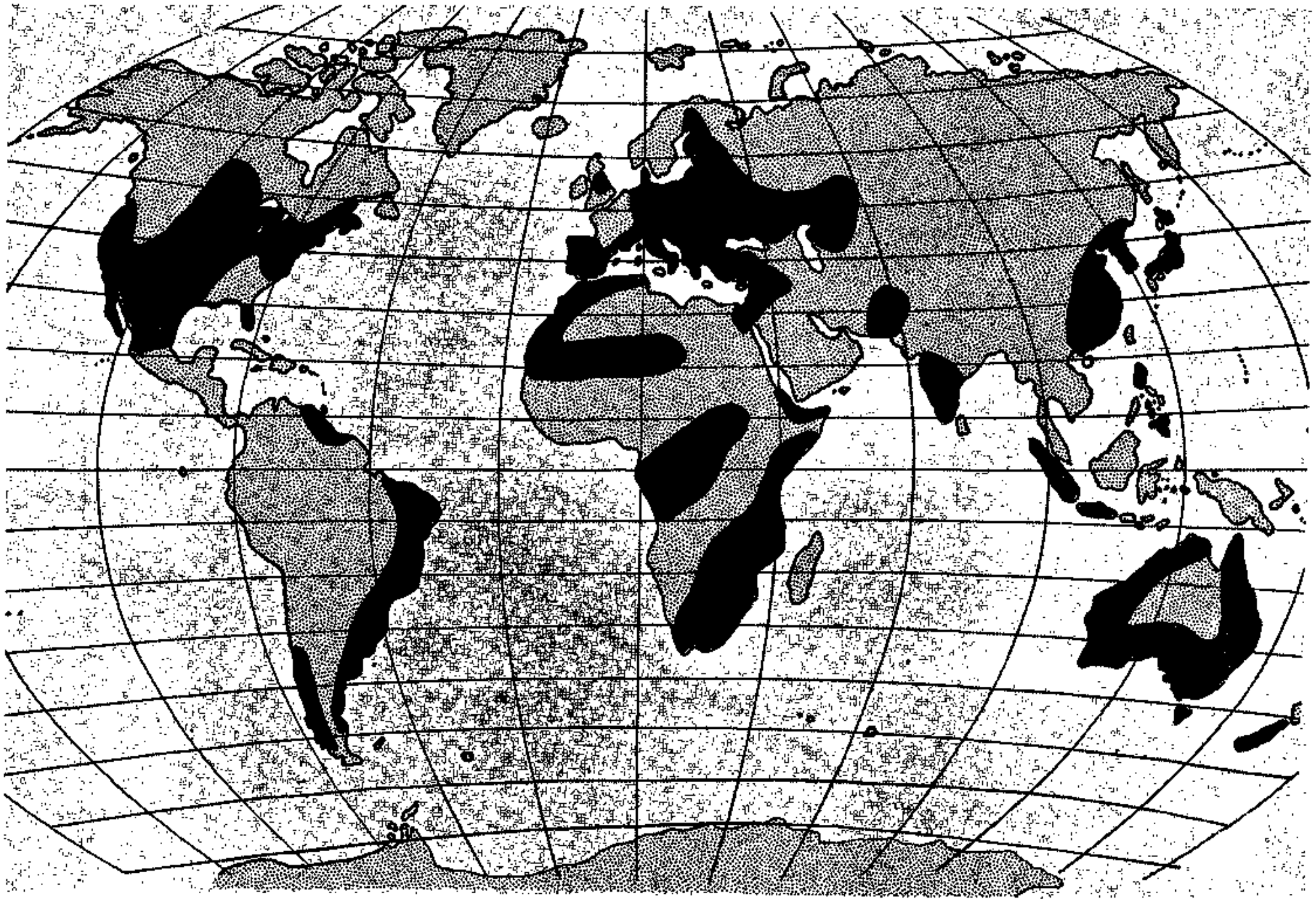


Figure 11 - Areas on Earth at least once affected by drought during 1948-1973 interval

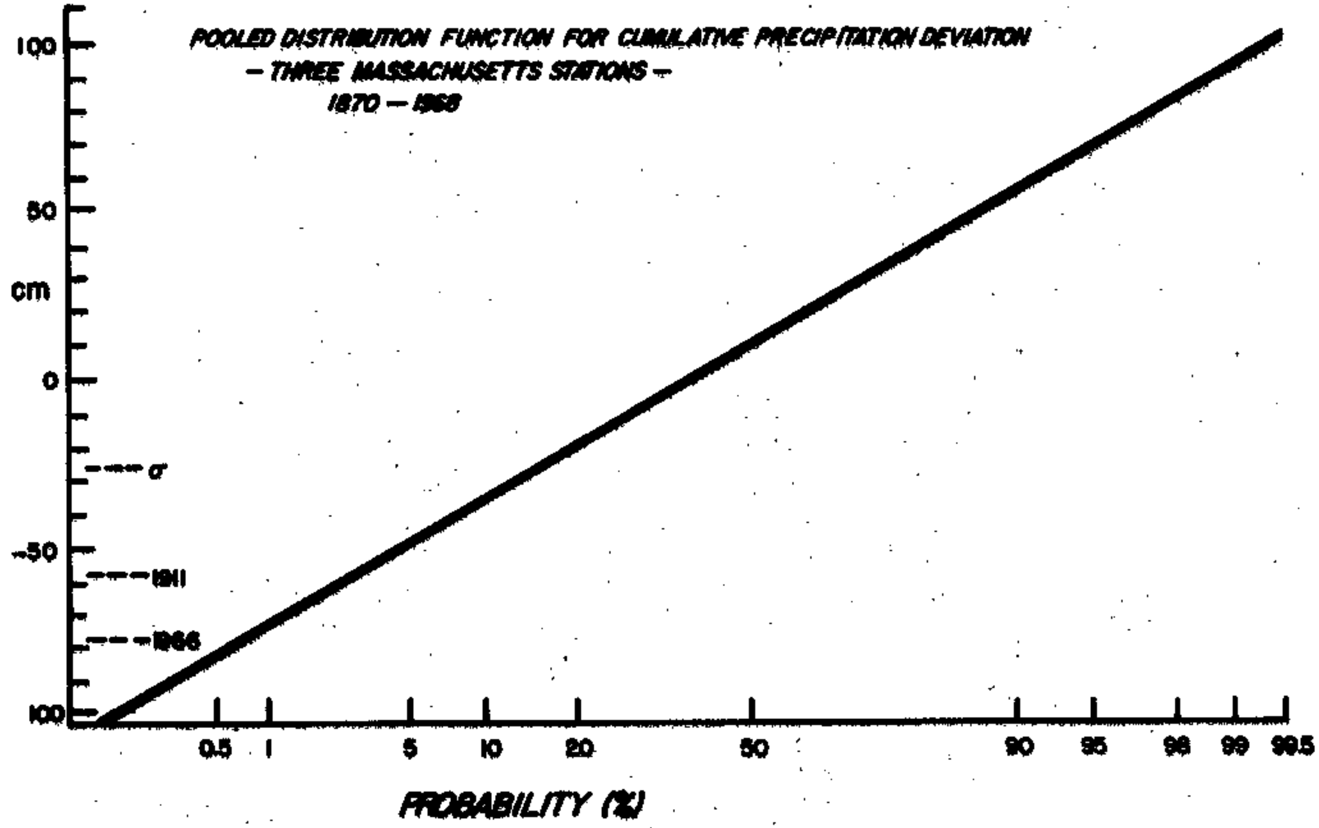


Figure 12 - Probability distribution of cumulative departures from mean for three stations in Massachusetts, 1870-1968 (after Russel et al., 1970)

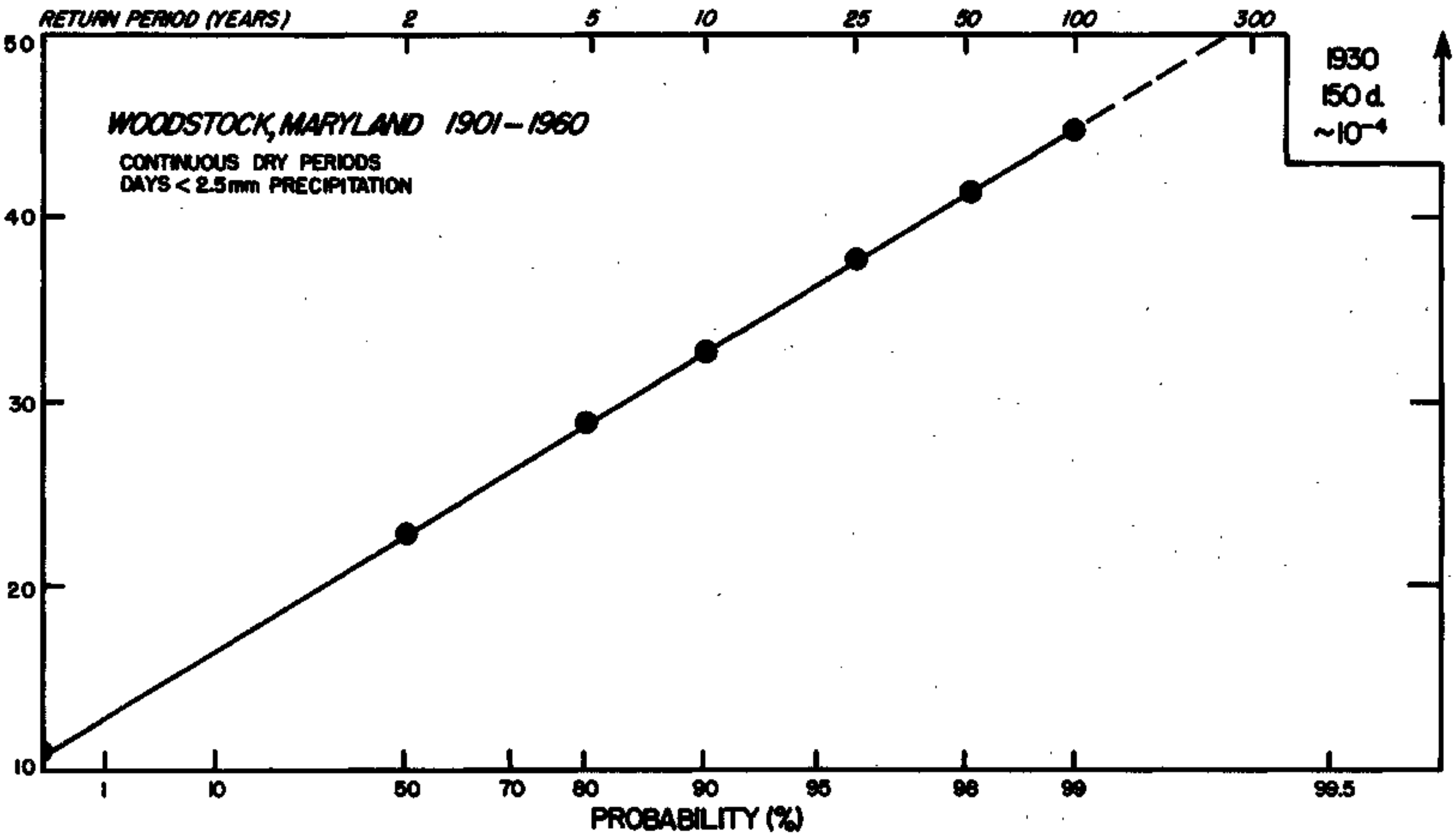


Figure 13 - Probability of dry-spell duration (days ≤ 0.25 mm precipitation) at Woodstock, Maryland (after Hershfield, 1971)

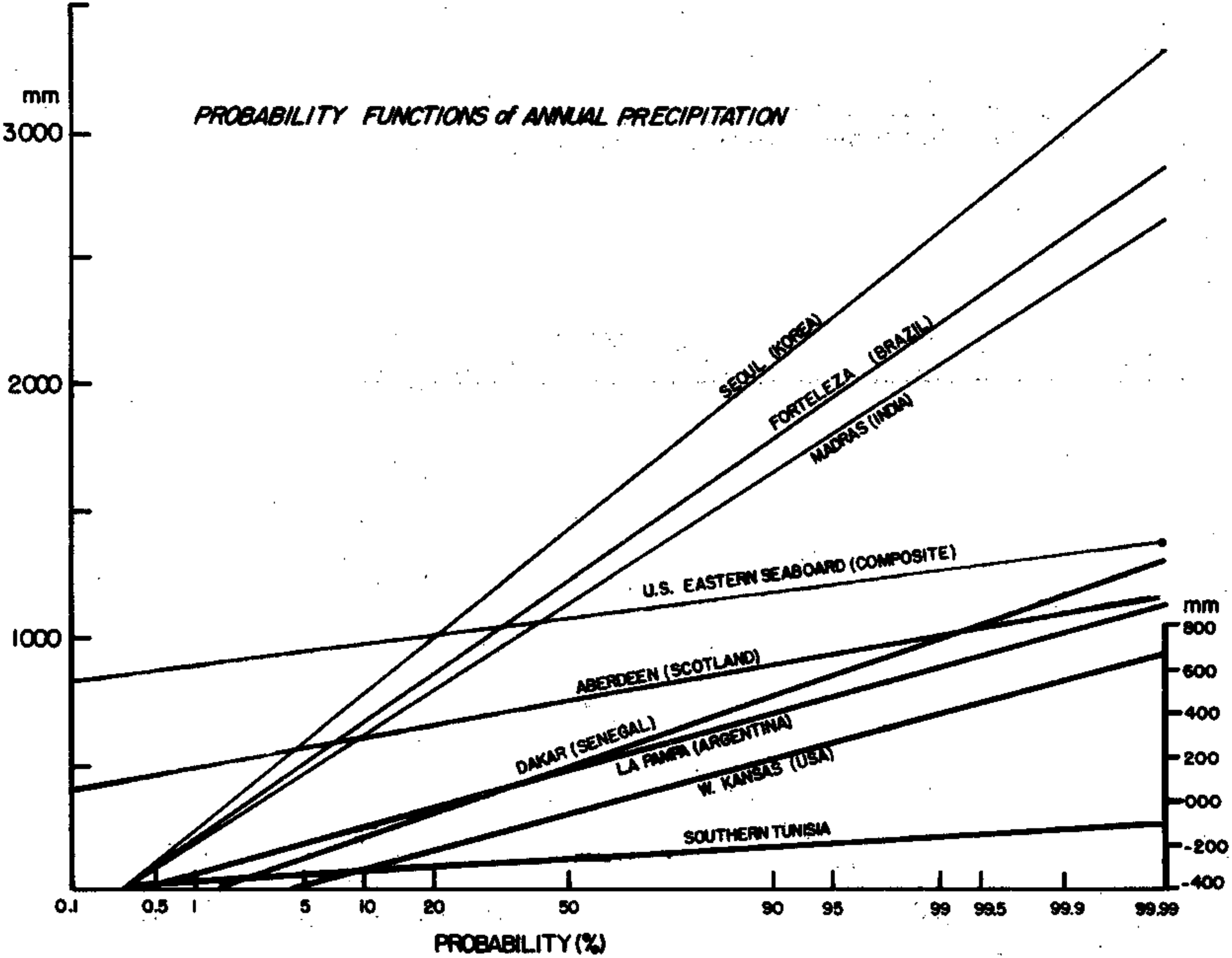


Figure 14 - Probability function of annual precipitation amounts at selected localities in different climatic régimes

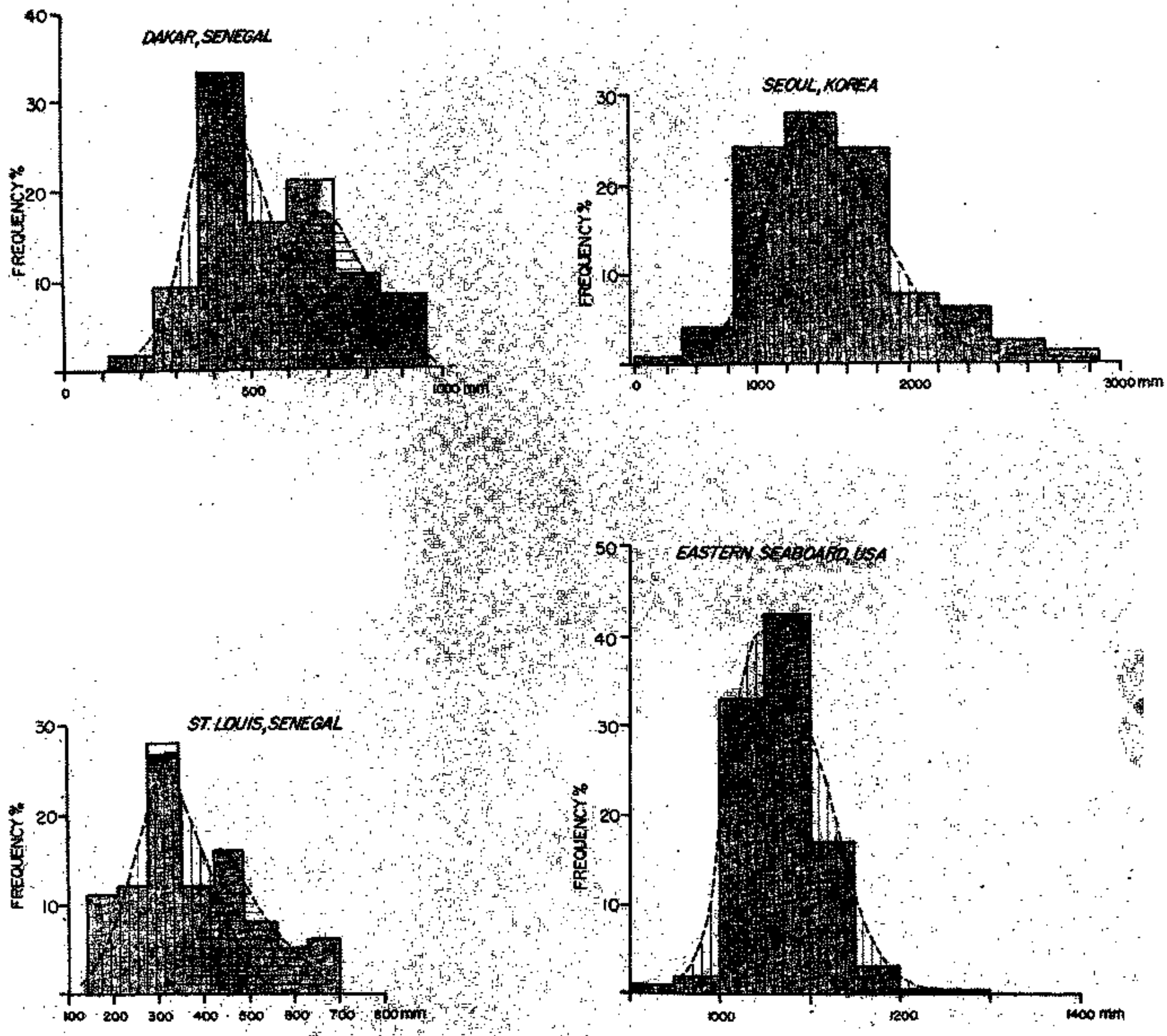


Figure 15 - Histograms of relative frequencies of annual precipitation amounts at Dakar and St. Louis (Senegal); Seóul (Korea); and Eastern U.S. Seaboard

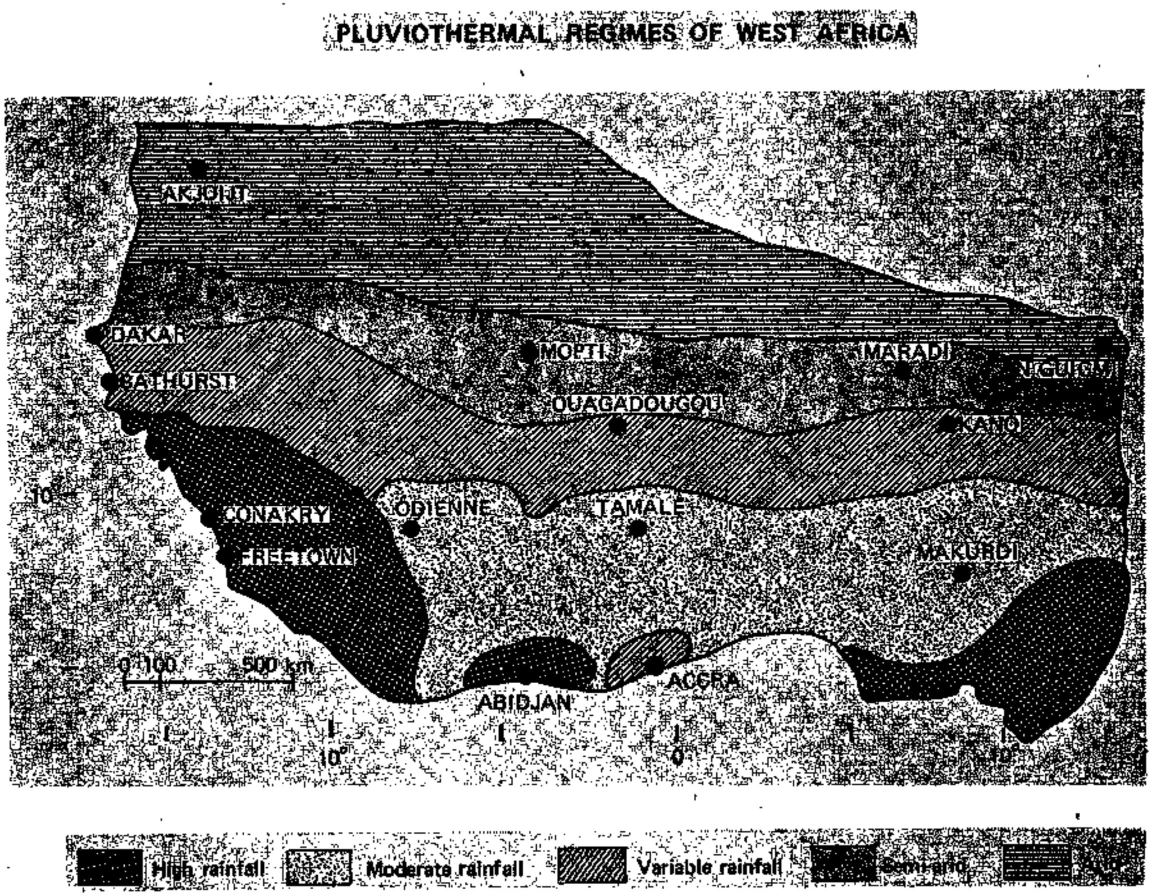


Figure 16 - Pluviothermal régimes of West Africa (after Moral, 1964)

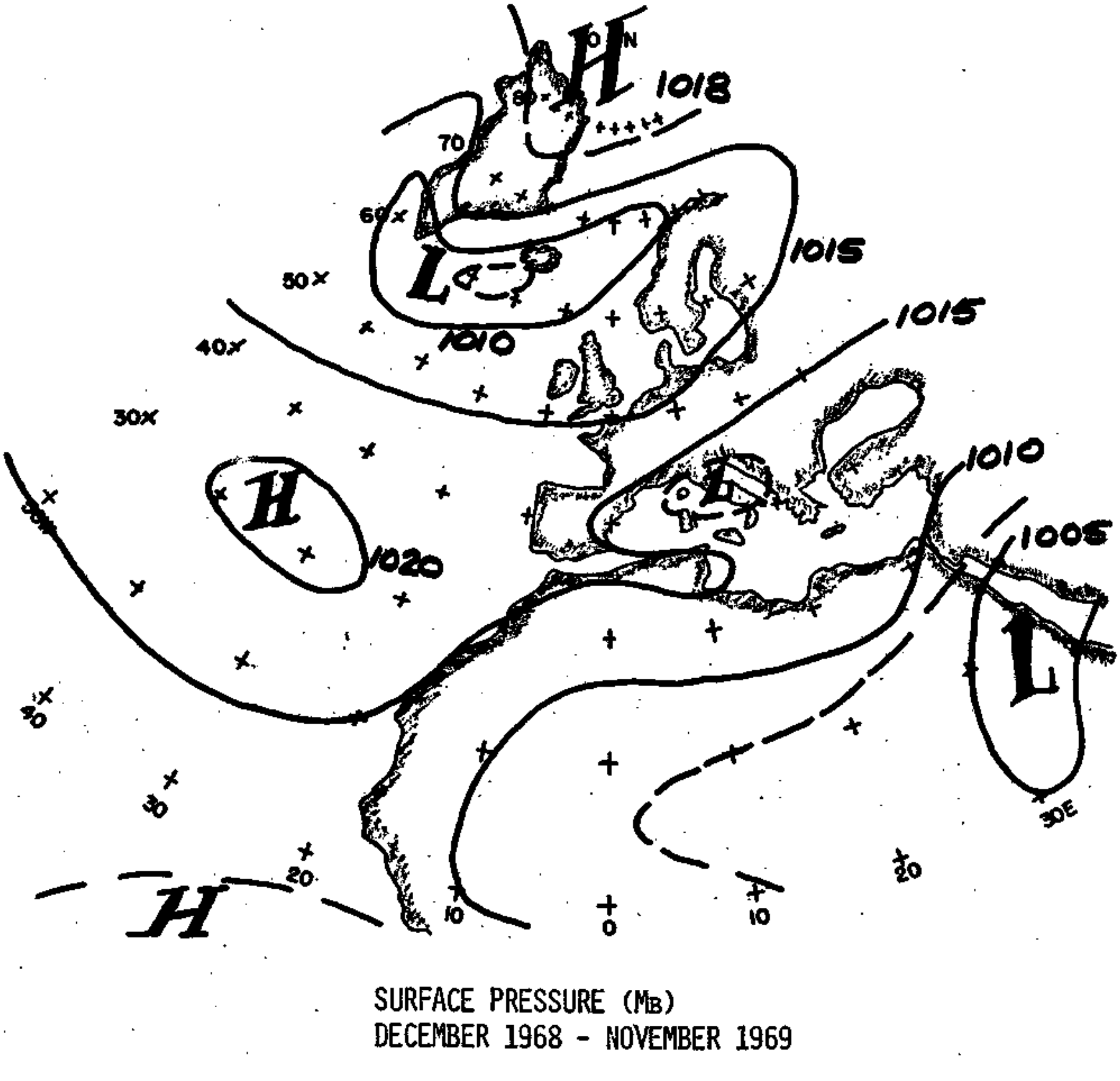
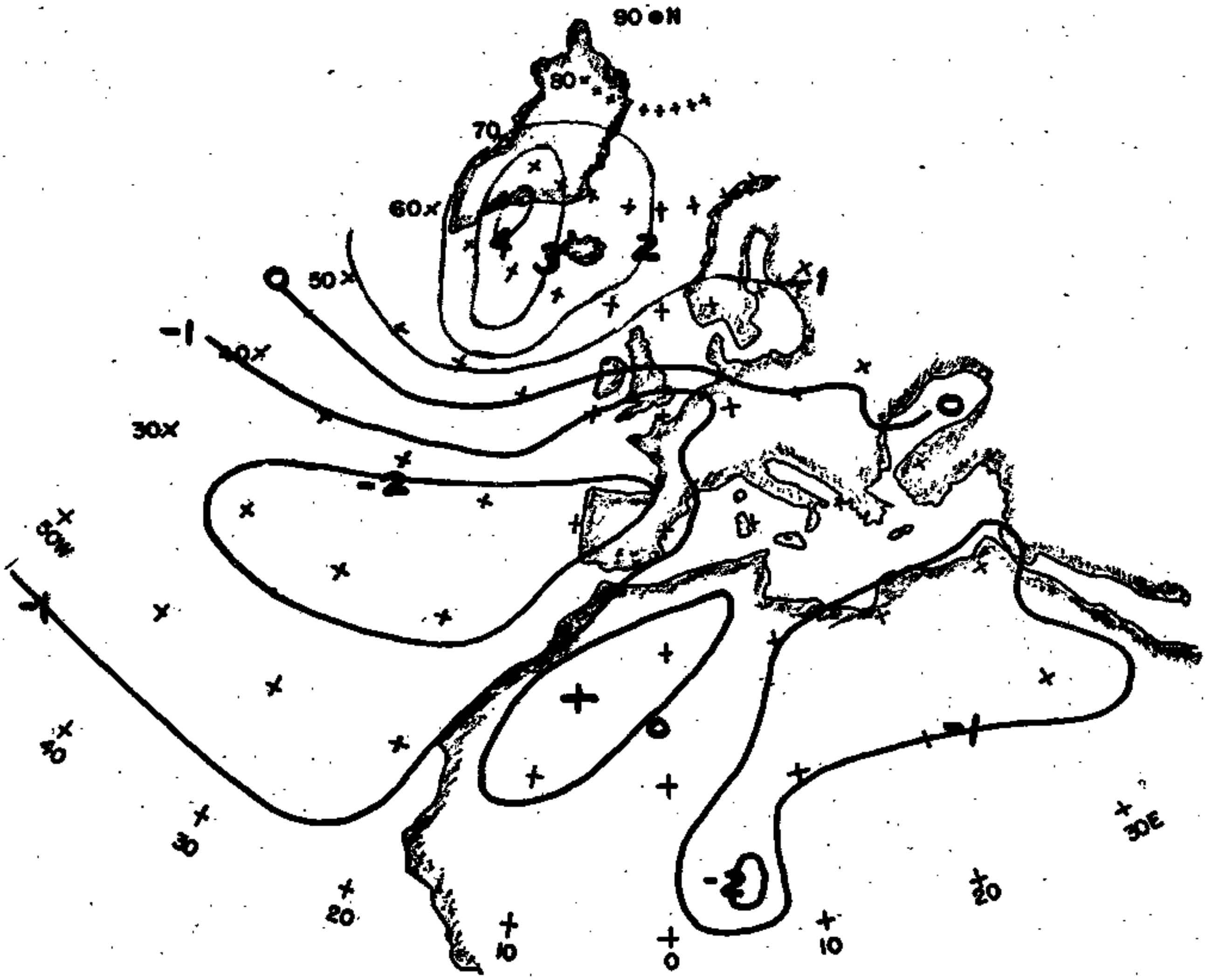
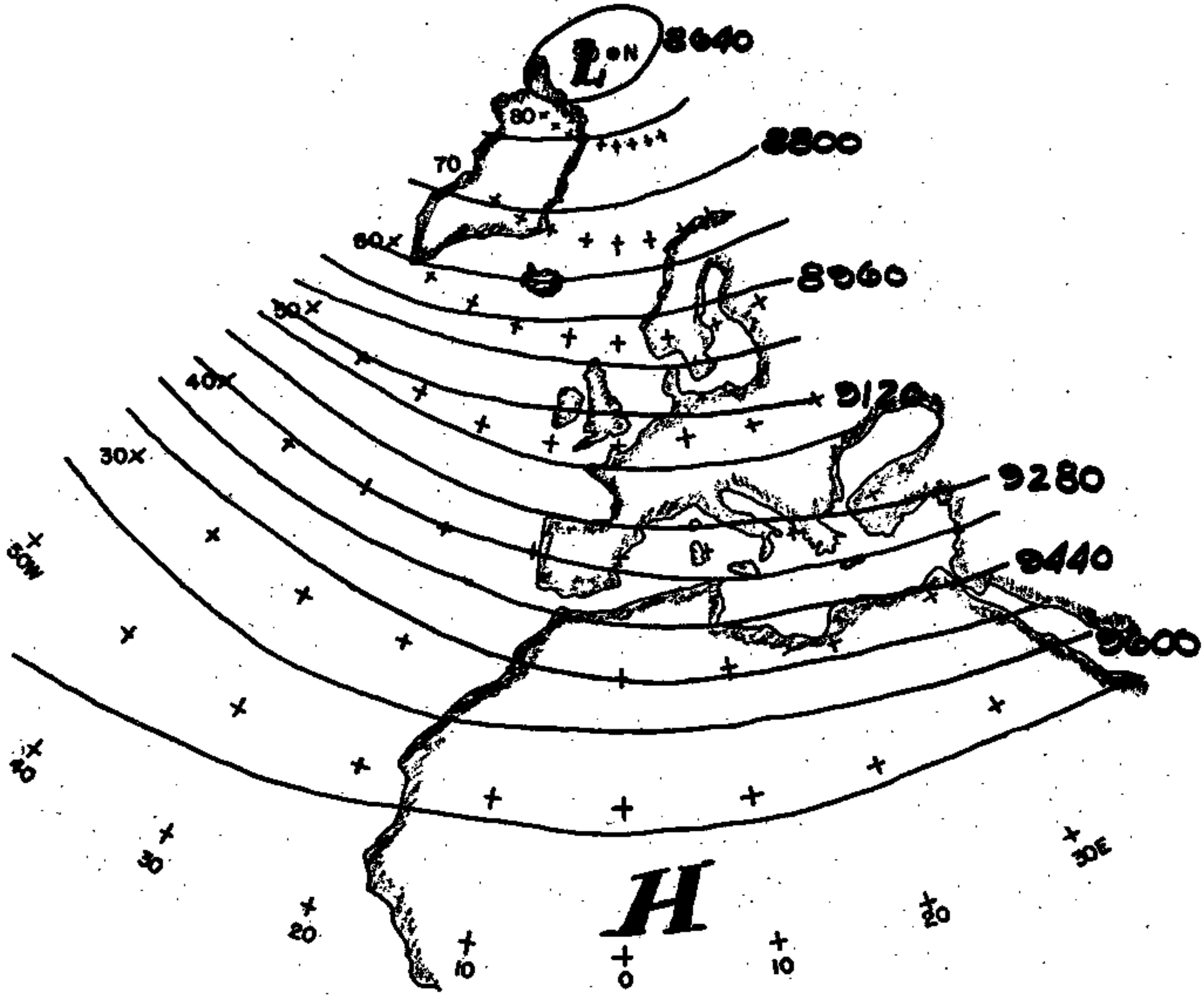


Figure 17 - Surface pressure, Atlantic Space, 1969 - (moist year in Dakar, Senegal)



SURFACE PRESSURE DEPARTURES FROM MEAN (MB)
DECEMBER 1968 - NOVEMBER 1969

Figure 18 - Surface pressure departure from mean, Atlantic Space, 1969



300 MB CONTOURS
DECEMBER 1968 - NOVEMBER 1969

Figure 19 - 300-mbar contours, Atlantic Space 1969

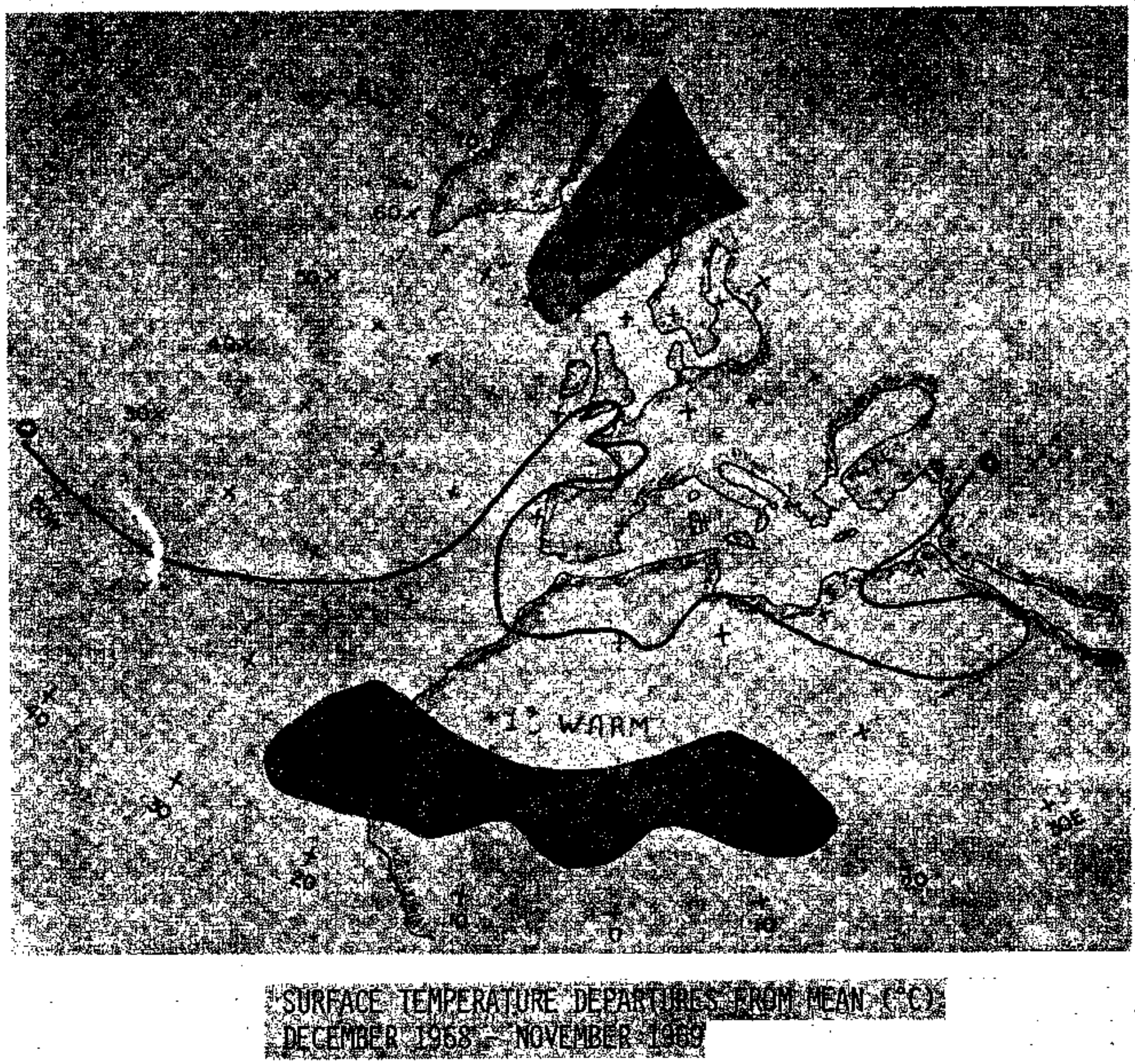
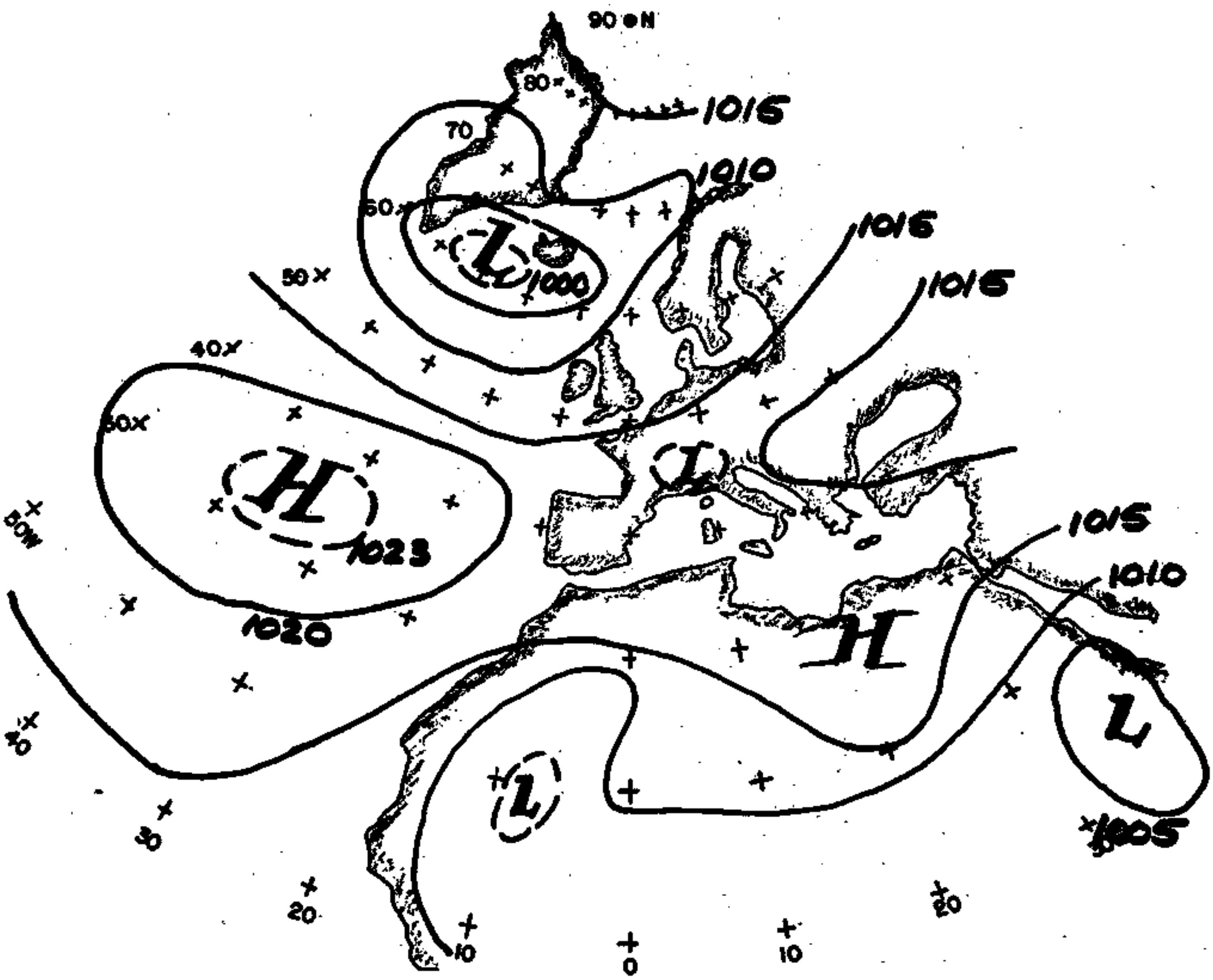


Figure 20 - Surface temperature departures from mean, Atlantic Space, 1969



SURFACE PRESSURE (MB)
DECEMBER 1971 - NOVEMBER 1972

Figure 21 - Surface pressure, Atlantic Space, 1972 (very dry year in Dakar, Senegal)

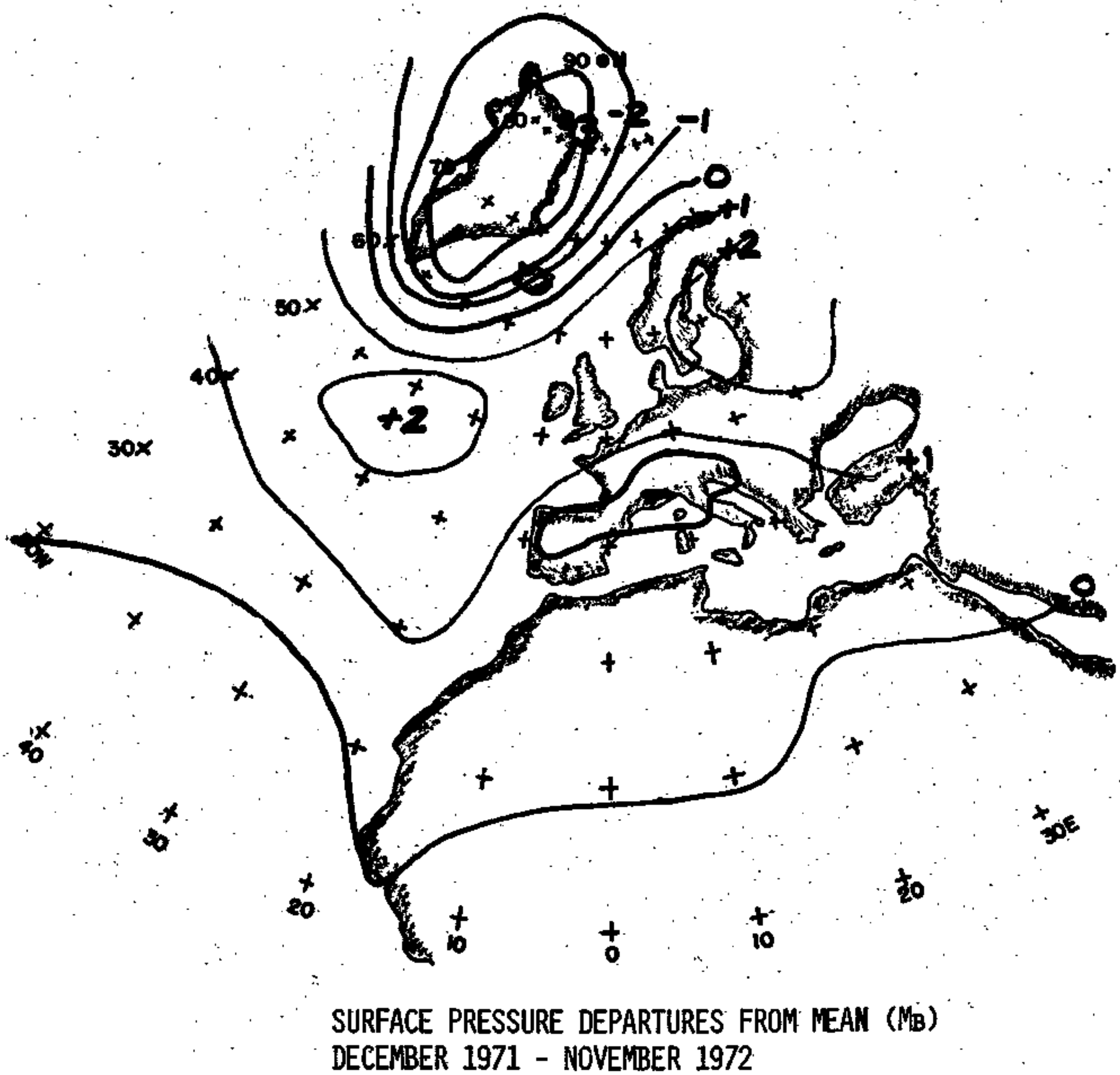
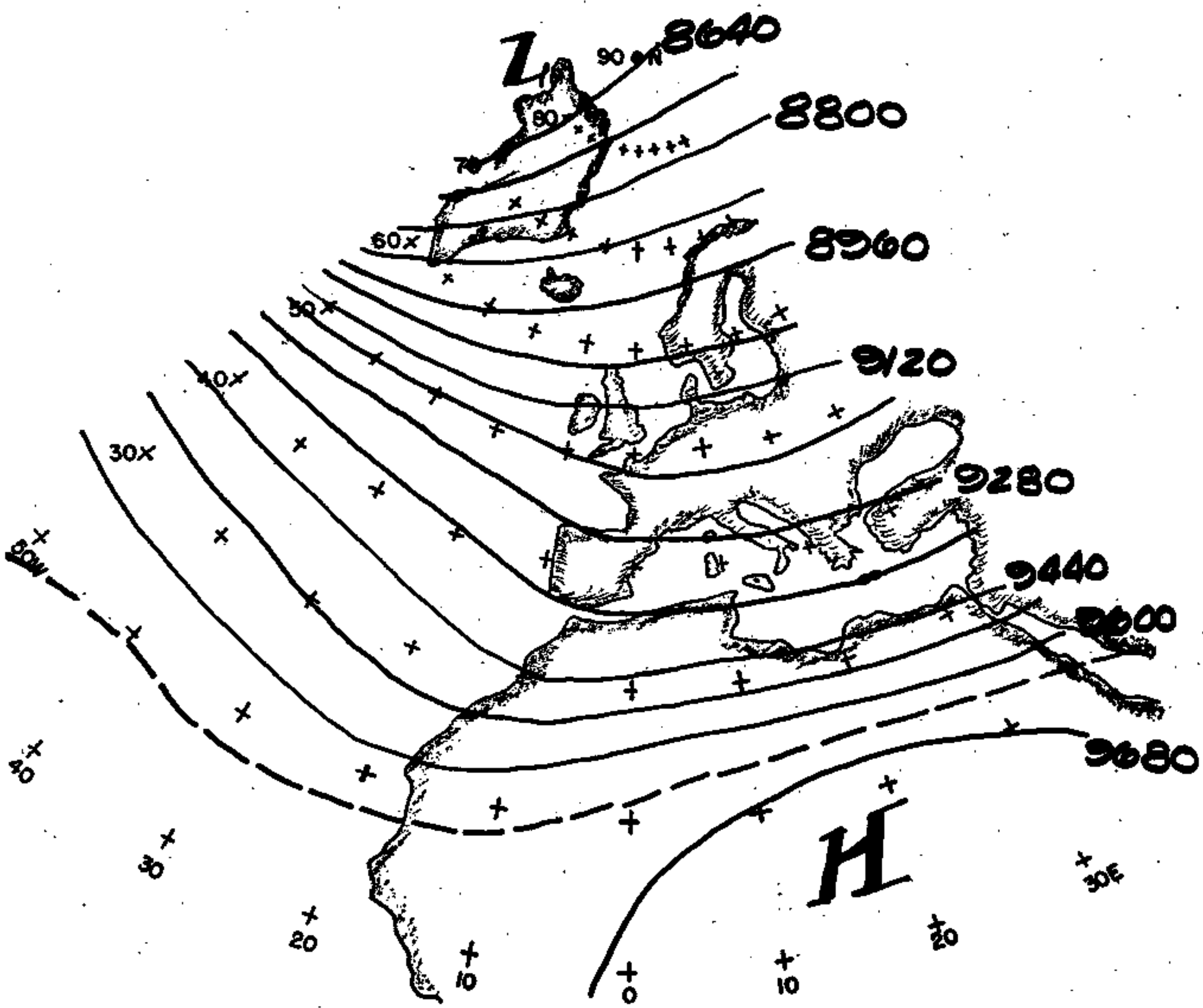


Figure 22 - Surface pressure departure from mean, Atlantic Space, 1972



300 MB CONTOURS
DECEMBER 1971 - NOVEMBER 1972

Figure 23 - 300-mbar contours, Atlantic Space, 1972

[redacted]

Figure 24 - Surface temperature departures from mean, Atlantic Space, 1972

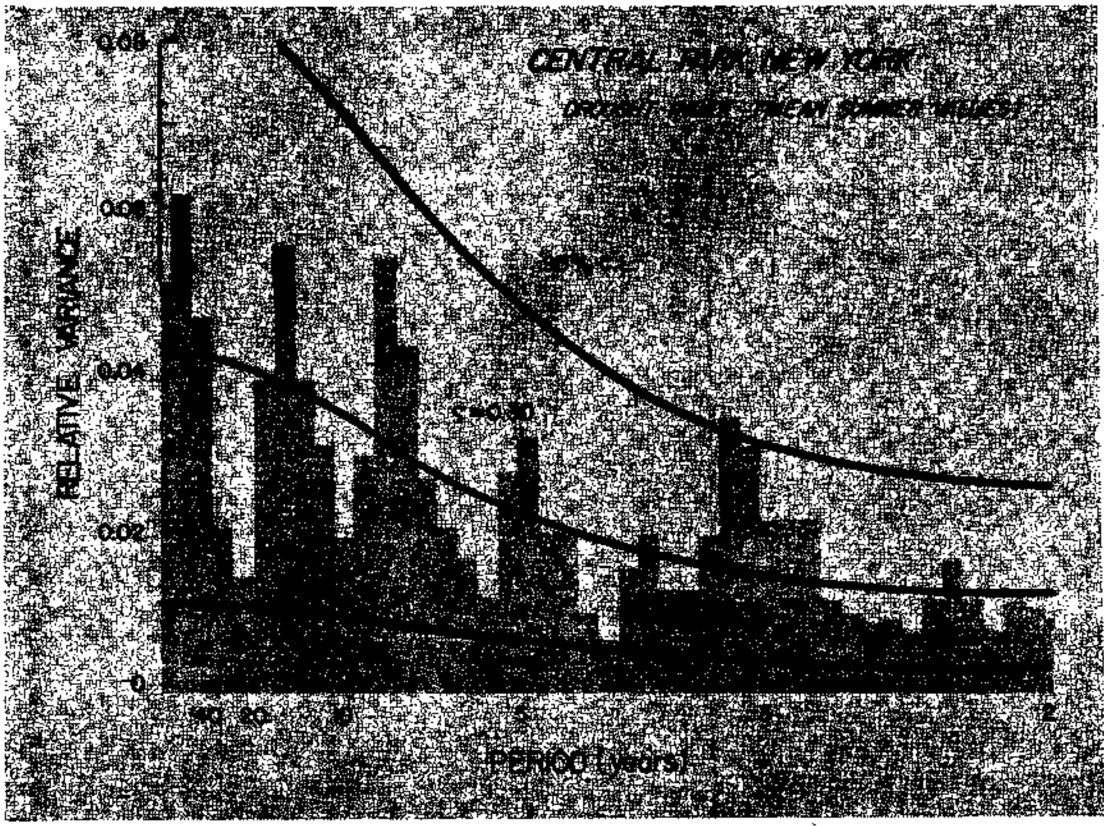


Figure 25 - Power spectrum of the Palmer drought index (summer) at Central Park, New York, 1826-1966 (after Mitchell, 1968)

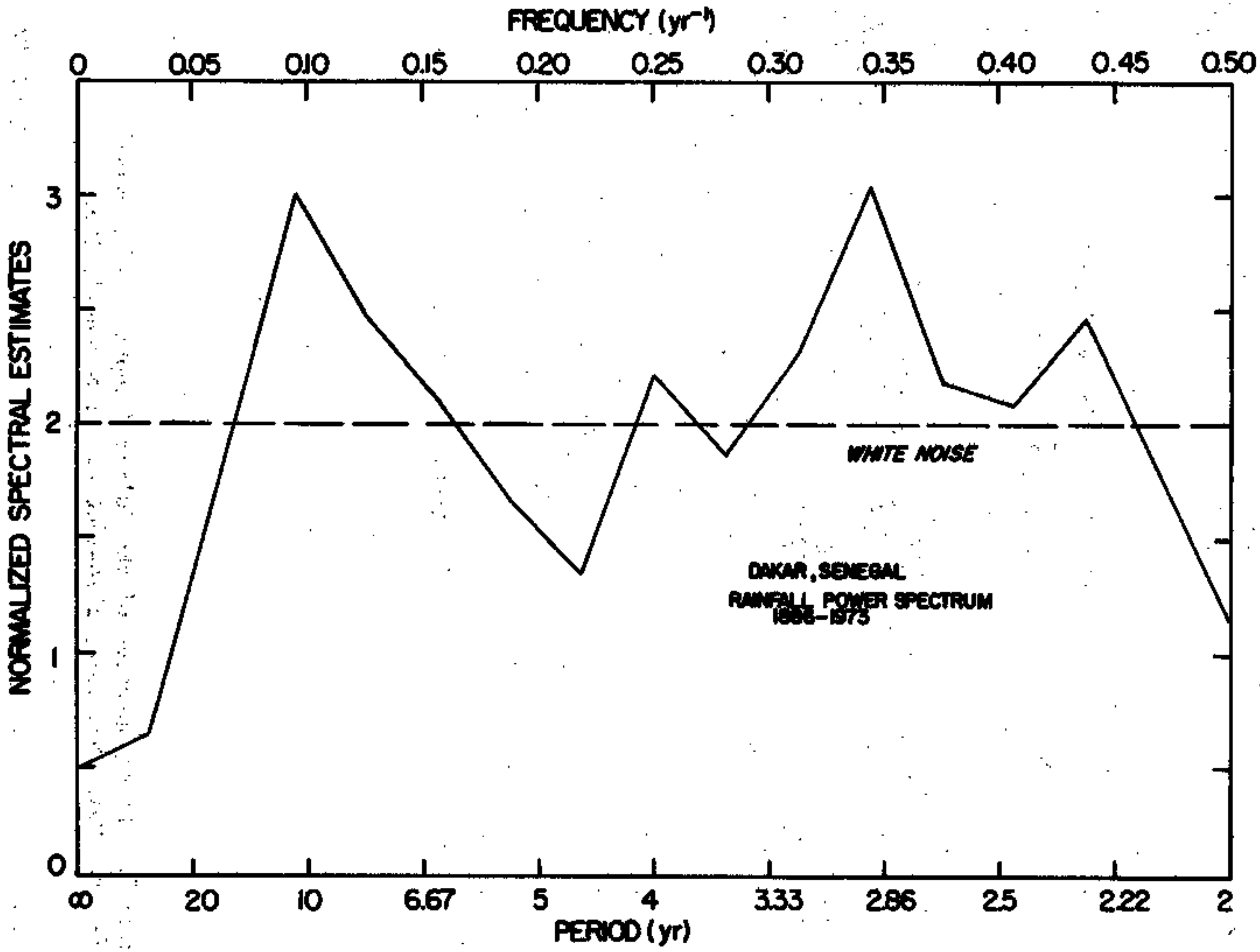


Figure 26 - Power spectrum of Dakar, Senegal, annual precipitation, 1887-1973

APERCU SUR LES DONNEES HYDROLOGIQUES DE LA SECHERESSE DE LA PERIODE 1970 - 1973 EN AFRIQUE TROPICALE

par

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(DAFECO)

SUMMARY

The observations, measurements and studies which have been carried out since 1970 by hydrologists of the ORSTOM (Office for Overseas Scientific and Technical Research) reveal the complex nature of a drought such as is being experienced in Africa: complex in its significance for the various aspects of the economy affected by the drought - stock-rearing, dry-farming, irrigated crops, hydro-electricity, etc.; complex in the spatial variations of the severity along the adversely affected belt extending from northern Brazil to India. The phenomena may be more readily studied from the hydrology of the large rivers, for which local singularities are eliminated.

The zone affected in Africa extends from the Sahara to the equatorial forest, while there is a second zone of drought in southern Africa.

In this study, some examples are given of values observed in the northern hemisphere of mean annual discharges, annual maximum values of discharges and the minimum values which followed in 1972 and, as far as possible, for the year 1973, particularly for the Senegal, Niger and Chari. The return period of these values for the two years varies in general from 50 to 100 years. The minimum values which followed the flood of 1973 are not known at the time of this study but, in many basins, the values are lower than those of the preceding year. Even if it is assumed that the amounts of annual precipitation, giving rise to the discharges during these two years, are independent (which is probably not the case), the annual flows are certainly not independent, on account of the soil-moisture deficit, at least in the flood channel of water courses. This may lead statisticians to think. As regards discharges, the present period is somewhat similar to 1913.

This can be seen from a few data relating to the situation in Lake Chad in 1973-1974, which is compared with what is known of previous situations.

RESUME

Les observations, mesures et études effectuées depuis 1970 par les hydrologues de l'ORSTOM mettent en évidence le caractère complexe d'une sécheresse telle que celle que l'on observe actuellement en Afrique : complexité dans sa signification pour les divers aspects de l'économie touchés par la sécheresse : élevage, culture sèches, cultures irriguées, hydroélectricité, etc., complexité dans les variations spatiales de sa sévérité sur la longue bande sinistrée qui va du nord du Brésil jusqu'à l'Inde. Les phénomènes sont plus faciles à étudier d'après l'hydrologie des grands fleuves pour lesquels les singularités locales sont éliminées.

La zone affectée en Afrique s'étend du Sahara à la forêt équatoriale; on retrouve une seconde zone de sécheresse en Afrique australe.

Le présent exposé donne quelques exemples des valeurs observées dans l'hémisphère Nord pour les débits moyens annuels, les valeurs maximales annuelles des débits et les valeurs minimales qui leur font suite pour l'année 1972 et, dans la mesure du possible, pour l'année 1973, en particulier pour le Sénégal, le Niger et le Chari. La période de retour de ces caractéristiques varie en général pour les deux années de 50 ans à 100 ans. Les valeurs maximales qui font suite à la crue de 1973 ne sont pas connues à la date de cet exposé mais, dans beaucoup de bassins, elles sont inférieures à celles de l'année précédente. Même si l'on suppose que les précipitations annuelles, à l'origine des débits de ces deux années, sont indépendantes, ce qui n'est probablement pas le cas, les volumes annuels écoulés ne le sont certainement pas par suite du déficit d'humidité des sols, au moins dans le lit majeur des cours d'eau. Ceci peut faire réfléchir les statisticiens. La période actuelle en ce qui concerne les débits est assez comparable à celle de 1913.

On peut le voir d'après quelques données sur la situation du lac Tchad en 1973-1974 qui est comparée à ce que l'on sait des situations antérieures.

РЕЗЮМЕ

Наблюдения, измерения и исследования, которые ведутся гидрологами ORSTOM (Ведомство зарубежных технических исследований) с 1970 г. показывают сложный характер засухи,наблюдаемой в Африке; сложная по значению своего влияния на различные аспекты экономики: животноводство, богарное земледелие, поливные сельскохозяйственные культуры, гидроэнергию и т.д; сложная по пространственным колебаниям интенсивности вдоль сильно поражаемой зоны, простирающейся от северной части Бразилии до Индии. Эти явления засухи можно более легко исследовать по гидрологии больших рек, для которых исключаются местные особенности.

Пораженная засухой зона в Африке простирается от Сахары до экваториальных лесов, в то же время имеется вторая зона засухи в Южной Африке.

В этом исследовании приведены некоторые примеры наблюденных в Северном полушарии величин средних годовых расходов, максимальных годовых расходов и минимальных расходов, которые наблюдались в 1972 г., а также и в 1973 г., особенно в Сенегале, Нигере и Чари. Интервал повторяемости этих величин для этих двух лет в общем колеблется от 50 до 100 лет. Величины минимальных расходов, которые последовали за паводком 1973 г., не были известны во время этого исследования, но во многих бассейнах величины расходов ниже по сравнению с величинами за предшествующий год. Если даже предположить, что количество ежегодных осадков, вызвавшее увеличение расходов за период этих двух лет, является независимым (что, вероятно, не так), то годовой сток, конечно, не является независимым, ввиду дефицита влажности почвы, по крайней мере, в паводковом русле водотоков. Это возможно заставит статистиков подумать. Что касается расходов, то нынешний период несколько аналогичен периоду 1913 г.

Это можно видеть по небольшому количеству данных, связанных с ситуацией на озере Чад в 1973-1974 гг., которые сравниваются с небольшим количеством известных данных предыдущих ситуаций.

RESUMEN

Las observaciones, medidas y estudios efectuados por los hidrólogos del ORSTOM desde 1970 revelan la índole compleja de la sequía que actualmente se observa en Africa: complejidad en su significación, por los diversos aspectos de la economía afectados por la sequía, tales como cría de ganado, cultivos secos, cultivos de regadío, hidroelectricidad, etc.; complejidad de las variaciones espaciales irregulares y complejas de la gravedad de esa sequía en la zona afectada que se extiende del norte del Brasil hasta la India. Los fenómenos son más fáciles de estudiar a partir de la hidrología de los grandes ríos, en los que las particularidades locales quedan eliminadas.

La zona afectada en Africa se extiende del Sahara a la selva ecuatorial. En Africa austral se puede observar una segunda zona de sequía.

En el presente estudio figuran algunos ejemplos de los valores observados en el hemisferio norte en lo que respecta a los caudales anuales medios, a los valores máximos anuales de los caudales y a los valores mínimos observados durante el año 1972 y, en la medida de lo posible, durante el año 1973, particularmente en Senegal, Níger y Chari. El período de retorno de esas características para los dos años varía por lo general de 50 a 100 años. Los valores mínimos que se observaron después de la crecida de 1973 no se conocen al momento de redactar el presente estudio, pero en muchas cuencas esos valores son inferiores a los del año anterior. Incluso si se da por supuesto que las precipitaciones anuales que han originado los caudales de esos dos años son independientes (lo cual no es probablemente el caso), los volúmenes anuales del flujo no son ciertamente independientes, debido al déficit de humedad de los suelos, al menos en el cauce o lecho mayor de los cursos de agua. Esto puede dar que pensar a los estadistas. En lo que respecta a los caudales, el actual período es bastante análogo al del año 1913.

Esto puede verse observando algunos datos relativos a la situación del lago Chad en 1973-1974, que se compara con lo que se sabe de las situaciones anteriores.

Il n'est pas facile de donner des sécheresses une définition qui puisse satisfaire tous les spécialistes intéressés par leurs divers aspects et c'est d'ailleurs une des raisons pour lesquelles il a été difficile de donner de la consistance aux projets qui avaient été prévus au début de la décennie hydrologique internationale pour l'étude de ce sujet.

En effet, la sécheresse correspond à une insuffisance temporaire d'eau, que cette eau provienne des pluies ou des apports d'une rivière, mais il n'est pas nécessaire que cette insuffisance affecte la totalité de l'année hydrologique, ou même de la saison des pluies, pour qu'elle porte préjudice aux populations affectées par cette sécheresse; il suffit qu'elle se produise à un moment critique pour la végétation, par exemple, ou que le début de la crue annuelle soit retardé de façon significative, alors que les apports annuels sont au total tout à fait normaux.

Il n'est pas rare d'observer des années pour lesquelles les précipitations présentent un total relativement déficitaire mais une distribution temporelle excellente pour les cultures non irriguées alors que l'écoulement dans les rivières est bien plus faible que d'ordinaire; l'agriculteur qui pratique la culture non irriguée a des raisons d'être satisfait, l'exploitant de centrale hydroélectrique qui voit ses barrages à moitié vides ne l'est pas du tout et estime que l'année est sèche et il peut en être de même de l'agriculteur installé dans les périmètres d'irrigation.

De même, les conditions optimales pour le remplissage des nappes sont loin de correspondre aux conditions optimales pour l'écoulement superficiel ou pour l'agriculture. Notons enfin que, dans les zones arides, une année peut être sèche pour les cultures non irriguées et ne pas l'être pour l'élevage extensif. Dans ce dernier cas, il suffit que les pluies permettent la germination et la croissance de la végétation utilisée par les animaux, mais il n'est pas nécessaire que la majorité des graines parvienne à maturité (il faut aussi que le bétail trouve de l'eau dans les puits et les mares). La culture non irriguée est nettement plus exigeante.

Mais, dans les cas extrêmes, par exemple lorsque dans le nord-est du Brésil on observe deux années consécutives pratiquement sans pluie, la sécheresse affecte tous les usages de l'eau et il y a accord unanime pour la reconnaître.

Les considérations qui précèdent montrent la complexité du problème et expliquent pourquoi on ne peut pas affecter la même fréquence statistique à une sécheresse suivant l'aspect particulier que l'on considère : élevage, cultures non irriguées, total pluviométrique, volume total des débits, débit minimal de basses eaux, etc.

Malheureusement la sécheresse qui, depuis 1970-1971, affecte l'Afrique tropicale au sud du Sahara est suffisamment sévère pour présenter un caractère exceptionnel quels que soient les aspects que l'on considère.

On limitera cet exposé sommaire à un examen rapide des précipitations et une analyse un peu plus approfondie des débits des cours d'eau parmi la zone la plus affectée. Nous disposons pour cette zone d'une documentation de base assez volumineuse puisqu'une quinzaine de nos hydrologues et de nos hydrométristes y travaillent en permanence depuis une vingtaine d'années et que nous avons dépouillé, revalorisé et interprété les données anciennes pluviométriques et hydrométriques depuis l'origine des observations.

Mais, même en restreignant l'étude de la sécheresse à ce seul aspect hydrologique, on se heurte encore à un second ordre de difficultés; malgré le caractère assez homogène des caractéristiques physiographiques de l'Afrique de l'Ouest et la relative simplicité des mouvements des masses d'air qui commandent la saison des pluies, les précipitations et les débits observés présentent des déficits assez variables d'un point à un autre si l'examen se limite à des surfaces inférieures à quelques milliers de km2. Par exemple, en 1972, en Haute-Volta, la région de Ouagadougou et une bonne partie du sud et du sud-est du pays ont été relativement épargnées. Dans la République du Niger, dans le bassin de la Maggia (2500 km2), le volume qui s'est écoulé pendant la saison des pluies n'est dépassé que six années sur dix. Il y a même eu pendant les saisons des pluies 1972 et 1973 des crues exceptionnelles de périodes de retour de dix ans sur certains petits cours d'eau. L'exemple du bassin alimentant le lac de Bam, au nord de la Haute-Volta, est très significatif.

Alors qu'une bonne partie de ce bassin a reçu en 1973 des précipitations nettement inférieures à la moyenne, les régions voisines du lac ont subi une averse exceptionnelle de sorte qu'en définitive le niveau de ce lac a dépassé en 1973 tous ceux qui avaient été observés depuis une dizaine d'année.

Une autre difficulté vient s'ajouter à ces quelques irrégularités spatiales, c'est la faible densité du réseau pluviométrique et la qualité très inégale des relevés actuels.

Pour ces diverses raisons, l'étude des débits des grands fleuves, pour laquelle les anomalies locales et de nombreuses erreurs se trouvent éliminées, conduit à des résultats plus faciles à interpréter. Nous la compléterons par l'étude du lac Tchad qui se comporte un peu comme un gigantesque pluviomètre naturel.

Sans pouvoir délimiter exactement l'extension de cette sécheresse du fait de certaines lacunes dans nos éléments d'information, nous pouvons indiquer qu'elle ne se limite pas, loin de là, au continent africain. Le nord-est du Brésil et l'Inde sont gravement touchés et l'Indochine l'aurait été sans deux perturbations cycloniques qui ont relevé sensiblement les totaux pluviométriques annuels et les volumes d'écoulement annuels pour 1972.

Certaines parties des régions tempérées ont connu en même temps une sécheresse de caractère parfois exceptionnel, très variable d'une région à une autre, mais, comme toujours dans ces régions, les phénomènes sont moins simples.

Comme nous l'avons observé pour la sécheresse de 1958 dans les régions équatoriales plus au sud, ce genre de sécheresse s'étend suivant des bandes à peu près parallèles à l'équateur.

Pour l'Afrique en 1972 et 1973, le phénomène est très net. Les régions situées au sud du Sahara ont été très touchées depuis le Sénégal et la Mauritanie jusqu'à l'Ethiopie.

Plus au sud, dans la majeure partie de la Côte-d'Ivoire, le Togo, le Dahomey et une partie du Cameroun, on relève des débits également déficitaires, mais le caractère de ce déficit est moins dramatique si les périodes de retour sont les mêmes.

Les régions méridionales, sud du Cameroun, Gabon, sud du Congo, n'ont pas présenté de déficit très marqué. Par contre, au sud du Zaïre commence une nouvelle bande déficitaire.

Le fait de ne considérer que les précipitations et les débits simplifie le problème mais nous irons plus loin dans la schématisation en ne considérant que quatre éléments : le total des précipitations annuelles pour l'année calendaire 1972, le volume de ruissellement des cours d'eau ou le débit moyen annuel pendant l'année calendaire 1972 (ou l'année hydrologique 1972-1973) pour certains grands cours d'eau, le débit maximal de 24 heures pour l'année 1972 et le débit minimal pour la saison sèche qui a suivi la crue de 1972.

Pour l'année 1973, nous avons considéré en principe les mêmes éléments sauf les valeurs minimales des débits qui ne sont pas encore toutes connues actuellement.

L'étude de la répartition mensuelle des précipitations serait tout aussi importante même au simple point de vue hydrologique, mais cette analyse nous entraînerait trop loin.

Etude des précipitations annuelles

Nous serons très brefs sur ce point pour lequel un certain nombre de cartes synthétiques ont été publiées (ASECNA, étude E.G. Davy). Etant donné la qualité inégale des observations, on n'a pris en considération pour 1972 et 1973 qu'un petit nombre de stations pluviométriques bien connues pour le caractère sérieux de leurs observations.

En allant du nord au sud, en partant du centre du Sahara, et en considérant des bandes parallèles à l'équateur, on trouve d'abord la zone typiquement saharienne pour laquelle la hauteur des précipitations moyenne annuelle est inférieure à 100 mm. Pour cette zone où il n'est pas rare que les précipitations annuelles soient nulles et où la densité des stations pluviométriques est extrêmement faible, les données des stations ne sont pas d'un grand secours, on sait simplement de façon qualitative que les années 1972 et 1973 ont été très sèches.

Plus au sud, la densité des stations est suffisante pour que l'on puisse arriver à une impression générale. Depuis le Soudan jusqu'à l'Atlantique, l'année 1972 a été extrêmement sèche sur la bande comprise entre les isohyètes 100 mm et 300 mm, limitée au sud par une ligne qui passe un peu au nord du fleuve Sénégal, à l'ouest, et qui coupe le lac Tchad à l'est. Dans cette région, quelques données tendaient à prouver que tous les 30 ou 50 ans les précipitations annuelles descendaient jusqu'à des valeurs comprises entre 30 et 60 mm pour des moyennes de longue durée de 200 à 500 mm. Ceci a été largement confirmé puisque, dans la zone en question, ont été observées en 1972 un bon nombre de hauteurs annuelles comprises entre 45 et 80 mm (déficit de l'ordre de 75%). Pour de telles hauteurs les phénomènes de ruissellement deviennent très rares et la culture du petit mil est en général impossible.

Au sud de cette zone, entre les isohyètes annuelles 300 mm et 750 mm, l'agriculture intéresse des surfaces beaucoup plus importantes et connaît en année normale des conditions beaucoup moins précaires; le déficit en valeur relative paraît nettement moins élevé mais les conséquences pratiques ont été tout aussi graves; entre les isohyètes 300 et 400 mm, le déficit varie généralement de 60 à 50%; enfin plus au sud, il varie entre 40 et 25%. La période de retour varie entre dix et 50 ans pour 1972, alors qu'elle était souvent comprise entre 50 et 100 ans dans la zone précédente, toujour pour 1972.

Si l'on considère la bande comprise entre les iyohyètes 100 et 750 mm pour 1971, les précipitations sont généralement plus élevées. Pour 1973, dans l'ensemble elles sont un peu plus fortes, mais certaines régions épargnées en 1972 ne l'ont pas été en 1973 et on retrouve pour cette dernière année un nombre non négligeable de valeurs minimales absolues correspondant à des périodes de retour de 50 ou 100 ans pour des postes qui, en 1972, avaient présenté des fréquences nettement plus élevées. La répartition des précipitations mensuelles a par endroits été plus favorable aux pâturages qu'en 1972.

Pendant la période sèche 1941-1945, dont la sévérité a été un peu moins grave, le minimum avait été atteint pour les diverses stations pendant l'une des années de cette période. Cette fois-ci, pour trouver le minimum, il faut considérer l'une des ces deux annés et parfois 1971. On peut procéder pour cette zone à une comparaison très grossière avec la grande sécheresse de 1907-1914 car il existe quelques relevés pluviométriques assez anciens à l'intérieur du continent. L'année 1913 paraît avoir été plus sèche que 1972 ou 1973, mais il ne semble pas qu'à cette époque l'ensemble des deux années 1913-1914 ait été aussi déficitaire que l'ensemble des deux années 1972-1973.

Au-delà, la période 1890-1900 a été excédentaire et avant 1890 il n'existait que quelques stations sur la côte du Sénégal. On trouve quelques indices d'une période sèche juste après 1860.

Au sud de l'isohyète 750 mm, la situation est beaucoup plus confuse en 1972 comme en 1973; on trouve très souvent une situation déficitaire mais avec des fréquences très variables. La période de retour varie souvent entre trois ans et 25 ans avec 50 ans pour quelques stations, mais d'assez vastes régions présentent des situations voisines de la moyenne : sud-est et sud de la Haute-Volta, par exemple, en 1972.

L'examen des relevés de débits des grands cours d'eau qui drainent ces régions permet d'arriver plus facilement à une vue d'ensemble de la sécheresse en 1972 et 1973.

CARACTERISTIQUES DES DEBITS DES GRANDS COURS D'EAU TROPICAUX D'AFRIQUE EN 1972 ET 1973

Une étude d'ensemble des cours d'eau originaires de la zone sahélienne serait particulièrement intéressante; malheureusement, il se trouve que seuls ceux du nord-est de la Haute-Volta et ceux de la République du Niger ont fait l'objet d'observations régulières en 1972 et 1973 et une bonne partie d'entre eux sont situés dans des zones relativement épargnées par la sécheresse. Les déficits atteignent parfois 50 à 75% pour le volume annuel mais la période de retour est rarement supérieure à dix ans. Il n'en aurait pas été de même pour les cours d'eau de Mauritanie et peut-être du Tchad, en 1972, qui ont très probablement présenté des périodes de retour de 50 ans.

La situation est très différente pour les grands fleuves situés plus au sud pour lesquels on dispose d'une documentation complète. Dans l'hémisphère Nord, ces grands cours d'eau sont, de l'ouest à l'est, le Sénégal, le Niger, la Volta, la Benoue, la Sanaga, la Sangha, le Chari, l'Oubangui et le Nil bleu. La plupart d'entre eux ont été l'objet de Monographies pour lesquelles une revalorisation complète des données anciennes a été faite; les courbes de transformation hauteur/débit sont sûres et précises jusqu'au maximum de débits, quant aux valeurs minimales, elles ont fait l'objet de jaugeages systématiques en 1972, 1973 et 1974.

Le Sénégal, le Niger, le Chari et le Nil, qui traversent ou rejoignent le Sahel, sont les plus intéressants.

La sécheresse de 1972 et de 1973 a sévi sur tous ces bassins avec, pour les diverses caractéristiques, des périodes de retour qui atteignent souvent 50 ou 100 ans.

Nous extrayons du tableau qui sera présenté conjointement par l'AISH et l'OMM les données relatives à trois stations concernant le Sénégal, le Niger et le Chari.

A titre de comparaison, nous y avons joint les données d'une station caractéristique du nord-est du Brésil, le Rio Jaguaribe, à Arneiroz, qui met bien en évidence des fréquences comparables mais avec une irrégularité interannuelle beaucoup plus forte que pour les trois grands fleuves africains.

Certaines valeurs des fréquences sont faussées dans une certaine mesure par le choix de l'année calendaire au lieu de l'année hydrologique pour la détermination des modules de 1972 et 1973. On vérifie bien ce que nous ont indiqué les données pluviométriques : les périodes de retour sont voisines de 50 à 100 ans.

Suivant les bassins, l'années 1973 est plus sèche ou moins que l'année 1972. Notons que comme le Logone, dont le régime est assez comparable, le Haut-Niger a été relativement favorisé pour l'année 1972. De façon générale, les débits maximaux ont été moins affectés par la sécheresse en 1973 que les débits moyens annuels.

Nous présentons ci-après les courbes de distribution des débits maximaux du Sénégal à Bakel, des modules ou débits moyens annuels du Niger à Koulikoro, des débits maximaux annuels du Chari à Ndjamena (Fort-Lamy) et des débits minimaux annuels.

Pour ces grands fleuves, surtout pour le Chari, il y a une assez bonne corrélation linéaire entre les modules et les valeurs maximales des débits, de sorte que les courbes de distribution des modules et des valeurs maximales sont à peu près les mêmes.

TABLEAU I

Stations	Maximum			Moyenne annuelle			Minimum	
	Moyenne m3/s	1972 fréquence	1973 fréquence	Moyenne m3/s	1972 fréquence	1973 fréquence	Moyenne m3/s	1973 fréquence
Sénégal à Bakel 218 000 km2	4 750 (69 ans)	1 430 0,02	2 520 0,08	764	264 0,01	367 0,05	2,3	0,25 0,02 - 0,05
Niger à Koulikoro 120 000 km2	6 250 (67 ans)	3 680 0,02	4 140 0,05	1 540	1 080 0,10	903 0,02	46,6	16 0,01
Chari à Ndjamena 600 000 km2	3 500 (37 ans)	1 430 0,01	2 130 0,04	1 280	578 0,01-0,02	577 0,01-0,02	163	48 0,01
Rio Jaguaribe à Arneiroz	210	≠ 0 0,03		3,5	0 0,03			

La distribution est presque gaussique pour le Niger à Koulikoro et le Sénégal à Bakel, elle est légèrement hypogaussique pour le Chari. C'est là l'effet des pertes dans les plaines d'inondation. La courbe du Jaguaribe est au contraire dissymétrique : hypergaussique comme il convient à la plupart des cours d'eau de régions semi-arides.

On voit que, pour le Sénégal, le maximum de 1972 est légèrement inférieur à celui de 1913 et nettement inférieur à celui de 1973. L'année 1944 est comprise entre 1973 et 1913. Pour le Niger à Koulikoro, l'année 1913 est la plus faible, 1973 étant encadrée par 1913 et 1914; 1972 est un peu plus forte. Les années 1942 et 1944 sont comprises entre 1973 et 1914. Le ressaut que l'on voit dans le haut de la courbe ne correspond ni à une erreur de mesure ni à une erreur de dessin. L'échantillon statistique est encore trop faible pour que la courbe de distribution soit bien lisse dans la partie haute. Pour le Chari à Fort-Lamy, on ne connaît pas le maximum de 1913, mais on a observé le niveau du lac Tchad et, d'après celui-ci, on peut en déduire que le débit maximal de 1913 a été voisin de celui de 1972. Celui-ci est nettement inférieur au module de 1973, lequel est voisin de ceux de 1940 et 1941. Pour le Rio Jaguaribe, on relève un module nul en 1915 et un autre en 1958 (période sèche dans les régions équatoriales). L'année 1942 est très faible avec un module de 0,39 m3/s (fréquence décennale).

On voit que pour ces quatre stations l'une des deux années 1972 ou 1973 a une période de retour très voisine de celle de 1913, l'une quelconque des années comprises entre 1941 et 1945 vient dans presque tous les cas se placer un peu au-dessus de l'année la plus faible des deux (1972 ou 1973).

Pour les valeurs minimales annuelles l'étude est plus difficile, les chroniques dont on dispose sont beaucoup moins longues et la valeur de ce minimum dépend non seulement de l'importance de la crue précédente mais aussi de la plus ou moins grande précocité de la saison des pluies suivante. Les valeurs minimales de 1973 ont toutes chances d'être plus faibles que celles de 1972. L'étude des basses eaux montre évidemment que, dans des cas pareils, les débits de toute la période de basses eaux et par suite les débits moyens annuels d'une année ne sont pas indépendants de ceux de l'année précédente. Ceci tient à la nécessité de recharger les nappes et les cuvettes de lits majeurs très vastes. Il en est de même, bien sûr, pour les années très humides.

L'hypothèse de base des valeurs annuelles statistiquement indépendantes n'est qu'une approximation, même si on suppose les précipitations annuelles indépendantes, et il y aurait beaucoup à dire sur ce dernier point. Ceci devrait faire réfléchir tous ceux qui se lancent à corps perdu dans des raffinements subtils sur les valeurs extrêmes sans approfondir la nature physique des phénomènes.

Sans vouloir aborder la question des cycles qui ne nous conduirait à rien de pratique, essayons de voir, d'après le comportement du lac Tchad, quelle a été la série des événements sur une période plus longue. Le lac Tchad est une cuvette fermée dont l'eau s'évapore à raison de 2,20 m par an. Lorsqu'elle est bien pleine, comme il y a une dizaine d'années, sa superficie était voisine de 22 000 km2, mais le lac a été complètement asséché au cours de la période des 50 000 dernières années (son fond est constitué par des dunes pas très anciennes); il a également débordé très au-delà des 22 000 km2 puisqu'il allait jusqu'aux pays bas du Tchad, il y a 3 000 ans.

La figure suivante présente le lac en année d'abondance médiocre avec ses eaux libres, les zones d'îlots-bancs, dunes émergeant ou arrivant à une très faible profondeur et recouvertes de végétation : papyrus ou typhas, surtout à l'ouest. Le lac est séparé en deux par un seuil : la grande barrière, submergée très nettement en période d'abondance et alors elle est débarrassée en grande partie de la végétation aquatique,et qui émerge presque en totalité en périodes sèches, elle est alors couverte de végétation à travers laquelle l'eau filtre non sans difficulté. La grande barrière sépare le lac en deux parties, la Cuvette Nord et la Cuvette Sud, l'alimentation se faisant par le sud; la Cuvette Nord arrive à s'assécher bien qu'étant la plus profonde.

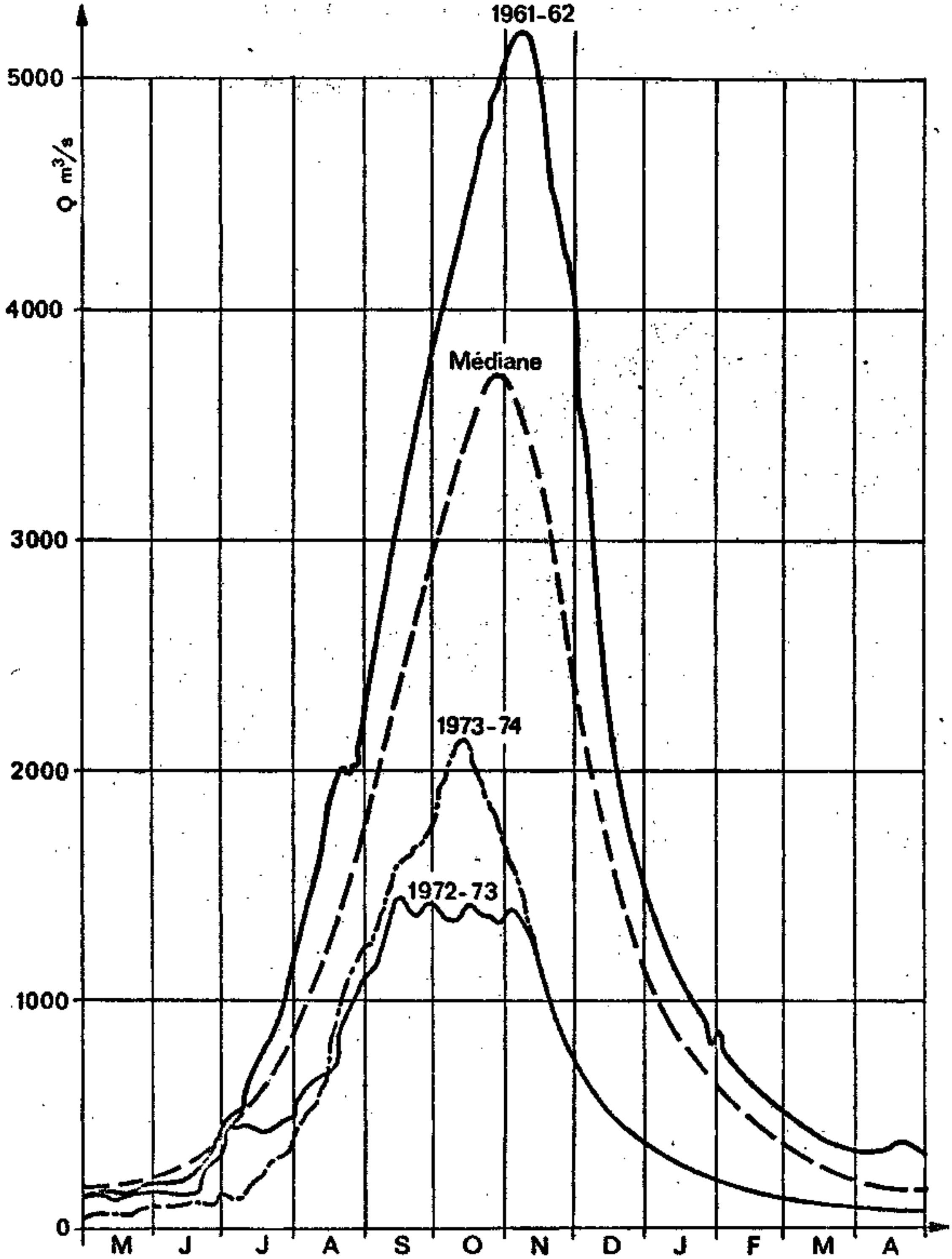
La figure suivante montre le lac Tchad à son niveau maximal à la fin de 1973-début de 1974. Une grand partie du lac est couverte par la végétation, le volume traversant la grande barrière a été insignifiant, de sorte que la Cuvette Nord va pratiquement s'assécher en 1974, comme en 1907-1908.

Le général Tilho, qui est arrivé au début du siècle au Tchad, a essayé, d'après des témoignages recueillis à cette époque, de reconstituer qualitativement les variations du niveau du lac Tchad, tout au moins les périodes sèches et humides.

La période très humide de 1870 à 1890 est assez bien connue; on la retrouve un peu partout de façon assez sûre, surtout sur le Nil. La période 1855-1860 a peut-être été beaucoup plus sèche que ne l'indique le général Tilho, les autres périodes sèches indiquées sur cette image montrent simplement qu'à intervalles plus ou moins réguliers on retrouve des sécheresses telles que celles de 1913 et 1972-1973, ou peut-être pires.

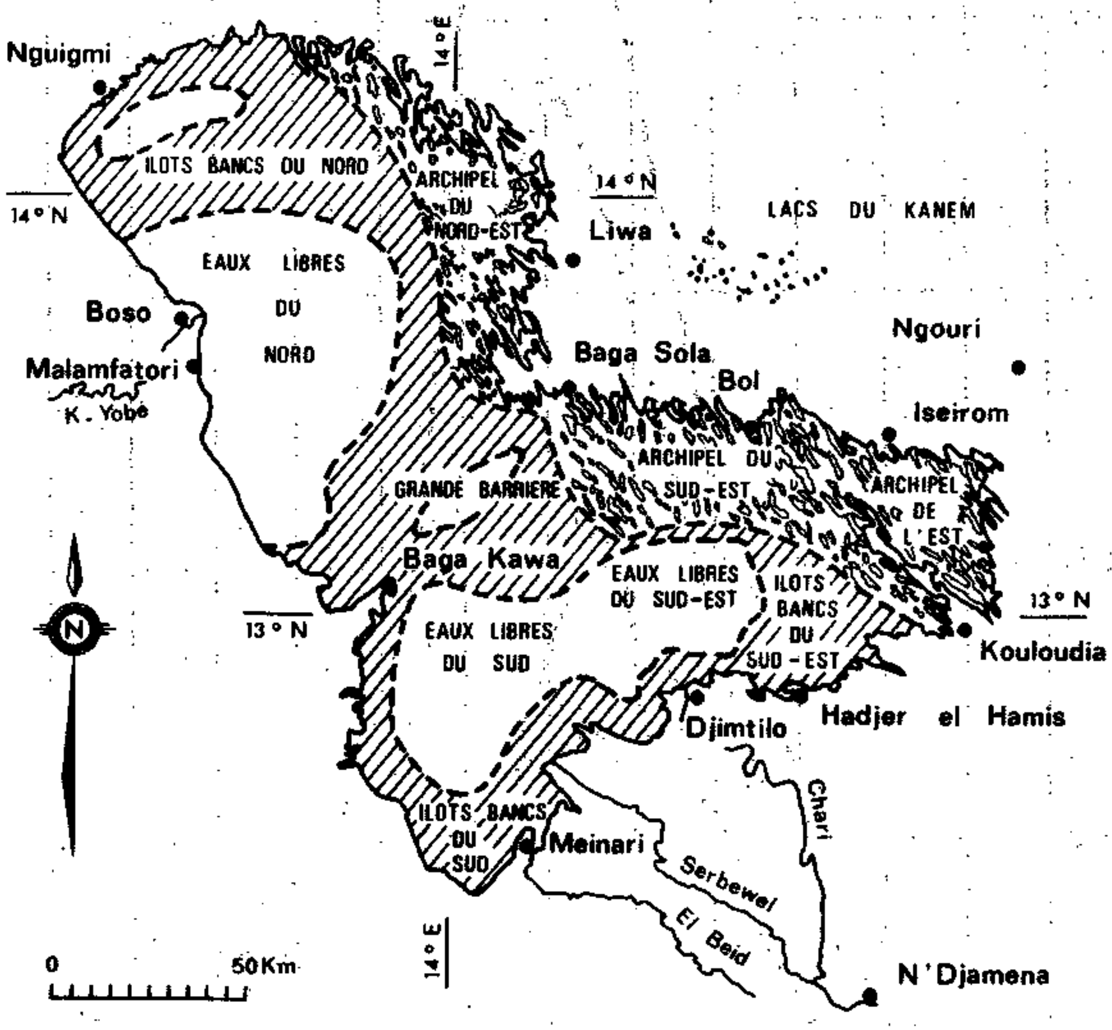
Voilà ce que peuvent indiquer les données hydrologiques; quelque effort que l'on fasse, les échantillons statistiques semblent insuffisants à eux seuls pour permettre une étude sérieuse des phénomènes de persistance ou des pseudo-cycles. L'observation très approfondie des débits est indispensable, certes, mais la solution du problème est dans l'étude approfondie des caractères particuliers des mouvements des masses d'air dans des périodes de ce genre, et peut-être aussi dans les variations des éléments du bilan hydrologique, ces recherches étant conduites à l'échelle mondiale.

LE CHARI A N'DJAMENA (FORT-LAMY) EN 1972 ET 1973



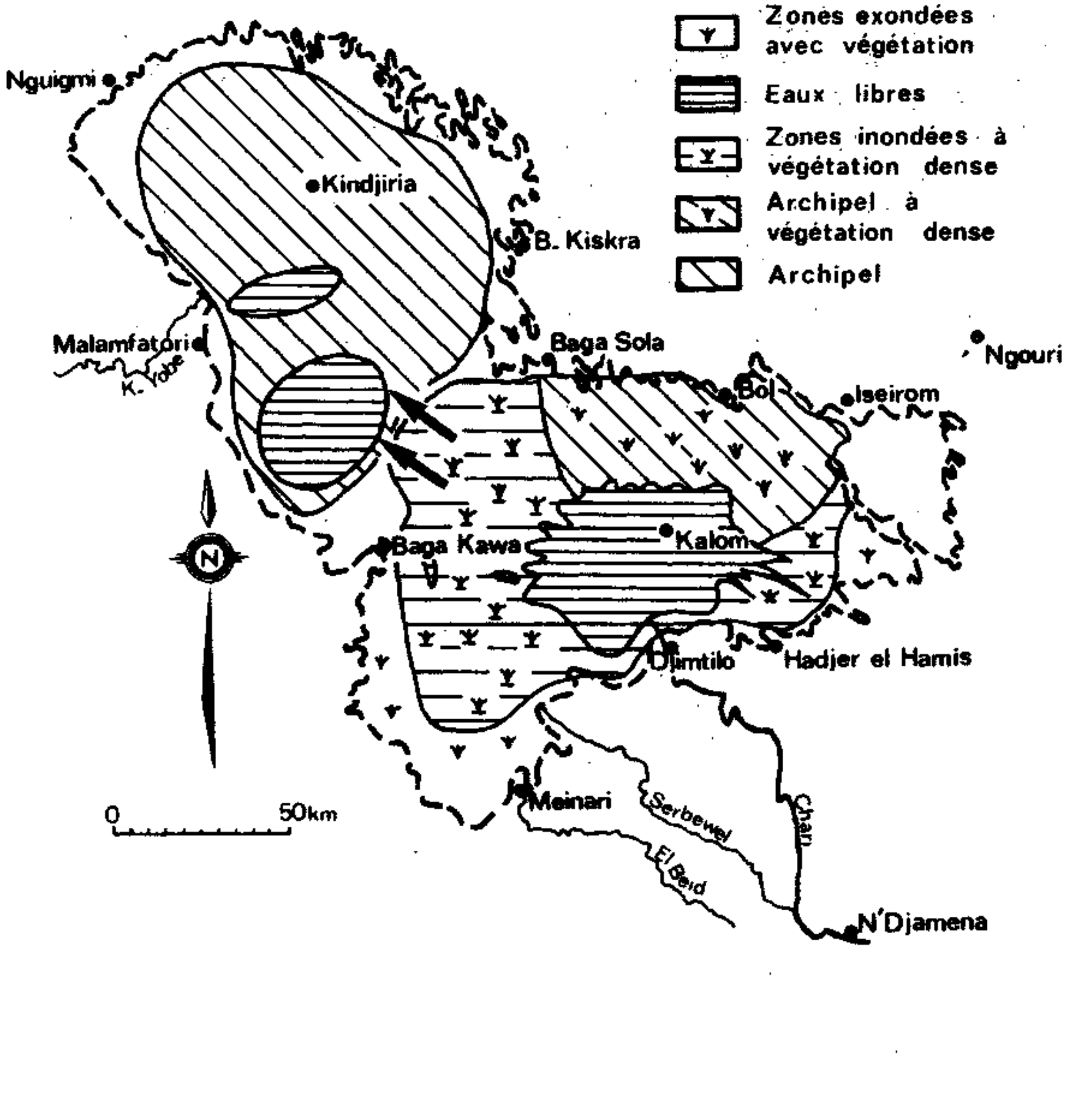
LE LAC TCHAD A LA COTE 281,50

(minimun en période de pluviosité moyenne)



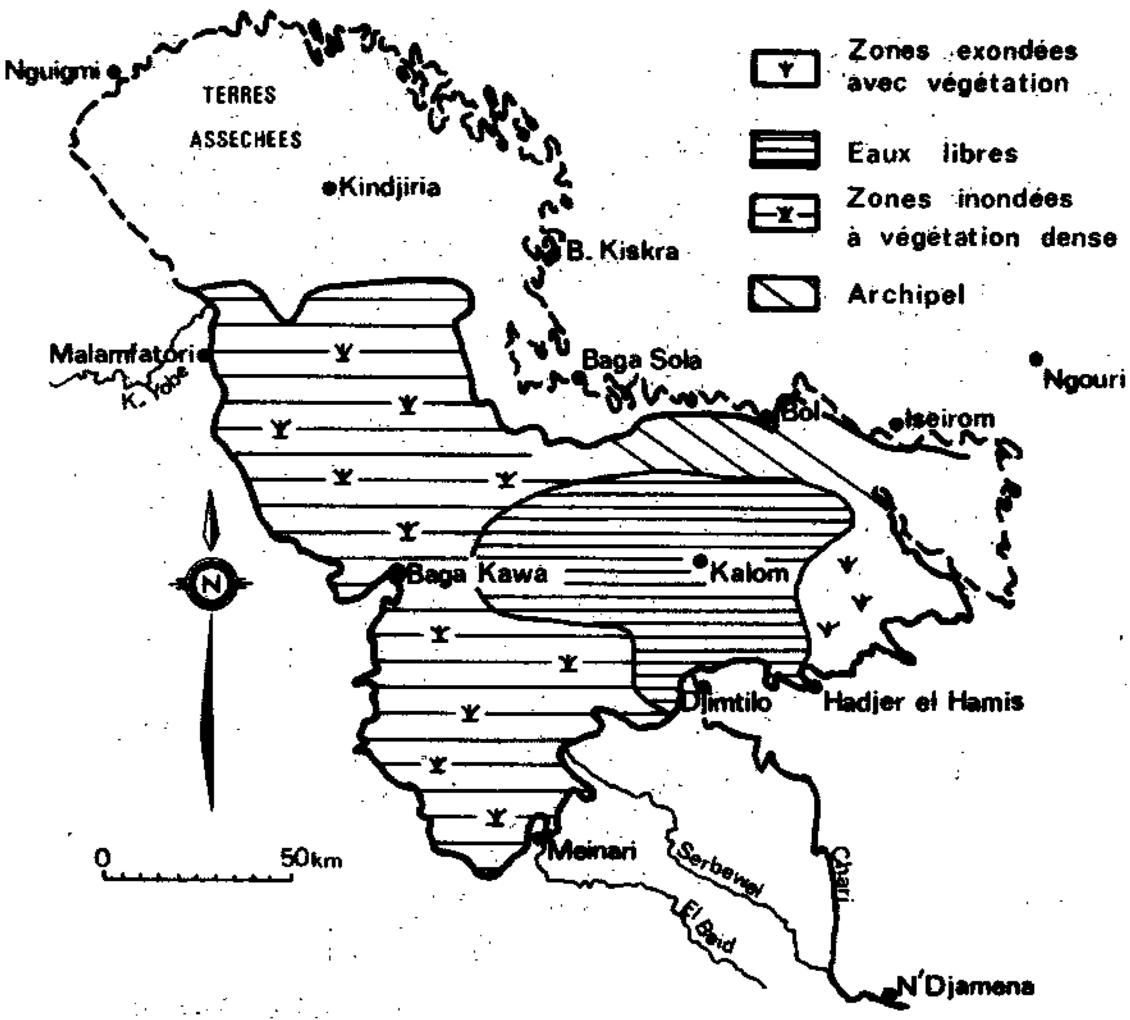
LE LAC TCHAD FIN 1973 _ DEBUT 1974

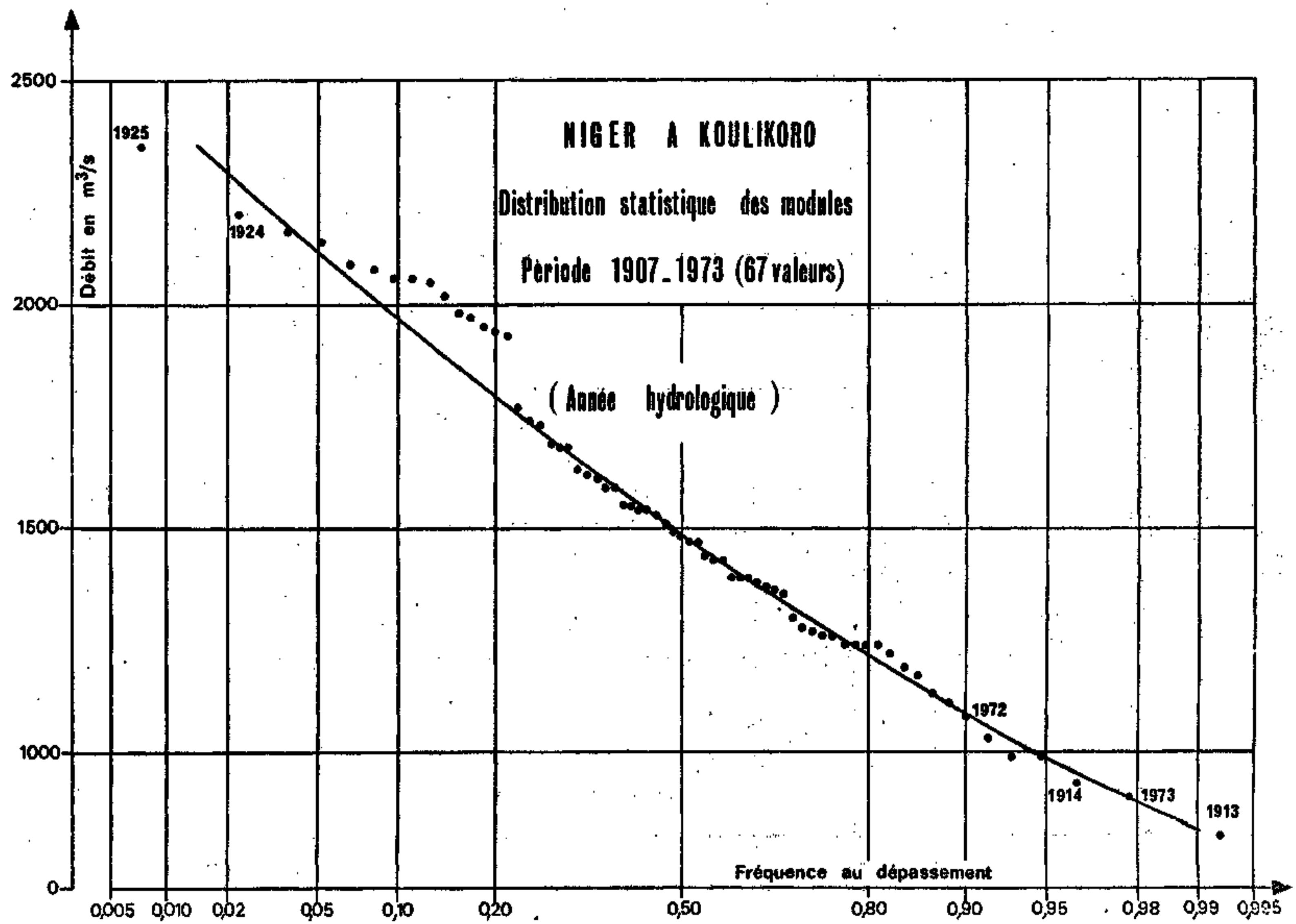
(niveau maximum 1973-1974)



LE LAC TCHAD AU DEBUT DE 1908 (d'après le Général TILHO)

(niveau maximum 1907-1908)

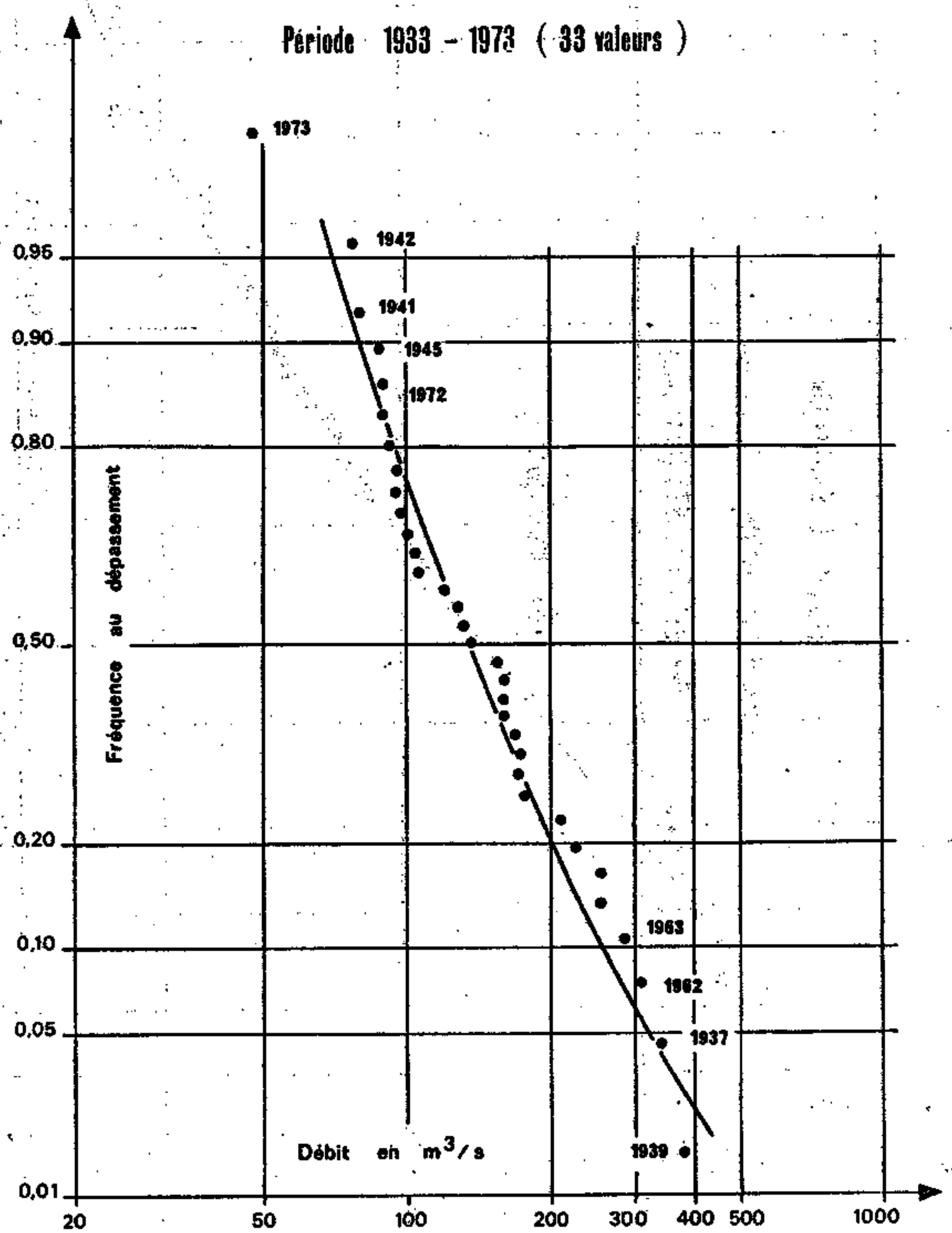


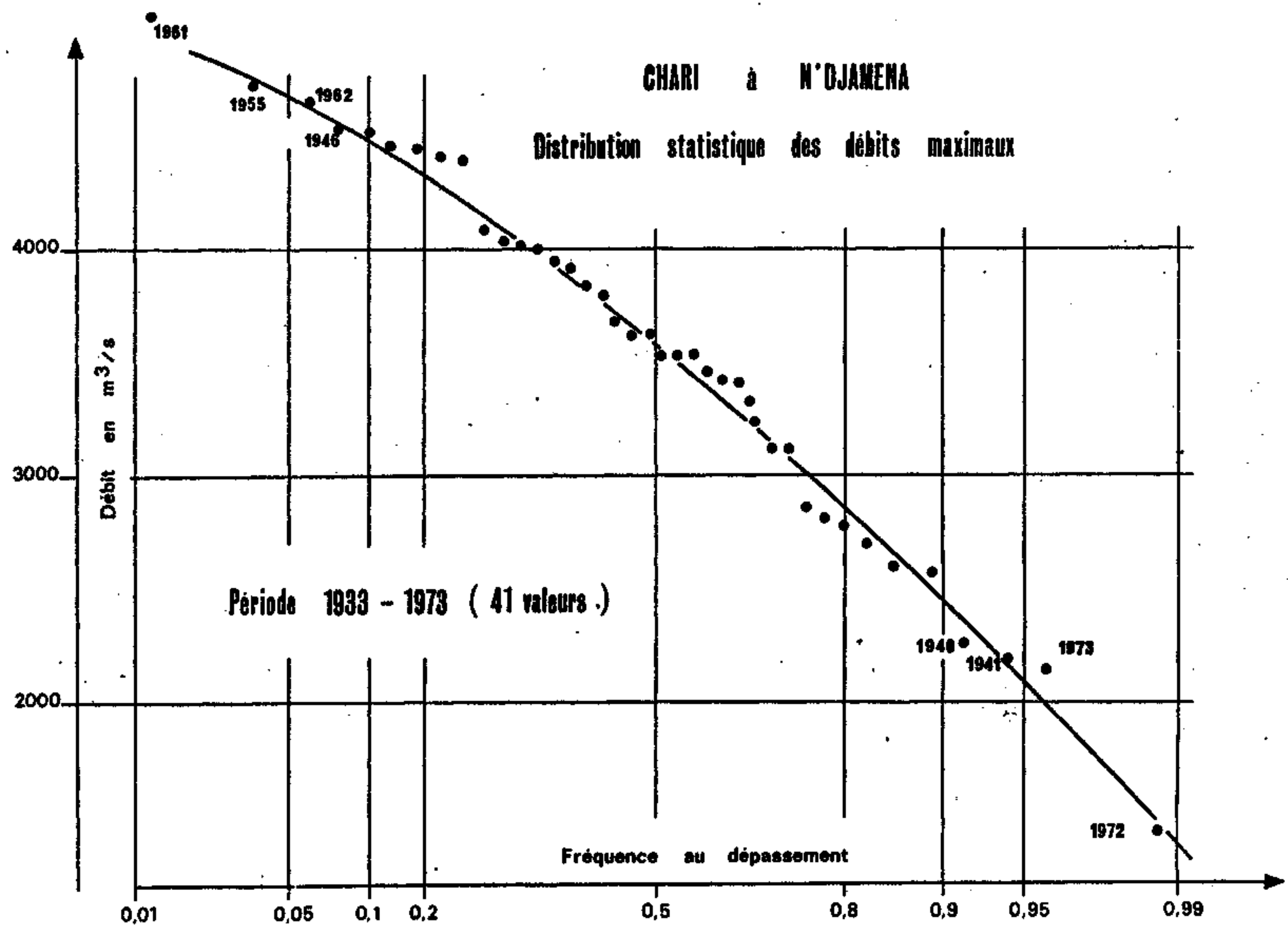

NIGER A KOULIKORO
Distribution statistique des modules
Période 1907_1973 (67 valeurs)
(Année hydrologique)
Débit en m3/s
2500
2000
1500
1000
0
Fréquence au dépassement
0,005
0,010
0,02
0,05
0,10
0,20
0,50
0,80
0,90
0,95
0,98
0,99
0,995
1925
1924
1972
1914
1973
1913

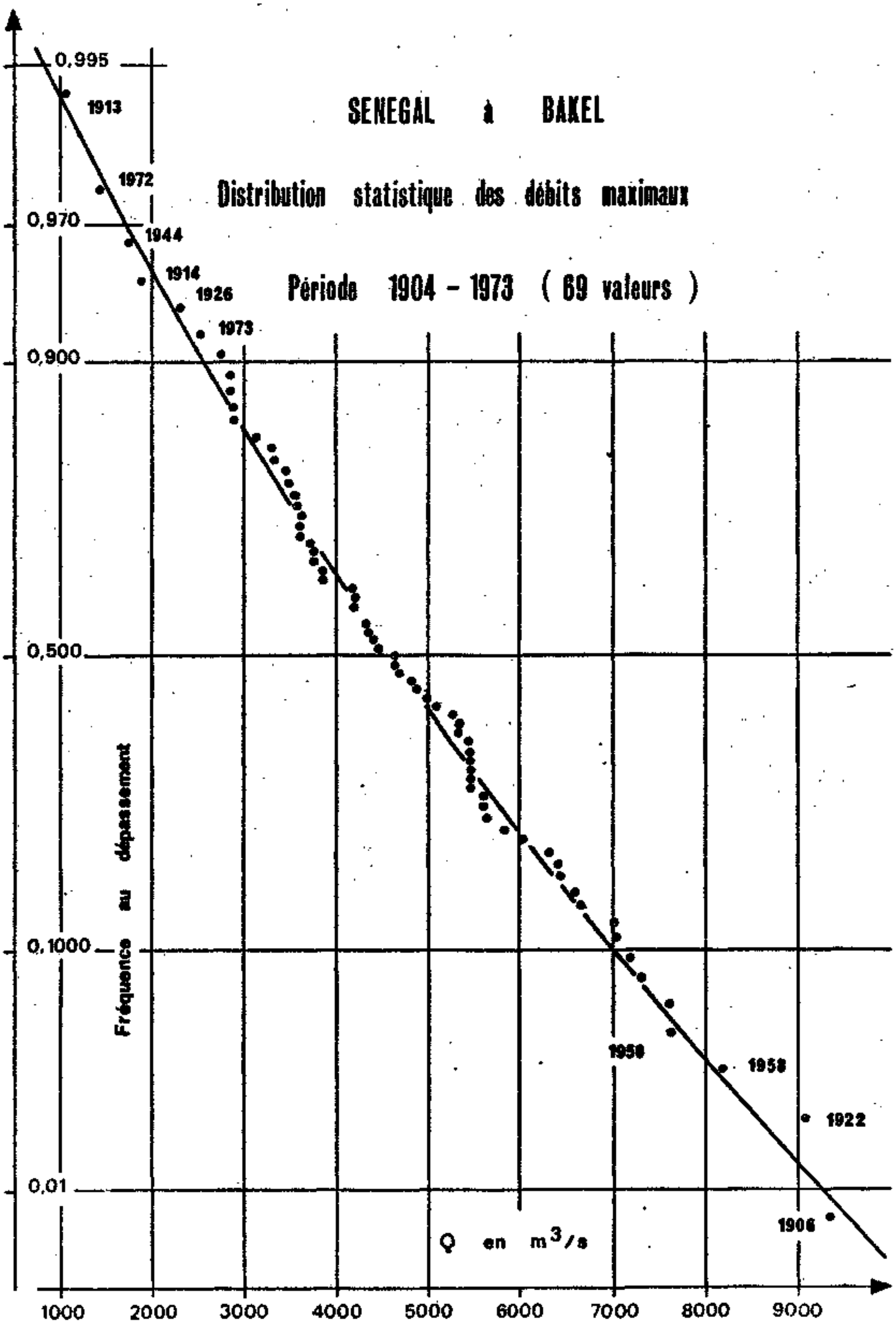
CHARI à N'DJAMENA

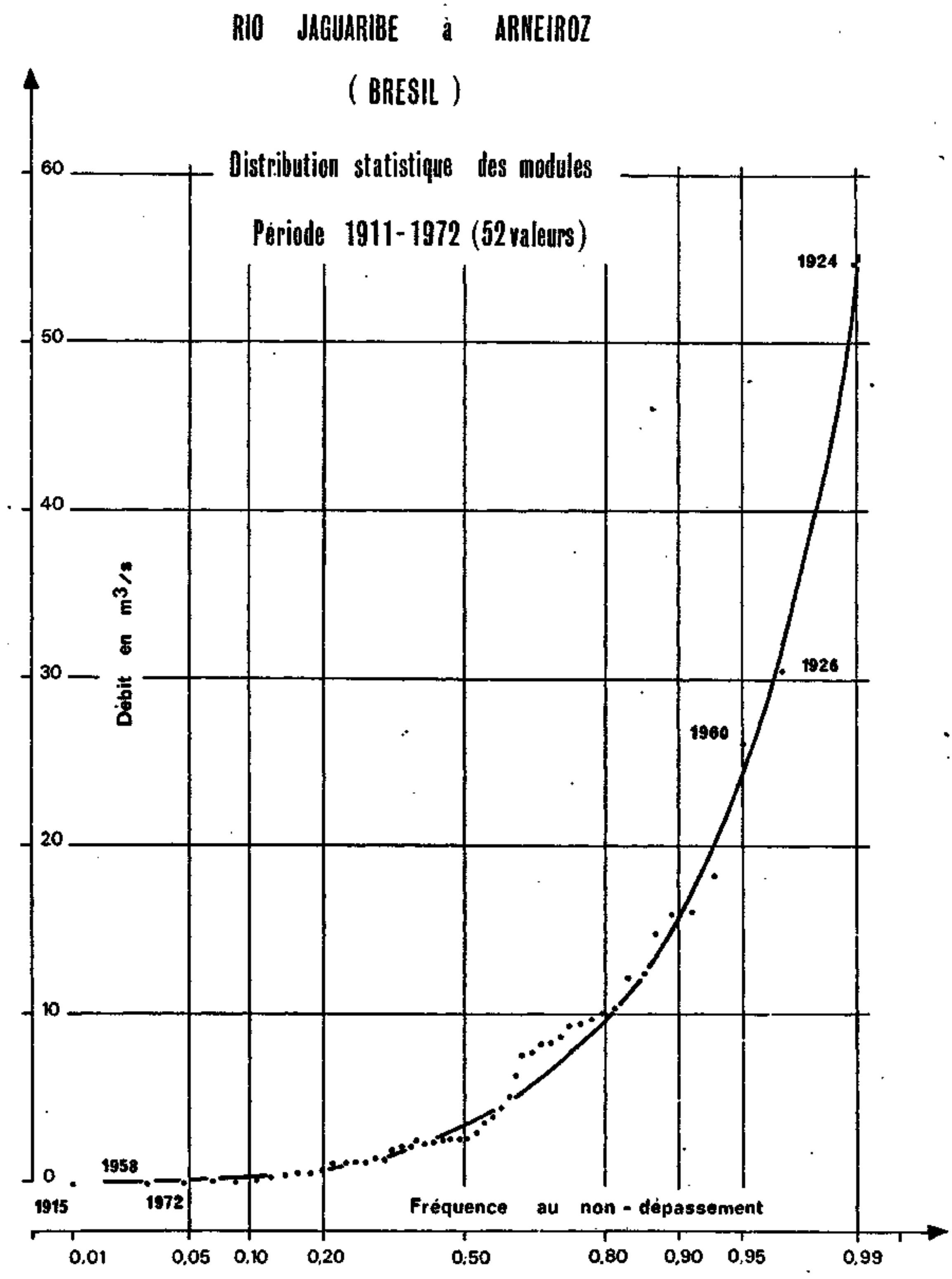
Distribution statistique des débits minimaux

Période 1933 - 1973 (33 valeurs)




CHARI à N'DJAMENA
Distribution statistique des débits maximaux
Période 1933 - 1973 (41 valeurs .)
Débit en m3/s
Fréquence au dépassement
4000
3000
2000
0,01
0,05
0,1
0,2
0,5
0,8
0,9
0,95
0,99
1961
1955
1962
1946
1940
1941
1973
1972


SENEGAL à BAKEL
Distribution statistique des débits maximaux
Période 1904 - 1973 (69 valeurs)
0,995
0,970
0,900
0,500
0,1000
0,01
Fréquence au dépassement
Q en m3/s
1913
1972
1944
1914
1926
1973
1950
1958
1922
1906
1000
2000
3000
4000
5000
6000
7000
8000
9000


RIO JAGUARIBE à ARNEIROZ
(BRESIL)
Distribution statistique des modules
Période 1911-1972 (52 valeurs)
Débit en m3/s
60
50
40
30
20
10
0
1924
1926
1960
1958
1915
1972
Fréquence au non - dépassement
0,01
0,05
0,10
0,20
0,50
0,80
0,90
0,95
0,99