UNCLASSIFIED

AD NUMBER

AD067256

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 1954. Other requests shall be referred to Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217-5660.

AUTHORITY

ONR ltr, 9 Nov 1977

THIS PAGE IS UNCLASSIFIED

AD 67256

Armed Services Technical Information Agency

Reproduced by
DOCUMENT SERVICE CENTER
KNOTT BUILDING, DAYTON, 2, OHIO

UNCLASSIFIED

THE JOHNS HOPKINS UNIVERSITY

LABORATORY OF CLIMATOLOGY

PUBLICATIONS IN CLIMATOLOGY

VOLUME VII NUMBER 4

CLIMATES OF AFRICA AND INDIA ACCORDING TO THORNTHWAITE'S 1948 CLASSIFICATION

by

Douglas B. Carter

FINAL REPORT

CONTRACT NO. NONR-248(40)

TASK NR 389 091

CENTERTON, NEW JERSEY

1954

PUBLICATIONS IN CLIMATOLOGY is issued as a medium for both regular and miscellaneous reports and papers of The Johns Hopkins University, Laboratory of Climatology, Centerton, N.J.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Work on Contract Nonr-248(40) has been directed toward the preparation of detailed climatic maps of Africa and the Indian sub-continent after the system of classification devised by Thornthwaite in 1948. To complete the work required, climatological records for more than 1200 selected stations in Africa and 400 stations in India and vicinity were collected, analyzed, and tabulated. Water balances for each station were derived from the climatic data alone using methods introduced by Thornthwaite. From such calculations, detailed estimates of potential evapotranspiration, actual evapotranspiration, soil moisture utilization, water surplus, and water deficiency were obtained. In addition, the moisture type and thermal efficiency of the climate were determined at each station.

Each of the principal water balance factors was studied in relation to its regional variations and a method of mapping was selected. The method recognized the effects of topographic diversity and the influence of oceans on climatic factors. Distribution of soils, vegetation, or hydrography were not used as the basis for interpolating data among stations although agreement between the climatic maps and such physiographic information is clearly apparent. It was found that each of the selected climatic factors was especially correlated with topography. The agreement with topography was most noticeable in the case of potential evapotranspiration and least noticeable with precipitation. The distributions of water surplus and deficiency, and the moisture regions which depend on both potential evapotranspiration and precipitation were intermediate in their agreement with topography.

Climatic maps at a scale of 1:5,000,000 of average annual potential evapotranspiration, water deficiency, water surplus, the moisture regions, and precipitation were prepared for Africa and India. The large-scale climatic maps could not be reproduced inexpensively for inclusion with this report so small-scale maps giving the general outlines of the patterns shown on these more detailed maps were prepared and are included as plates and II. Maps of precipitation are included in the text for comparison with the other elements of the water balance. Descriptions of each of the maps are provided.

CLIMATES OF AFRICA AND INDIA ACCORDING TO THORNTHWAITE'S 1948 CLASSIFICATION

by

Douglas B. Carter

The 1948 Thornthwaite climatic classification introduces the concept of potential evapotranspiration and uses it in the task of delimiting climatic regions. Potential evapotranspiration is defined as the quantity of water that would be evaporated and transpired from a vegetation-covered area when the soil always contains an optimum of moisture. Classifications based only on temperature and precipitation and their seasonal variations cannot delineate climates accurately for they fail to provide a rational interpretation of the moisture factor. One cannot tell whether a climate is moist or arid from a knowledge of precipitation alone. Only by comparing the precipitation or available water with the potential evapotranspiration or water need can a reasonable assessment of the moisture environment be made. Under Thornthwaite's 1948 classification, climatic boundaries are delineated on the basis of climatic factors alone and are independent of the distribution of vegetation or soil, criteria which might be used in any evaluation of the system.

A large number of regional studies utilizing Thornthwaite's new system of climatic classification has recently appeared.[1,2,3,4,5] In addition, under Air Force sponsorship, computations and maps of the classification have been prepared at the Laboratory of Climatology for Japan, Korea, Formosa, China, Australia, Southwest Asia, and continental Southeast Asia. Unfortunately, most of these previous maps are not comparable in scale or in method of mapping and the maps do not embrace whole continents. Computations and maps of Thornthwaite's new classification have been particularly lacking for Africa and India. Thus the present contract was begun in order to complete the mapping of the climatic classification for the largest land areas remaining unmapped - areas which are of considerable strategic importance in the present world situation.

RESEARCH OBJECTIVES

The objectives of the project were (1) the computation of the various climatic indices of the 1948 Thornthwaite classification of climate for the Indian sub-continent and all of Africa; (2) the mapping of these quantities on a scale consistent with the density of the climatic stations; and (3) preparation of a brief discussion and description of the resulting patterns.

ELEMENTS OF THE CLASSIFICATION

In some areas, precipitation is always more than the evapotranspiration, the water need, so that the soil remains full of water and a water surplus occurs. In other places, month after month, precipitation is less than potential evapotranspiration, there is not enough moisture for the vegetation to use and a moisture deficit occurs. Stations with both wet and dry seasons, or with cold seasons of low water need, normally show (1) a period of full storage, when precipitation exceeds water need and a moisture surplus accumulates; (2) a drying season when stored soil moisture and precipitation are used in evapotranspiration, storage is steadily diminished, the actual evapotranspiration falls below the potential and moisture deficiency occurs; and (3) a moistening season when precipitation again exceeds water need and soil moisture is recharged.

1. Burgos, J. J., and Vidal, A. L. Los Climas de la Republica Argentina Segun la Nueva Clasification de Thornthwaite. Meteoros, Ano I, No. 1, Enero 1951, pp. 3-32.
2. Erinc, Sirri. The Climates of Turkey According to Thornthwaite's Classifications. Annals Assoc. Amer. Geogr., Vol. 39, No. 1, March 1949, pp. 26-46.
3. Garnier, B. J. Thornthwaite's New System of Climatic Classification in Its Application to New Zealand. Trans. Roy. Soc. New Zealand, Vol. 79, Pt. 1, June 1951, pp. 87-103.
4. Howe, G. M. Climates of the Rhodesias and Nyasaland According to the Thornthwaite Classification. Geogr. Rev., Vol. 43, No. 4, 1953, pp. 525-539.
5. Sanderson, M. The Climates of Canada According to the New Thornthwaite Classification. Scientific Agriculture, Vol. 28, No. 11, Nov. 1948, pp. 501-517.

It was originally assumed, for convenience only, that the root zone of the soil contained a maximum of 10 cm of water in storage at field capacity and that this moisture would be used at the potential rate as long as any of it remained. Actually, we have known that the moisture holding capacity of the soil available for use by the roots may be much greater than 10 cm and that as soil moisture is utilized the rate of evapotranspiration will diminish. Recent work[1] suggests that at least 30 cm depth of water will be available for use by deep-rooted mature plants in most normal soils and that the evapotranspiration rate which diminishes as the soil dries is proportional to the amount of water in the soil. When the soil moisture is reduced to one-half of capacity the actual evapotranspiration rate will be only one-half of the potential rate. Somewhat comparable values of actual evapotranspiration, water surplus, and deficit are obtained using either the original 10 cm assumption or the new assumption of a 30 cm storage capacity and a varying rate of evapotranspiration as would be expected from a consideration of the assumptions themselves. The new procedure is preferable, however, since it is more realistic than the older empirical one and depicts more exactly the processes going on in nature.

Using the new procedure it is possible to work out a water balance sheet from climatological data alone showing at all times the soil moisture condition and providing values of moisture surplus and deficiency. In figure 1, precipitation is compared with both potential and actual evapotranspiration at selected stations in Africa and India while table I gives the water balance computations for two of them. The various operations indicated in table 1 are relatively straightforward. When the soil moisture is at field capacity, actual and potential evapotranspiration are the same and all precipitation in excess of the potential evapotranspiration is realized as water surplus. When precipitation does not equal potential evapotranspiration the difference is made up in part from soil moisture storage; but as the soil becomes drier, the part not made up is larger. This is the water deficit, the amount by which actual and potential evapotranspiration differ. The soil moisture storage change cannot be determined directly but must be obtained from an appropriate table.

Table 1

Water Balance for Selected Stations
(in centimeters)

	J	F	M	A	M	J	J	A	S	O	N	D	Y
Kayes, French West Africa													
Potential Evapo.	9.6	13.0	17.4	18.9	20.2	18.8	17.1	15.8	15.6	16.4	14.8	9.3	186.9
Precipitation	0	0	0.1	0.3	1.7	9.5	18.4	21.4	14.0	4.0	0.1	0.2	69.7
Difference	-9.6	-13.0	-17.3	-18.6	-18.5	-9.3	1.3	5.6	-1.6	-12.4	-14.7	-9.1	-117.2
Storage Change*	0	0	0	0	0	0	1.3	5.6	-0.7	-4.3	-1.9		
Soil Moist. Storage	0	0	0	0	0	0	1.3	6.9	6.2	1.9	0	0	16.3
Actual Evapo.	0	0	0.1	0.3	1.7	9.5	17.1	15.8	14.7	8.3	2.0	0.2	69.7
Water Deficiency	9.6	13.0	17.3	18.6	18.5	9.3	0	0	0.9	8.1	12.8	9.1	117.2
Water Surplus	0	0	0	0	0	0	0	0	0	0	0	0	
Srinagar, Kashmir													
Potential Evapo.	0	0.3	2.1	5.0	8.9	11.8	14.2	13.1	8.7	4.5	1.7	0.4	70.7
Precipitation	7.4	7.1	9.1	9.4	6.1	3.6	5.8	6.1	3.8	3.0	1.0	3.3	65.7
Difference	7.4	6.8	7.0	4.4	-2.8	-8.2	-8.4	-7.0	-4.9	-1.5	-0.7	2.9	
Storage Change*	7.4	6.8	3.2	0	-2.7	5.9	-5.8	-3.3	-1.9	-0.5	-0.2	2.9	
Soil Moist. Storage	20.0	26.8	30.0	30.0	27.3	21.4	15.6	12.3	10.4	9.9	9.7	12.6	
Actual Evapo.	0	0.3	2.1	5.0	8.8	9.5	11.6	9.4	5.7	3.5	1.2	0.4	57.5
Water Deficiency	0	0	0	0	0.1	2.3	2.6	3.7	3.0	1.0	0.5	0	13.2
Water Surplus	0	0	3.8	4.4	0	0	0	0	0	0	0	0	8.2

*Soil moisture utilization diminishes as the soil moisture storage becomes less.

1. Thornthwaite, C. W., and Mather, J. R. The Water Budget and Its Use in Irrigation. In Yearbook of Agriculture, 1955, U. S. Department of Agriculture (in press).

In regions where the water deficiency is large with respect to the need or potential evapotranspiration, the climate is dry; when water surplus is large with respect to the potential evapotranspiration the climate is moist. Where there is a water surplus and no water deficiency, the relation between water surplus and water need constitutes an index of humidity. Similarly, where there is a water deficiency and no surplus, the ratio between water deficiency and water need constitutes an index of aridity.[1]

Water surplus and deficiency will occur at different seasons in most places so that both must be taken into account in a moisture index, the one affecting it positively, the other negatively. When the humidity index is compared with the aridity index making due allowance for soil moisture storage and utilization a moisture index is obtained. Moist climates have positive values of the moisture index while dry climates have negative values. This index is the basis for the division of the world into moisture provinces. The divisions suggested are:

Moisture Province		Moisture Index
A	Perhumid	100 and above
B_4)		80 - 99.9
B_3)	--Humid	60 - 79.9
B_2)		40 - 59.9
B_1)		20 - 39.9
C_2	Moist sub-humid	0 - 19.9
C_1	Dry sub-humid	-19.9 - 0
D	Semi-arid	-39.9 - -20
E	Arid	-60 - -40

The moist and dry climates are separated by the moisture index of zero.

A second index used to define climatic provinces is the annual potential evapotranspiration itself. Evapotranspiration - the change in state of water from liquid to vapor - represents not only an important mass transfer from ground to atmosphere but also it is an important agency of energy transfer since considerable heat is used in evapotranspiration and it is transferred to the air with the vapor as latent heat. Evapotranspiration is more than the reverse of rainfall; it is also a reverse flow to the incoming radiation. A single parameter, hence, provides a picture of two of the principal exchanges between earth and atmosphere.

With moist soil practically all of the net radiation is used in evapotranspiration and little goes to warming the soil or heating the air. Under these conditions the actual evapotranspiration approximates the potential evapotranspiration. Thus, this latter quantity becomes an index of available energy - energy which is used in the evapotranspiration of water and in the growth of plants. As such, potential evapotranspiration can be expressed either in depth of water evaporated or in calories of energy used in evapotranspiration or plant growth. The thermal provinces defined by means of potential evapotranspiration or available energy are given below:

Thermal Province		Annual Potential Evapotranspiration: Depth of Water Used	Annual Potential Evapotranspiration: Energy Available
A'	Megathermal	>114.0 cm	>66.7 kg cal
B'4)		99.8 - 114.0 cm	58.5 - 66.7 kg cal
B'3)	- Mesothermal	85.6 - 99.7 cm	50.1 - 58.4 kg cal
B'2)		71.3 - 85.5 cm	41.8 - 50.0 kg cal
B'1)		57.1 - 71.2 cm	33.4 - 41.7 kg cal
C'2)	- Microthermal	42.8 - 57.0 cm	25.1 - 33.3 kg cal
C'1)		28.6 - 42.7 cm	16.7 - 25.0 kg cal
D'	Tundra	14.3 - 28.5 cm	8.4 - 16.6 kg cal
E'	Frost	0 - 14.2 cm	0 - 8.3 kg cal

1. Thornthwaite, C. W. An Approach Toward a Rational Classification of Climate. Geogr. Rev., Vol. 38, No. 1, 1948, pp. 55-94.

WATER BALANCES OF SELECTED STATIONS IN AFRICA

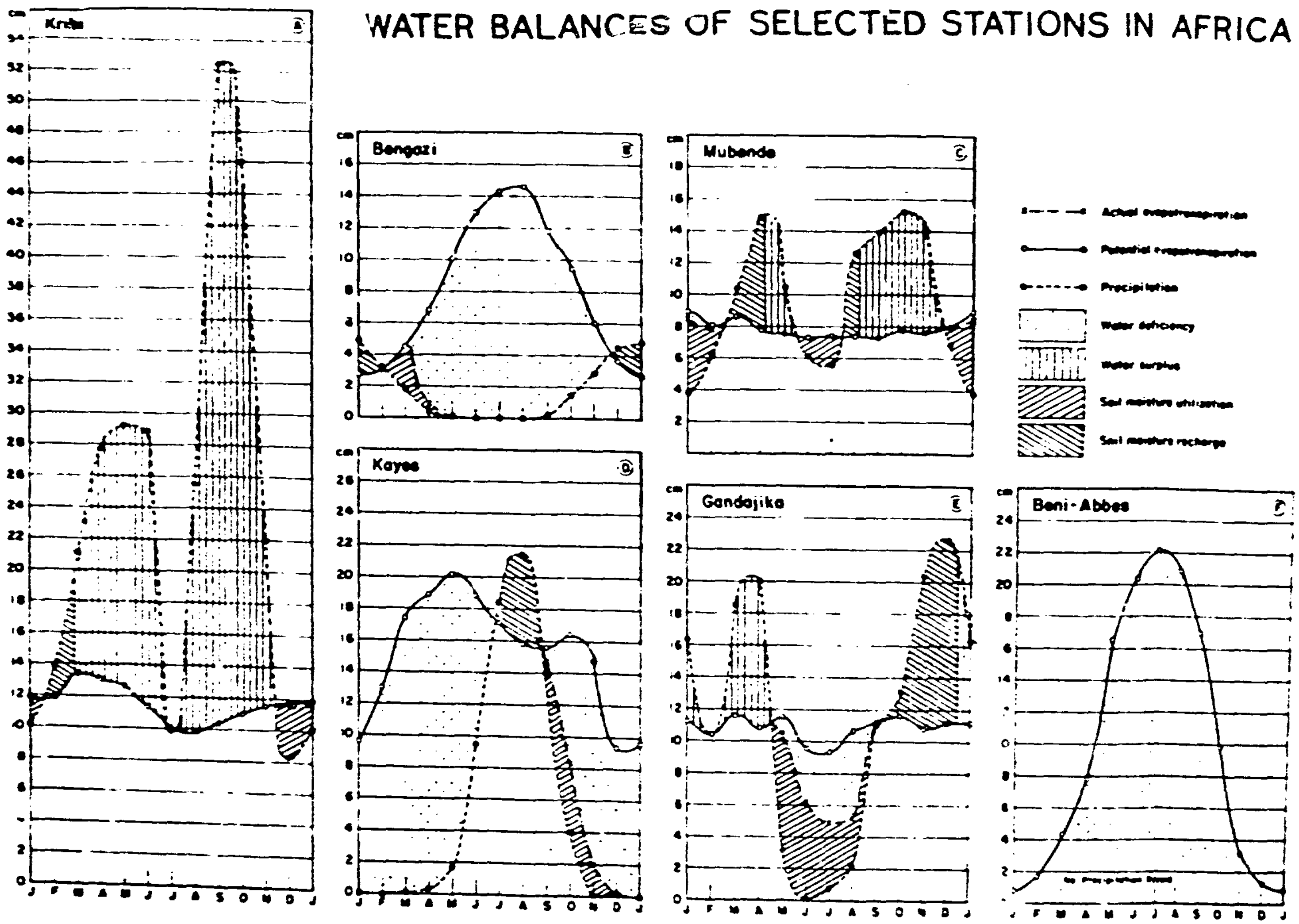


Figure 1

WATER BALANCES OF SELECTED STATIONS IN INDIA AND VICINITY

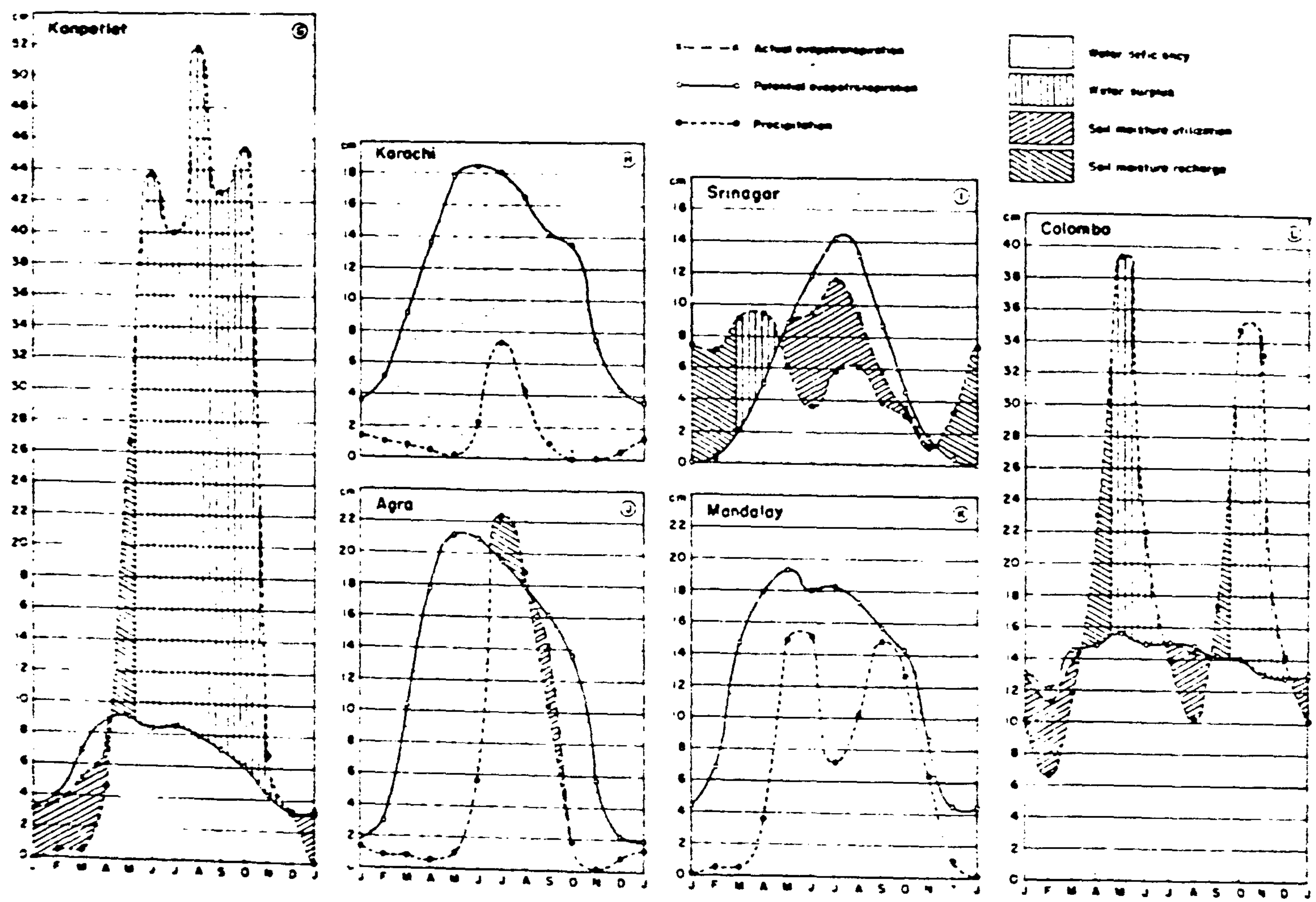


Figure 1 (continued)

It is worthy of stress that the indices which define these "provinces" specify at every point a thermal growth potential and the degree of moistness or dryness of the climate. In other words, the indices are continuously distributed about the earth, and do not exist merely along boundaries.

These then are important elements of Thornthwaite's classification. In addition, indices of the seasonal variation of each of the moisture and thermal indices are sometimes included. Because of the predominance of tropical conditions in Africa and India and the consequent lack of well-defined seasons, however, the seasonal indices have not been included in the material prepared under this contract. In their place, maps of two supplementary climatic elements, the water surplus and the water deficit have been included. Detailed maps of the distribution of precipitation which were constructed during the course of the work on the contract are also included in the present report.

The significance of annual water surplus is most apparent in appraising the water resources of any region. The annual surplus is the annual sum of monthly amounts by which precipitation exceeds water need and replenishments of soil moisture storage and so it is equivalent to the annual runoff. To map the water surplus the following scale of intervals has been arbitrarily selected.

less than 10 cm	80 - 99
10 - 19	100 - 149
20 - 39	150 - 199
40 - 59	200 - 299
60 - 79	300 - 399
	400 and over

The annual water deficiency is the sum of monthly deficits resulting from the failure of precipitation and soil moisture storage to supply the water needed for potential evapotranspiration. Intervals used in the mapping of water deficiency are completely arbitrary and are virtually the same as those used for mapping water surplus.

CONSTRUCTION OF CLIMATIC MAPS

The three major considerations in the preparation of climatic charts under this contract were: (1) the collection and analysis of all available climatological "normals" of monthly temperature and precipitation and the computation of potential evapotranspiration and the other climatic parameters from those data; (2) the standardization of a method of interpolating among station values; and (3) the selection of a suitable base map with a scale which is appropriate for the station density and method of interpolation.

Data of temperature and precipitation for practically all Indian stations were available in the Laboratory's files at the beginning of the contract. Such data for African stations were, however, generally lacking. The deficiency was rectified through two steps: (1) member nations of the World Meteorological Organization's Region 1 (Africa) were systematically addressed with requests for climatological normals; and (2) secondary sources in the Weather Bureau Library and the American Geographical Society's library were surveyed. As a result, the latest available climatological summaries were obtained from most areas. This effort to obtain data was materially hastened as a result of a rather complete list of climatological data which are available in leading libraries prepared for us by the Directorate for Climatology, Air Weather Service.

Most of the stations from which data were available had records of 10 to 30 years duration. It was not possible to reduce all the data to a standard period of observation because the periods utilised by the different countries are not coincident. Temperatures are particularly conservative in tropical regions and averages of even a few years are quite stable. Precipitation, however, varies greatly so relatively stable values can only be obtained from many years of record. Precipitation records from several stations had to be rejected as too short.

The computations of potential evapotranspiration, the moisture index, and the water deficit and surplus from mean monthly temperatures and precipitation were carried out with the objective of reducing errors to a minimum. In addition, a system of checks was instituted in order to validate the computations. The checking of potential evapotranspiration was carried out graphically while the computations of water surplus and deficit were most easily checked by the continuity of the moisture balance sheet (table 1). The final check for all values was the mapping of the actual values.

The numerical climatic data pertain strictly to the station locations so that data for intervening places can only be inferred from the influences of the local environment on the distributions of climatic elements. The factors of greatest significance for local interpolation are the oceanic and the topographic influences.

Maps of the parameters which are affected by thermal conditions should allow for a greater effect of cooling along coasts where the land-sea breeze is well developed than in the immediate interior. Cooling is also apparent at coastal stations adjacent to cold upwelling ocean waters where air movement is directed toward the shoreline. The oceanic influence is probably less effective along very wet coasts because of the similarity of the thermal balances over the ocean and wet coastal lands.

Topographic diversity is reflected in nearly all climatic distributions; consequently, the topographic map is to some degree a guide to interpolation among climatic values. For example, elevation is usually correlated with lowered potential evapotranspiration, with smaller water deficit and greater water surplus and precipitation. The pattern of potential evapotranspiration closely reflects the topographic diversity of a region although it does not usually correspond exactly with the elevation contours. By contrast, the precipitation pattern only generally resembles the topographic pattern. Since water surplus, and deficit, and the moisture index result from comparisons of potential evapotranspiration and precipitation amounts, the local topography exercises an influence on these parameters which is intermediate between its effect on precipitation and potential evapotranspiration.

Objective interpolation among station values for the purpose of drawing isopleths of climatic parameters is clearly basic to an accurate presentation of any climatic distribution. In order to construct maps which present only climatic data, interpolation has been based on only the known oceanic and topographic influences and not on evidence from other distributions such as vegetation or soils which would be utilized in evaluating the adequacy of the mapping. Coastal regions have been treated from the standpoint that the land-sea breeze should result in a narrow band of cooler, more moist climatic conditions. The coastal regions adjacent to cold ocean currents have been regarded as completely dominated by the cool dry air associated with the cold ocean currents. Elsewhere the effect of topography is the controlling factor so that hypsometric maps were required as base maps.

Every climatic pattern takes its major alignment from the principal topographic outlines. Regions of notable relief have the greatest climatic diversity while lowlands are distinguished for their relative uniformity. Although climatic data are often lacking in mountainous areas, the correlation of elevation and climatic parameters improves with height; thus, data are usually much more representative in the mountains than in regions of lesser relief.

The general results of the method of interpolation may be summed up as follows:

1. A pronounced coastal modification of isopleths along cool coasts
2. A localized pattern of cooling for the belt of land-sea breezes
3. Frequent assymetry between isopleths of the moisture parameters and the elevation contours
4. Virtual coincidence between potential evapotranspiration and contours of elevation for all small regions but only general correspondence between precipitation distribution and relief
5. Intermediate agreement of water surplus, water deficiency, and moisture regions with elevation contours.

The foregoing considerations have dictated the type of base maps to be employed. A relief map with reliable contours is needed and the number of stations for which reliable data have been obtained suggests a map scale of about 1:5,000,000. The World Aeronautical Planning Charts employing such a scale were adopted for the final base map for the Indian sub-continent. Maps from the same series and on the same scale which were available for Africa were less satisfactory since certain areas lacked contours. The 1:5,000,000 map of Africa being prepared by the American Geographical Society for publication in 1955-56 met our requirements adequately. Although this map is still in the production stage, it was possible to obtain prints of the compilation sheets showing relief and hydrography on scales of 1:3,000,000 and 1:5,000,000 through the cooperation of Dr. C. B. Hitchcock, Director of the American Geographical Society. The 1:5,000,000 sheets were utilized as the base map for the climatic maps of Africa.

The 1:5,000,000 maps of Africa and India are so large that reproduction at that scale would be too expensive for general distribution with this report. However, a Bruning print of each climatic map has been made at a scale of 1:5,000,000 and the print has been hand-colored. From the colored prints, other maps of the five principal parameters, potential evapotranspiration, water surplus and deficit, moisture index, and precipitation have been prepared in smaller scale, retaining as much as possible the detail in the large-scale maps. Copies of these small-scale maps are included in this report.

CLIMATIC MAPS OF AFRICA

Average Annual Precipitation

Traditionally, averages of precipitation have been an ingredient of climatic classifications. In Thornthwaite's classification, however, the annual amount is not utilized directly; instead, monthly amounts are compared with potential evapotranspiration and storage needs in order to determine surplus and deficiency of moisture.

In figure 2 the distribution of the average annual precipitation in Africa is shown. The principal features of precipitation in Africa have been described elsewhere[1] and need not be repeated here. However, it should be noted that a wide range of amounts occurs over the continent - from nil in southern Egypt to nearly 1000 cm at Debundscha, Nigeria. Moreover, as can be seen from the water balance graphs (figure 1) the annual amount may be concentrated in a few months or distributed more or less evenly through the year.

Average Annual Potential Evapotranspiration (Plate I-A)

It was indicated previously that potential evapotranspiration is equivalent to either the water need or the thermal efficiency of a climate and that the potential evapotranspiration and the precipitation are given in the same units. The distribution of average annual potential evapotranspiration in Africa is shown in plate I-A.

Although not shown, the value of potential evapotranspiration of 14.2 cm delimits the coldest, or frost (E') climates. In African latitudes E' climates occur only on the highest summits generally above 15,000 ft. Small islands of E' climate occur on Mts. Ruwenzori, Kilimanjaro, and Kenya; these islands are represented on the 1:5,000,000 map of potential evapotranspiration completed under the contract but no E' climate appears in the reduced map included in this report. Although more areas of D' climates than E' climates are represented on the 1:5,000,000 map, notably on Mt. Elgon, the Drakensberg, and several summits in the central and southern Ethiopian mountains, there is no significant extent of this climatic type in Africa so it, too, has been omitted from plate I-A.

The microthermal (C') climates in Africa are found only at relatively high altitudes in Morocco, in the Drakensberg, on the highest volcanoes of Kenya and Uganda, and in the Ethiopian Highlands. The C', D', and E' climates are restricted exclusively to mountain regions because warm water surfaces nearly surround Africa and separate it from source regions of truly cold polar air.

Mesothermal (B') climates comprise the range of annual potential evapotranspiration from 57 cm to 114 cm while megathermal (A') climates have an annual sum exceeding 114 cm. The B' and A' climates are the only two thermal types in Africa with an appreciable areal extent.

The map of potential evapotranspiration shows that, north of a line from Port Etienne on the Atlantic coast to central Tunisia thence southward including the tablelands of western Libya and eastward to the Sinai Peninsula of Egypt, the climate is mesothermal.

1. Kendrew, W. G. The Climates of the Continents. New York, Oxford Univ. Press, 3rd Ed., 1942, pp. 11-102.

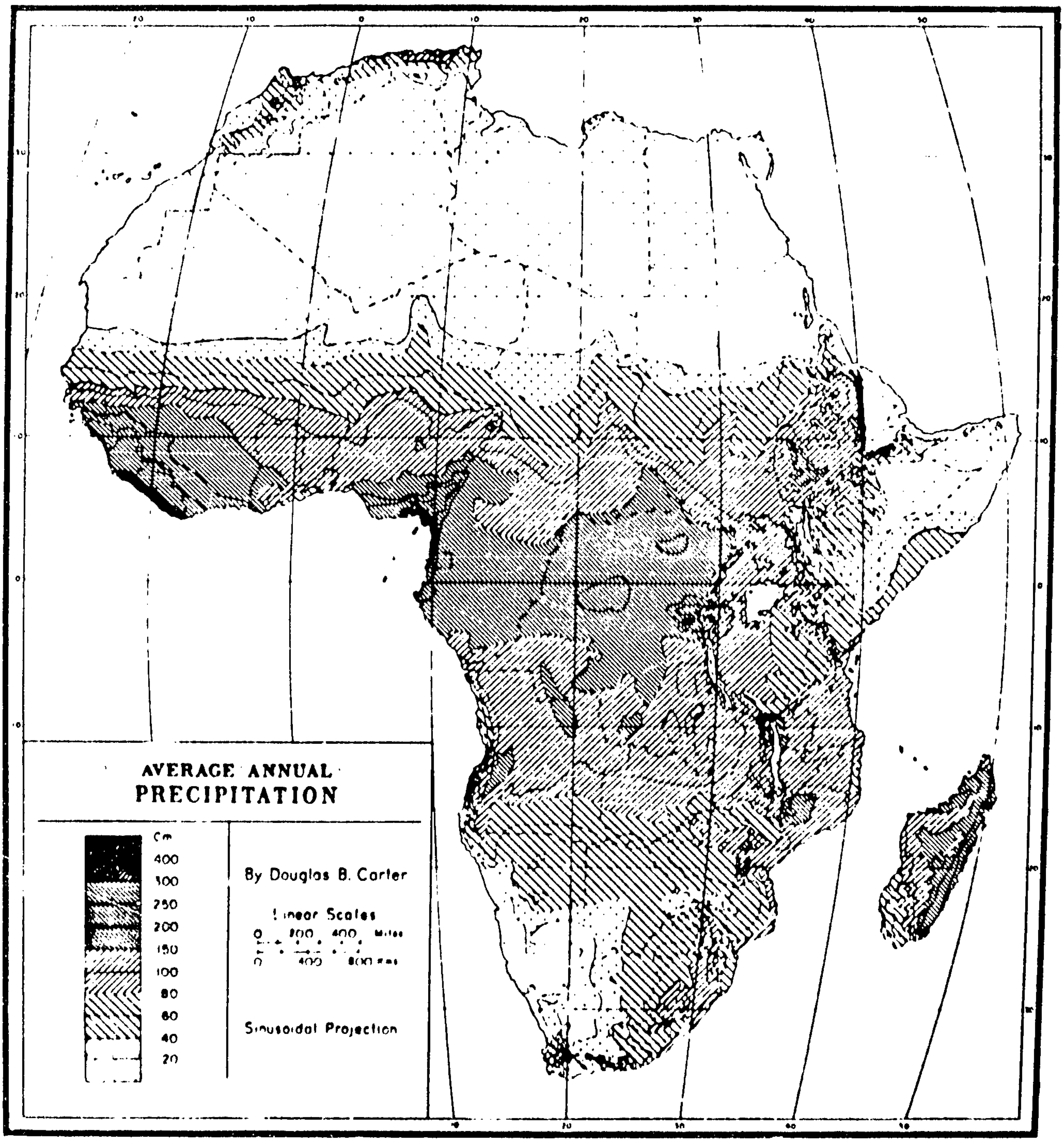


Figure 2. Average annual precipitation in Africa

South of the northern mesothermal climates, megathermal conditions prevail over all the Sahara except the Tibesti and Ahaggar Massifs. A' climates extend to the Guinea Coast and to nearly all of the Congo Basin in western and central Africa and large areas of A' climates surround the Ethiopian Highlands. Potential evapotranspiration increases southward in the megathermal climates to maxima which are located in four main basins in the Sahara and Somalia. Subsidiary centers are found in the Benue Valley of Nigeria and on the Red Sea coast. The largest area of potential evapotranspiration exceeding 171 cm is in French West Africa in the lowlands southwest of the Ahaggar. Other centers of more than 171 cm are located in the Chad Basin and in the Upper Nile province of Anglo-Egyptian Sudan. Along the Somalia coastal plain and into the Juba and Shibeli valleys there is another moderate area of more than 171 cm of potential evapotranspiration. Values of water need exceeding 171 cm apparently are not common in other continents and certainly annual sums exceeding 200 cm are presently unknown except at a single station in Somalia. At Lugh Ferrandi, the average annual potential evapotranspiration amounts to 206.7 cm.

The march of potential evapotranspiration in the megathermal climates of central and western Africa is extremely varied; a single peak, a double peak, or multiple peaks of water need occur at various places in this vast region. Along the boundary of northern mesothermal and megathermal climates, the march is characterized by a great annual range from January minima of one or two cm to July maxima of about 20 cm. Figure 1-F shows that at Beni-Abbes, Algeria, during July, the water need soars to 22.1 cm, an apparent record monthly maximum.

A double maximum of water need is common at latitudes lower than 20° in the megathermal climates. At Kayes, figure 1-D, it can be seen that peaks of water need occur just before and after the periods of greatest monthly rainfall. However, the amplitude of the annual range of potential evapotranspiration diminishes so greatly near the equator that some stations have multiple maxima because the differences in the lengths of the months are the dominant variation. For instance, Gandajika, Belgian Congo (figure 1-E) has a maximum in each of the four months with 31 days during its rainy season but each month with fewer than 31 days has a minimum; however, the annual range is less than 3 cm.

The mesothermal climates which embrace the interior plateaus of Ethiopia, Kenya, Tanganyika, Ruanda-Urundi, Angola, the Rhodesias and Nyasaland, Bechuanaland, and the Union of South Africa have rather distinct contrasts to the mesothermal climates which exist across the northern extremity of the continent. The mesothermal climates in the highlands of Tanganyika, Kenya, Uganda, Ruanda-Urundi, and Ethiopia have small annual ranges of potential evapotranspiration rather than pronounced winter and summer periods found in the mesothermal climate of northern Africa. Precipitation amounts and distributions are different, too, from the feast and famine regime of the Mediterranean so the east African mesothermal climates have a reasonably large percentage of the potential evapotranspiration satisfied by available moisture. The regime of water need at Mubende, figure 1-C, illustrates the small annual range of water need which is characteristic of upland equatorial Africa.

The mesothermal climates of the coast of southwestern Africa exhibit an "inversion" pattern. Potential evapotranspiration on the narrow, cold coastal plain is generally less than 85 cm and upland stations also have small annual sums but intermediate elevations have a water need which exceeds either the coastal or the upland places. For example, water need increases by 18 cm from 73 cm at Swakopmund to 91 cm at Windhoek only to diminish again to 85 cm at about 5000 feet in the mountains east of Windhoek. Inversions of potential evapotranspiration also occur, but in lesser degree, in the mesothermal climates of coastal Morocco and the megathermal climates of coastal Nigeria. Mesothermal climates of southern and northern Africa are basically similar in their thermal efficiency regimes, but the relief of the two regions is strongly contrasted so the areas of comparable types of thermal efficiency are dissimilar. Even more contrasting are the regimes of soil moisture in the two regions; hardly any area of the southern mesothermal climates except the Cape Province has conditions of agriculture and growth of natural vegetation comparable to those in the northern mesothermal region in spite of the fundamental similarities in growth potentials.

Madagascar's pattern of potential evapotranspiration is almost a replica of its relief pattern except that the water need is slightly larger in the northwest coastal plain than elsewhere.

Average Annual Water Surplus (Plate I-D)

A map of the average annual water surplus in Africa is included in plate I-D. Most of Africa has little or no reliable surplus. In the Mediterranean coastal region, the average surplus is nil at many stations such as Bengazi (figure 1-B) where average winter precipitation only partially refills the storage capacity of the soil.

Surplus in the Sudan from Gambia to the Gold Coast increases southwestward culminating in the phenomenal annual value of 346 cm at Schiefflin, Liberia. Surplus is a debatable asset in this region where the enormous amounts are further aggravating because of their confinement to a very few months.

In southeastern Gold Coast and adjacent Togo and Dahomey, the average annual surplus drops to less than 10 cm. This peculiar situation is due to the inadequacy of precipitation, primarily, since the rainfall pattern is interrupted here. The lack of surplus is accompanied by evidence of dryness in every climatic map of Africa presented in this report.

The largest region of appreciable surplus in Africa extends from northwestern Nigeria to Nyasaland and from southwestern Angola to southwestern Anglo-Egyptian Sudan. Within this region two main centers of surplus are apparent: the Cameroons and the uplands of the eastern Congo Basin.

Surplus in the Cameroons is greatest along the coast and decreases inland. Nevertheless, the principal range of the Cameroons has a surplus of more than 60 cm. The record precipitation at Debundscha, Nigeria, provides a surplus in every month but elsewhere in the Cameroons surplus is interrupted in at least one month and Kribi even has a dual regime of surplus as figure 1-A shows.

The western flank of the Mitumba Mountains in the eastern Congo Basin has a large surplus, particularly the portion in the vicinity of 0° to 3°S latitude. The largest amount is 200 cm at Mwindo where every month has a surplus.

The center of excessive surplus in the Cameroons and the corresponding focus of surplus on the eastern Congo ranges are separated by lesser values of surplus, especially along the lower Congo River where the river forms the western border of the Belgian Congo. An annual surplus of 6.9 cm at Inongo is the lowest indicated value in the region. Otherwise, from Nigeria to Nyasaland, surplus is abundant.

Surplus in the Ethiopian Highlands is common on nearly all elevated tracts. Greatest amounts occur in the southwest and south but little is found in Eritrea or Somalia. Surplus in Ethiopia is markedly seasonal with many months, particularly December, January, February, and March devoid of surplus even at the wettest of stations.

From Lake Rudolf to Lake Nyasa, maximum surplus in British East Africa occurs on the contorted discontinuous relief elements which punctuate the plateau. Moreover, gradients of surplus are steep on the slopes of the restricted relief. Over the plateau of Uganda-Tanganyika surplus varies only slightly above and below a value of 20 cm. Northern Mozanbique has more diversity in its surplus; indeed, the coastal plain north of Beira has less than 20 cm while a considerable area in the northwest has more than 40 cm of surplus.

Surplus of more than 20 cm occurs in the Union of South Africa on the Drakensberg, the plateau rim in the east, and on the ranges parallel to the south coast. From the Drakensberg, many streams carry away the summer surplus but the Orange River system is particularly noteworthy. The Orange crosses nearly the width of the Union without the benefit of any sizeable surplus after it leaves the uplands of the east.

Surplus on Madagascar ranges from 218 cm at Tamatave to nil at Tulear, Tsihembe and Morombe and insignificant amounts at the northern extremity of the island. A secondary maximum occurs along the north-central mountains.

Average Annual Water Deficiency (Plate I-C)

Deficit is equivalent to drought - it is the need for moisture that storage and precipitation have failed to meet. Only the regions without deficit are free from drought.

A glance at the map of average annual water deficiency, plate I-C, is sufficient to indicate that drought prevails over all Afric… except in the equatorial zone from the Cameroons to Lake Victoria, in eastern Madagascar, and in the cooler mountain districts.

The greatest average annual deficiencies occur in Somalia and in the Sahara where more than 150 cm of water is needed at many stations in order to rectify deficits. Three centers of extreme deficiency occur in the Sahara and another extends along the Red Sea coast and into Somalia. Each area of extreme deficiency in the Sahara coincides with a topographic basin. In southern Africa the drought is not as severe, quantitatively, as it is in northern Africa so the pattern of deficiency for the continent is much more asymmetric with respect to the parallels of latitude than is the case for precipitation distribution or the distribution of water surplus on the continent.

South of the Atlas Mountains and also south of the Libyan and Egyptian coasts, water deficiency increases in the Sahara to maximum values which are virtually equivalent to the potential evapotranspiration at each station. At Kharga in southern Egypt, the average deficit actually equals the water need because average precipitation is nil for a twenty-year record. Since many stations in the Sahara receive no rain for more than a year at a time, water deficiency there is clearly a persistent rather than a seasonal trait of the climate.

On the Ethiopian Highlands, deficiency is 11 cm at Addis Ababa even though the station has an altitude of 8000 feet. Elevation's effect on potential evapotranspiration eradicates deficit from only the highest peaks. Peaks in the Ethiopian Highlands are high enough to have a negligible deficiency but summits in Eritrea and Sudan are not.

The region with largest rainfall in Liberia, Sierra Leone, and Senegal also has a remarkable deficiency. No other large region in A..ca with more than 500 cm of precipitation has such a marked seasonal concentrat.. of rainfall and a resulting deficit of more than 20 cm. Throughout the equatorial forest region from Lake Tanganyika to Pt. Gentil and from the Camercons Mountains to the Kenya-Uganda boundary, deficiency is negligible.

British East Africa and the Portugese territories of Mozambique and Angola have essentially similar annual deficiency. South of the Kenya peaks, annual deficiency ranges from 20 to 60 cm on the uplands of Tanganyika and Mozambique but varies even less on the plateaus of Angola and the Rhodesias. Mountains with more than 5000 feet elevation have smallest deficits. Along the coast of Mozambique and Tanganyika, deficiency ranges from 60 to 80 cm and in the Limpopo and Zambezi valleys, the deficit approaches or exceeds 100 cm, a marked contrast to the adjacent uplands.

One of two coastal areas in Africa without a significant average deficiency is Natal in the Union of South Africa; the other is found in French Equatorial Africa and Nigeria. The Natal region of low deficiencies extends from the vicinity of East London to Empangeni then inland and northward to Ladybrand, Standerton, Carolina, and Pilgrims Rest. Continuations of the low deficit region radiate outward from the main area along the ridges near Pietersburg and also along the ridge toward Mafeking.

Other regions in Africa with 30 cm deficiency are extensive, particularly over the plateaus at 10°S and in the Sudan in North Africa. However, the latter are tropical; they have much larger amounts of precipitation, water need, and water surplus than the plateaus of South Africa.

Deficiencies in the Kalahari Desert reach almost 100 cm annually but the prevailing deficit is only about 80 cm. East of the desert, deficits decrease with increasing altitude although a low-altitude connection between areas with high deficiencies in the Kalahari Desert and the lower Zambezi Valley is maintained by a corridor where average deficiency exceeds 60 cm. The large deficiency in the lower Limpopo, however, is more or less isolated from the Kalahari by moderate deficits at Zeerust and Mafeking.

Average annual water deficiency is less along the Namib coast than it is on the mountains bordering the Namib because the need for water is greatly depressed at coastal stations by the pronounced cooling associated with the Benguela Current. The coastal area from the mouth of the Orange River to Mossamedes has negligible precipitation and so water deficiency is almost equivalent to water need.

Madagascar's water deficiency ranges from nil on the east coast to about 100 cm in the southwest, west, and the northern extremity of the island. In the valley which contains Lake Aloatra, the annual deficiency is 27 cm at Ambohitsilaozana. Except for this anomaly, the pattern of deficiency in Madagascar is quite regular.

Moisture Regions (Plate I-B)

The main types of moisture regions in Thornthwaite's classification of climate are perhumid, humid, subhumid, semiarid, and arid. Each of these types is shown in plate I-B. Furthermore, the dry subhumid and moist subhumid types are differentiated by a bold line which represents the zero moisture index. The bold line separates moist climates with prevailing moisture surplus from dry climates with prevailing deficiency of moisture.

Moist climates in Africa are not contiguous; they are found in five major groups on the continent. Moist climates occur in the Atlas Mountains, the Ethiopian Highlands the Guinea Coast, tha Congo Basin and its surrounding plateaus, and moist climates are found on the summits of various mountains in the peripheral ranges from the Cape Province to Lake Nyasa.

One major bloc of dry climates occupies the lowlands of the Mediterranean coast and all the Sahara; moreover, it extends to the coast in the Gold Coast Colony, in Togo, and Dahomey, and it encircles the Ethiopian Highlands, and projects across the equator in eastern Kenya to the vicinity of Kilimanjaro. The other large group of dry climates comprises the coastal strip south of 5°S latitude and the interior plateaus of southern Angola, and lowlands of northern Rhodesia and Mozambique, together with all lowlands and plateaus in British South Africa except a triangular bloc extending from Durban to Bloemfontein to Pietersburg.

Perhumid Climates

The perhumid climate of the Cameroon coast centers on Port Victoria and extends from the northern boundary of Spanish Guinea to the mouth of the Cross River but it is limited to the region within a hundred miles of the coast.

The Mitumba Mountains northwest of Lake Tanganyika have a perhumid climate with surplus occurring in the period from September until June. Summits have continuous surplus. On the western flank of the Mitumba range, perhumid climate extends to stations as low as 1000 meters such as Mwindo.

The perhumid climate of the Ethiopian Highlands is found at Gondar, elevation 7445 feet, and at Let Marefia, elevation 7898 feet. In southern Ethiopia, perhumid climates occur at about 7000 feet on the southwestern sides of the ranges where precipitation is excessive.

In Kenya, the perhumid climates are confined to the summits of volcanic peaks. One station, Kericho, elevation 6700 feet, has a moisture index sufficient for perhumid climate. However, the decrease of water need with height in central Kenya indicates the certainty of perhumid climates at well-exposed stations above 7000 feet.

North of Lake Tanganyika, more than 200 cm of precipitation fall on mountain stations but water need is less than 100 cm so the climate locally is perhumid. Moisture indices in the vicinity of Tukuyu indicate that perhumid climates occur above 5000 feet on rain-swept slopes.

Eastern Madagascar also has perhumid climate. Climatic conditions resemble those in the Cameroons where precipitation is excessive in spite of a moderately large water need.

Humid Climates

Humid climates appear in limited areas of Morocco, Algeria, and Tunisia. The humid climates of the Mediterranean are distinguished by moderate amounts of surplus and a comparable deficiency. Surplus occurs during winter but summer has large deficits because precipitation is only a few mm during July and August.

The most conspicuous moisture type of the Ethiopian Highlands is the humid group. All four sub-types of humid moisture regions are represented and many combinations of surplus and deficiency exist.

Humid climates in French Guinea and the Ivory Coast are shown in plate I-B as more extensive than the adjacent perhumid climate which dominates the coasts of Liberia and Sierra Leone. The humid climates of this region are almost the antithesis of humid conditions in the Mediterranean because the Guinea Coast has a large surplus in a few months and moderate deficit lasting for several months.

The principal bloc of humid climates in Africa extends in a band from south central Nigeria and Spanish Guinea on the west to Lake Victoria and Lake Tanganyika in the east. The largest expanse is in the Belgian Congo and French Equatorial Africa. The predominant moisture indices are in the lowest of the humid categories although a few stations, mainly with elevations of more than 1000 meters and an annual precipitation near or exceeding 200 cm, have high indices approaching perhumid conditions. Outliers of the main humid region are found in the mountains of Nigeria and on the plateau of northwestern Angola and the Crystal Mountains north of the lower Congo.

The remaining areas of humid climate on the continent are found on the uplands and mountains along the perimeter of the continent from Lake Nyasa to the Cape of Good Hope.

Subhumid Climates

Moist and dry subhumid climates in Africa occur where either megathermal (A') or mesothermal (B') conditions occur; apparently, subhumid and microthermal (C'), or colder, characteristics do not coexist anywhere in Africa. The subhumid climates occupy the lower slopes of the Atlas Mountains, the Ethiopian Highlands, and the southeastern plateau rim of the continent, the Sudan margin of the humid climates, the Lake Victoria plateau of Uganda, Kenya, and Tanganyika, the coastal region of central Mozambique and the coastal region of Natal. The region south of the lower Kasai River and the Katanga district in the Belgian Congo constitutes a remarkable expanse of subhumid climates which is interrupted only by islands of upland humid climate.

Subhumid climates everywhere in Africa have some deficiency and some surplus. On the Lake Victoria plateau, surplus and deficit are small, around 20 cm, and the resultant moist subhumid climates grade into dry subhumid varieties toward the south.

Subhumid climates occupy most of the lower elevations in Tanganyika and Mozambique; much of southern Rhodesia is also dominated by subhumid climate. The obvious difference between the subhumid climate of southern Rhodesia and the subhumid climate of lowland Mozambique is that the latter has a larger surplus, potential evapotranspiration, and precipitation.

The subhumid climates in east Africa are generally mesothermal while those in west Africa are megathermal. The mesothermal subhumid climate of the Natal hinterland is the result of a most remarkable coincidence between the marches of water need and precipitation. A small deficiency and virtually no surplus is characteristic of the westernmost part of the subhumid climate here while a small surplus without much deficiency is the prevailing condition along the coast near Durban.

Semiarid Climates

Semiarid climates in Africa are almost devoid of a significant surplus. Semiarid climate dominates the lowlands of Morocco and the interior of northern Algeria. In Libya, the semiarid climates occur only in the Gebel Nefusa, in the Gebel el Achdar, and along the coast near Sirte. Surrounding the Ethiopian Highlands and extending in a tapering band toward Dakar is the largest region of semiarid climate in northern Africa. The band of semiarid climate protrudes to the coast in the vicinity of Accra, Gold Coast Colony.

The two isolated segments of semiarid climate in Tanganyika, west of the mountain barrier and on the Mozambique-Tanganyika coast, coincide with local minima of precipitation.

The largest area of semiarid climate in southern Africa extends in an arc around the Kalahari Desert from southern Angola to the Karoo; it includes all of Bechuanaland and it has two ramifications eastward to Mozambique along the Zambezi and Limpopo valleys.

The relatively restricted semiarid climates of Madagascar are found in the southwestern plains and at the north coastal station of Diego Suarez. Semiarid climate in Madagascar presents little competition to other moisture regions for the development of agricultural pursuits.

Arid Climates

The arid climates are the most extensive in Africa. In addition to the coast-to-coast belt of arid climate across the Sahara, northern Africa has small outliers of arid climates in coastal Morocco, to the southeast of the Ethiopian Highlands and in the lowlands surrounding Lake Rudolf and Lake Natron in Kenya and Tanganyika. Arid climates in the southern hemisphere include the Kalahari Desert and the southwest coastal strip from Luanda to latitude 33°S. Two additional areas of arid climates are indicated in southwest Madagascar and in the valley of the Limpopo through the south of southern Rhodesia and adjacent Mozambique.

In the arid region of the Sahara, moisture indices are less than -50 close to the southern flank of the Saharan Atlas, as for example at Colomb Bechar, and the moisture index is less than -50 in all stations of Egypt except Gaza. Most of the Sahara has very low moisture indices because of deficient precipitation and large water needs; the moisture index is less than -50 throughout the central Sahara so that even as far south as Khartoum, Kidal, and Timbuktu, one finds indices of less than -50. Near the borders of the arid regions, the moisture index undergoes a moderately sharp transition where indices of -40 to -50 are arrayed in a narrow band around the main area of prevailing indices of -50 and less.

Moisture indices in other arid climates of Africa are rarely so low as in the Sahara. Because the coast of Somalia near Mogadisciu has a slightly greater amount of precipitation than elsewhere in its immediate vicinity the moisture index is locally only -40 rather than -50.

A moisture index of -55 at Lodwar, Kenya indicates that Lake Rudolf is surrounded by a relatively small region of arid climate. A similar spot of arid climate around Lake Natron in Kenya and Tanganyika is indicated by a moisture index of -48 at Magadi. The arid climate along the Limpopo in the south of southern Rhodesia embraces Beitbridge and two additional stations where moisture indices are from -42 to -47. The lowest index in Madagascar is -45 at Androka in the southwest of the island.

The Namib and Kalahari Deserts are the loci of the remaining arid climates of Africa. From Luanda, Angola to the vicinity of the mouth of the Olifants River, the climate is arid and moisture indices are mainly less than -40 in Angola and -50 in southwest Africa and the Union of South Africa. The zone of arid climates enlarges inland from the mouth of the Orange River to include indices of -50 around Upington. Generally, however, the moisture indices in the Kalahari do not appear to have a sharp gradient from -50 to -40 as was indicated in the Sahara.

CLIMATIC MAPS OF INDIA AND VICINITY

Average Annual Precipitation

In figure 3 the distribution of the average annual precipitation of India and vicinity is shown. This map is a generalized reduction by K. Nishimoto of a 1:5,000,000 map originally prepared by Varanasi P. Subrahmanyam and Gopal Y. Shanbhag.

Maxima of precipitation coincide with higher elevations in the Ghats, the eastern Himalaya and the Arakan Yoma but a general decrease from southeast to northwest is characteristic of the region between the Ghats and the Himalayas. The distribution of precipitation is markedly seasonal yet the west coast of the Deccan and virtually all the sub-continent east of the 80th meridian have annual totals exceeding 100 cm.

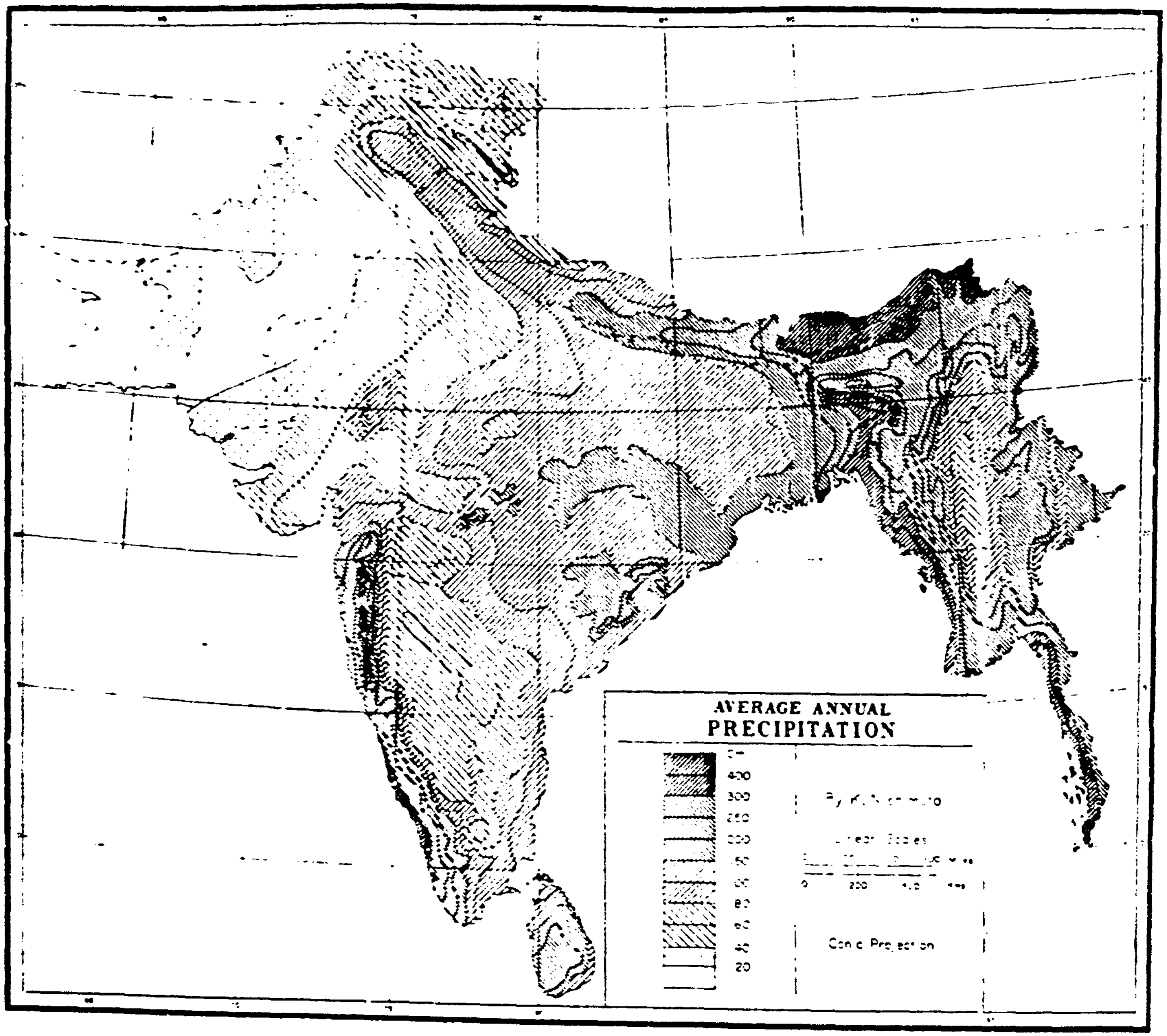


Figure 3. Average annual precipitation in India and vicinity

Minima of precipitation are found mainly in the northwest but subsidiary centers appear in the lee of the Ghats, the Khasi Hills, and the Arakan Yoma. The region of low precipitation in the Indian sub-continent corresponds in latitude to the extensive belt of sparse precipitation extending across Africa and Arabia along the Tropic of Cancer. The region of large precipitation amounts in India has annual totals comparable to the greatest amounts in central Africa; however, the zone of heavy precipitation in India extends to latitude 30° while its African counterpart is distinctly equatorial.

An appreciation of precipitation in relation to its adequacy, superfluity, or paucity can hardly be gained from perusal of the isohyetal pattern alone; precipitation must be compared with water need or potential evapotranspiration.

Average Annual Potential Evapotranspiration (Plate II-A)

In plate II-A, the same ranges of thermal efficiency (water need or potential evapotranspiration) are shown for India and vicinity that were portrayed for Africa in plate I-A.

The frost (E') climates and the taiga (D') climates occur on the Himalaya summits at high elevations but only a small area is represented in the aggregate so D' and E' climates are not shown on the small-scale map in this report. Microthermal (C'), mesothermal (B'), and megathermal (A') climates dominate the Indian sub-continent.

Microthermal climates in India are exclusive to the higher ranges in the Himalaya Mountains. No lowland microthermal climates exist in India and only two observatories at Leh and Dras in Kashmir have known average annual totals of potential evapotranspiration which fall into the microthermal category. Both stations are higher than 10,000 ft. elevation.

Mesothermal climates are prominent at moderate elevations especially above 2500 ft. in the Himalaya and Sulaiman Mountains, in the Khasi Hills, the Shan Plateau, and the Arakan Yoma. Mesothermal regimes are found at relatively higher levels in the western Ghats and the Aravalli Range, principally above 4000 ft.

Megathermal climates dominate nearly all the productive land of the Indian sub-continent except the valleys of Kashmir and most lowlands have about 150 cm of water need. Annual totals exceed 171 cm of water need in only four small regions: the Irrawaddy Delta, the Coromandel Coast, northern Ceylon, and the Malabar Coast. Although megathermal climates are found in a larger proportion of India than in Africa, the extremely high water needs of north Africa do not occur widely in India. It is particularly evident that the Thar Desert does not have annual amounts of potential evapotranspiration comparable to those found in the Sahara and Somalia deserts.

The seasonal distribution of potential evapotranspiration follows one of three general patterns in the area represented by the maps of plate II-A. In the northwest, monthly amounts of water need are arranged in a nearly symmetrical curve as is illustrated by the graph for Srinagar in figure 1-I. In lowest latitudes and at highest altitudes of this region, the monthly amounts of potential evapotranspiration are only slightly different from one another; this constancy of water need is shown in the graphs for Colombo and Kanpetlet in figure 1-E,G. The most prevalent type of march for water need is an asymmetrical curve. The skewed curve for Agra in figure 1-J is representative of the annual course of potential evapotranspiration at most stations in the Ganges Valley and in northern Deccan.

Average Annual Water Deficiency (Plate II-C)

There is no significant water deficit in the moderate and high elevations of the Arakan Yoma and the eastern Himalaya Mountains. At the other extreme, the largest area of excessive deficiency in the sub-continent is found in the Indus Valley. Virtually all the Indus Valley in Pakistan has more than 100 cm of deficit. Between the area of largest deficit in Pakistan and the Himalayan region of negligible deficit, the isopleths of deficiency are regularly arrayed.

Besides the Indus Valley, there are three smaller centers of excessive deficit: the central Irrawaddy Valley, the Kistna Valley in the central Deccan and a small area in northwest Ceylon opposite a similar area on the mainland.

deficit throughout the year in the Indus Valley is usually uninterrupted; even where there is reliable precipitation, it is not enough to satisfy the average monthly water need. At Karachi, as figure 1-H shows, there is never a month when average precipitation is as much as the average water need. In the Irrawaddy Valley, deficit is continuous as, for example, at Mandalay (figure 1-K) in the heart of the central section of the valley. The Kistna Valley and the lowland around Madura in Madras Province also have deficits which are virtually continuous.

The regions with negligible deficit have only a month or two, if any, when precipitation is inadequate for needs. Such deficits generally occur during March and April.

Average Annual Water Surplus (Plate II-D)

World record amounts of surplus occur in the Khasi Hills where Cherapundji has more than 1000 cm of surplus water in eight months. The coast of Burma near Gwa and the Mergui Coast farther south have astounding amounts of surplus, between 400 and 500 cm, while in the eastern Himalayas and in the central part of the Ghats some water surpluses exceed 200 cm. East of longitude 80°, surplus is copious everywhere except in the central sections of the Ganges and Irrawaddy valleys where there is only 20 cm of surplus.

The Ghats, the central Deccan uplands, and the coasts of Burma have a large surplus which generally reaches its peak in June and July just after the pinnacle of the drought season in April. Coastal Madras and the interior of Ceylon have a surplus during November and adjacent months. Some stations in southern Deccan and Ceylon have both a November and June-July maximum of surplus.

In the northwest, precipitation is maximum and water need is least in winter so that surplus also occurs in winter. Other seasons have no significant surplus; indeed, surplus occurs only at the high elevations where precipitation is appreciable.

Moisture Regions (Plate II-B)

The moisture regions of the Indian sub-continent range from arid to perhumid with all intermediate moisture categories represented. Moist climates and dry climates are separated by a bold line on the moisture regions map in plate II-B. Moist and dry climates are nearly equal in area in India. The Ghats, central Ceylon, the Aravalli Range, and peaks of the Sulaiman Mountains appear as outliers of the main area of moist climates to the east of the 80th meridian. On the other hand, dry climates appear as an isolated area in the central Irrawaddy Valley.

Perhumid climates on the Burma coast and the uplands of the Ghats, Arakan Yoma, Khasi Hills, and Himalaya Mountains have excessive moisture indices. At Cherapundji the index is 1254; at Akyab on the Burma coast it is 245. Although Cherapundji has no reliable deficit, there are moderate and consistent deficits at Akyab and many other perhumid stations with excessive moisture indices.

In spite of the large range of the moisture index which is included in the category of humid climates, there is not much area in India and vicinity which has humid climate. In fact, there is only slightly more area of humid climate than of perhumid climate.

Subhumid climates are most extensive in the uplands of the northern Deccan and the central part of the Ganges Valley. Surplus and deficit are nearly equal in this region, averaging about 50 cm per year. In coastal Madras and Ceylon where there are two small surplus seasons and two seasons of deficit, the climate is only subhumid in spite of the fact that annual precipitation totals exceed 100 cm.

Semiarid climate in the Deccan occupies most of the Kistna Valley and the coast of Andhra as well as the interior plains in the south of Madras. Semiarid climate also is prevalent at lowest elevations in the central Irrawaddy Valley. From the Kathiawar Peninsula to the Aravalli Range, then northward and northwestward to the Punjab an extensive area of semiarid climate is shown in plate II-B. On the middle slopes of the Sulaiman Mountains and contiguous ranges, semiarid climate continues from the Punjab to Afghanistan and Iran.

Arid climate is found in the lee of the Ghats although moisture indices there indicate only the most modest of arid conditions. A thoroughly arid region extends along the central and lower course of the Indus River and then westward along the coast of the Gulf of Oman. Arid climate also characterizes the interior basins in Baluchistan.

Arid climates are found mainly at low to moderate elevations where precipitation is small, but neither precipitation amounts nor elevations can serve to indicate everywhere that arid climates are to be found in India and vicinity.

DISCUSSION

In preparing the climatic maps it was accepted that they must depict the probable conditions where data are insufficient to indicate actual conditions. Accordingly, the map patterns fit the climatic data and, in various degrees, they correspond to the major relief patterns. In spite of this attribute, the maps must be regarded as generalized illustrations so that reference to the tabulated data is necessary for exact and detailed information.

Each map pattern carries out a pre-determined style of generalization, or interpolation, which is appropriate for the particular climatic parameter. Since the interpolation technique rests mainly on topographic information, the maps of Africa are especially detailed because they are based on a superlative physical map made available for our project by the American Geographical Society. In addition to their correspondence with data and topography, the climatic patterns resemble one another in certain instances.

The map of potential evapotranspiration is generally dissimilar to the maps of precipitation, water surplus and moisture regions, but the pattern of water deficiency resembles the pattern of potential evapotranspiration where precipitation is slight. Of course, if there were no precipitation, the water need and the water deficiency would be equivalent.

The pattern of moisture regions might be reasonably well anticipated from the distributions of precipitation, water surplus and water deficiency. Perhumid regions and regions of very high precipitation correspond closely; moist climates and regions of moderate water surplus are found nearly everywhere together; and dry climates are almost coincident with prevailing patterns of water deficiency. There is no clearly discernible agreement between the patterns of potential evapotranspiration and moisture regions except in the dry climates.

There is a close correspondence between areas of negligible deficit and regions of high annual precipitation. The similarities between certain water deficiency patterns and dry climates as well as the likeness between maxima of potential evapotranspiration and large deficits have been indicated previously. There is, however, a distinctive contrast between water deficiency and water surplus patterns. Where one is most intricate, the other varies only gradually. Still, the outline of least surplus generally defines maxima of deficiency and vice versa.

Water surplus patterns resemble patterns of precipitation where the precipitation is large and they also resemble the moist climates of the moisture regions map.

The map of precipitation in Africa was constructed from precipitation records of 1244 stations and from reference to large-scale precipitation maps of individual countries of Africa. The precipitation map in figure 2 agrees generally with authoritative precipitation maps published for various countries of Africa. Although those maps are based presumably on intimate acquaintance with the particular country and on complete precipitation records, they are not comprehensive of the whole continent and the method of mapping is not consistent from one map to the next. Our map, in the original, has a scale of 1:5,000,000 and it pertains to the whole continent but it is not a painstaking interpretation of the distribution of precipitation. The map of precipitation in India, figure 3, is rather similarly limited in its purpose and degree of articulation although more than 400 stations were available. Instead of presenting a more detailed map of the precipitation distribution, this general map was included merely to indicate that precipitation distribution does not serve adequately to represent either the climatic types or the hydrologic character of a region.

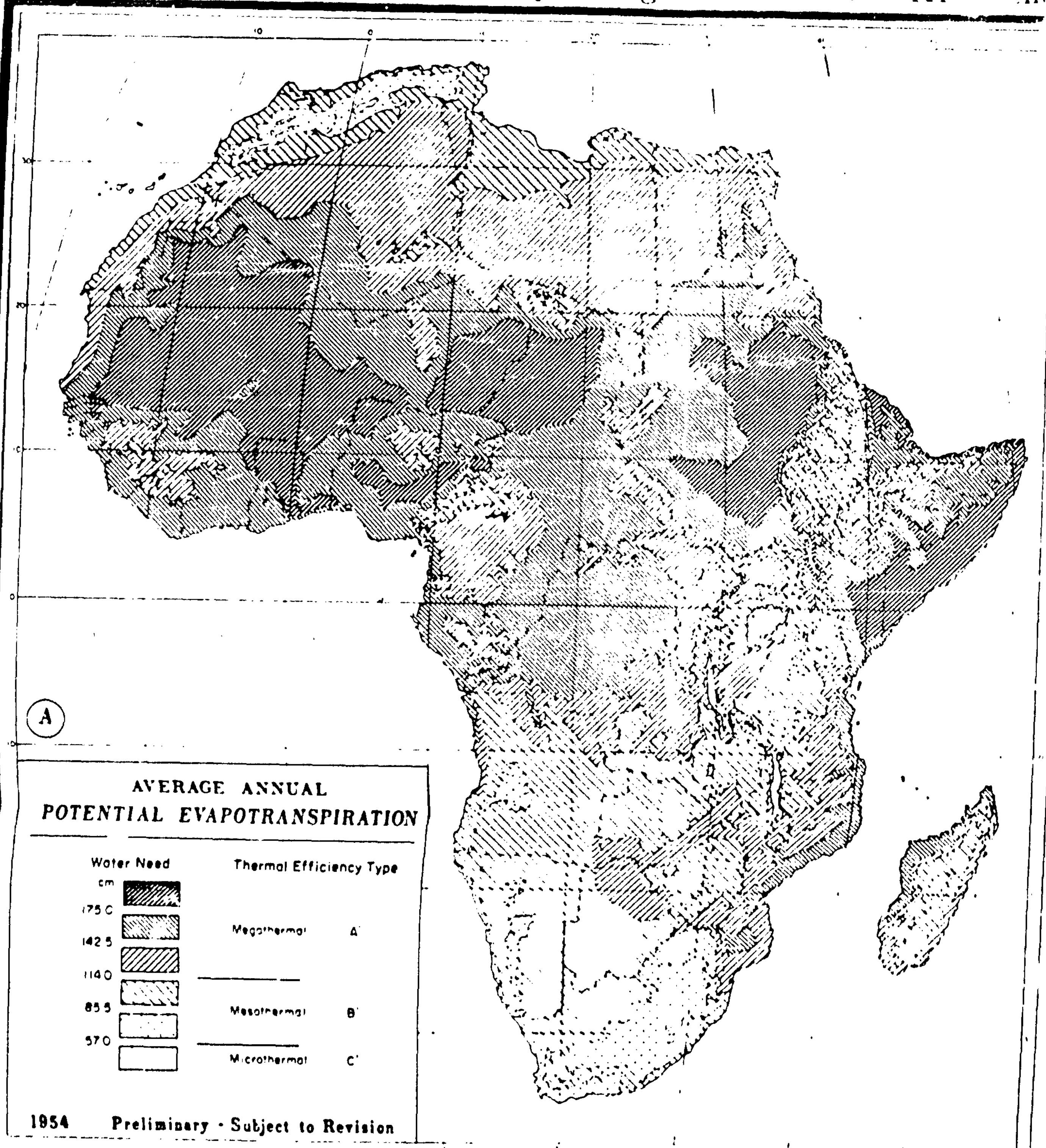
The maps of plates I and II should be regarded as preliminary in the sense that they are the first attempt to portray the continent of Africa and the Indian sub-continent in the Thornthwaite system of climatic classification. They are the first maps to include the principal features of the water balance or the hydrologic supply and demand of those large continental land masses. The maps are, of course, subject to corrections and modification based on later information and experience with the intricacies of vegetation, soils, hydrologic, climatic, and ecological conditions in specific areas.

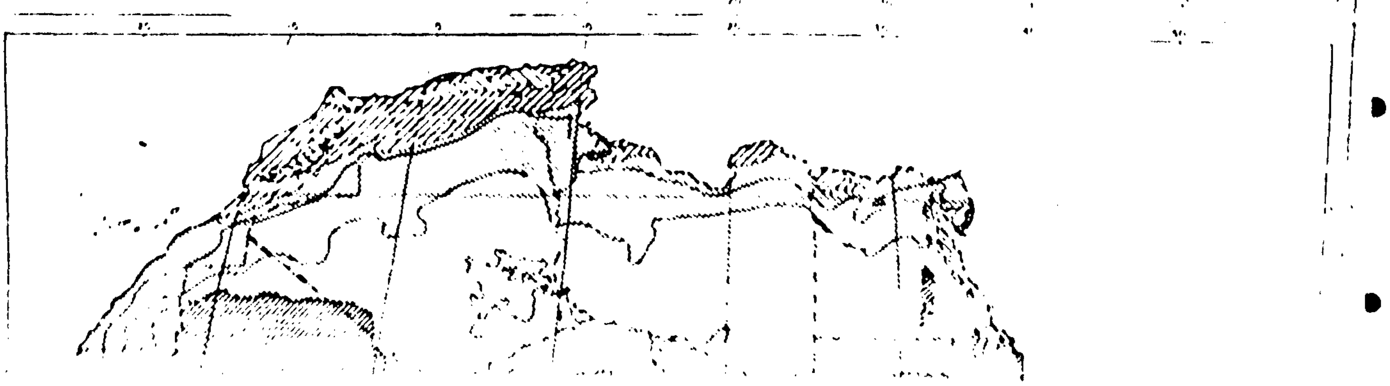
PLATE I

CLIMATIC MA

Sinusoidal Projection

By Douglas B. Carter Af th

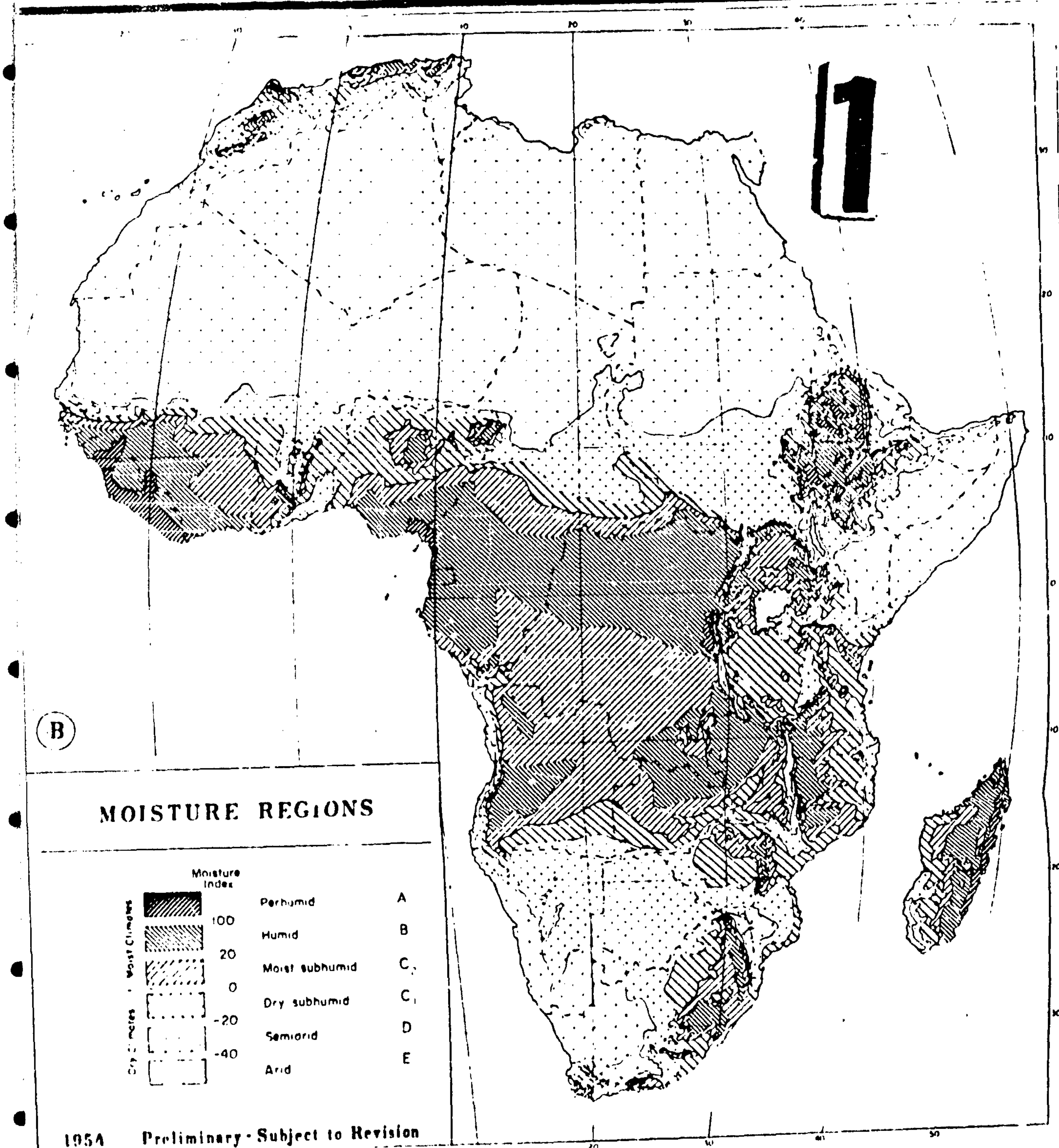


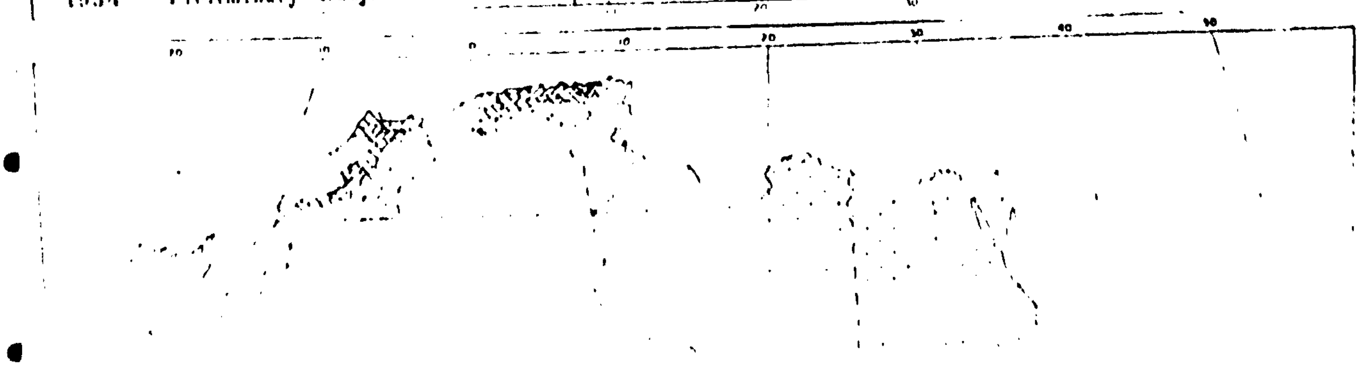


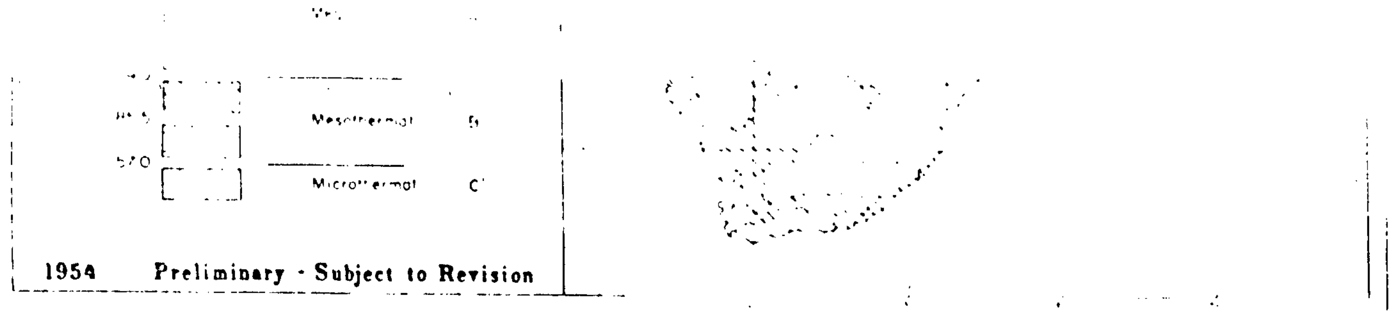
PS OF AFRICA

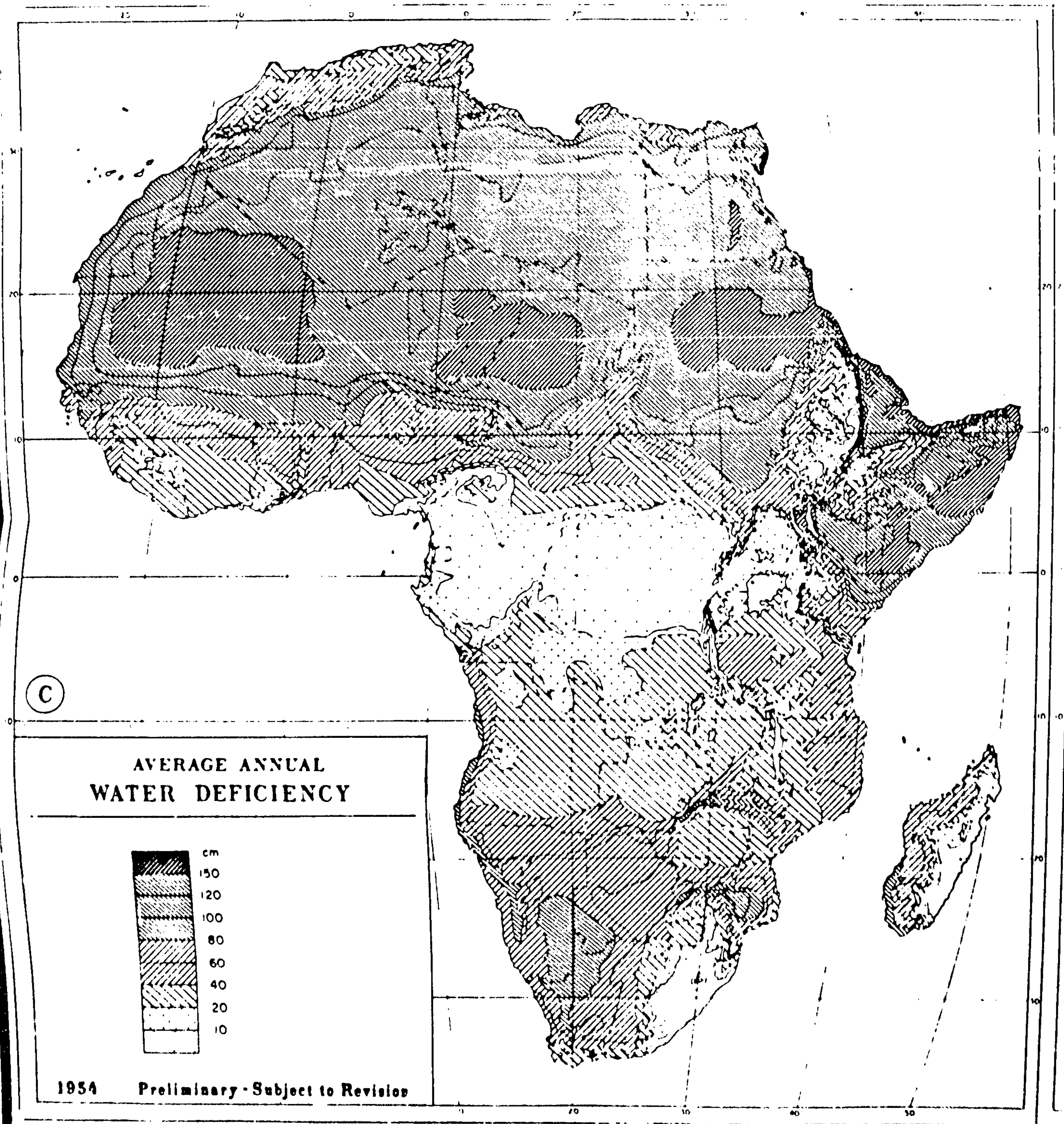
948 System of C.W. Thornthwaite

Drawn by K. Nishimoto





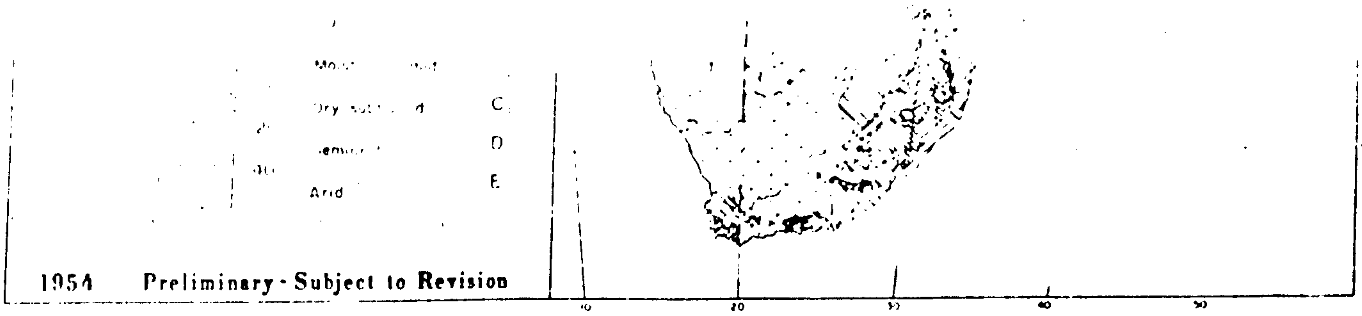


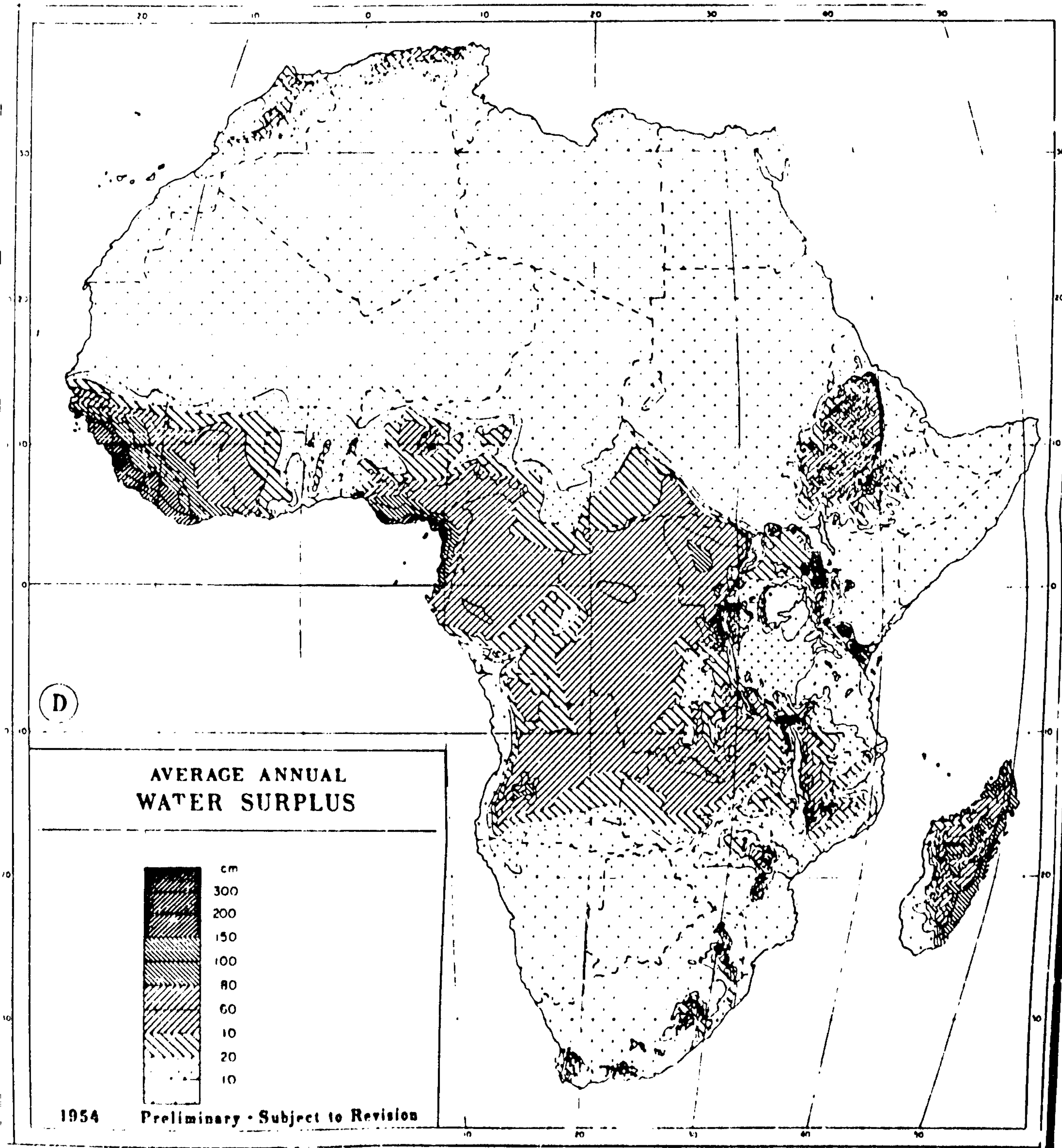


The Laboratory of Climatology, Centerton, N.J.

Scale 1:3(

0 400 800 Miles

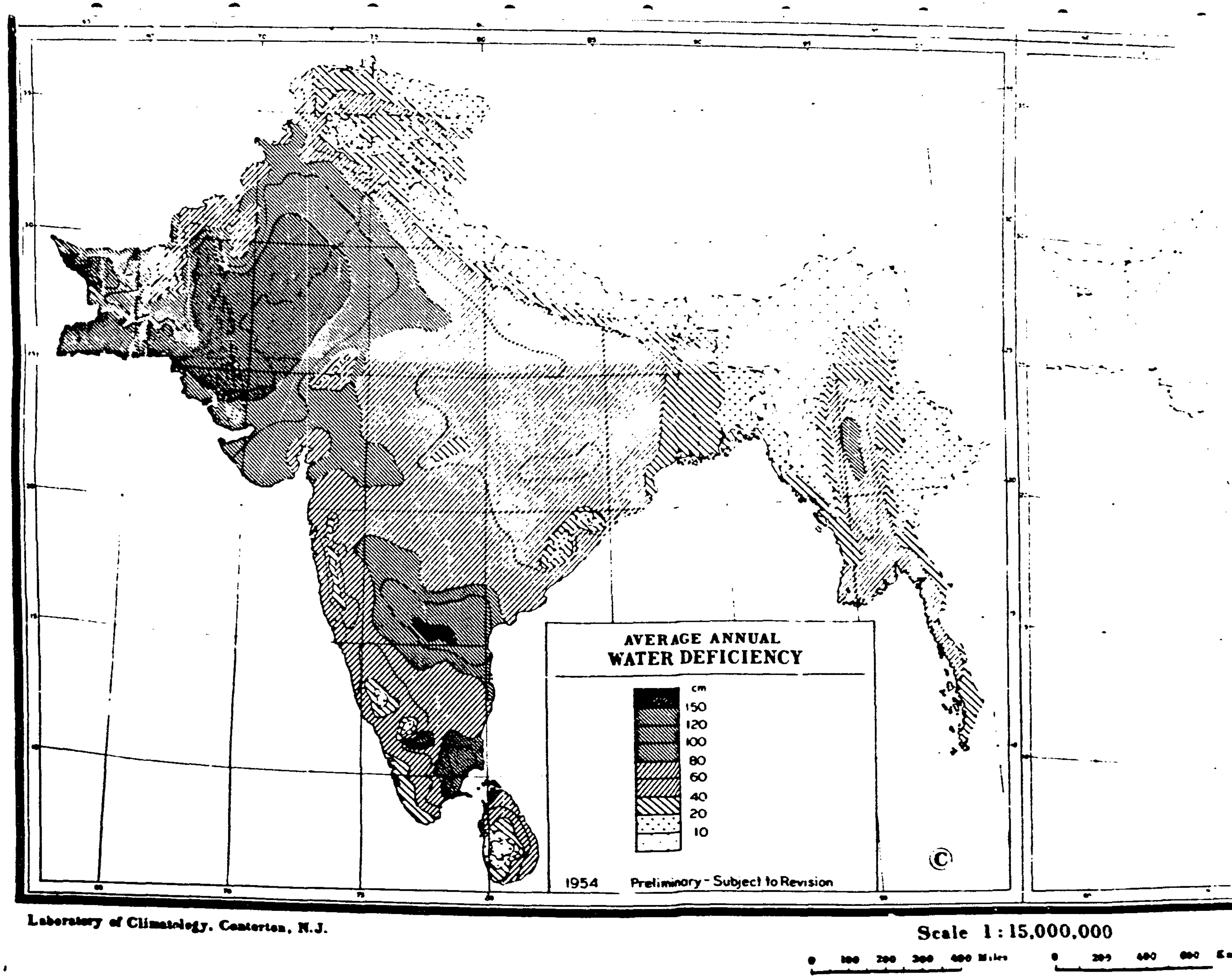




1:30,000,000

0 600 1200 Kms

Office of Naval Research Contract N R 389 091



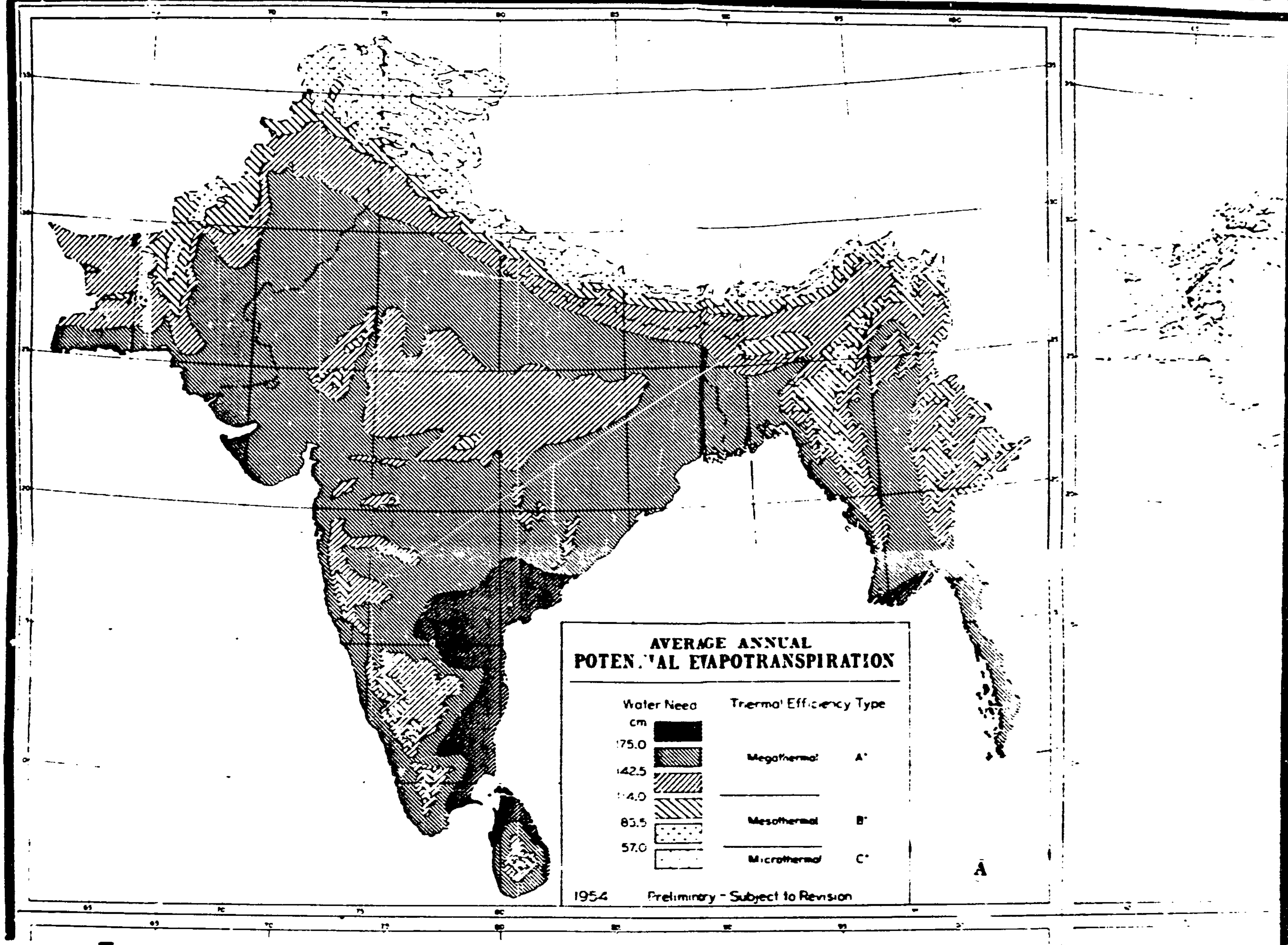
Laboratory of Climatology, Centerton, N.J.

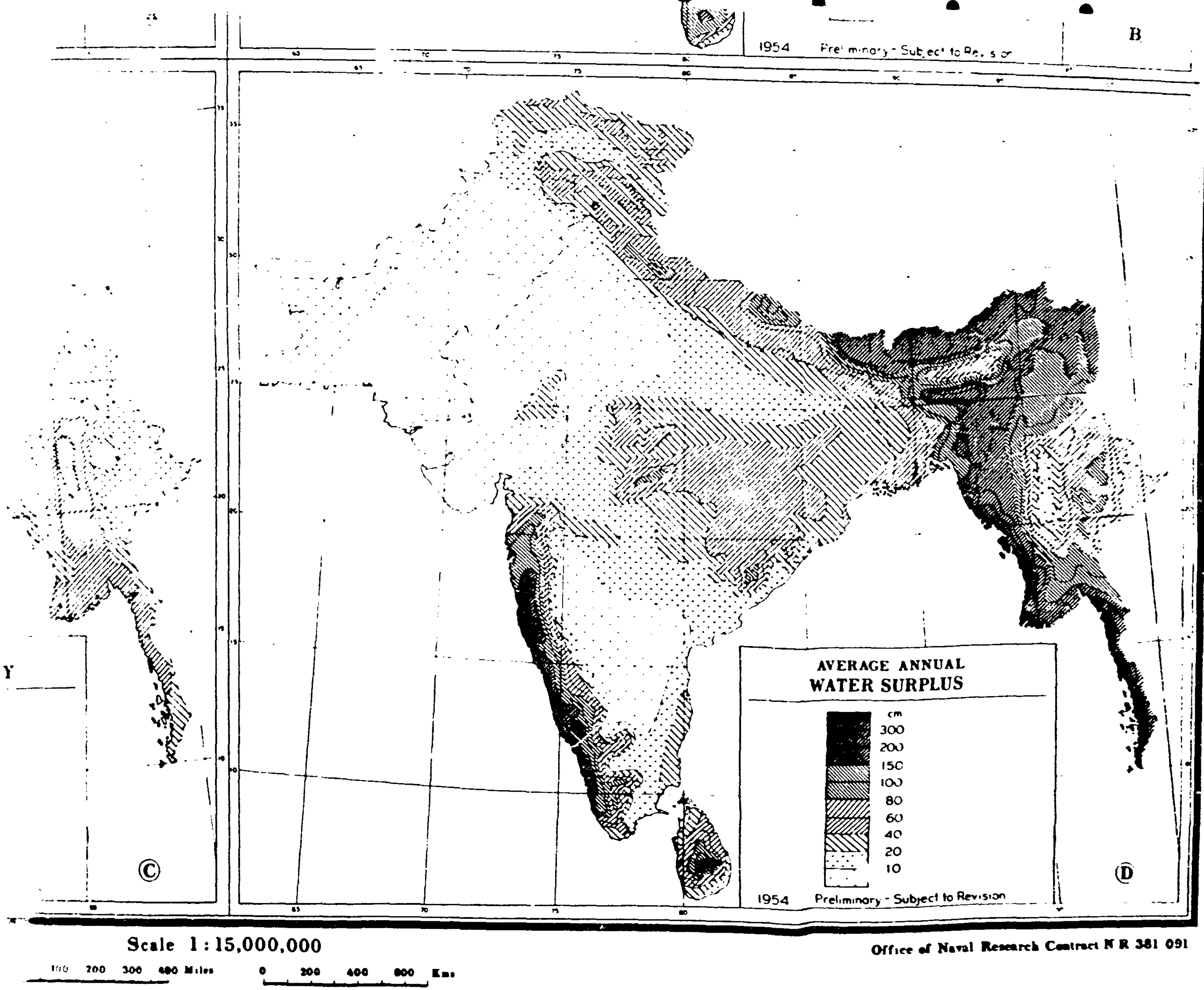
PLATE II

CLIMATIC MAPS OF INDIA

Conic Projection

By V.P. Subramanyam and Douglas B. Carter After the 1948



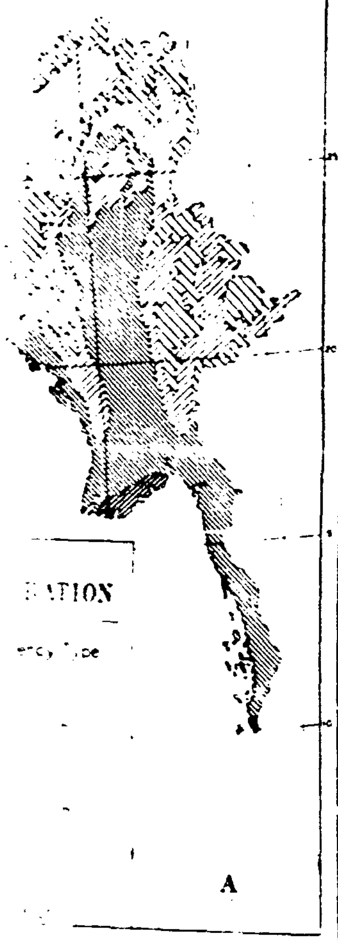


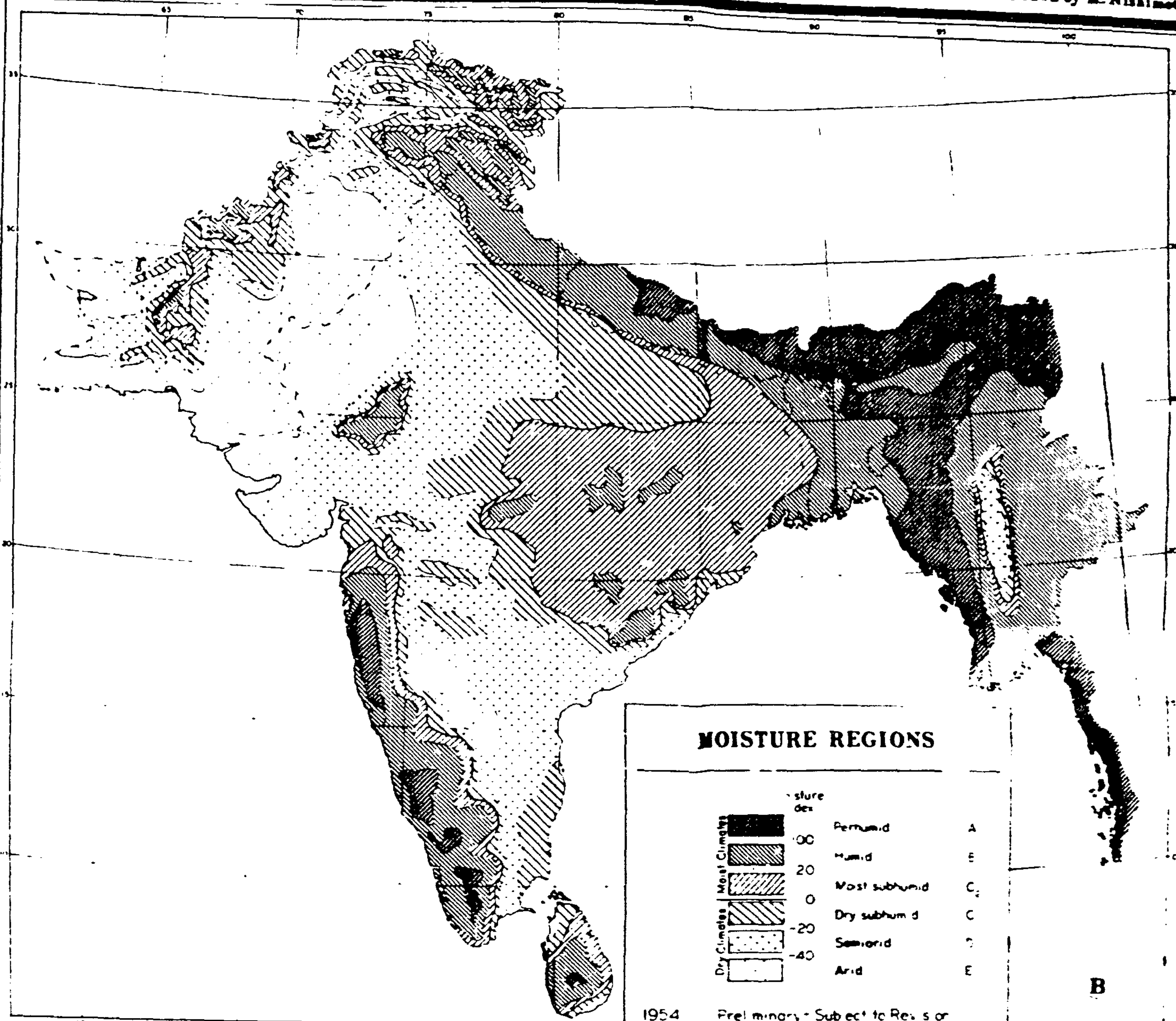
Office of Naval Research Contract N R 381 091

..PS OF INDIA AND VICINITY

..ouglas B. Carter   After the 1948 System of C.W. Thornthwaite

Drawn by K. Kishimoto





2