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Climatic Classification:

A Consultants' Meeting

14-16 April 1980

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics

ICRISAT Patancheru P.O.

Andhra Pradesh, India 502 324

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CONSULTANTS INVITED

TO THE MEETING ON CLIMATIC CLASSIFICATION

Mr. MICHEL FRERE is Senior Agrometeorologist in charge of the Crop Ecology Group of the Plant Production and Protection Division, Food and Agriculture Organization of the United Nations (via delle Terme di Caracalla, 00100 Rome, Italy). Mr. Frere is involved in the preparation of the report on agroecological zones covering the developing countries. He has also produced a simple method for agrometeorological crop monitoring and forecasting, which is currently used in some 20 countries. Mr. Frere maintains close cooperation with the Agricultural Division of the World Meteorological Organization.

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Dr. V.M. MEHER-HOMJI is the Head of the Department of Plant-Geography and Bioclimatology at the Institut Francais (B.P. No. 33, Pondicherry 605 001, India). He is a Fellow of the Paleobotanical Society, Botanical Society, International Society of Tropical Ecology, National Institute of Ecology, and Societe de Biogeographie (Paris). Dr. Meher-Homji has participated in the preparation of maps of vegetation and environmental conditions of peninsular India, including bioclimates. He has carried out phytosociologioal and phytogeographical studies of the semi-arid zones of India, and has to his credit several publications on bioclimatic topics, including "The bioclimates of India and their analogue types in the world."

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FOREWORD

The semi-arid tropics (SAT), which are of primary interest to ICRISAT, are characterized by unpredictable rainfall, poor soils, and high evaporation. These areas are spread over a wide belt between 10° and 30° north and south of the equator around the world. Characterization of crop climate in the SAT is an essential prerequisite in developing improved and economically viable farming systems. To this end, the agroclimatology subprogram at ICRISAT has been striving to develop an agronomically relevant classification of the climate to identify isoclimes for assisting in the transfer of technology. Two important questions that need a critical examination are:

What are the semi-arid tropics?
Where are the semi-arid tropics?

A review of the available literature on climatic classification by our agroclimatology subprogram showed that no single system can lend sufficient agronomic relevance to climatic classification. The current realization of the need to critically assess "agroclimatic resources" in the efforts devoted to classifying climates led us to the attempt to develop a satisfactory methodology that could be applied with the available data base.

It is with this background that we organized this consultants' meeting on climatic classification of the SAT. We are hopeful that the meeting will help us to define a strategy of our research in this important area. The papers presented herein should stimulate discussions in that direction.

J.C. Davies
Director for International Cooperation

CLIMATIC CLASSIFICATION: A CONSULTANTS' MEETING

ICRISAT, PATANCHERU, 14-16 APRIL 1980

Sitting (left to right) : V. M. Meher-Homji, A. T. Grove, G. D. V. Williams, S. Gadgil, J. S. Kanwar, M. Frere, R. P. Sarker, A. Krishnan, S. Venkataraman, S. M. Virmani

Standing (left to right): J. M. Peacock, S. J. Reddy, K. S. Gill, B. C. Biswas, K. L. Sahrawat, A. K. S. Huda, J. Hari Krishna, M. V. K. Sivakumar, R. K. Bansal

WELCOME ADDRESS

L.D. Swindale*

*Dr. Swindale is Director General of ICRISAT.

I welcome you all to ICRISAT; it is a pleasure to have you here. We would like you to see what is going on at ICRISAT in the field because, as I will stress later, our research is very much field-oriented. ICRISAT is now nearly 8 years old. I have been asked to give you some background of the institute, but I know that is going to be done more completely by our colleagues in Visitors' Services. So I shall concentrate on what we are interested in accomplishing in agroclimatology.

The objectives of the institute—what we call its mandate—are:

- to serve as a world center for the genetic improvement of sorghum, pearl millet, pigeonpea, chickpea, and groundnut;
- to develop farming systems that will help to increase and stabilize agricultural production through more effective use of natural and human resources in the seasonally dry semi-arid tropics;
- to identify socioeconomic and other constraints to agricultural development in the semi-arid tropics and to evaluate alternative means of alleviating them through technological and institutional changes; and
- to assist national and regional research programs through cooperation and to contribute further by sponsoring conferences, operating international training programs, and assisting in the extension activities.

Sorghum, pearl millet, pigeonpea, chickpea, and groundnut are the five crops that come within the mandate of ICRISAT and for which we have major crop improvement programs. In addition, we work on improving farming systems, including land-preparation techniques and water and crop management, implements, and sources of power—all combined—keeping in mind the resources that are likely to be available to the farmer in this region of the world.

In the semi-arid tropics, for a part of the year rainfall does indeed exceed both actual and potential evapotranspiration and water is in surplus. We should try to make the best possible use of that water at other times of the year. This possibility figures very largely in the nature of the improved cropping systems that we are trying to develop.

The map of the semi-arid tropics, as defined by ICRISAT using Troll's classification, covers a very large area of the world, with some 600 million people living within its boundaries. Much of the world's total production of the five ICRISAT crops is produced and consumed as human food in the semi-arid tropics. These crops are low in cash value. They tend to be grown under rainfed conditions, and the yields *are* highly unstable. They are least researched in the developed countries; because of their subsistence nature, they are ignored even in the countries where they are grown. The fertilizer-responsive genes that have pushed up the yields of rice and wheat have yet to be discovered for these crops, particularly pulses and groundnut.

There is, however, considerable potential for their improvement. In ICRISAT experiments, yields three to four times greater than the average yields have been obtained under rainfed conditions. The Governing Board of ICRISAT is convinced that farming by improved technology is the key to the improvement of farmers' welfare in the semi-arid tropics and to enable them to contribute to a larger degree of food production in the world.

Now what would be the role of agroclimatology in helping the farmers and in helping ICRISAT to achieve its mandate? To me it would appear that there are two major parts or themes: first, to assess the climatic risks associated with various improved farming systems at a particular location, or, conversely, to decide on the best farming systems that may be followed or could be associated with certain climates; and second, to assist in stratifying the environment, particularly the climatic environment, for purposes of technology transfer, especially with regard to improved farming systems. For both themes I believe that field research and hypothesis-testing must be part of the program. It does not seem to me that there is much research on climate that includes empirical and experimental research. We ourselves have only one example of something accomplished: I believe that we have assessed fairly well the climatic risks associated with the improved farming systems for deep Vertisols in the semi-arid tropics. Obviously no one institute will have the resources to test all of these things at one time. The All India Coordinated Research Project for Dryland Agriculture is working on proposing new cropping systems for certain climatic regions and has issued a book entitled "Improved Agronomic Practices for Dryland Crops in India." I don't know to what extent they have actually tested the success of these recommendations at the locations.

The climate of two regions is often said to be the same; how well that fact can be used to transfer a particular type of agricultural technology is not tested very often. It is not sufficient to say that the natural vegetation in the two places is the same, because in agricultural systems you remove natural vegetation and manipulate the remaining resources. When you do that, you may reveal great diversities in farming systems.

Before I finish I wish to speak of a project dealing with soil classification where classification goes hand in hand with testing of hypotheses so that one can transfer the technology if the classification is developed properly. The soil taxonomy adopted by the Soil Survey of the US Soil Conservation Service has six basic levels of classification—soil orders, suborders, groups, subgroups, families, and series. The soil family is the heart of the taxonomy and the key to the whole system; the soils grouped together at this level require similar management for agricultural and engineering purposes. The Benchmark Soils Projects of the University of Hawaii and University of Puerto Rico have tested the hypothesis that soils in a single family have similar management problems, similar potentials. For example, the soils in one family that occur in Hawaii also occur in Indonesia, the Philippines, Rwanda, Burundi, the Canary Islands, and in various other places around the world where recent volcanic activity has taken place. What you can grow on one of these soils in the family you should be able to grow on the others, and the problems of managing the crops should be somewhat similar. In order to test that hypothesis the Benchmark Soils Project has laid out a series of experimental plots using maize and soybeans as test crops. The curves of crop growth versus input-supplied production function appeared to come from one single group of curves, showing that the hypothesis was correct. This sort of empirical testing of a hypothesis by classification, and the examination of its relevance to agriculture is what the agroclimatologists should attempt so that what they do is relevant to the needs of the people of the semi-arid tropics.

We welcome you most heartily. We hope that you will be reasonably comfortable while you are here and that the conference will be most productive.

NEED, RELEVANCE, AND OBJECTIVES OF THE CONSULTANTS' MEETING ON CLIMATIC CLASSIFICATION

S.M. Virmani*

*Dr. Virmani is Principal Agroclimatologist in the Farming Systems Research Program at ICRISAT.

Climatic classification has been primarily the domain of plant geographers. It is only very recently that some inroads have been made by statistical mathematicians and meteorologists in attempting quantitative classification. Several climate classifications exist. The users of climate classification information are from all walks of life, because climate and weather affect all human activities. For this meeting, however, we will consider climatic classification in relation to agricultural development and planning.

Let me talk about some basic questions that we should discuss over the two days of our meeting.

Why Classify?

I think there are two basic functions of climate classification. First, to identify, organize, and name climatic types in an orderly fashion and stimulate the revelation and formulation of relationships within the climatic population. Second, to serve as a base for the application of technology, for the interpretation of resources as classified and delineated on soil-climatic maps, and for the transfer of experience.

Let me quote Cline, who wrote about 30 years ago, on some basic principles of soil classification, which apply to climate classification as well: (1) "Classification should deal with the knowledge existing at the time. As knowledge changes, the classification must also change." (2) "Classification is a creation of man for a specific purpose and the classification should be designed to serve that purpose." (3) "Classification consists of creating classes by grouping objects on the basis of their common properties."

Thus, we classify to identify and often locate geographically entities that are similar in properties or performance, and that can be recognized as being different from or unlike other entities in some important ways.

HIERARCHIAL ARRAY OF CHARACTERS

To be useful, the classification must embrace all the "climates" that are known. The system should be multicategoric, with a few categories in the higher orders and many in the lower. Such an arrangement would permit comprehension of climatic information by classes at different levels of generalization and provide for an orderly scheme. It would provide a basis for the design of cartographic units for climatic maps of different scales and degrees of detail.

Climatic elements useful in characterization for classification recognize a hierarchial array of characteristics under the primary elements: thermal energy (measured as temperature) and moisture (measured as precipitation).

Philosophic Problem of Reducing Continua

These primary elements exhibit continuous variation in time and space; some of these are more or less regular—for example, temperature--and some have to be treated stochastically, for example, precipitation. The "climate" is a collection of contiguous "climates," all of which have characteristics lying within the defined limits. An infinity of combinations of primary and secondary climatic elements can, in principle, be created by factorial combination. Thus there is the philosophic problem of reducing continua to a finite number of discrete units (or classes). The global climatic classifications are primarily conceptual. So there is bound to be inherent artificiality of boundaries.

The Question of Scale

In the light of the above, the basic question of scale arises in agroclimatological applications. Three levels of scale are generally recognized. First, local or experimental; second, regional; and third, national or global. The data source and the approaches used will be different for studies at these three scales. Studies on a regional scale usually require an extensive data source and computer facilities, while studies related to a local or experimental scale require in-depth empirical data.

While discussing the problem of scale and application of agroclimatic classification for agricultural research and development, I would like to bring to your notice the question of assessment of land for agricultural potential . This is one of the primary uses of information on climatic classification. It is based on the information on soils and climate. Since within a "climatic type" several "soil types" are likely to occur, any consideration of land-use potential based on climatic parameters alone is not likely to be meaningful.

Let me briefly point out the relevance of climatic classification for ICRISAT.

GLOBAL COVERAGE AND FEATURES OF THE SEMI-ARID TROPICS (SAT)

A large area covering 10° to 30° latitude in both the hemispheres, between the tropical rainforests and deserts, is generally termed semi-arid tropical. It has an alternating wet and dry climate. This belt broadly covers 49 countries around the globe and is inhabited by about 600 million people. The soils are low in organic matter and fertility. The rainfall is low, variable, and undependable. Lack of moisture is the key limiting factor to stabilized and improved agriculture in these regions. The farmers in these areas through centuries of experience know that crop yields are a gamble. They and others who depend upon them pray for better and more uniform weather. Some years their prayers are heard; in others, ignored.

Resource-oriented and Location-specific Technology

It is in this setting that the farming systems research program of ICRISAT has been launched to produce a technology that will help increase and stabilize the agricultural production of this region. It has three major goals:

- to aid the generation of technology
- to assist in development of technology for improving land and water management, and
- to assist in raising the economic status and quality of life for the people of the semi-arid tropics.

ICRISAT has developed a watershed-management and resource-oriented technology. The last 7 years' research has conclusively shown that crop yields can be stabilized at much higher levels than those currently realized by farmers. Grain yields varying from 4000 to 7000 kg/ha have been harvested from deep Vertisol areas.

But the technology is location specific. The semi-arid tropics have variable spatial distribution of the natural endowments. Thus there exists a strong element of location specificity in terms of moisture environment during the crop-growing season. These areas, therefore, pose a unique set of circumstances to those involved in the programs of agricultural development.

We at ICRISAT are therefore interested not only in questions related to where and what the semi-arid tropics are but also in assessment and quantification of their climatic resources.

ORIGIN AND SCOPE OF THE MEETING

In 1978, we wrote a small report on approaches used in classifying dry climates. It was sent to 30 scientists located around the world and well known in the field of agroclimatological research and applications. This meeting was organized based on their replies.

Objectives of the Meeting

In view of the foregoing, the meeting has been convened to deal with and formulate guidelines for the following objectives:

- To review the present state of knowledge regarding ecoclimatic classification, with emphasis on agronomic relevance, and to identify gaps in research.
- To understand the present methodologies in the classification of climate.
- To evolve a future plan of action involving the identification of priority areas of research and formulation of hypotheses for each area, and
- To establish a network of research institutes that will produce ideas, collaborative work, and research results that can be disseminated.

CLIMATIC CLASSIFICATION:
CONCEPTS FOR DRY TROPICAL ENVIRONMENTS

A.T. Grove*

SUMMARY

Two approaches to climatic classification - divisive and agglomerative - are possible. Among the divisive classification systems, those of Koppen and Thornthwaite are discussed in relation to their applicability to the tropics. Spatial and temporal variations in rainfall need to be considered. With the recent advances in electronic computers, the agglomerative kinds of classification appear to be promising. In applying climatic classification systems to crop planning, use of satellite imagery should be useful.

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Classifications, if they are to be useful, should be widely understood and accepted. One of their main functions is to allow a single descriptive term to encompass a large number of individual cases. In an environmental context this may allow areas to be characterized and boundaries to be drawn around contiguous areas that can be regarded as homogenous in certain respects. The term *region* is often applied to such mappable units.

Classifying plants and animals that breed and multiply is somewhat easier than classifying phenomena like soils and climate that form continua varying in time and space. Two approaches are possible, which we can distinguish as *divisive* and *agglomerative.*

In discussing approaches used in classifying climates, Virmani et al. (1978) have summarized several classifications. Among the divisive kind, Koppen's (1936) is one of the earliest and best known. In selecting the values defining the boundaries of his climatic regions he adopted de Candolle's (1874) vegetation classification, and the correspondence between the vegetation and climatic regions is remarkably good. Such a classification, like that of de Martonne (1957), has the advantage of simplicity, availability of data, and widespread acceptance. It allows maps to be made distinguishing the climatic regions on a global, continental, or subcontinental scale.

A more elaborate classification devised by Thornthwaite (1948) concentrates more deliberately on the climatic factors that affect plant growth through the growing season. It recognizes that whereas temperature is critical in high latitudes, availability of moisture is the controlling factor in low latitudes. It relates available rainfall to potential evapotranspiration by means of the moisture index, assumes a certain soil storage capacity, and allows one to trace the availability of water for plants from month to month through an individual or an average year.

Conceived in the United States of America, Thornthwaite's classification has been applied very widely. Carter (1954) classified the climates of Africa and India accordingly, using a limited number of stations, and Krishnan (1968) produced a more detailed map, using not only records from meteorological stations, but also from provincial rain gauges. The best-known and most widely accepted classification of the dry climates, that prepared by Meigs (1953) in connection with the arid zone program of UNESCO, is based on Thornthwaite.

Certain defects appear when Thornthwaite's classification is applied to the tropics. His values for potential evapotranspiration were developed from the relationship between temperature and water losses from moist, vegetative surfaces in the USA. These values have been found to underrate water losses in the tropics, where dry seasons are commonly more intense than in North America. The expression used for calculating potential evapotranspiration can be modified accordingly. The figure Thornthwaite adopted for soil water storage was 100 mm, but values as high as 400 mm are believed to be more appropriate for some soils.

In the review of climate in relation to desertification that he prepared for the U.N. Desertification Conference held in Nairobi in 1977, Hare (1977, pp.71 and 118-120) preferred to use Budyko's (1974) radiational index of dryness in defining the arid zone and its subdivisions. Here the dryness ratio, D, is derived from the mean annual net radiation at a location divided by the heat energy required to evaporate the precipitation falling at that location:

$$D = R/LP$$

D = Budyko's dryness ratio
R = radiation balance
P = mean annual precipitation
L = latent heat of vaporization

In dry areas the ratio is comparatively high, with semi-desert falling between 2 and 3. The classification has the defect that it is troublesome to calculate the radiation balance, notably because it is necessary to adopt values for albedo. In any case, as Hare demonstrates, the correspondence in the tropics between the isolines of Budyko, Thornthwaite, and Meigs is good, so there would not seem to be any particular advantage in using Budyko's approach.

In fact it seems doubtful to me whether it is worth attempting to refine classifications of climate very much further unless one has rather specific targets in view. One recognizes that, especially in the tropics, even rainfall observations are specific to the particular place where they are made; I understand that even within the ICRISAT domain annual totals recorded vary markedly from 1 rain gauge to another. Admittedly, over a long period of years the spatial variations in means will diminish, but the fact remains that climates do vary over quite short distances according to topographic and other conditions of which it is not always easy to take account.

More important than spatial inconsistency is the variability of climate from year to year. According to Virmani et al. (1978a), Hargreaves (1971) recognizes this as a problem, and his classification compares potential evapotranspiration with the 75% probability of precipitation. However much one attempts to take into account rainfall variability, the problem will remain that such variability is not random and properly speaking cannot be treated as such. There are persistence effects; dry years and still more, dry months, tend to be clustered together in time series. Steps occur that result in the mean values for 1 run of years sometimes differing markedly from the means of a succeeding run. Longterm trends are very seldom distinguishable. Regular periodicities are less rare but not sufficiently well established to allow prediction.

It can well be argued that for special purposes variables additional to temperature and precipitation should be employed in distinguishing and characterizing climates. It would seem likely that this can best be done by turning to agglomerative kinds of classifications that can be readily used if electronic computers are available. I cannot claim any expertise in these matters and I see that according to the program, Mrs. Gadgil is to discuss the use of principal component analysis. I will merely point to papers that have been written by 2 scientists at Australia's Council of Scientific and Industrial Research Organization, Russell and Moore (1970 and 1976). They point to the possibility of using computer methods such as similarity coefficients, grouping procedures, sequential analyses, as well as principal coordinates analysis, for detecting homoclimates or isoclimates. They have analyzed the pattern of data from 300 stations in Africa and Australia (the number they could use was limited by computer capacity), taking 16 climatic attributes on a monthly basis, giving 192 attributes per station. Analyses based on the whole year, on the summer, and on the winter allowed them to produce dendrograms and to group stations into 20, 30, and 40 sets. The stations within each set fall within a few regions that can be mapped. Once the data have been assembled and stored one clearly has a very adaptable tool available for drawing up classifications to suit particular purposes. One can decide to include, exclude, or weight individual attributes and produce maps for individual years or sets of years.

The problem remains of relating the growth history of particular crops and strains of crops to the sequence of weather events in a particular year, or the average year (however that is defined). Bishnoi's (1977) paper on crop-weather models for Sikar is interesting in this respect. He has compared the performance of 4 different crops in the course of 4 particular years with the weekly values of the climatic elements. In calculating water availability he has used Penman's formula (1948) rather than Thornthwaite's, and as it happens the years he has chosen, 1970-73, cover a wide range of climatic conditions. I would suspect that the kinds of data he has handled could be computerized in such a way as to obtain a display or printout similar to his useful diagrams.

I realize that I am wandering away from the subject of climatic classification and I will wander a little further, in the hope that my diversions may stimulate some discussion of unorthodox procedures that may eventually be productive. Writing to Dr. Virmani last year, I speculated on the possibility of bringing together climatic data, cropping data, and satellite imagery.

Satellite pictures are normally produced from data that have been transmitted from sensors on satellites and recorded on tapes. From the tapes the pictures are made on scales of between 1:1 m and 1:0.25 m, that is 1 mm:l km and 4 mm:l km. Such pictures taken in the growing season are likely to be obscured by cloud, and there may be other difficulties.

Many of the pictures used today employ "false colors," the images sensed at different wavelengths being printed in different colors selected to bring out features of interest being studied by the specialist involved. In some cases, of course, such a specialist may be an agronomist, and the pictures he uses may provide information about the distribution and health of particular crops. What I have in mind is the possibility of using satellite imagery and the false color principle for portraying climatic data. One can readily imagine the kind of picture that might result from printing precipitation in shades of blue on top of potential evapotranspiration in shades of yellow. The color patterns that emerge might be compared with the performance or the percentage area occupied by specific crops.

I am making the point that the visual perception of climatic variation from 1 area to another is important. If classifications of climate become too elaborate and difficult for the nonspecialist to understand and appreciate they are not of much value. I am inclined to think that at least as much attention must be paid to the question of presentation of the results in a way that is visually attractive and informative as to the further refinement of analytical techniques.

CLASSIFICATION OF THE SEMI-ARID TROPICS: CLIMATIC AND PHYTOGEOGRAPHIC APPROACHES

V.M. Meher-Homji*

SUMMARY

The arid and the semi-arid zones of India merit classification within the tropics because the term subtropical is unsuitable from the point of view of vegetation. The climatic and phytogeogr'aphic approaches are reviewed for their suitability to assess the degrees of aridity and semi-aridity.

This paper also highlights the variability in the amount of rainfall, its duration, and seasonal distribution, and points out the need to delineate a probable year rather than an average year, taking into consideration the instability of the climates of the dry belts. The natural vegetation that expresses the variability of the climate provides convenient guidelines for delimiting the arid, serm'-arid, and marginal subdry zones. In the last category, it is mainly through excessive anthropogenic interference that the terrain becomes drought-prone. Those areas of peninsular India having good forest formation or those containing teak or sal forest may be excluded from the arid or the semi-arid category; a probable exception may be the **Acacia-Anogeissus pendula** *forests of the Aravallis, but these are, in fact low or open formation.*

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TROPICAL VERSUS SUBTROPICAL LOCATION OF THE DRY ZONES

In order to delimit the semi-arid tropics, we must first define the tropics and then the semi-arid areas within the tropical belt.

As the deserts of the world are generally concentrated in the geographic latitudes of the subtropics,there is a tendency to associate the arid zones with the subtropical climates. Evidently this association is not wholly correct, as Hyderabad (Pakistan) and Cherrapunji, located on the same 25°N parallel, witness extremes of rainfall.

The term subtropics has been defined climatically as areas with temperatures and precipitation generally lower than those in the tropics or having rains in seasons inverse to those of the tropics. Vegetationally, the subtropics have been equated with deserts, with areas having mediterranean types of scrubs, or even with the medium elevation of tropical hills. In terms of flora, the diversity is marked, and no typical family or even genera can characterize the subtropical geographic zone.

Champion and Seth (1968) created the subtropical forest category as a transitional step to pass from the tropical to temperate types of India. They based the limits of the subtropical climate on temperature: mean annual value 17° to 24°C, January mean being 10° to 18°C.

Vegetation that could perhaps pass as subtropical in India purely on account of its extra-tropical geographic location is in arid and semi-arid zones; the *Anogeissus pendula* Edgew. forest of eastern Rajasthan and Bundelkhand is the case in point for the semi-arid zone, and the northern tropical desert thorn forest for the arid zone.

The *Anogeissus pendula* forest type is assigned "tropical deciduous Edaphic" status by Champion (1936). The Edaphic appendage may be questioned as there is no peculiar soil factor controlling this type. The tropical designation may be defended by the temperature figures of the meteorological stations within the *A. pendula* tract. The data monitored at the forest sites by thermographs would probably reveal figures different from those obtained from the observatories located in the towns. However, the most salient fact is that in spite of its restricted occurrence in the subtropical latitude, almost all the species associated with *A. pendula* occur further south in the tropical deciduous forests of peninsular India.

The other probable candidate for latitudinal subtropicality is the northern tropical desert thorn forest of Champion, but once again its main constituents like *Pvosopis cineraria* (L.) Druce, *Capparis decidua* (Forsk.) Pax, and *zizyphus* spp. among others also occur on the Deccan plateau.

Thus from the point of view of vegetation, indications are that all the dry regions, arid or semi-arid, within the Indian territory merit classification within the tropical framework.

CLIMATIC CRITERIA OF ARIDITY AND SEMI-ARIDITY

To assess the degrees of aridity-humidity, we have on one hand climatic parameters and on the other plant criteria. Each has its merits and demerits. The latter (i.e., vegetational features) however, are in many cases so much disturbed or altered by man that a careful interpretation becomes necessary so that the plant indicators can be judiciously used.

The word aridity expresses a deficiency of water resulting from either insufficient precipitation or from excess of water loss as compared to the water supply. The aridity of a region increases in inverse proportion to rainfall, and so different limits of precipitation have been suggested to define the arid and semi-arid regions. However, these limits expressed in annual average precipitation vary from country to country and from author to author.

Aridity Based on Precipitation and Temperature

Under these criteria may be mentioned the systems of Koppen (1918, 1936), Lang (1920), de Martonne (1926), Emberger (1930), and Shanbhag (1956).

Aridity Based on Precipitation and Evaporation

Formulae of Transeau (1905), Meyer (1926), Thornthwaite (1933, 1948), Capot-Rey (1951), and Bharucha and Shanbhag (1957) need mention in this category.

Aridity Based on Precipitation and Relative Humidity

Mangenot's (1951) contribution for tropical Africa may be listed here.

Aridity Based on Number of Dry Days

Reference may be made to the works of Stefanoff (1930), Thomas (1932), Walter (cf. Moreau 1938), Aubreville (1949), and Bagnouls and Gaussen (1953).

However, application of the above-mentioned formulae to 78 representative stations of the Indian subcontinent has shown that none of these formulae give perfectly satisfactory results in classifying all the stations according to their vegetation types (Meher-Homji 1962).

Aridity Based on the Precipitation-Evapotranspiration Ratio

There has been recent trend in the use of this ratio as a measuring tool. UNESCO (1979) and Chowdhury and Sarwade (1980) have used Penman's formula of evapotranspiration, whereas Virmani et al. (1978a) have considered Troll's formula as well as that of Penman.

Degrees of Aridity

Several degrees of aridity may be recognized. The extremely arid zones are the ones not experiencing any rain for more than a year at a stretch. Only a very small portion of the extreme western Rajasthan belongs to this category. In other cases there may be a few sporadic showers but of *very* low intensity and duration so that in all 12 months in a year no month may be characterized as humid. Subsequent degrees of decreasing aridity may be recognized on the basis of the number of dry months. Defining a dry month in terms of rainfall poses several problems; the definition of Bagnouls and Gaussen (1953), though empirical, is shown to be of practical use (Meher-Homji 1963,1965 b) The length of the dry period in itself does not convey a true picture of one aridity, and the amount of precipitation must also be taken into consideration. A station, such as Bombay, receiving 2000 mm of rainfall annually has a dry season of 8 months; but Mysore having a dry season of 4 months may have an annual average rainfall of 800 mm.

Therefore in my index of aridity-humidity (1962, 1965a), I proposed a combination of the value of the "precipitation quantity" factor with that of the length of the dry period. The stations having the index values 8.5 to 10.5 characterize the semi-arid zones and correspond to the thorn forest. Index values of 11 to 12 correspond to desert vegetation typifying the arid zones. According to this classification, there are 2 main belts of semi-arid climates in India, 1 in the north contiguous with the desert of Thar and the other in the south (Fig.1). The northern zone lies between 22 and 32° N and between 70 and 79° E, comprising parts of Rajasthan, Punjab, Uttar Pradesh, Madhya Pradesh, and northwest Gujarat. The southern semi-arid zone, situated between 15 and 21° N and 73.5° and 79.5° E, includes the Deccan plateau. Besides, there are 2 small patches of semi-arid climate in the south; one in the region of Coimbatore situated in the shadow of the Nilgiri and the Palni hills, the other in the extreme southeast corner of India comprising parts of the Ramananthapuram-Tirunelveli districts of Tamil Nadu. The semi-arid regions of north and south are separated by a narrow humid strip comprising the hilly region of the Stapura Mountains and the plain of the Tapti River.

The arid climate occurs in the extreme northwest corner of Rajasthan and in Pakistan. These limits of arid and semi-arid climates tally well with the results given by Bagnouls and Gaussen's 1957 classification of biological climates (Meher-Homji 1967).

Another approach that I followed (1972) to define the arid regions is to apply the climatic formulae of several authors (discussed in Meher-Homji 1967). The stations that were considered to be arid, according to the formulae of all authors for each year, were classified as *iruly arid.* A lower degree of aridity may be assigned to stations that turned out arid on the average based on these formulae, although all the years did not fall into the arid category. Further degrees may be recognized on the basis of the number of formulae classifying the stations as arid, semi-arid, or subhumid. Finally, the climatic regimes (the season of occurrence of rain)[1] may vary for the stations having the same degree of aridity.

Stability of Climate

From the above paragraph, it can be seen that the climatic data are subject to

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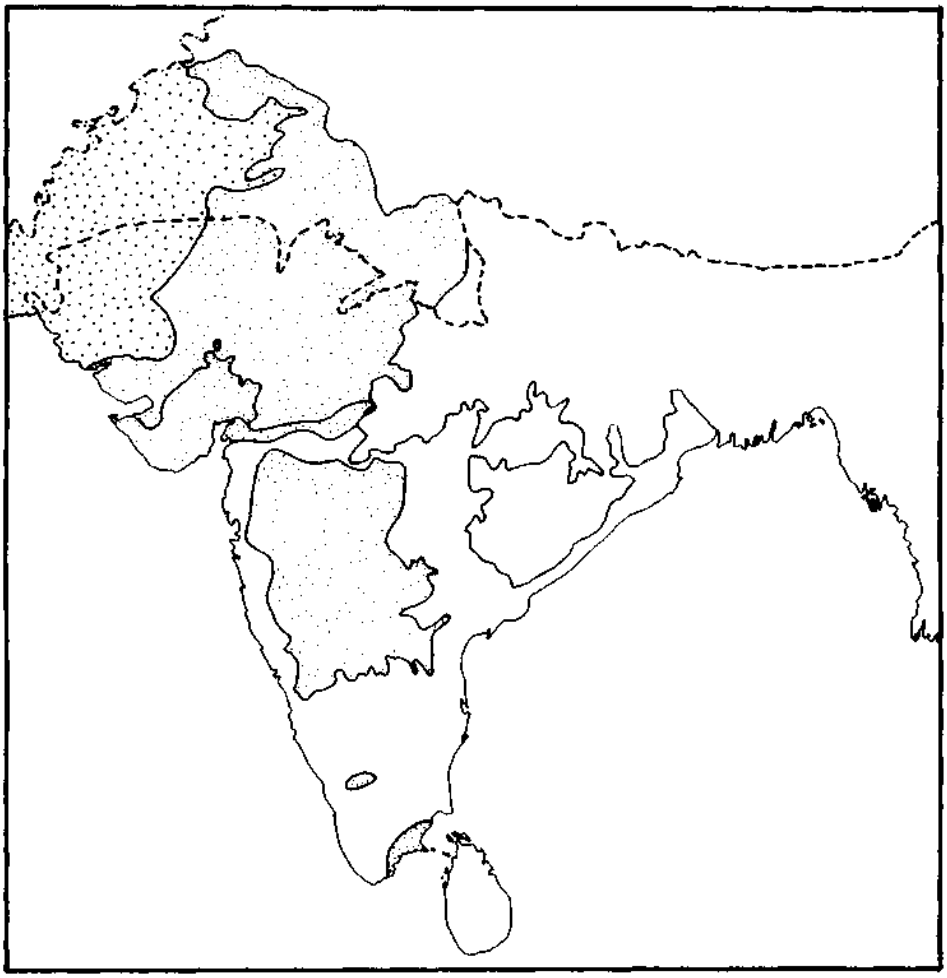
1. The regime based on the season of occurrence of rains is either of tropical, mediterranean, bixeric, or irregular type. In the tropical regime rains are concentrated in summer, and in winter-spring in the mediterranean regime. The bixeric type is characterized by 2 dry periods and 2 rainy seasons in a year. The remaining type, without seasonal rhythm, is termed irregular.



Arid regions with the values of the index (S + X) 11 to 12

Semi- orid with the values of the index (S+X) $8\frac{1}{2}$ to $10\frac{1}{2}$

Mean temperature of the coldest month 10°C

Mean temperature otthe coldest month 15°C

Mean temperature of the coldest month 20°C

Figure 1: Arid and semi-arid regions of the Indian subcontinent (from Meher- Homji 1965a).

strong interyearly fluctuations, especially in the dry zones (Meher-Homji 1971, 1972, 1973). There are variations not only in the amount of rainfall, but also in its duration and regimes. In 1972 I proposed the assessment of climate in terms of a probable year than in terms of an average year, as the latter tends to mask the bioclimatic phenomena.

The degree of climatic stability of 31 stations of the Indian sub-continent (Table 1) was established on the basis of the percentage of the number of years that tally with the probable year, the latter being defined as one during which the values of precipitation, rainy days, and dry months correspond to the figures of the mean value (plus or minus the standard deviation) and the regime is of the most common type(s). The more stable the climate, the higher the percentage of years tallying with the probable year. Only a few individual years agree with the probable year in the case of unstable climates. In Table 1, at one extreme lies Ahmedabad with 65% of the years conforming to the pattern of the probable year in all 4 factors. At the other extreme is Dera Ismail Khan, with only 8 years agreeing with the probable year, in which case neither the average year nor the probable year applies in view of the small number falling within the limits set by the probable type.

Table 1. Degree of stability of 31 stations of the Indian subcontinent (Meher-Homji 1974).

Station	Percentage No. of years tallying with probable year	Station	Percentage No. of years tallying with probable year
Ahmedabad	65	Gilgit	39*
Peshwar	60*	Dalbandin	39
Sriganganagar	60*	Bombay	38
Sibi	57*	Drosh	38*
Bannu	56*	Kalat	35
Las Bela	56*	Srinagar	33*
Parachinar	49*	Wana	33*
New Delhi	49*	Sukkur	33*
Rawalpindi	48*	Barmer	33*
Sialkot	47*	Lahore	32
Ambala	46*	Nokkundi	31*
Miranshah	44*	Coimbatore	30*
Fort Sandeman	44	Murree	28
Quetta	42	Chitradurga	20
Chaman	41	Dera Ismail Khan	8
Sholapur	40*		

*Probable regime of more than one type

Given the variability of the climatic factors, another logical approach would be to delimit the bioclimatic zones purely on the basis of the natural vegetation. The plant cover is a good indicator of the environmental conditions and also integrates the variability aspect of climate. Further, the regions, derived from vegetational criteria correspond to the various land units having a certain ecological uniformity and a particular degree of aridity.

THE PHYTOGEOGRAPHIC CRITERIA

These may be reviewed under the following heads: floristic, morpho-ecological or epharmonic, agronomic, and vegetational.

Floristic Criteria

The fact that there are certain species, if not genera and families, peculiar to the arid or the humid regions makes it possible to delineate these regions on a floristic basis. The characterization of floral elements as Sahara-Sindian implies arid conditions, while Sudano-Deccanian and Malayan refer to semi-arid and humid conditions, respectively. The relative percentage of different floral elements in the flora of a given region could also reflect its climatic conditions. The semi-arid zones of northern and southern India have been characterized on the basis of floristic elements (Bharucha and Meher-Homji 1965).

Floristic statistics such as the number of species per area have been used in combination with the climatic characters to give an indication of the bioclimatic degrees of aridity-humidity (Meher-Homji 1975).

Morpho-Ecological Criteria

These are manifested by the adaptations of plants to the climate. For example, the percentage of xerophytes tends to be highest in the dry regions and lowest in the perhumid. In the same way, the prevalence of certain types of growth forms or life forms is controlled by climate, as shown by Raunkiaer (1934). On the basis of his biological spectra, he proposed phanerophytic phytoclimate for the humid tropics, therophytic for the desert, and hemicryptophytic in the greater part of the cold temperate zone. I have traced (1964) the gradual evolution of the *phanerophytic* (tree) life form of the humid regions of India from the *therophytic* (annual growth form) of the arid regions and the *thero-chamaephytic* type of the semi-arid regions.

Agronomic Criteria

From the agronomic point of view, Meigs (1952) classes regions as arid where the quantity of rain is not sufficient for any type of cultivation. In the semi-arid regions, the precipitation is sufficient for certain dry types of crops only; further, grasses constitute an important element of the natural vegetation.

A somewhat different definition is given by Contreras Arias (cf. Whyte et al. 1959). In the semi-arid zone the cereal production is very irregular and 50% or more is lost each year due to lack of precipitation. In the arid zone, the crop cultivation is almost impossible without irrigation.

Vegetational Criteria

The flora of a region is an enumeration of species growing there. The vegetation of the region is the plant *cover* that clothes it. It is formed of species associated in diverse quantities and proportions to constitute the landscape. Whereas flora are the result of biological evolution and geological history, vegetational aspects are above all the expression of the prevailing ecological conditions. Similar climates induce the emergence of similar kinds of plant structure, in the physiognomic sense, in widely separated parts of the world. The climate strikes at the structure of the vegetation whatever its floristic composition. Based on physiognomy are recognized types of vegetation like rain forest, deciduous forest, thorn forest, steppe, savanna, etc.

The physiognomic aspect of the arid region is poor, scanty, xerophytic vegetation, widely dispersed, leaving large areas bare. The semi-arid regions comprise the steppe and the thorn-forest formations; whereas the steppe is the expression of the cold semi-arid climates, the thorn forest is the rule under hot but equally dry regions.

The following vegetation types of India may be listed under the category "arid" in its broadest sense in decreasing order of aridity: (1) *Calligonum polygonoides;* (2) *Prosopis cineraria, Capparis decidua, Zizyphus,* and *Salvadora;* (3) *Acacia* and *Capparis decidua;* (4) *Acacia Senegal* and *Anogeissuc pendula;* and (5) *Acacia catechu* and *Anogeissus, pendula.* The arid zone in the classical sense would include only the first 2 types, i.e., *Calligonum;* and *Prosopis, Capparis, Zizyphus,* and *Salvadora.* The type *Acacia-Capparis* would characterize the semi-arid zone of Rajasthan, northern Gujarat, and the Deccan. The *Acacia plani frons* type (the southern umbrella thorn forest of Champion 1936) and the *Acacia - Anogeissus, pendula* types of the Aravallis would also be included in the typical semi-arid class. Figure 2 shows the potential areas of the major vegetation types of India.

Some other types, Such as *Anogeissus, pendula* and *Anogeissuc latifolia, Albizia amara; A. amara* and *Anogeissuc, lati folia; Hardisickia binata* and *A. latifolia,* which do not include teak *(Tectona grandis* L,f.) and mostly fringe the semi-arid *Acacia - Capparis* Community, may be included under the marginally subdry category, as they grow under conditions less favorable than the subhumid belt where teak makes its appearance.

One may well question the placement of forests and other arborescent formations of these marginal types in the arid category. However, although the optimum physiognomic state that these types reach is a forest; under pressure of a high density of man and his domesticated animals, the woodlands often degenerate into thickets and savannas, and such formations are frequently subject to water stress (Meher-Homji 1977).

The destructive activities of man have their repercussions on the climate. For example, our latest study shows that large-scale deforestation results in declining precipitation. We measured the area of deforestation around 28 stations of western Karnataka by comparing the old Survey of India toposheets with recently revised maps. Wherever the extent of forest clearance exceeded 25% of the area within a radius of 16 km around a station, 7 to 11 criteria out of 12 of rainfall and rainy days revealed a waning tendency. Where the deforestation has been negligible, 3 or fewer criteria presented a decreasing trend (Meher-Homji 1980).

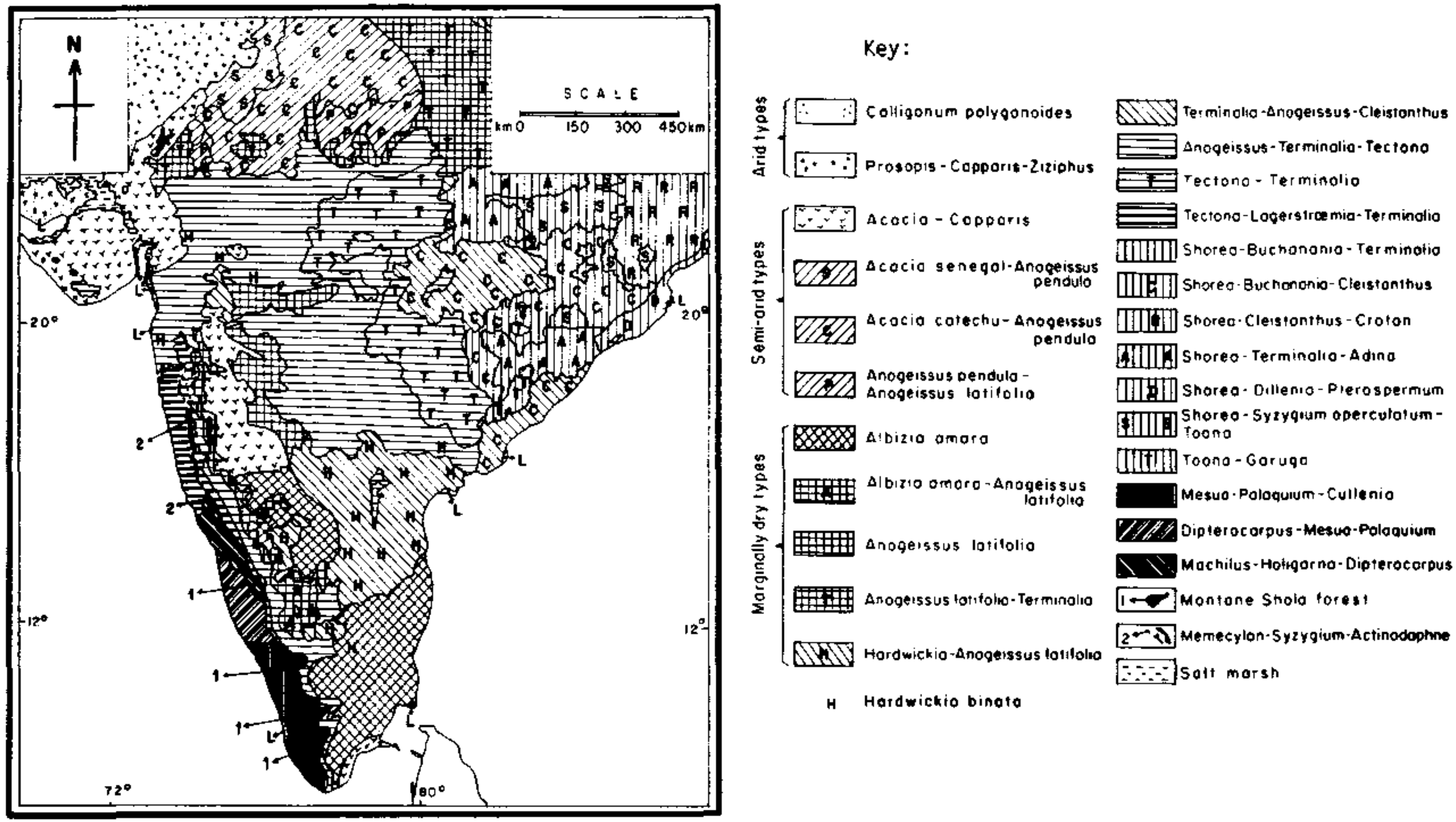


Figure 2: Potential area of the major vegetation types.

USE OF PRINCIPAL COMPONENT ANALYSIS IN RATIONAL CLASSIFICATION OF CLIMATES

Sulochana Gadgil and N.V. Joshi*

SUMMARY

Principal component analysis is applied to the mean pentad rainfall-data of 145 stations in the Indian region to derive patterns of temporal variation in terms of which the differences in the profiles are most strikingly exhibited. It is found that all the profiles can he adequately represented as superimpositions of 2 leading eigenvectors. Natural groups of the stations can thus he identified by a cluster analysis of the distribution of points representing the stations in the coordinate space of the associated amplitudes. Such a clustering provides a rational classification of the Indian rain-fall stations.

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INTRODUCTION

The climate of any locality or region is composed of a great variety of elements and it may not be possible for 2 places to have identical climates. The objective of climatic classification is to group the innumerable individual climates in such a way that all those having certain characteristics in common belong to 1 class. There are a number of ways in which the climate of any region or the earth as a whole can be classified, according to different choices of the distinguishing attributes of a class.

There are 2 possible general approaches to the problem of climatic classification. In the first, the distinguishing attributes are specified a priori, and different meteorological stations are assigned to a set of predetermined classes or categories. In the second approach, the problem is treated as one of clustering rather than of classification. Thus, given the nature of variation of climatic elements over the region of interest, the objective is to discover climatic patterns in terms of which the stations can be sorted into natural groups so that the degree of association is high among members of the same group and low between members of different groups. This yields what could be called an objective or rational classification, with each natural group or cluster forming 1 class.

The first approach has been widely used. In this case the choice of the criteria for classification is subjective and is guided by the application envisaged. Some of the classifications are based on the distribution of climatic elements such as temperature, rainfall, etc. The earliest classification, which divided the earth into equatorial or torrid, temperate, and polar zones, belongs to this category. However more complicated functions of meteorological variables, whose variation may be directly related to that of vegetation, have also been used to define criteria for classifications. Thus Thornthwaite (1948) used a moisture index defined in terms of the surplus water available over and above potential evapotranspiration, as an estimate of the intensity of aridity of the soil for classification of North America. In Koppen's classification (1900), native vegetation is looked upon as the best expression of the totality of a climate, and the criteria for determining climatic boundaries are suggested with vegetation units in mind.

We adopt the second approach for climatic classification of the Indian region. Since in the tropics the single most important climatic element for vegetation is the rainfall, in this first analysis we utilize only rainfall data for the classification. However, it is clear that such a classification can be pertinent for the associated vegetation and crops only if it is based on a detailed temporal profile of the rainfall rather than on its seasonal or annual mean. We therefore use the climatological mean pentad (5-day) rainfall profile at stations distributed throughout India as the basic data for classification. Note that even when we restrict our attention to a single climatic element (rainfall) the information to be analyzed is enormous, with 73 values at every station.

However, all these 73 pentad rainfall values are not uncorrelated. Further, the extent to which the rainfall in any given pentad varies over the region of interest depends upon the specific pentad. For example, the variation is minimal when the whole region has rainless spells. Thus all the pentad values are not equally effective in bringing out the differences between the profiles at the various stations. This suggests the use of principal component analysis, which yields new uncorrelated variables (rainfall patterns) in terms of which the differences between the character of the stations are most effectively exhibited. We consider here such an application of principal component analysis, which has yielded natural groups of rainfall stations throughout the Indian region.

DATA

The mean pentad (5-day) rainfall compiled by Ananthakrishnan and Pathan (1971) from the norms of daily accumulated rainfall for the period 1901-50 published by the India Meteorological Department [Undated] is the basic data set for this study. We have considered 145 stations distributed throughout the Indian region (Fig. 1). Since stations located at high altitudes have rainfall profiles that are not typical for the surrounding geographical region, they appear as anomalies in the climatic classification of the region (Gadgil and Iyengar 1980). Hence in this study at the outset we omit all stations at altitudes greater than or equal to 2 km. The temporal profile at each of the 145 stations chosen is thus specified in terms of the 73 pentad values, implying a data matrix of 145 x 73.

PRINCIPAL COMPONENT ANALYSIS

Notation and Formulation

We do not expect the 73 pentad values of the mean rainfall profile at any station to be uncorrelated. Hence it is possible to reduce the dimensionality required to specify the rainfall profiles and get a more economical description that maximizes the differences between various profiles by using principal component analysis.

The rainfall R (i,j) at station i (i from 1 to N) in pentad j (j from 1 to 73) can be expressed as the sum of the products of the coefficients or amplitudes An (i), which vary in space and associated temporal profiles B_n (j), i.e.,

$$R(i,j) = \sum_{n=1}^{73} A_n(i)\, B_n(j);$$
$$i = i,\ldots,N; \quad j = 1,\ldots,73$$

B_n's are the eigenvectors of the covariance matrix

$$C(k,m) = \sum_i [R(i,k) - \{R(k)\}]\, [R(i,m) - \{R(m)\}]$$

where

$$\{R(k)\} = \frac{1}{N} \sum_{i=1}^{N} R(i,K)$$

These eigenvectors are orthonormal and the indices are arranged so that the first, $B_i(j)$, corresponds to the largest eigenvalue; and in general the k^{th} eigenvector $B_k(j)$ corresponds to the k^{th} largest eigenvalue λ_k. The kth

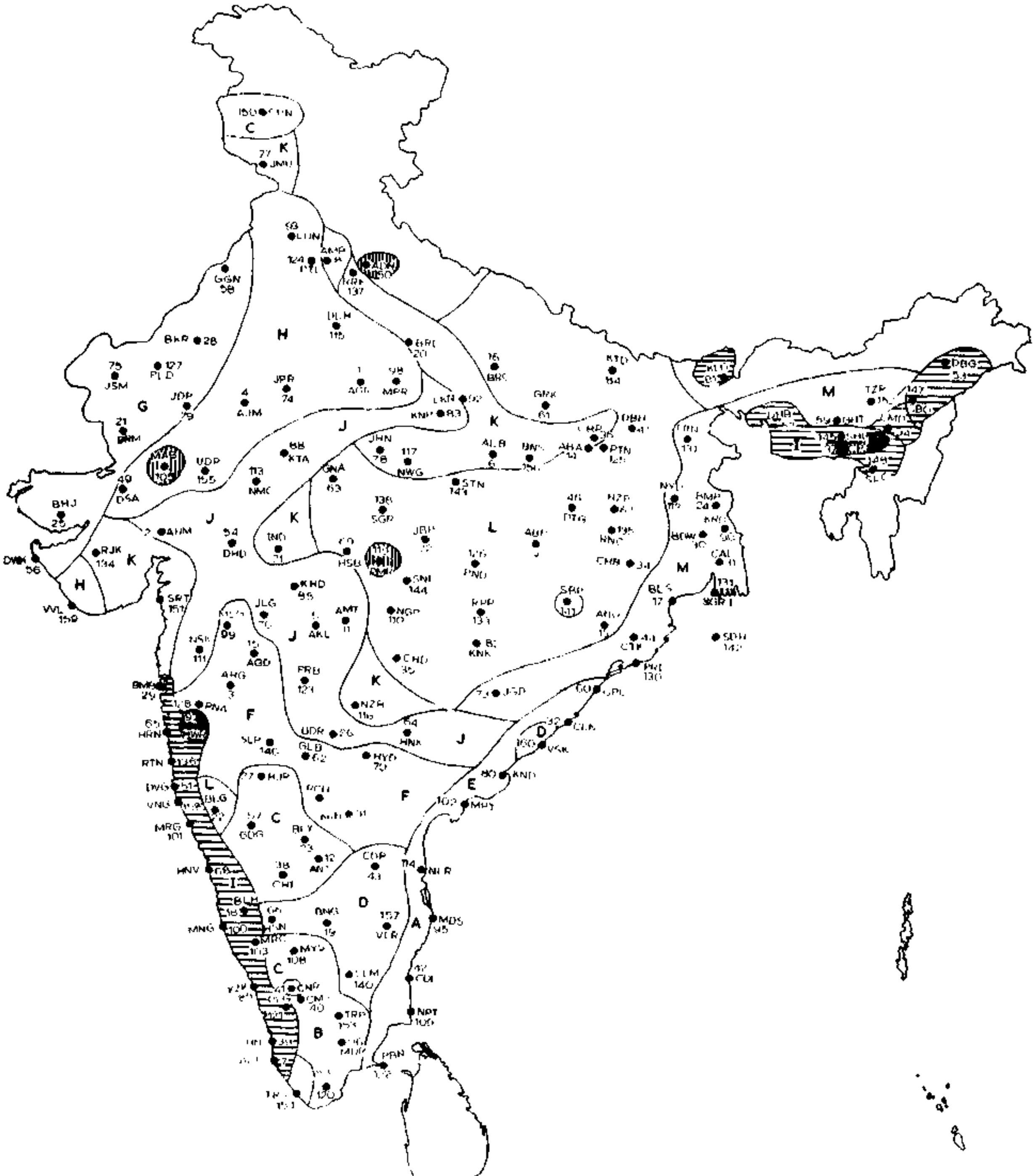

Figure 1: The locations of the stations considered in this study. The clusters and subclusters to which they belong are shown in Figure 3 (hatched regions) and Figure 5.

principal component is defined as the linear combination of the values at different pentads, with the coefficient of the value of the jth pentad being $B_k(j)$. The total variance vk, explained by the k^{th} principal component, is

$$v_k = \frac{\lambda_k}{\sum_m \lambda_m}$$

The first principal component has the largest variance of any linear combination of the pentad values and explains a proportion λ_1 of the variance. Given $B_n(j)$, the amplitudes $A_n(i)$ can be readily found from the data. Then the rainfall profile at any station can be expressed as a point in the n dimensional space of the amplitudes A_n.

Characteristics of Rainfall Patterns

Upon application of principal component analysis to the mean pentad data, we find that the first eigenvalue accounts for 80.4% of the variance and the second and the third for 10.5% and 3.2%, respectively. Thus the first 2 principal components seem to be adequate for describing most of the variance. The first eigenvector with significant magnitude from 1 May to 8 October and a maximum during 5 to 9 July may be interpreted as a southwest monsoon component (Fig. 2). In the second eigenvector, the premonsoon and postmonsoon epochs are negatively correlated with the southwest monsoon epoch. A linear superimposition of these 2 eigenvectors with a sufficiently large weightage for the second one results in a bi-modal distribution of rainfall with a minimum around August, separating the 2 maxima, as pointed out by Ananthakrishnan and Pathan (1971).

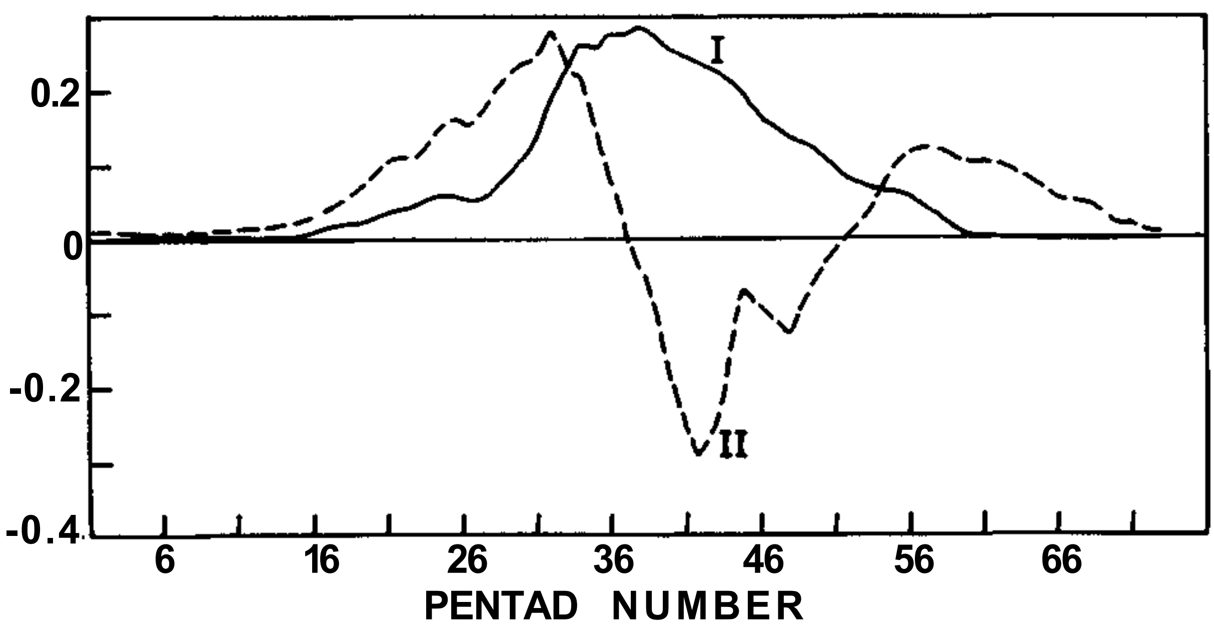

Figure 2: First 2 eigenvectors from the principal component analysis.

CLUSTERING BY A TWO-STEP APPLICATION OF NEAREST CENTROID METHOD

First-Order Clustering

Since the first 2 principal components explain 90.9% of the variance, the rainfall profile at any station i can be adequately described in terms of the associated amplitudes $A_1(i)$, $A_2(i)$. Thus every station can be represented as a point in the coordinate space of the amplitudes A_1, A_2, and the Euclidean distance between points representing 2 stations in this coordinate space is a direct measure of the difference between their profiles. Figure 3 depicts the locations of the stations in this coordinate space.

We use the method of nearest centroid sorting (Anderberg 1973) for determining the clusters. First we identify a set of seed points, which are used as cluster nuclei, subjectively by an examination of the distribution of points in the A_1-A_2 space. For example, for the case in Figure 3, we take points representing stations 159, 101, and 50 as seed points of 3 possible clusters. The points representing Mahabaleshwar and Cherrapunji (stations 97, 37, respectively) are isolated points that fall outside the diagram shown. Next we take any 1 of the remaining stations, measure the distance between the point representing it and the 3 seed stations in the A_1-A_2 space, and assign it to the cluster with the nearest seed point. The centroid of the cluster that has gained in membership is then calculated. This process is repeated for the next station, which is also assigned to the cluster with the nearest centroid. After all stations have been thus assigned, a final pass is made, taking the existing centroids of clusters as seed points and assigning each station to the nearest seed point. In the case shown in Figure 3, this yields the clusters I, II, and III.

Cluster I consists of 20 stations, of which 14 are along the west coast and the rest in the high rainfall region in the northeast. The large cluster II contains stations distributed over the rest of the Indian region, while cluster III is made up of 3 isolated hill stations (Fig. 1). The stations in cluster I are characterized by larger-than-average amplitude of the southwest monsoon component, whereas those in cluster II are characterized by a low amplitude of this component. The stations Mahabaleshwar and Cherrapunji, which are singular in having exceptionally large rainfall, form single-member clusters in the network of stations used.

Second-Order Clustering

The new variables determined by principal component analysis have been effective in bringing out the differences between the stations located in the high rainfall regions (along the west coast and in northeastern India) and those in the rest of India. With respect to these new variables, the profiles of the stations in the latter group are rather similar and they form a densely packed cluster in the A_1-A_2 space. In order to bring out the differences, if any, between the rainfall profiles of these stations, and hence determine the subclusters, we repeated the principal component analysis separately for stations belonging to clusters I and II. It was found that whereas the first group did not yield any subclusters, 12 subclusters emerged clearly from cluster II.

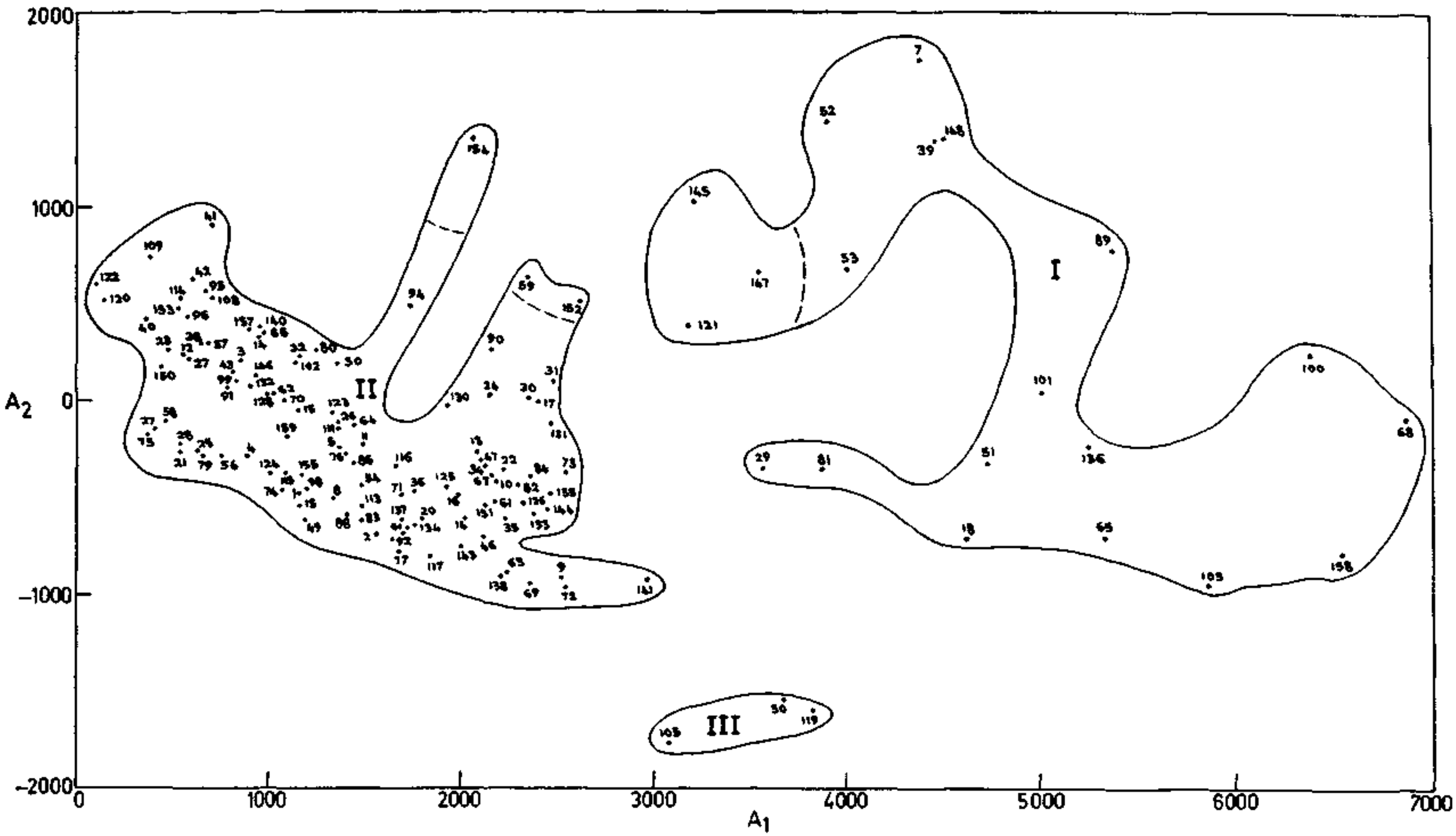

Figure 3: All the stations represented as points in the A_1- A_2 space of amplitudes of the 2 eigenvectors of Figure 2.

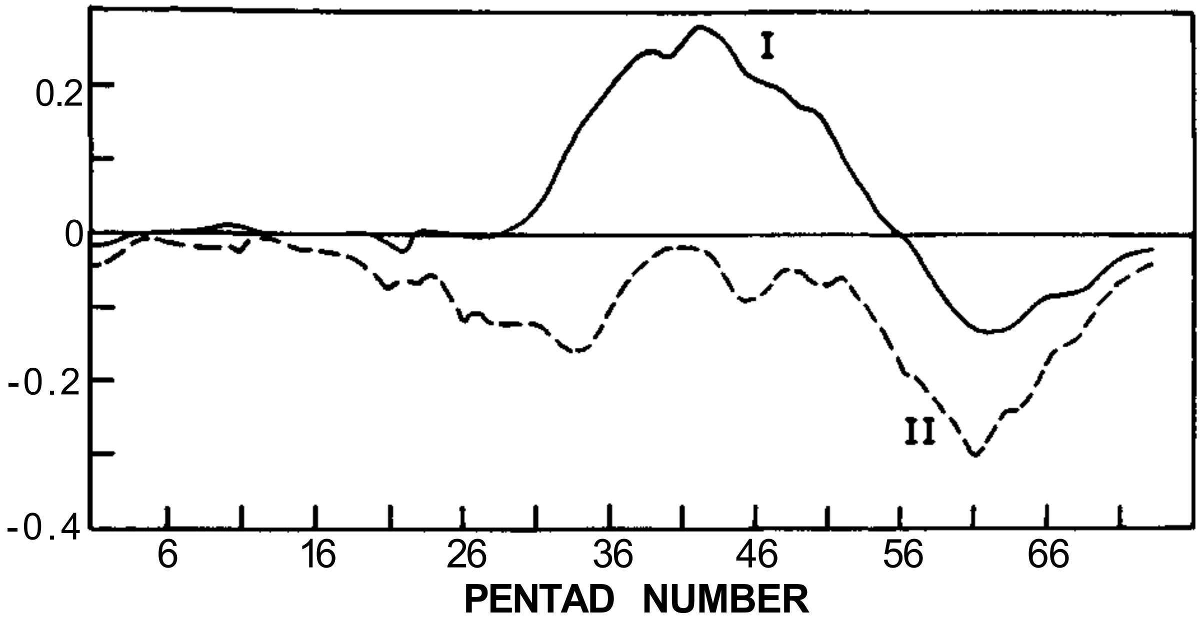

Figure 4: First 2 eigenvectors for the pentad rainfall data of the stations belonging to cluster II of Figure 3.

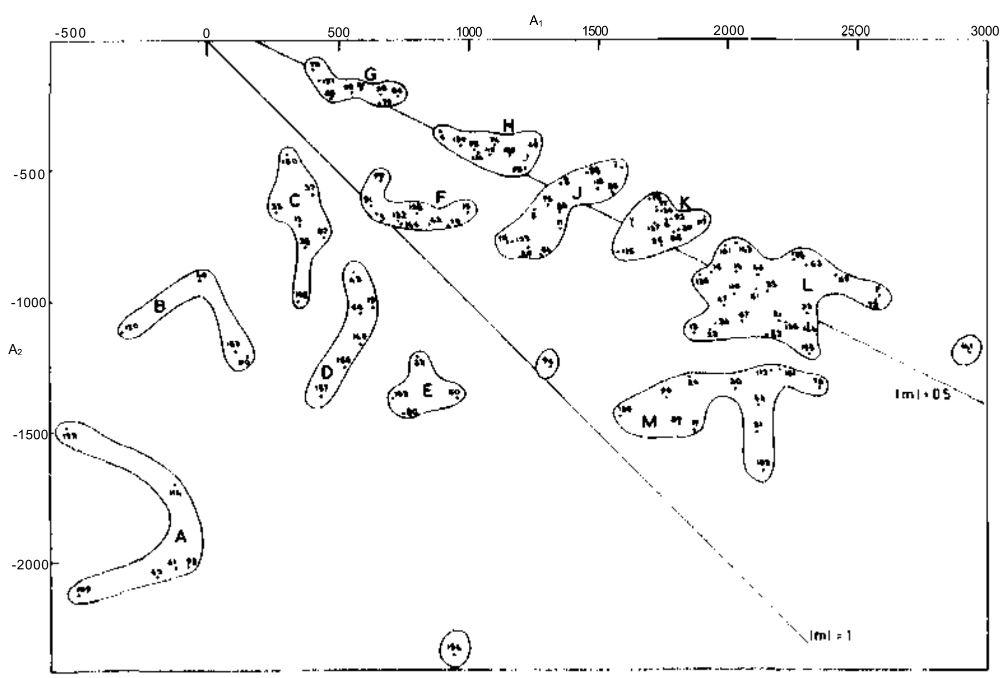

Figure 5: The stations belonging to cluster II of Figure 3, represented as points in the $A_1^{\prime}-A_2^{\prime}$ of amplitudes of the 2 eigenvectors of Figure 4.

The first 2 eigenvectors for this group are shown in Figure 4. The leading eigenvector is positive through most of the year with a maximum during 25-29 July. It is negative during the northeast monsoon season, with maximum negative value during 28 October to 1 November. The second eigenvector, having a larger peak in the latter season, is a combination of premonsoon and northeast monsoon. The first component accounts for 58.5%, while the second component accounts for 18.8% of the variance. The distribution of the points representing the stations of cluster II in the new coordinate space of amplitude $A_1'-A_2'$, and the resulting clusters are shown in Figure 5. Note that the vast majority of the stations can be unambiguously assigned to the various clusters. The geographical location of these clusters is also shown in Figure 1, along with that of clusters I, II, III obtained in the first sorting. It is seen that all the clusters fall into geographically contiguous areas.

DISCUSSION

Regions that may be considered as homogeneous with respect to variations in rainfall profile have been identified (Fig. 3) by our application of principal component analysis. It is important to note that although no information about geographical locations was used in the analysis, in general, stations belonging to a cluster are found to occur in geographically contiguous areas. The clusters obtained by the method used have been shown to be stable with respect to changes in network density (Gadgil and Iyengar 1980). Thus it appears that a reasonable first-order classification has been achieved.

In addition, this analysis indicates remarkably smooth behavior of the rainfall profiles in the zone of the monsoon trough. Note that the clusters G to M going from Rajasthan to the Bay of Bengal along this region lie along the line $dA_2/dA_1 = -0.5$ in the amplitude space of the first 2 principal components. This suggests that over this belt, the profile is given by superimposition of the first 2 eigenvectors, with half the weight for the latter, and variations occur largely in association with those in the total rainfall. This is strikingly different from the behavior in the peninsular region, where the profiles show far greater variation from cluster to cluster.

CLIMATIC CLASSIFICATION OF THE SEMI-ARID TROPICS IN RELATION TO FARMING SYSTEMS RESEARCH

S.M. Virmani, M.V.K. Sivakumar, and S.J. Reddy*

SUMMARY

The International Crops Research Institute for the Semi-Arid Tropics has a mandate to increase and stabilize the agricultural production of these areas. The region is characterised by a highly variable-low seasonal rainfall. A number of generalized climatic classification approaches have been reviewed; of these, the approach suggested by Troll to distinguish climates is important. The dry semi-arid tropics need to be mapped on the basis of the large volume of rainfall and evaporation data that is currently available. This paper points out that agroclimatic classification of the semi-arid tropics aims at addressing specific problems like risk to crops/cropping patterns, likelihood of intra- and inter-seasonal droughts, and adequacy of soil moisture in the seeding zone for dry seeding. The selection of criteria for each classification should be based on empirically derived parameters.

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INTRODUCTION

Divergent statements about tropical climates in the literature seem to call for a clearer definition of the characteristics and variability of these climates in relation to agricultural applications. Many misconceptions stem from the fact that the tropical climates range from extreme deserts to evergreen tropical forests, for which generalized global classification systems are rather broad and of limited utility. A drawback of most systems is that their limitations are known only to the meteorologists who devised them and applied them to a particular ecological zone.

The current and potential land use of a region is determined by its unique natural resources (climate, soils, and life forms), together with economic and human resources. Land-use planners seek information on land capabilities and limitations. Base-line data that describe *what is* are used to predict *what can be.* The results must be displayed in such a way that the distribution of resources and their potential come out clearly. Climate maps are essential for depicting the land use potential of different regions of the world.

Climate classifications have assumed various forms relating directly to the sophistication of the techniques imposed by climatic analysts. This paper attempts to discuss some of the climate-related classifications developed for or including the semi-arid tropics (SAT), and to report initial work on the adequacy of rainfall for crops in these areas.

Climatic Classification: Background

Climatic classification, originally a concern of plant geographers and biologists, has progressed considerably, from the simple division of hemispheres into 3 broad temperature zones by the early Greeks to the sophisticated divisions proposed by Thornthwaite (1931, 1948). Koppen (1936), often called "the father of modern climatic classification," hypothesized that the delineation of vegetation boundaries can be accomplished by means of quantitative averages of climatic parameters.

Quantification of climate for agricultural production should be based on the ability of the climate to meet crop demands for water and the suitability of the thermal regime. Thornthwaite's work in this area is monumental. The classifications proposed by him are ecological, making extensive use of P-E and P-T indices to account for factors that are directly important in furthering plant growth. A major problem with this type of classification is the inadequate representation of the crop demand for water.

A classification should differentiate between types and show the relationships among them. It should also supply the framework for differentiation of the microclimates that make up a climatic type. Thornthwaite (1948) holds that, no matter how numerous or complex the techniques of this field of study become, a major problem will remain: "Climate is an extremely complex phenomenon and any classification of it necessitates great oversimplification and involves the risk of serious error."

Classifications have ranged from identifying broad global zones to attempts to specify on a local scale. The work by Trewartha (1968), Koppen

(1936), Thornthwaite (1948), Thornthwaite and Mather (1955), Hargreaves (1971), and Troll (1965) is valuable because the classifications proposed by them represent quantitative systems and numerical values for defining the boundaries of the climatic groups.

The Characteristics of the Tropics

While in the astronomic sense the term tropics refers to the region between 23°27' North and South parallels, no climatic classification accepts these as the only criterion. Traditionally, climatologists have relied on the atmospheric climate to delineate the different climatic types. The criteria most often used are air temperature and precipitation.

According to Miller (1971), "Supan delimited the tropical climates by the mean annual isotherm of 68°F (20°C); actually 70°F (21°C) may be a better limit." Koppen (1931), in defining the tropical belt as having 12 months above 68°F, accepted the temperature of the coldest months as the boundary criterion. Later he preferred the isotherm of 64°F (18°C), which runs very close to the mean annual isotherm of 70°F. The special characteristic of the hot climates is that they essentially do not experience temperatures too low for plant growth; even winter is warm, and crops requiring considerable heat to mature and ripen can be grown at any time of the year if there is sufficient moisture. Thus, rainfall availability will have the deciding influence on the vegetation types. In Figure 1, the isotherms of 18°C for all 12 months and the annual average are shown for India. Table 1 shows that in Sholapur (Lat.I7°40') the mean daily maximum air temperature is 31°C and the minimum is 16°C in January, while in New Delhi in the same month the figures are 21°C and 7°C, respectively. Such differences have serious implications for crop planning.

Rainfall in the tropics varies from practically zero to more than 8000 mm per year. Some areas receive more than 400 mm per month which, under all circumstances, exceeds the monthly evapotranspiration. At the other extreme, there are tropical deserts with no precipitation in any month of most years. In between, one finds climatic types with alternating wet and dry seasons, with 1 or 2 rainfalls per year. The 1957 diagram of de Martonne, shown in Figure 2, illustrates the monthly distribution of rainfall as it follows the zenithal course of the sun. This is an oversimplification, as it disregards the effects of monsoons and orographic air circulation.

CLASSIFICATION OF THE SEMI-ARID TROPICS

The semi-arid tropics (SAT) pose a unique set of circumstances to those involved in agricultural development programs. On the basis of temperature, such areas are suitable for the production of any crop that does not require a cold period in its life cycle. Unreliable moisture is the key limiting factor to more stable and improved agricultural production in these regions.

In recent years, there is a growing appreciation of the climatic constraints of the SAT, and attempts are being made to increase our understanding of the crop moisture environment and the duration of the growing period in this ecological zone. Efforts to this end will involve the fitting of appropriate crops to climatic zones of given characteristics. In certain instances this

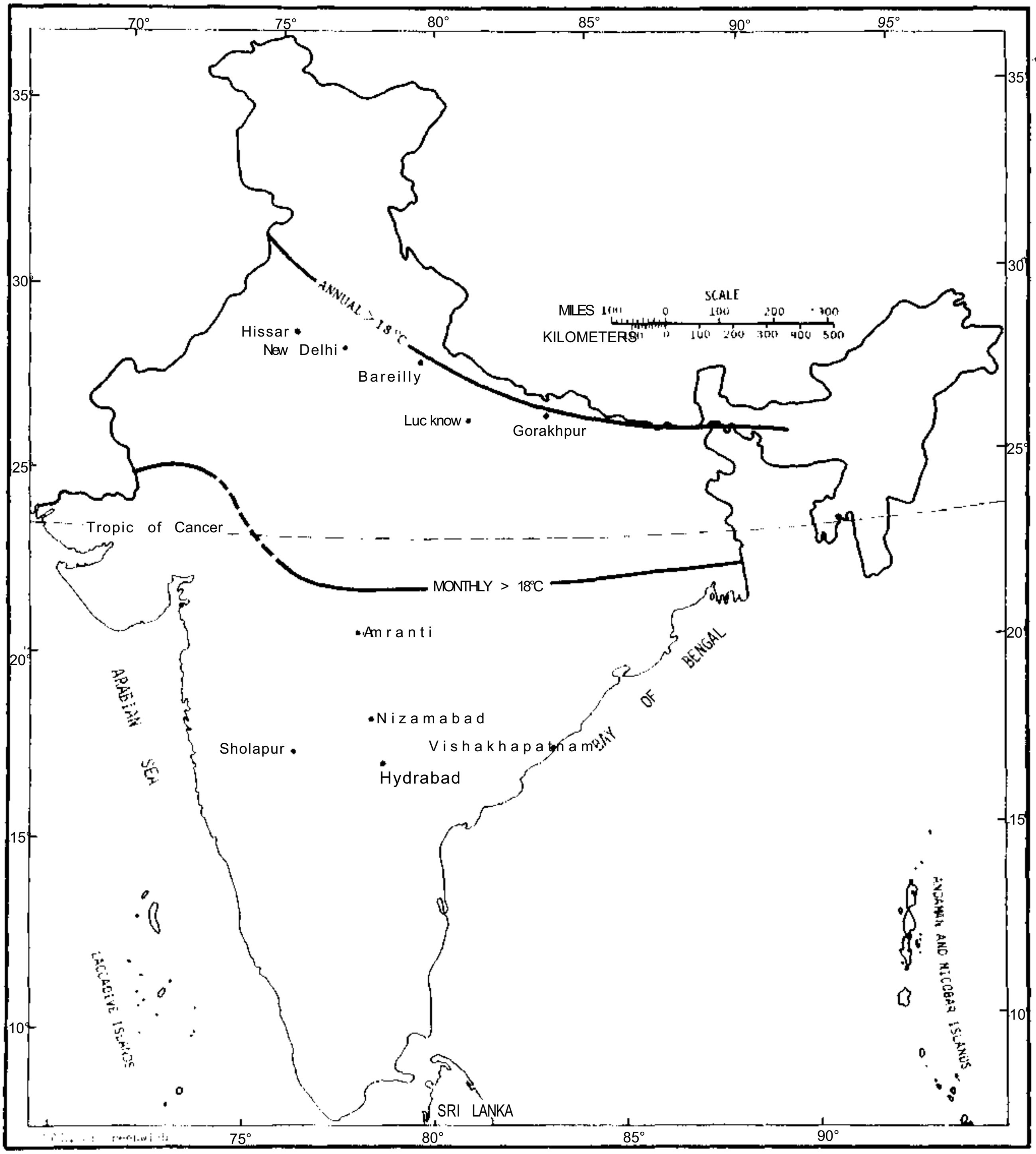

Figure 1: India, Isotherms of at least 18°C mean annual and mean monthly temperature.

Table 1: Air temperature for some representative Indian locations.[a]

Location	Lat.	Summer Max. (°C)	Summer Min. (°C)	Summer Ave. (°C)	Rainy Max. (°C)	Rainy Min. (°C)	Rainy Ave. (°C)	Winter Max. (°C)	Winter Min. (°C)	Winter Ave. (°C)	Annual Ave. (°C)
a) Mean annual temperature 18°C											
Hissar	29 10	41.6	24.6	33.1	35.5	26.1	30.8	21.7	5.5	13.6	25.1
New Delhi	28 35	40.5	26.6	33.6	33.7	26.1	29.9	21.3	7.3	14.3	25.3
Bareilly	28 22	40.5	25.8	33.1	32.6	25.6	29.1	22.0	8.6	15.3	25.2
Lucknow	26 52	41.2	26.5	33.8	32.5	26.0	29.3	23.3	8.9	16.1	25.9
Gorakhpur	26 45	39.0	25.9	32.5	32.3	26.2	29.3	23.0	9.9	16.5	25.7
b) Mean monthly temperature 18°C											
Amraoti	20 56	42.2	27.8	35.0	29.8	23.0	26.4	28.9	15.5	22.2	27.2
Sholapur	17 40	40.4	25.5	32.9	31.3	21.9	26.6	30.8	15.8	23.3	27.1
Vishakha-patnam	17 43	34.0	27.8	30.9	32.0	26.0	29.0	27.7	17.5	22.6	27.3
Nizamabad	18 40	41.5	27.7	34.6	30.1	23.0	26.5	30.0	15.3	22.6	27.0
Hyderabad	17 27	38.7	26.2	32.4	29.5	22.1	25.8	28.6	14.6	21.6	25.9

Season[b]

a. Based on 1930-1960 norms published by India Meteorological Department.
b. Data of the months of May, August, and January have been taken to represent the summer, rainy, and winter seasons, respectively.

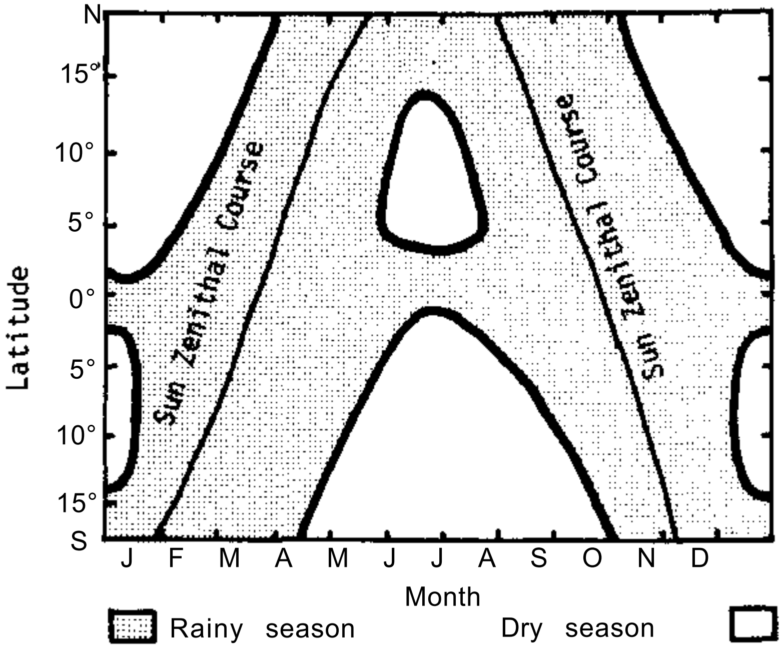

Figure 2: Theoretical monthly distribution of rainfall between latitudes 20°N and 20°S, according to de Martonne (1957).

may require extensive crop substitution and introduction. Therefore, relevant climatic classification is important both for defining the climatic resources and for developing transferable farming systems technology, which in the SAT tends to be highly location-specific.

Virmani et al. (1978) examined 7 important climatic classification systems in relation to the SAT environments (Thornthwaite 1948, Thornthwaite and Mather 1955, Cocheme and Franquin 1967, Schreiber 1975, Papadakis 1966, Hargreaves 1971, and Troll 1965). They concluded that classification systems using precipitation and potential evapotranspiration as inputs have definite advantages because these 2 parameters are of primary importance in evaluation of the climatic moisture adequacy. This has special significance in the semi-arid areas of the world where water is the basic constraint.

Two of the approaches need special mention:

1. Troll (1965) proposed a classification based on 2 main variables-thermal and hygric. The emphasis in this classification is on the duration of dry and humid months rather than on an assignment of climatic boundaries based on annual values of precipitation, temperature, and humidity. According to Troll, the following climatic values prove satisfactory to explain the vegetation zones of tropical Africa and South America.

Humid months	General vegetation
12 to 9.5	Tropical rainforest and transitional forest
9.5 to 7	Humid savannah
7 to 4.5	Dry savannah (wet-dry semi-arid tropics)
4.5 to 2	Thorn savannah (dry semi-arid tropics)
2 to 1	Semi-desert (arid)
1 to 0	Desert (arid)

The approach used for defining humid months is simple: a month having a mean rainfall exceeding the mean PE is termed a humid month. These data are available from national meteorological services. The classification proposed by Troll has been adopted by ICRISAT for defining the geographical extent of the semi-arid tropics.

2. Hargreaves (1971) developed a "moisture availability index" (MAI), which is a measure of the adequacy of precipitation in supplying crop water needs. Areas with 3 or 4 consecutive months with an MAI of more than 0.33 are defined as semi-arid. Hargreaves further hypothesized that such areas are suitable for the production of crops requiring a 3- to 4-month growing period. However, this approach involves the computation of dependable precipitation (PD), which requires the calculation of specified probabilities. For most cases, he defined PD at the 75% probability level of the expected rainfall. MAI is a ratio of PD/PE, where PE is the mean potential evapotranspiration.

Calculations of precipitation probabilities require long-term rainfall records and are based on the choice of a suitable mathematical function that appropriately describes the distribution of rainfall in a particular climatic zone. These requisites impose a serious restriction on the universality of use of MAI in climatic classification systems.

The classification systems of Hargreaves and Troll are somewhat unique because average annual amounts of rainfall are not critical to these systems. This represents a strength because the annual average rainfall indeed says little about the. agricultural potential in the dry tropics. It should be remembered that the number of months used in the classification criteria do not describe the entire rainy season; rather, they represent the core of the rainy period, which builds up to and drops from those key months. This is another strength of the 2 classification systems, for there is a direct correlation between the overall effectiveness of the rainy season and the number of months with precipitation equal to or more than potential evapotranspiration (or PD/PE > 0.33).

World maps of climatology were published by Troll in 1965. The number of observations on which this global survey is based is not reported. The map on semi-arid tropics is quite effective in giving a general impression about the extent and distribution of the SAT. However, a detailed study revealed that further refinements were needed.

The semi-arid tropical regions of India as classified by Troll (Fig.3) show large areas of Rajasthan, Gujarat, and parts of Madhya Pradesh in the 2 to 4.5 humid months' zone, i.e., the dry semi-arid tropics. The region con-

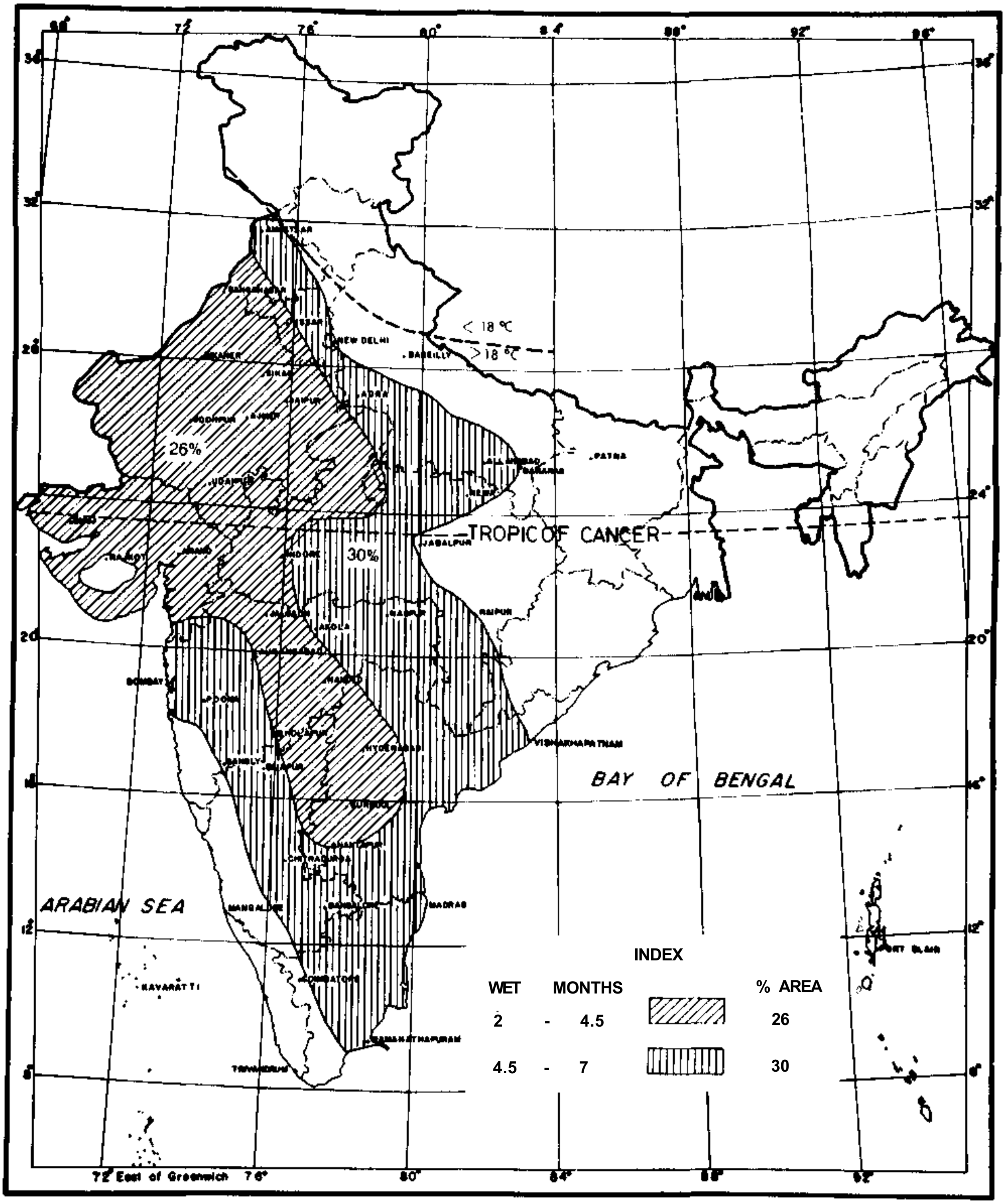

Figure 3: Semi-arid tropics in India, adapted from the World Maps of Climatology published by C. Troll (1965). Names of stations have been superimposed by us to define the geographical distribution of dry and wet/dry semi-arid tropics in India. We could not ascertain the number of locations used for demarcation of the boundaries of SAT or the methodology employed to evaluate potential evapotranspiration.

stitutes 26% of the total area of tropical India and represents 47% of the Indian SAT as defined by him. The wet-dry zone having 4.5 to 7 humid months forms a 200- to 500-km-wide belt running from northwest to south India around the dry semi-arid zone. It constitutes 30% of the total area of tropical India and 53% of the semi-arid region of the country so defined. The total SAT area according to this map amounts to 56% of total tropical India. This figure is very close to the estimate of 54% made by the Economics Department of ICRISAT (Ryan and Subrahmanyam 1975).

The India Meteorological Department (1967) published 30-year (1931-60) climatic normals for over 300 locations of India. In 1971, the Department published monthly potential evapotranspiration values for most of these locations (Rao et al. 1971). We combined this information to obtain a detailed climate map of semi-arid India according to Troll's methodology (Fig. 4). India was taken for this initial study because (1) there is ready access to a large volume of published rainfall and PE data, and (2) Troll's map (Fig.3) did not seem to adequately represent the climatic zones of India.

It is evident from Figure 4 that most of the area of tropical India (64%) is covered by the dry semi-arid tropics with 2 to 4.5 humid months, compared to the 27% of Troll. The wet and dry tropics cover 16% of the area. The map also shows a considerable area lying between 12 to 20°N and 74 to 80°E, which is part of the arid tropics. Similarly, most of the areas of western India are shown in the arid category (< 2 humid months), which appears in line with the actual climate.

If Troll's definition is accepted, most of the area of the Indian SAT falls between 600- and 1400-mm isohyets of annual rainfall (Figs. 4 and 5). "High-rainfall" areas with more than 1200 mm annual rainfall (east and southeast India) have rice as the main crop in the lowlands of the toposequence, with maize or other upland crops in the upper reaches.

The main regions of semi-arid India, according to Hargreaves[1] 1971 classification are shown in Figure 6. Since the definition of semi-arid areas is restricted to those with an MAI greater than 0.33 for at least 3 to 4 months, the area in SAT India is much reduced compared to Troll's definition. However, a comparison between the areas covered under Hargreaves' definition and those arrived at according to Troll's criteria show a reasonable correlation. Most of the areas that are defined as arid tropics on Troll's map (Fig. 4) are shown in the same class on Hargreaves' map.

Mather (Personal Communication)[1] suggested that 1 of the ways to evaluate climates of the semi-arid tropics is by determining the central tendencies. Thornthwaite (1948) tried to express this by a study of the frequency of different climate types. The results clearly illustrate that the areas classed as arid by Troll have 6 times greater incidence of less than 2 humid months than those classed as semi-arid (Table 2). This remains true even when the total annual precipitation of some of the locations in these 2 classes is rather similar. In about 90% of the years, the semi-arid areas had more than 2 humid months (over 50% of these years were characterized by 3 or more humid months).

It seems that the approach proposed by Troll may continue to be used by ICRISAT to define the boundaries of semi-arid tropical zone. With regard to the thermal regime, the mean annual air temperature of more than 18°C as

1. Mather, J.R. University of Delaware, Newark, Delaware 19711, U.S.A.

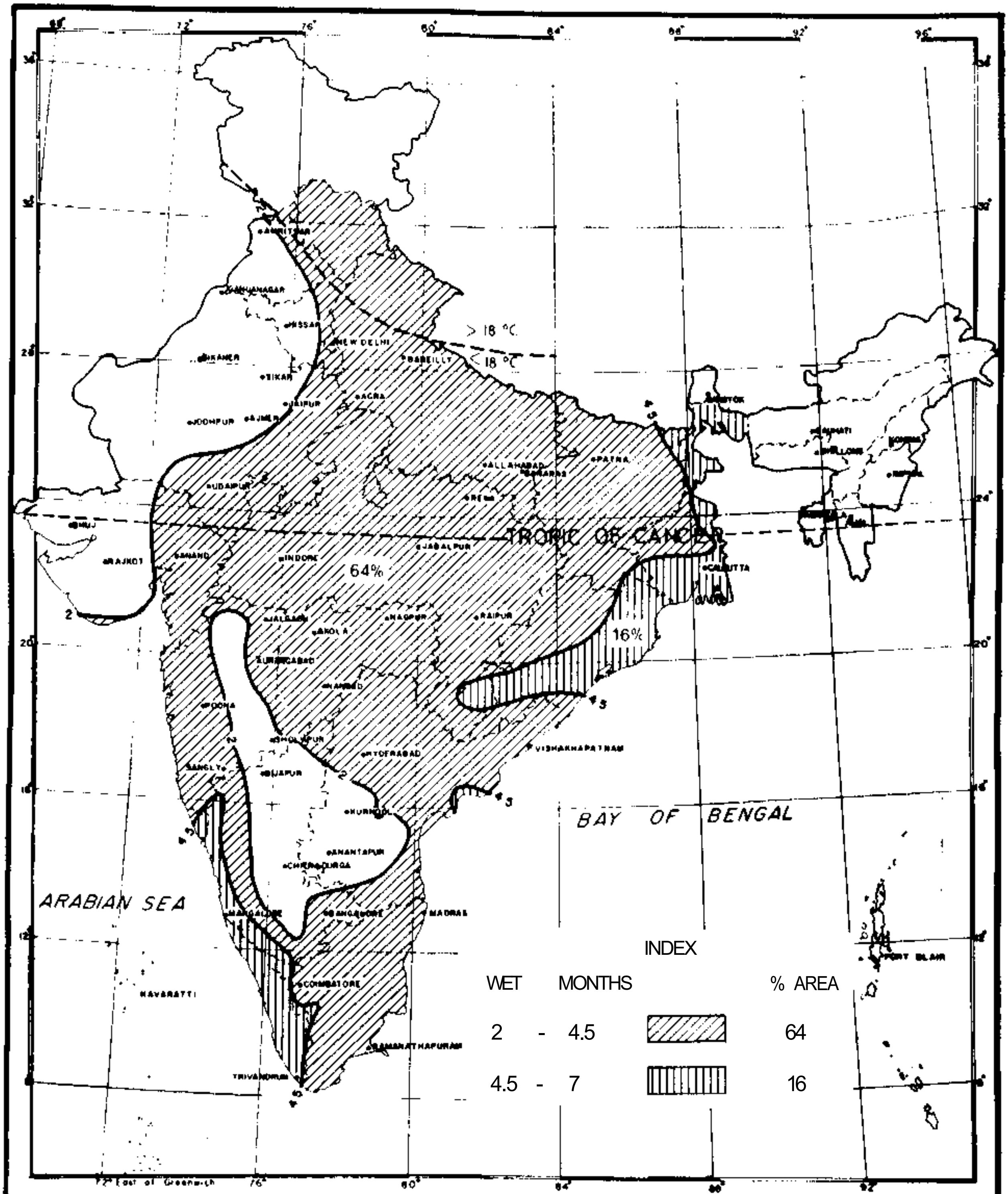

Figure 4: Semi-arid tropics in India (ICRISAT). Troll's (1965) methodology for characterizing the humid periods and classifications was used for over 300 locations in India. The resultant map shows the zonation of the dry and wet/dry semi-arid tropics throughout India.

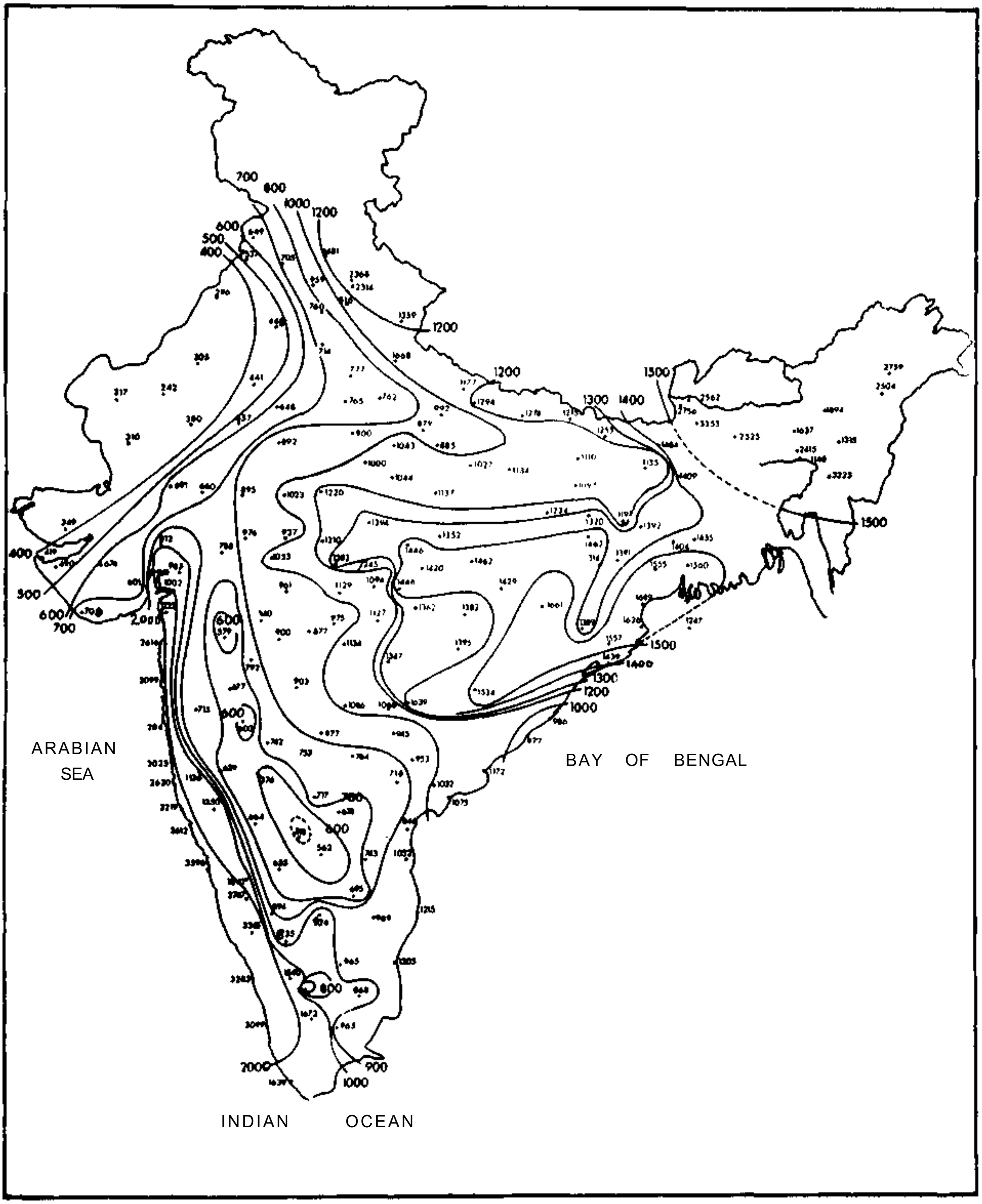

Figure 5: Rainfall isohyets in India.

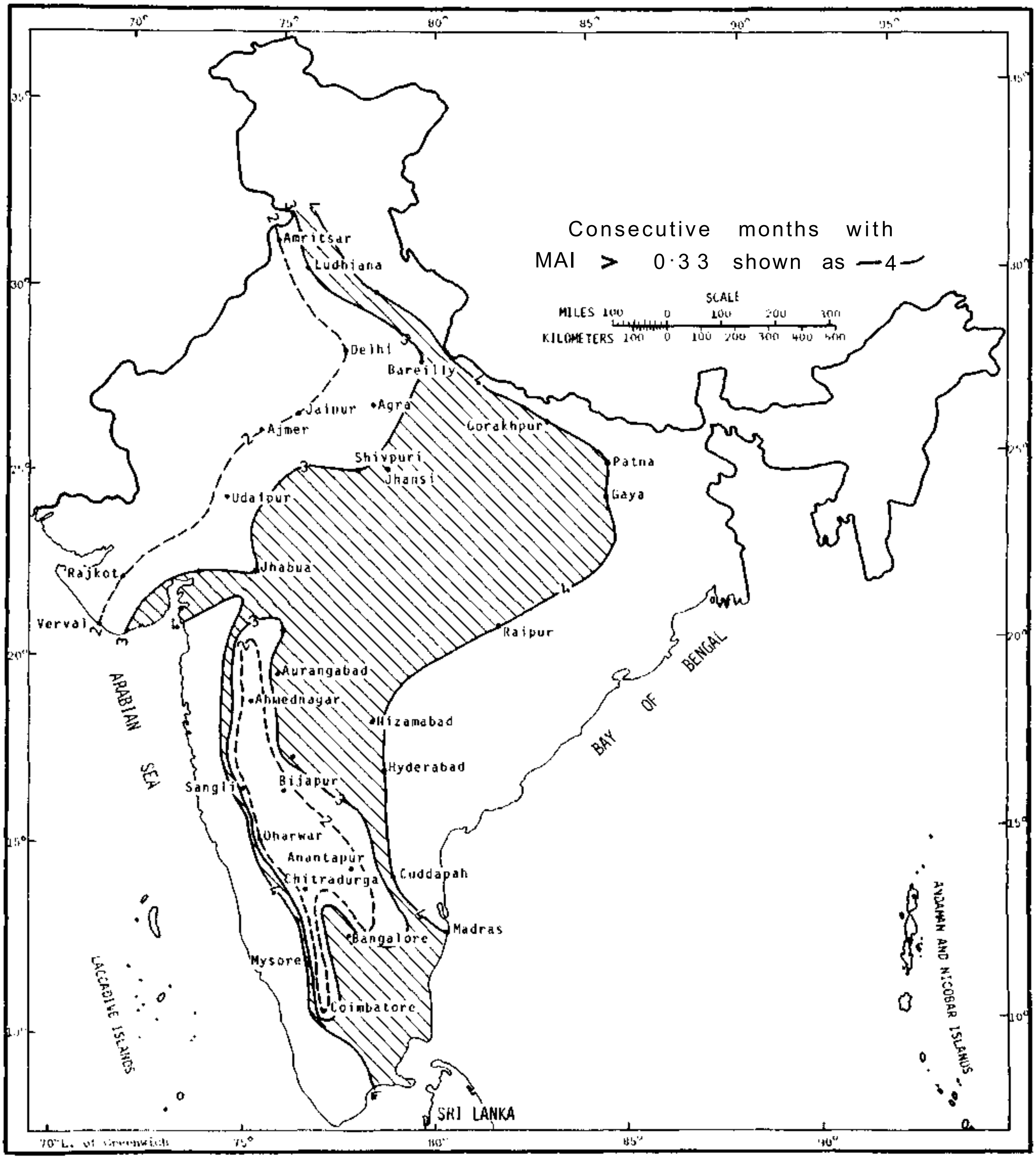

Figure 6: India, climatic classification (Hargreaves ' method).

Table 2: Frequency of humid months at selected Indian locations[a].

Location	Latitude °	'	Annual rainfall (mm)	% frequency of number of humid months <1	2	>3
Arid areas[b]						
Hissar	29	10	400	85	13	2
Jodhpur	26	18	383	80	13	7
Ahmednagar	19	05	617	47	35	18
Sholapur	17	40	755	40	13	47
Bijapur	16	49	565	60	32	8
	Average		544	62	21	16
Semi-arid areas[b]						
Jaipur	26	49	669	20	53	27
Udaipur	24	35	686	6	50	44
Dohad	22	50	805	11	26	63
Indore	22	43	1001	0	17	83
Anand	22	34	909	13	27	60
Hyderabad	17	27	783	16	33	51
Mahboobnagar	16	44	831	10	24	66
	Average		812	11	33	56

a. Based on 30-70 years' data.
b. As per Figure 3.

proposed by Koppen (1931) may be adopted to define the tropical regions. Workers who tested the generalized approaches based on vegetation types to establish a close correspondence of vegetation and climate for any particular geographical area have found them inadequate.

Climatic boundaries are never sharply defined; they exist as broad transition zones across which one type merges imperceptibly into its neighbor. The question to be asked is: "How does the climate change across the boundary?" and the answers will vary. The essence of the transition may, for example, be a decrease in the quantity of rainfall or a change in the onset of the dry or wet season. In the majority of cases, significant change of climate is reflected in a change of natural vegetation and cultivated crops. However, one must remember that the aim is to distinguish climates that are distinct in themselves.

THE QUESTION OF AGRONOMIC RELEVANCE

The broad climatic zonation of the SAT by empirical calculation of the hygric regime is important for defining the geographical extent of the climatic region globally, but for agronomic relevance it must be more location-specific.

Some specific objectives of the climatic classification for agronomic application in the ICRISAT program are:

1. to identify isoclimes at national research centers and benchmark locations in the SAT for the transfer of the suitable crop improvement and production technology developed at ICRISAT,
2. to provide adequate indices of moisture availability for successful crop production in the SAT, and
3. to recognize and quantify the risk levels associated with cultivation in broad SAT zones, and to identify climatic constraints to agricultural production.

As a general principle, therefore, we must first determine and isolate the operative climatic influence and then search for the best method of expressing the critical value of that quality.

Climatic resources must be examined in agronomically relevant terms, and such approaches could lend greater flexibility to crop planners in the choice of an appropriate classification system.

Agroclimatic Analysis for Crop Planning: an Example

In 1978, we chose 2 locations, Hyderabad and Sholapur, which are ecologically and edaphically similar. An examination of the annual, seasonal, and monthly rainfall data; moisture index; length of the growing season; and soil type, etc., for these 2 locations showed close similarity in the agroclimatological features. Russell and Moore (1976) utilized numerical methods in pattern analysis based on 16 climatic attributes on an annual and seasonal basis for climatic classification. It was shown that Hyderabad and Sholapur fell in the same summer climate class (Russell 1978). Similarly, Gadgil and Iyengar (1980), using principal component analysis of long-term rainfall, showed that these 2 locations were similar in terms of their short-term rainfall distribution pattern.

Even though climatic resource analysis showed close similarity between Hyderabad and Sholapur, agronomic research at the 2 locations showed distinct differences. Monsoon cropping at Sholapur was undependable with medium- or long-duration crops, and yields from year to year were highly variable with low rainfall-use efficiency. But at Hyderabad, cropping systems involving maize/pigeonpea intercrop or maize/chickpea sequential crop showed good promise and the rainfall-use efficiency was high. Differences in the agronomic potentialities at the 2 locations can be explained by the following 2 approaches.

1. Rainfall probability analysis. Using weekly rainfall (R) and potential evapotranspiration (PE) data for the 2 locations, we (Virmani et al. 1978) showed that rainfall distribution at Sholapur is highly erratic, whereas at Hyderabad the rainfall distribution is highly dependable between mid-June to the end of July and from mid-August to mid-September. The reason for low agricultural-production efficiency at Sholapur can be explained by the erratic rainfall distribution.

2. Water balance approach. A weather-driven, process-based, soil moisture simulation model was run for the surface layers of the profile and for the entire root profile (available water storage capacity, 230 mm). Long-term climatological records for Sholapur and Hyderabad were used for this simulation. The model predicts the daily soil moisture status of defined layers and thereby the moisture available to a crop. Table 3 presents the probabilities of crops having fully adequate moisture regimes. As the footnotes to this table amply demonstrate, these probabilities were calculated on the basis of given definitions of moisture required. Nevertheless, the probabilities represent orders of magnitude of potential risk that can be compared across locations and lead to clear inferences. Much can probably be done to improve the estimates for each location in an absolute sense.

Column 7 of Table 3 shows that the total probability of a 90-day crop finding good growth conditions throughout the growth period was only about 1 out of 3 years at Sholapur. As shown in column 1, the biggest disadvantage in Sholapur arose from a much lower probability of emergence before July 15 (only 2/3 of the years). However, as all subsequent conditional probabilities show, the plant was at a higher risk in Sholapur than in Hyderabad area at every stage after it had completed the earlier stages successfully. A 33% probability of a fully adequate soil-moisture regime is too low a basis for encouraging *kharif* (rainy-season - June-Sept) cropping on a year-after-year basis in the Sholapur region. At Hyderabad the probability of adequate moisture for good growth is provided in 62% of the years.

The probabilities of good soil moisture for a *rabi* (postrainy-season - Oct-Jan) crop after *kharif* fallow (Table 3, col 9) are high in the Sholapur region (80%). This value exceeds the total probabilities of good growth conditions for a *kharif* crop in Hyderabad (col. 7). However, if a *kharif* crop is taken in Sholapur, the chances of the *rabi* crop are reduced by 20%. Thus,

Table 3: Reliability of a 90-day kharif *crop on Vertisols of 2 areas (%).*

	Probability of emergence to July 15	Probability of seeding survival		Probability of adequate soil moisture through growing period		Probability of adequate water in seed set stage	Probability of good growth condition	Probability of adequate soil moisture for *rabi* after *kharif* crop	Probability of adequate soil moisture after *kharif* fallow
		Conditional**	Total	Conditional	Total	Conditional	Total	Total	Total
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Sholapur deep Vertisols*	65	76	49	84	41	80	33	60	80
Hyderabad deep Vertisols*	85	90	76	90	69	90	62	50	n.a.

* Water-holding capacity for deep Vertisols (230 mm)

** Conditional probability is conditional on meeting all prior conditions, while total probability is the product of conditional x prior, i.e., it is the total probability to successfully complete the stages and refers to all years.

NOTE TO COLUMNS

(1) Assuming dry seeding and using 1 inch of rainfall as sufficient for emergence
(2), (3) Defined as no water stress in top soil layer for 2 weeks after emergence
(4), (5) Soil moisture more than 50 mm during all weeks
(6) Soil moisture more than 100 mm during seed setting period
(7) Probability of fulfilling all previous conditions
(8) Total probability of having more than 150 mm of stored water between mid-September and mid-October after growing a *kharif* crop
(9) As (8) but with *kharif* fallow.

the data show that not only would consistent *kharif* cropping be unprofitable, but it would also endanger the profitability of the more important *rabi* crop in this region.

The results of both the rainfall analysis and the soil water balance study generally support the agronomic field experience from ICRISAT watersheds on deep Vertisols and experimental evidence at the Sholapur research station.

CONCLUSIONS AND FUTURE OUTLOOK

Our aim of climatic classification is to identify geographical locations with similar properties, e.g., a hierarchical array of characteristics under the primary elements of precipitation and temperature. Questions of variations of these elements in time and space, the scale of application of the classification system, and the reduction of a finite number of discrete units or classes must be taken into account.

The generalized classification of semi-arid tropical areas according to Troll's (1965) approach seems to be adequate. The dry SAT areas with 2 to 4.5 humid months would be of primary interest to ICRISAT. Cartographic work will be necessary to map SAT areas globally with an enlarged data base. Available meteorological data from published sources can facilitate this work.

For agronomic relevance, the choice of criteria for classification is very important. This choice will probably be dictated by the utility of the particular element or combination of elements chosen. Agronomic field research and crop-weather modeling efforts could help us identify the appropriate criteria. For example, our current work with sorghum modeling has shown that, apart from crop and soil factors, climatic criteria such as rainfall, solar radiation, air temperature, and open-pan evaporation are of agronomic significance.

We believe that the climatic-resource-index approach suggested by Williams and Masterton (this volume) needs careful attention. For our mandate areas, initial emphasis must be placed on rainfall climatology and water balance work. Attention must be paid to the numerical classification systems. The pattern analysis techniques suggested by Russell (1978) and principal component analysis method by Gadgil and Joshi (this volume) are likely to be of potential use for agroclimatic classification. The use of interpretive overlay soil maps in such approaches (Nielson 1978) could aid the crop planner immensely.

CLIMATIC CLASSIFICATION, AGROCLIMATIC RESOURCE ASSESSMENT, AND POSSIBILITIES FOR APPLICATION IN THE SEMI-ARID TROPICS

G.D.V. Williams and Joan M. Masterton*

SUMMARY

The choice of an approach to climatic classification is dictated by the ultimate objectives. Provision of the required information to enable the best use to be made of climatic resources for agriculture could be one of the rational objectives. Variations in the responses among different kinds of plants are rarely dealt with in general classification systems. It will be useful to consider 3 categories of thematic mapping, i.e., climatic, agroclimatic, and agroclimatic resource mapping. Detailed analysis for specific regions such as the semi-arid tropics may need a different classification system than that required for the world overview. A method of agroclimatic resource index (ACRI) is proposed and discussed for use in the semi-arid tropics. Computation of the crop climate resource index (CCRI), which is outlined, could facilitate spatial comparison of the availability of moisture, as it affects agricultural production, among different parts of a region. An integration of the agroclimatic resource analysis with the ecological land classification is proposed.

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INTRODUCTION

According to Hare (1951), climatic classification is an essentially geographic technique that allows the simplification and generalization of the multitude of statistics accumulated by climatologists. Such a classification should be used to define climatic types in statistical terms so that climate as a geographic factor has definite and uniform characteristics permitting the definition of rational climatic regions. Thus, in Hare's estimation, many of the past attempts at classification have not been statistical and are therefore not considered adequate for geographical purposes. His emphasis, then, is on classification systems that are purely climatic, without reference to other types of information such as vegetation or soils patterns.

Prohaska (1967) presents a somewhat different point of view. He questions the usefulness of a climatic classification based on climatic factors only, and asks whether such a classification would bring new insights or new understanding. In scientific investigations, every kind of classification should be a means to an end only, and never a goal per se. Prohaska states "it is more than questionable that a new general classification without a special purpose would give us a deeper knowledge of the world's climates even if it were logically constructed, had coherently chosen terms, and adequately determined limits" (p.3). New classifications, he believes, may become very useful and perhaps even indispensible if they are designed for special purposes and directed at well-defined and concise objectives. Thus, climatic classifications with sharply defined goals and based upon well-chosen criteria can serve a valid and useful purpose.

These 2 approaches to climatic classification serve different needs; neither is "better" nor "more useful" than the other. The choice of approach depends on the ultimate objective. In this paper, the objective of concern is provision of the required information to enable the best use to be made of climatic resources for agriculture.

For agricultural development planning, adequate assessment of the agroclimatic resources is an essential prerequisite. The agroclimatic zonation work in Sao Paulo State, Brazil (Estado de Sao Paulo 1974, 1977), is an outstanding example of such an assessment. Failures or disappointing results of agricultural development projects in various parts of the world, including projects to produce pineapples in the Philippines, sugar in Puerto Rico, groundnuts in East Africa, and rubber in the Amazon basin, may have been largely due to failure to properly assess and classify agroclimates (Chang 1968).

In this paper we review some of the characteristics of various systems of classifying climates from the standpoint of their possible applicability to agricultural development. We then discuss the concept of the climate as a resource and suggest how this concept might be employed in assessing for agriculture the climate of a zone such as the semi-arid tropical zone. Finally we discuss agroclimatic resource analysis as part of the broader field of ecological land resource classification.

THE NEED FOR SYSTEMS ADAPTABLE TO DIFFERENT SCALES OF APPLICATION

There are several limitations to most climatic classification systems that seriously restrict their usefulness for either agricultural applications or other resource analysis purposes. In systems that are developed primarily for world overviews, 1 category often covers far too wide a range of climates to be of use for national or local agricultural development and planning, and often no mechanism is provided for subdividing categories.

Typically the label identifying a climatic category or class is composed of at least 2 parts. In its simplest form, this approach uses a letter and a number, one representing thermal conditions, the other moisture (Chapman and Brown 1966, Jeanneret and Vautier 1977a). This approach is not conducive to subdividing. A class such as "3H" is not readily broken down into finer divisions for local planning purposes without making a major modification to the system by introducing a new level of detail through the use of subclasses. Conversely, any attempt to build a system to handle the range of scales from local to national or world applications using such non-quantitative identifiers would lead to a bewildering proliferation of classes.

Many of the classification schemes are based on quantitative criteria, and one could, of course, make comparisons using the original data rather than the derived classes. Most agroclimatic comparisons are, in fact, done using the original quantitative data, but even this may still leave some problems, as can be illustrated with reference to an analysis by Field (1968). He used 2-way tables of estimates of degree-months and the ratio of actual to potential evapotranspiration in comparing 2 parts of the Northern Hemisphere. One could subdivide his classes as finely as the data warranted without changing his system. Thus one could readily compare 2 locations in which either the temperature was similar and the moisture differed, or vice versa, but the relationship between the agroclimates of 2 places between which both the thermal and moisture climates differed would not be readily quantifiable.

Some agroclimatic mapping systems where 1 factor, either the thermal or the moisture climate but not both, is of concern, have employed a continuous variable that could readily be either subdivided or generalized for use at greater or lesser levels of detail. Examples are growing degree-days (Chapman and Brown 1966) and the climatic moisture index developed by Sly (1970) and Agrometeorology Research and Service (1976).

The index of agricultural potential developed by Turc is a quantitative approach to classifying climates for agriculture that attempts both to combine thermal and moisture aspects and to provide for changing the level or scale of detail considered without changing the system. In mapping this index for France, Turc and Lecerf (1972) used a system of class identifiers to label value intervals, so minor modification of the labelling would be needed to map at different scales of details, but Barreto and Soares (1974), on the other hand, used isolines in mapping Mozambique. Depending on data quality and availability, greater or lesser detail can be obtained by altering the number of isolines employed.

Another approach to the problem of classifying climates at a relatively detailed scale is implied in comments by Slayter (1968). He suggests that there are 3 general types of agroclimatic surveys. At one extreme are the broad classification systems such as those of Thornthwaite (1948) and Koppen (1936), which are "of very limited value in regional planning, but may be useful in roughly and rapidly comparing major climatic zones in different continents" (p.36). At the other extreme is the sophisticated growth model approach, which may provide an unnecessary degree of detail. He suggests that the most appropriate approach for regional planning will often be to use types of models that are intermediate between these extremes, and which commonly involve soil-water balance, temperature, photoperiod, and consideration of specific agroclimatic hazards, A practical response to the need for means of classifying climates both for world overviews and for more detailed regional scales, then, would be to employ 2 different systems, 1 designed for use at the global and the other at the regional scale.

DIFFERENCES IN CLIMATIC REQUIREMENTS FROM ONE SPECIES OR CROP TO ANOTHER

Variations in climatic requirements among different species are rarely dealt with in general climatic classification systems. This is of particular concern to agricultural interests. A climate that is quite satisfactory for wheat may be poor for rice. Even between 2 crops as similar as wheat and barley, substantial differences have been revealed in agroclimatic mapping in Canada (Williams and Oakes 1978, Williams et al. 1980).

Because of the variations in responses among different kinds of plants, many agroclimatic and bioclimatic studies have dealt with particular groups of species, such as ornamental trees and shrubs (Ouellet and Sherk 1967), with individual species or crops, or even with different varieties of a crop. Dansereau (1957) provided a map showing the thermal and moisture limits for the sugar maple in North America, and these would be quite different for other tree species on that continent. Some, for example, would tolerate more cold in the north but would not grow as far south as the maple due to intolerance of the heat. Unstead (1912) and Williams (1969) mapped climatic limits for growing wheat in Canada. Chapman and Brown (1966) mapped heat units for growing maize ("corn heat units"), and Primault (1969) mapped the suitability of Switzerland for maturing several different maize varieties.

In spite of differences from crop to crop, it is sometimes possible to use 1 crop as an indicator for a group of crops, as was done by Jeanneret and Vautier (1977b) in mapping the climatic suitability of Switzerland for cereals on the basis of data for wheat. They recognized that there are interspecies differences in the crop responses, but it appeared that under Swiss conditions, the more unfavorable a zone was for wheat, the poorer it would be for the other cereals also. It was therefore justifiable to use wheat data in deriving the cereals map.

The studies by Williams and Oakes (1978) and by Williams et al. (1980) use the number of days from crop ripening to first fall freeze as an index for mapping areas where the crop would mature, so for these areas the analysis can readily be changed to a more detailed one where the data and objectives warrant it by using more isolines. The analyses of Primault (1969) and of Ouellet and Sherk (1967) could also be rather easily mapped in greater detail, where appropriate, by making a finer breakdown of their mapping classes in relation to the indices on which the classes are based.

AGROCLIMATIC RESOURCE ANALYSIS

The concept of resources has been developed in detail by Hunker and Zimmermann (1964). A resource is that upon which one relies for aid, support, or supply. It does not refer to some substance or condition as such, but to a function that the substance or condition may perform or facilitate. For instance, iron ore is not a resource in the absence of technology for an iron-mining function to exploit it, and incoming solar radiation was not a resource on earth before there was life to use it. Resources may function directly as factors of production, e.g., coal, wood, animals, or they may take the form of conditioning factors, such as climate, topography, or location, that affect the efficiency of the production process. Dansereau (1957) defined resources as "conditions of elements of the environment exploitable by living beings."

Climate was described as a resource some years ago by Miller (1956), and this concept has been more generally employed in recent years (Williams 1971, Taylor 1974, McKay 1976). Several recent papers have dealt specifically with climate as a resource for agriculture (Williams and Oakes 1978, Williams et al. 1978, Williams et al. 1980).

Most applications of climatic analyses and classifications involve preparation of maps to aid subsequent combination of climatic data with other types of data such as information on soils, vegetation, demography, and agricultural systems. For the present purpose it is useful to consider that there *are* 3 general categories of thematic mapping based on climatic data:

Climatic mapping	-	of climatic variables, e.g., July mean temperature, annual precipitation
Agroclimatic mapping	-	of derived variables of particular interest to agriculture, e.g., growing degree-days, climatic moisture indices
Agroclimatic resource mapping	-	of variables derived with some agricultural use in mind and often intended to assist in making comparative evaluations of different climates for some form of agriculture. This could be considered a special case of ecological land classification.

Agroclimatic resource analysis and mapping involve implementation of relationships, whether recognized or not, between climate and agriculture, and between the climates of areas and those of observing points. The relationship between agriculture and climate may be implicit, as when information from the literature and from agronomists on the climatic requirements is used in selecting appropriate agroclimatic boundaries between suitable, marginally suitable, and unsuitable zones for each crop, as was done in the agroclimatic zonation of Sao Paulo State (Estado de Sao Paulo 1974, 1977). Or it may be explicit, as when biophotothermal time-scale equations were used in mapping the climatic resources of Canada for maturing cereals (Williams and Oakes 1978).

The spatial climatic relationships may also be implicit, as when data are plotted and then overlaid on maps showing topographic information. The analysis locates the isolines on the basis of both the station data and the topography. This was done, for example, in mapping the agroclimatic resources for maturing cereals in Canada (Williams and Oakes 1978). Explicit spatial climatic relationships may be incorporated in equations, such as those used for the Canadian Great Plains by Williams (1969, 1971) and Williams et al. (1980), or those derived by Solomon et al. (1968) for Newfoundland, Canada, and by Pinto et al. (1972) for Sao Paulo State, Brazil.

The agroclimatic resource data may be in the form of a single index for agriculture in general, such as those of Williams (described by Simpson-Lewis et al. 1979) and Turc and Lecerf (1972), or they may be represented by a 2-part identifier (Chapman and Brown 1966, Jeanneret and Vautier 1977a, b). The analysis may be macroscale, as when the Canadian prairies or all of Canada are mapped (Williams 1969, Williams and Oakes 1978), or mesoscale, as when an area of only about 1 or 2 degrees of latitude and longitude in extent are mapped (Williams et al. 1980).

In analyzing the agroclimate or bioclimate of a district or region in the context of providing information for land management, it is useful to first relate the district to other parts of the nation or zone of interest, and then to analyze patterns within the district. In a recent climatological contribution to a monograph on land systems mapping for the Wynyard, Saskatchewan, map sheet area, the position of that area on national maps was located by use of an overlay. Average values of Williams' agroclimatic resource index, of the climatic resources for maturing wheat and barley, and of derived temperature and moisture values were abstracted from the national map and employed in comparing the area with other parts of Saskatchewan and of Canada. The variation within the Wynyard map area was then described on the basis of mesoscale analysis procedures similar to those of Williams et al. (1980), The same sort of approach, with variable appropriate to the particular case, could be used in a bioclimatic analysis of some area being assessed in an ecological land classification study, or in evaluating, for example, the agroclimatic resources of a semi-arid tropical state in India and comparing it to other parts of India and of the semi-arid tropics.

A POSSIBLE APPROACH TO AGROCLIMATIC RESOURCE MAPPING IN THE SEMI-ARID TROPICS

In proposing a set of procedures (Fig. 1) that might be used for the agroclimatic resource analysis and mapping of the semi-arid tropics, we follow the suggestion of Slayter (1968) that a different classification system is needed for the world overview than for the more detailed analysis within regions. A number of authors have produced original or modified world maps of climatic classes. That of Walter (1973) seems appropriate here and has been used as

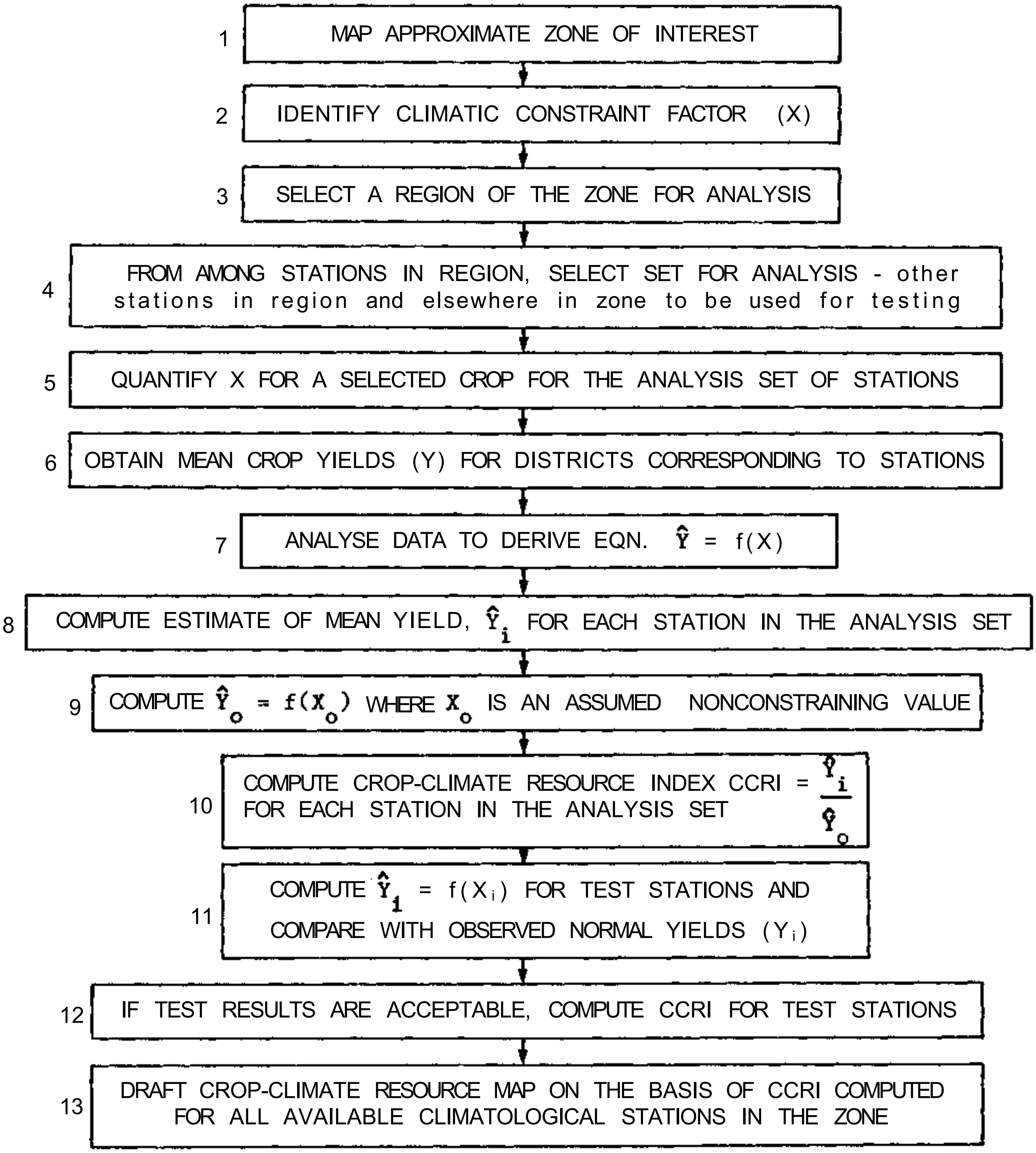

***Figure 1:** Steps in proposed system for analyzing and mapping agroclimatic resources of a zone such as the semi-arid tropics for a particular crop.*

the basis of a first approximation of the geographical distribution of the semi-arid tropics (Fig.2).

For the more detailed analyses, we propose methods evolved from some of those used in developing an agroclimatic resource index (ACRI) for Canada, as described by Simpson-Lewis et al. (1979). However, ACRI is a general index and for the present purpose it would be preferable to use methods that reflect differing needs among crops. Some applications of the results will involve decisions about different crops, and for applications such as irrigation planning the differences may also be important.

ACRI was derived by assuming thermal constraint to be the major factor in Canada and computing initial index values using freeze-free season length, or growing degree-days in some areas, and then adjusting the values downward in parts of the country with major moisture limitations. In the semi-arid tropics, as a first approximation one can consider that the thermal

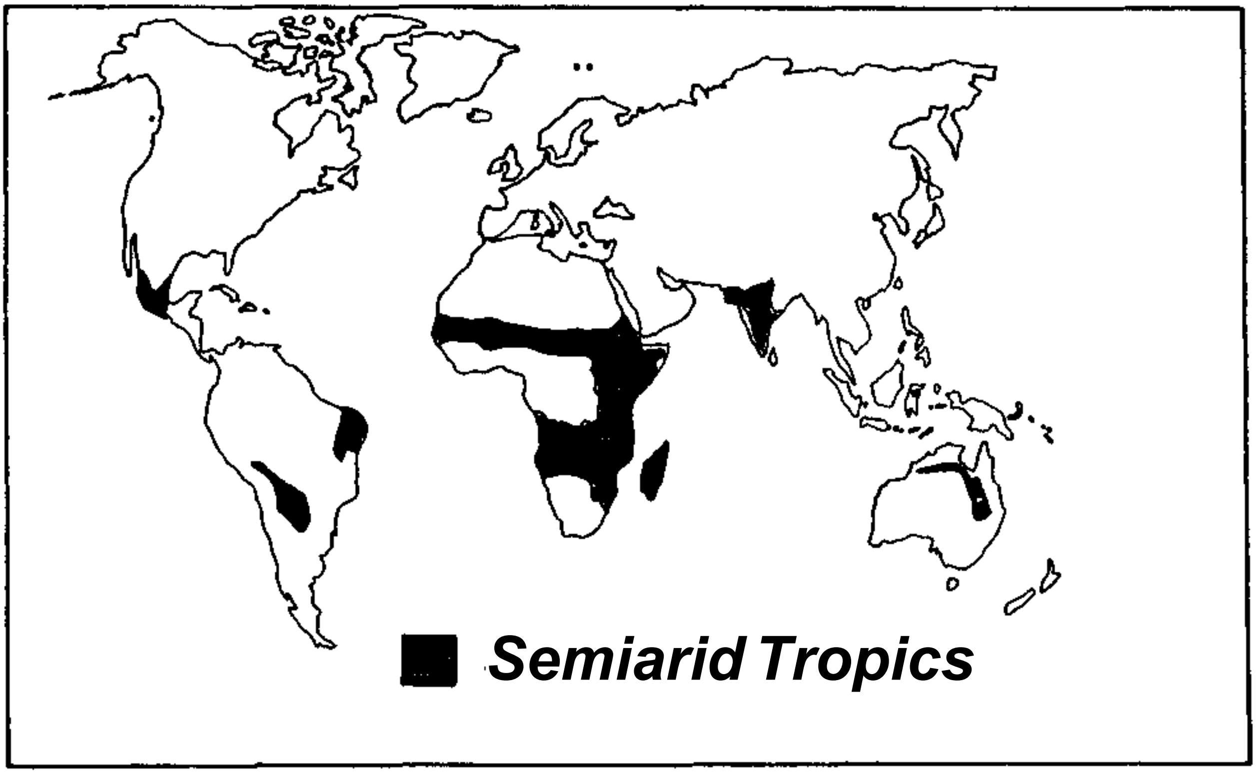

Figure 2: A first approximation of an answer to: "Where are the semi-arid tropics?" (adapted from Walter 1973).

aspect has been taken into account by limiting the zone of interest to the tropics. The attention for the more detailed analyses is then on moisture.

We would suggest selecting some region, such as the semi-arid tropical part of India, for analysis. Some expression, X, considered to be indicative of the growing season moisture conditions for some particular crop of interest, would then be computed for a number of stations in the region. A long-term average yield, Y, for that crop would be obtained for a "district" containing each station, district here being defined as the smallest geographical unit for which appropriate yield data are readily available.

Steps 7 to 10 (Fig. 1) would then be performed. An equation relating average district wheat yield, Y, to the moisture factor, X, would be derived, as illustrated here for wheat yield with some Canadian prairie climatological stations (Figs. 3 and 4). In that region wheat is normally planted in May and harvested in August or September, and moisture conditions to the end of June seem particularly important for yields. The moisture factor, X, used for illustration here was the average deficit to the end of June obtained in water balance calculations as described by Thornthwaite and Mather (1955). The annual district wheat yields and June deficits for 15 or 16 years were averaged to obtain the Y and X values used here.

The equation, which was of the form $Y = a_0 + a_1X$ (Fig, 4), was used to make a moisture-based prediction of the average yield at each station. It was also assumed that in this region a June deficit of less than 15 mm would not be particularly constraining, and the yield for X = 15 (27.925 bu/a) was divided into the moisture-based average yield predictions to obtain a crop-climate resource index (CCRI) for each station. The interpretation is that the climatic resource for wheat production is considered to be approximately proportional to this CCRI, for example the value of the climatic resource for this crop at Brandon is nearly 1.5 times that at Medicine Hat.

Our suggestion would be to derive an equation for predicting average yield from normal moisture using a set of stations in India or some other region of the semi-arid tropical zone and test it by predicting average yields for other stations in the region or elsewhere in the zone and comparing the predictions to average observed yields. If the results were judged satisfactory for the purpose, CCRI for the selected crop could be computed and plotted for stations throughout the zone to obtain a map of the climatic resources for that crop in the semi-arid tropics. Similar procedures (Steps 2 to 13, Fig.1) could be followed for several other important crops, and the resulting CCRI maps would then provide agroclimatic resource information to help in the planning of agricultural development and in the transfer of technology from the International Crops Research Institute for the Semi-Arid Tropics to other parts of the zone.

The moisture deficit variable used in the example here is only 1 of many possible expressions that might be used for X. Another factor that was tested during our computations was the climatic moisture index of Sly (1970), but that index reflects precipitation amounts through to the end of September and was less well correlated with the wheat yields (r = 0.68) than was the end of June moisture deficit, although it might be superior for another crop. The choice of variable for X will depend on the particular crop, climate, and type of application, and on what data and computational facilities are available to the investigator.

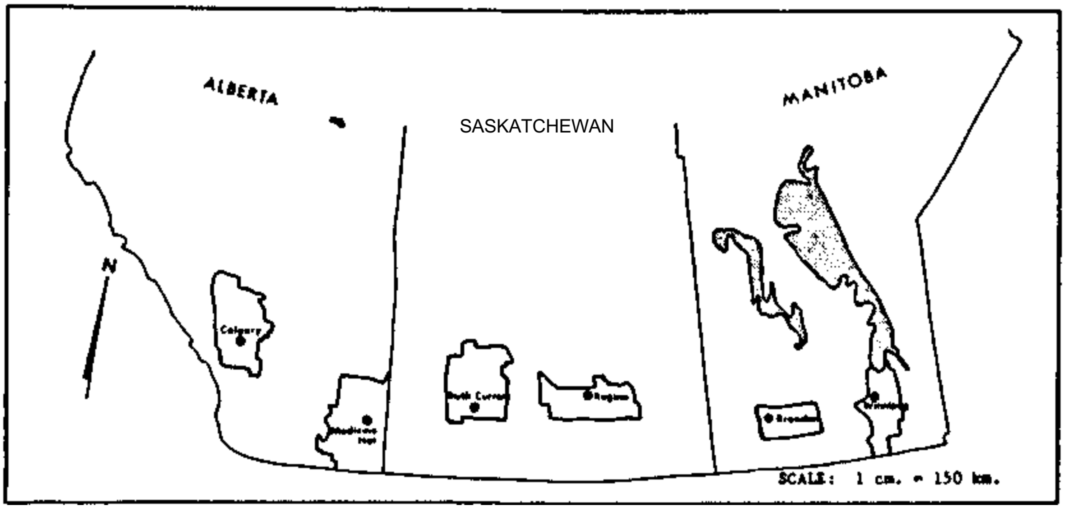

Figure 3: Southern portions of Canadian Prairie Provinces, showing stations and districts used for sample calculations.

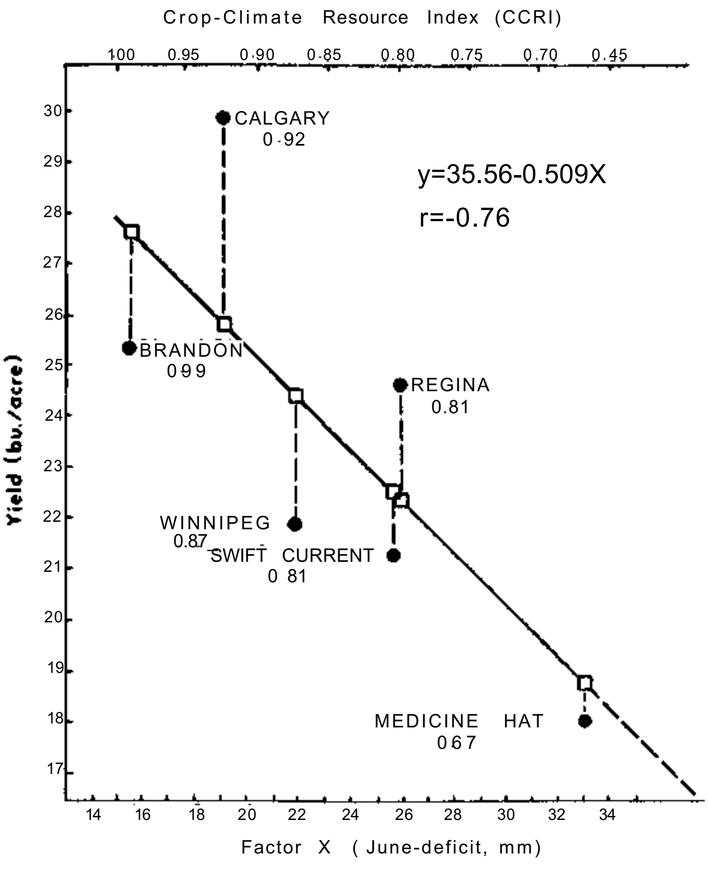

Figure 4: Illustration of the procedures for obtaining CCRI (shown below station names) for wheat, using the stations in Figure 3 and an assumed nonconstraining value of 15 mm for X.

It may be desirable, at least in some parts of the semi-arid tropics, to incorporate additional factors, For example a moisture-based crop-climate resource index might be adjusted downward in cases where temperature was judged to be a significant constraint, just as the thermally based ACRI index values in Canada were adjusted downward for moisture limitation as discussed previously.

If empirical large-area yield prediction equations such as those developed for the Canadian prairies (Williams et al. 1975) are available, it may be possible to use them with climatic data, or to use them to predict yields over a number of years and then average the predictions, to derive an alternative to Steps 2 to 9 (Fig. 1). Such an empirical model might be primarily based on moisture, or it might also reflect other factors. If such equations are not available for the semi-arid tropics, it might be worthwhile to consider the possibility of deriving them, as such models can be expected to be most effective under semi-arid conditions with rainfed agriculture, and they have several useful applications.

Whatever approach is used, care must be taken to ensure that the crop yield data used in modeling for rainfed agriculture does not include significant amounts of irrigated crop data. A quite different approach would be needed in analyzing such data, and data for a district that combined significant amounts of irrigated and nonirrigated crops would probably have to be excluded from the analysis data set.

The fact that moisture is expressed in the example (Fig. 4) as a deficit, so that moisture and the resource value decrease with increasing X, should not be cause for concern. One may wish to think of the deficit as a "resistance" just as one may call climate a resource factor and drought a resistance within the overall resource concept (Hunker and Zimmermann 1964). The important point is that moisture is the natural element or condition involved, and that for the conditions under consideration here, the greater the moisture the higher the resource value in general, which is what the crop-climate resource index indicates, regardless of whether the X being employed has the same or opposite sense as moisture changes. If the climatic moisture index of Sly (1970), which increases with increasing moisture, had been used, the CCRI values obtained (Fig. 4) would have been higher for higher moisture amounts, just as they were when the deficit was used.

The steps in the procedures suggested in Figure 1 should be viewed as iterative, in that in many cases further refinements would be appropriate. In the case of Step 1, the map of the semi-arid tropics (SAT), presented here is only a first approximation. There will be SAT "islands" beyond the zone mapped, for example some mountain valleys elsewhere will have semi-arid tropical climates, and there will be areas with other types of climate within the SAT zone. It would probably not be too useful to devote a great deal of effort to defining the precise extent of the zone however, because the definition would be rather arbitrary and the boundaries would be subject to continual change with climatic fluctuations and technological changes, but more importantly because it is doubtful if great precision in defining the limits of the zone would have much practical value. For example a winter crop in the SAT may have quite similar environments to a summer one in the temperate zone; dry-season conditions in the SAT may often be quite similar to arid zone conditions; thus research in the SAT may be applicable far beyond this zone and research elsewhere may often be quite useful within the SAT, so the question of precise boundaries is rather academic.

AGROCLIMATIC RESOURCE ANALYSIS IN RELATION TO ECOLOGICAL LAND CLASSIFICATION

The primary objective of ecological land classification is the development and application of a uniform ecological interdisciplinary approach to land classification for resource planning, land management, and environmental impact assessment. The approach taken is holistic in nature, recognizing that the several components of any region (soils, vegetation, climate, etc) interact to a point where it may become difficult to distinguish discrete limits or boundaries and major influencing factors. Agroclimatic resource analysis can provide input to the classification scheme when there is a desire to relate directly to land use planning for agriculture.

Difficulties in integrating climatic information into the ecological land classification process generally relate to (1) deficiencies in climatic data, (2) the incomplete use of available climatic data, and (3) doubt as to which climatic elements are ecologically critical. Agroclimatic resource analysis attempts to identify 1 or more of the critical elements, either climatic or derived, in a particular geographical area of interest. For example, water balance relationships may be applied to climatic data to provide a measure of moisture availability. The crop climate resource index facilitates spatial comparison of the availability of moisture, as it affects agricultural production, among different parts of a region. Such information, related specifically to the agricultural potential of a region, could be integrated into the larger ecological land classification process, which would also introduce other factors such as soil qualities, significant land forms, and other climatological information (such as temperature constraint data). The resulting classification would bear most directly on agricultural resource planning, management, and assessment.

Associating agroclimatic resource analysis with the larger field of ecological land classification can be mutually beneficial to both types of endeavor. Crop data that can be associated with climatic data are often more readily available on a regional scale basis than *are* other types of biological data. Regional bioclimatic analyses are therefore more feasible with respect to agriculture than to other types of land use and management, and the understanding gained through agroclimatic analyses can contribute to the general field of bioclimatic knowledge and thus to ecological land classification beyond agricultural land. In turn, ecological land classification work in general can contribute to understanding of agroclimatic resources and can help focus attention on important factors that might otherwise be missed in agroclimatic analyses.

AGROCLIMATIC CLASSIFICATION METHODS AND THEIR APPLICATION TO INDIA

A. Krishnan*

SUMMARY

The delineation of homogenous soil-climatic zones can help interpret present cropping patterns and can also suggest new cropping patterns. The classification systems of Koppen, de Martonne, Gaussen, Emberger, Thornthwaite, and Thornthwaite and Mather are discussed with regard to their relevance to the semi-arid tropics. Classifications based on the duration of moisture availability periods that include the approaches of Troll, Hargreaves, Papadakis, and Cocheme and Franquin and their applicability to regional crop planning are presented. The climatic water budgeting approach has been used to prepare maps of India, and soil climatic zones of India have been demarcated in this paper. The distribution of rainfall amounts is related to the moisture requirements of crops. A precise evaluation of climatically analogous regions in the semi-arid tropics for crop planning would require realistic water budget computations in the crop-growing season using short-term data.

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INTRODUCTION

Several methods have been suggested for the classification of climates. Attempts have been made to obtain a classification that will permit the establishment of regional boundaries between areas of uniform climatic conditions. Classification systems will vary according to the purpose for which classification is made. In regard to agricultural needs, the suitability of different crops to various areas is in large measure controlled by climate interacting with soil. Thus, it is important to delineate homogeneous soil-climatic zones, not only to interpret cropping patterns as they exist, but also to locate inappropriate land use, if any, and to project new cropping patterns in consideration of ecological factors.

However, most of the climatic classifications are bioclimatological in nature and attempt to relate the extent and type of natural vegetation on the surface of the earth to the climatic conditions:

KOPPEN'S CLASSIFICATION

Koppen (1936) divided the world climate into the following 5 principal groups.

1. Tropical rainy climate with subdivisions relating to the absence of a dry season or its occurrence in summer or winter.
2. Dry climate with subdivisions for semi-arid or steppe, and arid or desert climates.
3. Warm temperate rainy climate with subdivisions on the basis of occurrence of a dry season.
4. Cold and snow climate.
5. Polar climate.

The boundaries between desert and steppe as well as dry and tree climates were drawn by Koppen (1936) on the basis of mean annual temperature and mean annual precipitation. Using Koppen's method, Bharucha and Shanbhag (1957) determined the climatic types for 104 stations in India (preparation) and Burma. Koppen's classification was also applied to India by Subrahmanyam et al. (1965).

de MARTONNE'S CLASSIFICATION

The following index was employed by de Martonne (1926) to delimit different vegetational zones of the earth. This is a slight modification of the rain factor introduced by Lang (1920).

$$I = \frac{\text{Annual precipitation (mm)}}{\text{Mean annual temperature (°C)} + 10} \quad .... \quad (1)$$

According to this classification, indices below 5 characterize true desert, while those indices in the 10 to 20 range correspond to dry steppe, and 20 to 30 to prairies. Indices above 30 correspond to forest vegetation. This method was used by Pramanik et al. (1952) and Krishnan and Shankarnarayan (1964) for classification of the climate of Rajasthan.

GAUSSEN'S CLASSIFICATION

In this classification (Gaussen 1955), a dry month is defined as a month in which the total precipitation (P) expressed in mm is equal to or less than twice the mean temperature (T) of the month expressed in degrees Celsius.

$$P \leq 2T \qquad \ldots. \quad (2)$$

An ombrothermic diagram drawn with these parameters indicates the duration and severity of dry months. This classification is based on the xerothermic index, which takes into account factors of temperature, precipitation, number of days of rain, atmospheric humidity, mist, and dew.

The climate is classified as warm, warm temperate, or temperate when mean temperature is greater than zero, and cold and cold temperate if negative mean temperature occurs at certain periods of the year. The climate of regions with negative mean temperatures for all months of the year is classified as glacial.

When the xerothermic index is over 300, a region is termed a desert, and when it is between 200 and 300 the region is classified as subdesert. Mediterranean climate is classified for xerothermic index values ranging from 0 to 200, with a number of subdivisions depending on the range of the index values. Axeric climates have a xerothermic index of 0. Since rainfall is adequate for vegetation in this case, the factor for delimitation of the bioclimates is mean temperature (t), as indicated below.

$t > 20°C$	Equatorial
$15° < t < 20°C$	Subequatorial
$10° < t < 15°C$	Warm temperate
$0° < t < 10°C$	Temperate

Similar subclassification of cold and cold temperate climates is done on the basis of the combined duration of frosts and dry seasons in the case of desert, subdesert, and subaxeric climates, and the length of the frosty season in respect of cold axeric climates. Detailed study of xerothermic indices in India and climatic classification by this method was done by Legris and Viart (1959) and Meher-Homji (1960).

EMBERGER'S CLASSIFICATION

Emberger (1955) suggested the delimitation of various bioclimates by means of a pluviothermic quotient (Q) defined as

$$Q = \frac{100\ P}{(M-m)\ (M+m)} \qquad .... \quad (3)$$

Where M is the mean maximum temperature (°C) in the hottest month, m is the mean minimum temperature (°C) in the coldest month, and P is the annual rainfall in mm. Unlike other classification systems, Emberger's quotient cannot be used by itself to make a valid climatic map. After mapping the vegetation zones, Emberger (1955) determined the associated moisture quotients and other climatic values corresponding to these zones. Thus the northern limit of the arid zone in northwest Africa varies from a Q value of 16 to 40. In characterizing the different climates, he utilized the Q values as well as the actual mean daily minimum temperature of the coldest month. Climatic classification of Rajasthan by this method was tried by Krishnan and Shankarnarayan (1964).

THORNTHWAITE'S CLASSIFICATIONS

Rational Classification (1948)

The main limitation of Koppen's widely used climatic classification is lack of a rational basis for selecting temperature and precipitation values for different climatic zones. Thornthwaite (1948) improved on this by introducing the water balance concept in his classification. He introduced the concept of potential evapotranspiration and devised an elaborate method for its computation. He compared the potential evapotranspiration with precipitation in order to obtain a moisture index. Since the water surplus (S) and water deficiency (d) occur at different seasons in most places, both must enter into a moisture index, one affectinq it positively and the other negatively. Although a water surplus in one season cannot prevent a deficiency in another, the former may compensate the latter to a certain extent, for water surplus means seasonal addition to subsoil moisture and ground water. So, deep-rooted perennials and trees make partial use of this water surplus and thus minimize the effect of drought. Transpiration proceeds, but at a reduced rate. For this reason, Thornthwaite assumed that a surplus of 6 inches in one season will counteract a deficiency of 10 inches in another. Thus he gave greater weight to the humidity index I_h = (100.S./n) than the aridity index I_a = (100.d./n) in the climatic classification, where S is water surplus, d is water deficiency, and n is water need. For classification purposes he defined a moisture index (I_m) by the following relation:

$$I_m = I_h - 0.6 \cdot I_a = \frac{100\ S - 60\ d}{n} \qquad .... \quad (4)$$

On the basis of this moisture index, he determined the following climatic types by the criteria indicated beside each.

Climatic types			Moisture index
A	-	Perhumid	100 and above
B_4	-	Humid	80 to 100
B_3	-	Humid	60 to 80
B_2	-	Humid	40 to 60
B_1	-	Humid	20 to 40
C_2	-	Moist subhumid	0 to 20
C_1	-	Dry subhumid	-20 to 0
D	-	Semi-arid	-40 to-20
E	-	Arid	-60 to-40

In moist climates, if there is a dry season, it is necessary to know how dry it is, and in dry climates to know how wet a wet season is. Water deficiency in moist climates or surplus in dry may be large, moderate, small, or nonexistent. Therefore, it is important to know whether a place is continuously dry or whether it is wet in one season and dry in another.

To do this, Thornthwaite classified the following subdivisions in terms of humidity and aridity indices.

	Moist climates (A, B, C_2)	Aridity index
r	Little or no water deficiency	0 - 10
S_1	Moderate summer water deficiency	10 - 20
W_1	Moderate winter water deficiency	10 - 20
S_2	Large summer water deficiency	≥ 20
W_2	Large winter water deficiency	≥ 20

	Dry climates (C_1, D, E)	Humidity index
d	Little or no water surplus	0 - 16.7
S_1	Moderate summer water surplus	16.7 - 33.3
W_1	Moderate winter water surplus	16.7 - 33.3
S_2	Large winter water surplus	≥ 33.3
W_2	Large summer water surplus	≥ 33.3

Thornthwaite's method for determining potential evapotranspiration specifies it as an expression of daylength as well as of temperature. Hence the potential evapotranspiration can be used as an index of thermal efficiency. It is not merely a growth index but expresses growth in terms of the water needed for growth.

In equatorial regions where there are very little seasonal variations in temperature, a mean annual temperature of 23°C is taken as the boundary between megathermal and mesothermal climates. In subtropical areas where there are seasonal variations in temperature, a mean annual temperature of 21.5°C is taken as the boundary because the reduced growth and low water need of winter are more than offset by an accelerated growth and increased water need in summer. For a station in the equator with a mean temperature of 23°C during each month, the potential evapotranspiration is 114.0 cm. This was taken by Thornthwaite as an index separating megathermal and mesothermal climates, and other limits for boundaries were taken in an arithematic progression with a common difference of 14 cm. The various limits specified by him are as follows:

T-E index (cm)	Climatic type	
14.2	E' Frost/D' Tundra	
28.5	C_1	
42.7	C_2	Microthermal
57.0	B_1	
71.2	B_2	Mesothermal
85.5	B_3	
99.7	B_4	
114.0	A'	Megathermal

The seasonal variation of potential evapotranspiration is small at the equator. Since the variations in temperature there are small, no season can be called summer, and the sum of the potential evapotranspiration of any 3 consecutive months will be roughly 25% of the annual total. In the case of polar regions where the growing season is within the 3 summer months, the potential evapotranspiration of these months will constitute 100% of the total. The summer concentration of the potential evapotranspiration thus lies between these limits and gradually rises from 25% to 100% with the increase in latitude owing to an increase in the length of midsummer days and increase in the length of winter. The following climatic subdivisions have therefore been suggested in terms of summer concentration of PE values.

Summer concentration percentage	Summer concentration types
	a'
48.0	b_4
51.9	b_3
56.3	b_2
61.6	b_1
68.0	C_2
76.3	C_1
88.0	d'

Based on Thornthwaite's method, Subrahmanyam (1956) and Carter (1954) classified India's climate into 6 regions, i.e., arid, semi-arid, dry subhumid, moist subhumid, humid, and perhumid, and 5 thermal efficiency types. Subrahmanyam (1956) subdivided the major climatic types into subtypes on the basis of moisture deficiency or surplus in winter and summer seasons. Shanbhag (1956) and Bharucha and Shanbhag (1957) also applied the above-mentioned classification method to 104 stations in India (preparation) and Burma.

These climatic classification studies of India were based on the data only of meteorological observatories for which long period normals were available. Since the network of such stations is not dense enough for detailed climatic delineation of arid and semi-arid zones in the country, I classified (1968) the arid and semi-arid zones in India by utilizing not only normals of meteorological observatories but also those of provincial raingauge stations, which are considerably more numerous (Fig. 1). The areas by states of arid and semi-arid zones thus determined are presented in Table 1.

Table 1: Areas of arid and semi-arid zones of India, classified state by state.

State	Area (sq km)		Percentage of area in each state		Remarks
	Arid	Semi-arid	Arid	Semi-arid	
Jammu and Kashmir	70 300	13 780			Cold desert
Rajasthan	196 150	121 020	61	13	
Gujarat	62 180	90 520	20	9	
Punjab	14 510	31 770	5	3	
Haryana	12 840	26 880	4	3	
Uttar Pradesh		64 230		7	
Madhya Pradesh		59 470		6	
Maharashtra	1 290	189 580	0.4	19	
Karnataka	8 570	139 360	3	15	
Andhra Pradesh	21 550	138 670		15	
Tamil Nadu		95 250		10	
Total area, excluding Jammu and Kashmir	317 090	956 750			

Thus, next to Rajasthan, Gujarat has the largest area in arid zone. In south India, the arid zone is mainly confined to Rayalaseema and adjoining parts of Karnataka. As regards the semi-arid zone, 59% of its area is in peninsular India.

As already mentioned, Krishnan and Shankarnarayan (1964) delineated various climatic zones of Rajasthan by the classification methods described above and found that the classification systems of Emberger and Thornthwaite best reflected the vegetation pattern.

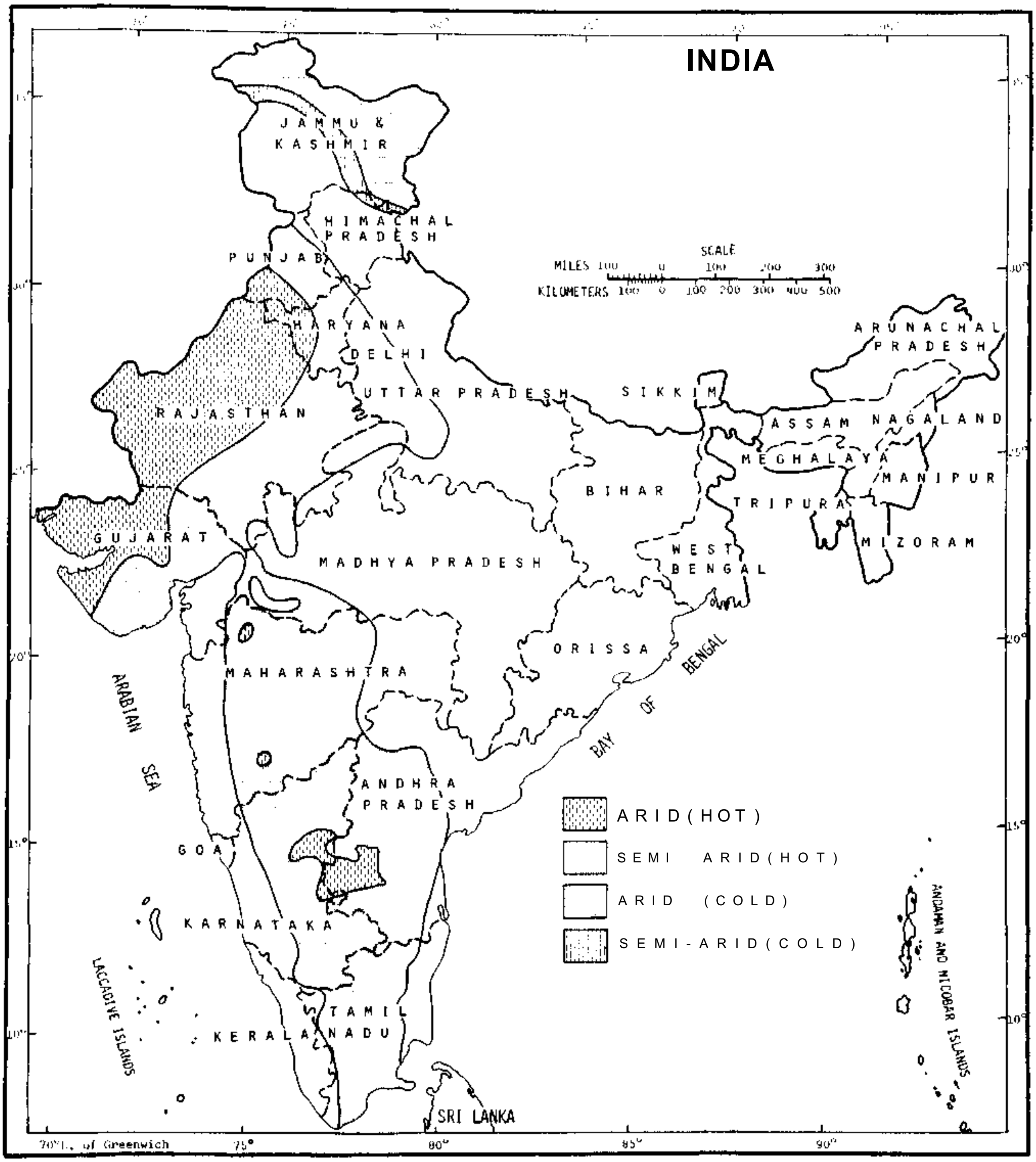

Figure 1: Arid and semi-arid zones of India.

Thornthwaite and Mather's Revised Classification

The bookkeeping procedure and methods of computing the water balance in Thornthwaite's 1948 system was improved by Thornthwaite and Mather (1955). In the original bookkeeping procedure it was assumed that the soil mantle has a capacity to hold 10 cm of water for purpose of evapotranspiration and whenever precipitation (P) falls short of the water need, i.e., potential evapotranspiration (PE), the shortage can be made good from the stored soil moisture so long as it is available. When P is in excess of PE, the excess will go first to recharge the soil to its field capacity, and the surplus will be available for runoff. To convert this surplus into runoff, a factor of 1/2 is used in monthly water balance computations. Thornthwaite and Mather introduced revised procedures for the assumption of the moisture-holding capacity of the soil as well as for the rate of utilization of soil moisture for evapotranspiration when P falls short of PE, for the moisture-holding capacity of a soil depends on its depth, type, and structure. The depth can vary from a few millimeters in shallow sandy soil to 300 mm in deep silt loam soil. But in sandy soil, plants may be more deep-rooted than in clay or silt soil, and thus there may be some compensation. However, considerably varying moisture capacities exist in nature. Further, as the soil dries, it becomes difficult for the additional water to become available from storage to make up the deficiency caused by the excess of PE over P. So Thornthwaite and Mather increased the moisture-holding capacity of the soil from 100 mm to 300 mm and also introduced an exponential depletion pattern of soil moisture during dry periods. For instance, they assumed the following relationship:

$$\text{Storage} = \text{Field capacity} \cdot \exp\left[\frac{\text{Accumulated potential water loss}}{\text{Field capacity}}\right]$$

$$\text{i.e., } S = F \cdot e^{A/F} \qquad \ldots. \quad (5)$$

Where A is the accumulated potential water loss, i.e., accumulated values of PE-P over different periods, and F is the field capacity

Taking logarithm we get

$$\text{Log } S = \log F + A/F \qquad \ldots. \quad (6)$$

Expression of this in differential form, produces

$$\Delta S/S = \Delta A/F \qquad \ldots. \quad (7)$$

Where Δ S is the amount available from soil moisture storage for Et and Δ A is the PE-P value for the period concerned. Thus, ultimately we get a linear model, implying that the change in soil moisture storage that will be available for making up the deficiency for the period concerned is equal to: (Storage/Available moixture capacity) x Deficiency. Thus a linear model has been assumed by Thornthwaite and Mather.

Yet another change made in 1955 in Thornthwaite's classification is the elimination of the weighting factor of 0.6 for the aridity index in the moisture index formula so that moisture index I_m is now defined as $I_H - I_A$, where I_H is the index of humidity defined as 100 S/n, and I_d is the aridity index defined as 100 d/n where S is the water surplus and d is water deficiency. Using average annual data we get:

$$S = P - AE \qquad .... \quad (8)$$

$$d = PE - AE \qquad .... \quad (9)$$

Where P is rainfall, and AE is the actual evapotranspiration, which is equal to the sum of rainfall and change in soil moisture storage for the period concerned, i.e.,

$$AE = P + \Delta S \qquad .... \quad (10)$$

Thus the revised moisture index of the Thornthwaite and Mather (1955) method can be written as

$$I_m = 100 \left[\frac{P-AE-PE+AE}{PE}\right] \qquad .... \quad (11)$$

i.e.,

$$I_m = 100 \left[\frac{P-PE}{PE}\right] \quad \text{OR} \quad 100 \cdot \left[\frac{P}{PE} - 1\right] \qquad .... \quad (12)$$

The moisture regions according to this revised classification are as follows:

	Climatic type	Moisture index
A	Perhumid	100 and above
B_4	Humid	80 - 100
B_3	Humid	60 - 80
B_2	Humid	40 - 60
B_1	Humid	20 - 40
C_2	Moist subhumid	0 - 20
C_1	Dry subhumid	-33.3 - 0
D	Semi-arid	-66.7 - -33.3
E	Arid	- 100 - -66.7

Thus changes in the limits from the 1948 classification are affected only for dry climates. One obvious limitation in the 1955 formulation is the omission of AE based on the actual water balance from the specification of limits for different climatic types. The limits depend only on annual P and PE. The aridity and humidity indices for defining seasonal variation of effective moisture thermal efficiency and its concentration are, however, the same as those of the 1948 classification.

The modified criteria were adopted by Subrahmanyam et al. (1965) for mapping climates of India in terms of moisture and thermal regions. Rao et al. (1972) classified India's climate according to the Thornthwaite and Mather method. However, they used in the water budgeting procedure the potential evapotranspiration values computed by Penman's method (1948). They used data of 230 stations in India and also took into account available water capacity of soil on the basis of soil type.

According to this classification, Saurashtra, Kutch, and west Rajasthan constitute the principal arid regions of the country. The Bellary-Anantapur area in the states of Karnataka and Andhra Pradesh, respectively, and the Tirunelveli region of Tamil Nadu also come under this category. Practically the whole of the peninsula east of the Western Ghats, except for its northeast portion, and small areas around Visakhapatnam-Kalingapatam region in coastal Andhra Pradesh and the Gaya-Jamul area in Bihar fall within the semi-arid zone. A strip around the arid zone of northwest India also falls in this category. The west coast and adjoining Ghats, the Himalayas, Assam, and Meghalaya and small areas at high altitudes in Aravallis and Vindhyas fall within the humid to per-humid zone. The remaining areas in India are classified as subhumid. The findings of this classification broadly conform to the features brought out by Subrahmanyam et al. (1965) using Thornthwaite's PE values for water budgeting except for a semi-arid pocket in Bihar and an arid strip around Tuticorin in Tamil Nadu.

CLASSIFICATION USING RATIOS OF PRECIPITATION TO EVAPORATION

Transeau (1905) suggested the use of both precipitation and evaporation data in an attempt to combine in a single number the influences of temperature and moisture on the distribution of forest trees in the eastern USA. Owing to lack of reliable evaporation data, Meyer (1926) recommended the use of a partial substitute for evaporation, i.e., the ratio of precipitation (in millimeters) to the absolute saturation deficit of the air expressed in millimeters of mercury. Prescott (1934) and Trumble (1937) used this approach for their studies of moisture conditions and effective soil moisture, respectively, and Hosking (1937) used it for India.

In the earlier classification of Koppen (1936), Thornthwaite (1931, 1933), and others, evapotranspiration was assumed to depend mainly on mean monthly or mean annual temperature, which may not be the case. So, the ratio of precipitation to evaporation, if used in climatic classification, may explain the vegetation better. The main limitation in this procedure, however, is that the evaporation data are extremely scanty in the world and more so in India. Hence for this approach, estimation of evaporation from meteorological parameters becomes important. Considerable effort has been made in this direction by scientists throughout the world; the earliest ones in India were by Leather (1913) and Raman and Satakopan (1934). Based on evaporation data collected at Pusa, Leather developed a formula for evaporation in terms of mean temperature, atmospheric moisture deficit, and wind speed. Adopting the approach of Rowher (1931), Raman and Satakopan used the following formula to compute evaporation at several stations in India.

$$E = (1.465-0.0186B)\ (0.44 + 0.118W) \left[\frac{100}{h} - 1\right] e \quad .... \quad (13)$$

Where E is the mean evaporation in inches in 24 hours,
B is the mean barometer reading in inches of mercury,

W is the mean wind velocity in miles per hour,
h is the mean relative humidity in percent, and
e is the mean vapor pressure in inches of mercury.

Using this formula, Bharucha and Shanbhag (1957) computed the P/E index for 104 stations in India (prepartition) and Burma and compared the ranges of these indices with the native vegetation types of India, as presented by Champion (1936). Their main findings were as follows:

Arid and semi-arid regions with thorn forest as characteristic vegetation have indices ranging from 1 to 5. Places with deciduous forests have P/E indices that fall in the range 5 to 15. Tropical moist deciduous (soil) regions fall in the range 15 to 20. While the range for the tropical semi-evergreen region is above 50.

In the USSR, indices of K = P/E where P is annual precipitation in millimeters and E is annual evapotranspiration in millimeters have been used (Ivanov 1948). In this formula, E is derived from the following relationship:

$$E = 0.0018\ (25 + t)^2\ (100-a) \qquad \ldots\ (14)$$

Where t is the mean monthly temperature (°C), and
a is the mean monthly relative humidity (%).

The critical values for different climatic regions are as follows:

Insignificant moisture regions, i.e., deserts	0.00 - 0.12
Scanty moisture regions, i.e., semideserts	0.13 - 0.29
Insufficient moisture regions, i.e., steppes	0.30 - 0.59
Moderate moisture regions, i.e., forested steppes	0.60 - 0.99
Sufficient moisture regions	1.00 - 1.49
Excess moisture regions	≥ 1.50

According to Popov (1948) the index of aridity (P) is given by the following equation:

$$P = \frac{\Sigma g}{2.4\ (t - t')\ r} \qquad \ldots\ (15)$$

Where Σg is annual amount of effective precipitation, t-t' is annual mean wet bulb depression (in °C), r is a factor depending on daylength.

Budyko (1956) suggested the following hydrothermal coefficient (K) for classification purposes.

$$K = \frac{r}{0.18\ \Sigma\theta} \qquad \ldots\ (16)$$

Where $0.18\ \Sigma\theta$ gives the potential evapotranspiration in millimeters, $\Sigma\theta$ is the annual sum of daily mean temperatures higher than 10°C, and r is annual precipitation in millimeters.

As already stated, Prescott (1938) in Australia found that a climatic index P/S.D would be useful in delineating climatic boundaries. Prescott (1949) further established that the degree of soil leaching or the intensity of evapotranspiration was determined by some power of evaporation or saturation deficit close to 75% and the indices P/E 0.75 or P/S.D 0.75 were suggested for universal application as aridity indices. Thus with the improvement of the earlier index, he found that the index 5 S.D 0.75 was in effect the first measure of evapotranspiration for the limiting conditions of arid regions in Australia (Prescott 1956).

In Canada, a climatic index I, given by the following formula suggested by Sly (1970), has been used for soil climatic classification purposes.

$$I = \frac{P}{P + SM + IR} \times 100 \quad .... \quad (17)$$

Where P is the growing season precipitation, SM is the water in the soil at the beginning of the growing season available to crops, and IR is the growing season's irrigation requirement (calculated).

Thus the index is the ratio of percentage contribution of growing season precipitation to the total amount of water required by the crop, if lack of water is not to limit its production. Baier and Robertson (1966), Holmes and Robertson (1958), and Robertson and Holmes (1959) have evolved methods for calculating irrigation requirements from climatic data. These approaches have been used in the index suggested by Sly (1970), who found that there was good relationship between the values of the index and Canadian soil-climate zones.

CLASSIFICATIONS BASED ON DURATION OF MOISTURE AVAILABILITY PERIODS

Troll's Classification

Troll (1965) defined humid months as those in which mean rainfall exceeds mean potential evapotranspiration. He divided the tropical climates into the following classes.

1. Tropical rainy climate with 9.5 to 12 humid months
2a. Tropical summer-humid climates with 7 to 9.5 humid months
 b. Tropical winter-humid climates with 7 to 9.5 humid months
3. Wet-dry tropical climates with 4.5 to 7 humid months
4a. Tropical dry climates with 2 to 4.5 humid months (in summer)
 b. Tropical dry climates with 2 to 4.5 humid months (in winter)
5. Tropical semidesert climates with less than 2 humid months

According to Troll, this classification has been found to be satisfactory to explain vegetation zones of tropical Africa and South America. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) adopted this method for classification of semi-arid tropics in India. However, their recent study shows that application of this system for delineation of semi-arid zones in India using mean monthly potential evapotranspiration computed by Penman's method (1948) is not satisfactory, since it places in the semi-arid zone areas of the west coast as well as some regions in Bihar and Orissa that normally fall under subhumid to humid zones. Such discrepancies may be partly due to a rather stringent stipulation in the method that mean monthly rainfall (P) should exceed potential evapotranspiration (PE) if the month concerned is to be a humid month. The duration when $P \geqslant PE/2$ is computed on a weekly basis would probably be sufficient, since that would fairly adequately represent the duration of the growing season.

Hargreaves' Classification

Hargreaves (1971) defined a moisture available index (MAI) as the ratio at the rainfall value expected with 75% probability for the concerned period to the estimated potential evapotranspiration. If this ratio is 0 to 0.33 during all months in a region, the climate of the region is classified as *very* arid. If there are only 1 or 2 months with MAI values exceeding 0.34 in the year, the climate is classified as arid, and if there are 3 or 4 consecutive such months the climate is considered semi-arid. Hargreaves (1975) gave the following moisture deficit classifications.

MAI	
0.00 to 0.33	Very deficient
0.34 to 0.67	Moderately deficient
0.68 to 1.00	Somewhat deficient
1.00 to 1.33	Adequate moisture
> 1.34	Excessive moisture

The probability level as well as ranges of MAI chosen in this classification appear to be rather high. Hargreaves (1971) himself stated that,for some crops or special conditions, a different probability level may be more appropriate. It is useful to try this method for climatic delineation in India with an MAI of 0.25 as the limit for moderate droughts and 0.50 for the growing season.

Papadakis' Classification

Papadakis (1961, 1970a, 1975) evolved a new climatic classification of the world incorporating the following special features:

a. Average daily maximum and minimum temperatures were used and greater importance was attached to night temperatures and the vernalization effect of low temperatures.

b. Winter severity and length of the frost-free season were considered as a fundamental characteristic of climate.

c. The water balance concept was included, with potential evapotranspiration being determined as a function of the saturation deficit at midday.

d. A large number of thermic and hydric types were recognized for classifying monthly climates of different locations in the world.

There is a very large number of thermic types in Papadakis' climatic classification. His main thermic types are as follows:

1. Tropical (with 9 subtypes)
2. Terra fria (with 9 subtypes)
3. Desert (with 9 subtypes)
4. Subtropical (with 7 subtypes)
5. Pampean (with 9 subtypes)
6. Mediterranean (with 9 subtypes)
7. Marine (with 8 subtypes)
8. Humid continental (with 3 subtypes)
9. Steppe (with 8 subtypes)
10. Polar-Alpine (with 5 subtypes)

Various ranges of values of lowest, average daily maximum and minimum temperatures, average vapor pressure and precipitation are prescribed in the classification for different thermic types, thereby facilitating elaborate climatic delineations for different regions.

To determine the hydric type of the climate, mean monthly potential evapotranspiration (E) is calculated from the data of mean daily maximum temperature and vapor pressure. The following formula suggested by Papadakis (1975) is used.

$$E = 5.625\ (e_{ma} - e_d) \qquad \ldots\ (18)$$

Where E is the monthly potential evapotranspiration in millimeters of water, e_{ma} is saturated vapor pressure in mb corresponding to the average daily maximum temperature, and ed is the average vapor pressure of the month in mb.

On the basis of monthly precipitation (P) and E, the water stored (W) from the previous rains is determined. Then the following moisture index (H) is defined.

$$H = \frac{P + W}{E} \qquad \ldots\ (19)$$

On the basis of this index, hydric types are determined using the following criteria.

P+W/E value	Climatic type (hydric)
< 0.25	Arid (a)
0.25 to 0.50	Dry (s)
0.50 to 0.75	Intermediate (c)
0.75 to 1.00	Intermediate humid (y)
> 1.00 (with P<E)	Posthumid (P)
1.00 to 2.00 (with P+W-E<100 mm)	Humid (G)
> 2.00 (with P+W-E>100 mm)	Wet (W)

Information on winter severity, length of the frost-free season, leaching rainfall, drought stress, and seasonal variation of temperature, etc., are also incorporated in the classification. Papadakis (1970b) also studied the climatic requirements of individual crops and was able to explain the distribution of crops in terms of an elaborate climatic classification method introduced by him. His method is oriented towards agriculture and crop requirements, and criteria for different thermic and hydric subtypes of climate have been chosen mainly from this point of view. Hence there is considerable scope for the application of this method in India for detailed climatic classification.

Method of Cocheme' and Franquin

Matching the duration of a crop's growth cycle to that of water availability in different regions is an important task in agricultural planning. In this connection, duration of periods during which rainfall (P) exceeds selected levels of evapotranspiration (ET) is a most useful index of agricultural potential. Accordingly, in the studies of Cocheme and Franquin (1967) on semi-arid areas south of the Sahara in West Africa and of Brown and Cocheme (1969) on the highlands of East Africa the following limits of water availability were chosen.

$P > ET$	Humid
$ET > P > ET/2$	Moist period
$P = ET/2$ to $ET/4$	Moderately dry period
$P = ET/4$ to $ET/10$	Dry period
$P < ET/10$	*Very* dry period

Apart from rainfall, the available water in the root zone (i.e., sum of rainfall and soil moisture storage) was also compared with PE for the above ranges, and crop water availability calendars were prepared for the seeding, emergence, growth, and maturation stages. Adopting this approach, Raman and Srinivasamurthi (1971) worked out water-availability periods for crop planning for 220 stations in India. They also produced calendars of water-availability periods for various stations in India and presented maps of several water-availability regimes. They noticed that the climatic classifications do not show a simple relationship with lengths of water-availability periods. They also pointed out that climatic classifications by Thornthwaite and Mather's approach are too broad to bring out the differences in the productivity potential of stations within the same class. The differences in agricultural potential appear to be closely related to the durations of water-availability periods.

The Climatic Water Budgeting Approach to the Growing Season

In the Central Arid Zone Research Institute, Jodhpur, maps of India showing the normal duration and commencement and cessation dates of the crop-growing season with nil or slight water stress under rainfed farming with normal rainfall were prepared by Krishnan and Thanvi in 1972 (Figs. 2-4). These were computed by the climatological water-budgeting approach of Thornthwaite and Mather (1955), taking into account soil storage values for various major soil types of the country and using mean monthly potential evapotranspiration values computed by Penman's method.

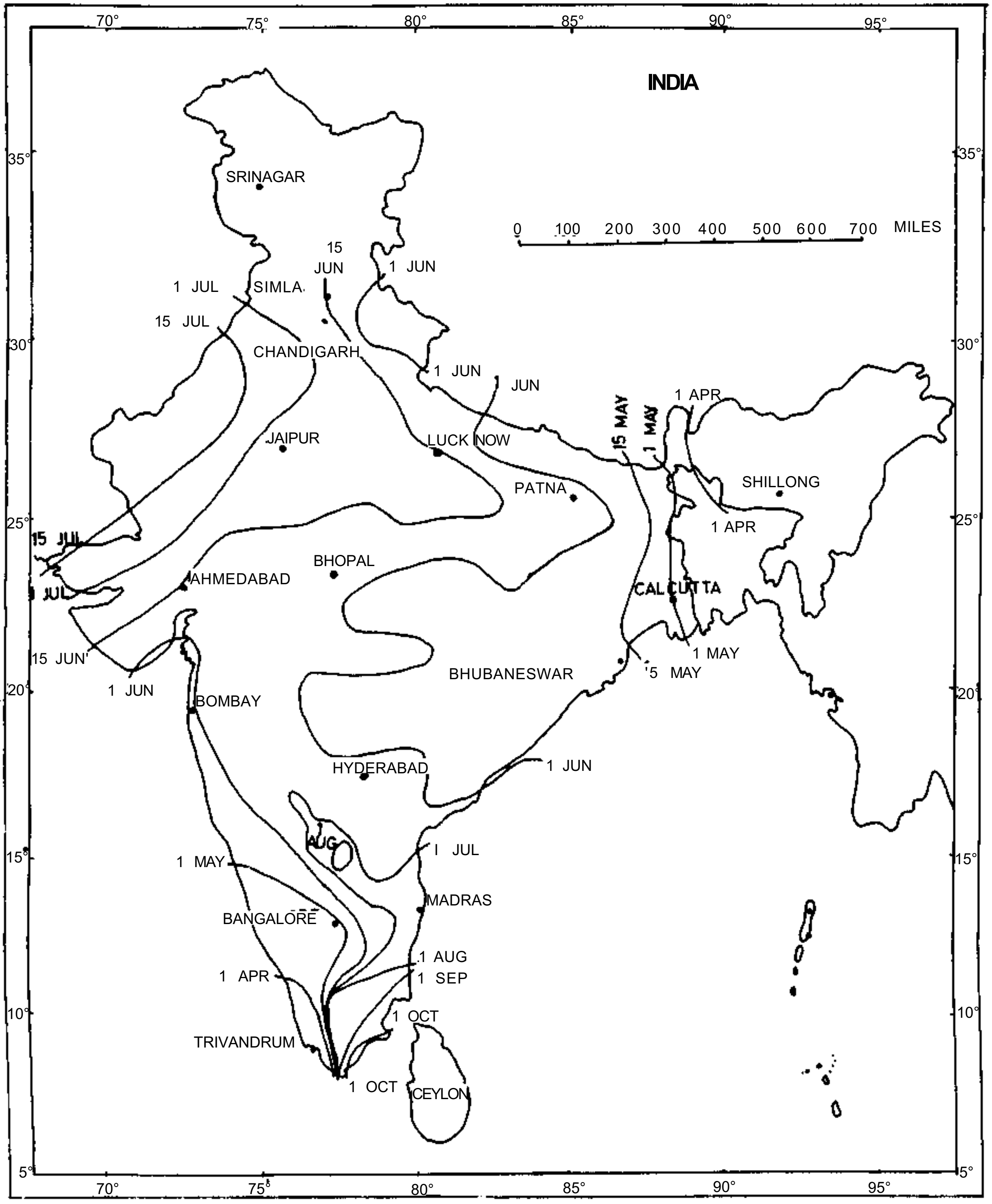

Figure 2: India, normal commencement date of crop growing season with nil or slight moisture stress under rainfed farming.

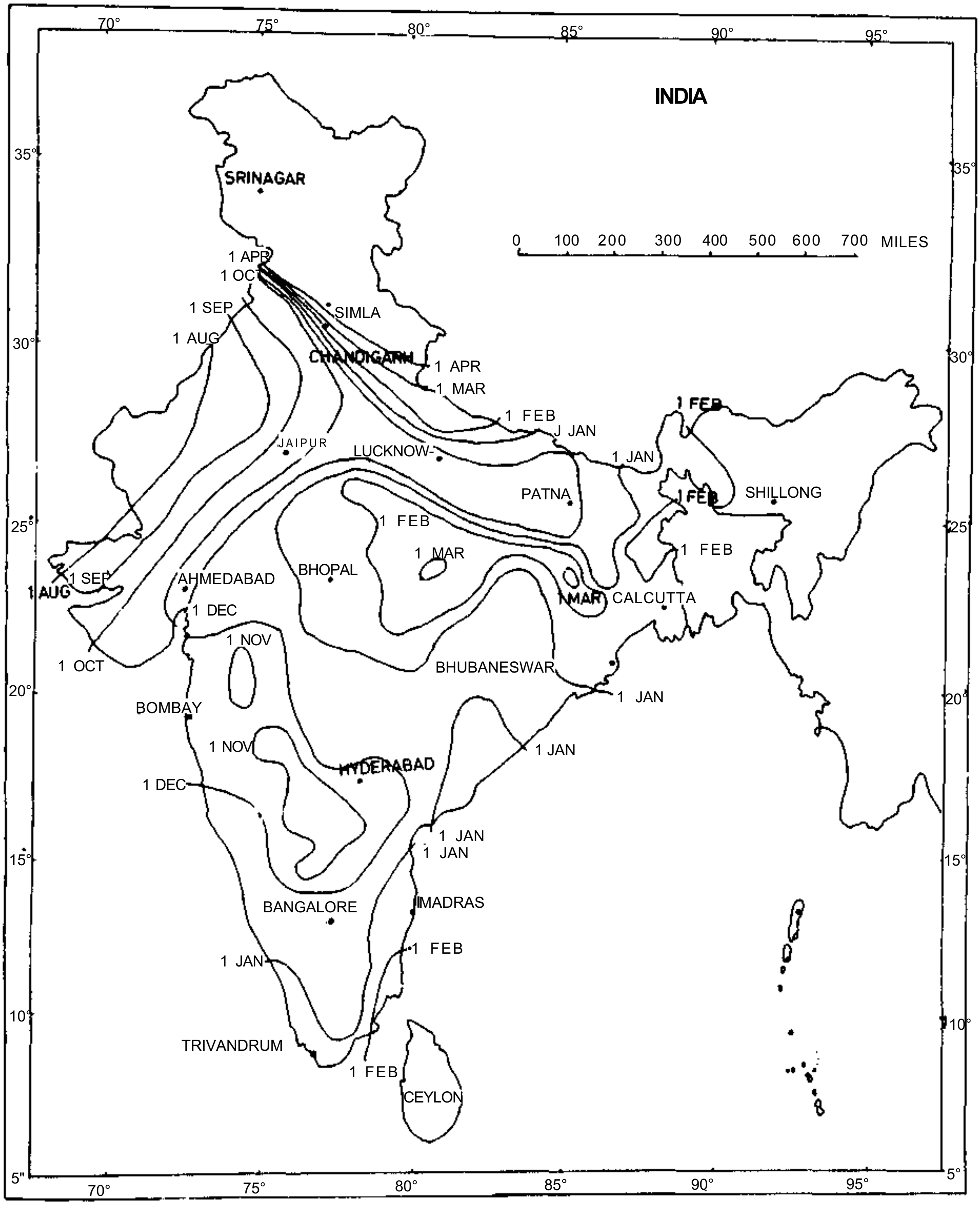

Figure 3: India, normal cessation date of crop season with nil or slight moisture stress under rainfed farming.

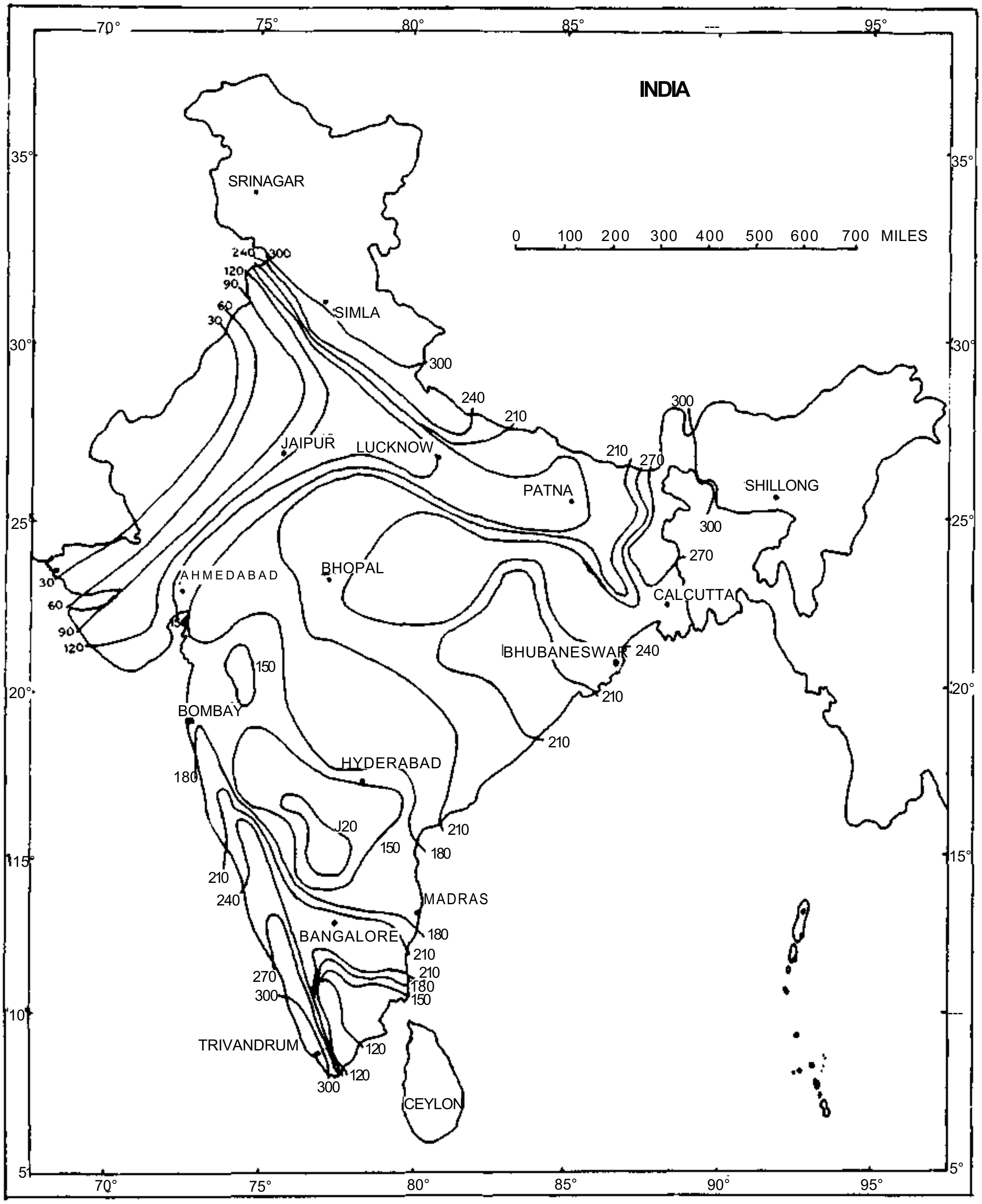

Figure 4: India, normal duration in days of crop growing season with nil or slight water stress under rainfed farming.

The crop-growing season with nil or slight water stress under rainfed farming was defined as the period for which actual evapotranspiration (AE), estimated by taking into account both the rainfall and the stored soil moisture, exceeds half the value of potential evapotranspiration (PE), i.e., the period for which $AE \geqslant PE/2$.

The period of moderate drought under rainfed farming was defined as the period for which actual evapotranspiration lies between 1/4th and half of the value of the potential evapotranspiration, i.e., $PE/2 > AE \geqslant PE/4$. The period of severe drought under rainfed farming was defined as $AE < PE/4$.

The crop-growing season with little water stress under rainfed farming for the year with normal rainfall conditions varies from less than a month in the Jaisalmer district and western portions of Barmer, Jodhpur, Bikaner, and Ganganagar districts in western Rajasthan to more than 300 days in Assam and parts of Kerala. The period covers the entire 365 days in many parts of Assam. The portions of the northwest and arid zone other than the districts mentioned above have a normal growing season of 30 to 90 days, while the arid zone in the southern peninsula has an average growing period of 120 days, due to receipt of rainfall during the northeast monsoon. Another region having less than 120 days of growing season is the southernmost districts of Tamil Nadu, which receive most of their rainfall during the northeast monsoon.

The black-soil regions of Vidarbha, Madhya Pradesh, and adjoining Rajasthan, as well as coastal Andhra Pradesh, Orissa, Bengal, and eastern Bihar have a growing season exceeding 210 days. In the Gangetic alluvial plains of Uttar Pradesh and western Bihar, the growing season is less than 180 days, with an increase towards the south as well as north. In the western coastal areas, the growing season gradually increases from 180 days in Maharashtra State to more than 300 days with the progressive increase in rainfall due to northeast monsoon and premonsoon thunder showers. Interior peninsular India has generally less than 180 days of growing season, except for the portions covering south Karnataka and adjoining Tamil Nadu, where values exceed 210 days because of contributions from both monsoon and premonsoon thunder showers.

Dates of commencement. Commencement of the crop-growing season is generally much ahead of the normal onset of the southwest monsoon in Bengal, Bihar, Orissa, Madhya Pradesh, Assam, Kerala, and Karnataka, due to considerable premonsoon thunder showers there. This feature is specially marked in Karnataka, Kerala, West Bengal, and Assam. The beginning of the growing season in the west peninsula varies from April in Kerala to the first week of June in north Maharashtra. The gradient is from east to west in north India. It varies from 1 April in Assam to later than 15 July in western Rajasthan. In Tamil Nadu, the growing season begins only in September/October in the Ramanathapuram and Tirunelveli districts, etc., which receive rainfall mainly during the northeast monsoon.

Date of cessation. The growing season ends by the end of September in the arid zone of northwestern India, while it ends in October-November in the southern arid regions. The extension of the growing season beyond February occurs mainly in east Madhya Pradesh, and southern Bihar, West Bengal, and Assam. In southeast Tamil Nadu the growing season also extends beyond January-February, but here it also starts very late.

Maps of India showing the beginning and end of the severe drought period under rainfed conditions (Figs.5-6) were also prepared by Krishnan and Thanvi (1972). Such droughts do not occur in Assam, South Kerala, and eastern part of West Bengal. The severe drought begins on 1 October in the northwest arid zone and even much earlier in the western part. In the southern arid zone and adjoining interior portion of Maharashtra State, the severe drought begins by the end of November. However, in most of the central portion of the country to the east of the line joining Delhi, Udaipur, and Baroda, the commencement is only in the month of February or later. This is due to high water-holding capacity of the black soil region. In the western coastal region of Maharashtra and Karnataka states, the rainfall is very high. In spite of this severe drought begins by December-January, probably because of the lower water-holding capacity of the soil. Severe drought commences only after April in Gwalior, Guna, Jabalpur Pendra, and Satna region of Madhya Pradesh.

On the average, the severe drought ends outside the regions of east Bihar, Tamil Nadu, Karnataka, and southern Andhra Pradesh only by 1 May; in most of these regions it ends mainly after 15 May. In the arid zone of northwest India the severe drought ends normally during the second fortnight of June, except in the Jaisalmer and Bikaner regions where normal cessation of severe drought is only by the first week of July.

CRITERIA FOR DEMARCATION OF SOIL CLIMATIC ZONES OF INDIA

Krishnan and Mukhtar Singh (1968) demarcated soil climatic zones of India by superimposing the moisture index ([P-PE]/PE x 100) and mean air temperature isopleths on a soil map of India showing major soil types. Mean annual potential evapotranspiration values (PE) were computed by Thornthwaite's method, and P is mean annual precipitation (Fig. 7). Values for all stations in India and neighboring countries for which long-term normals are available were utilized for the study. The following scale was adopted in defining climatic zone in terms of moisture indices.

Zone No.	Moisture-index value	Moisture belt
1	< - 80	Extremely dry
2	- 60 to - 80	Semidry
3	- 40 to - 60	Dry
4	- 20 to - 40	Slightly dry
5	0 to - 20	Slightly moist
6	0 to + 50	Moist
7	+ 50 to +100	Wet
8	> 100	Extremely wet

The classes in terms of temperature were as follows:

	Mean annual temperature	Temperature belt
A	28°C or more	Very hot
B	25°C to 28°C	Hot
C	20°C to 25°C	Mild
D	10°C to 20°C	Cold
E	10°C or less	Very cold

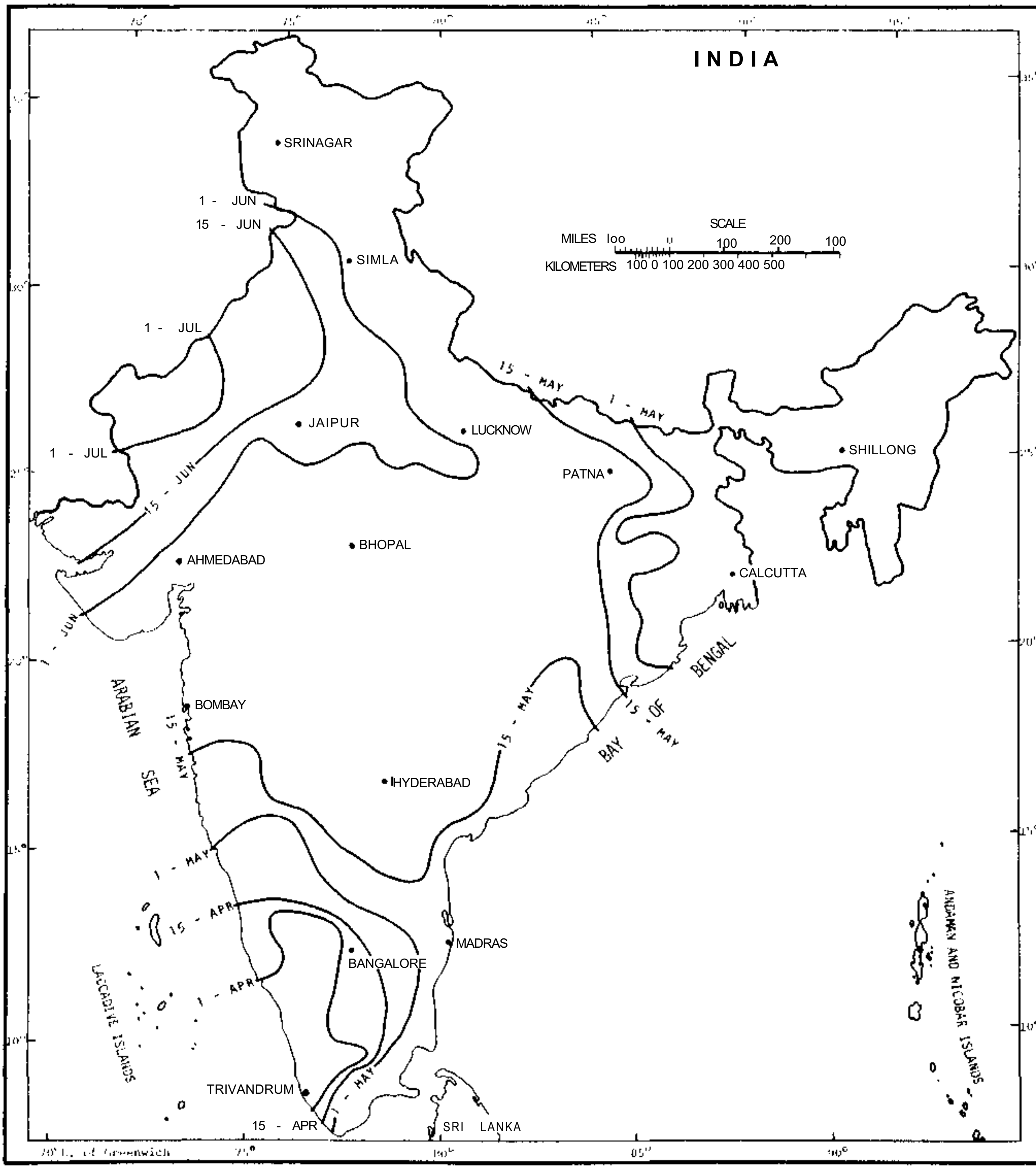

Figure 5: Normal cessation date of severe drought periods under rainfed farming.

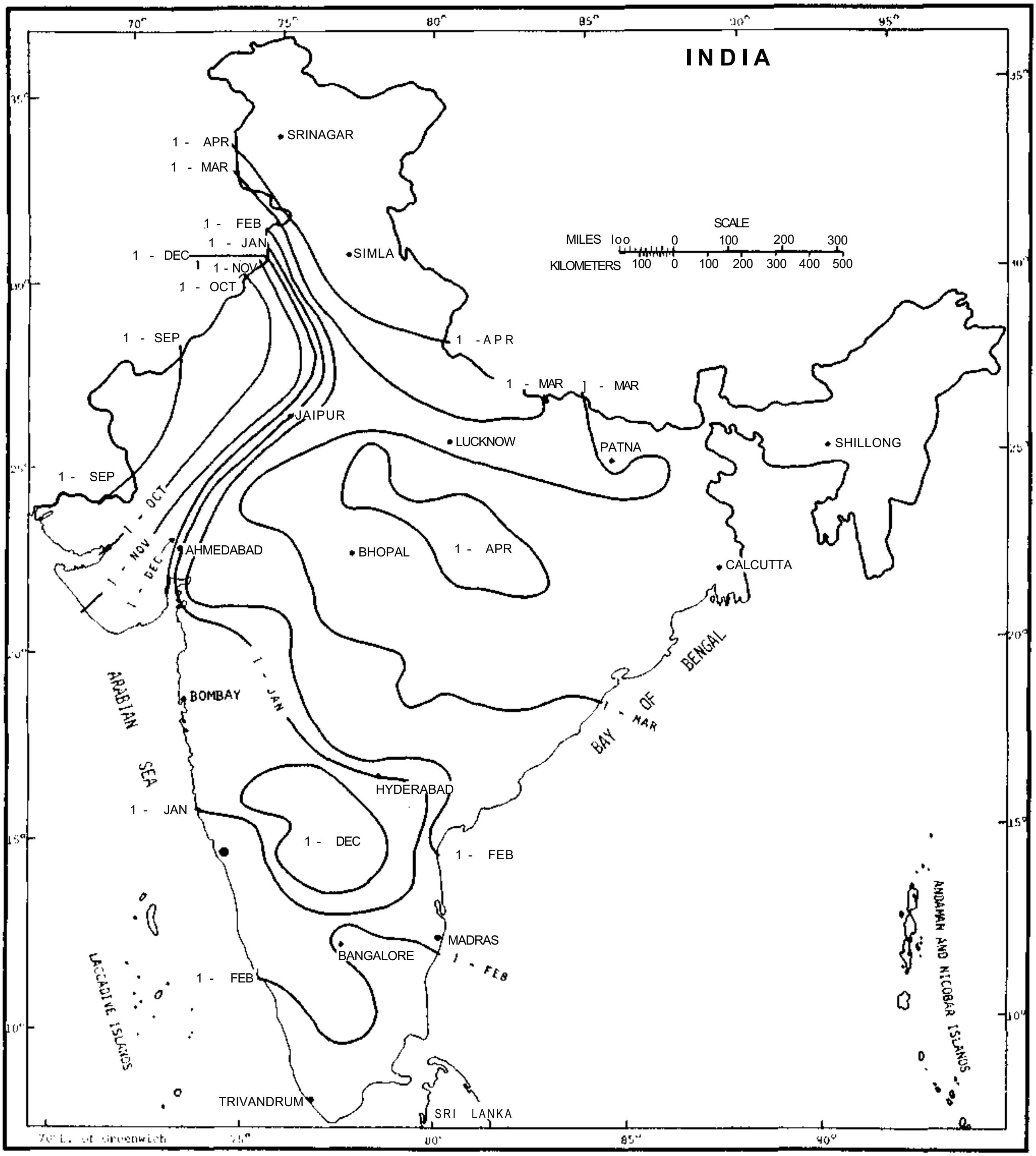

Figure 6: Normal commencement date of severe drought periods under rainfed farming.

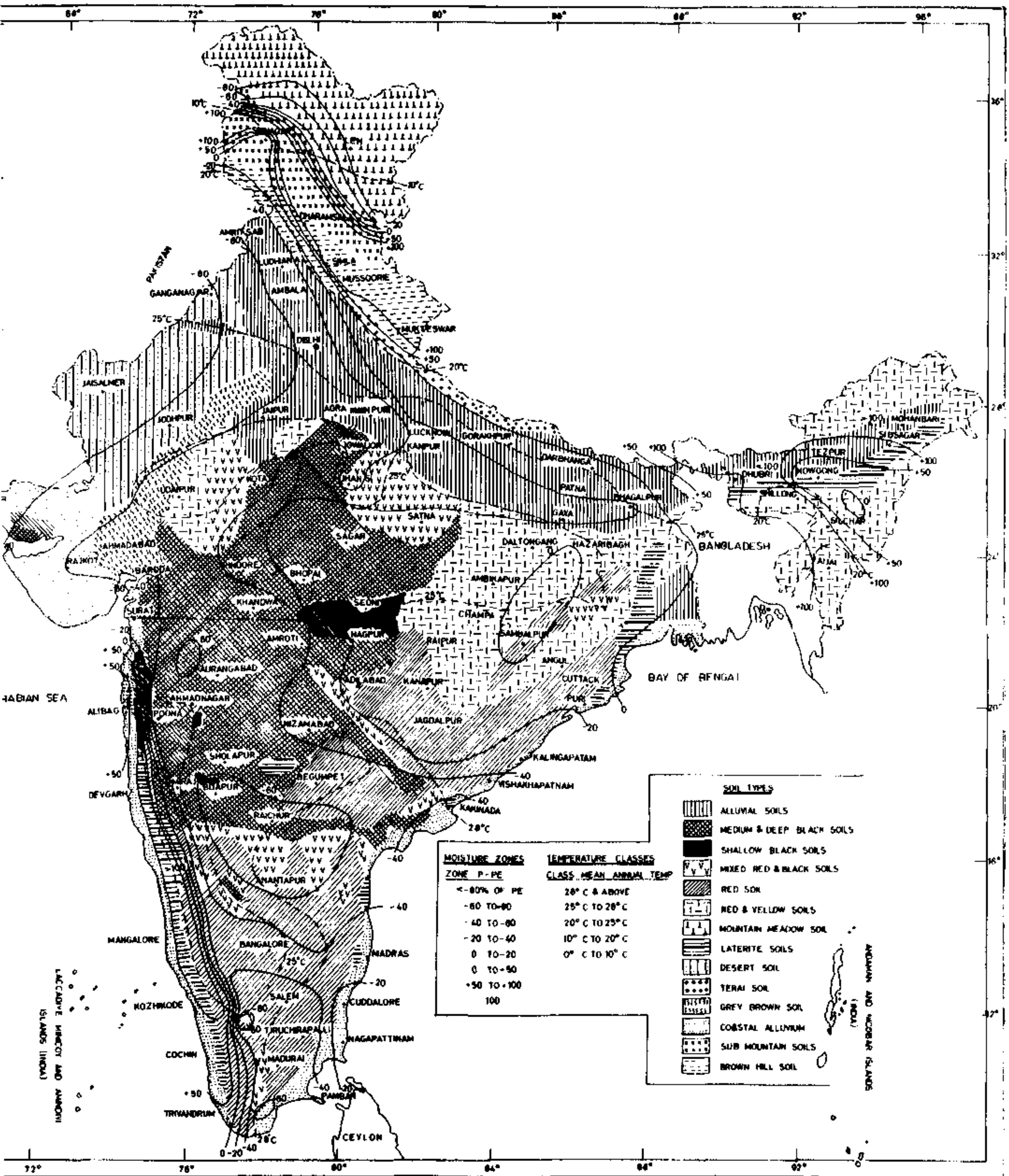

Figure 7: Soil-climatic zones of India.

The climatic zones based on the moisture index and thermal index were superimposed on a soil map of India showing major soil types to demarcate 64 soil climatic zones of India. The districts included in each of these soil climatic zones, their geographical coverage, and a critical analysis of their cropping patterns have been presented by Krishnan and Mukhtar Singh (1968). The water deficiency and temperature patterns during *kharif* (rainy season - Jun—Sep) and *rabi* (postrainy season - Oct-Jan) cropping seasons were also discussed.

The Crop-Growing Season in Different Climatic Zones

Table 2 shows the duration of the crop-growing season under rainfed farming of 30 selected stations representing typical soil climatic zones of India. While climatic zone 1 has a duration of 10 days, the duration is a whole year in portions of Assam and Kerala coming under zone 8. Duration of the crop-growing season also varies considerably within a particular climatic zone with the variation in the water-holding capacity of the soils. For instance, the duration of the crop-growing season in alluvial soil and medium to deep-black soil stations of climatic zones No.2 to 6 is shown below.

Zone	Alluvial soil	Medium to deep black soil
2	70 days	127 days
3	119 days	207 days
4	157 days	244 days
5	195 days	253 days
6	195 days (Red sandy soil)	275 days

Thus considerable variation exists in the crop-growing season in the same climatic zones under different soil types. In the climatological water budgeting mentioned above, the available soil moisture storage in each station, depending upon its soil type, has been taken into account. Accordingly, in a region with black soil and high available moisture storage, soil moisture is available to plants from storage for a long time after the rains cease. This results in longer crop-growing seasons in these soil climatic zones. Such factors must be taken into account in selecting the proper cropping pattern for each of these zones. Similarly in determining other forms of land use, such as establishment of different types of forests, pasture lands, etc., such a water budgeting analysis on a short-term basis would be very useful. Ecologically, the native vegetation as well as forest types of different regions are also dependent on temperature conditions, soil type, and moisture-availability periods based on the water-balance, etc., as described above. Therefore, a detailed analysis would be valuable in making resource inventory and in land-use planning.

Table 2: Duration of the crop-growing season at typical stations in several soil climatic zones.

S. No.	Name of station	Soil climatic zone: Moisture zone	Soil climatic zone: Soil type	Total annual PE (mm) (Penman)	Total annual rainfall (mm)	Moisture index (%)	Duration of crop-growing season under rainfed farming: Duration	Duration of crop-growing season under rainfed farming: No. of days
1	2	3	4	5	6	7	8	9
1.	Bikaner	Zone 1	Desert soil	1779	305	-83	9 Aug to 18 Aug	10
2.	Jodhpur	Zone 2	Desert soil	1843	380	-79	8 Jul to 14 Sep	59
3.	Hissar	Zone 2	Alluvial soil	1616	446	-72	8 Jul to 15 Sep	70
4.	Bijapur	Zone 2	Medium to deep black soil	1650	574	-65	30 Jun to 3 Nov	127
5.	New Delhi	Zone 3	Alluvial soil	1659	714	-57	27 Jun to 23 Oct	119
6.	Udaipur	Zone 3	Red and yellow soil	1381	660	-52	15 Jun to 27 Nov	166
7.	Ahmedabad	Zone 3	Grey, brown soil	1677	823	-51	14 Jun to 26 Nov	166
8.	Hanamakonda	Zone 3	Red soil	1787	945	-47	4 Jun to 8 Dec	188
9.	Khandwa	Zone 3	Medium black soil	1729	961	-44	7 Jun to 3 Dec	207
10.	Bangalore	Zone 4	Red loam soil	1501	924	-38	27 Apr to 23 Dec	241
11.	Allahabad	Zone 4	Alluvial soil	1527	1027	-33	15 Jun to 18 Nov	157
12.	Nizamabad	Zone 4	Red sandy soil	1591	1086	-32	31 May to 28 Dec	212
13.	Nowgong	Zone 4	Mixed red and black soil	1428	1044	-27	6 Jun to 8 Feb	238
14.	Guna	Zone 4	Medium to deep black soil	1512	1220	-26	6 Jun to 14 Feb	244

Continued

Table 2. *Continued*

S. No.	Name of station	Soil climatic zone: Moisture zone	Soil type	Total annual PE (mm) (Penman)	Total annual rainfall (mm)	Moisture index (%)	Duration of crop-growing season under rainfed farming: Duration	No. of days
15.	Angul	Zone 5	Red and yellow soil	1540	1329	-14	6 Jun to 6 Jan	215
16.	Saugor	Zone 5	Medium black soil	1543	1394	-10	3 Jun to 31 Jan	243
17.	Dharbanga	Zone 5	Alluvial soil	1363	1257	- 8	26 May to 6 Dec	195
18.	Asansol	Zone 5	Red soil	1468	1392	- 5	23 May to 30 Jan	253
19.	Jamshedpur	Zone 5	Mixed red and black soil	1438	1391	- 3	22 May to 20 Feb	275
20.	Umaria	Zone 6	Medium to deep black soil	1343	1352	+ 1	1 Jun to 2 Mar	275
21.	Seoni	Zone 6	Shallow black soil	1420	1446	+ 2	29 May to 15 Feb	263
22.	Jagdalpur	Zone 6	Red loam soil	1393	1534	+10	22 May to 5 Jan	229
23.	Ranchi	Zone 6	Red and yellow soil	1304	1463	+12	25 May to 3 Mar	283
24.	Sambalpur	Zone 6	Red sandy soil	1452	1661	+14	30 May to 10 Dec	195
25.	Calcutta	Zone 6	Alluvial soil	1377	1582	+15	30 Apr to 14 Jan	260
26.	Marmagoa	Zone 7	Coastal alluvium	1601	2612	+63	17 May to 16 Dec	214
27.	Mangalore	Zone 8	Coastal alluvium	1463	3467	+137	25 Apr to 26 Dec	246
28.	Jalpaiguri	Zone 8	Terai soils	1250	3353	+168	24 Mar to 19 Jan	302
29.	Silchar	Zone 8	Red and yellow soil	1186	3225	+172	Entire year	365
30.	Dibrugarh	Zone 8	Alluvial soil	996	2759	+177	Entire year	365

Classification According to Rainfall Criteria Related to Moisture Requirements of Various Crops

In 1976, the National Agricultural Commission carried out the climatic delineation of India by examining the monthly rainfall distribution at all provincial raingauge stations of India. They chose limits that have a closer relation to the broad requirements of crops. Since the time-span of most of the crops is usually 90 days or more, the following limits were set by them.

1. Rainfall of greater than 30 cm per month for at least 3 consecutive months would be suitable for a crop like paddy whose water need is high.
2. 20 to 30 cm per month for not less than 3 consecutive months would be suitable for crops whose water need is high but less than that of paddy, e.g., maize and black gram.
3. 10 to 20 cm per month for at least 3 consecutive months is considered suitable for crops requiring less water, e.g., pearl millet and small millets.
4. 5 to 10 cm per month is just sufficient for crops that have low water requirements, e.g., field beans (*P. aconitifolius*) and ephemeral grasses.
5. Rainfall less than 5 cm per month is not of much significance for crop production.

Accordingly they adopted the following symbolic representation for rainfall levels:

Symbol	Monthly rainfall (cm)
A	Greater than 30 cm
B	20-30
C	10-20
D	5-10
E	Less than 5 cm

In denoting the year's distribution of rainfall the southwest monsoon months of June to September are given the central position in brackets. To the right is the distribution for the postmonsoon months of October to January and to the left is that of premonsoon months, February to May. The number of months in the respective season in which monthly rainfall is within the specific limit mentioned above is indicated by a number as a subscript to the symbols given above. Maps showing different rainfall categories were drawn for various states, and interrelated rainfall categories were drawn for various states and combined with *tahsil* ("county") cropping patterns and relative yield indices of crops of different states by the National Agricultural Commission.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

There is considerable scope for detailed climatic delineation of India using the concepts of Hargreaves and Papadakis. Precise evaluation of climatically analogous regions in the semi-arid tropics of the world for improvement of cropping patterns and introduction of improved crop varieties from one region to another requires realistic water-budget computations in the crop-growing season using short-period data (a week or 5 days). The linear model of Thornthwaite and Mather (1955) assumes the relationship mentioned in equation 5 ($S = F . e\ A/F$). This model can be improved by considering the soil as made up of 2 layers, i.e., a top layer where removal at a potential rate can be assumed and a deeper layer where the linear model suggested by Palmer (1965) can be assumed. Further refinement can be introduced by assuming a multi-layer approach and application of the versatile moisture budget as proposed by Baier and Robertson (1966) and Baier (1967). Numerous details along these lines were given by me in 1979. Considerable international teamwork with good coordination is required to achieve these objectives

AGROCLIMATIC CLASSIFICATION FOR ASSESSMENT OF CROP POTENTIAL AND ITS APPLICATION TO DRY FARMING TRACTS OF INDIA

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SUMMARY

To assess the agroclimatic potential of a region, it is necessary to classify it into different agroclimatic zones. This paper develops a theory for agroclimatic classification based on Hargreaves' "moisture availability index" (MAI), which is defined as the ratio of assured rainfall to potential evapotranspiration. Three improvements have been made on the earlier methodology: (1) the MAI has been taken on a weekly basis; (2) minimum assured rainfall has been considered at different probability levels; and (3) different values of MAI and their duration have been used as appropriate to various crop phases. The classification, however, is recommended with the MAI at the 50% probability level, which is considered to be optimum for dryland areas. The main classification has been further subdivided according to the duration of the water stress period and the range of daily average temperature. This theory so developed has been applied first to the dry farming tract of India and then to a microanalysis of the state of Gujarat.

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INTRODUCTION

With the ever-increasing need for food, shelter, and energy, the task of maximizing agriculture and silviculture has become an important concern for the entire human race and is perhaps the first priority for an agricultural country like India.

It was once thought that farmers could learn to live with the limitations of their local climatic conditions through trial and error over generations. But that is no longer true. Modern agriculture requires precise information on rainfall, and on flood- and drought-prone areas. It is now clear that to obtain maximum yield from agriculture (including horticulture) and silviculture, a proper knowledge of agroclimatic conditions is necessary to plan the most effective cropping pattern and supplemental irrigation for different zones. It is therefore not surprising that considerable work has been done on this subject to generate knowledge that could be used with benefit by the agricultural community.

This paper discusses a theory of agroclimatic classification and its application to the dry farming tract of India, with a more detailed application to the state of Gujarat. The theory may serve agricultural scientists as a guide for practical agriculture.

REVIEW OF LITERATURE

Earlier attempts to classify climate mainly centered round the identification of average annual, seasonal, or monthly rainfall and/or temperature regimes that naturally produced certain types of vegetation of crops in abundance (Koppen 1936, Prescott 1938, Trewartha 1968, Burgos 1958). Thornthwaite (1948) used the concept of average monthly potential evapotranspiration, along with the corresponding rainfall, to classify climates. Later, Thornthwaite and Mather (1955) improved upon this classification with a "Rational Classification," which introduced various degrees of water deficit and water surplus. Subrahmanyam (1956) used this Rational Classification method to classify the climate of India. To assess the agricultural potential of various countries, Papadakis (1966, 1975) used a very simple water-balance technique along with average maximum and minimum temperature. Although Thornthwaite and Mather and Papadakis used some kind of comparison between the moisture required by plants and that available from precipitation, the results obtained by them are not quite satisfactory, as the respective empirical formulae used by them to compute evapotranspiration are not universally applicable. Moreover, the period used by them is too long in comparison with the life cycle of an agricultural crop. Also, their methods do not enable planners to assess the element of risk involved for farmers.

Cocheme and Franquin (1967) computed the water balance following the simple bookeeping procedure of Thornthwaite and Mather (1955) and tried a classification based on different degrees of monthly ratio of P'/PE, where P' is the sum of rainfall and ground storage (available water in the root zone) and PE is the potential evapotranspiration. The ratios of P'/PE equal to 1/8, 1/4, 1/2, and 1 were successively computed, and the intervals between the successive limits were defined as dry (D), moderately dry (MD), moist (M), and humid (H), respectively. The condition P'/PE > 1 was called humid (H).

The merit of this approach is that the length of the growing season can be determined for crop planning at a particular location. They used this method in interpreting the semi-arid areas south of the Sahara in West Africa. However, the method appears rather difficult for global classification of climates. They also suggested inclusion of the risk factor from probability or rainfall determined by semi-logarithmic distribution.

Troll (1965) proposed a classification called the "Seasonal Climates of the Earth," using monthly rainfall and potential evapotranspiration calculated by Penman's method (1948). His classification was based on the duration of arid and humid months. The month having more mean rainfall than mean potential evapotranspiration is defined as a humid month; otherwise it is an arid month. He divided the climate of the world into 6 groups, each group associated with some type of vegetation. For example, the semi-arid area is defined as one where the humid months are from 2 to 7. The method appears quite satisfactory in delineating areas in very broad terms, but cannot provide the kind of large-scale information needed for agriculture.

Troll's classification, when applied to the climate of India, is found to suffer from a number of defects. For example, the Kutch area and the western extremity of West Rajasthan are classified as semi-arid though they are actually arid. A number of stations like Jodhpur, Hyderabad, and Jalgaon are placed in the same group, which is difficult to accept from the point of view of vegetation. The same method has been applied by ICRISAT in utilizing data for about 300 locations. The map developed by ICRISAT also is not satisfactory. In this map, the areas around Saurashtra and the central parts of East Rajasthan have been placed in the arid zone, but it is well known that groundnut and other oilseeds, and sorghum and pearl millet are grown in these areas. Similarly, areas in part of Karnataka and Rayalaseema and parts of Madhya Maharashtra have beenclassified under the arid zone, although seasonal crops are grown in most of these areas. Another large area in Orissa, West Bengal, Bihar, and Andhra Pradesh has been categorized as semi-arid, although the rainfall is more than 150 cm and rice is grown in plenty. Some of these points are mentioned in ICRISAT's Agroclimatology Progress Report 2 (1978). In view of these shortcomings, one would hesitate to accept Troll's classification, particularly for tropical areas. Chowdhary and Sarwade (1980) suggested that a combination of humid and arid months would give a more satisfactory classification.

Another important classification, proposed by Hargreaves (1971), was based on the monthly moisture availability index (MAI), which he defined as the ratio of monthly precipitation at the 75% probability level to monthly potential evapotranspiration. He introduced the risk factor by using a probabilistic rainfall value instead of the monthly average. He emphasized the importance of continuity of the period when MAI is less than 0.34. Although he took into account the risk factor, which is necessary for crop planning, we feel that his classification has the following shortcomings:

a. Only 1 risk factor has been taken into account
b. The month is too long a period for modern cereal crops
c. An MAI value > 0.34 has been considered adequate for all the growth stages of the crops.

PRESENT STUDY

In this paper we present a methodology for agroclimatic classification using the MAI but introducing the following 3 modifications in the methodology developed by Hargreaves (1971).

a. Consider weekly MAI, rather than monthly
b. Consider different risk factors, instead of one, so that the planner can choose his own risk level
c. Consider MAI > 0.3 and > 0.7, depending upon the crop-growth phase.

On the basis of the MAI, we made a broad classification, which we further subdivided on the basis of the duration of the water stress period. Further subdivisions were made depending upon the average daily temperature range, and soil types were superimposed to get real agroclimatic classification.

Moisture Availability Index (MAI)

For our specific classification, the moisture availability index (MAI) is defined as follows:

$$MAI = \frac{\text{Assured rainfall}}{\text{Potential evapotranspiration}}$$

Choice of Different Probability Levels

It goes without saying that the planner, whether a farmer or a hydrologist, must know the extent of risk involved in his endeavor. A study that uses average or normal rainfall cannot include this risk factor. In the dry farming tract or low rainfall areas, there is considerable year-to-year deviation from the normal. In such low rainfall areas, the normal rainfall (monthly, seasonal, or annual) is quite often far too short of the water requirements of the crops. But experience shows that on a number of occasions crops are successfully raised. Apparently, in such years the rainfall is more than the normal value and meets the water demand of the crops. So, for any crop planning, one should know from long records the chances of meeting the water requirement of the crops. Accordingly, planning has to be done on a probabilistic basis, which takes into account the chance of success or failure. We have computed this minimum assured rainfall (AR) at different probability levels by use of incomplete gamma distribution, which forms the basis of this study.

Range of MAI Used

A plant growing under natural conditions requires water mainly for 3 purposes: (1) transpiration for maintenance of its life process, (2) evaporation from soil, and (3) growth. The first 2 together constitute evapotranspiration. The last component is so small compared to the sum of the first 2 that it is neglected in agrometeorological studies, and actual evapotranspiration is taken as a good measure of the water requirement of crop plants.

It is difficult to obtain data on actual evapotranspiration, which varies with the growth of the plant and also, to some extent, from crop to crop. However, it is assumed in all agrometeorological studies that the potential evapotranspiration covers the maximum requirement of fully-grown crop plants (the peak period of their moisture demand) covering the soil surface completely. It has been found that during the early stage of crop growth (first 3-4 weeks) the actual evapotranspiration is about one-quarter of the potential rate owing to small and sparse foliage, and that the maximum demand may even slightly exceed the potential rate if the size of the field is not too large and there is considerable advection of sensible heat into the crop field (Riplay 1966). But experiments have shown that due to its built-in natural protective capacity, a plant can narrow its stomatal openings to restrict transpiration when there is moisture stress and can grow almost normally as long as the moisture supply does not fall below about three-quarters of the potential rate (Arnon 1972). After completion of grain formation, the water demand declines rapidly, becoming very small at the ripening stage (Holmes and Robertson 1963).

In view of the above, classification in the present study has been made on the assumption that a crop will be nearly normal if it gets moisture varying from 0.3 to 0.7 of potential evapotranspiration commencing from germination to completion of the grain-formation stage.

Choice of Interval

As mentioned earlier, a month is too long a period compared to the crop life. Plant breeders are constantly evolving shorter-duration varieties with a view to producing a larger number of crops per year. Use of monthly rainfall suffers from another defect also. There are areas where even during the height of the wet season the daily rainfall varies immensely in amount; so much so that a month's average rainfall may be realized in only a few days (say a week or even less), while the rest of the month may go dry. If this happens during the early part of the life of a crop, this may cause it irreparable damage. In the tropics where the rainfall is showery and highly freakish in intensity, amount, and distribution (both in time and space), the week must be used as the unit of time, at least for the first 3 to 4 weeks of the crop life and not more than 2 weeks beyond this.

Optimum Moisture Availability Index

An index called the "optimum moisture availability index (OMAI)" has been calculated for the respective area units. This is defined as the ratio of assured rainfall (weekly, biweekly, or monthly) at the 50% probability level to the potential evapotranspiration of the same period. Although the MAI index has been calculated for 40, 50, 60, and 70% probability levels, our climatic classification has been done on the basis of the index at 50% level for the following reason:

In calculating MAIs at any probability level the minimum assured rainfall figures have been used, but the MAIs of many individual years may have higher values than indicated by that particular probability and may have a better chance of agricultural success. Use of assured rainfall at the 50% probability level indicates a chance of agricultural success higher than 50%.

It has been observed that the MAI for many weeks for most of the stations is 1.0 or more and very small or zero for 40 and 70% levels of probability, respectively. Hence the use of these probabilities may lead to unrealistic results. An examination of the MAIs for the remaining 2 probability levels (50 and 60%) shows that all of them give almost the same relative gradation.

It is accepted that 40% is too low a probability for planning. On the other hand, with the 60% level of probability, the duration of MAIs at the 0.7 level (the minimum necessary for most of the crop's life) becomes too little. The 50% probability satisfies the criterion of MAI values of 0.3 for early and 0.7 for subsequent growth stages of the crop life.

Table 1 gives the MAIs of weekly and biweekly assured rainfall at different probability levels for a few selected stations. It can be seen that classification based on weekly MAIs at the 50% probability level remains practically the same as that of biweekly at the 60% level. In other words, for the purposes of classification, use of weekly MAIs at the 50% probability level is equivalent to using biweekly MAIs at 60% probability, both in duration and in accumulated rainfall during the period when the MAI is more than 0.3. An examination of MAIs and assured accumulated rainfall (AAR) at various levels leads to the conclusion that, in general, dependability increases by 10% if one switches over from weekly to biweekly analysis. But, as mentioned earlier, it should be kept in mind that though the minimum water requirement for the crop in its early stage is low, it is very susceptible to moderately prolonged moisture deficiency. Hence choice of a biweekly assured rainfall is not desirable for the early growth stage, particularly in areas where time variability of rainfall is high. Therefore, use of weekly assured rainfall at the 50% probability level seems to be the best choice for classification of areas on the basis of the MAI, as it also covers 60% probability with biweekly rainfall for that growth stage when the crop has developed the capacity to stand moisture stress for a week or so. Hence the MAIs obtained by using assured weekly rainfall at 50% are called the optimum moisture availability index (OMAI) and are used in the method applied here.

By means of the OMAI mentioned above, for the 23rd to the 42nd week (4 June-21 October) the area under study has been classified into broad agroclimatic zones as given below. Increasing OMAI both in duration and magnitude is denoted in alphabetical order of the English capital letters starting from "D." Some letters at the beginning, i.e., "A" to "C," have been reserved for classification of the arid zone where annual rainfall is less than 400 mm.

Classification	No. of weeks of OMAI at $\geq$ 0.3	No. of weeks of OMAI at $\geq$ 0.7
D	< 10	< 1
E	> 10	> 1
F	> 11	> 4
G	> 14	> 7

Table 1: MAI and AAR in weekly and biweekly period.

Proba-bility level	Weekly No. of weeks MAI				Accumulated assured rainfall (mm) for period when MAI ≥ 0.3	Biweekly No. of weeks MAI				Accumulated assured rainfall (mm) for period when MAI ≥ 0.3
	≥.3	≥.5	≥.7	≥.9		≥.3	≥.5	≥.7	≥.9	
					Hissar (Lat.29°10'N Long.75°44'E)					
40	10	7	3	0	214	12	10	6	0	277
50	8	3	0	0	119	10	6	0	0	180
60	2	0	0	0	25	8	0	0	0	108
70	0	0	0	0	0	2	0	0	0	23
					New Delhi (Lat.28°35'N Long.77°12E)					
40	12	11	9	7	396	18	12	12	8	503
50	11	8	7	3	255	12	10	8	4	338
60	8	5	3	0	141	10	8	4	2	226
70	5	0	0	0	61	8	4	2	0	142
					Banaras (Lat.25°18'N Long.83°01'E)					
40	17	16	15	13	849	18	16	16	14	839
50	16	14	13	12	625	16	16	14	12	760
60	14	12	11	9	441	16	14	12	12	615
70	12	10	9	6	286	16	12	12	10	479
					Bhopal (Lat.23°16'N Long.77°25'E)					
40	16	15	14	13	980	16	16	14	14	1068
50	15	14	13	12	738	16	16	14	12	877
60	14	12	12	11	539	16	12	14	12	709
70	12	11	10	8	367	14	12	12	12	548
					Rajkot (Lat.22°18'N Long.70°47'E)					
40	15	9	5	5	398	16	14	10	6	489
50	10	5	3	1	203	14	10	6	4	322
60	5	1	0	0	82	10	4	2	0	182
70	1	0	0	0	12	6	0	0	0	86

Continued

Table 1. *Continued*

Probability level	Weekly No. of Weeks MAI ≥.3	≥.5	>.7	>.9	Accumulated assured rainfall (mm) for period when MAI ≥ 0.3	Biweekly No. of weeks MAI ≥.3	≥.5	≥.7	≥.9	Accumulated assured rainfall (mm) for period when MAI ≥ 0.3
					Barsi (Lat.18°14'N Long.75°42'E)					
40	19	16	10	5	478	22	18	14	6	552
50	15	8	4	1	288	18	14	6	2	404
60	11	2	1	0	142	18	8	2	2	302
70	3	0	0	0	34	10	2	0	0	139
					Bellary (Lat.15°09'N Long.76°51'E)					
40	14	6	4	3	241	20	8	6	6	342
50	6	3	3	1	103	12	6	6	2	189
60	4	2	0	0	48	6	6	2	0	101
70	2	0	0	0	20	6	2	0	0	69
					Kovilpatti (Lat.09°10'N Long.77°52'E)					
40	16	12	8	8	410	22	12	10	6	513
50	12	8	5	5	247	14	10	6	6	331
60	8	5	4	1	146	12	6	6	4	238
70	5	3	1	1	75	8	4	4	2	153

Subdivisions based on water stress period. The midmonsoon-season water stress period (i.e., when OMAI is less than 0.3), has been designated by the use of numerical suffixes to the above classification in the ascending order of duration. Suffix 1 indicates that there is hardly 1 week's water stress period, while suffixes 2, 3, and 4 indicate 2 to 3 weeks', 4 to 5 weeks', and more than 5 weeks' water stress, respectively.

Classification for Temperature

The use of potential evapotranspiration in this classification takes into account air temperature, radiation (sunshine duration), relative humidity and aeration (wind speed), and the meteorological factors known to influence the health and growth of plants.

Over and above these integrated factors, it is felt that average air temperature during the growing season plays a vital role in the yield. So, the general classification must also be based on temperature range. In our classification, the daily average temperature is categorized in the following way:

Symbol		Average daily temperature (°C)	Duration in the year
Polar	T_1	5-10	2-4 months (warmer part of the year)
Subpolar	T_2	5-10	5-7 months (warmer part of the year)
Temperature	T_3	5-10	6-8 months (cooler part of the year)
	T_4	10-20	4-7 months (warmer part of the year)
Tropical	T_5	10-20	4-6 months (cooler part of the year)
	T_6	20-30	6-8 months (warmer part of the year)
Equatorial	T_7	25-30	Throughout the year

Thus a station may be classified as D_1 T_5, D_2 T_6 etc.

END OF THE GROWING SEASON

Cessation of the rainy season does not mean the end of the crop season. Crops can thrive on stored moisture. It is therefore necessary to determine the amount of moisture stored in the soil at the end of the season when the MAI is only 0.3. This could be done by the water-balance technique, which is not within the scope of this study. However, the cumulative seasonal evapotranspiration for dry-land crops like sorghum, etc., even under relatively favorable moisture conditions, may be only 65% of PET (Jensen 1968). Riplay (1966) observed that in many farm crops seasonal water use ranged from 55% to 75% of PET.

The India Meteorological Department installed about 35 lysimeters in various soil and climatic zones of the country to determine the water requirement of various crops. Venkataraman et al. (1976) found that the cumulative seasonal ET is about 70% of PET. It has, therefore, been assumed in this study that the difference between the seasonal total assured rainfall and two-thirds of the PET of the same period will go into the stored soil moisture and the plant can use it even after the end of the rainy season.

APPLICATION OF THE METHODOLOGY

The theory of agroclimatic classification developed here has been applied to the dry farming tract of India (comprising 87 districts). In the case of the entire dry farming tract we have taken 1 station for each district. On the basis of the above analysis, the dry farming tract of India has been divided into 4 agroclimatic zones--D, E, F, and G (Figs. 1-4).

Before we discuss the zones and their crop potential, it is necessary to have an idea about the water requirements of crops of various durations. This information is not available, but it has been recognized that about 325 to 525 mm of water are necessary in the low rainfall zone to raise a summer crop like sorghum, pearl millet, cowpea, etc. Our present analysis shows that accumulated assured rainfall (AAR) for 10 to 12 weeks during which MAI is equal to or more than 0.3 (of which 3-6 weeks' MAI > than 0.7) varies from 220 to 270 mm. We therefore believe that a short-duration crop (10-12 weeks) requires about 250 mm of AAR. Similarly, a medium-duration crop of 12 to 16 weeks would require about 350 mm, and a long-duration crop of more than 16 weeks would require more than 400 mm. Our discussion in the following paragraphs regarding crop potential at different probability levels has been based on these assumptions.

The Crop Potential Zones

Area D. This is the low-crop-potential area of the dry farming tract. Figure 1 shows that area D occurs in 3 places in the tract. The first is the western part of the tract extending from the Jamnagar district of Gujarat to Ferozepur in Punjab. The second includes parts of Ahmednagar, Pune, Satara, Sholapur, and Sangli districts of Maharashtra. The third falls in Karnataka and includes portions of the districts of Bijapur, Raichur, Bellary, Kurnool, and Anantpur.

In area D, there may be a break of 0MAI of 1-week duration, and in many cases it may be of 4 to 5 weeks. Assured rainfall is 80 to 100 mm in the western part of the tract in Gujarat and 200 to 225 mm in Punjab at the 50% probability level (Fig. 3). Crop production without irrigation is almost a speculation. However, at some stations where AAR is from 200 to 250 mm and there is hardly any break in 0MAI, a short-duration crop may be raised.

At the 40% probability level, accumulated rainfall is low-around 220 to 250 mm-in the Pali area of Rajasthan, Dhond in Pune district of Maharashtra, and the Bellary district of Karnataka. A short-duration crop may be raised in most parts of area D.

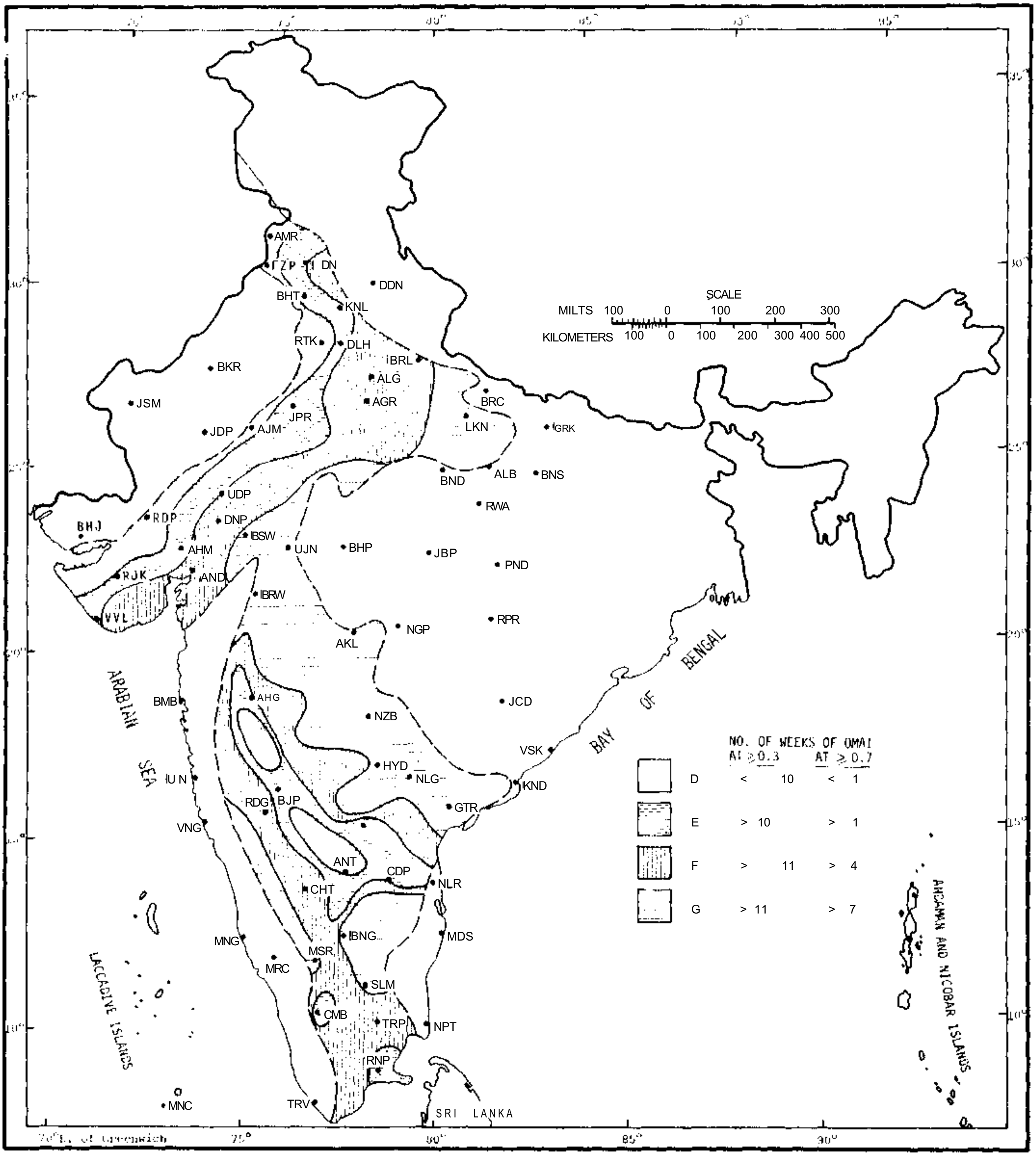


Figure 1: India, agroclimatic classification (dry farming tract of India).

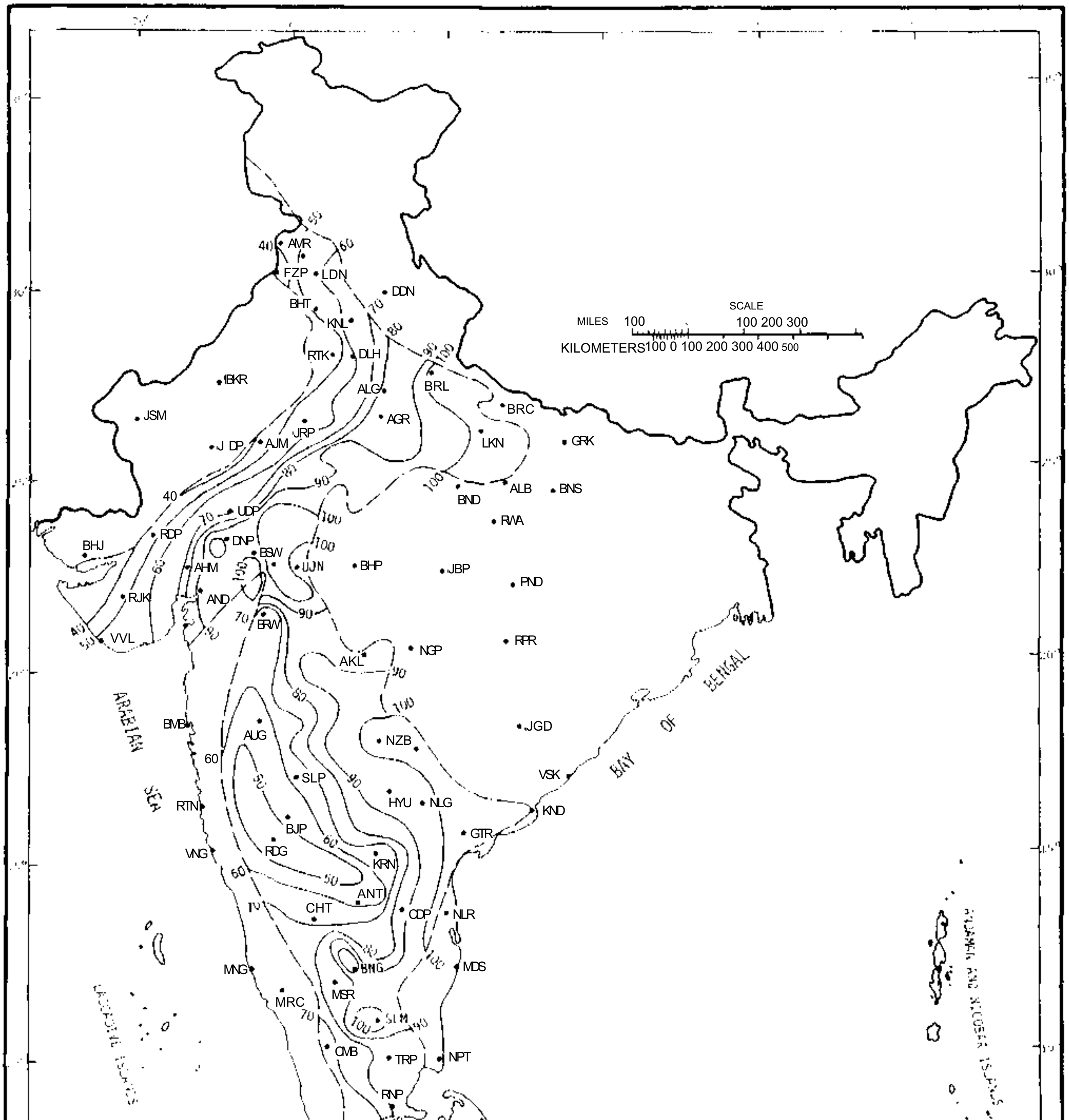


Figure 2: India, accumulated assured rainfall (cm) at 30% level.

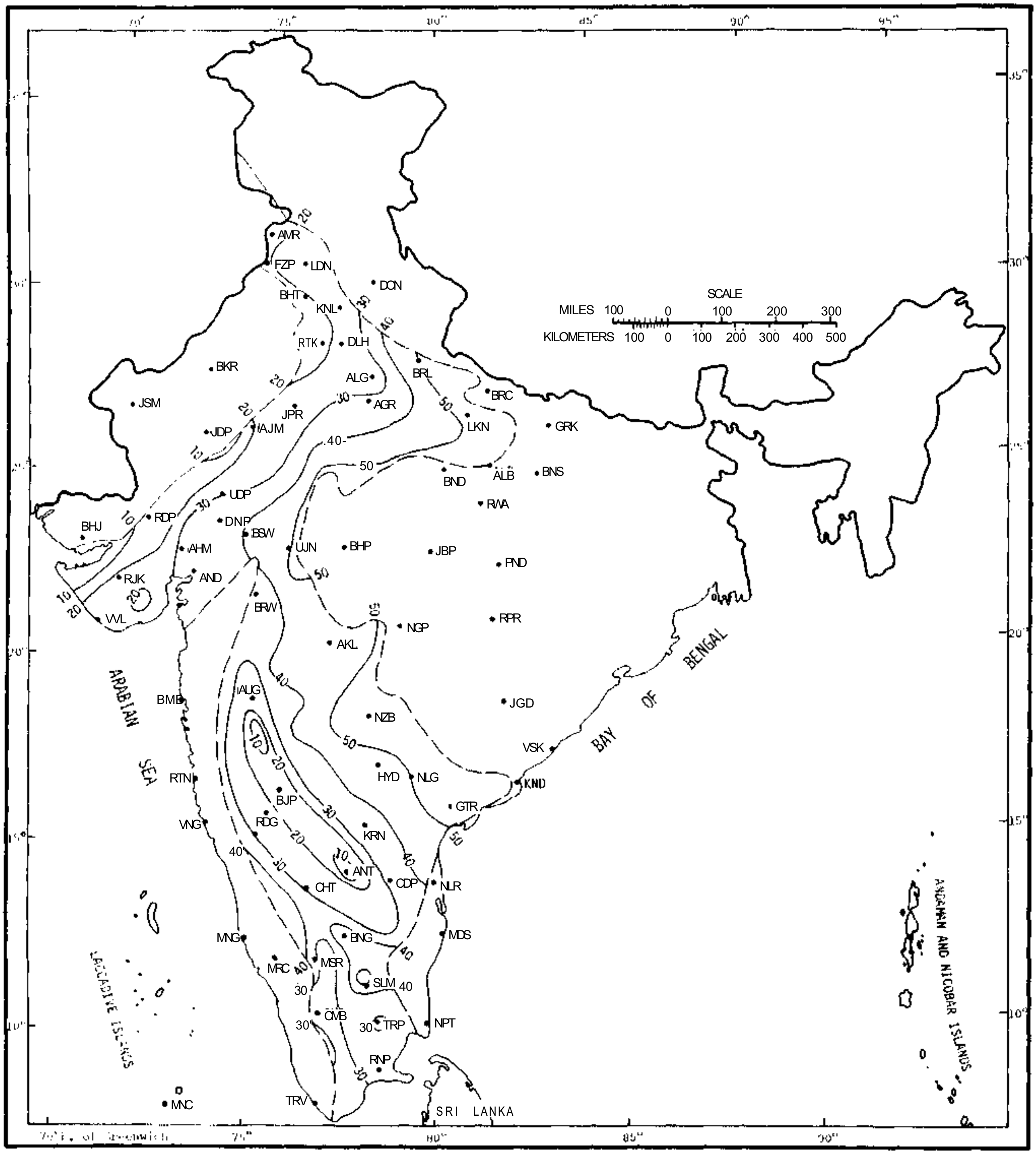


Figure 3: India, accumulated assured rainfall (cm) at 50% level.

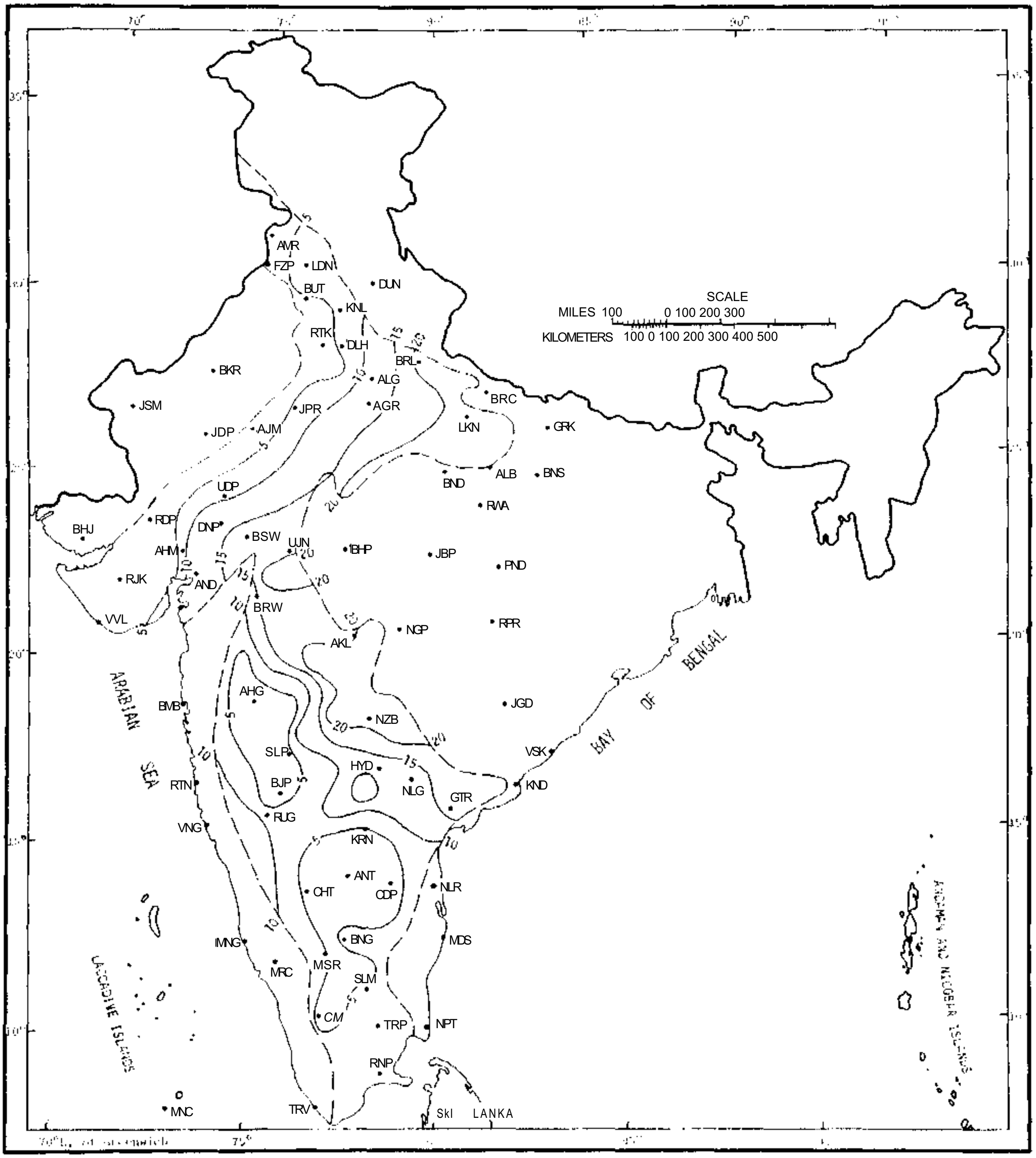


Figure 4: India, accumulated assured rainfall (cm) at 70% level.

Crop prospect is high at the 30% probability level, as assured rainfall is as high as 500 mm at some of the stations (Fig. 2).

As rainfall is the limiting factor of crop production, all sorts of commercial crops may be discouraged in this region. Areas where the break is more than 2 weeks are suitable for pasture development and cattle rearing.

Area E. Figure 1 shows that area E extends from Rajkot in Gujarat along the east side of area D up to Punjab through Rajasthan and Haryana. A second part is spread from Ahmednagar district in Maharashtra up to the coastal area of the Cudappah district in Andhra Pradesh through Satara, Pune, Sholapur, and the Sangli districts of Maharashtra and Bijapur, and the Bellary and Tumkur districts of Karnataka. The crop potential of this area is not very high because the duration of the OMAI at more than 0.3 ranges from 10 to 13 weeks, and at more than 0.7 it ranges from 1 to 5 weeks. Figure 3 shows that assured rainfall is about 200 mm in the Sirohi district and adjacent area of Rajasthan, and 350 to 375 mm in Karnataka and Andhra Pradesh at the 50% probability level. A short-to-medium-duration crop may be raised at most of the stations.

Many stations receive as much as 460 mm accumulated assured rainfall at the 40% probability level, so some soil moisture may be available at the end of the rainy season. A medium-to-long-duration crop may be raised from this area, as crops can thrive on stored moisture for a few weeks even after cessation of the rainy season.

A long-duration crop may be raised at most of the stations in this area once in 3 years, as the AAR ranges from 530 mm at Ahmednagar in Maharashtra to 940 mm at Tumkur in Karnataka (Fig. 2) and crops can use stored moisture at the end of the rainy season.

Area F. Like region E, area F also occurs in 2 places. The northern part comprises vast areas of Gujarat, Rajasthan, Uttar Pradesh, and a small portion of Haryana and Punjab (Fig. 1). The southern part stretches from the Nasik district of Maharashtra to Kanyakumari in Tamil Nadu. A large portion of Karnataka and Andhra Pradesh also comes within this agroclimatic zone.

Figure 3 gives the AAR at the 50% probability level. As there is hardly any break of the OMAI and assured rainfall is 230 to 450 mm around the Sangli area of Maharashtra and Madhpura in Rajasthan, a medium-duration crop may be raised at most of the stations once in 2 years.

At the 40% probability level the crop prospect is high, as the AAR ranges from 330 mm at Sangli (Maharashtra) to 730 mm at Idar (Gujarat). Two short-duration crops or a mixed crop may be raised in this region at this level.

A short-duration crop may be raised at the 60% probability level at some of the stations where the AAR is from 225 to 250 mm.

Area G. This is the highest crop potential zone of the dry farming tract. This area consists of small portions of Uttar Pradesh, Madhya Pradesh, Gujarat, and Tamil Nadu, and considerable parts of Maharashtra and Andhra Pradesh. The portion in Tamil Nadu enjoys the northeast monsoon. The growing season, therefore, differs significantly from the rest of the areas of this region.

The OMAI at 0.3 or more ranges from 14 to 19 weeks and is from 7 to 13 weeks at 0.7 or more; the AAR ranges from 330 to 480 mm. Some stored moisture will be available at some of the stations. A crop of 13 to 18 weeks' duration may be raised in this region under rainfed conditions once in 2 years.

At the 60% probability level, most of the stations have the potential to grow a medium-to-short-duration crop, as assured rainfall ranges from 180 mm at Dharmapuri district of Tamil Nadu to 380 mm at the Nanded district of Maharashtra.

The AAR at the 70% level, shown in Figure 4, is from 200 to 250 mm at a number of locations. A short-duration crop may, therefore, be raised at these places in 7 out of 10 years.

Crop prospects are very high at the 40% probability level, as the AAR ranges from 460 to 850 mm. Two short-duration crops or a mixed crop may be raised in this region at this level.

Although classification has been done on the basis of 50% probability of rainfall, it *can* be seen that sometimes in a particular area the prospect of producing a crop at this probability level is very dim. For example, in the agroclimatic zone D, at many stations the accumulated assured rainfall at 50% probability level is not sufficient to grow a crop, but there could be sufficient moisture at the 30% probability level to grow a crop, which means one could grow a crop once in 3 years. Similarly, in high rainfall zones (G) there could be many stations where the assured moisture may be sufficient to grow a crop at the 60 to 70% probability level, which means that one could expect to produce a crop in 6 to 7 years out of 10. We have therefore given the assured accumulated rainfall at 30, 50, and 70% probability levels in Figures 2, 3, and 4,respectively.

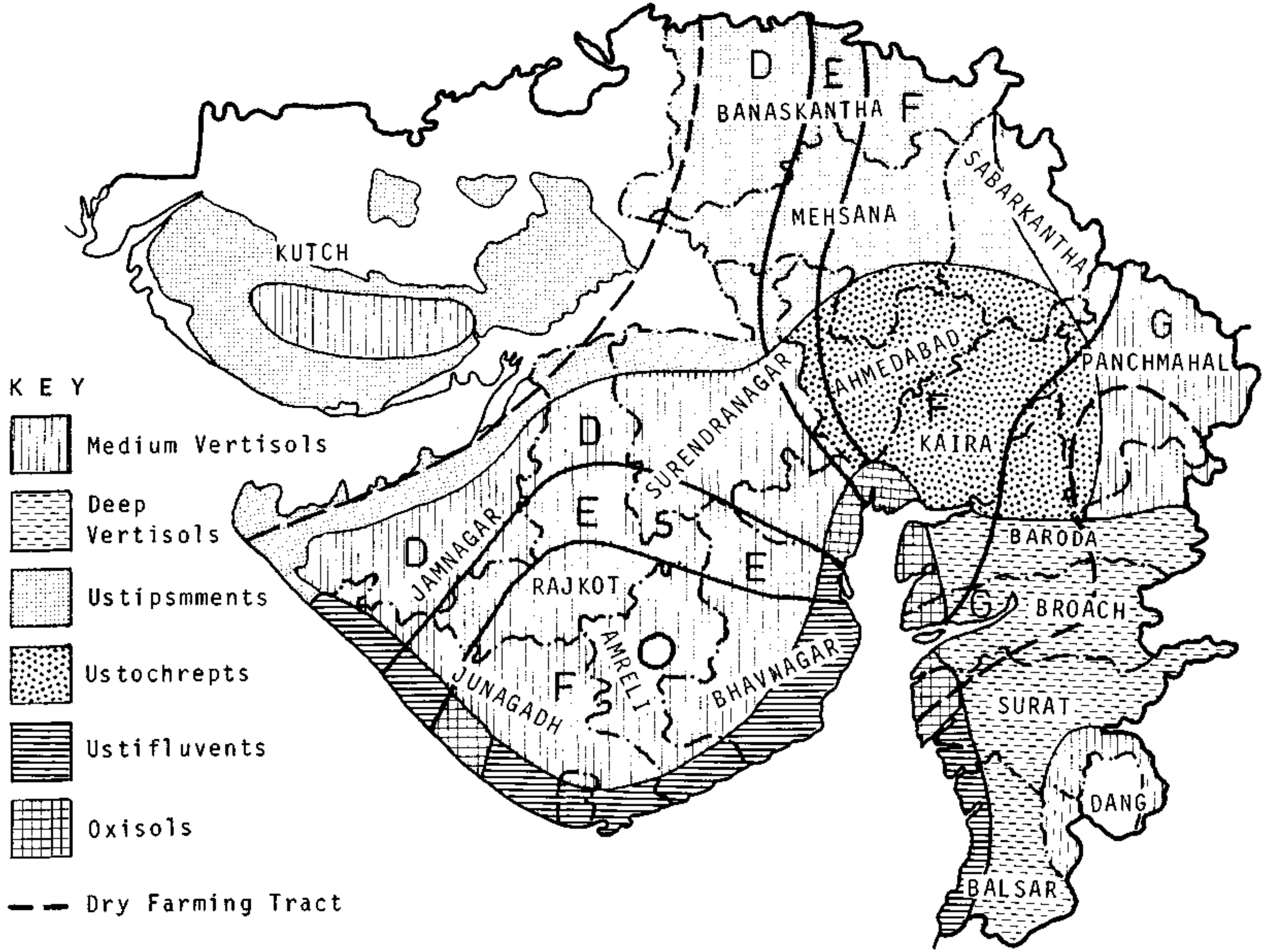
APPLICATION TO GUJARAT

We have also divided the dry farming tracts of Maharashtra and Gujarat into 4 agroclimatic zones, D, E, F, G, by using 84 and 81 stations, respectively. Figure 5 shows the results for Gujarat. This microanalysis divides the small areas into different agroclimatic zones that could not be located in the macroanalysis of the entire dry farming tract. This brings out clearly the necessity of microanalysis to assess the crop potential of small areas. In Figure 5, we have also superimposed broad soil information, which shows that an agroclimatic zone can be further subdivided on the basis of the soil characteristics.

It may be mentioned that the entire dry farming tract of Gujarat falls in the temperature category T6.

CONCLUSION

The agroclimatic classification of all the dry farming tracts of India has brought out many interesting features. The area could be divided into 4 agroclimatic zones of different crop potentials. The lowest crop potentials, area D, comprises 3 parts. Rainfed agriculture does not suit this area. However, a short-duration crop may be raised in this area once in 3 years. Area E has the potential to raise crops in about 40% of the years. Rainfed crops can be successfully raised in area F once in 2 years. Region G, where crops may be grown about 60% of the years is the highest-crop-potential area.



For the key to climatic zones D,E,F,G, see Figure 1.

Figure 5: Agroclimatic classification superimposed on a soils map of Gujarat.

The core of the low-crop-potential area, or scarcity zone, could be clearly identified from the accumulated assured rainfall at the 50% level. Further, it appears from this analysis that while a macro-scale analysis can give some broad aspects of crop potential, it is essential to do the analysis on a microscale so that the specific areas of varying crop potential and the scarcity zone can be pinpointed and specific recommendations drawn up.

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SUMMARY OF DISCUSSIONS

FIRST SESSION

CLIMATIC CLASSIFICATION: CONCEPTS FOR DRY TROPICAL ENVIRONMENTS

A.T. Grove

Venkataraman: In many classifications, precipitation deficits include those outside the rainy season. The nonrainy-season deficits are large and outweigh the comparatively small deficits in the rainy season. So attention must be paid to evaluating these deficits on a seasonal basis. In looking for isoclimes a 1:1 correspondence in time scale is not required. For example our winters may be comparable to springs in higher latitudes. This aspect should be kept in view.

Grove: My impression is that the method of Russell and Moore allows one to compare the growing season of one part of the world with the growing season in another part of the world which in fact may be outside the semi-arid tropics. Seasonal classification seems to have a distinct advantage.

Gadgil: Is there any way in which one can choose the attributes that are relevant to agricultural purposes?

Grove: It is possible to select the attributes fairly readily.

Virmani: I like your reference to the two kinds of classification systems. You say that ICRISAT should adopt a known methodology or system of classification, but when we do that we get into difficulties. We used Troll's methodology. When we use sparse data and extensive data, we get two cartographically different kinds of situations. Again, when we rely more on the kind of flora that are found on the ground, those areas are delimited entirely differently. What are your views on this subject? How should we really go about it?

Grove: I have some views on this myself; I would also like to hear views of others. Troll's classification has a neatness and simplicity about it that is attractive. On the other hand, it obviously gives rise to the sort of patterns that appear on the map. I am afraid that this may be due to stations that have 1 or 2 months with *very* high rainfall and other months in which rainfall is quite high but not as high as potential evapotranspiration to appear in the semi-arid tropics. One might improve on that considerably by using some sort of general principle.

Biswas: How can we use satellite pictures to classify the climate and use that classification to transfer technology?

Grove: I would like to hear the views of others on this.

Meher-Homji : Satellite imagery is seen to fit well with the pattern of natural vegetation. The zone of the evergreen forests comes out in grey color, deciduous forests in brown, and so on. Now, knowing the association of rainfall quantum with forest types, we do get an idea about climatic zones in the Western Ghats where the climatic stations are few and are widely dispersed. The agricultural zones do not come out so distinctly and we do not have very detailed photographs. The French satellite that will be going into orbit in 1982 will have a much better resolution, down to about 20 meters. So we expect much more from satellite imagery in the years to come.

Krishnan: I want to supplement what Dr. Meher-Homji said. In arid areas, wherever the network of observatories is very scanty, satellite imagery has been handy and been used to assess the process of desertification.

Sarker: It is too early to comment on the suggestion that ICRISAT should adopt one of the accepted classifications. For climatic classification we require the climatic and vegetation conditions throughout the year, while satellite images give only the current conditions of crops. This really is insufficient for classification purposes. You had mentioned that a particular place may be semi-arid in one year, arid in another, and so on. We cannot expect to classify on a year-to-year basis. We can base our classification either on an average or on a probabilistic basis, using long-term records. A number of methods had been reviewed by you but I find some of the recent ones, like Hargreaves' method, are not dealt with.

Grove: I am willing to accept these criticisms. Just a word about satellite imagery. I think it is of great value in drawing boundaries to the semi-arid zone or divisions within it. It would be useful on some occasions to have some correspondence between the maps of the climatic regions or subregions and the satellite imagery, so that by superimposition one can obtain satellitic inventories, which are often very revealing. I think those climatic classifications I have omitted have been referred to in other papers. No doubt you will be hearing about them at a later stage.

Sivakumar: Regarding satellite imagery I think what Dr. Grove refers to is getting visual perception of the climatic variation from one area to another. I do not think he is suggesting it as a method of classification by itself. In mentioning that an area is humid in one year, semi-arid in another year, and arid in a third year, Dr. Grove is trying to make a point about the variability rather than saying that we need a classification every year, if I understand him right.

Grove: Quite right.

Virmani: In most of the classification systems, which originated in Europe, temperature has been taken as a proxy for potential evapotranspiration. For arid and semi-arid areas, advection, etc. are much more important as contributing factors to potential evapotranspiration. What is your view, as a geographer, on the use of temperature as a proxy for potential evapotranspiration?

Grove: I don't think I am in a position to speak for geographers in general on this subject. In recent years there have not been many publications by geographers on this subject, as far as I . know, at least outside the tropics. However, temperature is no longer being used in lieu of potential evapotranspiration.

CLASSIFICATION OF SEMI-ARID TROPICS: CLIMATIC AND PHYTOGEOGRAPHIC APPROACHES

V.M. Meher-Homji

Biswas: One should use probability rainfall and not average rainfall in classifications. Again it is not the quantum of the rainfall but mainly the distribution that is important. Do you not therefore feel that considering the year as a unit is unreliable and that the period should be 10 or 15 days?

Meher-Homji: Yes. I fully agree with you. In fact we have for certain regions considered the daily rainfall during the main rainy season and looked into spells with regular and irregular rains. For example, we found that at Anantapur in many years the first rains arrive in the second week of June. But after this there is a period of unreliable rainfall. Rainfall tends to become regular in the second week of July. So we suggested that instead of doing the sowing of paddy with the first rain, the farmer should wait for a period of 2 weeks or 20 days and do the sowing when the rain becomes regular. I think we have to consider the critical spells that would affect agricultural production or affect the vegetation. And I am of the opinion that we should not look at the drought spells for the semi-arid climate only. We have to look into variability for the humid-zone stations also because high value cash crops are grown there. For example, in 1976 the rains arrived late at Mercara and the crops of the coffee and cocoa were affected.

Biswas: On the basis of your study, could you quantify the extent of decrease of rainfall due to deforestation? There are conflicting reports in the literature. In the Andamans we noticed a 7 to 10% decrease due to lack of forest cover.

Meher-Homji: I tried but I could not arrive at a definite figure, because there are so many problems. Unless we carry out a survey ourselves, I think quantification is rather difficult. But we are trying to get at that figure.

Virmani: I like your probable-year concept. If we could define the environment of say, a millet crop with reference to sensitive periods and agronomic criteria it would give us an index of dependability of agriculture in the semi-arid tropics.

Meher-Homji: I agree that if these two are linked together, this could help in crop planning.

Virmani: What you are considering is the duration of aridity. Now if two stations receive different amounts of rainfall in the same period, say 3 months, the aridity duration is 9 months. When the rainfall ceases, the soil moisture storage may not be different for the stations and they end up with the same kind of plant on the ground. Therefore, this kind of classification would make a lot of difference agriculturally.

Meher-Homji : Could you give an example?

Virmani : Let us say Jodhpur and Delhi; both have rainfall for 3 months.

Meher-Homji: But the value of the aridity factor would be different and it would be higher for Jodhpur than for New Delhi.

Virmani: They are classified in the same zone.

Meher-Homji: I am using a range of values from 8.5 to 10.5, so you have all possibilities according to that degree of aridity.

Krishnan: When you take only the aridity as a measure of the duration and intensity of the dry spell, it does not give good classification of the vegetation type.

Meher-Homji : Yes. but if you consider it in relation to the classification factor then it gives good correspondence with the vegetation type.

Krishnan: You said that some kinds of vegetation are found both in the arid and semi-arid areas. This is vague and needs to be very clearly known. What criteria can we use to delimit the tropics? I think for all practical purposes we can adopt the limit given by the 18°C mean annual isotherm. We can also define the subtropical climate on the basis of the amplitude of temperature and the difference between the summer rainfall and the winter rainfall. In India the mountain system of the Himalayas superimposes some features on the temperature of the subtropical plains.

Hari Krishna: In the table relating to the probable year, how and why were only 31 stations selected?

Meher-Homji: They were selected at random, mainly from the dry belt of India, to serve as examples.

Hari Krishna: Only 6 out of 31 stations had over 50% of years as probable years. This raises the question of applicability of the probable-year concept.

Meher-Homji: I agree that we have to take into consideration more stations, and the idea has to be studied in detail. We should confine ourselves to the growing period situation, and I would like to develop this aspect more. That is, if the rainfall is on the excess side, it does not do any damage but when the deviation is on the minus side then it is going to affect the growing crop.

G.D.V. Williams: Now the geographic approach covered some of my related work in the same area, I am using phenology, bloom date, etc., of the crop, which can produce that particular connection.

Meher-Homji: Unfortunately the phenology is not understood completely for our evergreen forests. That is, the same tree does not flower every year. If you ask the forester, he would say that the species flower every year, but not the same tree. But we are trying to get a correlation between leaf fall and climatic data. In Kodaikanal the leaf fall varied from 3.5 tonnes/ha per year to about 8 tonnes/ha per year in 3 successive years. We are trying to examine in greater detail leaf fall in relation to climatic factors.

USE OF PRINCIPAL COMPONENT ANALYSIS IN RATIONAL CLASSIFICATION OF CLIMATES

S. Gadgil

Hari Krishna: In your analysis you have used rainfall data, but more relevant to agriculture is the moisture availability; this of course would involve not only rainfall but also other components of moisture balance, such as evapotranspiration. This is something I would like you to keep in mind in future analysis.

Gadgil: I have also been thinking about including potential evapotranspiration and working in terms of excess or deficit of precipitation over potential evapotranspiration. If you have any concrete suggestions, I would appreciate them.

Hari Krishna: I do not have a concrete suggestion. In our situation any formula based on the temperature alone would not be appropriate.

Sarker: The zero order clustering does not give anything more than what is available in the annual pattern of rainfall. The three hill stations that you have isolated should have also come under Category 1. Again you could not get a subcluster between and in the Western Ghats and Assam. Even with 4000 raingauge stations we feel sometimes that this network is not sufficient; then how, with only 145 stations, could you consider the network sufficient and stable for cluster analysis? You say that the classification done by ICRISAT and the classification done by you are similar. Now, potential evapotranspiration has been taken into account in the classification done by ICRISAT. You are getting the same from rainfall analysis only. Does it mean that one need not consider evapotranspiration at all?

Gadgil : I did not compare or contrast Troll's classification with mine. What I did point out was that if you superpose the classification of Virmani et al., based on Troll's method, on to my clusters, you find that what tended to be a relatively homogeneous arid zone in fact is comprised of two climatic regimes or two clusters with distinct rainfall patterns. I don't claim that without potential evapotranspiration you can get realistic or appropriate classification for agroclimatological purposes. All I tried to show was that this has a level of detail that is absent in Troll's classification. I agree with your remarks on the zero order classification. However, the effectiveness of the principal component method comes out in the first order. Regarding the west coast and Assam, I had only Mahabaleshwar as the peak station in the Western Ghats; altogether I have something like 20 stations. Regarding network and stability of classification I wish to clarify that what I meant by stability was with respect to methodology. The use of data from only 145 stations, I agree, is a constraint, and to that extent there will be a limit to the number and kind of climatic regions that will emerge. If you use 4000 stations you are likely to get more, but perhaps not many more, clusters. I would like to test this.

Sivakumar: You have stated that you dropped about 70 stations and the boundaries are still the same. This point has great relevance if it can help decide the data base to which we can restrict ourselves.

Gadgil: The dropping of the stations was not random. Roughly half of the stations from each cluster were omitted. This is important.

Venkataraman: In your groupings under "F, Hyderabad, Sholapur, and Ahmednagar come under one cluster. At Ahmednagar it is difficult to get a kharif (rainy-season) crop without irrigation. At Sholapur one can with some difficulty get a rabi (postrainy-season) crop. At Hyderabad one can get more assured kharif crops. Similar discrepancies are seen in the "J" and "K" clusters. We know that even a high-rainfall zone like the west coast will have subclusters. I therefore feel that the output is certainly questionable from the clustering point of view. Secondly, you have used the mean values of all the pentads. But you could as well have taken care of year-to-year variations by using probability figures for these pentads. The need for using a moisture availability factor has been mentioned by Mr. Peacock and Dr. Harikrishna. We find that the length of the period of assured rainfall of about 2 cm per week at 50% probability brings out the clustering quite effectively. My point is whether, by use of involved and complicated methodology, we are achieving anything better than what is brought out by a probability analysis with some consideration of moisture availability?

Gadgil: I will leave the final question to the decision of the experts gathered here. Regarding the clustering of stations associated with different agricultural seasons I would be worried only if stations having totally different rainfall patterns had come in one cluster. As far as I can see, the clusters that have emerged are consistent. It is not fair to imagine that you will get agroclimatic zones solely from rainfall data input. I did not have time-series data and can also use probability data, if available.

Krishnan: Have you taken rainfall amounts into account?

Gadgil: Yes, both rainfall variation and the actual amount go in as basic data. Now if you had two stations with an identical pattern, but with different amounts of rainfall they would lie on the same line through the origin but they would not coincide.

G.D.V. Williams: After having uniform spacing of isolines in any variable, you will not get any grouping, but you are going to have something very relevant agriculturally. You have a bunch of variables that you put into the system and come out with ones that will give you the demarcations or groupings. I am wondering if this system biases towards variables that lend themselves to grouping, whether or not the variables are relevant. A related question here depends on the principal-component stage: supposing the most relevant variations come up in the first or the second stage climatically they would be more relevant.

Gadgil : The point is well taken. Where there are monotonic changes, you do not get good clusters. Still, principal component analysis helps in the most economic representation of the variation, and if at all any clusters are possible, they ought to be brought out by this. In certain features things would not cluster and it would be better to look at their variations. I think that what you are trying to say is that the first pattern is highly predictable in some places and that it is variability in the second that determines agriculture. Therefore, the second may be more relevant. One has to keep this in mind when one analyzes time-series data and adopt an appropriate definition that would get the maximum variation out in the first.

SECOND SESSION

CLIMATIC CLASSIFICATION OF SEMI-ARID TROPICS IN RELATION TO FARMING SYSTEMS RESEARCH

S.M. Virmani, M.V.K. Sivakumar, and S.J. Reddy

Sarker: As per Troll's classification large areas in Orissa and Madhya Pradesh, where rainfed rice is grown, are classed as semi-arid. Parts of Karnataka, Madhya Pradesh, Maharashtra, and Andhra Pradesh, are classed as arid. This does not seem correct.

Virmani: The important part of Troll's classification is that it emphasizes the dry season, ranging from 7.5 months to 10 months in a year. So from the agricultural potential you have a 75-day to a 150-day crop-growing period. I don't think it is very important whether you grow rice or maize or a millet.

Frere: We may grow rice in the arid areas where special soil characteristics make it capable of retaining the excess water necessary for the growth of rice. Similarly, you may find rice in the semi-arid areas. What is important is the length of the growing season. I think we should use that criterion to delimit the semi-arid tropics.

Sivakumar: The areas Dr. Sarker mentioned are on the boundaries of the delineated area. Where you draw the boundary exactly is a question open for discussion. But what is probably more important is to look at the general delineation of the areas.

Krishnan: In Troll's classification growing season is defined in terms of P/PE. If one uses PE/2 instead of PE many problems could be overcome.

Reddy: Hargreaves has shown that his MAI of 0.34 is equal to 0.5 of mean P/PE.

Peacock: Based on my experience I feel that the Penman formula when applied in the semi-arid tropics gives grossly incorrect figures. Therefore, in your capacity as consultant with the FAO, I would like your comments on the use of Penman's formula in the classification of Semi-Arid Tropics.

Frere: If we consider the agricultural implications of the use of the Penman formula we will use it for periods when agriculture is possible. This means that for that period the rainfall will be generally adequate enough to allow agriculture. Therefore, relative humidity will be higher than during the dry season and you come back to the situation of humid tropics for that period. However, if you use the formula for the dry-season months, where it is recognized that the aerodynamic term of the Penman equation is underweighted, potential evapotranspiration is grossly underestimated. Therefore, in our agroecological zones project we have been led to introduce a modification based on the range between maximum and minimum temperature to correct this underestimation for agroclimate. But I wish to repeat that this underestimation is much less serious for the cultivation period during the rainy season.

Venkataraman: I would like to congratulate Dr. Virmani for bringing in the two approaches, namely, the risk factor, to be essentially used for demarcation, and the water-balance approach to answer specific. agronomic questions. I think the most important part of Dr. Virmani's paper has not received much comment. I would like to add one or two points. In the rainy season potential evapotranspiration hardly varies 4 to 5 mm per day. Therefore periods of dependable precipitation, defined as the one which at 50% probability has at least 2 cm of rain per week, very clearly brings out all the demarcations. In the water balance approach it has been stated that at Sholapur if you take a <u>kharif</u> crop the <u>rabi</u> crop is affected to only 20%. I find that double crop is possible in only 20% of the years at Sholapur on deep soils. So if you take a <u>kharif</u> crop there is an 80% chance of losing the <u>rabi</u> crop. This needs to be looked into and corrected.

Meher-Homji: In the map the Kaveri basin where we have 3 to 4 rice crops per year is also classed semi-arid.

Venkataraman: In the Kaveri basin rice crops are raised under conjunctive use of various irrigation resources. But climatically it is semi-arid. This applies to other Deltaic areas, Punjab, Rajasthan, etc.

Virmani : The basic question is, what do we understand by semi-arid? As I understand, it is an area where there is a risk to crop growing and rainfall water would be available for 60 to 135 days. The quantity is not important because the soil has a limited capacity and not more than 20 cm of available water can be held even in deep Vertisols. There is a little confusion here on dry-farming areas and semi-arid tropical areas. The definition of the dry farming is entirely different. When we are looking at the semi-arid tropics we are not looking at irrigation potential. Again one can ask how you define dry-farming areas. After all there are areas in Madhya Pradesh also that are dry-farmed. One could ask how you define dry farming.

Frere: The question of concern is the definition of rainfed rice. I know there are many difficulties. But it has to be defined. Do you consider the tank system as an irrigated system?

Virmani: One has to differentiate between two tank systems; in the first, water from everywhere comes into the tank and is then applied; in the second, you collect the rain water that falls on your land and guide it to a tank. But you will not get the water from your neighbor's land. The latter situation is treated as unirrigated.

Grove: There is one quite important variable, that is topography, that affects the stability for cropping. On a small scale it is important because it affects the individual farmer, depending on the position of his holdings on a slope.

Biswas: To delineate the semi-arid tropics, we should consider what type of crop is expected to be grown.

Gadgil: Regarding Dr. Sarker's reaction that too large an area is covered by the SAT, I would like to take an opposite view from a dynamical viewpoint. Troll is trying to distinguish classes by how long the rainy season is, irrespective of how much rain falls in that season. The entire Indian continent gets the rainfall from the monsoon system and it is not surprising that in a broad classification you find that the whole of the country lies in the same system. Dynamically this is what we would expect. The second point is whether one should use potential evapotranspiration in Troll's classification. Given all the uncertainties and given that we have a lot of parameterization that has gone in into the system, I would like to submit that perhaps it is not wise to use factors of 2 or 4.

Krishnan: What method had Troll used for his PE estimate?

Virmani: I learn that temperature was used as a proxy for PE and that is why I thought he has gone wrong.

Krishnan: When you use AE = PE you get all the humid areas also coming into semi-arid zones. Why not consider PE/2.

Virmani: We are mixing crop issues with environmental climate water-balance issues. If we use say PE/2 I think large arid areas will also come into the semi-arid tropics.

Peacock: As I understand it, this symposium is about classification of a macroclimate. At some stage in this symposium people have introduced into this classification edaphic factors. We have gone further and made the thing even more complicated and confusing by introducing plant types and different vegetation. Perhaps the Chairman or Dr. Virmani may clarify that point.

Gill: Previous soil classifications were mostly based on the land-use capability. But recent classifications use soil characteristics per se. So if we classify the climate and superpose the soil and plant characters per se it would be an advancement.

CLIMATIC CLASSIFICATION, AGROCLIMATIC RESOURCE ASSESSMENT, AND POSSIBILITIES FOR APPLICATION IN THE SEMI-ARID TROPICS

G.D.V. Williams

Venkataraman: I carried out a climatic resource analysis for wheat. Our problem is to adjust the timing of heading of wheat so that it doesn't get into too high a temperature. I agree with Mr. G. D.V. Williams on the need for testing of the agroclimatic resource index. He has suggested that we should use the district level or large area yields for this verification. Our experience with large-area yields is, to say the least, very discouraging. Again if you use recent data there is a clear discontinuity after the green revolution. Now at many of the agromet stations we have the meteorological records and we have the crop data for the last 10 years. My question is whether--and how--we can verify the agroclimatic resource index with the uniform crop data that is available for the most recent decade only.

G.D.V. Williams: I avoid using experimental station data because I have always felt that they are not a really good reflection of what could be attained in practice. If you use experimental data, however, you could probably come up with something satisfactory that you might want to check with external data. As we are looking not so much at real production but are making a relative comparison of locations, this may be a good way. I would recommend the use of both district-level and station data for the checking.

Meher-Homji: I would like to refer to Williams' paper, Figure 2; the semi-arid tropics. I think you have modified it from Walters, who does not call these curves either semi-arid or tropical. He calls the regions semi-evergreen and deciduous forests, dry woodland, natural savannah, etc.

G.D.V. Williams: Yes.

AGROCLIMATIC CLASSIFICATION METHODS AND THEIR APPLICATION TO INDIA

A.Krishnan

Biswas: In many areas where the normal growing season is shown to start on June 1, premonsoon rainfall is very little and the growing season generally starts with monsoon rain. Can you please explain?

Krishnan: The time when the monthly rainfall curve passes the PE/2 curve was taken as the commencement. Though the premonsoon activity is less, on an average rainfall exceeds PE/2.

Sarker: I presume you have taken the monthly average rainfall as available at the middle of the month.

Krishnan: Yes.

Venkataraman: In Table 2 one finds that many of the locations have more than 7 months and some have 365 days of crop-growing season under rain-fed farming. This of course does not agree with ground truth. Secondly, in the table relating to growing seasons in different soils, we find that just by changing the soil the duration of the crop is increased by 60 to 90 days and the increase is more in black soils than alluvial soils. Now for some possible reasons for these, for determining length of rainy season by the graphical method, it doesn't matter whether we use PE/2 or PE. Now we can show that unless the weekly rainfall exceeds PE, the crop season cannot start. Similarly at the end of the season when weekly rainfall goes down below PE, the crop season must end in about a month's time at most. However, if PE/2 is applied for rainfall-cum-moisture storage, the growing period will be exaggerated. Again, I am afraid that the moisture-holding capacity has been used in water-balance computations. But we have to take only the crop-available moisture (i.e. the moisture available between the field capacity and wilting point) at the particular evaporative demand. We have got lysimetric observations to show that it can vary from about 10 cm to about 13 cm for most kharif crops and soils. So by changing the soil types one can increase the crop life duration a little, but not to the extent of 60 to 90 days. This brings us back to Dr. Virmani's question, i.e. how far are our climatic analyses justified? Obviously when we change the period or the probability, the criteria must change.

Krishnan: In our new work we invariably take the first adequate rainfall week and we also now take into account the actual available soil moisture capacity. At some of the places listed, they grow a kharif and also a rabi crop and to that extent the ground truth has been verified by me. I am really grateful to Mr. Venkataraman for his point about finding the ground truth. For this we need collaboration between soil physicists and agroclimatologists at ICRISAT, agricultural universities, and ICAR.

Frere: I think it is as important to take into account what happens under the soil as above it.

AGROCLIMATIC CLASSIFICATION FOR ASSESSMENT OF CROP POTENTIAL AND ITS APPLICATION TO DRY FARMING TRACTS OF INDIA

R.P. Sarker

Frere: India is blessed in the abundance of weekly data for many stations and years compared with the conditions in other parts of the world, in particular the Sahel area and South America.

Reddy: Hargreaves has used not only an MAI of 0.34 but has given moisture adequacy limits according to different values of MAI.

Sarker: Although different criteria have been laid down by Hargreaves, for the delineation of the tropics he has gone only by the value of 0.34.

Gadgil: In the definition of classes, I notice that the intervals by which you have defined them are varying from class to class. May I know what led you to the specific choice for the class intervals?

Sarker: The criteria are to some extent subjective and arbitrary. We have drawn them up from the point of view of life periods of short-, medium-, and long-duration crops.

Gadgil: Would you say your classification tries to delineate regions of varying stability with respect to given rainfall regions rather than rainfall regions themselves? The reason I ask this is that the class G, which is the most favorable one from the point of view of crop production, has stations of diverse rainfall profiles.

Sarker: In the analysis we have gone by the minimum assured rainfall estimated by incomplete gamma distribution based on 70 or 80 years of data. As regards a number of stations coming under one category, we are trying to get further refinement.

Virmani: Did Dr. Sarker and Mr. Biswas compare the monthly and the weekly data and find any difference? Why not take the mean value instead of 50% probability? The other point is that there should be some ground truth attached to this kind of classification before one says which is the best level of probability.

Venkataraman: The statement that weekly rainfall equal to 20 or 30% of potential evapotranspiration is sufficient for seedling growth is not correct. Although the moisture need for or the moisture consumption by transpiration of the crop is only 20% in the early stages, to get the moisture down to the seed level the rainfall requirements are high, on account of the evaporation barrier. On a weekly basis it has to equal the potential evapotranspiration demand. Actually the rainfall requirement of the crop does not vary if you consider the week as an independent unit. At the 50% probability level MAI should throughout be 0.7. So when one combines MAIs of 0.7 and 0.3 there is a lot of unreal bunching of stations regarding growing season duration.

Meher-Homji: There is good resemblance between Figure 1 given by Dr. Krishnan and Figure 1 by Dr. Sarker, though the methods are different.

Sivakumar: How do we define dry-farming tract?

Sarker: We define the dry-farming tract as the region where the mean rainfall is to 1000 mm per annum and where irrigation facility is poor and evaporation is high.

PLENARY SESSION

REPORT ON CLIMATIC CLASSIFICATION-CURRENT CONCEPTS AND APPROACHES

G.D.V. Williams summarized the discussion on this session as follows:

There is a great diversity of crops in semi-arid tropics and it will be a long time before the climatic resources of the SAT can be assessed and mapped for each crop. In the meantime, there is a need for climatic information of use to agriculture in general. The session considered various approaches to general-purpose climatic classification that may be helpful in making a first approximation of the agroclimatic resources of the SAT.

Three papers were presented in this session. In the first, Grove discussed what he called "divisive" systems, such as those of Koppen and Thornthwaite, and then referred to "agglomerative" approaches such as those using principal component analysis and pattern analysis. He questioned the usefulness of trying to further refine climatic classifications without some specific end in mind. He drew attention to various problems of climatic classification, including the depiction of year-to-year variability and of the sequence of climatic events within the year, and the lack of spatial representativeness; he also stressed the need to present results in ways that are both informative and visually attractive.

In the second paper Meher-Homji discussed climatic criteria for specifying aridity and semi-aridity and the stability of climate. He then dealt with a phytogeographic approach to classifying climate, noting that plant cover reflects environmental conditions, including the variability of climate. Floristic, morpho-ecological, agronomic, and vegetational criteria were discussed, but the use of plant phenology data in climatic classification and mapping was not mentioned. The aridity and vegetational criteria were illustrated by maps relating to India. It was also pointed out that where human activity greatly modifies the natural vegetation, it has adverse effects on the climate.

In the final paper, Gadgil and Joshi demonstrated the use of principal component analysis and clustering in classifying India's climates. They claim that the choice of criteria used for such a classification is not subjective. In this first study only mean precipitation data of 73 pentads have been used. The results of their mapping appear reasonable. The method provides a tool for economic representation of the observed variation in rainfall and facilitates sorting stations into groups such that variations are minimized within groups and maximized between groups.

A major problem that would have been appropriate for full discussion in this session but was only touched upon very briefly is that many climatic classification systems are based largely on various computations performed with data from climatological stations. For agricultural applications it must be kept in mind that the data should be drawn from the agrometeorological stations. Some form of spatial climatic modeling seems to be needed, because probably in many parts of the semi-arid tropics, results from analyzing only data from existing stations are likely to be quite biased due to inadequate representation by the stations. The phytogeographic approach is an outstanding example of a method that does not suffer from this drawback, although it has its own limitations, particularly when the natural vegetation is much disturbed by man.

RECOMMENDATIONS

1. ICRISAT should investigate various spatial climatic modeling procedures for best determining climatic patterns in areas of inadequate station representation. The procedures could include, for example, the use of topographic and vegetation information. Ways of best applying the results in classifying climates to assist agricultural development in the SAT should be investigated.

?.. ICRISAT should be involved in studying the feasibility of using phytogeographic procedures to help classify climates for its farming systems applications.

3. Principal component analysis (PCA) and related and associated methods of classifying climate should be studied to determine their relevance for agricultural application in the SAT.

4. An integrated use of the best available methods or submodels should be aimed at some methods involved summing monthly indices to obtain an annual one, but perhaps PCA might be a more appropriate way of obtaining the overall index. As a first step towards an integrated approach, detailed comparisons could be made of the various climatic maps of India in the report of the April 1980 Consultants' Meeting on Climatic Classification.

5. In climatic classification studies, we should keep in mind such factors as climatic stability, climatic sequence from one part of the year to another, effects of human activities, and the best graphic means of presenting the results to facilitate their application to SAT problems.

PLENARY SESSION

REPORT ON DEVELOPMENT OF PRACTICAL CLIMATIC CLASSIFICATION SYSTEM FOR AGRICULTURE IN THE SEMI-ARID TROPICS

Mr. Frere summarized the discussion after the second session as follows:

Four papers were presented in this session. This session is unique in that it has dealt with all the three aspects of classification, namely (1) climatic classification, to define what the semi-arid tropics are (2) agroclimatic classification to subdivide the SAT into agronomically relevent homogeneous zones, and (3) bioagroclimatic classification or agroclimatic resource mapping, to understand climatic suitability in areal extent of an individual crop. Virmani and Krishnan discussed several classification approaches that are used to climatically delineate the SAT. Virmani, Krishnan, and Sarker discussed some of the ways to subdivide the SAT in agronomically relevant homogeneous zones. Williams suggested a method of agroclimatic resource indexing for identifying the regions that are best suited to a crop.

Virmani expressed the view that Troll's approach may continue to be used by ICRISAT to define the boundaries of the semi-arid zone. He also suggested that mean annual temperature of 18°C as suggested by Kb'ppen (1931) can be taken as the limit for defining tropics. With regard to agroclimatic analysis for crop planning, Virmani also suggested two methodologies, namely, rainfall probability analysis and water-balance approaches for defining moisture environment during the growing season.

Williams expressed the view that in the SAT moisture is the most important parameter that needs attention and detailed analysis, as the thermal aspect has been taken into account by limiting the zone of interest to the tropics. He also emphasized the nonapplicability of general classification systems to different kinds of plants. He suggested three categories of thematic mapping, i.e., climatic, agroclimatic, and agroclimatic resource mapping. He proposed an agroclimatic resource index (ACRI) and discussed its use in the SAT. He outlined the need to integrate the agroclimatic resource analysis with the ecological land classification and to verify the results of the analysis with regional crop yields.

In the first part of his paper, Krishnan discussed the climatic classification systems of Koppen, de Martonne, Gaussen, Emberger, Thornthwaite, and Thornthwaite and Mather and their relevance to the semi-arid tropics. In the second part he discussed the agroclimatic classification systems of Troll, Hargreaves, Cocheme and Franquin and their applicability to regional crop planning. He emphasized the importance of using realistic water budgeting techniques using short-period data for improvement of cropping patterns in the SAT.

Sarker and Biswas recommended the modification of Hargreaves' approach as a tool for agroclimatic zoning. They considered short-term (weekly) rather than monthly rainfall and suggested 50% probability level as the level of dependability. For classification of dryland areas, they had used a subjective combination of periods over which dependable rains equaled 33% and 70% of potential evapotranspiration. They further divided these classes according to daily average temperature and the water stress period.

On the basis of the considerable discussion on the four papers presented in this session, it would appear that climatic classifications need to be carried out along three different lines, depending on the objectives:

CLASSIFICATION FOR DIFFERENTIATING BROAD TYPES OF CLIMATE

These classifications will generally make use of mean yearly (monthly) data and will at the most differentiate between broad climatic types. As regards the semi-arid tropics, the general interest is to (a) delineate tropical areas on the basis of limitations to the raising of traditional tropical crops on account of unfavorable temperatures during the year, such as mean annual temperature < 18°C and (b) differentiate the semi-arid areas from the arid areas on the one hand and humid areas on the other, on the basis of duration of effective consecutive rainy months ranging from 2 to 4.5.

CLASSIFICATIONS FOR EVALUATING POTENTIAL FOR AGRICULTURE

This type of classification will be interdisciplinary in essence, because the agricultural assessment will have to take into account not only the climatic potential but also the requirements of particular crops in terms of aerial (temperature, radiation, humidity, etc), edaphic (soil moisture and aeration), pedologic (soil depth, salinity, etc), technological (fertilizer, pesticides), and other factors. This evaluation of the climatic potential will generally be based on monthly average of climatic factors and will call upon derived parameters such as heat units, photothermal units, sunshine hours, calculated potential evapotranspiration, length of rainy season, crop-growth days, and dry matter or biomass production (according to different photosynthetic assimilation pathways of crops).

CLASSIFICATIONS FOR TRANSFER OF TECHNOLOGY

For this type of classification, one needs to understand the climatic limitations of different regions that will help in modification and transfer of technology of land and water management or cropping systems practices. Therefore, it is essential to define attributes that relate to these problems rather than to limit oneself to a particular method or attribute.

For this, in place of average values of climatic parameters, one needs to use conditional criteria for agricultural planning purposes and/or allow an estimate of the <u>variability</u> in agricultural production in an area for which the overall production potential has been evaluated, as in the second type of classification. It appears that the only way to obtain a fair picture of this production variability is to calculate—using short-period (5-10 days) short-series (15-20 years) rainfall data—the water balance of the crops that will be grown in a given place. From this cumulative water balance, an index showing the degree of satisfaction of the crop water needs may be calculated. A grouping of the index values will provide a frequency analysis of the number of years out of 15 or 20 where the harvest may be expected to be good, satisfactory, or bad. The availability of crop-yield data over the same period could then help to verify, quantify, and extend in time and space this frequency analysis.

The meeting has also pointed out that in areas where the network for climatological observations is scarce, other methods, such as the analysis and mapping of vegetation cover, the remote sensing imagery verified by ground truth, etc., could be used for the purpose of climatic classification for agriculture.

RECOMMENDATIONS

1. The agrometeorological work carried out by ICRISAT is global in nature. Therefore the quantification of the climate in terms of resources is necessary for the development and transfer of improved technology. It should take into account the agricultural requirement using climatic factors and derived values of relevance to agriculture.

2. The nature of the resources to be considered as well as the criteria adopted should be based upon field agronomic research, empirical evidence, and the use of methods of analysis proven in other dry tropical environments.

3. Work on crop modeling in relation to weather and climate and micro-climatoiogical research should be emphasized. In particular, a network of experimental benchmark sites should be developed across the semi-arid tropics for the purpose of collecting simultaneously agrometeorological and relevent crop data.

4. The delineation of the tropics according to Koppen, i.e., 18°C mean annual temperature, seems suitable for adoption by ICRISAT.

5. Methods and scales of study must be different according to the objectives of the studies undertaken. This point must be clearly envisaged from the beginning.

6. In developing its agroclimatological activities ICRISAT should take advantage of the experience of FAO and WMO and develop projects in close cooperation with these agencies.

GENERAL DISCUSSION

Kanwar: I am impressed with your discussions and am sure you have reached some conclusions as to what and where the semi-arid tropics are. ICRISAT's interest in the delineation of the SAT chiefly relates to the transfer of technology. Because ICRISAT is located in Hyderabad we are working on the soils that exist here, under the climate that exists here. But we also have the responsibility for the 49 countries of the semi-arid tropics that include a whole range of physical environments and widely varying political and socioeconomic backgrounds. We have a geographical mandate and a crop mandate. How under these conditions, do we transfer technology?

An international institute cannot afford to have many stations even in one country; even in India the results that we obtain at Hyderabad may not be applicable to all situations. What should be our approach? Virmani's presentation of the two very good examples of Sholapur and Hyderabad shows that gross analysis of the climate cannot give us real confidence for transferring a technology in cropping system and resource management. Accepting Troll's classification system, we delineated the semi-arid regions and the semi-arid area was held to be only 25% of the country. But with detailed analysis the percentage of dry semi-arid tracts becomes 64%, and if we include the wet semi-arid tropics, it becomes 80%. We now operate a number of stations in West Africa, a few in East Africa, and one in Latin America; they cover important areas for sorghum and millets and other crops we are interested in. But could we, from considerations of climates, soils, and weather, choose some 10 additional centers that could serve all these conditions of 49 countries? Where are the boundaries of the SAT? What is the minimum number of centers we should have, and where should they be? We seek answers to these and related questions from this learned group so that we may better fulfill our mandate.

Virmani: This morning we saw maps drawn as per different classification systems. We at ICRISAT are interested in knowing how to delimit the semi-arid tropics. Many feel strongly that the moment we go beyond 1000 or 1100 mm of mean annual rainfall in India the region is no longer semi-arid. I would like some discussion on this issue in terms of ICRISAT's mandate. What are the lower and upper limits that we should be looking at? Regarding the thermic regime, there is not much controversy about the use of the mean annual value of 18°C. Regarding the hygric regimes the controversy can be settled if there is some feedback information.

Sarker: First we must define what the semi-arid tropics are; only then can we decide where they are. There is some discrepancy between Troll's map and the map produced by ICRISAT, based on data of 300 stations. So the definition should clearly bring out the limits and should be practically independent of the network of stations that we use in our computation. We find that if we modify Troll's classification using various ranges of moisture availability indices, we get a better agreement between the vegetation type and the classification.

Virmani: I want to focus the attention of the group on two points. First, whether the method can differentiate the arid zones from the semi-arid zones. Second, how far the SAT extend into the higher rainfall regions. Please refer to the Table on page 40. We took the five locations that primarily fall in the arid zone as per the revised map and we worked out the frequency of aridity. We found that 62% of the years showed less than 2 humid months. In the second set of stations in the semi-arid class only 11% of the years showed aridity. If you look at two or more than two locations, it is about 90% of the years in the semi-arid class and only about 40% of the years in the arid class. The point I want to make is that the central tendency is very clearly exhibited by these zonations, namely, arid and semi-arid. If this is accepted, then probably we can go to the higher part later in ICRISAT's program. I would like to have the comments of the group on this.

Frere: This question of differentiating arid and semi-arid zones also came up in the FAO when we started our work on agroecological zones. Finally we came to define an area as semi-arid that can allow one to grow a millet crop of 90 days duration. This is the bare minimum. In terms of this we limit ourselves to a 75-day growing season for an arid zone.

Venkataraman: I have used the 50% probability weekly values published by the IMD (India Meteorological Department) and taking 2 cm of rain at this level as sufficient to produce soil moisture recharge. I find that semi-aridity begins around 8 weeks' duration and we get into the upland rice area when the period extends to about 15 weeks. We have three contiguous states in India--Maharashtra, Karnataka, and Andhra Pradesh—wherein we have all the situations according to the existing classification, from humid to arid. Here our data set is available even on a taluk basis. So before we come to define the lower or the upper limit, I think a comparison of the various methods may be carried out and then the one that is substantiated by ground-truth observations can be accepted. We can then see whether we are gaining anything by using probability figures instead of means or by using weekly periods in place cf monthly ones. The exercise is suggested in Dr. Williams' paper also. If sophisticated analysis doesn't give much finer detail, there is no point in reducing the period or going in for stochastic analysis, etc.

Gadgil: Once you define aridity in terms of atmospheric parameters like P and PE, over as dense a network of stations as possible, that defines the limit of the semi-arid tropics. It becomes a difficult problem if we also try to see if the crops are the same or not. It may be a valid one for bioclimatologists, but it can cause a lot of problems because we would be mixing issues. Also, this kind of approach is likely to be very consistent with the scale of the dynamical system, that is, giving you the rainfall.

Virmani: I would agree with Mrs. Gadgil on this issue. I think the group sees no special difficulty in accepting Troll's methodology as such. It is only when we put it on the map that some difficulty arises. If this is taken care of in the methodology, we can soon prepare an international map.

Kanwar: All the comments so far relate to India. If a single country can cause so much difficulty, what type of map will be produced when we are dealing with 49 countries? We should evolve some objective parameters that can be followed consistently.

Sivakumar: The most important question that still remains to be answered is, if we consider only transfer of technology, what are the parameters that need to be considered? If it is precipitation and potential evapotranspiration at what scale does this need to be applied?

Peacock: A recent book by Bird suggests classification based on net radiation vorticity, and atmospheric moisture content as developed from satellite imagery.

Grove: Such data would be too sparse for classification purposes.

Kanwar: You have accepted 18°C mean annual temperature as a limit for the tropics. Virmani proposed that the upper limit should be mean annual rainfall of 1000 mm. Any comment on this?

Frere: I think that the best criterion to judge the semi-arid zone is the length of the growing season—between 90 and 150 days.

Venkataraman: From analysis of precipitation records we can determine when it is possible to start the crop season. Now after the rains terminate, the cropping can be carried on for 1 more month, plus or minus 10 days, depending on the quantum of moisture storage when rains cease. So if we accept a growing season of 75 days to 135 days, estimated as suggested above, I think we can separate out the semi-arid tropics from the arid and sub-humid zones. How to determine the start and end of effective rains will be a question of methodology.

Harikrishna: My suggestion is that we use the two criteria of Troll's classification as it stands and check the ground truth with cropping patterns in areas where semi-aridity has not been shown by Troll's classification.

Sarker: We can come out with a final definition of the semi-arid tropics, if we use all the suggested methodologies and delineate areas that are common to all the methodologies and yet satisfy the criteria of the crop duration of 90 to 120 days.

Kanwar: I think in this discussion we are forgetting all about soils, which condition crop success.

Virmani: The soils will, I agree, make a lot of difference to the crops raised. The same area will have pearl millet on sandier soil and sorghum on heavier soil. So as parameters in global classification, we should stick to rainfall and potential evapotranspiration. If we take the amount of water received in a global classification we will be in trouble. Troll's criteria give you a crop duration of about 3 to 5 months. The crops grown will depend on the soil types. Troll unfortunately, had used very little Indian data; he says so in his paper.

Kanwar: Not a single example was cited from Africa in all our discussions.

Reddy: The south Indian situation is seen in Brazil, and the north Indian situation is seen in Africa. In south India the semi-arid tropics are confined to 750 to 2000 mm of mean annual rainfall and in north India range from 500 to 1300 mm. So there will be difficulty in adopting lower and upper limits of rainfall in different regions.

Grove: I was just going to mention Africa. I could see much difficulty arising in a place where one has two rainy seasons, as in Kenya and southern Sudan.

Venkataraman: We need not be deterred by the fact that we don't have potential evapotranspiration data. Because if you go through the data in the semi-arid tropics you will see that 30 mm per week in the rainy season will be a very good approximation. The influence of soil types on crops is on the quantum of available soil moisture. For a given crop where root growth is unrestricted this is a conservative quantity, largely independent of soils. We have lysimetric data to show that it is of the order of 10 to 20 cm. So the growing season duration can easily be delineated and compared with other systems of classification.

Kanwar: Dr. Sarker, your organization is quite big and you have all the data available to you. Can you redraw those on lines on the basis of the suggestion you and your group have made? That could be a very useful exercise.

Sarker: I am agreeable to carrying out the exercise for India.

Virmani: First we must define the semi-arid tropical areas looking only at the climate. In the second step we can introduce soils into the definition, and in the third step we may fit a crop into it. We are at the start of our classification business. We have neither the data source nor the manpower available to do all the kinds of things that we are looking for. Data availability is extremely limited in Africa, particularly West Africa, and northeast Brazil. This is why I was trying to see if we could arrive at an internationally uniform and quick method of classification with easily available and published data. One cannot get into specifics like soils types, crop types, crop phenology, etc. in this kind of classification. We could start at a zero level and then go on to other levels. We need the national and other international agencies to assist us in carrying out some of this work. I am glad that Dr. Sarker has agreed to do this for India. We can probably find some other sources in Africa and Brazil to carry out detailed work of this type also.

Frere: The FAO is ready to extend all help regarding Africa and South America.

Kanwar: I am pleased to listen to your discussions on various methodologies for climatic classification. Each methodology has its own merits and demerits. Although we have not been able to agree upon a single methodology as the most satisfactory tool, it is gratifying to see that a few guidelines are emerging that are satisfactory for the purpose of delineating areas of our interest. We should continue our endeavours in this direction. Collaborative efforts between different organizations interested in this line would enlarge our data base and strengthen the applicability of the classification system.