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

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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.17°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

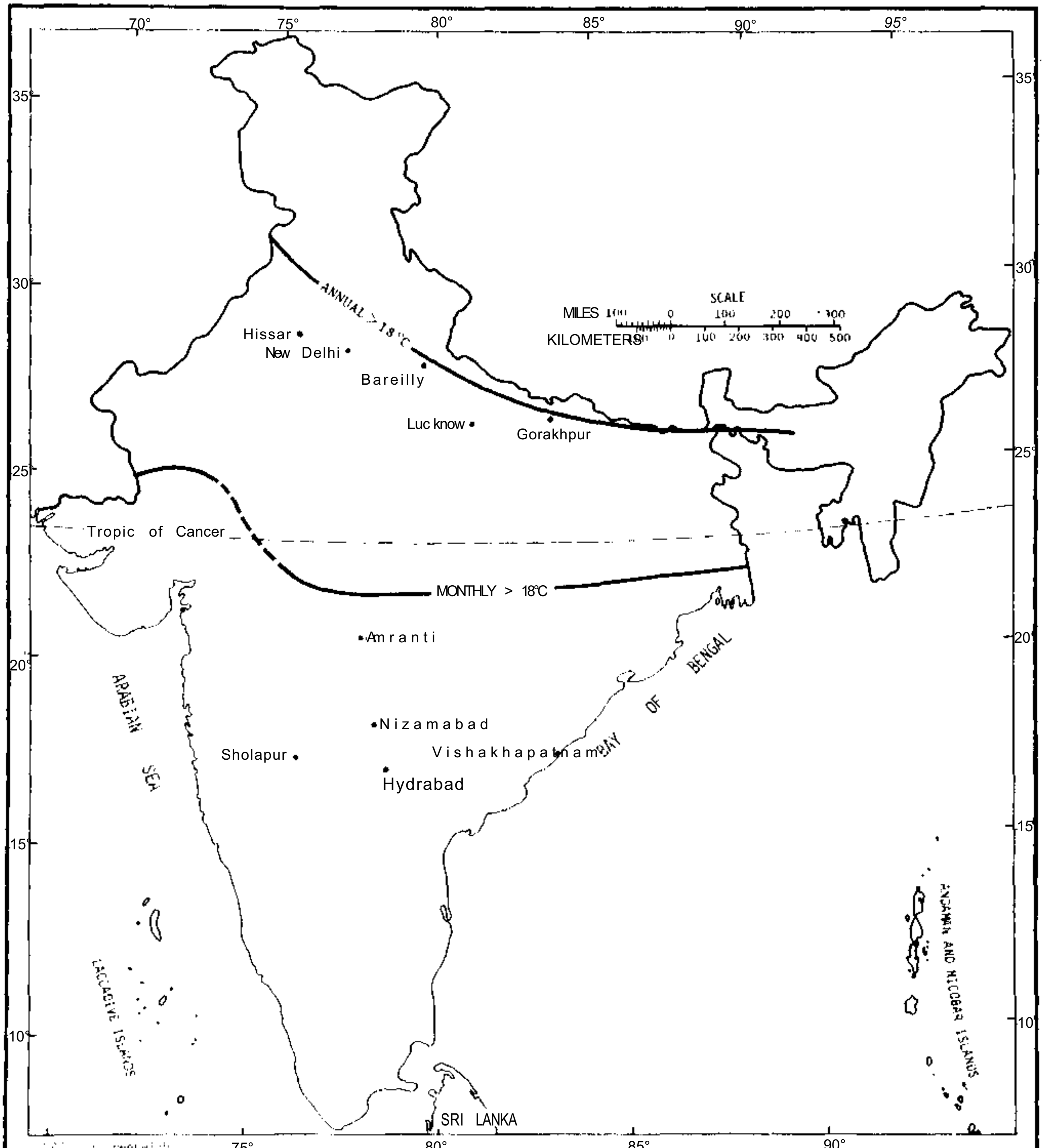

Figure 1: India, Isotherms of at least 18°C mean annual and mean monthly temperature.

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

Location	Lat.	Season[b]									Annual
		Summer			Rainy			Winter			
		Max. (°C)	Min. (°C)	Ave. (°C)	Max. (°C)	Min. (°C)	Ave. (°C)	Max. (°C)	Min. (°C)	Ave. (°C)	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

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.

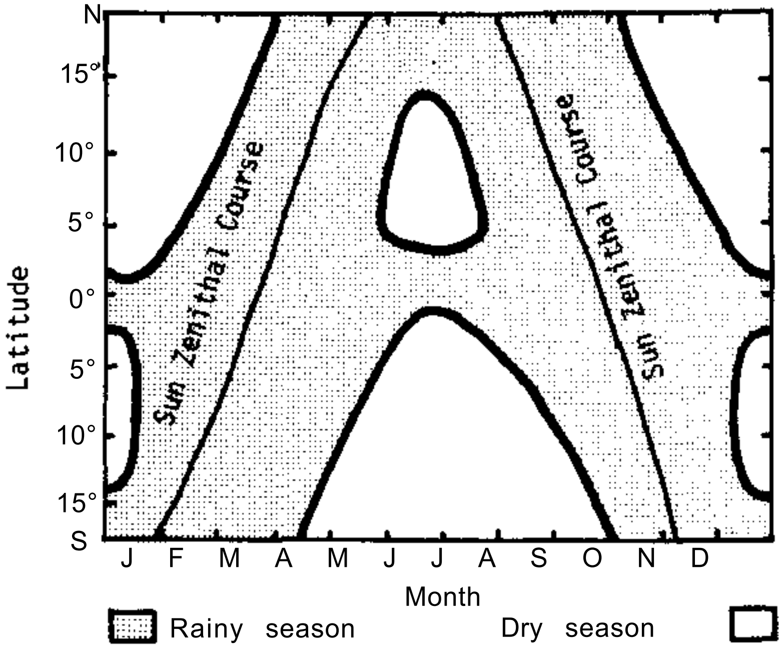

Figure 2: Theoretical monthly distribution of rainfall between latitudes 20°N and 20°S, according to de Martonne (1957).

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-

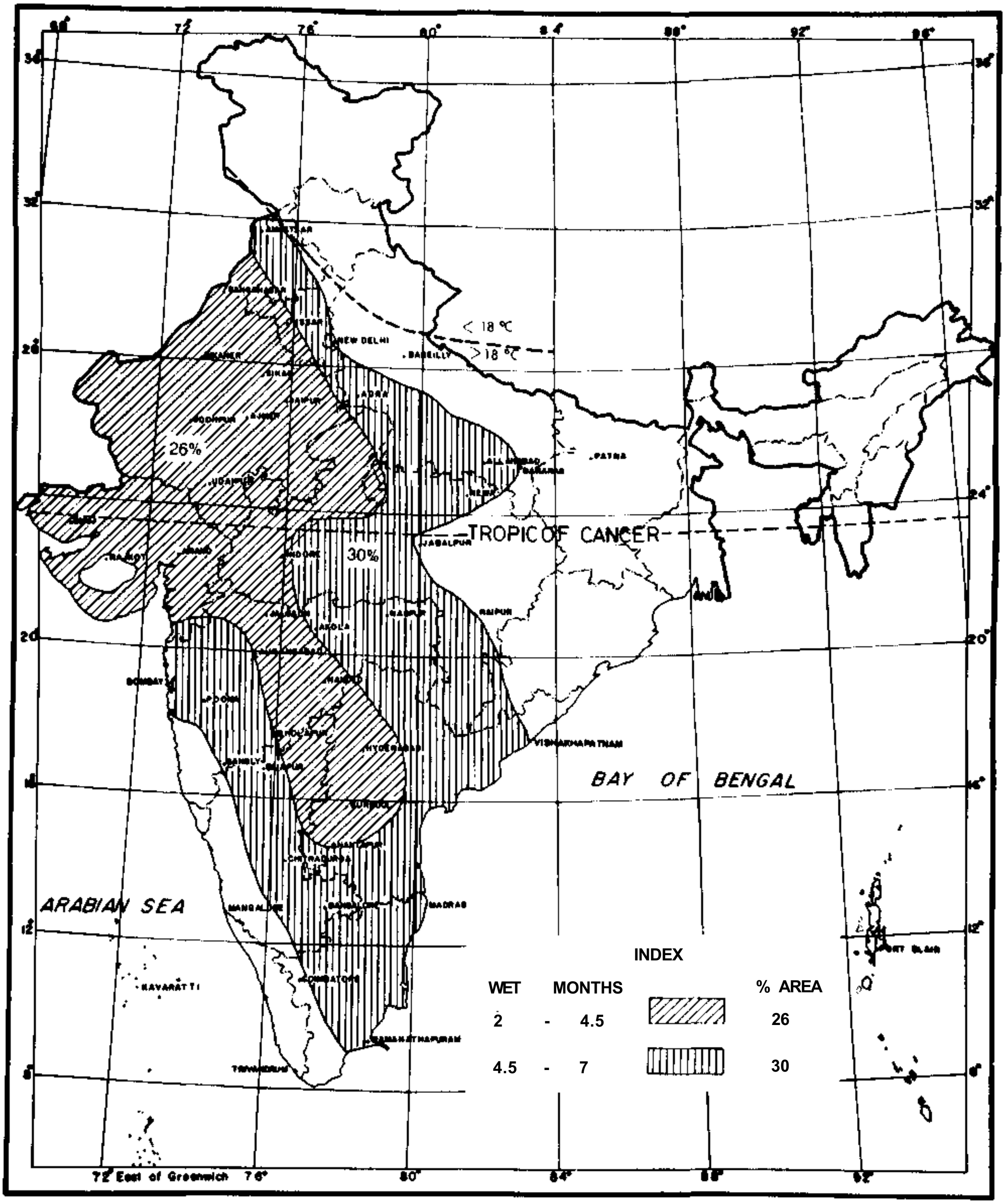

Figure 3: Semi-arid tropics in India, adapted from the World Maps of Climatology published by C. Troll (1965). Names of stations have been superimposed by us to define the geographical distribution of dry and wet/dry semi-arid tropics in India. We could not ascertain the number of locations used for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

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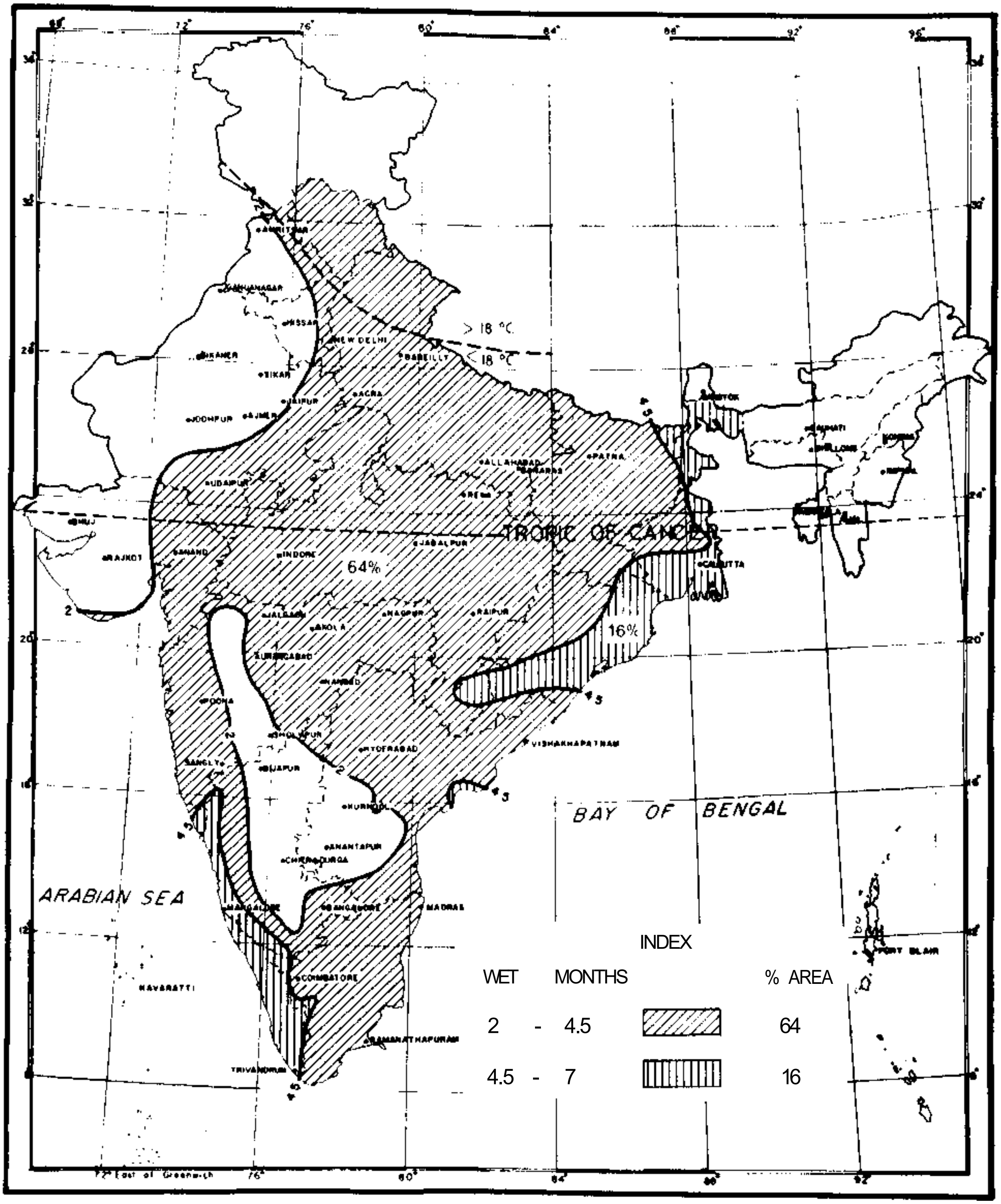

Figure 4: Semi-arid tropics in India (ICRISAT). Troll's (1965) methodology for characterizing the humid periods and classifications was used for over 300 locations in India. The resultant map shows the zonation of the dry and wet/dry semi-arid tropics throughout India.

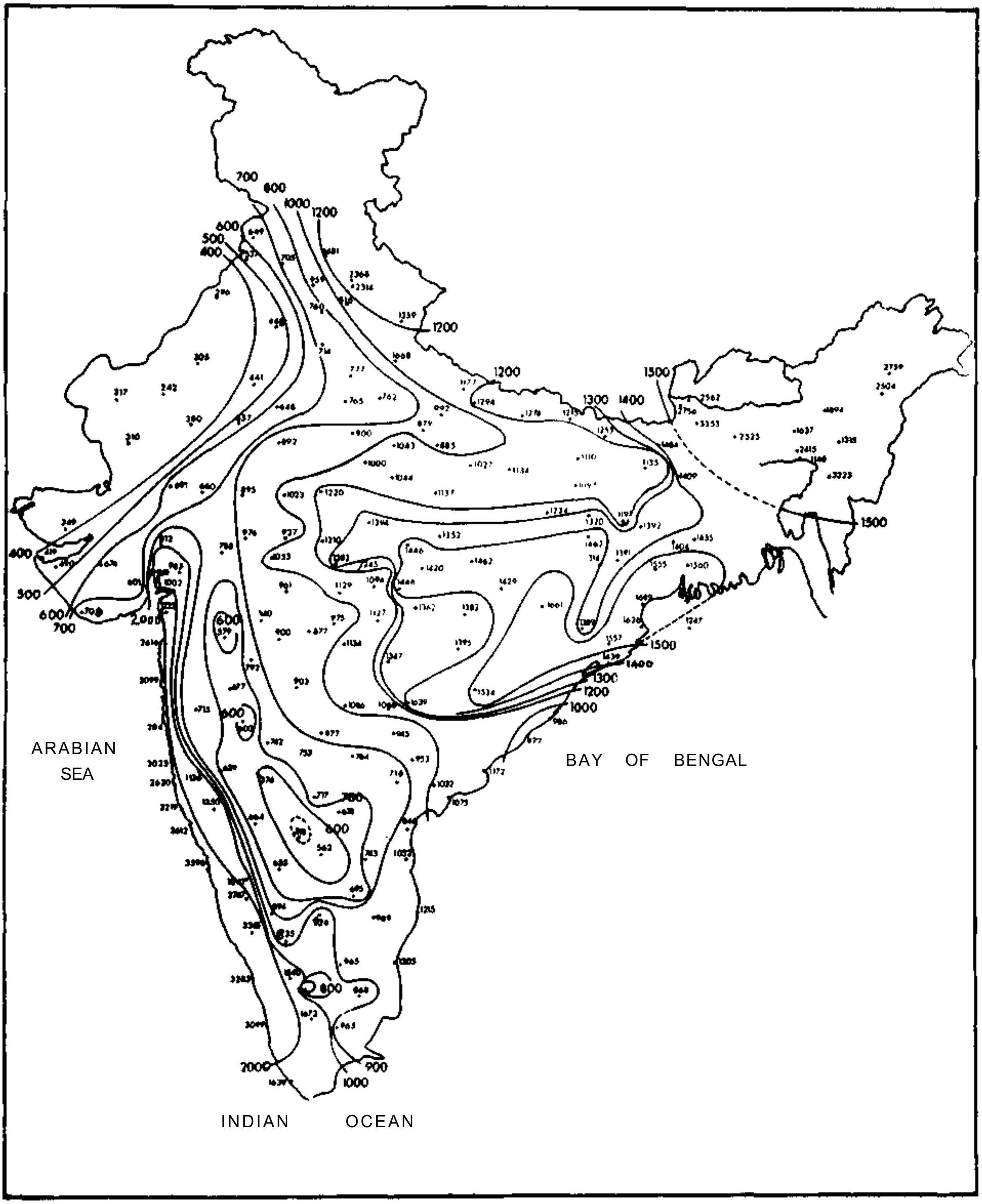

Figure 5: Rainfall isohyets in India.

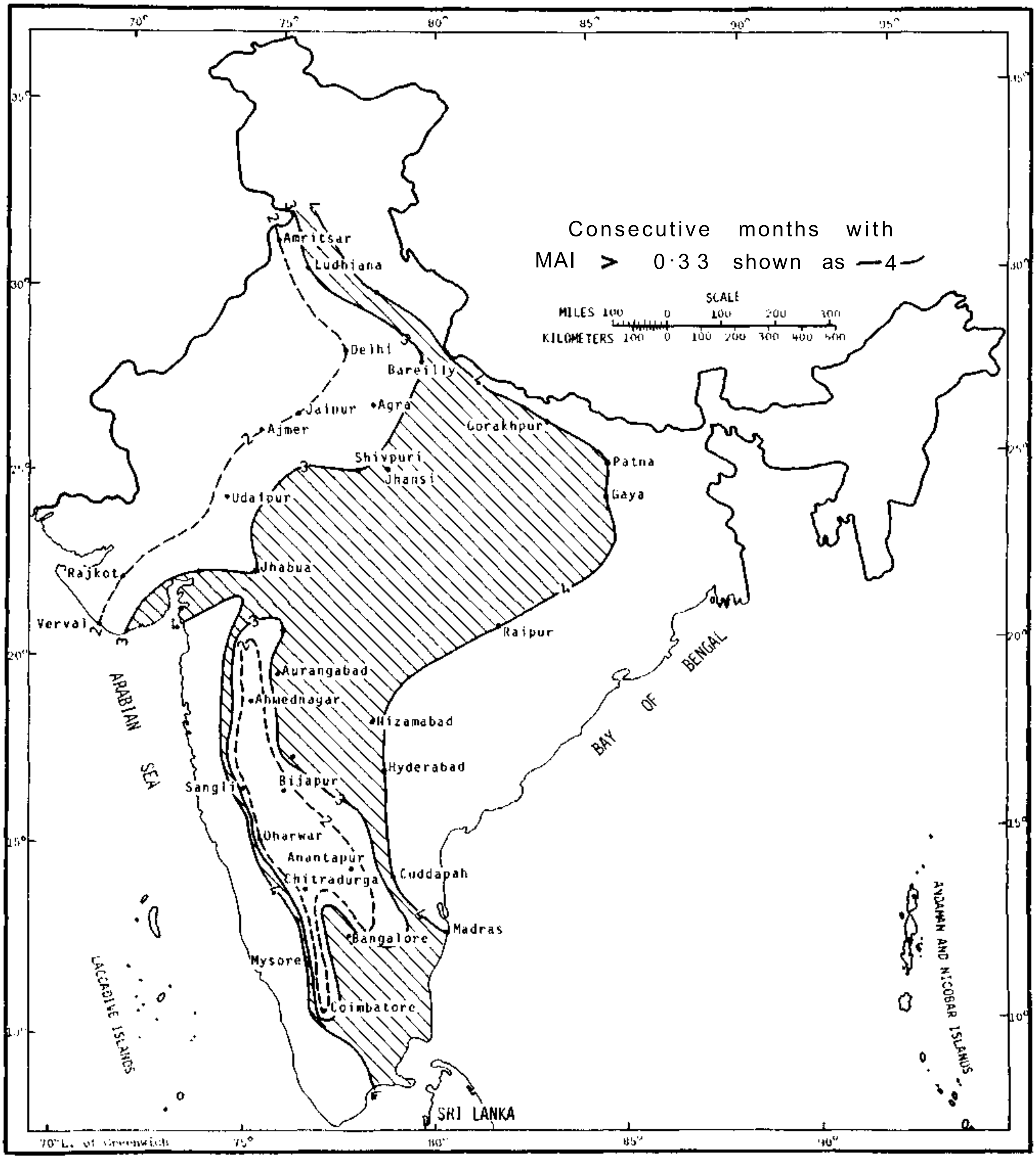

***Figure 6:** India, climatic classification (Hargreaves ' method).*

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.