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Modelling of water budget elements—Extreme events

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Increased variability in the monsoon systems might be the causal factor for the prevalence of extreme events of humidity, aridity and climate type. Yearly hydroclimate indices obtained from the water balance model serve as the basis for the extreme events. The investigation addresses the probable maximum values of humidity and aridity along with the climate type employing the Hersh-field statistical model.

Keywords: Water cycle, Water balance concept, Probable maximum climate indices
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1 Introduction

The aberrated global climate system with regional implications due to acquired radiative forcing might be the reason in triggering extreme climate events of floods, droughts, storms, heat and cold waves, etc. across the world, whose footprints are already traced[1] and are not an exception to India. Apart from this, the global rain bearing systems in the respective principal rainy season might be modulated through global climate teleconnections and the notorious short-term climate signal of El Nino-southern oscillation (ENSO)/La Nina-southern oscillation (LNSO) from the southern tropical Pacific is the principal one among them[2]. Further, the present state of climatic scenario across the globe is due to the changes in land surface dynamics coupled with atmospheric aerosol loading which might be the causal factors in modulating atmospheric circulation pattern and might have altered surface energy and water balances. The chaotic nature of monsoon weather systems on different spatio-temporal scales might be responsible for the occurrence of droughts and floods in space and time over India[3,4]. The occurrence and frequency aspects of droughts and floods over India are reported by Bhalme and Mooley[5,6], while the variability in floods during the monsoon season was dealt by Chowdary and Mhasawade[7]. The present investigation addresses some of the aspects of the probable extremes of hydrological events over south India through the revised water balance model[8] based on the earlier work by Sarma[9] and others[10-13]. The humidity and aridity indices are employed for the occurrence, intensity and frequency of floods and droughts in India. The annual indices of humidity and aridity derived from the water balance model determine the water deficit and the water surplus in relation to rainfall and water-need (evapotranspiration) through the year on a monthly basis. For this reason these are also termed as seasonal effectivity of moisture[14]. It is not only the change or delay either in arrival or strength of monsoon systems current pattern, but also the number of monsoon depressions, cyclones and the storms that breed from the Indian Ocean, determine the amount of rainfall over India which is the principal component of the hydrological cycle and, in turn, paves the way either for flood or drought over India[12]. The present investigation is an attempt to estimate the probable maximum values of humidity, aridity and climate type at selected stations in the dry regions of south India. Chow[15] and Hershfield[16] suggested methods for the probable maximum events. The derived yearly climatic indices of humidity, aridity and climate type are used for the Hershfield statistical model[16] in obtaining the probable maximum events. Figure 1(a) depicts the climate types of India and Fig. 1(b) presents the location of the selected stations representative from dry climates of south India.

2 Materials and methods

Rainfall and potential evapotranspiration serve as the input for the water balance concept of Thoronthwaite[14]. Annual water deficit and water surplus are derived following the revised book-

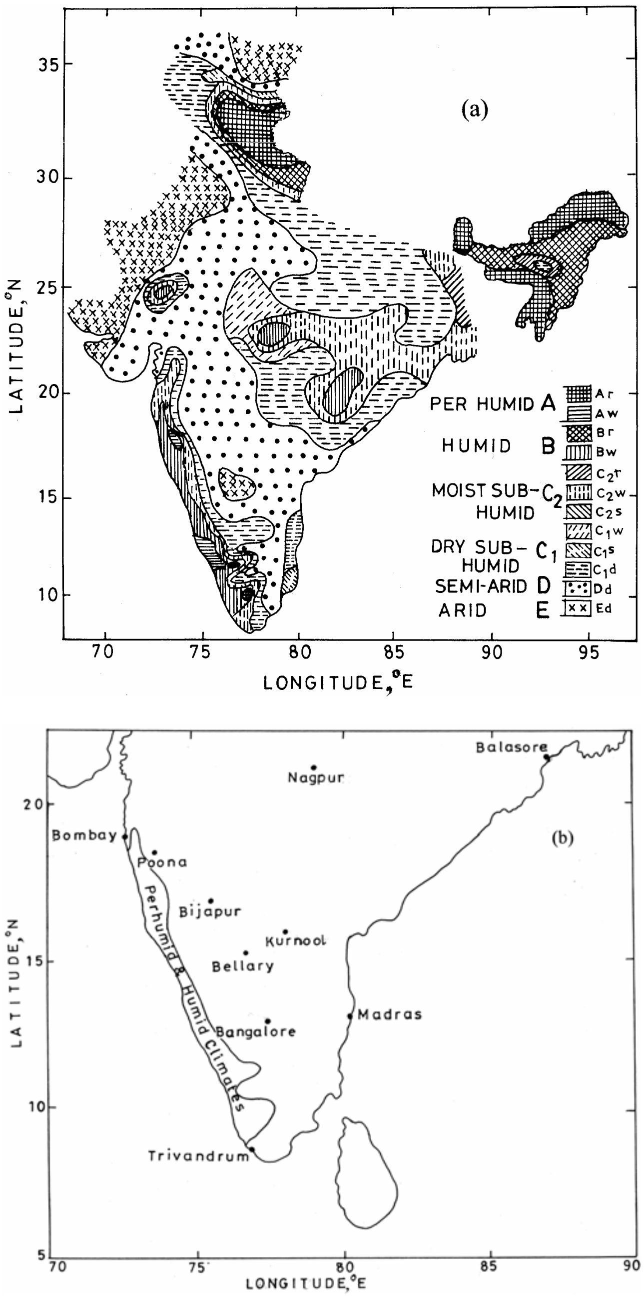

Fig. 1—(a) Climatic types of India (Moisture regime) and (b) Location of the selected stations (South India)

keeping procedure of Thoronthwaite and Mather[8] for about 50 stations which are drawn from sub-humid, semi-arid and arid climatic zones of south India. The absolute amounts of these elements cannot be used as such and are, therefore, expressed as a percentage ratio of potential evapotranspiration and are termed as humidity and aridity indices, respectively, that speak about the seasonal effectivity of moisture at the selected stations. The moisture index tells how moist or how dry a particular station is, and is obtained by subtracting the aridity index from the humidity index. To delineate the various climates the limits suggested by Carter and Mather[17] have been adopted. To appraise the characteristics of the selected stations in terms of humidity, aridity and moisture status the spatial variability statistics have been made use of. Statistic such as maximum, minimum, mean, median, intersequence variability, interquartile range $[(Q_3–Q_1)/2]$, decile $[(D_2+8)/2 \pm (D_8–2)/2]$ and skewness have been obtained for the water budget indices at all selected stations for the period 1901-1975. The expressions for this type of statistic is available in every statistics book and is omitted here for brevity sake.

An attempt has been made in the present paper for the probable maximum value and return periods of the aforesaid water budget indices. To obtain the probable maximum values for the water budget indices the Hershfield technique[16] has been employed. The yearly data of water budget indices have been used instead of daily values in the Hershfield technique. The annual data of water budget elements have been divided into segments consisting of five year duration each and from these segments, a string of maximum values have been obtained by selecting the maximum value for each one and substituted in the following expression of Hershfield. The expression for the probable maximum value for an event is as follows:

$$X_m = \bar{X} + \sigma K_m \quad \text{...(1)}$$

where X_m is the estimate of year instead of one day probable maximum value for a station and for an index.

The factor K_m is calculated by using the expression

$$K_m = (X_L - \bar{X}_{N-1})\, \sigma_{N-1} \quad \text{...(2)}$$

where, X_L is the largest value of the extreme annual value in the string of maximum values. The values of $\bar{X}$ and σ in Eq. (1) are calculated by taking all the values including the largest value X_L from the string of maximum values. In Eq. (2), the same procedure is adopted with the largest value omitted. But the frequency factor K_m depends upon the probability distribution of the event to be analyzed. Chow[15] suggested scientific relationships of K_T and the return period T for different probability distribution as

$$X_T = \bar{X} + K_T \sigma^2 \quad \text{... (3)}$$

where, X_T is the extreme value of the event corresponding to the return period T and $\overline{X}$ and σ^2 are mean and variance of the data of length N and K_T is the frequency factor. The frequency factor K_T is not a constant number, but depends upon the return period T and its value for the extreme value distribution is given by

$$K_T = -[1.00 + 1.75 \log\{\mathrm{Log}\,(T/T-1)\}] \qquad \ldots(4)$$

where K_T is a function of return period T and is also a function of observed record of N-years. So, one can either obtain K_T that corresponds to the length of the period for which X and σ are obtained or one can refer Weiss[18] table of values K_T for various return periods T corresponding to various lengths of record. Using the foregoing procedure the values of the probable maximum values for the water budget indices are obtained.

3 Results and discussion

3.1 Variability statistics of seasonal effectivity of moisture and moisture status

3.1.1 Humidity status

Table 1 presents the statistics of the humidity index at selected stations of sub-humid, semi-arid and arid climate types of south India. The range of humidity index is constantly reducing from moist sub-humid to arid climates and is minimum at the arid zone. The intersequence variability of the index is maximum at the arid zone. The interquartile range is also decreasing from moist sub-humid climates to arid, thereby unfolding the density of observations which is much greater inside this range than outside. The degree of asymmetry is least at Bombay. The decile statistic of Bombay indicates that the density of observation spread is maximum and is least for Bijapur (Table 1). The variability statistic of the humidity index indicates that the variability is decreasing from moist sub-humid to arid climates. The small variability in the seasonal effectivity of moisture is as a result of small variations in the quantum of rainfall at semi-arid and arid climates. But in the sub-humid climates the variability is high because of the frequent violent fluctuations of rainfall from year to year.

3.1.2 Aridity status

The aridity status of the sub-humid, semi-arid and arid climatic provinces of the south India is given in Table 2. The range of aridity is high in the dry climates compared to moist sub-humid zone. The intersequence variability of aridity is mild at the selected stations and is taking a maximum value of 9.8 for Madras (Table 2). The interquartile range also suggests that the density of observations is confined to a small range. Among the stations that are selected for the present investigation of aridity analysis, the decile band magnitude of Bangalore is high and is low for Trivandrum. The tendency of aridity at Bombay,

Table 1—Variability statistics of seasonal effectivity of moisture–Humidity index

Station	Effectivity of moisture (humidity)								
	Max	Min	Range	Mean	Median	ISV	IQ	$[(D_2+8)/2\pm(D_8-2)/2)]$	Skewness
Moist sub-humid zone									
Bombay	162.2	3.60	158.6	64.2	63.2	32.7	17.7	7.6 to 131.4	0.10
Balasore	101.1	0.0	101.1	23.9	22.7	20.5	15.4	14.8 to 26.0	0.17
Trivandrum	103.2	0.0	103.2	28.9	25.8	24.5	13.4	8.9 to 46.1	0.42
Dry sub-humid zone									
Bangalore	47.7	0.0	47.0	11.0	8.4	14.3	8.0	0 to 19.2	0.66
Madras	51.5	0.0	51.5	12.6	8.2	15.2	9.2	17.6 to 21.4	0.96
Nagpur	42.1	0.0	42.1	13.0	10.8	13.8	10.2	0 to 24.7	0.55
Semi-arid zone									
Kurnool	17.6	0	17.6	1.5	0	2.9	0.5	0 to 4.6	1.36
Bijapur	25.5	0	25.5	1.2	0	2.2	0	0 to 0.8	0.89
Pune	50.0	0	50.0	3.7	0	5.4	2.8	0 to 6.8	1.40
Arid zone									
Bellary	11.5	0	11.5	1.0	0	1.9	1.3	0.6 to 3.9	1.38

Note: ISV: Intersequence variability; IQ: Interquartile variability; D: Decile

Madras, Pune and Bellary is onto the negative side and is perceptible at Bombay. The positive skewed nature of seasonal effectivity of moisture is observed at Balasore, Trivandrum, Nagpur, Kurnool and Bijapur.

3.1.3 Moisture status

The range in the moisture status of the moist sub-humid zone is high compared to dry climates because of the frequent violent fluctuations in the quantum of seasonal rains. The intersequence variability is high in moist sub-humid climates and is continuously decreasing from this zone and is low at arid zone (Table 3). The decile statistic clearly indicates that the width of the moisture band is also decreasing and thereby explaining the natural conservation of the semi-arid and arid zones with respect to their climatic status.

3.2 Probable maximum humidity field

The probable maximum value of humidity together with the highest observed value and the ratio of these two are presented in Table 4. For all selected representative stations the estimated value is higher

Table 2—Variability statistics of seasonal effectivity of moisture–Aridity index

Station	Effectivity of moisture (aridity)								
	Max	Min	Range	Mean	Median	ISV	IQ	$[(D_2+8)/2 \pm (D_8-2)/2)]$	Skewness
Moist sub-humid zone									
Bombay	58.1	32.0	26.1	49.1	49.5	4.7	3.8	44.2 to 53.9	– 0.20
Balasore	40.2	5.4	34.8	20.2	19.7	6.8	4.7	13.0 to 38.1	0.23
Trivandrum	32.0	8.0	24.0	17.0	16.7	5.6	2.9	12.7 to 20.6	0.21
Dry sub-humid zone									
Bangalore	53.9	20.2	33.7	36.4	36.5	8.2	5.3	30.1 to 44.4	– 0.03
Madras	63.3	18.5	44.8	41.1	41.6	9.8	6.5	33.0 to 49.5	– 0.13
Nagpur	54.8	12.6	42.2	34.9	34.6	6.6	4.0	26.7 to 36.2	0.14
Semi-arid zone									
Kurnool	84.2	47.9	36.3	64.5	63.4	8.0	5.7	58.9 to 71.5	0.49
Bijapur	81.9	45.3	36.6	63.2	62.7	7.5	6.5	53.4 to 72.5	0.16
Pune	75.1	29.4	45.7	53.9	54.0	7.6	6.0	47.2 to 60.5	– 0.01
Arid zone									
Bellary	82.8	44.8	38.0	68.3	68.5	7.6	6.3	61.4 to 76.6	– 0.05

Table 3—Variability statistics of moisture status–Moisture index

Station	Moisture status								
	Max	Min	Range	Mean	Median	ISV	IQ	$[(D_2+8)/2 \pm (D_8-2)/2)]$	Skewness
Moist sub-humid zone									
Bombay	111.0	– 48.0	159	16.3	150	34.5	17.7	– 6.5 to 37.1	0.14
Balasore	95.7	–33.7	129.4	3.1	– 0.3	24.5	18.0	–20.9 to 23.5	0.41
Trivandrum	86.5	– 22.8	109.3	11.8	7.4	26.1	15.9	– 11.1 to 29.3	0.57
Dry sub-humid zone									
Bangalore	11.0	– 52.0	63.0	– 24.9	– 27.0	16.8	10.6	– 37.1 to – 14.8	0.43
Madras	20.6	– 59.0	79.6	– 28.5	– 31.4	17.3	11.7	– 44.6 to 14.2	0.48
Nagpur	17.9	– 54.3	72.2	– 21.9	– 20.8	17.2	11.5	– 36.6 to – 10.4	– 0.20
Semi-arid zone									
Kurnool	– 39.0	– 84.0	45.0	– 62.5	– 62.0	10.5	7.0	– 75.0 to – 51.0	– 0.18
Bijapur	– 26.0	– 81.0	55.0	– 61.5	– 62.0	9.3	6.5	– 72.6 to – 52.0	0.12
Pune	– 15.0	– 75.0	60.0	– 50.4	– 52.0	11.8	8.1	– 60.1 to – 42.5	0.41
Arid zone									
Bellary	– 36.0	– 82.0	46.0	– 67.2	– 67.8	9.4	– 6.5	– 72.2 to – 60.5	– 0.30

Table 4 — Estimated probable maximum humidity index

Station	Probable maximum humidity index	Highest observed humidity index	Ratio *R* (Col.2/Col.3)
Moist sub-humid zone			
Bombay	190.2	162.2	1.17
Balasore	130.3	101.1	1.28
Trivandrum	121.5	103.2	1.17
Dry sub-humid zone			
Bangalore	51.6	47.7	1.08
Madras	54.3	51.5	1.05
Nagpur	56.9	42.1	1.35
Semi-arid zone			
Kurnool	21.1	17.6	1.19
Bijapur	37.8	25.5	1.48
Pune	71.1	50.0	1.42
Arid zone			
Bellary	13.0	11.5	1.13

than the observed one and the ratio is varied from 1.05 to 1.48. It is observed that the probable humidity value is increasing as the return period increases (Table 5).

The spatial distribution of the probable and the observed seasonal effectivity of moisture in terms of humidity index is presented in Fig. 2. Stations such as Bombay, Belgaum, Balasore, Trivandrum and Jagdalpur that belong to moist sub-humid climates recorded an index value of 190.2, 172.3, 130.4, 121.5 and 125.9, respectively. Cuddalore, Solapur and Chitradurga which are drawn from the dry sub-humid and semi-arid climates of south India could even assumed more than 100 as their index value, a feature that indicates the swing of these climates on to the extreme perhumid side. Stations that are located in Maharashtra, Karnataka and Andhra Pradesh could only record an index value of 15 only, a feature that explains the locations which cannot witness higher effectivity of moisture values. A well marked cell with a core value of less than 20 is observed in the heart of south India [Fig. (2b)]. The notable feature of the observed values of seasonal effectively of moisture are less in magnitude compared to the respective probable values [Fig. (2b)].

3.3 Probable maximum aridity field

Table 6 represents the ratio of probable aridity to the observed ones and is varying from 1.01 to 1.09 at the representative stations. For all the selected stations

Table 5—Estimated one year humidity index for different return periods.

Station	Humidity index for return period (in years)				Ratio = Col.5/Col.2
	5	25	50	100	
Moist sub-humid zone					
Bombay	122.1	163.6	180.9	197.9	1.62
Balasore	67.2	98.4	111.2	124.0	1.85
Trivandrum	75.6	105.1	117.4	129.5	1.71
Dry sub-humid zone					
Bangalore	37.5	52.4	58.5	64.7	1.73
Madras	41.9	62.5	71.2	79.7	1.90
Nagpur	35.4	49.9	55.9	61.9	1.75
Semi-arid zone					
Kurnool	10.0	18.1	21.4	24.7	2.47
Bijapur	12.2	23.9	28.9	33.7	2.76
Pune	23.9	43.9	52.2	60.4	2.53
Arid zone					
Bellary	7.2	12.5	14.6	16.8	2.33

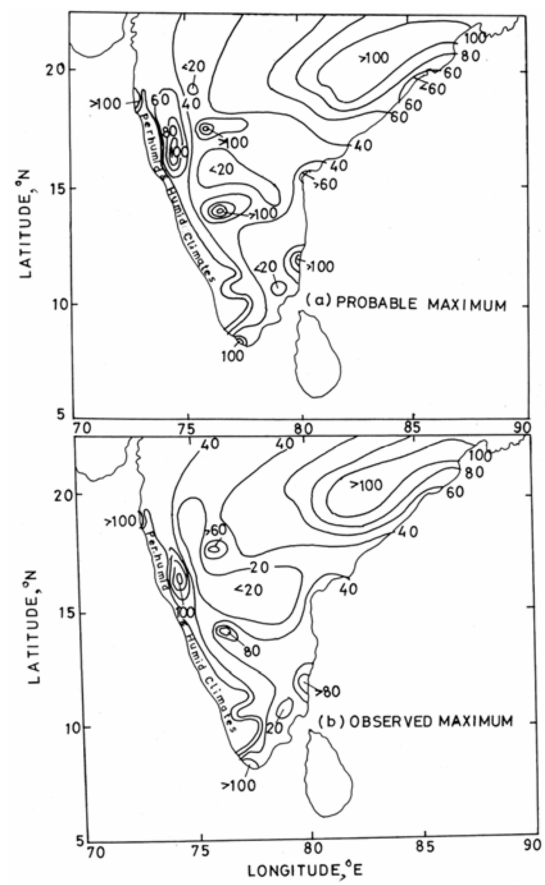

Fig. 2—Seasonal effectivity of moisture (humidity index), the dry climates of South India

the aridity for different periods is increasing just as in the case of humidity (Table 7).

Figure 3 presents the aridity pattern in the dry climates of south India. Among the three cells that are observed the one that occupied Kakinada and its adjoining areas has recorded a core value of greater than 100 [Fig. (3a)]. The observed aridity cells are less compared to the probable ones. The aridity field charts may be of immense help in introducing appropriate crops that could withstand for the probable or observed aridity.

Table 6—Estimated probable maximum aridity index

Station	Probable maximum aridity index	Highest observed aridity index	*R* (Col.2/Col.3)
	Moist sub-humid zone		
Bombay	58.8	58.1	1.01
Balasore	43.9	40.2	1.09
Trivandrum	34.6	32.0	1.08
	Dry sub-humid zone		
Bangalore	55.3	53.9	1.02
Madras	66.1	63.3	1.04
Nagpur	56.9	54.8	1.03
	Semi-arid zone		
Kurnool	86.2	84.2	1.02
Bijapur	83.7	81.9	1.02
Pune	81.7	75.1	1.08
	Arid zone		
Bellary	83.6	82.8	1.01

Table 7—Estimated one year aridity index for different return periods

Station	Aridity index for return periods (in years)				*R* (Col.5/Col.2)
	5	25	50	100	
	Moist sub-humid zone				
Bombay	56.1	59.8	61.4	62.9	1.12
Balasore	33.0	42.4	46.2	50.0	1.51
Trivandrum	27.0	33.4	36.0	38.7	1.43
	Dry sub-humid zone				
Bangalore	50.1	55.8	58.2	60.5	1.20
Madras	56.9	64.0	67.0	69.9	1.22
Nagpur	48.7	57.4	61.1	64.7	1.32
	Semi-arid zone				
Kurnool	78.2	87.7	91.7	95.6	1.22
Bijapur	77.3	86.2	89.9	93.5	1.20
Pune	66.3	73.2	76.1	73.9	1.11
	Arid zone				
Bellary	78.8	86.2	88.8	91.4	1.15

3.4 Probable maximum moisture status

The probable moisture status of the selected stations of south India is higher compared to the observed ones with an exception to Bellary and the ratio is varied from 1.39 to 0.71 (Table 8). The probable one-year moisture status for different return periods is increasing from sub-humid to semi-arid climates (Table 9). But the moisture status of Bellary which is drawn from the arid pocket of south India is showing a decreasing trend for different return periods as is shown in Table 9.

It is observed from the present investigation that the sub-humid and even semi-arid climatic provinces are elevated to more than perhumid moisture status [Fig. (4a)]. The regions that maintain semi-arid and arid might just cross the dry sub-humid limits and Anantapur has assumed a probable value of – 43.6, while its observed status is – 50.

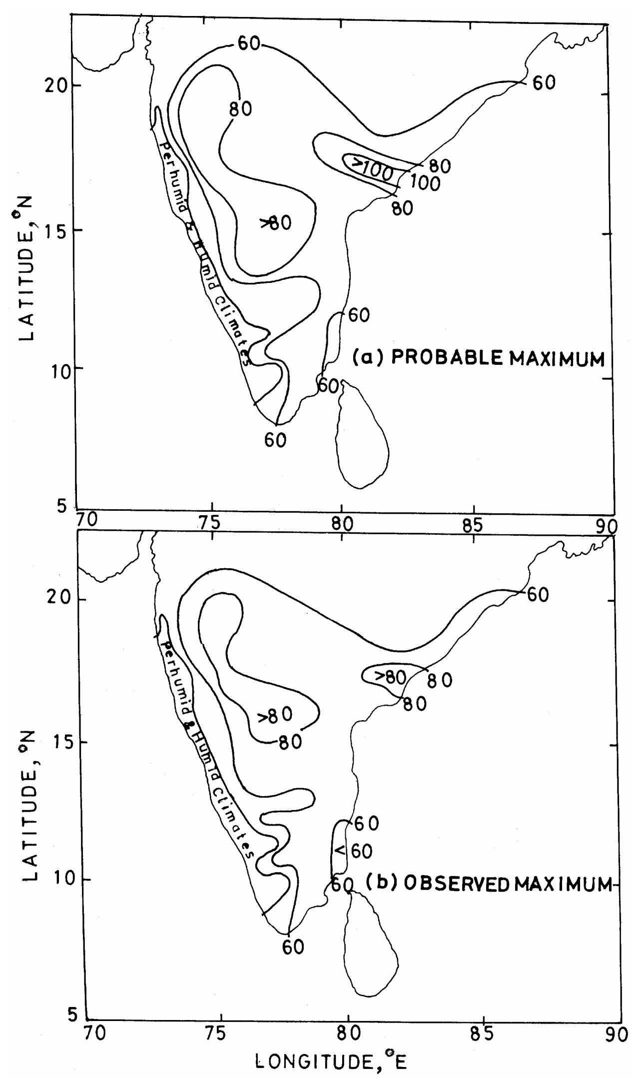

Fig. 3—Seasonal effectivity of moisture (aridity index)

3.5 Probable year maximum/minimum hydroclimate indices – a 100-year return period

Even on a 100-year return period, a narrow elongated zone extending from south-east peninsula to interior as far as Rentachintala on the east and Bellary on the west could register less than 20 as its value of seasonal effectivity of humidity [Fig. 5(a)]. This zone of low index is surrounded on all sides by higher values. The surge of high effectivity of moisture from north-east part of the diagram is clearly evident in [Fig. 5(a)].

Table 8—Estimated probable maximum moisture index

Station	Probable maximum moisture index	Highest observed moisture index	*R* (Col.2/Col.3)
Moist sub-humid zone			
Bombay	139.2	111.0	1.25
Balasore	132.6	95.7	1.39
Trivandrum	105.3	86.5	1.22
Dry sub-humid zone			
Bangalore	14.2	11.0	1.29
Madras	26.2	20.6	1.27
Nagpur	22.1	17.9	1.23
Semi-arid zone			
Kurnool	– 35.9	– 39.0	0.92
Bijapur	– 18.9	– 26.0	0.73
Pune	– 10.6	– 15.0	0.71
Arid zone			
Bellary	– 30.3	– 36.0	0.84

Table 9—Estimated one year moisture index for different return periods

Station	Moisture index for return periods (in years) 5	25	50	100	*R* (Col.5/Col.2)
Moist sub-humid zone					
Bombay	72.5	111.2	127.2	143.2	1.98
Balasore	55.1	91.5	106.6	121.5	2.21
Trivandrum	59.0	87.9	99.8	111.6	1.89
Dry sub-humid zone					
Bangalore	1.8	18.1	24.9	31.7	17.6
Madras	4.3	29.1	39.4	49.6	11.5
Nagpur	5.7	24.2	31.8	39.4	6.91
Semi-arid zone					
Kurnool	–48.9	–36.8	–32.7	–28.5	0.58
Bijapur	–38.9	–22.7	–15.9	–9.3	0.24
Pune	–26.8	–10.5	–3.7	3.0	0.11
Arid zone					
Bellary	–62.0	–74.2	–79.2	–84.2	1.35

The area occupied by 80% and greater than 80% aridity isoline of the 100-year return period [Fig. 5(b)] is large compared to probable aridity [Fig. 3(a)]. Among the stations that are selected for the present investigation, Ahmedanagar, a semi-arid station has registered a higher value of 98.8 compared to Bellary (91.4) which is a typical arid station from south India.

The moist sub-humid stations recorded a perhumid status for the 100-year return period moisture status. The typical and arid station, namely Bellary indicates a status as low as –84.3 for a 100-year return period [Fig. 5(c)]. The vast expanse of dry climatic zones of south India is fluctuating around the dry sub-humid limits. A very small isolated pocket at and around Bellary is under the purview of semi-arid to arid.

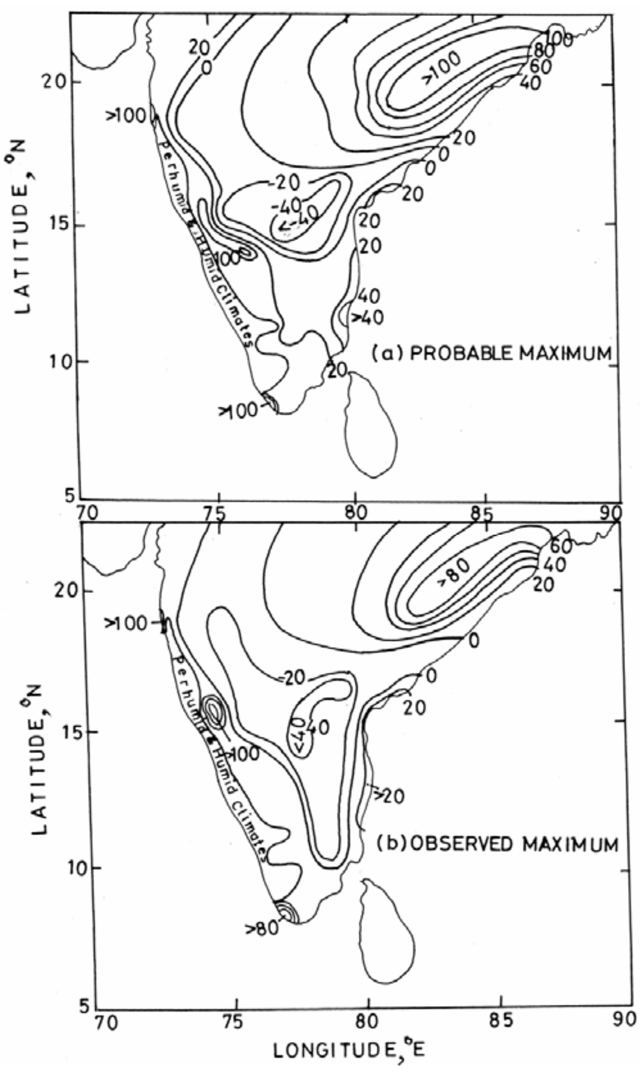

Fig. 4—Contour plots showing the moisture status of dry climates of South India

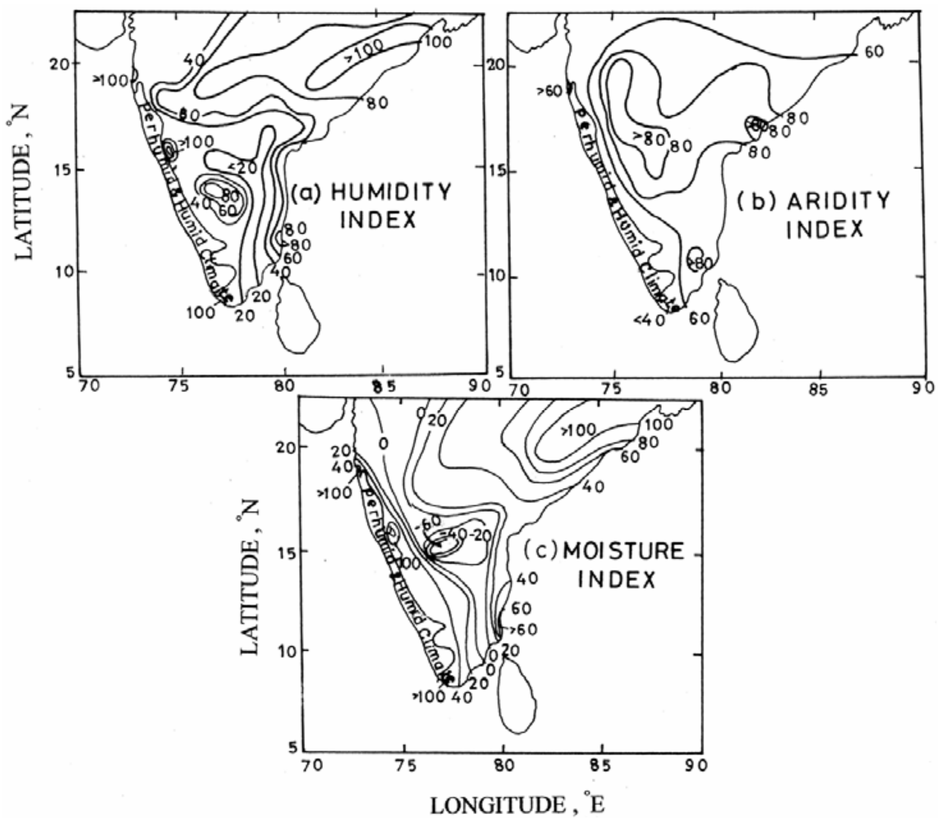

Fig. 5—Contour plots showing the one-year hydro-climatic indices (100-yr return period)

4 Conclusions

The range, not only in seasonal effectivity of moisture in terms of humidity index but also the intersequence variability, is decreasing from moist sub-humid to arid zone. The mean and median values of aridity are increasing from moist sub-humid to arid zone. The intersequence variability in moisture status is higher in moist sub-humid zone compared to the higher order of dry climates. The probable maximum values of humidity, aridity and moisture status in the sub-humid, semi-arid and arid climates are reasonably simulated compared to the observed ones. It is observed that the simulated year-main-climate type is improved from sub-humid to semi-arid zones, while that of arid zone is deteriorated, a fact that explains clearly that it is the prevalence and variability of rain bearing weather systems in sub-humid and semi-arid zones compared to very little and highly seldom weather events of arid zone that are responsible in imparting the respective climate types for the corresponding geographical realms.

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