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SOME ASPECTS OF DAILY RAINFALL DISTRIBUTION OVER INDIA DURING THE SOUTH-WEST MONSOON SEASON

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ABSTRACT

This paper presents the results of an analysis of the daily rainfall at 365 Indian stations for the 80-year period, 1901–1980. The rainfall data relate to the south-west monsoon season June to September (122 days), which accounts for the major part of the annual rainfall over most parts of the country. For each of the stations the rain-days are arranged in ascending order of rain amount, and the association between the cumulated percentage rain amount (x) and the cumulated percentage number of rain-days (y), designated as the normalized rainfall curve (NRC), is calculated. It has been shown in an earlier study that x and y are related by the equation $x = y \exp[-b(100-y)^c]$, where b and c are empirical constants that depend on the coefficient of variation (CV) of the rainfall series. This equation has been utilized to study various parameters of the daily rainfall distribution.

The coefficient of variation of the daily rainfall series varies between 100 per cent and 230 per cent at individual stations, with nearly half the number of stations having CV values in the range 130–150 per cent. The number of days of significant rainfall (days with rainfall greater than the mean intensity per rain-day) constitute about 30 per cent of the total number of rain-days and account for about 75 per cent of the seasonal rainfall at almost all the stations.

KEY WORDS South-west monsoon Daily rainfall distribution Normalized rainfall curves

1. INTRODUCTION

Much of the information about the rainfall climatology of India is based on monthly, seasonal, and annual rainfall data, which are derived from daily rainfall recorded at individual stations. It is of interest and importance to study the climatological aspects of the daily rainfall distribution over the country, which has a wide variety of rainfall regimes. Such information is of relevance for the efficient management of water resources systems, agricultural operations, etc., as well as for a better understanding of the processes producing rainfall.

One interesting way of studying the characteristics of the distribution of daily rainfall is by examining the association between the cumulated percentage rain amount (x) and the cumulated percentage number of rain-days (y) after arranging the rainfall series for a period of years in an ascending sequence of daily rainfall. In this case, the values of x and y range from 0 to 100 per cent in ascending order. We shall, in what follows, refer to the curve showing the association between x and y as the normalized rainfall curve (NRC). Earlier studies on NRCs (Olascoaga, 1950; Riehl, 1954, 1979; Rai Sircar, 1955; Martin, 1964; Wexler, 1967; Cobb, 1968; Harrison, 1983) and their applications have been reviewed by Ananthakrishnan and Soman (1989).

Ananthakrishnan and Soman (1989) made a detailed study of the NRCs by utilizing the daily rainfall data of 15 Indian stations for the 80-year period, 1901–1980. This study included monthly, seasonal and annual daily rainfall data and the stations chosen covered a wide variety of rainfall regimes. They found that:

(i) a universal NRC to represent all rainfall regimes does not exist;
(ii) the nature of the NRC is uniquely determined by the coefficient of variation (CV) of the rainfall series;
(iii) widely different rainfall regimes can be represented by the same NRC if the different rainfall series have the same CV;

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(iv) the NRCs for all the stations can be represented by the analytical equation

$$x = y \exp[-b(100-y)^c] \tag{1}$$

where b and c are empirical constants that depend on the CV of the rainfall series.

The rain intensity (rain amount per day) corresponding to any point on the NRC is inversely proportional to the slope of the tangent to the curve at that point. The point on the NRC where the slope of the tangent is 45° corresponds to the mean daily rain amount $r = R/N$, where R is the cumulated total rain amount and N is the cumulated total number of rain days. Unlike the original equation for NRC, equation (1) can account for the high-intensity rainfall at the upper extremity of the NRC in accordance with observation.

2. NATURE AND SCOPE OF THE PRESENT STUDY

The present study deals with the spatial variation of different parameters of the daily rainfall distribution over India during the south-west monsoon season, June to September (122 days), and uses the daily rainfall data of 365 stations (spread more or less uniformly over the country) for the period 1901 to 1980. The study is confined to the rainfall data of the summer (south-west) monsoon season only, as most of the rainfall over India is received during this season. In some respects the study presented here is an extension and elaboration of the earlier work of Ananthakrishnan and Soman (1989) in which they considered only 15 representative stations. Figure 1 shows the spatial distribution of the stations; the isolines in the diagram show the major features of the spatial distribution of the south-west monsoon rainfall. As is well known, the heaviest seasonal

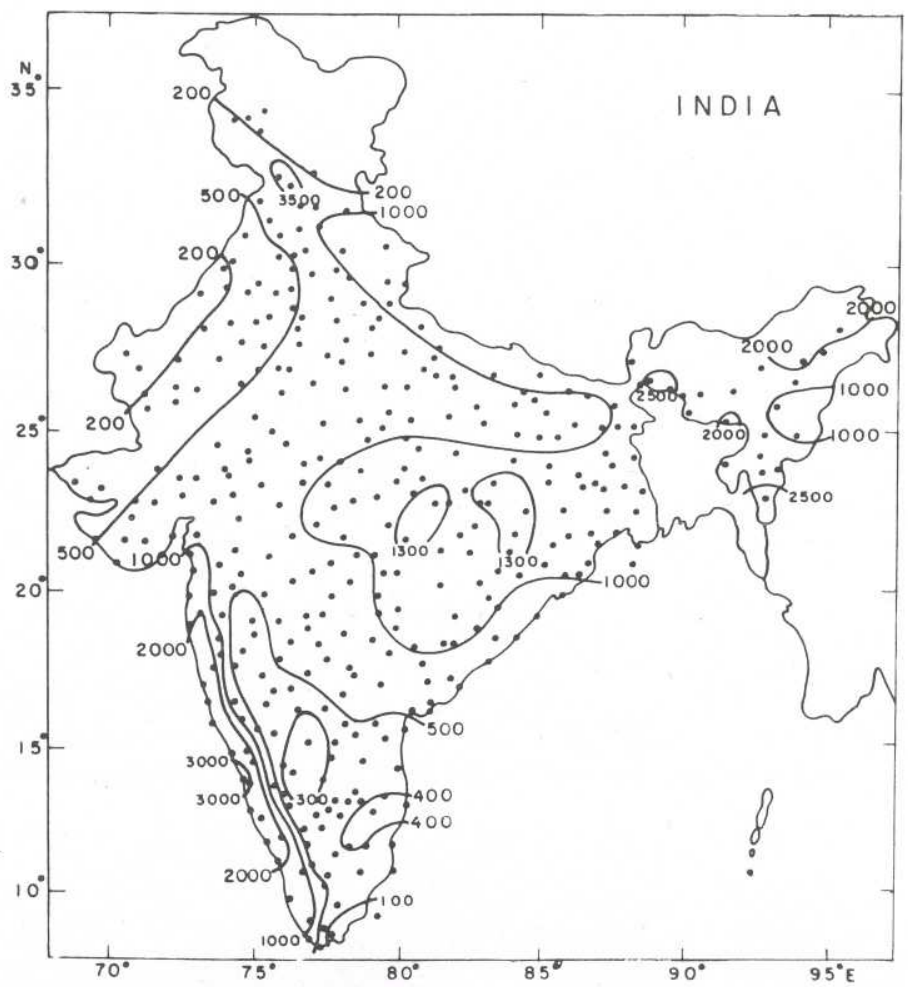

Figure 1. Location of the 365 rain-gauge stations selected for the study, and isolines of mean south-west monsoon rainfall (1901–1980) distribution (mm)

rainfall occurs along the west coast and also over north-east India, while the lowest rainfall occurs over the extreme western parts of the Rajasthan Desert and, more strikingly, over the extreme south-eastern parts of peninsular India.

In what follows, we use the term 'rain-day' to indicate a day on which a measurable amount of rain (0·1 mm or more) has been recorded at any station. This is different from what is known as a 'rainy day' in Indian meteorological literature (India Meteorological Department, 1962) which refers to a day with a rain amount of 2·5 mm or more. The relation between these two parameters is dealt with in a later section of this paper. At rain-gauge stations in India the rainfall for a day is reckoned as the rain amount collected from 03Z (0830 Indian Standard Time) of the previous day to 03Z of that day. The rainfall is measured correct to 0·1 mm. We shall use the term 'rain intensity' to indicate the 24-h rainfall amount.

From the daily rainfall data at the individual stations for the 80-year period we have evaluated for each station the following parameters:

(i) the total rainfall (R) in millimetres and the total number of rain-days (N);
(ii) the mean rainfall per rain-day $r = R/N$ (mm day^{-1});
(iii) the standard deviation (σ) in millimetres of the rainfall series of N daily values;
(iv) the coefficient of variation CV $= 100\ (\sigma/r)$ of the rainfall series;
(v) the mean number of rain-days per year ($n = N/80$) and its coefficient of variation;
(vi) starting from the zero-point of the NRC, the upper limit of rain intensity (mm day^{-1}) contributing 50 per cent of the seasonal rainfall using equation (1);
(vii) estimated rain intensity (mm day^{-1}) at 99 per cent and 99·9 per cent of the cumulated number of rain-days from the zero-point of the NRC ($y = 99$ per cent and $y = 99{\cdot}9$ per cent) using equation (1);
(viii) the difference between the number of 'rain-days' and 'rainy days' expressed as a percentage of the number of rain-days.

For the sake of clarity of presentation the normalized rainfall curves for the south-west monsoon season in respect of two stations (Ahmedabad and Mangalore) are shown in Figure 2. The methodology for the present study is the same as that explained in the paper by Ananthakrishnan and Soman (1989) referred to earlier.

3. RESULTS

The results are briefly presented and discussed with the help of diagrams that illustrate the essential points.

3.1. Mean rain amount per rain-day (r)

The spatial distribution of mean rain amount per rain-day during the south-west monsoon season is shown in Figure 3. The lowest intensities, of the order of 10 mm day^{-1}, occur over the rain-shadow regions immediately to the east of the western Ghats in peninsular India. Large areas of the peninsula and western parts of north-west India experience intensities of 10–15 mm day^{-1}. Major parts of the north Indian plains receive a mean rain amount between 15 mm and 20 mm day^{-1}, while the highest values (20–30 mm day^{-1}) occur along the west coast and cover parts of north-east India.

3.2. CV of the daily rain amounts

As shown in the earlier study (Ananthakrishnan and Soman, 1989) the CV of the daily rain amounts (Figure 4) is a significant parameter of the daily rainfall distribution, which uniquely determines the shape of the NRC. It is found that the CV of the daily rainfall at the network of stations covered by the present study varies from 100 per cent to 230 per cent. The frequency distribution is shown in Table I. Note that 331 out of 365 stations have CV values in the range between 110 per cent and 170 per cent. The maximum frequency is in the range 130–150 per cent, which accounts for nearly half the number of stations.

The largest values of CV from 160 per cent to 230 per cent, are found over Gujarat State and parts of the west coast north of 17°N. This is the region affected by mid-tropospheric cyclones that form over the north-east area of the Arabian Sea and the adjacent land areas, and also by monsoon depressions from the Bay of Bengal

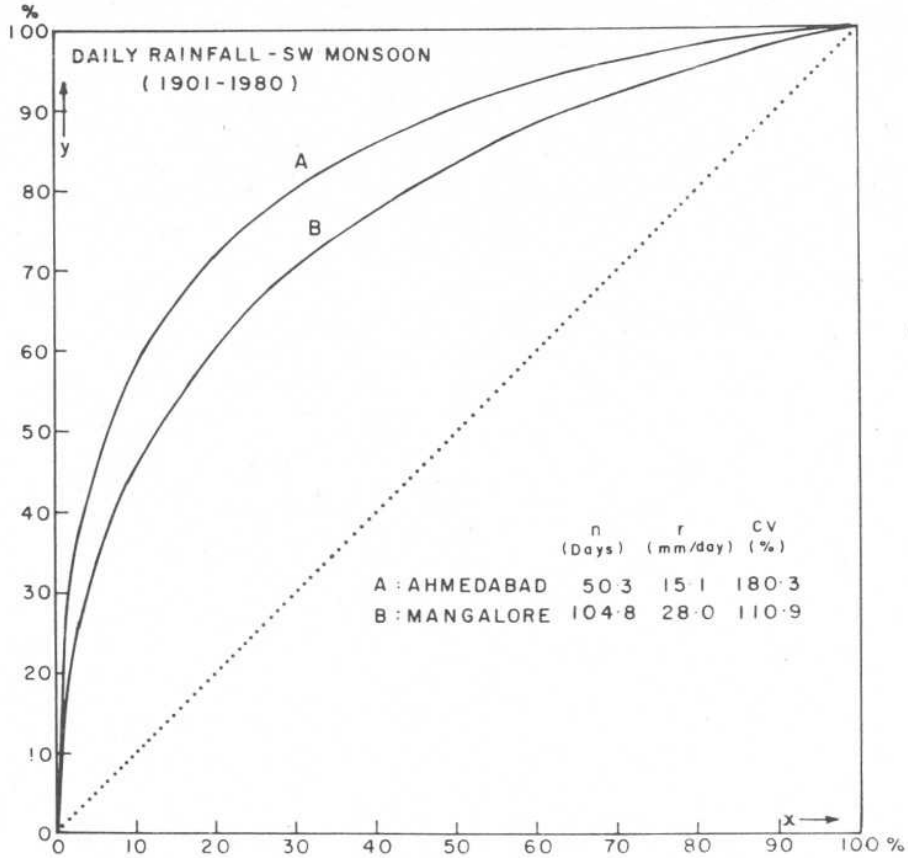

Figure 2. Normalized rainfall curves of Ahmedabad and Mangalore: x = cumulated percentage rain amount; y = cumulated percentage rain-days

Table I. Frequencies of coefficients of variation

	CV per cent						
	<110	110–130	130–150	150–170	170–190	>190	Total
Number of stations	9	94	169	68	20	5	365

moving towards Gujarat; both systems occasionally produce very heavy rainfall. Along the southern parts of the west coast and over western parts of Rajasthan and some areas of north-east India, the daily rain amounts are less variable, the CV being less than 120 per cent. It is interesting to note that western Rajasthan, where the annual and monsoon seasonal rainfall shows maximum variability, is one of the areas with minimum CV of daily rainfall when only rain-days are considered, as in the present study. Over north India and eastern parts of the peninsula, the CV values range between 120 per cent and 140 per cent and over the remaining parts of the country between 140 per cent and 160 per cent.

3.3. Number of rain-days (n) *and its variability*

As seen from Figure 5, stations on the west coast between 10°N and 20°N have on average more than 100 rain-days during the monsoon season, while over north-east India n varies from 80 to 100. The central and northern parts of the country have values of n between 40 and 80; the extreme western parts of north-west

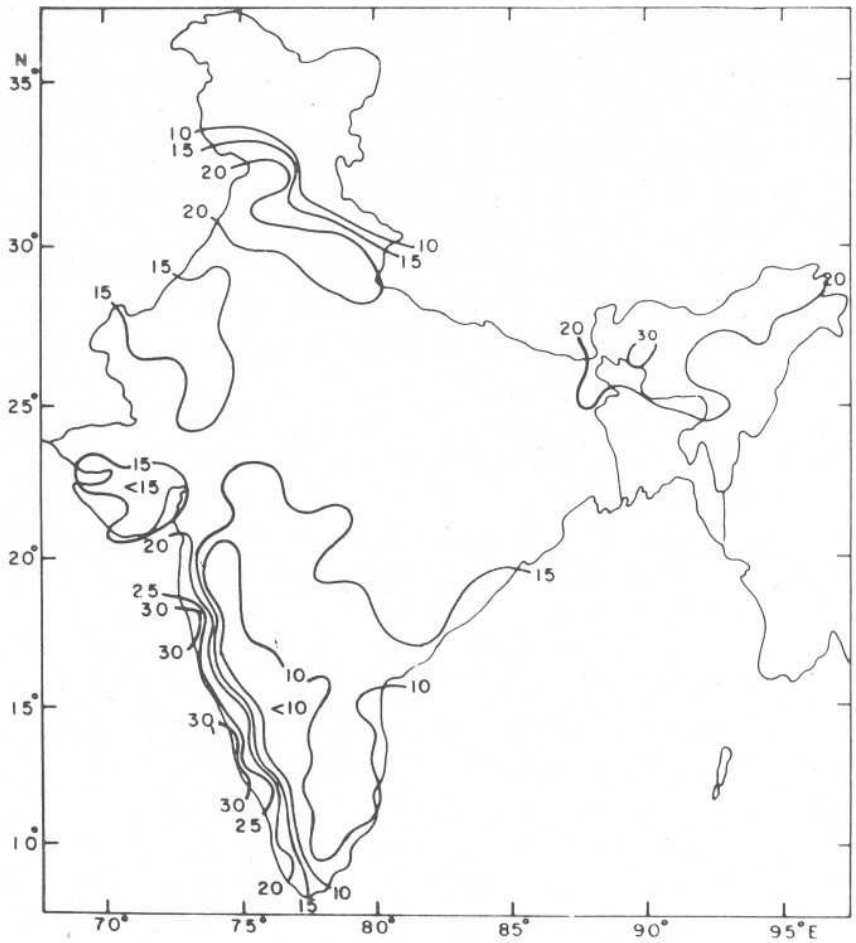

Figure 3. Mean intensity (r) of rainfall (mm day^{-1}) on a rain-day during the south-west monsoon season

India and the extreme south-eastern parts of the peninsula have $n < 10$. As is to be expected, the CV values of the rain days are large over regions with smaller number of rain-days (Figure 6).

3.4. Rain intensities contributing 50 per cent of seasonal total rainfall

It is well known that a large number of rain-days in a season are of low intensity, contributing only a small fraction to the seasonal total, whereas a few days of high rain intensity contribute substantial amounts. This aspect of the rainfall distribution can be seen readily from the NRC for Ahmedabad and Mangalore in Figure 2. Since the NRC is directly related to the CV of the rainfall series, the cumulated percentage number of rain-days that contribute 50 per cent of the rain amount, calculated from the zero end of the NRC, is directly related to the CV of the rainfall series of the respective stations. Our study shows that at most of the stations, 50 per cent of the rainfall, calculated from the upper end of the NRC, is received in the 10–20 per cent of rain-days with heavy falls, while the other 50 per cent is contributed by the 80–90 per cent of rain-days with falls of low intensity. The threshold of rain intensity (mm day^{-1}) that accounts for 50 per cent of the cumulated rainfall has the spatial distribution shown in Figure 7. Like the mean daily rainfall (Figure 3), the intensities that contribute 50 per cent of the cumulated rainfall are at a minimum (20–30 mm day^{-1}) over the peninsula east of the western Ghats. Over major parts of north India, 50 per cent of the rainfall is contributed by amounts above/below 40–50 mm day^{-1}, except over north-west India where the intensity is 30–40 mm day^{-1}. Along most of the west coast this intensity is about 50–60 mm day^{-1}. It is important to note that 50 per cent of the seasonal rain is contributed in 80–90 per cent of rain-days from falls of low intensity. A good

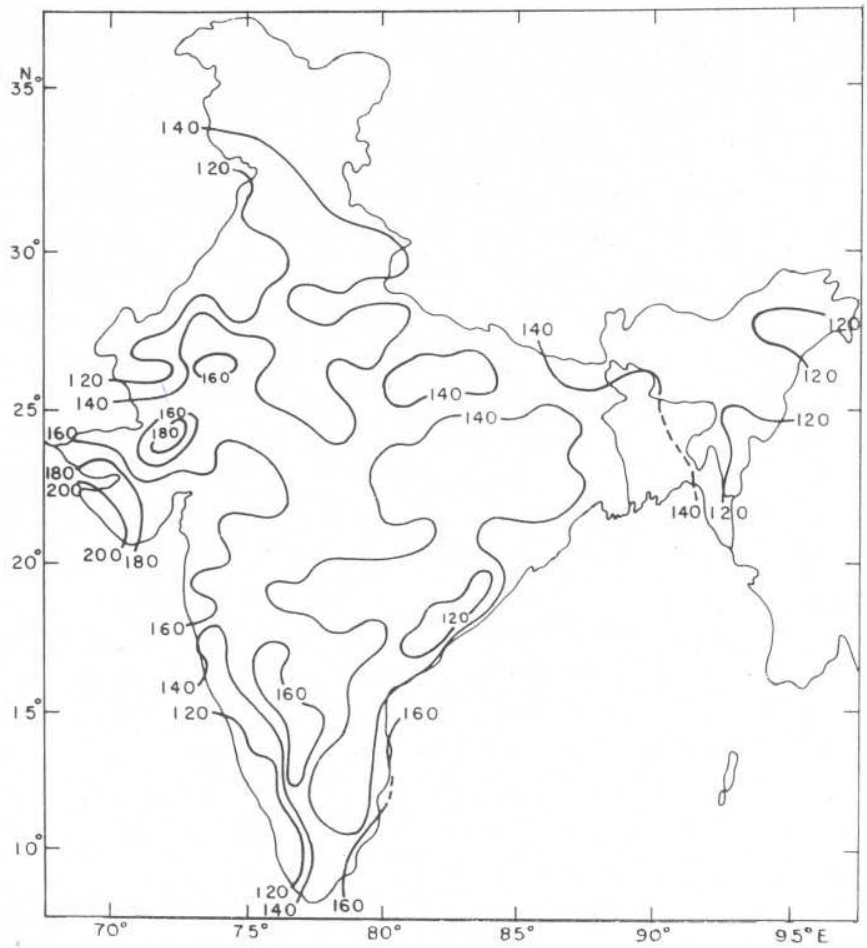

Figure 4. Coefficient of variation (per cent) of rainfall on rain-days during the south-west monsoon season

percentage of this may be lost by evaporation from the surface. The remaining 50 per cent of the rainfall, contributed by falls of higher intensity in 10–20 per cent of the rain-days, is of major importance for the recharge of surface water resources, in producing floods, causing soil erosion, etc.

3.5. The intensities of rainfall at the upper end of the NRC

By the very nature of its construction, high-intensity rain-days are clustered around the upper end of the NRC, where the values of x and y approach 100 per cent. As the cumulated percentage frequency of rain-days, y, approaches 100, the slope of the curve tends to zero if the empirical constant c in equation (1) is <1. This accounts for falls of high intensity at the upper end of the NRC. The value of the constant c depends on the CV of the rainfall series, and it is significantly <1 for large values of CV. Hence, in the case of rainfall series with large values of CV, the slope approaches zero faster at the upper end of the curve, indicating high intensities of rainfall. Where the mean rain intensities at stations are comparable, the actual rainfall data series also show that higher intensities are observed at those stations with larger values of CV. This aspect has been discussed in detail in the paper by Ananthakrishnan and Soman (1989).

Isopleths of daily rain intensities calculated at the point $y=99$ per cent are shown in Figure 8. On an average once in 100 rain-days, the stations can be expected to receive rainfall in excess of the calculated intensities shown in the diagram. Along the west coast north of 10°N, this intensity is more than 120 mm day^{-1}. The Gujarat region and adjoining parts of the west coast is an area of high intensities, exceeding 150 mm day^{-1}. It

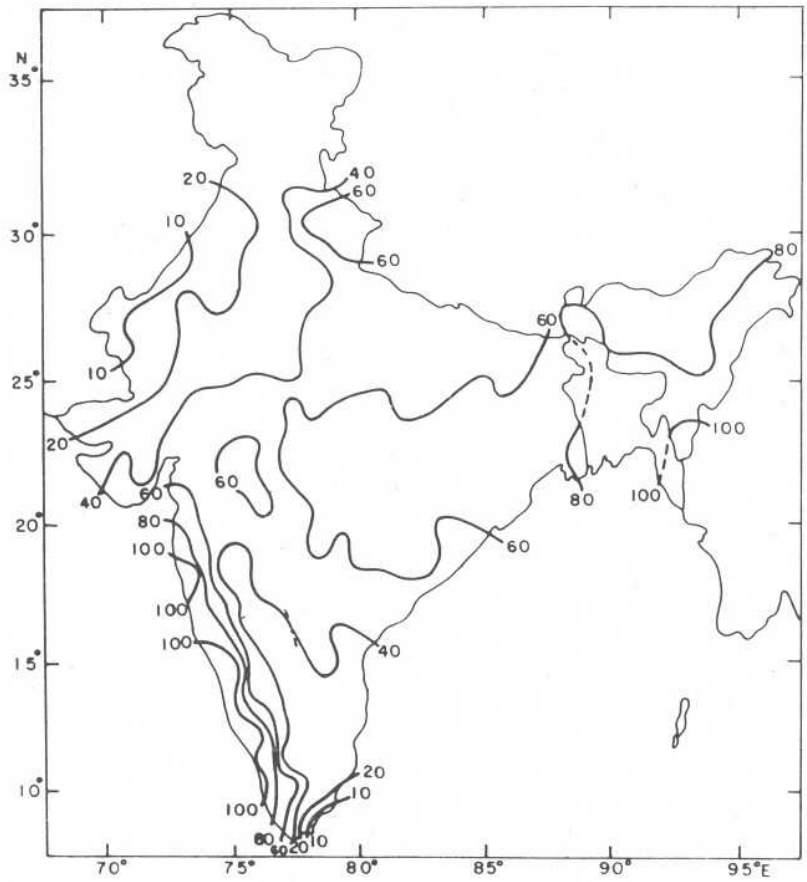

Figure 5. Mean number of raindays (n) during the south-west monsoon season

is of interest to note that there is a difference between the rainfall over these two regions. Over the west coast, the calculated intensities are high because of higher mean daily rainfall, whereas over the Gujarat region it is because of the higher CV of the rainfall series. As shown in the earlier study (Ananthakrishnan and Soman, 1989), both of these factors enter into the calculation of rain intensity. The minimum values are found over the rain-shadow regions of the peninsula and over western Rajasthan. Over wide areas of northern India the intensity varies from 80 mm to 120 mm day^{-1}. The average contribution to the total seasonal rainfall by intensities more than the calculated intensities at $y=99$ per cent varies from 5 per cent to 16 per cent over different parts of the country. (This is the contribution by the last 1 per cent of the rain-days at the upper end of the rainfall sequence).

The general pattern of distribution of intensities is similar in the case of $y=99{\cdot}9$ per cent (Figure 9), but as is to be expected the values are higher. Intensities in excess of these values can be expected to occur on average once in 1000 rain-days. Owing to the high CV of the rainfall series over the northern parts of the west coast and Gujarat region, the values increase rapidly to 250–300 mm day^{-1}. The values are less than 150 mm day^{-1} over most parts of the peninsula, Rajasthan and north-east India. It is less than 100 mm day^{-1} in the south interior parts of the peninsula and extreme western parts of Rajasthan. Rainfall in excess of these intensities contributes on average 0·6 to 3·6 per cent to the seasonal rainfall over different regions.

3.6. Rain-days and rainy days

In section 2 we drew attention to the distinction between 'rain day' (days with rain amount $\geqslant 0{\cdot}1$ mm) and 'rainy day' (days with rain amount $\geqslant 2{\cdot}5$ mm). If we indicate these two parameters by n and n' for a given

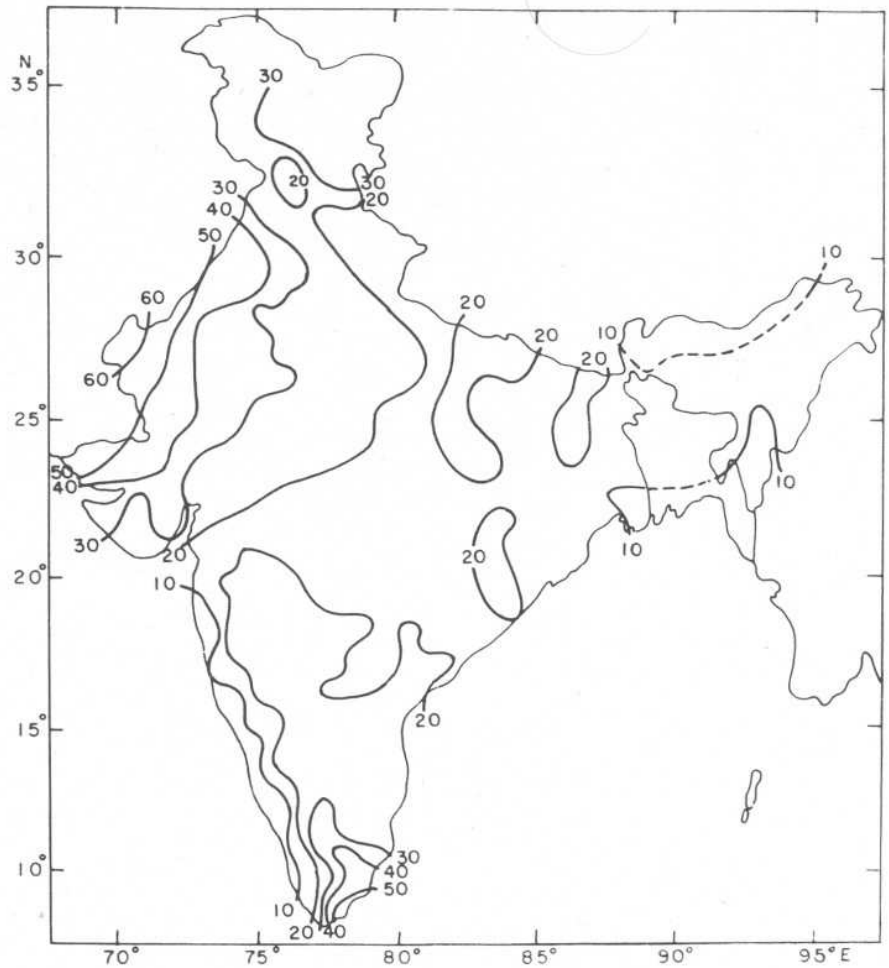

Figure 6. Coefficient of variation (per cent) of the number of rain-days during south-west monsoon season

station, then it is obvious that $n' < n$. Figure 10 shows isopleths of the quantity $z = 100(n - n')/n$ for the south-west monsoon season. It may be noted that the value of z is the least (about 10 per cent) along the west coast of India between 10° and 17°N and also over the extreme western parts of Rajasthan. Large values of 40–50 per cent are found along the east coast of the southern parts of peninsular India and over Gujarat and adjacent regions. Elsewhere, the values range from 20 per cent to 30 per cent.

In calculating the total seasonal rainfall, the rain amounts contributed by days with falls of less than 2·5 mm day^{-1} are also taken into account. Hence the mean daily rainfall for a rainy day (r') is always higher than for a rain-day (r). For example, at Madras for the month of July, $n = 13{\cdot}2$ while $n' = 6{\cdot}8$. The corresponding values of mean daily rainfall are $r = 7{\cdot}0$ mm day^{-1} and $r' = 13{\cdot}5$ mm day^{-1}. For a station like Bombay, the corresponding values are $n = 28{\cdot}7$ days and $r = 23{\cdot}2$ mm day^{-1}, and $n' = 22{\cdot}2$ days and $r' = 29{\cdot}9$ mm day^{-1}.

It is obvious that the pattern of distribution of mean daily rainfall over the country will be significantly different for r and r', particularly over areas where n and n' are appreciably different. While days with rain amount $< 2{\cdot}5$ mm day^{-1} may not have much significance when we are dealing with heavy rainfall stations, as, for example, along the west coast of India where most of the 'rain-days' are also 'rainy days', in areas of low rainfall the difference between n and n' becomes significant with regard to agriculture.

In a recent study concerning relationships between rain-days, mean daily rain intensity, and monthly rainfall at tropical stations, Jackson (1986) drew attention to the difficulties encountered in the analysis

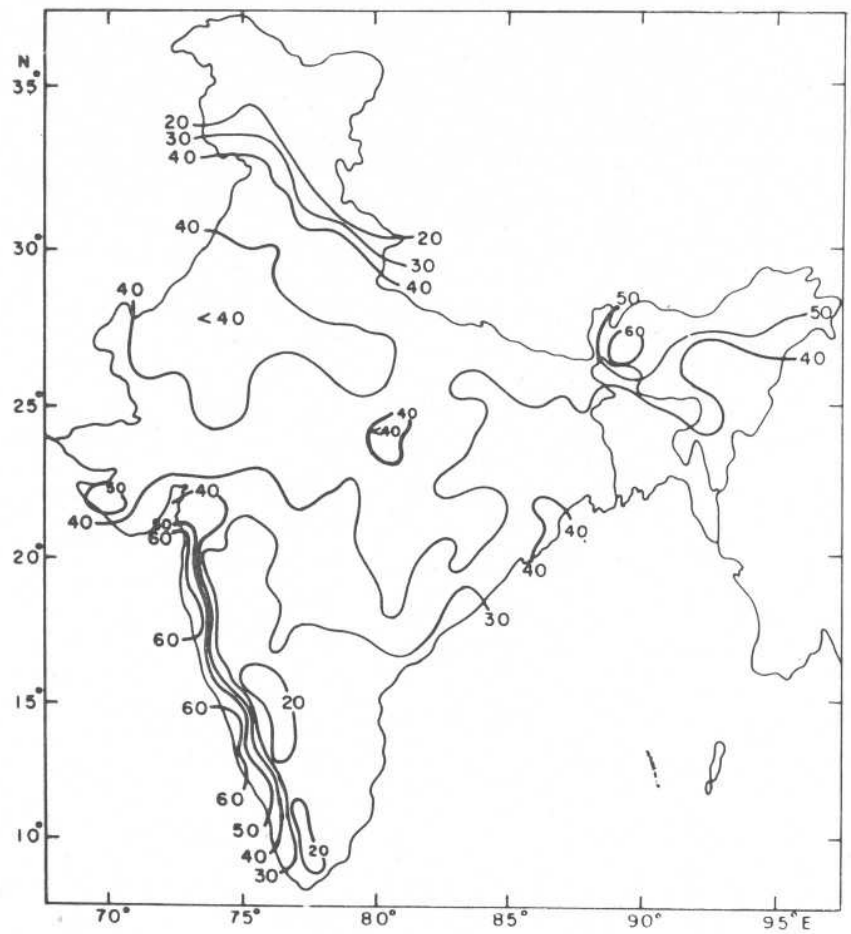

Figure 7. Threshold of rain intensity (mm day^{-1}) contributing to 50 per cent of cumulated rain amount ($x = 50$ per cent)

because of different threshold values of rainfall used by different countries for defining what is called a 'wet day'.

3.7. Mean daily rainfall (r) *and the percentage contribution to the seasonal rain amount and rain-days by days with rain intensity* $\geqslant$ r

In Figure 3 the spatial variation of mean rainfall for a rain-day (r) has been depicted. It is of interest to ascertain the percentage contribution to the seasonal rainfall by days with rain amounts $\geqslant r$ and also the percentage number of such days out of the seasonal total of n rain-days (Figure 5). Equation (1) for the NRC can be used for this purpose. The point on the NRC where the slope of the tangent is unity corresponds to the mean daily rainfall (Ananthakrishnan and Soman, 1989). Denoting the coordinates of this point by x_r and y_r it can readily be shown that

$$1/x_r = 1/y_r + bc(100 - y_r)^{c-1} \tag{2}$$

Also from equation (1)

$$1/x_r = 1/y_r \exp\left[b(100 - y_r)^c\right] \tag{3}$$

Equating the right-hand side of equations (2) and (3) we can evaluate y_r if b and c are known. These empirical constants are linked with the CV of the rainfall series and can be estimated when the CV is known from the rainfall data series (Ananthakrishnan and Soman, 1989). Knowing y_r, we can readily calculate x_r.

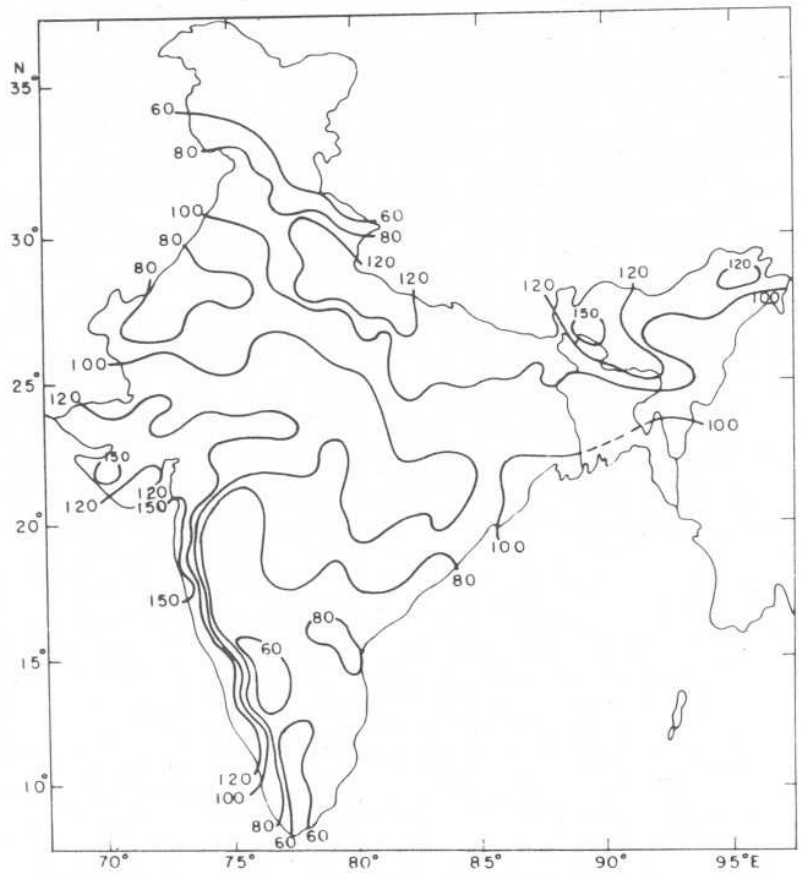

Figure 8. Estimated threshold of high rain intensity occurring once in 100 rain-days

Table II.

	x_r (per cent)				
y_r (per cent)	15–20	20–25	25–30	30–35	Total
60–65	0	11	5	0	16
65–70	1	177	65	2	245
70–75	5	84	8	2	99
75–80	2	3	0	0	5
Total	8	275	78	4	365

The frequency distributions of the stations for ranges of x_r and y_r corresponding to each other (at 5 per cent intervals), as derived from the data, are given in Table II.

The interesting fact that emerges from the study is that at most of the stations, days of rainfall $< r$ contribute about 25 per cent of the rainfall in about 70 per cent of the number of rain-days. Following Riehl *et al.* (1973) and Riehl (1979) we indicate days with rain amount $> r$ as *days of significant rainfall.* We thus arrive at the interesting finding that such days comprise about 30 per cent of the total number of rain-days and contribute about 75 per cent of the seasonal rainfall at most rainfall stations, despite the wide diversity in the characteristics of the rainfall at the different stations. This appears to be a general feature of tropical rainfall.

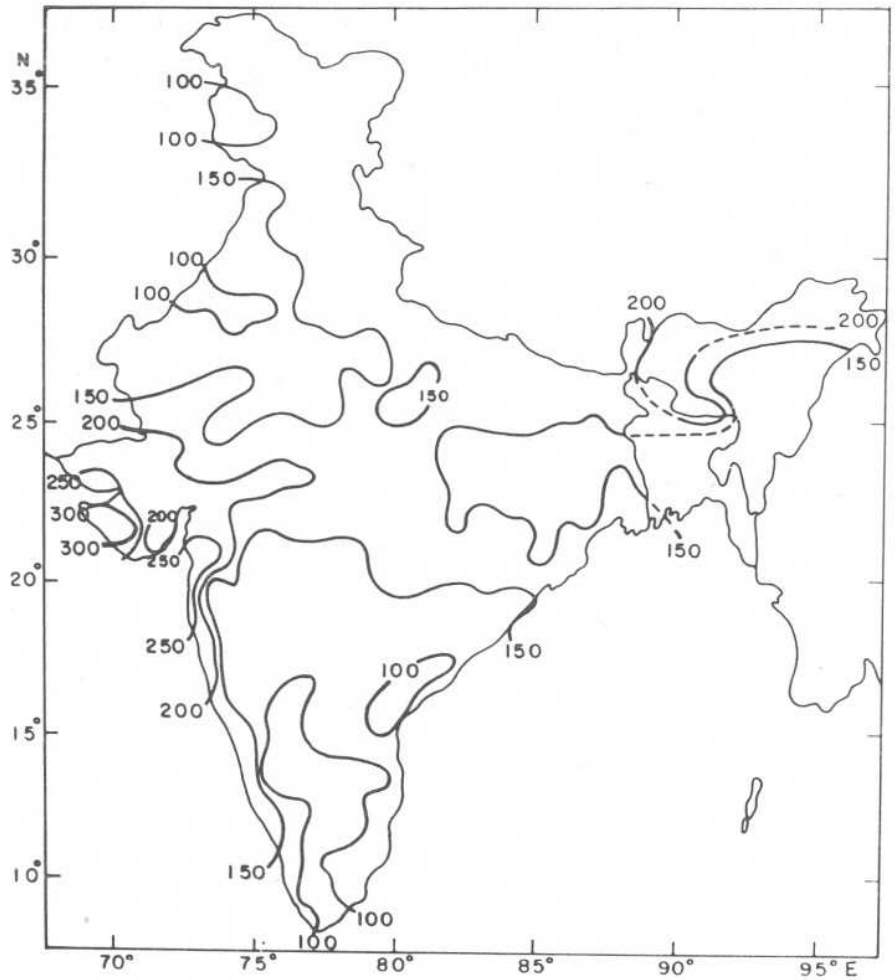

Figure 9. Estimated threshold of high rain intensity occurring once in 1000 rain-days

The frequency distribution of x_r and y_r, as shown in Table II, is associated with the frequency distribution of the CV values shown in section 3.2.

4. CONCLUSIONS

In this study we have presented a detailed analysis of several features of the daily south-west monsoon rainfall at 365 stations distributed over India for the 80-year period 1901–1980. This study is an extension of earlier work (Ananthakrishnan and Soman, 1989) in which it was shown that the daily rainfall distribution can be delineated by a normalized rainfall curve (NRC). The NRC can be represented by an analytical mathematical equation, from which a number of interesting parameters of the distribution can be derived. The main results and conclusions of the present study are listed below.

(i) The mean daily rainfall (r) per rain-day at Indian stations during the south-west monsoon season varies from less than 10 mm day^{-1} to more than 30 mm day^{-1}.

(ii) The CV of the daily rainfall amounts varies from 100 per cent to 230 per cent over different parts of the country, with many stations in the interval of 120–160 per cent. The maximum values of CV of the daily rainfall series are found over Gujarat State and northern parts of the west coast, where very heavy rainfalls of more than 500 mm day^{-1} have been recorded.

(iii) The average number of rain-days (n) over the stations in the network varies from less than 10 to more than 100 (out of a seasonal total of 122 days); the coefficient of variation of n ranges from 10 per cent to 60 per

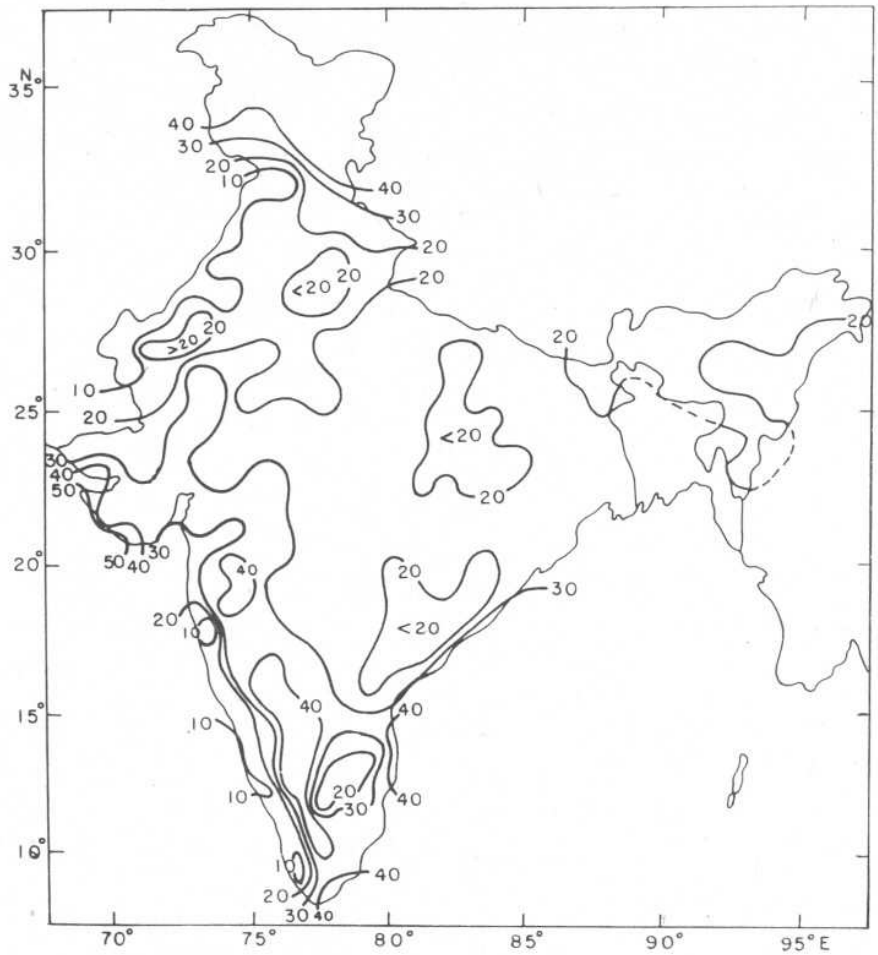

Figure 10. Isopleths of $z = 100\ (n-n')/n$ where n = number of rain-days and n' = number of rainy days

cent, the larger values of CV being associated with stations with smaller values of n.

(iv) 10–20 per cent of the total number of rain-days with heavy falls account for 50 per cent of the seasonal rainfall at the individual stations.

(v) The computed rain intensities (mm day^{-1}) at 50 per cent of the cumulated seasonal rainfall amount vary from about 20 mm day^{-1} to more than 60 mm day^{-1}.

(vi) By using the equation for the NRC it is shown by calculation that the rain intensities likely to be exceeded once in 100 rain-days and once in 1000 rain-days have largest values over the Gujarat region and adjacent parts of the west coast of India.

(vii) The average contribution by the last 1 per cent of the cumulated rain-days to the total rainfall varies from 6 per cent to 16 per cent, the larger amounts being associated with stations with large CV values for the rainfall series.

(viii) Over the central parts of peninsular India the number of 'rain-days' exceeds the number of 'rainy days' by 30–50 per cent; along the west coast this difference is only about 10 per cent. This aspect has to be taken into consideration in certain rainfall studies.

(ix) Days of significant rainfall, defined as days in which rain amounts exceed the mean daily rainfall (r), constitute about 30 per cent of the total number of rain-days and contribute nearly 75 per cent of the seasonal rainfall at almost all stations, despite the diversity of rainfall regimes. This appears to be a general feature of tropical rainfall.

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