Relationship between Indian Summer Monsoon Rainfall and Location of the Ridge at the 500-mb Level along 75°E

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ABSTRACT

Banerjee et al. showed for the first time that the number of Indian subdivisions with normal or above-normal monsoon rainfall is related to the location of the April 500-mb ridge along 75°E. Thapliyal brought out the relationship between monsoon rainfall of peninsular India and this ridge.

A detailed investigation of the relationship between all-India (India taken as one unit) monsoon rainfall, as well as monsoon rainfall of the subdivisions of India, and the location of the April 500-mb ridge along 75°E, and of the stability and consistency of the relationship has been made in this study, which is based on data for 1939–84. The relationship between all-India monsoon rainfall and the ridge location is positive (correlation coefficient = 0.71) and is significant at the 0.1% level and that between the subdivisional monsoon rainfall and the ridge is significant at 5% or above for all the subdivisions lying west of 84°E and north of 12°N. During the years when all-India monsoon rainfall is deficient, the ridge position is south of its normal position and the contribution by these years to the covariance is very high.

The stability and consistency of the relationship between all-India rainfall and the ridge location have been examined over sliding 10-, 15-, and 20-year periods, and it is found that the relationship is significant at the 1% level for all 20-year periods. Thus the relationship is characterized by high stability and consistency for periods of 20 years or more.

The contingency table for the two parameters shows that when the ridge is south of the mean position by more than one standard deviation, all-India rainfall is deficient on 80% of such occasions and that when the ridge is similarly located to the north of the mean, all-India rainfall is excessive on two-thirds of such occasions. The regression equation between all-India monsoon rainfall (y, in cm) and the ridge location (x, in degrees), based on data for the period 1939–80, is $y = 38.02 + 3.10x$. This relationship explains about 53% of the total variance. So far, the ridge location appears to be the only single parameter that explains such a high percentage of the variance of all-India monsoon rainfall. Estimates from this relationship for the independent years 1981–84 are found to be quite good, except for 1983, the year of excessive rainfall.

The southernmost ridge location was 11°N and the northernmost, about 18°N. It is intriguing to find that a variation of 7° in the latitude of the ridge location over western peninsular India during April makes a large difference in all-India monsoon rainfall (from deficient to excessive). Possibly, the ridge locations with relatively high departures from the normal in April have a tendency to persist, resulting in early or delayed transition to the tropospheric conditions from premonsoon season to the monsoon season.

1. Introduction

In view of the highly monsoon-dependent economy of India, there has been an acute need for an advance estimate of the country's monsoon rainfall. For nearly a century, attempts have been made to evolve methods for obtaining the estimate. A review of these attempts has been made by Savur (1931), Normand (1932, 1953), Jagannathan (1960), Rao (1965), Thapliyal (1984) and Shukla (1985).

The potential of upper-air parameters for forecasting the monsoon rainfall was brought out by Jagannathan and Khandekar (1962). Banerjee et al. (1978) considered for the first time the location of the ridge at the 500-mb level along 75°E during April as a predictor parameter. They obtained a relationship between the number of Indian meteorological subdivisions with normal or above-normal monsoon rainfall and the ridge location and showed that the estimate of the number of such subdivisions from the relationship was reasonably accurate. They agreed that rainfall over the plains of the country as a whole should have been used in deriving the relationship, but due to some difficulty in constructing a proper monsoon rainfall series for India as a whole they could not do so. The subdivisions of India vary largely in size, by more than one order of magnitude, the ratio of the largest to the smallest subdivisions being about 13 (Parthasarathy, 1984). In a situation when all except five subdivisions or so have normal or above normal monsoon rainfall, the impression could be created that overall rainfall position for the country is good. But the impression would

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be erroneous if the five subdivisions or so with deficient rainfall are large subdivisions, since in that case they could cover about 30% of the country. Thus, the number of subdivisions with normal or above-normal monsoon rainfall does not appear to be a satisfactory measure of monsoon rainfall over the country as a whole. In fact, the use of the percentage area of the country with normal or above-normal monsoon rainfall as a predictand might have been relatively better than merely the number of subdivisions with normal or above normal rainfall.

Thapliyal (1981, 1982) has used the April 500-mb ridge location along 75°E as a leading indicator in developing the ARIMA (Auto-Regressive Integrated Moving Average) model for forecasting monsoon rainfall for peninsular India. Thapliyal (1981) brought out that the regression relation between peninsular monsoon rainfall and the ridge location gives estimates which are less accurate than the estimates from the ARIMA model; in the same study, he has also examined stability and significance of the cross correlation by computing the cross correlations for the first 10, 11, 12, . . . , 40 years of data, so that each period is contained in the succeeding period. This approach, however, is unable to specify the lowest period for which stability and consistency in significance are attained.

After considering the studies in which the ridge location has been used as a predictor parameter, we find that the following questions remain unanswered: (i) What is the relationship between all-India/subdivisional monsoon rainfall and the ridge location? If the relationship is highly significant, what is the error of the estimates of all-India rainfall obtained from it for the independent years? (ii) What is the smallest length of the period (10, 15, 20 years, etc.) for which the relationship is stable and consistently significant? Once we know this period we can develop regression equations for this length of the latest period and use the same for forecasting all-India rainfall. (iii) What are the subdivisions of India where monsoon rainfall is significantly related to the ridge location? An attempt has been made in this study to answer these questions.

2. Details of data

a. Indian summer monsoon rainfall

Three hundred and six raingage stations, one from each of the districts in the plain regions of India, have been selected to form the fixed network. The raingage network in most hilly areas is meager, and, in addition, a raingage station in a hilly area is representative of a small area only. In view of this position, the hilly areas of the country consisting of Jammu and Kashmir, Himachal Pradesh, hills of West Uttar Pradesh, Sikkim (part of subHimalayan West Bengal) and Arunachal Pradesh (part of Assam) have not been considered. Figure 1, which shows the different subdivisions of India also shows, by hatching, the hilly areas not considered in this study. The relevant monthly rainfall data of these 306 stations for the period 1939–84 were collected from the records of the Office of the Additional Director General of Meteorology (Research), India Meteorological Department, Pune. From these data, series of area-weighted monsoon (June through September) rainfall were constructed for India (to be referred to hereafter as all-India rainfall series) and for each of the 29 meteorological subdivisions of India; the weights assigned to each station were the area of the district in which the station was located. (For details see Mooley and Parthasarathy 1983b, 1984b, and Parthasarathy, 1984.)

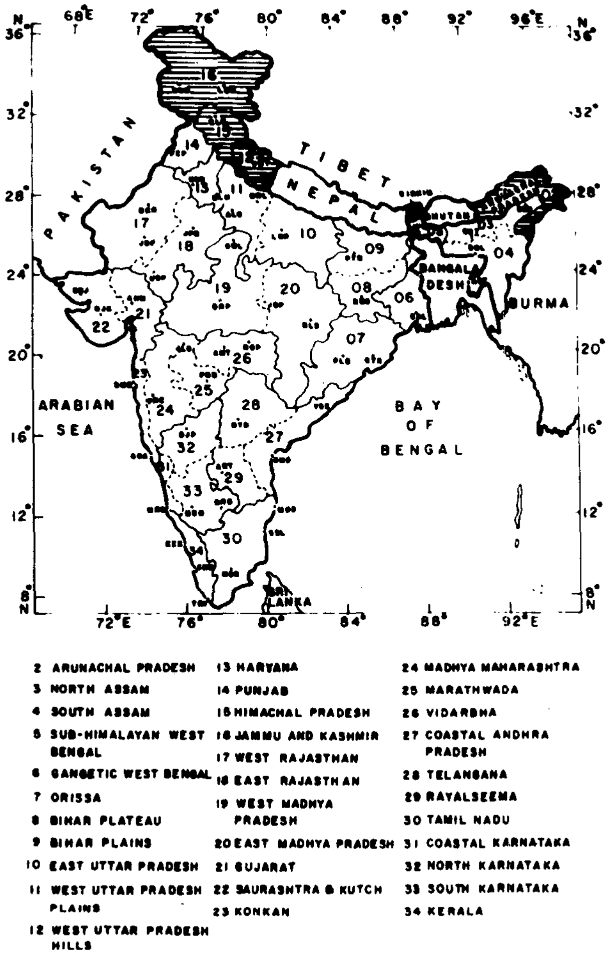

FIG. 1. Meteorological subdivisions of contiguous India. Shaded hilly portions have not been considered.

The application of suitable statistical tests indicates that these monsoon rainfall series are homogeneous, generally Gaussian-distributed and free from persistence. For the period 1939–80, the mean ($\bar{R}$), standard deviation (S) and coefficient of variation of all-India monsoon rainfall are, 85.84 cm, 8.14 cm and 9.5 percent respectively. It is reasonable to assume that the monsoon rainfall in standard units [$t_i = (R_i - \bar{R})/S$]

within the interval -1.0 to $+1.0$ can be taken as normal, and when it is ≤ -1.0 or $\geq +1.0$, it can be taken as deficient/excessive (Shukla and Paolino, 1983; Ananthakrishnan and Parthasarathy, 1984). As identified by these criteria, the deficient years are 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979 and 1982 (in all, 9 years) and the excessive years are, 1942, 1947, 1956, 1961, 1970, 1975 and 1983 (in all, seven years). It may be noted that during the last 25 years, the monsoon rainfall was deficient in seven years but was excessive in only four years. In fact, the high incidence of deficient monsoon rainfall during the decades 1961–70 and 1971–80 may be comparable to that in 1911–20 (Mooley and Parthasarathy, 1984b). During the period under consideration, there were three cases of a deficient monsoon rainfall year being followed by an excessive monsoon rainfall year: 1941–42, 1974–75 and 1982–83. There is no case of an excessive year being followed by a deficient year. While there is only one case of deficient monsoon rainfall in successive years, 1965–66, there are no cases of successive years of excessive rainfall.

b. Mean 500-mb ridge axis along longitude 75°E during April

An important feature of the tropospheric circulation over India is the subtropical ridge with its seasonal north–south migration. Its southernmost location is observed in January, and northernmost, in July. It can be located at all levels from 850 to 100 mb during January–April. With height, this ridge has an equatorward slope. While summer conditions begin to be established in the lower troposphere over peninsular India in March, winter circulation prevails over north India until the beginning of May. With the southward shift of the extratropical westerly belt in winter, the circulation over north and central India during winter becomes westerly and is periodically influenced by the passage of deep lows or troughs (known locally as western disturbances) in the westerlies. In the rear of these disturbances in the westerlies, very cold air from much higher latitudes flows in over north and central India in the troposphere above 700-mb level. Mountains to the north of India prevent the flow of very cold air at lower levels. The ridge demarcates the westerly circulation regime to the north from the easterly tropical regime to the south. At 500 mb, the seasonal movement of the ridge is found to be regular and organized from January to May. As observed from the normal charts (India Meteorological Dept., 1972), based on the data for the period 1951–65, the 500-mb ridge along 75°E is located at 11.5°N in January, 15°N in April, 28.5°N in July, and 20°N in October. The shift is largest from April to July, the period which covers the transition from summer to monsoon season.

In the opinion of the authors, the location of the ridge in April at the 500-mb level along 75°E (to be hereafter referred to as the ridge) is a measure of the influence exerted by the troughs in the westerlies on the upper tropospheric thermal conditions over north and central India. A location much south of the normal April location, viz., 15°N, suggests a much colder troposphere in April and persistence of colder than normal conditions up to June, which would adversely affect the monsoon. Influence of the westerly troughs over the upper tropospheric thermal conditions over north and central India, as seen by the location of the ridge in April over India and the persistence of the anomalous thermal conditions in the upper atmosphere, appears to be the physical reason for the observed correlation between the ridge location and monsoon rainfall. It is, however, intriguing to find that a variation of the ridge location by about 7 degrees of latitude, from 11°N to 18°N in April, over India makes a substantial difference in the all-India monsoon rainfall, from deficient to excessive. Possibly, relatively larger departures of the ridge location in April have a tendency to persist through June. The relationship between the 500-mb ridge along 75°E during April and May has been examined over the period 1948–66. The correlation coefficient between the two is 0.63, which is significant at the 5% level, suggesting persistence from April to May. The ridge locations for the period 1939–80 were obtained from Banerjee et al. (1978) and Thapliyal (1981, 1982). For the period 1981–84, these were obtained by analyzing mean 500-mb wind flow over India during April. The mean location of the ridge for the period 1939–80 is 15.4°N, the standard deviation is 1.9°, and autocorrelation coefficient with lag + 1 is -0.20, which is not significant even at the 10% level. On the basis of the Gaussian distribution, the ridge is expected to be located between 11.6° and 19.2°N in 95% of the years.

Figure 2 shows the location of the ridge and all-India monsoon rainfall. It may be noted that during 1961 and 1983 the monsoon rainfall was excessive and the location of the ridge was expected to be above the mean; however, it was slightly below it. This disagreement with expectation on the basis of the relationship poses the question, What are the other parameters which influence all-India monsoon rainfall?

3. Relationship between all-India monsoon rainfall and the ridge location

The relationship between all-India monsoon rainfall and the ridge location has been obtained on the basis of data for 1939–84, and it has been examined (i) for significance, stability and consistency; (ii) for contribution of each year to the relationship; (iii) by looking into the behavior of the ridge location during years of deficient and excessive monsoon rainfall; and (iv) with reference to the contingency table constructed for the two variables.

Finally, the regression equation developed from the data for 1939–80 is tested on an independent period for 1981–84.

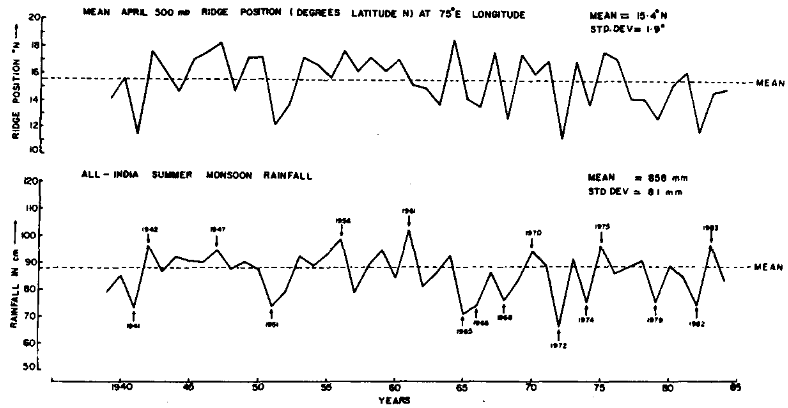

FIG. 2. Mean April 500-mb ridge position (°N) over India at 75°E and corresponding all-India summer monsoon rainfall (cm) during 1939–84.

Quenouille (1952) and Sciremammano (1979) have pointed out that while assessing the significance of cross correlation between two concurrent series, persistence in the individual series should be considered. There is no persistence in the all-India and subdivisional monsoon rainfall series (Mooley and Parthasarathy, 1984b; Parthasarathy, 1984). The first three autocorrelation coefficients for the ridge location series are small and insignificant; thus the series shows no persistence. In view of no persistence in the two series, the degrees of freedom can be taken as $(N - 2)$ while testing the significance of the correlation coefficient between the two series; N is the number of years of data.

a. Significance, stability and consistency of the relationship

The cross correlation between the all-India monsoon rainfall and the ridge location over the period 1939–84 is 0.71, which is significant at the 0.1% level or above. The positive relationship accounts for about 50% of the total variance. So far, this is the only single parameter which could explain such a high variance.

The stability and consistency of the relationship has been examined by computing the cross correlations by the sliding window method (Bell, 1977), using 10-, 15- and 20-year periods. These series of cross correlations are shown in Fig. 3. The main features of Fig. 3 are (i) cross correlations are always positive for all three periods; (ii) cross correlations for 10-year periods are significant at 5% or above during 1939–51 and 1962–80; (iii) cross correlations for 15-year periods during 1939–1980 are generally significant at 5% or above; (iv) all 20-year cross correlations are significant at 1% or above. Thus, the lowest period for which the relationship is stable and consistently highly significant is 20 years.

b. Contribution of each year to the relationship

The value of the covariance between the two parameters determines the strength of the relationship. Contribution of each year, viz., $(x_i - \bar{x})(y_i - \bar{y})$, to the covariances has been computed. It has also been examined for the sets of years (a) when the values of both the parameters, viz., all-Indian monsoon rainfall and the ridge location, in standard units were within the limits ±0.5, (i.e., when both parameters were fairly close to the respective means simultaneously); (b) when the values were within ±1.0 simultaneously but were not within ±0.5 simultaneously; (c) when rainfall was deficient; and (d) when rainfall was in excess. The means of the covariances contributed by these four sets of years, along with the number of years, number of years with positive contributions to the covariance, and the highest and lowest contribution to the covariance are given below.

Category	Number of years	Number of years with positive contribution	Mean contribution	Maximum annual contribution	Minimum annual contribution
(a)	6	2	−0.05	+2.1	−1.3
(b)	20	12	+1.8	+9.8	−6.9
(c)	9	9	+40.5	+90.3	+21.2
(d)	7	5	+11.0	+25.4	−9.1

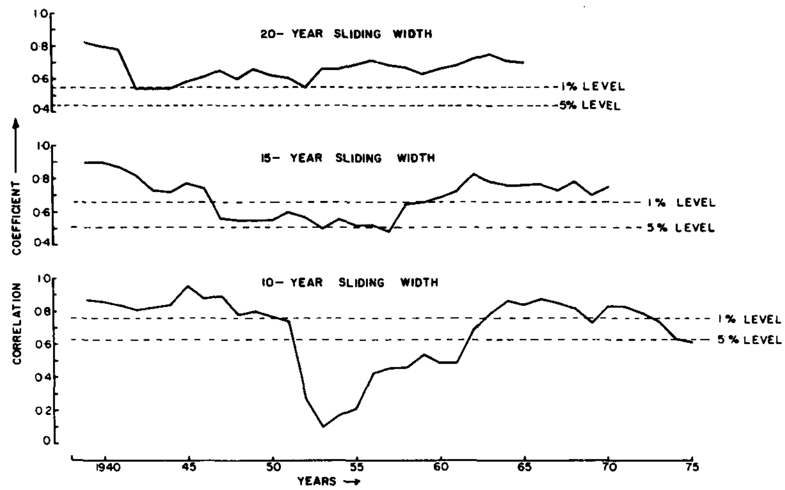

FIG. 3. Variation of correlation coefficient (CC) with 10-, 15- and 20-year sliding window widths between all-India summer monsoon rainfall and mean April 500-mb ridge position over India during 1939–84.

It may be noted that for each of the nine years of deficient monsoon rainfall, the contribution to the covariance is positive and greater than 21.0; however, for the years of excessive rainfall, the contribution is positive for five years and negative for two years. Thus the years of deficient monsoon rainfall contribute a maximum to the positive relationship, but the years of excessive monsoon rainfall contribute to the positive relation to a much smaller extent. In view of this situation, we feel that estimates from the relationship will be much better for years of deficient monsoon rainfall than for years of excessive monsoon rainfall.

c. Behavior of the ridge location in deficient and excessive monsoon rainfall years

The mean location of the ridge for the nine deficient monsoon rainfall years is 12.4°N and that for the excessive monsoon rainfall years is 16.5°N. The mean ridge location of the period 1939–80 is 15.4°N. The deviation of the mean ridge location for deficient rainfall years from the overall mean ridge location is higher than that for excessive rainfall years. This would mean that a low-latitude location of the ridge is a better indication of deficient monsoon rainfall than a relatively higher than mean latitude location is of excess monsoon rainfall.

d. Analysis of the contingency table for the two parameters

While the correlation coefficient gives only the linear relationship between the two parameters, the contingency table brings out the complete relationship. The contingency table has been prepared for the three class intervals: $\leqslant -1.0$ (deficient); between -1.0 and $+1.0$ (normal); and $\geqslant +1.0$ (excessive), for rainfall and the same class intervals for ridge location, but designated as south of normal, normal and north of normal. The contingency table is shown in Table 1. The concentration of the frequencies along the diagonal from top left to bottom right in Table 1 brings out the excellent relationship between the two parameters. The salient points of the table are given below.

(i) When the ridge is south of the mean location by more than one standard deviation, all-India monsoon rainfall is deficient on 80% of such occasions but is rarely in excess. In the reverse situation, when the ridge is north of the mean location by more than one standard deviation, rainfall is in excess on two-thirds of such occasions, but is rarely deficient.

(ii) When the ridge is within one standard deviation of the mean location, rainfall is normal (within one standard deviation of the mean) on 87% of such occasions.

(iii) Percentage of the years in which there is agreement between the classes of the variables equals the

TABLE 1. Contingency table showing the frequencies of each of the three class intervals for all-India summer monsoon rainfall and the April 500-mb ridge. Period of data: 1939–84.

	Ridge position (standard units)		
Rainfall (standard units)	South of normal ($\leqslant -1.00$)	Normal, (-1.00 to $+1.00$)	North of normal, ($\geqslant +1.00$)
Deficient ($\leqslant -1.00$)	8	1	0
Normal, (-1.00 to 1.00)	2	26	2
Excess ($\geqslant +1.00$)	0	3	4

sum of the diagonal elements from top left to bottom right expressed as percentage of the total number of years [=100(8 + 26 + 4)/46 = 83]. Similar percentage on the hypothesis of independence of the two parameters [=100(1.96 + 19.56 + 0.91)/46 = 49]. The large difference between the two percentages clearly brings out the closeness of the positive relationship between the two parameters.

e. Development of regression equation

The regression equation relating all-India monsoon rainfall (y, in cm) to the ridge location (x, in degrees) on the basis of data for the period 1939–80 has been developed. It is given by

$$y = 3.10x + 38.02.$$

Figure 4 shows the regression line along with the scatter of the data points. This relationship explains 53% of the total variance of the rainfall.

Utilizing this regression equation, all-India monsoon rainfall has been estimated for the years 1981–84. The estimated and the actual rainfall and the percentage errors are given below.

Year	Estimate (mm)	Actual (mm)	Percentage error
1981	907	842	+7.6
1982	731	736	−0.6
1983	830	959	−15.0
1984	838	835	+0.4

The estimates agree fairly well with the actual rainfall, except in 1983—an excessive rainfall year—when error of the estimate is relatively high. From the detailed consideration of the contributions to the relationship by the different years, it was mentioned that the contributions to the relationship by years of rainfall excess is much smaller than by years of deficient rainfall, and on this basis it would be expected that the relationship may not be able to give reasonably good estimates of excessive rainfall. On verification, it is found to be so for the one excessive rainfall year during the period 1981–84. Apparently, there are some other circulation features, apart from the ridge, which influence the rainfall. Estimation of all-India monsoon rainfall on the basis of ridge location alone will have its own limitations.

The Indian monsoon is an important component of the global atmospheric circulation. It is the basic manifestation of the seasonal heating and cooling cycle over the Asian land mass. Its predictability, therefore, depends not only on its own dynamics but also upon the dynamics of the global circulation. It is shown by many scientific workers that monsoon rainfall is related to global circulation features, such as the Southern Oscillation (Pant and Parthasarathy, 1981; Mooley and

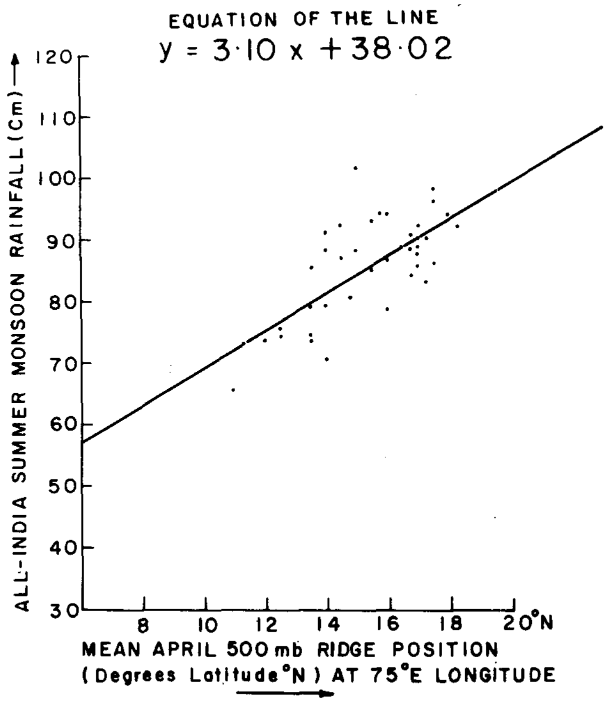

FIG. 4. Scatter diagram showing relationship between all-India summer monsoon rainfall (cm) and mean April 500-mb ridge position over India during 1939–80.

Parthasarathy, 1983b; Shukla and Paolino, 1983; Bhalme et al., 1983; Bhalme and Jadhav, 1984; Shukla, 1985; Parthasarathy and Pant, 1984, 1985; Mooley et al., 1985), east equatorial Pacific sea-surface temperature (Angell, 1981; Rasmusson and Carpenter, 1982; Khandekar, 1979, 1982; Mooley and Parthasarathy, 1983a, 1984a), and El Niño events (Sikka, 1980; Mooley and Parthasarathy, 1983a; Rasmusson and Carpenter, 1983; Ramage, 1983). Inclusion of the global circulation parameters along with 500-mb ridge location in the final multiple regression equation may result in better estimation of all-India monsoon rainfall.

4. Relationship between subdivisional monsoon rainfall and the ridge location

India as one unit, though too big an area for practical purposes, provides an overall view of the rainfall fluctuations and abnormalities which are helpful to the planners and scientists studying circulation and changes therein. It is well known that the spatial variability of rainfall within the country is large. The rainfall of meteorological subdivisions in the northeastern part of the country is poorly or negatively correlated with the subdivisions in the other regions (Mooley and Parthasarathy, 1983a; Parthasarathy, 1984). In view of this, we have examined the relationships between the ridge position and the summer monsoon rainfall of different subdivisions of India (Fig. 1) for the period 1939–80. The correlation coefficients and their significance are shown in Fig. 5. There are 19 contiguous subdivisions for which the correlation coefficients are positive and significant at the 5% level or above, these subdivisions being mostly north of 12°N and west of 84°E. For 14 subdivisions, the correlation coefficients are significant at the 1% level, and for 9 of these, they are significant at 0.1 percent level. The highest correlation coefficient is 0.67 for the Madhya Maharashtra subdivision. Monsoon rainfall over Assam, West Bengal, Orissa, South Karnataka and Tamilnadu does not appear to have any relationship with the ridge location.

5. Conclusions

The statistical analysis of the mean April 500-mb ridge location along 75°E in relation to the Indian summer monsoon rainfall, for the period 1939–84, brings out the following features:

(i) The relationship between the ridge location and all-India monsoon rainfall is positive and highly significant (at the 0.1% level) and accounts for about 50% of the total variance in the rainfall.

(ii) The lowest period for which the relationship is stable and consistently highly significant (1% level) is 20 years.

(iii) The mean ridge location is about 3° south of its normal location during years of deficient all-India monsoon rainfall and 1.1° north of the normal position during years of excessive rainfall.

(iv) When the ridge is south of the mean location by more than one standard deviation, all-India monsoon rainfall is deficient 80% of the time. In this position of the ridge, all-India excessive monsoon rainfall can be practically ruled out.

With the ridge north of the mean position by more than one standard deviation, all-India monsoon rainfall is excessive two-thirds of the time, but rarely deficient.

When the ridge lies within one standard deviation of the mean position, all-India monsoon rainfall is normal (i.e., within one standard deviation of the mean) 87% of the time.

(v) The regression equation between all-India summer monsoon rainfall and the ridge, developed from the data for 1939–80, when applied to the independent period 1981–84 gave reasonably good estimates of rainfall, except for the excessive rainfall year of 1983, for which the estimate was in error by 15%.

(vi) The relationship between subdivisional monsoon rainfall and the ridge location is significant at the 5% level or above for 19 contiguous subdivisions, mainly over the area north of 12°N and west of 84°E, and at the 1% level and above for 14 of these subdivisions.

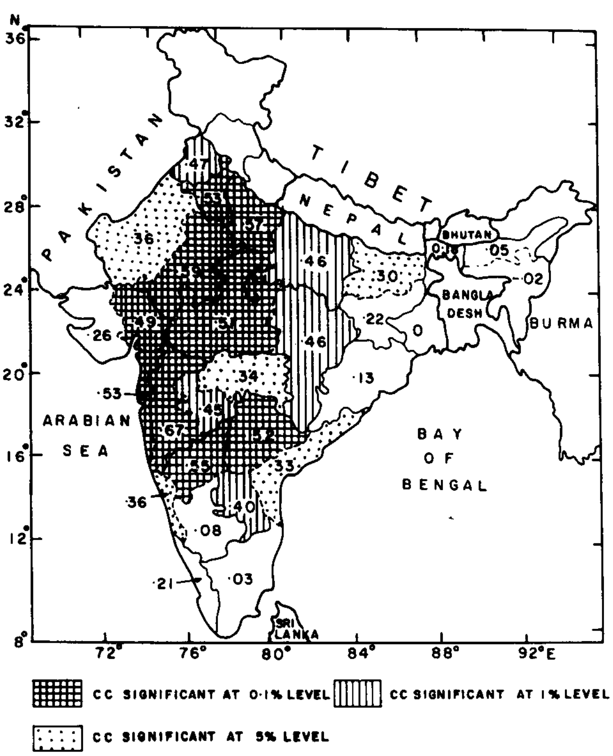

FIG. 5. Correlation coefficients between monsoon rainfall of different meteorological subdivisions and mean April 500-mb ridge position over India during 1939–80.

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