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SEASONAL RELATIONSHIPS BETWEEN INDIAN SUMMER MONSOON RAINFALL AND THE SOUTHERN OSCILLATION

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ABSTRACT

Association between the all-India summer monsoon (June to September) rainfall and an index of the Southern Oscillation (SO) is studied in relation to the vagaries of the monsoon rainfall and the seasonal characteristics of the SO. The Southern Oscillation index (SOI) used is the difference of normalized sea surface pressure between Tahiti and Darwin, two stations located in the core regions of the circulation systems associated with the SO. The data length of 46 years from 1935 to 1980 is used in the detailed examination of the nature of association between these parameters.

The SOI values of different months and standard seasons show opposite tendencies during deficient and excess years of all-India monsoon rainfall. The correlation coefficients (CC) between the all-India monsoon rainfall series and the SOIs of summer monsoon (JJA), autumn (SON) and winter (DJF) minus spring (MAM) seasons are significant at the 1 per cent level. The correlations have been examined by dividing the series into two equal halves of 23 years and different sliding window widths of 10, 20 and 30 years. The least squares fit line is represented by the equation y (all-India monsoon rainfall) $= 85{\cdot}9 - 2{\cdot}7x$ (DJF minus MAM, SOI), the variance explained by this line is about 13 per cent. In view of the large spatial variability of the summer monsoon rainfall the correlations are examined for the rainfall series of various meteorological subdivisions of the country. The CC between the monsoon rainfall of the subdivisions north of 16°N and west of 80°E and the SOI series of DJF minus MAM is significant at the 5 per cent level or above.

Potentialities of the SOI of DJF minus MAM, an important premonsoon circulation parameter, are examined for the seasonal prediction of Indian summer monsoon rainfall, and the limitations of single parameter prediction models are discussed.

KEY WORDS Indian summer monsoon rainfall Southern oscillation Correlation analysis

INTRODUCTION

The Indian summer monsoon, which provides 75 to 90 per cent of the total annual rainfall over the country during the four months, June to September, is vital to the national economy. Food production, power generation and drinking water supply are all dependent on the monsoon rainfall, which has crucial control on the national economy (Mooley *et al.*, 1981; Mooley and Parthasarathy, 1982). Owing to the great socio-economic importance of the fluctuation of the Indian monsoon rainfall, there has been a growing desire and efforts in the recent past to develop improved understanding of the causes of the changes in Indian rainfall in relation to changes and fluctuations of large-scale atmospheric and oceanic circulation features. Many recent studies, especially those of Sikka (1980), Angell (1981), Pant and Parthasarathy (1981), Mooley and Parthasarathy (1983b), Bhalme *et al.* (1983), Rasmusson and Carpenter (1982, 1983), Ramage (1983), Shukla and Paolino (1983) and Parthasarathy and Pant (1984) have shown close relationships between variations in Indian summer monsoon and Southern Oscillation and El Niño phenomena. The El Niño–Southern Oscillation (ENSO) fluctuation is of central importance for prediction purposes because of its global nature, strong signal, interannual time scale, and

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inherent lag relationships. Oceanographers and meteorologists have recently been devoting considerable effort to understanding the underlying causes and consequences of the large-scale, ocean–atmosphere phenomenon of ENSO. ENSO events are accompanied by major changes in the pattern of convection and latent heat release in the tropics. These changes in turn affect not only the tropics but also the mid-latitude circulation systems through teleconnections and mechanisms that are partly understood. The Southern Oscillation (SO) exhibits a spatial signal and a continuous temporal signal. Each field exhibits one or more 'core regions' where the temporal signal is clearly displayed. An index of SO may be formed from each field in the core region. The present study is intended to examine in detail the relationship between the monsoon rainfall of India and its different meteorological subdivisions with an SO index (based on the pressure difference between two core regions, i.e. Tahiti and Darwin) in different seasons during the available data period, 1935–1980, and explore the possibility of its use as one of the parameters in long-range prediction of the Indian summer monsoon rainfall.

DETAILS OF DATA

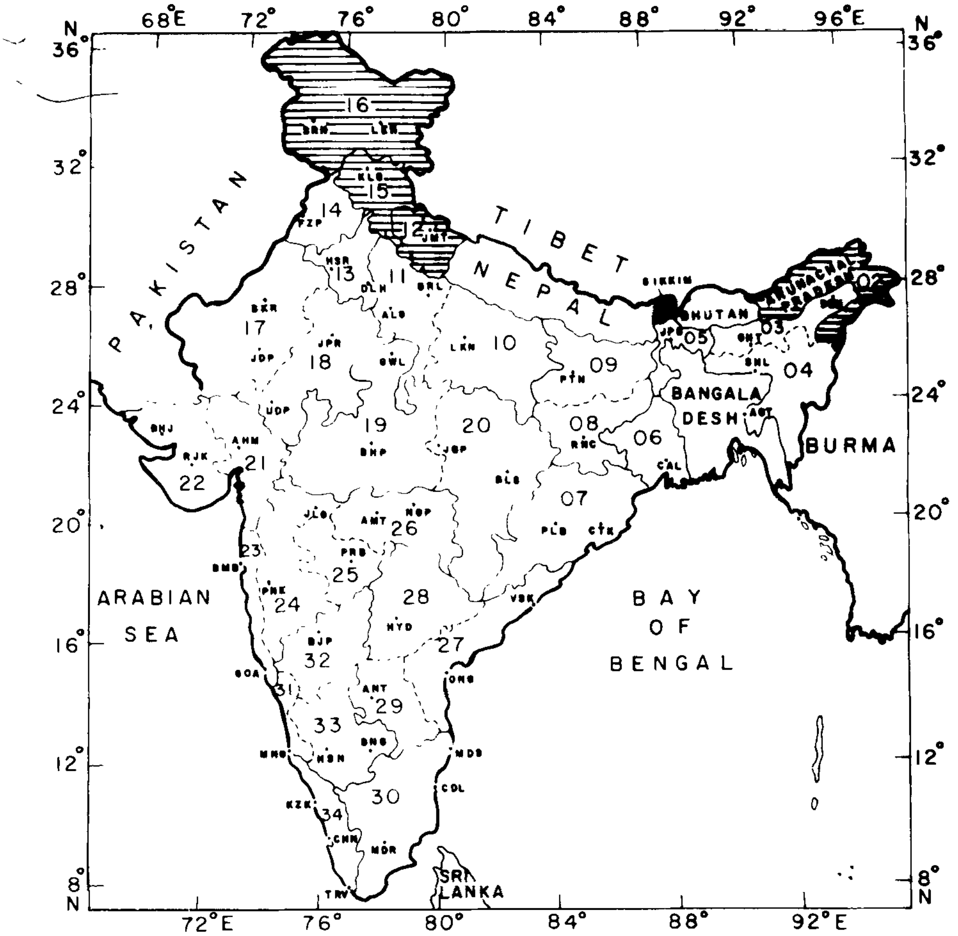
Indian summer monsoon rainfall

Three hundred and six rain-gauge stations, one from each of the districts in the plain regions of India, were selected to form the network. These stations are more or less uniformly distributed over the country. The rain-gauge network in most hilly areas of the country is inadequate; therefore, the hilly areas of the country consisting of Jammu and Kashmir, Himachal Pradesh, the hills of west Uttar Pradesh, Sikkim (part of sub-Himalayan west Bengal) and Arunachal Pradesh (part of north Assam) have not been considered. Figure 1 shows the regions of India considered for this study. The relevant seasonal rainfall data of these 306 rain-gauge stations are collected from the records of the office of the Additional Director General of Meteorology (Research) India Meteorological Department, Pune. The seasonal (summer monsoon period, June to September) area-weighted rainfall series were prepared for India (to be referred to as all-India series) and for 29 meteorological subdivisions of the country by assigning area weights to each rain-gauge station (for details see Mooley and Parthasarathy, 1983a, 1984). Statistical examination of these time series for the period 1935–1980 shows that they are homogeneous, Gaussian distributed and free from persistence.

Southern Oscillation index

The Southern Oscillation or Walker Circulation (Bjerknes, 1969) is an important mode of the tropical atmosphere, generally characterized by the exchange of air between the eastern (predominantly land) and western (predominantly ocean) hemispheres. The pressure change occurs in a see-saw fashion, one end of the see-saw being in the Australian–Indonesian region and the other in the south-east Pacific Ocean. A parameter which measures this see-saw is the difference of pressure between the two core regions represented by the stations, Tahiti and Darwin, and is used as an index of the Southern Oscillation (SOI). During the strong or normal period of the Southern Oscillation, the westward trade winds that prevail over most of the tropical Pacific Ocean converge on the north Australian–Indonesian low pressure zone where the air rises and there is considerable cloudiness and rainfall. The air returns eastwards at greater altitudes and sinks over the cold, dry south-east Pacific high pressure belt. However, this normal circulation is disturbed during the periods with warm east tropical Pacific sea temperatures, i.e. during the El Niño events which may contribute to deficient rainfall in India. Therefore, the monitoring of the El Niño–Southern Oscillation phenomena will help in the long-range forecasting of the Indian summer monsoon. In order to make the series comparable in all respects; the monthly/seasonal sea-level pressure data series of Tahiti and Darwin are normalized. These normalized series have the property of zero mean and unit standard deviation: fluctuations in the series are thus non-dimensional, and the series can be compared with any other series.

The mean sea-level pressure field index given by Wright (1975), though reliable with its long data period, and used by many, is not easily updated because it is based on principal component analysis of



2 ARUNACHAL PRADESH
3 NORTH ASSAM
4 SOUTH ASSAM
5 SUB-HIMALAYAN WEST BENGAL
6 GANGETIC WEST BENGAL
7 ORISSA
8 BIHAR PLATEAU
9 BIHAR PLAINS
10 EAST UTTAR PRADESH
11 WEST UTTAR PRADESH PLAINS
12 WEST UTTAR PRADESH HILLS
13 HARYANA
14 PUNJAB
15 HIMACHAL PRADESH
16 JAMMU AND KASHMIR
17 WEST RAJASTHAN
18 EAST RAJASTHAN
19 WEST MADHYA PRADESH
20 EAST MADHYA PRADESH
21 GUJARAT
22 SAURASHTRA & KUTCH
23 KONKAN
24 MADHYA MAHARASHTRA
25 MARATHWADA
26 VIDARBHA
27 COASTAL ANDHRA PRADESH
28 TELANGANA
29 RAYALSEEMA
30 TAMIL NADU
31 COASTAL KARNATAKA
32 NORTH KARNATAKA
33 SOUTH KARNATAKA
34 KERALA

Figure 1. Latest meteorological subdivisions of contiguous India. Shaded hilly portion not considered

the pressure data of 8 stations (Cape Town, Bombay, Djakarta, Darwin, Adelaide, Apia, Honolulu and Santiago) which lie between 30°S and 20°N. The requirement for a simple and reliable index, i.e. an index formed from each field in its core region, appears to be met best by the index recommended by Chen (1982), who used changes in sea-level pressure near the two antinodes or centres of action, one in the Australian–Indonesian region (low pressure area) and another in the southern Pacific high (anticyclone region); these are generally represented by Darwin (12°S, 131°E) and Tahiti (18°S, 150°W). The pressure data for Tahiti are available from 1935 onwards only: therefore, our study is confined to the period 1935 to 1980. The well scrutinized monthly sea-level pressure data for Darwin and Tahiti were obtained from Parker (1983). We computed the monthly/seasonal normalized sea-level pressure difference series between Tahiti and Darwin for the period 1935 to 1980. This index has been represented as the Southern Oscillation index (SOI). This index is used by several workers to denote the Southern Oscillation and the current values are published in the *Climate Diagnostics Bulletin* published by NOAA, U.S.A. for immediate use by interested scientists.

RELATIONSHIP BETWEEN INDIAN SUMMER MONSOON RAINFALL AND SOUTHERN OSCILLATION INDEX

In order to understand the association between the Indian summer monsoon rainfall and the SOI we adopted the following procedure: (i) correlation analysis between two series, and (ii) examination of SOI values for extreme, excess or deficient, rainfall years during the period.

Persistence in the individual series has been considered while assessing the significance of the cross-correlation between two concurrent series as suggested by Quenouille (1952) and Scirremammano (1979). It is already known that there is no persistence in the all-India and 29 meteorological subdivisions rainfall series (Mooley and Parthasarathy, 1984; Parthasarathy, 1984). Thus there is no change in the number of degrees of freedom required for testing the significance of the correlations between the data series.

All-India rainfall series

Figure 2 shows the all-India summer monsoon rainfall series (normalized values) for the period 1935–1980. The mean summer monsoon rainfall ($\bar{R}$) for the period is 860 mm, the standard deviation (s) is 80 mm and the CV is 9·3 per cent. It is reasonable to assume that the rainfall values in excess of $R + s$ are taken as excess rainfall years and less than $\bar{R} - s$ as deficient rainfall years. There are six excess rainfall years, i.e. 1942, 1947, 1956, 1961, 1970 and 1975 and eight deficient rainfall years; they are 1941, 1951, 1965, 1966, 1968, 1972, 1974 and 1979: these years are suitably marked and shown in Figure 2. It is observed from Figure 2 that the excess rainfall years are more abundant during the period 1941–1964 and the deficient rainfall years are more abundant during 1965–1980.

The composite monthly and seasonal mean SOI values for all the deficient and the excess rainfall years of the all-India series are shown in Figure 3. The anomaly series for the 46-year period, 1935–1980, were divided into standard seasons relative to the major summer monsoon rainfall season, i.e. June, July, August and September (JJAS) as follows: the preceding winter season (DJF, lag -2); the spring (MAM, lag -1); concurrent summer (JJA, lag 0); succeeding autumn (SON, lag $+1$). It is observed from the Figure that during excess rainfall years the pressure difference is negative for January, February and March, but from April onwards this difference is positive and increases and reached the highest value during December. However, the reverse is the case for the deficient years. This increase in the difference of SOI during excess years and decrease during deficient years can be seen clearly as the season advances from winter (DJF) to autumn (SON). It can be understood from Figure 3 that the SOI anomaly is positive in excess rainfall years and negative in deficient rainfall years. However, this anomaly is prominent during the months April to December. The SOI decreases from winter (DJF) to spring, (MAM) for deficient years and increases for excess years. Therefore, we believe that the preceding factor, i.e. winter (DJF) minus spring (MAM), of SOI anomaly may be useful for

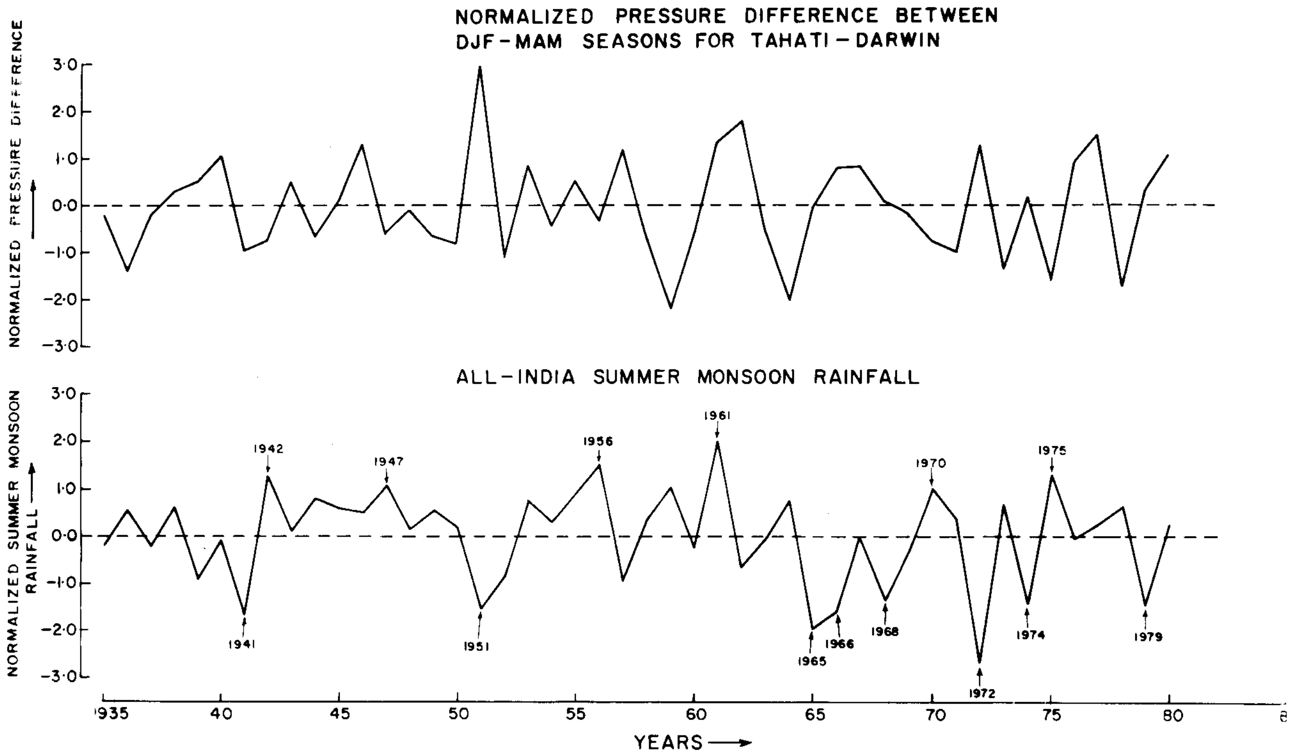


Figure 2. Normalized surface pressure difference between Tahiti and Darwin for winter (DJF) minus spring (MAM) series along with normalized all-India summer monsoon rainfall (excess/deficient years are shown) for the period 1935 to 1980

long-range forecasting purposes. In view of this, we examined the correlation coefficients between normalized all-India rainfall and SOI for different seasons and winter minus spring values (DJF − MAM). These correlation coefficient values (CCs) are shown in Table I.

Table I shows CCs between the all-India rainfall series and four different standard seasons' SOI series; the seasons are (i) winter—DJF, (ii) spring—MAM: (iii) summer—JJA and (iv) autumn—SON. It is observed from Table I that the CCs are significant at the 1 per cent level for the JJA, SON and DJF − MAM series for whole period, i.e. 1935–1980; when the series is divided into two equal periods, for the first period (1935–1957) JJA and SON CCs are significant at the 5 per cent level and for the second period (1958–1980) the CC is significant at the 5 per cent level for the SON and (DJF − MAM) series.

Consistency of the relationship for different periods of the series is examined by calculating the variations of the CCs by the sliding window method (Bell, 1977) using window widths of 10, 20 and 30 years. The importance of the DJF − MAM, SOI series for the seasonal rainfall over India has already been illustrated. Therefore, the relationship between the all-India rainfall series and the SOI series for DJF minus MAM is studied in detail. The variations of the CCs are shown in Figure 4: the CC which is significant at the 5 per cent level has been marked on the CC curves. The Figure shows the CC values for a particular sliding interval plotted against the first year of the interval. Thus, all curves commence from 1935 and terminate in different years given by (1980 − W) + 1, where W is the width of the sliding window. It is observed for the 10-year period that the CC has jumped considerably from a positive value (0·14) to a high negative value (−0·85). The CC is significant for a few years, but it is more negative and continuously significant from 1963 onwards. For the 20-year sliding window the CCs have little variation compared to the 10-year period and the CCs are negative throughout. The CC values are not significant up to the year 1956, afterwards the CCs values are high and negative and mostly significant at the 5 per cent level up to the present. The CCs for the 30-year window are more stable and have become

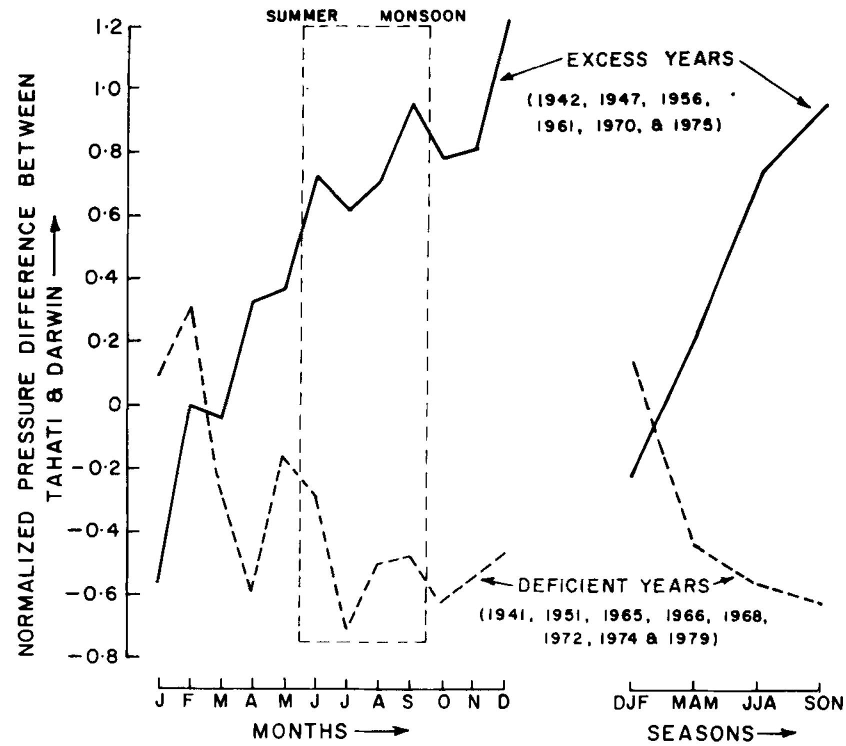


Figure 3. Composite values of normalized pressure difference between Tahiti and Darwin during all-India deficient/excess rainfall years for the period 1935–1980.

significant at the 5 per cent level: after 1942 they have obtained values as high as −0·45 which is significant at the 1 per cent level.

In order to understand the relationship between the all-India summer monsoon rainfall and the SOI of DJF − MAM series, the data points are plotted on a scatter diagram and a least-squares line is fitted through the data points. The scatter diagram is shown in Figure 5 along with the regression line represented by the equation $y = 85{\cdot}9 - 2{\cdot}7x$, where y is the all-India monsoon rainfall and x is the DJF minus MAM value of the SOI. This relationship explains 13 per cent of the total variance. It is observed from Figure 5 that the fitted line represents the data reasonably well at many points except for nine points where the fitted line is apart. On the basis of this equation the all-India rainfall values are estimated for the independent years 1981, 1982 and 1983; the details are presented in Table II. The SOI values for these three years are obtained from Parker (1983) and actual all-India monsoon rainfall values from Mooley and Parthasarathy (1984). In these three years considered, the monsoon rainfall

Table I. Correlation coefficient between All-India summer monsoon rainfall and normalized MSL pressure values for Tahiti minus Darwin (SOI)

S. No.	Details	46 years 1935–1980	23 years 1935–1957	23 years 1958–1980
1	DJF (Lag − 2)	−0·16	0·03	−0·31
2	MAM (lag − 1)	0·22	0·34	0·16
3	JJA (lag 0)	0·42**	0·48**	0·40
4	SON (lag + 1)	0·51**	0·58**	0·50*
5	DJF − MAM	−0·36**	−0·31	−0·42*

* Significant at 5 per cent level.
** Significant at 1 per cent level.

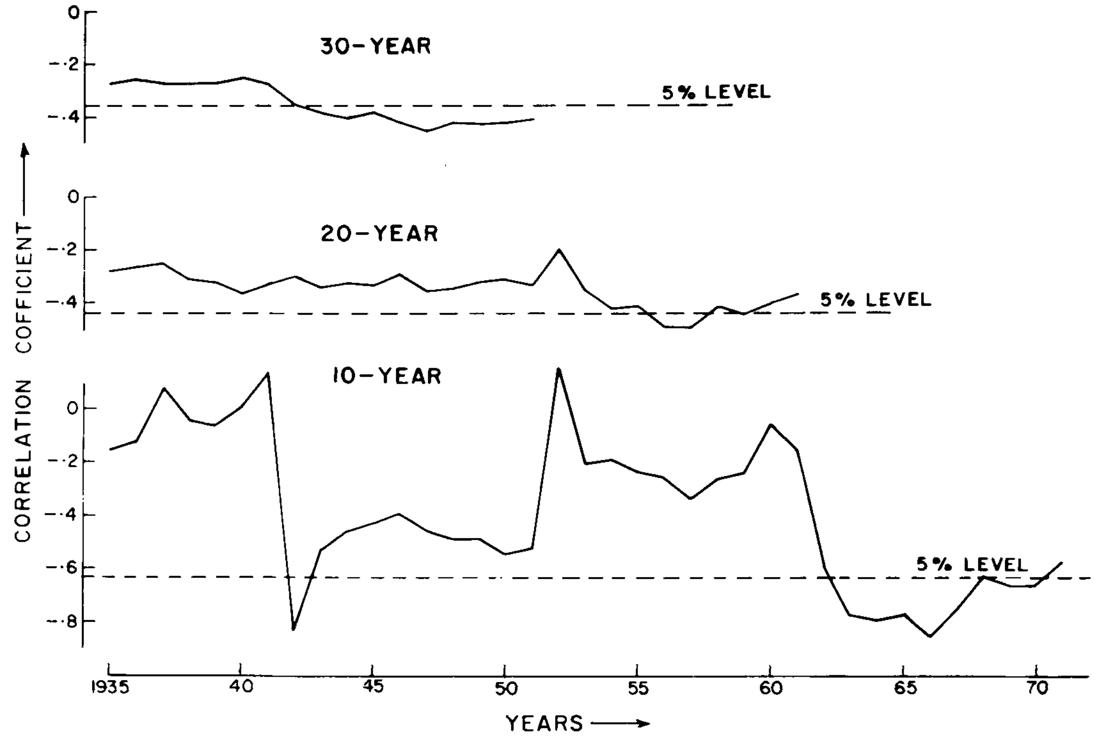


Figure 4. Variation of correlation coefficient between all-India summer monsoon rainfall and normalized pressure difference between Tahiti and Darwin for DJF – MAM series with 10, 20 and 30 year sliding window widths over the period 1935–1980

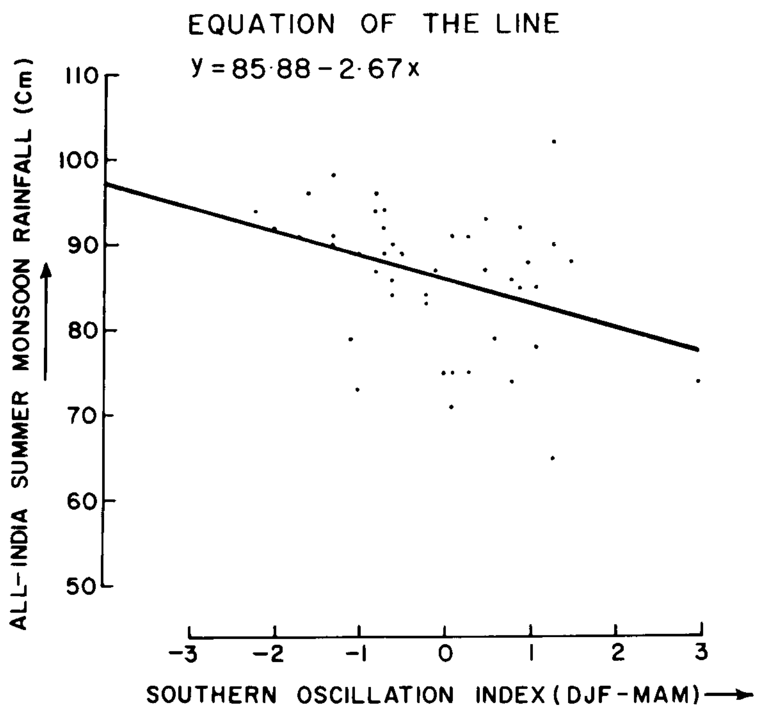


Figure 5. Scatter diagram showing relationship between normalized all-India summer monsoon rainfall and normalized pressure difference between Tahiti and Darwin for DJF minus MAM for the period 1935–1980

Table II. Estimation of all-India summer monsoon rainfall on the basis of the regression equation $y = 85{\cdot}9 - 2{\cdot}7x$

Year	SOI:DJF		SOI:MAM		SOI of	All-India summer monsoon rainfall			
	mbs	Standardized value	mbs	Standardized value	DJF − MAM	Calculated y, mm	Actual, mm	Difference	Difference expressed as percentage of mean
1	2	3	4	5	6	7	8	9	10
1981	4·1	−0·07	1·8	−1·00	0·93	834	845	−11	−1·2
1982	5·2	0·67	2·3	−0·44	1·11	829	739	92	10·7
1983	−1·7	−3·93	0·5	−2·44	−1·49	899	968	−69	−8·0

has been abnormal during two years. The year 1981 received about 2 per cent less rainfall than the long-term mean (normal) value, whereas the year 1982 received 14 per cent less and the year 1983 received 12 per cent in excess of the normal.

It can be observed from Table II that the pressure change from winter (DJF) to spring (MAM) has a decreasing tendency during the deficient year 1982 and an increasing tendency during the excess year 1983; these changes agree with the earlier results shown in Figure 3. The change in pressure tendency from winter to spring thus seems to be a good indicator to determine whether the all-India monsoon rainfall will be deficient or excess.

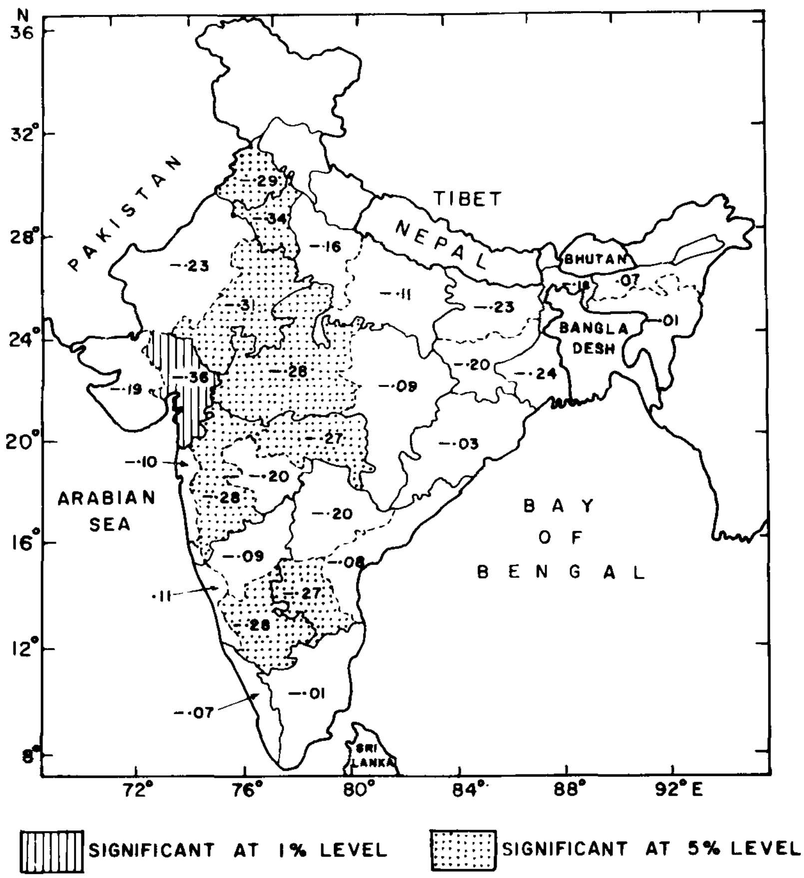


Figure 6. Correlation coefficients between normalized summer monsoon rainfall of different subdivisions of India and the normalized pressure difference between Tahiti and Darwin for the DJF minus MAM series during the period 1935–1980

The details of the estimates of all-India monsoon rainfall based on the regression line presented in Table II give the difference of estimated and actual all-India rainfall expressed as a percentage of the long-term mean. It is seen that the values almost agree for the year 1981, whereas for 1982, a deficient year, the estimated rainfall value is 11 per cent more and it is 8 per cent less for the excess rainfall year, 1983.

It may, however, be inferred that the pressure change from winter to spring as an indicator of deficient or excess rainfall is an improvement over the climatological values. Estimation of all-India rainfall on the basis of this regression equation requires great caution and is not advocated in the present case.

Different meteorological subdivisions

The spatial variability of rainfall within the country is large. The rainfall of meteorological subdivisions in the north-eastern part of the country is poorly correlated with that for the subdivisions in the other regions (Parthesarathy, 1984). In view of this, we have examined the relation between the SOI series for the DJF minus MAM seasons and the summer monsoon rainfall of different subdivisions of India for the period 1935–1980. The CC values are shown in Figure 6. It is observed that there are nine subdivisions for which the CCs are significant at the 5 per cent level, among which for one subdivision (the Gujarat region) the CC (−0·36) is significant at 1 per cent. For these nine subdivisions where the monsoon rainfall is highly variable, a significant relation of the rainfall of this area with the (DJF − MAM) SOI series will have useful predictive value. This area is mainly to the north of 16°N and west of 80°E.

The relationship between the all-India summer monsoon rainfall and the SOI of winter (DJF) minus spring (MAM) seasons is significant for the whole period as well as the current 30 year period at the 1 per cent level. The CCs have become stable during the current 30-year period. The fluctuations in the CCs with smaller window lengths may be attributed to the noise in the input data or local circulation features which might have been dominant during those periods.

DISCUSSION AND CONCLUSIONS

The search for significant climatological parameters for use in multivariate statistical prediction models of the summer monsoon rainfall over India has been pursued for about half a century. Some parameter or other related with the Southern Oscillation has always been included in these models and has shown consistent relations. It is shown by several recent studies, namely those of Angell (1981), Pant and Parthasarathy (1981), Bhalme *et al.* (1983), Mooley and Parthasarathy (1983a) and Parthasarathy and Pant (1984) that the all-India monsoon rainfall and the SOI of the MAM, JJA and SON seasons are positively and significantly correlated at the 1 per cent level of significance. The limitations and change with time of these correlations are discussed by Ramage (1983); further, Shukla and Paolino (1983) have shown that these relationships can be successfully used in the long-range prediction of the Indian summer monsoon rainfall. The present study has shown that a signal of the all-India summer monsoon rainfall anomaly is present in the premonsoon winter-to-spring pressure change. The important results emerging out of this study are summarised below:

(i) The distributions of monthly and seasonal SOI values during deficient and excess rainfall years tend to be opposite.

(ii) The SOI anomaly tendency decreases from winter (DJF) to spring (MAM) during deficient years and increases during the excess rainfall years. This is useful information for long-range prediction.

(iii) The CC between the all-India summer monsoon rainfall series and the SOI for the JJA, SON and DJF minus MAM seasons for the entire period and for the current 30-year period are significant at the 1 per cent level.

(iv) The regression line between all-India summer monsoon rainfall and the SOI for the DJF minus

MAM season is given by $y = 85{\cdot}9 - 2{\cdot}7x$, which explains only 13 per cent of the variance and hence suggests limited utility as a linear prediction equation.

(v) The correlations are significant at the 5 per cent level over different meteorological subdivisions north of 16°N and west of 80°E.

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