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Indian Institute of Tropical Meteorology, Pune, India

Surface and Upper Air Temperatures over India in Relation to Monsoon Rainfall

B. Parthasarathy, K. Rupa Kumar, and **N. A. Sontakke**

With 9 Figures

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Summary

The relationship between the all-India summer monsoon rainfall and surface/upper air (850, 700, 500 and 200 mb levels) temperatures over the Indian region and its spatial and temporal characteristics have been examined to obtain a useful predictor for the monsoon rainfall. The data series of all-India and subdivisional summer monsoon rainfall and various seasonal air temperatures at 73 surface observatories and 9 radiosonde stations (1951–1980) have been used in the analysis. The Correlation Coefficients (CCs) between all-India monsoon rainfall and seasonal surface air temperatures with different lags relative to the monsoon season indicate a systematic relationship.

The CCs between the monsoon rainfall and surface-air temperature of the preceding MAM (pre-monsoon spring) season are positive over many parts of India and highly significant over central and northwestern regions. The average surface air temperature of six stations i.e., Jodhpur, Ahmedabad, Bombay, Indore, Sagar and Akola in this region (Western Central India, WCI) showed a highly significant CC of 0.60 during the period 1951–1980. This relationship is also found to be consistently significant for the period from 1950 to present, though decreasing in magnitude after 1975. WCI MAM surface air temperature has shown significant CCs with the monsoon rainfall over eleven sub-divisions mainly in northwestern India, i.e., north of 15 °N and west of 80 °E.

Upper air temperatures of the MAM season at almost all the stations and all levels considered show positive CCs with the subsequent monsoon rainfall. These correlations are significant at some central and north Indian stations for the lower and middle tropospheric temperatures.

The simple regression equation developed for the period 1951–1980 is $y = -183.20 + 8.83x$, where y is the all-India monsoon rainfall in cm and x is the WCI average surface air temperature of MAM season in °C. This equation is significant at 0.1% level. The suitability of this parameter for inclusion in a predictive regression model along with five other global and regional parameters has been discussed. Multiple regression analysis for the long-range prediction of monsoon rainfall, using several combinations of these parameters indicates that the improvement of predictive skill considerably depends upon the selection of the predictors.

1. Introduction

Within the earth's atmosphere, there is rarely a significant local change isolated from the changes elsewhere. The Indian summer monsoon, for example, is found to be strongly linked to the hemispheric temperatures and circulation changes. Cold periods in the climatic history have winter-like circulation patterns with a weak monsoon circulation, while warm periods are characterised by a strong monsoon (Bryson and Cambell, 1981).

It is generally known that the development of southwest monsoon over the Indian sub-continent is closely linked to the hottest regions over the southern parts of Arabia, Pakistan, Baluchistan and adjoining northwestern parts of India during the summer months. The evolution of a heat low over the south Asian continent is an important annual cycle precursor of the southwest monsoon, favouring as it does a strong meridional pressure gradient from the south Indian Ocean high to south Asia, and hence a strong lower tropospheric cross-equatorial flow, which transports large amounts of water vapour into the Northern Hemisphere (Hastenrath, 1985, p. 286). Therefore, it is logical to presume that the years with high temperatures during March, April and May over these regions may get good monsoon rainfall over Indian sub-continent and vice/versa. Such relationships, if quantiatively established, can provide useful predictors for the Indian summer monsoon rainfall. In view of this, we made a detailed study of the relationships between all-India monsoon rainfall and surface/upper air temperatures over the Indian region, using data for the recent period 1951–1980. The consistency of significant correlations over different periods in the past has also been examined. An attempt has been made to incorporate the results in a long-range prediction scheme for the Indian summer monsoon rainfall.

2. Past Studies

2.1 Hemispheric and Regional Temperatures and Indian Monsoon

Sikka (1980) examined the all-India summer monsoon rainfall and Northern Hemispheric surface air temperature series during the period 1875 to 1975 and observed that the high rainfall epoch (1921–1950) was associated with higher temperatures and the low rainfall epoch (1951–1970) with lower temperatures. Parthasarathy (1984 a) and Verma et al. (1985) made a detailed examination of the relationship between all-India monsoon rainfall and Northern Hemispheric surface air temperatures and found that the winter (DJF) temperatures show the most significant positive correlation with the subsequent monsoon rainfall and that this correlation is dominant in the current 50 years. Walker (1914) obtained a Correlation Coefficient (CC) of -0.02 between the average surface air temperature in the month of May at 15 stations in south Asia (namely, Baghdad, Teheran, Ispahan, Chaman, Quetta, Hyderabad (Sind), Deesa, Jacobabad, Multan, Dera Ismail Khan, Lahore, Sirsa, Jaipur, Allahabad and Jhansi) and the monsoon rainfall of India for the period 1875 to 1913, and concluded that a hot month of May need not be followed by a good monsoon, although he could not explain this paradox. Later, for a long time, no attention has been given to these relationships.

Recently, Mooley and Paolino (1988) studied the mean monthly surface thermal field over India during the pre-monsoon months in association with the Indian monsoon rainfall during the period 1901–1975 and found that the mean May minimum temperature over south Gujarat state and adjoining southwest Madhya Pradesh showed highly significant positive correlation with the subsequent monsoon rainfall. Verma (1982) found out that the years of cooler upper troposphere over north and northwestern regions of India during the pre-monsoon months April and May were generally associated with normal/below normal rainfall activity of the subsequent Indian summer monsoon.

2.2 Regression Models for Long-Range Prediction

Walker (1924) developed several regression models to predict seasonal monsoon rainfall over different regions of India. These regression equations are periodically reviewed by the India Meteorological Department (IMD) and modified by including new parameters. The surface air temperatures (mean, minimum and maximum) are also used in these regression models along with other parameters. Temperatures at the stations in Punjab, Rajasthan and along the east coast are mainly involved in these equations (Jagannathan, 1960). The performance of these equations was discussed in detail by Thapliyal (1987) and Shukla (1987). The current regression model used by IMD to forecast the monsoon rainfall of Peninsular and Northwest Indian regions relies upon surface air minimum temperature during March at four east coast stations (namely, Calcutta, Visakhapatnam, Masulipatnam and Madras) and during May at two stations of central India (namely, Akola and Nagpur), besides other circulation parameters. Hastenrath (1987) used the April surface air temperature of Bombay in his prediction equation for Indian monsoon rainfall.

3. Details of Data

Earlier studies of Parthasarathy (1984 a), Hastenrath (1987) and Parthasarathy et al. (1988 a) of the relationships between Indian monsoon rainfall and regional/global circulation parameters indicated that a data length of about 20 to 30 years is necessary and sufficient in order to establish a stable CC useful for prediction purposes. Also, a period of 30 years is generally considered adequate for establishing climatic normals. In the present study, we have mainly considered the data period 1951–1980, for which excellent data sets on various parameters related to Indian monsoon are available. However, for the purpose of studying consistency of significant correlations and testing of regression predictions on independent samples, data during 1891–1988 have been used.

3.1 All-India Summer Monsoon Rainfall

All-India (India taken as one unit) and the 29 different meteorological sub-divisional summer monsoon (June through September) rainfall have been prepared by properly area-weighting 306 well distributed raingauges over the country. The reader is referred to Mooley and Parthasarathy (1984 a) and Parthasarathy et al. (1987) for a detailed discussion of preparing these data sets and listing of the data from 1871 onwards. Mooley and Parthasarathy (1984 a) established that the All-India summer monsoon rainfall series for the period 1871–1978 was homogeneous. Gaussian-distributed and free from persistence.

The mean ($\bar{R}$), standard deviation (S) and coefficient of variation for all-India summer monsoon rainfall for the period 1951–1980 are 850 mm, 90 mm, and 10.5 percent, respectively. The monsoon rainfall of an individual year is classified as deficient when it is less than $\bar{R} - S$ and as excessive when it is more than $\bar{R} + S$ (Ananthakrishnan and Parthasarathy, 1984). Figure 5 shows the all-India summer monsoon rainfall series during 1951–1988, with the deficient and excess years marked on the rainfall curve.

India as one unit, though too large an area for practical purposes, provides an overall view of the rainfall fluctuations and abnormalities which are helpful to the planners and scientists studying general circulation and changes therein. However, there are certain regional differences in the monsoon rainfall variability which are of important consequence. For instance, the rainfall of meteorological sub-divisions in the north-eastern parts of the country is poorly correlated with the rest of the country (Parthasarathy, 1984 b).

3.2 Surface Air Temperature

The mean monthly surface air temperature data of 73 well distributed observatories in India, based on the daily mean of maximum and minimum temperatures, for the period 1951–1980, are used in the present study. Details of these data were described by Hingane et al. (1985). For some selected stations, the surface-air temperature data during the period 1891–1988 have been used for detailed analysis.

3.3 Upper Air Temperature

Mean monthly upper air temperature at four levels, viz., 850, 700, 500 and 200 mb, over India for 9 radiosonde stations for the period 1951–1980 are considered. The data are taken from the Monthly Climatic Data for the World (NOAA/WMO); the homogeneity and reliability of these data sets were discussed by Rupa Kumar et al. (1987).

4. Methodology

To study the association between the Indian summer monsoon rainfall and surface/upper air temperatures over the Indian region and to develop prediction equations, the following approach has been used: (i) simple correlation analysis (ii) consistency of significant CCs over long period using sliding windows of different widths, (iii) composite of temperature anomalies during the excess and deficient years of all-India monsoon rainfall and (iv) stepwise regression analysis.

To understand the temporal characteristics of the relationship between temperatures and the all-India monsoon rainfall, the CCs with seasonal temperatures of up to 3 lags on either side of the monsoon season have been calculated for the period 1951–1980. The seasons for which the temperature series are prepared, with the seasonal lag relative to monsoon season (JJAS) given in parantheses, are: (i) the previous autumn, SON (lag -3); (ii) the current winter, DJF (lag -2); (iii) the current spring, MAM (lag -1); (iv) the current summer, JJA (lag 0); (v) the current autumn, SON (lag $+1$); (vi) the succeeding winter, DJF (lag $+2$); and (vii) the succeeding spring, MAM (lag $+3$). Besides these, the seasonal tendency (MAM-DJF) of temperature between current spring and previous winter (lag -1 minus lag -2) has also been considered for correlation analysis, in view of the importance of this seasonal feature as demonstrated by Shukla and Paolino (1983), Parthasarathy and Pant (1985) and Shukla

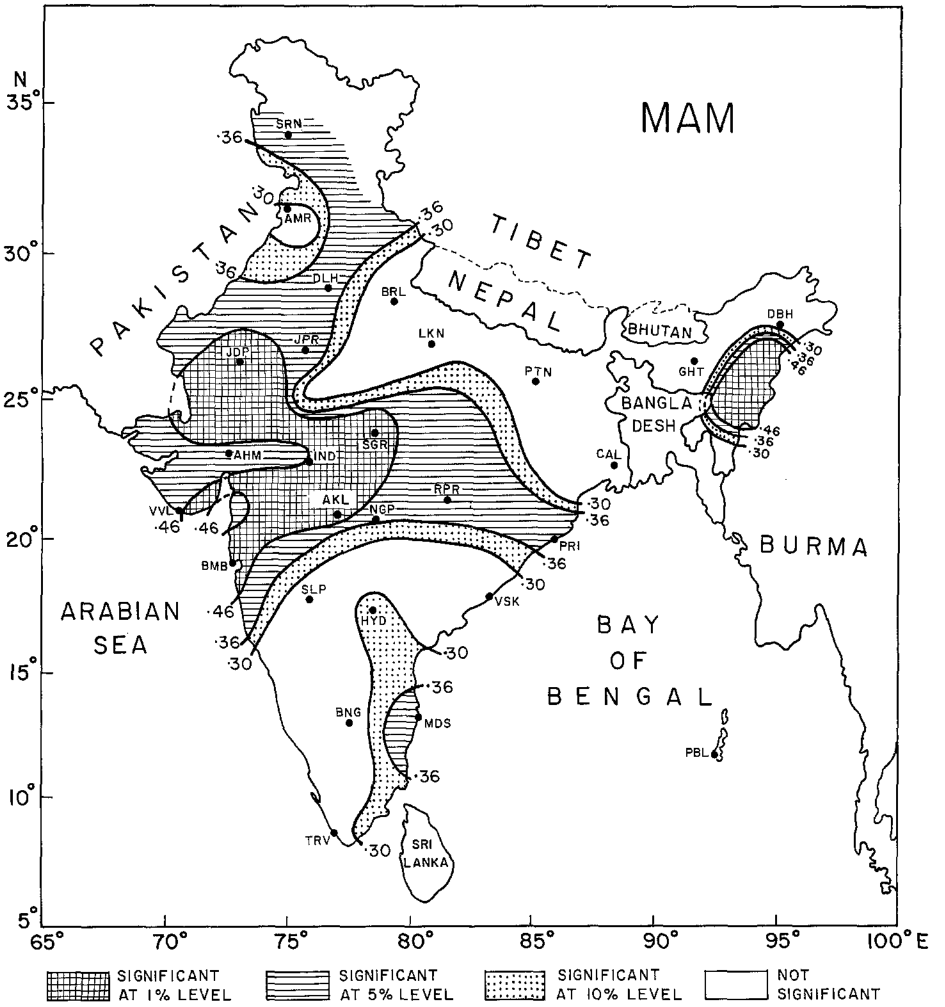

Fig. 1. Correlation Coefficients between All-India summer monsoon rainfall and surface air temperature for the MAM season of different stations over India for the period 1951–1980

and Mooley (1987), relating the Southern Oscillation to the Indian monsoon.

The persistence (as indicated by the serial correlation) of the data series involved has been taken into consideration while assessing the statistical significance of the correlations, by reducing the degrees of freedom wherever necessary as suggested by Sciremammano (1979). However, the serial correlations of almost all the series are found to be insignificant.

The consistency of significant correlations over a long period of time has been examined as suggested by Bell (1977), by calculating the CCs over sliding windows of widths 21, 25 and 31 years during the period 1891–1988 in the case of surface air temperature.

In order to see the strength of the signal of extreme monsoon rainfall years in the temperature series of the region showing significant correlations, composite values of spatial average surface air temperature anomalies (from the 1951–1980 mean) for lag -3 to lag $+3$ seasons and MAM-DJF have been calculated for years of deficient and excess all-India summer monsoon rainfall during the period 1951–1980. There were seven deficient (1951, 1965, 1966, 1968, 1972, 1974 and 1979) and five excess (1956, 1959, 1961, 1970 and 1975) monsoon rainfall situations during this 30-year period.

Multiple regression is a useful empirical approach to long-range forecasting. It incorporates the relevant synoptic statistical information into a linear prediction equation, using observational data, although the atmospheric processes are ba-

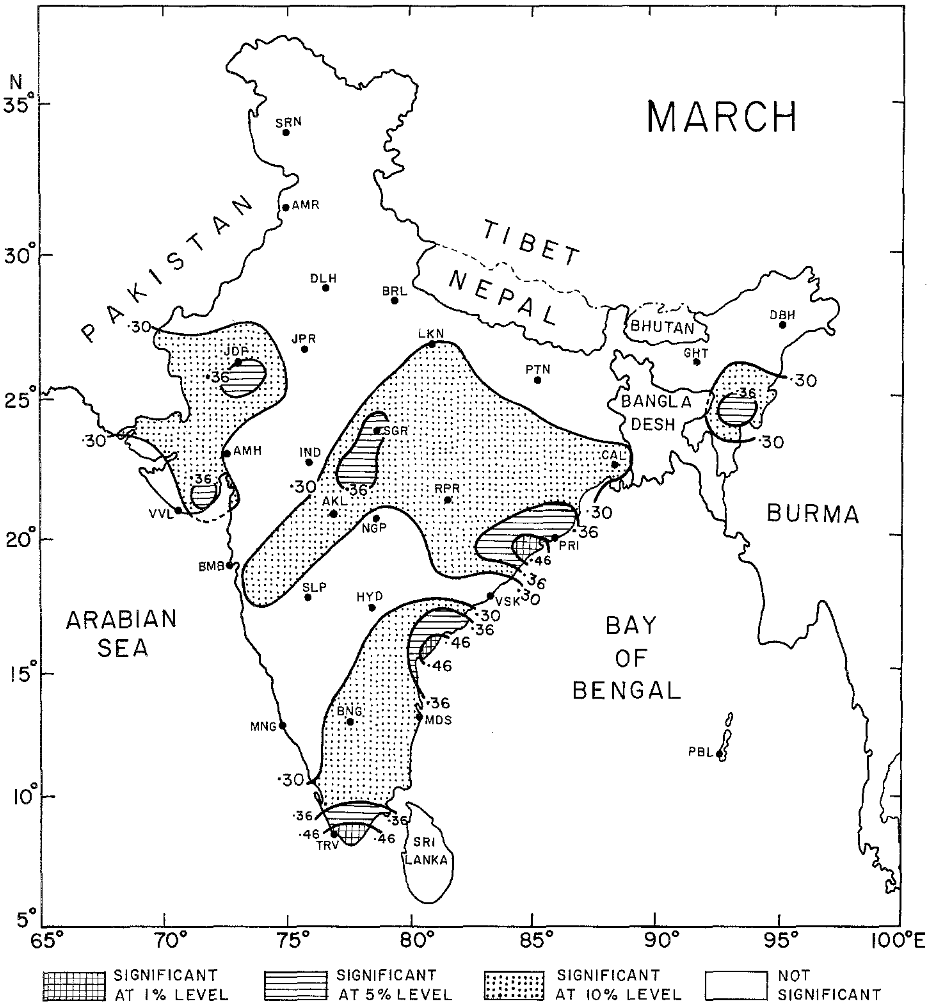

Fig. 2. Same as Fig. 1, but for the month of March

sically non-linear. To develop the equation in the present study, dynamically plausible predictor parameters of regional/global circulation which are significantly correlated with All-India monsoon rainfall, including the regional temperature parameter identified in the present study, are considered. A stepwise procedure of entering variables into the equation following the algorithm developed by Jennrich (1977) has been adopted. The entry of a variable into the equation is determined by its F-value being significant at 5% level or its contribution to the total variance being more than 1%.

5. Relationships with Surface Air Temperatures

The CCs between all-India monsoon rainfall and the different seasonal surface temperatures (lag -3 to lag $+3$ and MAM-DJF) of all the 73 stations during the period 1951–1980 have been computed. These CCs show a systematic change as the season advances from lag -3 to lag $+3$. The CCs of spring season (MAM, lag -1) show a strong and spatially coherent association over certain regions of the country (Fig. 1).

It can be seen from Fig. 1 that significant (at 1% level or above) positive CC values occur over the contiguous regions between latitudes 17°–27°N and longitude 70°–80°E, mainly consisting of Gujarat state, southern parts of Rajasthan and northern parts of Maharashtra state. As argued by Hastenrath (1985) earlier, this result is important and needs further detailed examination. For this purpose, the CC maps for individual months of March, April and May are prepared (Figs. 2 to 4).

In March (Fig. 2), the significant CCs are

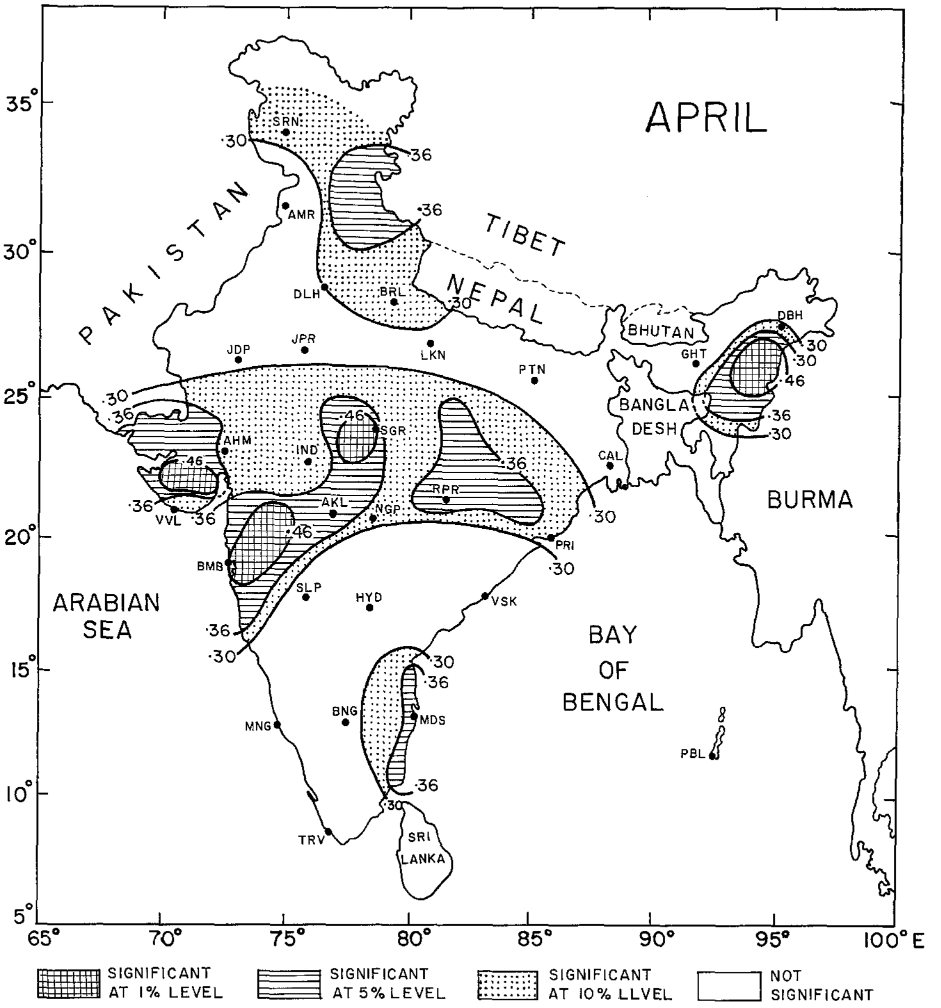

Fig. 3. Same as Fig. 1, but for the month of April

mainly noticed in the regions of southeastern, central and northwestern parts of India. In April (Fig. 3), the CCs are stronger than those in the month of March and mainly concentrated over the central parts of the country. The temperatures in May over the central and northwestern parts of India show strong association with the subsequent monsoon rainfall over India (Fig. 4). These monthly CCs generally indicate a south to north progression of the areas of significant positive correlations from March to May; this fact can be associated with the seasonal migration of maximum solar heating over the corresponding regions of the country, resulting in high temperatures. Thus, these correlations indicate a broad region over the central and northwestern parts of India where the pre-monsoon heating has an important bearing upon the subsequent all-India monsoon rainfall. Though the regions identified by Mooley and Paolino (1988) as having good thermal contrast for deficient and good monsoon situations also fall in the same area, they are relatively limited in extent probably because of the approach involved. Further, Mooley and Paolino (1988) mainly dealt with individual monthly maximum and minimum temperatures. The present study indicates a signal of seasonal nature over a broader region, which is spatially and temporally consistent.

To make a detailed study of the surface-air temperatures and prepare a predictor candidate for the monsoon rainfall, six representative stations well spread over west central and northwestern India and showing significant correlations with the all-India monsoon rainfall, have been selected. The six stations selected are Jodhpur (JDP), Ahmedabad (AHM), Bombay (BMB), In-

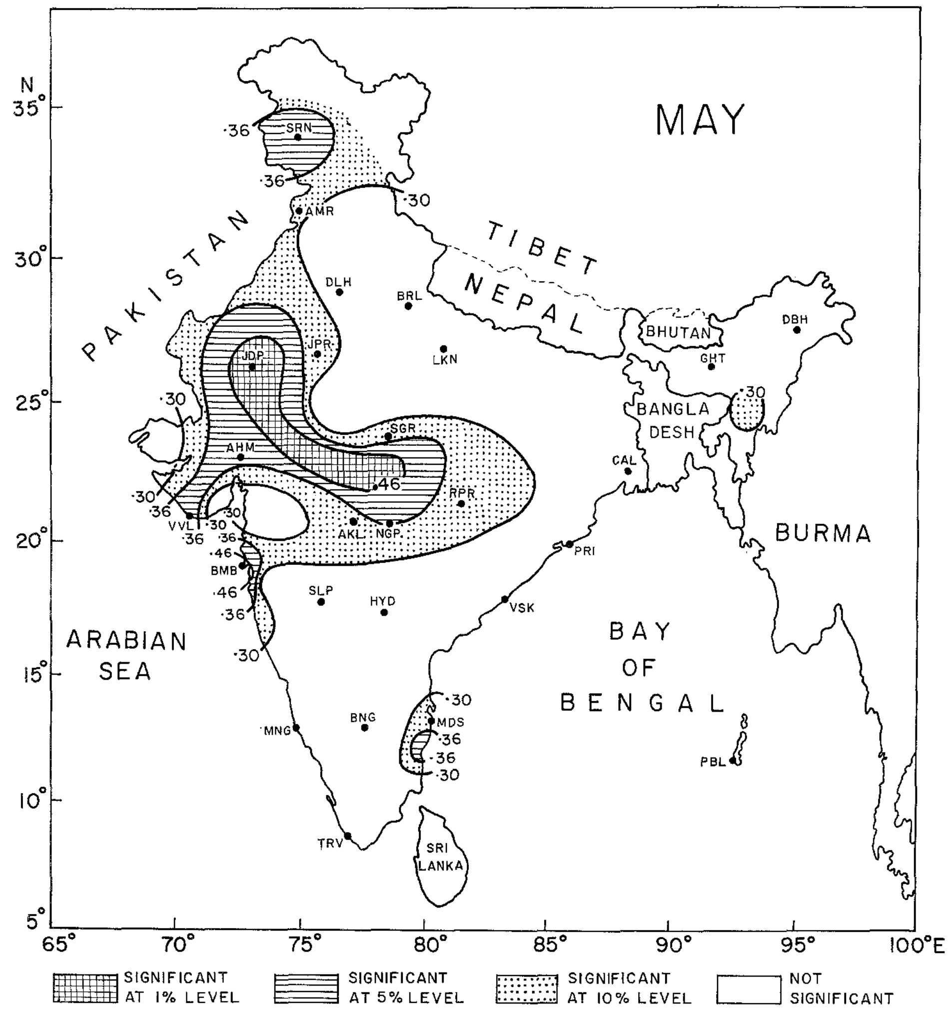

Fig. 4. Same as Fig. 1, but for the month of May

dore (IND), Sagar (SGR) and Akola (AKL) (see Fig. 1). The following important features are taken into consideration while selecting these six stations: (i) representativeness of the region identified above, covering different climatic regimes (i.e., from humid to arid type) and spatial distribution of solar heating during the pre-monsoon months and (ii) availability of data for real-time updating and international data access (these data are regularly published in Monthly Climatic Data for the World). The arithmatic average temperature of all these six stations, called West Central Indian (WCI) temperature hereafter, which effectively minimizes the noise component due to local variations at individual stations and amplifies the large-scale spatial signal, has been subjected to further analysis. The CCs between monsoon rainfall and the lag $+3$ to lag -3 and MAM-DJF temperatures at the six stations and their average (WCI) are presented in Table 1. A systematic change in the CC values, from positive before the monsoon (lag -3 to lag -1) to negative during and after the monsoon (lag 0 to lag $+3$), can be noticed at all the six stations and dominantly in the case of WCI temperatures (Fig. 6a), which suggests that the large-scale circulation features of the monsoon system may be undergoing a low frequency transition during anomalous monsoon years. The CCs are positive for the MAM-DJF temperature tendency. During the pre-monsoon season, MAM (lag -1), the CCs are highly positive (0.44 to 0.60) and significant at 1% level or above at most of the stations. The extremes of WCI temperature (MAM) series and the all-India monsoon rainfall series for the period 1951–1988 (Fig. 5) are well matched in most cases, suggesting

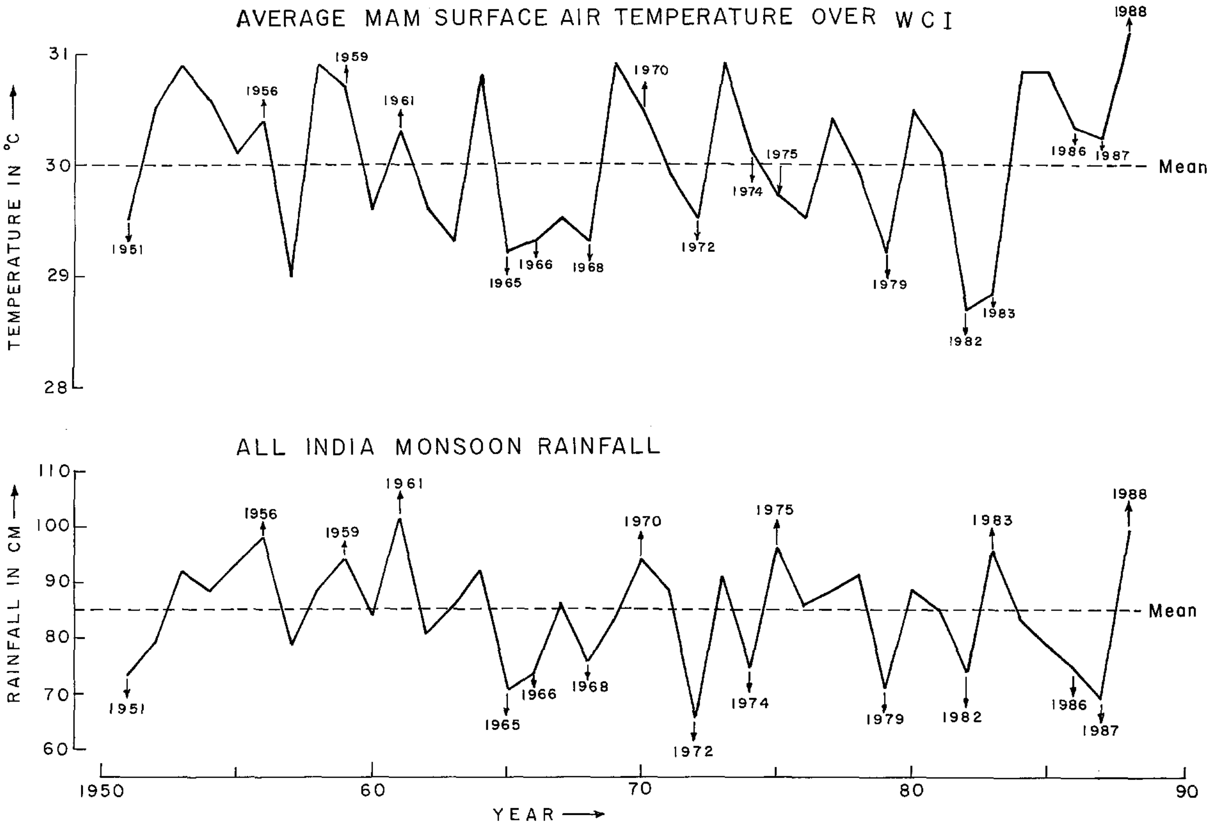

Fig. 5. All-India summer monsoon rainfall and WCI MAM surface air temperature during the period 1951–1988

Table 1. *Correlation Coefficients Between All-India Summer Monsoon Rainfall and Surface Air Temperature of Six Stations and Their Average* (WCI) *for the Period 1951–1980*

Name of the station	lag −3 SON	lag −2 DJF	lag −1 MAM	lag 0 JJA	lag +1 SON	lag +2 DJF	lag +3 MAM	MAM-DJF
1. Jodhpur	0.07	0.15	0.52**	−0.26	−0.58**	−0.26	−0.22	0.24
2. Ahmedabad	0.12	0.14	0.44*	−0.68***	−0.75***	−0.48**	−0.27	0.20
3. Bombay	0.13	0.16	0.53**	−0.57**	−0.40*	−0.12	−0.20	0.26
4. Indore	0.13	0.28	0.45*	−0.65***	−0.64***	−0.54**	−0.38*	0.19
5. Sagar	0.05	0.21	0.54**	−0.35	−0.50**	−0.51**	−0.27	−0.42*
6. Akola	0.09	0.27	0.48**	−0.58**	−0.45*	−0.40*	−0.41*	0.14
WCI Region	0.06	0.26	0.60***	−0.63***	−0.66***	−0.47**	−0.36*	0.31

* Significant CC at 5% level
** Significant CC at 1% level
*** Significant CC at 0.1% level

that active monsoon conditions over the country are preceded by strong seasonal heating during MAM over west central and northwestern parts of India and vice versa.

The composite values of seasonal temperature anomalies for lag −3 to lag +3 and MAM-DJF at the WCI stations (Table 2) as well as their spatial average (Fig. 6b) for extreme years of deficient and excess all-India summer monsoon rainfall show opposite signs from lag −1 to lag +3 and a gradual transition in magnitude with the season. It is interesting to note that the monsoon

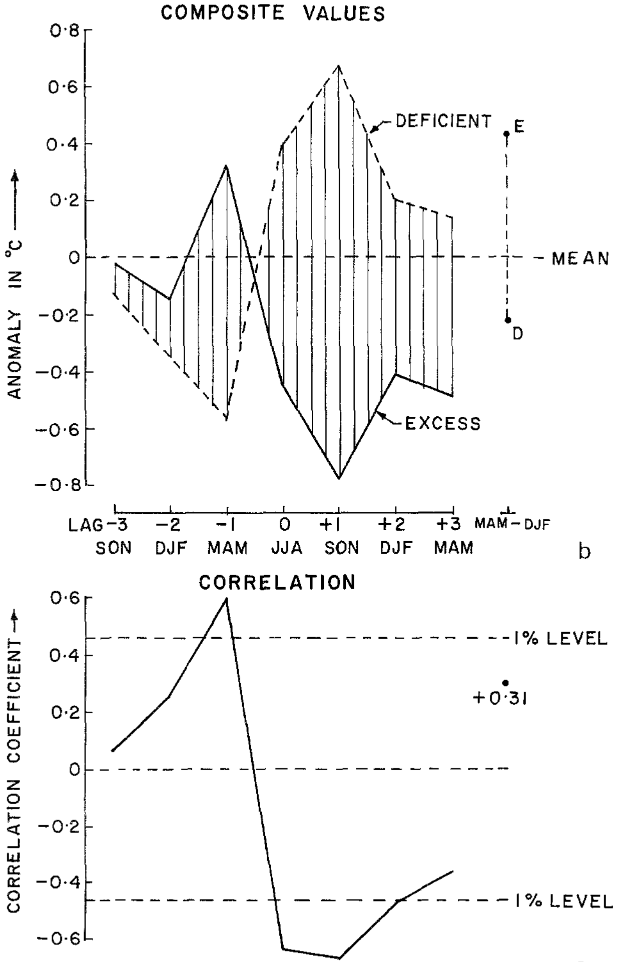

Fig. 6. (a) Correlation coefficients between WCI seasonal temperatures and all-India summer monsoon rainfall; (b) Composite values of WCI seasonal temperature anomalies during years of excess and deficient all-India monsoon rainfall

rainfall is positively correlated (significant at 1% level) with the previous MAM (lag −1) temperatures and negatively correlated (significant at 5% level) with the subsequent MAM (lag +3) temperatures (Figs. 5 and 6). Thus, a good monsoon leads to a cold temperature anomaly during the next MAM season, which in turn results in a deficient monsoon, and vice versa. This feature could be a part of the quasi-biennial oscillation in the monsoon rainfall as reported by Mooley and Parthasarathy (1984 a). Similar explanation was offered by Joseph (1983) in connection with the triennial oscillation observed in the sea surface temperature over the north Indian Ocean.

The monthly data of WCI temperatures are also subjected to correlation analysis with all-India monsoon rainfall to understand the monthly transition of the relationship. Thus, the all-India summer monsoon rainfall is correlated with 24 monthly temperatuers, consisting of 6 months in the previous year (July to December), all the 12 months of the current year and 6 months in the following year (January to June). These correlations are presented in Fig. 7. The CCs of monsoon rainfall with the temperatures of preceding months are positive and significant for March, April and May. The correlations suddenly drop to highly significant negative values during the monsoon months, which is quite expected. Later, the CCs gradually increase, still on the negative side, and reach near zero value by June of next year. Thus, there is a clearly defined signal of pre-monsoon temperatures affecting monsoon performance. However, since some noise component is also noticeable in the monthly correlations, the seasonal values may provide a better representation of the signal.

5.1 Consistency of the Relationship

The WCI temperature for the season MAM, which has shown a highly significant CC (0.60) with the subsequent monsoon rainfall, may be considered as one of the predictors in the seasonal monsoon rainfall forecast. In this connection, it is important to examine the consistency of the relationship over a period of time. Figure 8 shows the variation of the correlation between all-India monsoon rainfall and WCI temperatures during MAM for the period 1891–1988 with sliding window widths of 21, 25, and 31 years; the CC value is plotted in central year of the window.

It can be seen from Fig. 8 that the CCs are generally negative up to the year 1940 and positive thereafter; however, the positive CCs are significant at 5% level only around the period 1950–1975. It is also observed that the CCs for windows of 21 and 25 years are more oscillatory than those for 31 years. The CCs over 31 year windows are more stable, being negative up to 1940 and significantly positive at more than 5% level thereafter. Similar changes in CCs have been noticed around 1940 by Verma et al. (1985) and Elliott and Angell (1987) between the winter (DJF) surface air temperature of the Northern Hemisphere and all-India monsoon rainfall. The predominance of the correlation in the recent period is a

Table 2. *Composite Values of Temperature Anomalies* (from 1951–1980 mean) *in °C for years of Deficient* (D) *and Excess* (E) *All-India Monsoon Rainfall During the Period 1951–1980*

Name of the station	Rainfall Classification	lag −3 SON	lag −2 DJF	lag −1 MAM	lag 0 JJA	lag +1 SON	lag +2 DJF	lag +3 MAM	MAM-DJF
1. Jodhpur	D	−0.08	−0.44	−0.66	0.12	0.75	0.10	0.01	0.22
	E	0.43	−0.13	0.51	−0.42	−1.01	−0.24	−0.43	0.63
2. Ahmedabad	D	−0.26	−0.27	−0.45	0.64	0.99	0.28	0.04	−0.19
	E	0.05	−0.14	0.30	−0.57	−1.01	−0.54	−0.52	0.45
3. Bombay	D	−0.22	−0.33	−0.50	0.18	0.32	−0.03	0	−0.17
	E	−0.21	−0.08	0.03	−0.19	−0.39	−0.10	−0.19	0.11
4. Indore	D	−0.13	−0.27	−0.41	0.59	0.88	0.26	0.20	−0.23
	E	−0.22	−0.15	0.26	−0.45	−0.72	−0.48	−0.60	0.42
5. Sagar	D	−0.09	−0.39	−0.78	0.39	0.76	−0.49	0.26	−0.38
	E	−0.09	−0.46	0.34	−0.56	−0.83	−0.50	−0.58	0.80
6. Akola	D	−0.01	−0.39	−0.62	0.42	0.46	−0.09	0.29	−0.23
	E	−0.21	0.14	0.33	−0.54	−0.69	−0.62	−0.66	0.19
WCI Region	D	−0.13	−0.34	−0.57	0.39	0.67	0.20	0.14	−0.22
	E	−0.02	−0.14	0.32	−0.45	−0.78	−0.41	−0.49	0.43

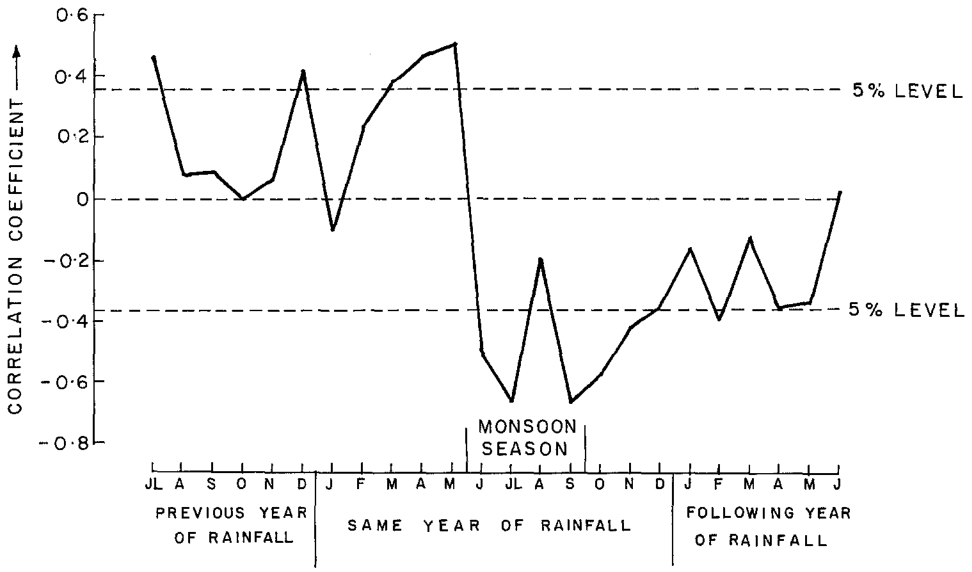

Fig. 7. Correlation coefficients between all-India summer monsoon rainfall and WCI monthly surface air temperatures for the period 1951–1980

useful result for monsoon prediction in the near future. The poor and negative relationship in the beginning of the century may be one of the reasons for Walker's (1914) failure to identify a predictor from regional temperatures.

The seemingly indifference of the strength of heat low over WCI to the development of monsoon circulation in the pre-1940 period does not quite fit into any of the causal mechanisms usually put forth. An examination of the residual mass curve analysis of all-India monsoon rainfall (Mooley and Parthasarathy, 1984 a) indicates a turning point of decreasing to increasing rainfall tendency around the same period. This phenomenon has been linked by Joseph (1983) to the substantial changes that are observed in the frequencies of storms/depression and break monsoon conditions over India, which have a strong bearing

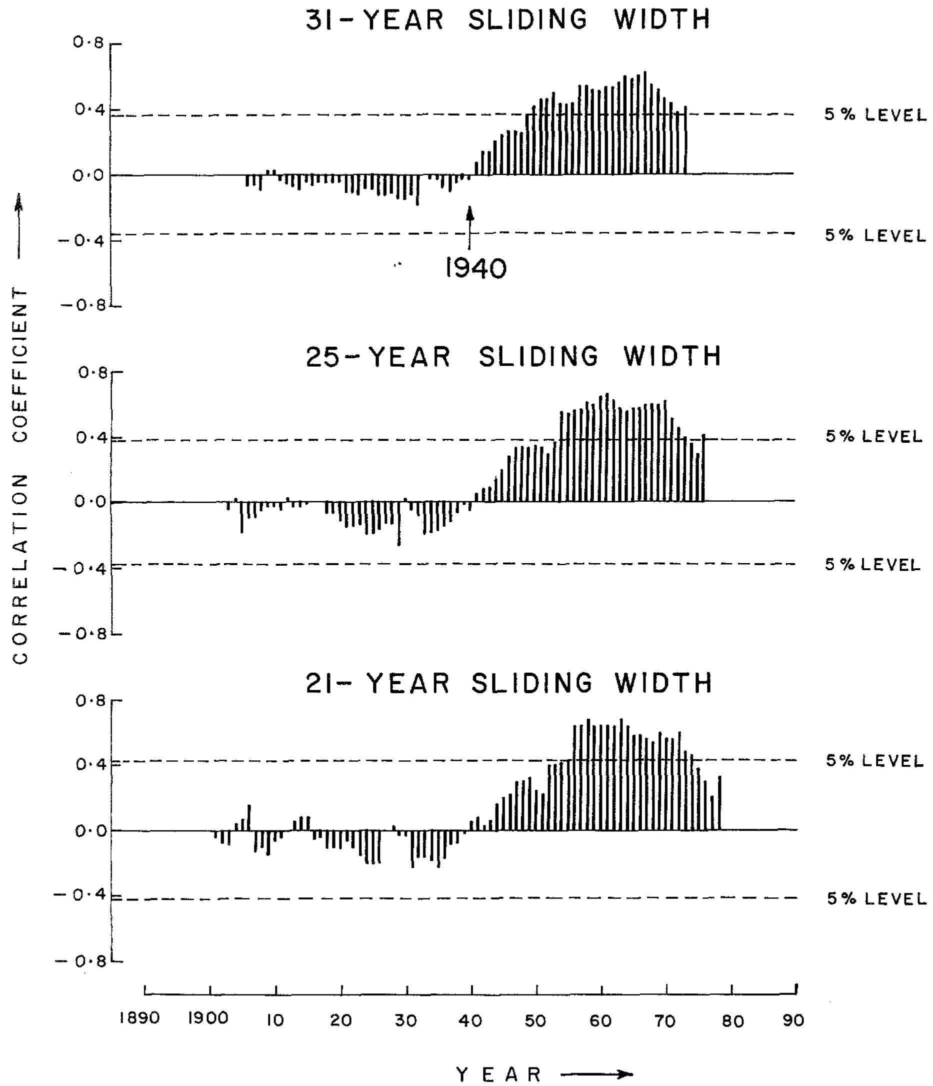

Fig. 8. Variation of correlation coefficient over sliding window widths of 21, 25 and 31 years, between all-India summer monsoon rainfall and WCI MAM surface air temperature during the period 1891–1988

on the monsoon rainfall. Further studies relating the all-India monsoon rainfall and different circulation features like Southern Oscillation (Parthasarathy and Pant, 1984; Elliott and Angell, 1988) sea surface temperatures over the tropical Pacific Ocean (Mooley and Parthasarathy 1984 b), mean sea level pressure over equatorial south American regions and snow cover over Himalayan area (Thapliyal, 1987), and annual sunspot numbers (Ananthakrishnan and Parthasarathy, 1984) have shown substantial changes in relationships that have taken place around the same period in these parameters. Recently, Fu and Fletcher (1988) delineated large signals of climatic variation in the Asian monsoon region on the basis of surface winds over the Indian and western Pacific Oceans. They identified distinct climatic regimes with changes occurring in the years around 1875, 1900, 1940 and 1960; the period 1875–1900 is characterized by what they call meridional monsoon and the period 1900–1940 by zonal monsoon over the Indian Ocean, which are also synchronous with high and low epochs of the Indian monsoon rainfall. Thus, it may be reasoned that the change over in the sign of correlations around 1940 in the present study could be a part of the large-scale changes in the climatic regime over the area. As Elliott and Angell (1987) noted, it remains to be seen if the climate system did indeed behave differently in the first half of the century than it has

Table 3. *The Arithmetic Average* (six stations) *of Surface Air Temperature in °C for the Spring Season* (MAM) *over WCI Region During the Years 1891–1989*

Decade	Year									
	0	1	2	3	4	5	6	7	8	9
1890	–	29.2	29.9	28.5	29.7	29.7	30.9	30.1	30.7	30.2
1900	30.5	30.0	31.1	28.9	29.8	29.0	29.8	28.8	29.5	29.6
1910	29.5	29.3	30.0	29.4	29.5	29.9	30.7	27.7	29.4	29.9
1920	29.3	31.2	30.3	30.0	30.8	30.4	28.8	29.2	30.1	30.8
1930	29.8	30.3	29.8	29.1	29.6	29.0	29.7	29.0	30.5	28.9
1940	29.0	30.6	30.5	30.1	29.4	29.4	30.2	29.9	30.7	30.8
1950	29.6	29.5	30.5	30.9	30.6	30.1	30.4	29.0	30.9	30.7
1960	29.6	30.3	29.6	29.3	30.8	29.2	29.3	29.5	29.3	30.9
1970	30.5	29.9	29.5	30.9	30.1	29.7	29.5	30.5	29.9	29.2
1980	30.5	30.1	28.7	29.1	30.8	30.8	30.4	30.3	30.9	30.2

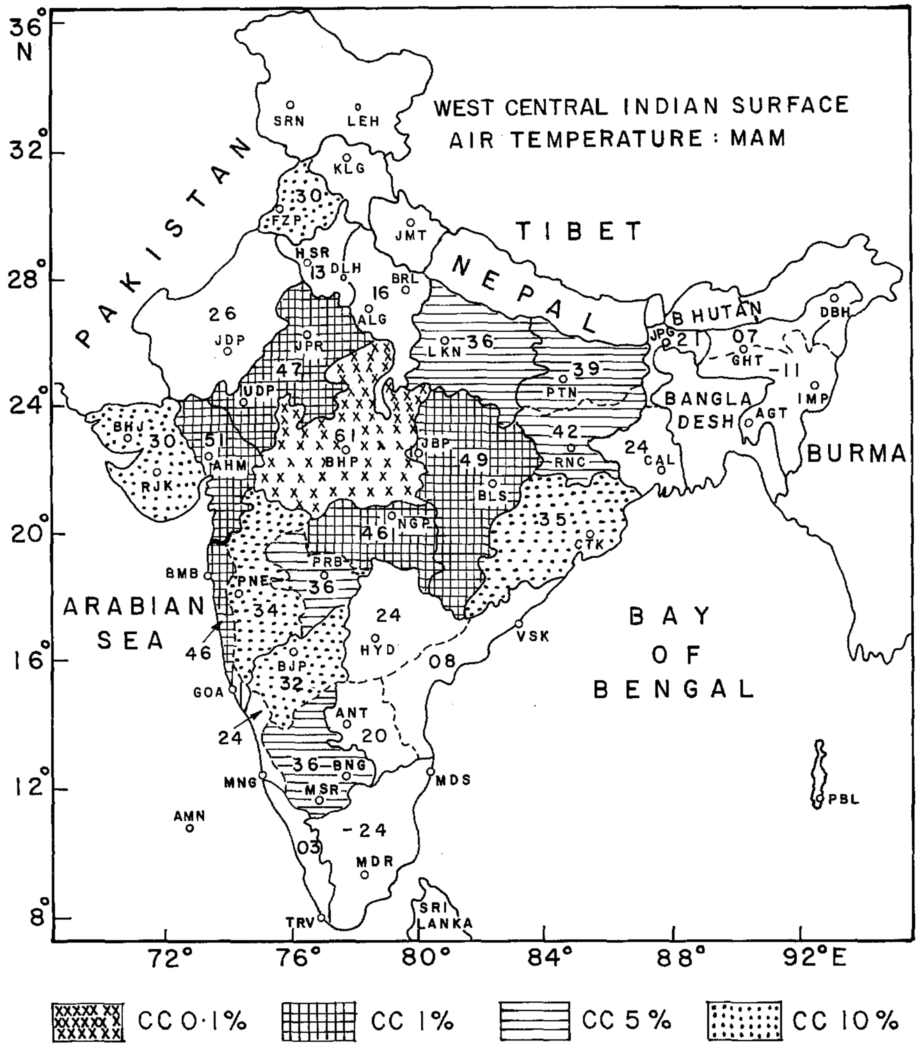

Fig. 9. Correlation coefficients between monsoon rainfall of different meteorological sub-divisions of India and WCI MAM surface air temperature for the period 1951–1980

in the last 30 to 40 years. The drop in the magnitude of correlations after about 1975 may also be a pointer towards a similar recent change. Further work on these aspects is necessary to understand the mechanisms involved. In this connection, it is interesting to note that the WCI temperatures provide a useful trace of the signal of long-term changes in the monsoon regime. In view of its potential applications for further research in this area, a listing of the WCI MAM surface temperatures during 1891–1988 is presented in Table 3.

5.2 Relationship Between Surface Air Temperature and Sub-Divisional Monsoon Rainfall

To understand the manifestation of the signal of the relationship between WCI MAM temperatures and the monsoon rainfall on a smaller spatial scale, we considered the monsoon rainfall data of 29 different sub-divisions of India for the period 1951–1980 for correlation analysis. The CCs and their significance are shown in Fig. 9. The CCs are generally positive for a major part of India and significant at 10% level or above for 16 contiguous sub-divisions, mainly north of 15 °N and west of 80 °E, for 11 sub-divisions the CCs are significant at 5% level or above. The highest CC is 0.61 for west Madhya Pradesh, significant at 0.1% level. The variation of correlations as shown in Fig. 9 could be partly another facet of the relationships between all-India and sub-divisional monsoon rainfall however, they give an idea of the core area where the WCI MAM temperature can be used to predict sub-regional scale monsoon rainfall.

6. Relationships with Upper Air Temperatures

To get a comprehensive idea of the relationship between monsoon rainfall and tropospheric temperatuers over India, the upper air temperatures have also been considered for correlation analysis. The CCs between all-India monsoon rainfall and different seasonal upper air temperatures (850, 700, 500 and 200 mb levels) of nine stations well distributed over India (DLH, JDP, GHT, CAL, NGP, BMB, VSK, MDS and TRV; see Fig. 1) and the temperature difference between Jodhpur and Trivandrum representing north-south gradient for the period 1951–1980 for lag − 3 to lag + 3 and MAM-DJF have been computed. The CCs of the MAM and MAM-DJF temperatures with the all-India summer monsoon rainfall are positive at almost all the stations at all levels (Table 4). The correlations are significant at 5% level or above at some northern (Delhi and Jodhpur) and central (Nagpur, Bombay and Visakhapatnam) stations for the lower and middle tropospheric temperatures. The MAM temperatures give better correlations than the MAM-DJF temperature tendency. The correlations are generally higher at 700 mb and insignificant at the upper troposphere (200 mb). The north-south temperature gradient

Table 4. *Correlation Coefficients Between All-India Summer Monsoon Rainfall and Upper-Air Temperatures at 4 Levels over Indian Stations During the Period 1951–1980*

	MAM (lag − 1)				MAM-DJF			
	850 mb	700 mb	500 mb	200 mb	850 mb	700 mb	500 mb	200 mb
1. Delhi	0.40*	0.46**	0.46**	0.41*	0.38*	0.52**	0.48**	0.15
2. Jodhpur	0.46**	0.33	0.51**	0.30	0.39*	0.33	0.38*	0.06
3. Gauhati	0.22	0.28	0.21	0.26	0.20	0.39*	0.19	0.16
4. Calcutta	0.17	0.28	0.42*	0.19	−0.02	0.30	0.37*	0.18
5. Nagpur	0.52**	0.54**	0.20	0.16	0.31	0.34	−0.05	0.03
6. Bombay	0.53**	0.52**	0.38*	0.32	0.37*	0.20	0.18	0.06
7. Visakhapatnam	0.40*	0.44*	0.19	0.15	0.07	0.24	0.07	0.03
8. Madras	0.32	0.29	0.09	0.31	0.27	0.15	−0.02	0.23
9. Trivandrum	0.17	0.24	−0.02	0.10	−0.11	0.06	−0.20	0.02
10. Jodhpur minus Trivandrum	0.39*	0.19	0.49**	0.15	0.42*	0.27	0.39*	0.03

* Significant at 5% level.
** Significant at 1% level.

represented by Jodhpur minus Trivandrum temperature difference also shows similar correlations.

It can be concluded that the influence of thermal low over WCI is felt up to 700 mb level height and up to 200 mb towards the north. The CC magnitudes at higher levels are smaller than those at the surface. This indicates that the thermal signal weakens with increasing height. Therefore, in the development of the regression models the WCI surface values are used.

7. Development of Regression Equation for All-India Monsoon Rainfall Prediction

The mean WCI surface air temperature of MAM season (x, in °C) which shows a stable and consistent relationship during the recent period has been used to develop a regression equation with the all-India monsoon rainfall (y, in cm) using the data for the period 1951–1980. The estimated equation is:

$$y = -183.20 + 8.93x \tag{1}$$

which explains 36% of the variance, significant at 0.1% level (F-Value being 16.0) with a standard error of estimate of 7.34 cm.

Though the Indian monsoon is a manifestation of the seasonal heating and cooling cycle over the Asian land mass, its development and activity depend upon many other global circulation features (Shukla, 1987; Hastenrath, 1987; and Parthasarathy et al., 1988 a). Therefore, it would be more comprehensive and physically realistic to consider the regional surface air temperature for the pre-monsoon season (MAM) along with other circulation parameters for inclusion in the prediction formulae of Indian monsoon rainfall. During recent times many attempts have been made, notably by Bhalme et al. (1986), Hastenrath (1987), Shukla and Mooley (1987), Thapliyal (1987), Mooley and Shukla (1987) and Parthasarathy et al. (1988 a, 1989), to develop multiple regression equations for long-range prediction of Indian monsoon rainfall, based on a variety of regional and global parameters. These studies indicate that the Indian summer monsoon rainfall generally depends upon (i) conditions over the Indian region, (ii) meridional pressure gradient and cross-equatorial flow over the Indian Ocean and (iii) the Southern Oscillation. Some of the important parameters, along with their physical significance given in parentheses, are:

x_1 = Bombay (19 °N; 73 °E) msl pressure, MAM-DJF (an indicator of the seasonal change of low pressure or thermal high center over the western region of India);

x_2 = April 500 mb ridge position (°N) along 75 °E (representing seasonal transition of the mid-trospheric circulation over India);

x_3 = Tahiti (18 °S; 150 °W) minus Darwin (12 °S; 131 °E) msl pressure, MAM-DJF (indicating the change in the strength of the Southern Oscillation);

x_4 = Darwin msl pressure, MAM-DJF (seasonal tendency in a core region of the Southern Oscillation in the proximity of Indian monsoon region);

x_5 = Pressure difference over the Indian Ocean region, Nouvelle (38 °S; 78 °E) minus Agalega (10 °S; 57 °E) MSL pressure, MAM-DJF (change from winter to spring strength of the south east trades over the south Indian Ocean).

The first four parameters of the above, majority of which represent the preceding winter to spring (MAM-DJF) tendencies, contribute to a large part (81.3%) of the variance in the rainfall prediction model developed by Parthasarathy et al. (1988 a) for the period 1951–1980 (Multiple CC = 0.902). In their regression analysis, they used data for the parameters x_1, x_3, x_4 and x_5 obtained by standardizing the isolated seasonal means of pressures at the corresponding stations for the period 1951–1980 to make the different series comparable in terms of variance.

In the present study, the same variables have been used for the development of a regression model, but with a slightly different approach of data preparation. In view of the times of observation for Bombay pressures (x_1) around 1961 in the World Weather Records as used by Parthasarathy et al. (1988 a), we have taken the data from the Bombay Observatory Records, ensuring a uniform time of observation (0 830 Indian Standard Time or 0 300 UTC) throughout the data period. Regarding x_3 and x_5, the pressure differences between the stations have been computed for individual seasons using standardized data of MAM and DJF. These station differences are further standardized and then the seasonal tendencies are calculated.

The WCI mean surface air temperatures (x_6, °C) for the season MAM, which is identified as a predictor in the present study, is added to the above five parameters and a multiple regression equation is developed using a stepwise procedure. The inter-CCs between these parameters are presented in Table 4. The high inter-CCs may not pose a serious problem as the screening technique of the regression analysis effectively eliminates multi-collinearity by regressing the residual components of a predict and on predictors after deciding the first entrant in the stepwise process. The resultant equation is:

$$\begin{array}{llll} y = -7.10 + 1.93x_2 & - 3.60x_1 & - 4.68x_3 & \\ \quad\quad\quad\quad (48.9) & \quad (18.0) & \quad (5.1) & \\ \quad - 3.09x_4 & + 1.57x_5 & + 2.09x_6 & \\ \quad\quad\quad\quad (4.2) & \quad (3.1) & \quad (1.3) & \quad (2) \end{array}$$

Values given in parentheses below the regression coefficients, in this and subsequent equations, indicate the increase in percentage of variance accounted for by the corresponding variable as it enters the regression equation, in the given order. The multiple CC of this equation is 0.898, accounting for 80.6% of the total variance in rainfall. The slightly lower value of multiple CC than that obtained by Parthasarathy et al. (1988 a) is mainly due to the differences in data preparation. Even so, we feel that our data sets are better prepared and more reliable. Though x_1 and x_2 show identical CCs with the monsoon rainfall (0.696 and 0.699 respectively), x_2 enters the equation first. However, the relative magnitudes of the CCs may fluctuate depending upon the data period and either of them may be the first entry into the regression equation. Though the contribution of x_6 to the variance explained (1.3%) may appear to be too small, it should be viewed as a part of the unexplained variance remaining (20.7%) when this parameter entered the equation. As such, addition of WCI MAM surface temperature can significantly contribute to the efficiency of the prediction equation. Using this equation the predicted anomalies of all-India summer monsoon rainfall have been obtained for the independent data period 1981–1987 (Table 6). The table also shows the contribution of each of the predictors to the resultant anomaly in the all-India monsoon rainfall. These are calculated by multiplying the deviation from mean of each of the independent variables with the corresponding regression coefficient. Thus, the table indicates the behaviour of each predictor in individual years during 1981–1987. The major failures of the prediction occurred in the years 1983 (excess predicted as deficient) and 1987 (deficient predicted as normal). It can be seen from the table that x_3 (Tahiti-Darwin pressure, MAM-DJF) was the major contributor to the failure of the equation for both years. These

Table 5. *Inter-Correlations Among the Parameters Used in the Development of the Regression Model for Long-Range Prediction of Indian Monsoon Rainfall for the Data Period 1951–1980*

Parameter	All-India Monsoon rainfall	Bombay MAM-DJF	April 500 mb ridge	Darwin MAM-DJF	WCI MAM	Tahiti-Darwin MAM-DJF	Nouvelle-Agalega MAM-DJF
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1. All-India Monsoon rainfall	1.00						
2. Bombay MAM-DJF Pressure	−0.70***	1.00					
3. April 500 mb Ridge	0.70***	−0.46**	1.00				
4. Darwin MAM-DJF Pressure	−0.63***	0.80***	−0.47**	1.00			
5. West Central India MAM Temperature	0.60***	−0.49**	0.49**	−0.50**	1.00		
6. Tahiti-Darwin MAM-DJF Pressure	0.43*	−0.73***	−0.47**	−0.83***	0.40*	1.00	
7. Nouvelle-Agalega MAM-DJF Pressure	0.44*	−0.30	0.36*	−0.16	0.25	0.23	1.00

* Significant at 5% level
** Significant at 1% level
*** Significant at 0.1% level

Table 6. *Estimated Anomalies in the All-India Summer Monsoon Rainfall (Eq. 2) During Independent Data period 1981–1987, Along with the Contributions of Individual Predictors to the Estimation*

Year	Contribution in cm from each parameter to the departure from mean of all-India monsoon rainfall					All-India summer monsoon rainfall departure (cm)			
						Estimated	Actual	Prediction Error	
	x_1	x_2	x_3	x_4	x_5	x_6	y	r	$y-r$
1981	−0.48	+3.34	+3.34	−5.41	−1.00	+0.24	+0.03	+0.17	−0.14
1982 D	−2.45	−7.66	+4.51	−1.56	−0.40	−2.79	−10.35	−11.53	+1.18
1983 E	−0.65	−1.49	−7.00	+3.93	−2.35	−1.94	−9.50	+10.47	−19.97
1984	−4.69	−0.91	+2.63	−1.36	−0.96	+1.73	−3.56	−1.53	−2.03
1985	−7.72	−1.10	−2.50	+5.08	+0.51	+1.69	−4.04	−6.33	+2.29
1986 E	−0.52	−0.52	+0.31	−3.22	−0.93	+0.70	−4.18	−10.33	+6.15
1987 E	−1.49	−2.45	+5.97	−6.22	+1.75	+0.47	−1.97	−16.23	+14.26

Note: D = Deficient rainfall year
E = Excess rainfall year

prediction failures may be due to the abnormal circulation pattern associated with unusual ENSO development and decay.

The six parameters discussed above are involved, in some form or other, in most of the prediction schemes of Indian monsoon rainfall. These may be grouped as (i) three (x_1, x_2 and x_6 representing the regional circulation features over India, (ii) two (x_3 and x_4) connected with the Southern Oscillation and (iii) one (x_5) indicating the strength of the southeast trades over the south Indian Ocean. To understand the nature of the multiple regression model with parameters selected on the basis of some logical (though subjective) considerations, the following combinations of parameters have been attempted. The equations and the variance explained by each parameter are given below:

(i) Excluding April 500 mb ridge (x_2) which involves some subjectivity in locating the position (see Shukla and Mooley, 1987) and considering all the remaining five parameters:

$$\begin{aligned} y = -31.98 - {} & \underset{(48.5)}{3.64x_1} + \underset{9.0)}{3.90x_6} \\ & + \underset{(4.4)}{2.33x_5} - \underset{(2.3)}{4.07x_3} - \underset{(5.7)}{3.45x_4} \end{aligned} \tag{3}$$

The multiple CC is 0.835 and the variance explained is 69.9%. The WCI surface temperature (x_6) is the second parameter to enter, adding 9.0% to the variance explained, indicating its importance.

(ii) Only the three parameters representing regional circulation over India:

$$y = -32.43 + \underset{(48.9)}{1.93x_2} - \underset{(18.0)}{3.40x_1} + \underset{(2.6)}{2.93x_6} \tag{4}$$

The multiple CC is 0.833 and the variance explained is 69.5%

(iii) One parameter from each of the three different regions of action as stated above:

$$y = 85.03 - \underset{(48.5)}{3.44x_1} + \underset{(6.0)}{2.33x_5} - \underset{(2.3)}{1.68x_4} \tag{5}$$

The multiple CC is 0.753 and the variance explained is 56.8%.

(iv) Excluding the parameters from the Indian region:

$$y = 85.02 - \underset{(40.0)}{6.24x_4} + \underset{(13.0)}{3.31x_5} - \underset{(5.7)}{3.64x_3} \tag{6}$$

The multiple CC is 0.754 and the variance explained is 56.8%.

All the Eq. (2) to (6) are significant at more than 1% level.

It appears from the above considerations that improvements and perhaps even maintenance of predictive skill in forecasting Indian monsoon rainfall may result as much from selection of suitable parameters as by improvements in the statistical methodology. Hence the importance of the new parameters should always be judged in conjunction with the phase of relationship shown by other parameters. Also, because the variability of the Indian monsoon is inherently a planetary scale phenomenon, a relatively large number of variables may be needed to represent or monitor those conditions. However, updating these parameters is most important for accurate operational forecasting.

8. Conclusions

A study of the relationships between Indian monsoon rainfall and surface/upper air temperatures over the Indian region for the period 1951–1980 leads to the following conclusions:

(i) The tropospheric temperatures during premonsoon season over India are positively correlated with the subsequent monsoon rainfall and they are highly significant over west, central and northwestern parts of India.

(ii) Spatial average of MAM surface air temperature at six stations (Jodhpur, Ahmedabad, Bombay, Indore, Sagar, Akola) of Western Central India (WCI) shows a highly significant signal of subsequent monsoon activity. This relationship was dominant in the recent 4 decades.

(iii) The composite means of surface-air temperature anomalies for deficient and excess monsoon years show opposite signs for lag -1 to lag $+3$ at all the above 6 stations and their average (WCI).

(iv) On a smaller spatial scale, the monsoon rainfall of eleven contiguous sub-divisions lying north of 15 °N and west of 80 °E is significantly correlated with the WCI temperatures of preceding MAM season.

(v) Upper air temperatures (upto 500 mb level) at Delhi, Jodpur, Nagpur, Bombay and Visakhapatnam for the season MAM show significant and positive correlations with the subsequent all-India summer monsoon rainfall, indicating that a warm lower and middle troposphere over the north and central Indian region is followed by a good monsoon.

(vi) A simple regression equation $y = -183.20 + 8.93x$ for the period 1951–1980 between all-India rainfall (y in cm) and WCI average surface air temperature for the season, MAM (x °C) shows a good fit.

(vii) WCI temperature of MAM season can be used as a parameter in the long-range prediction scheme of the Indian monsoon rainfall, along with other parameters.

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Authors' address: B. Parthasarathy, K. Rupa Kumar and N. A. Sontakke, Indian Institute of Tropical Meteorology, Dr H. N. Bhabha Road, Pune-411008, India.