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LONG-TERM VARIABILITY OF THE INDIAN SUMMER MONSOON AND RELATED PARAMETERS

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ABSTRACT

The long-term variability of the Indian summer monsoon rain-fall and related regional and global parameters are studied. The cubic spline is used as a digital filter to smooth the high frequency signals in the time series of the various parameters. The length of the data series varies from 95 to 115 years during the period 1871–1985. The parameters studied within the monsoon system are: (a) monsoon rainfall of the country as a whole; (b) number of break-monsoon days during July and August; (c) number of storms/depressions in Bay of Bengal and Arabian Sea during summer monsoon season; and (d) dates of onset of summer monsoon over South Kerala Coast. The parameters studied outside the monsoon system are: (a) the Wright's Southern Oscillation Index (June–July–August); (b) the January mean Northern Hemispheric surface air temperature anomaly; and (c) the East-equatorial Pacific sea surface temperature anomaly.

In order to examine the variability under various degrees of the smoothing, the series are filtered with splines of 50% variance reduction frequency of one cycle per 10, 20 and 30 years. It is observed that the smoothed time series of the parameters within the monsoon system comprise a common slowly varying component in an episodic manner distinctly showing the excess and deficient rainfall epochs. The change of intercorrelations between the time series with increasing degree of smoothing throws some light on the time scales of the dominant interactions. The relation between Southern Oscillation and East equatorial Pacific sea surface temperature and the Indian summer monsoon seems to be dominant on the interannual scale. The low frequency variations are found to have significantly contributed to the instability of the correlations of monsoon rainfall with parameters outside the monsoon system.

I. INTRODUCTION

The Asian summer monsoon, which is basically a manifestation of the influence of the seasonal heating and cooling over Asiatic land mass, constitutes an important component of the global atmospheric and oceanic circulation. Therefore, the monsoon over India, as a part of planetary-scale circulation, is represented in terms of long-term climatic anomalies of many variables. Sikka (1980) established the relation of the year-to-year fluctuations of summer monsoon rainfall with several planetary and regional scale circulation features like the El Nino, Northern Hemispheric tropospheric temperatures, equatorial Pacific sea surface temperatures, monsoon depressions and lows, break monsoon, etc. During the last few years, long-term data series of several regional and global atmospheric/oceanic parameters have been prepared and their relationship with Indian summer monsoon rainfall has been studied extensively. The following are some important parameters with which the relationship of the Indian Summer monsoon rainfall has been studied by different workers: (i) dates of onset of the monsoon (Dhar et al., 1980); (ii) storms and depressions in the Bay of Bengal and Arabian Sea (Mooley and Parthasarathy, 1983; Mooley et al., 1984); (iii) break-monsoon days in July and August (Mooley and Parthasarathy, 1983); (iv) different indices of Southern Oscillation (Pant and Parthasarathy, 1981; Shukla and Paolino, 1983; Parthasarathy and Pant, 1984, 1985; Bhalme and Jadhav, 1984; Mooley et al., 1985, Wu and Hasternath, 1986); (v) equatorial Pacific sea-surface temperatures (SST) (Angell, 1981; Mooley and Parthasarathy, 1984b); and (vi) Northern Hemispheric surface air temperatures (Parthasarathy, 1984; Verma et al., 1985).

The inferences drawn from the above studies generally indicate that the Indian monsoon rainfall is related to many regional and global circulation features and that for a stable correlation, time series of data of length 30 years or more is essential. It is an emerging scientific opinion that the relationship between the onset, active, break and withdrawal phases of the monsoon and the low frequency modes need to be studied in detail for a better understanding of interannual variability of monsoon (Shukla, 1985; Parthasarathy and Pant, 1986). The low frequency signals representing the episodic changes in monsoon behaviour may provide information on slowly changing modes otherwise masked by the high frequency fluctuations. Therefore, an attempt has been made in this paper to examine the relationship between the low frequency components of the Indian summer monsoon rainfall and other regional and global parameters using cubic spline smoothing technique on the data series of the longest available period.

II. DATA

To study the long-term variations by the cubic spline smoothing technique, it is desirable that the longest available homogeneous data series are considered. Therefore, the Indian summer monsoon rainfall for the period 1871–1985 has been considered in this study. For the other parameters, the longest available data series lying within the period 1871–1985 have been considered. In selecting the seasonal or monthly mean values of some data, the availability of long and reliable series relevant to the monsoon system is only considered and, since the prediction aspects of monsoon rainfall are not intended to be examined, many series are concurrent with monsoon season.

(1) *All-India summer monsoon rainfall*

A long homogeneous summer monsoon (June to September) rainfall series has been prepared by Mooley and Parthasarathy (1984a) and Parthasarathy et al. (1987) for the period 1871–1984 for the country as one unit (All-India series) as well as various subdivisions. They considered a fixed number of 306 raingauges and gave an appropriate area-weighted to each of the raingauges throughout the period of study. The All-India rainfall series has been updated to 1985 (Parthasarathy and Pant, 1986).

(2) *Date of onset of Indian summer monsoon*

The date of onset of the southwest monsoon over the Indian peninsula is determined on the basis of a sharp increase and characteristic persistence in the rainfall over the South Kerala coast. The onset depends on a series of earlier events such as the change in the circulation pattern and on the heat and moisture content of the atmosphere over the Arabian Sea. The date of onset of monsoon is determined by the India Meteorological Department (IMD) on a real-time basis, and may have some amount of subjectivity. However, subsequent determinations of the onset using objective criteria (Ananthakrishnan and Soman, 1987) also resulted in series of similar nature in terms of mean as well as variability. The onset of monsoon over Kerala, though may appear to be of local character, is generally considered to be a pointer for the advancement of monsoon over India. For example, Deshpande et al. (1986) found that the anomalies in the dates of onset were similar at Kerala and Bombay on 70% of the occasions. The normal date of onset is 31st May; however, it varies from 11th May to 15th June. The tabulated values of these dates are obtained from the publications of Ramdas et al. (1954), Ananthakrishnan et al. (1979) and Parthasarathy and Pant (1986) for the period 1891–1985.

(3) *Storms and depressions in Bay of Bengal and Arabian Sea during monsoon*

The cyclonic storms and depressions in the Bay of Bengal and Arabian Sea during monsoon (June-September) are not as frequent and intense as their post and pre-monsoon counterparts. However, since the embedded vortices are an important element of monsoon cyclogenesis, their number and frequency are considered to help the monsoon system to establish as they move across the country. The data on the number of storms and depressions in Bay of Bengal and Arabian Sea are obtained from the publication of the India Meteorological Department (1979) for the period 1877–1970 and updated for the period 1971–1985 from the recent weather charts.

(4) *Number of break-monsoon days in July and August*

The monsoon over India is in general vigorous and active over the entire country during the months of July and August each year. During this period, on several occasions, situations characterised by cessation of rain and disappearance of monsoon like synoptic conditions occur. This intervening dry period in most parts of the country except the Himalayan foothills, between two active spells of monsoon is referred to as the break-monsoon. The number of break-monsoon days in the months of July and August of each year for the period 1888–1965 are obtained from the study of Ramamurthy (1969) and the series is updated to 1985 from the recent records of the India Meteorological Department.

(5) *Southern Oscillation Index*

Wright (1975) prepared an index of the Southern Oscillation, based on the seasonal mean sea-level pressure data at eight tropical stations, namely, Cape Town, Bombay, Djakarta, Darwin, Adelaide, Apia, Honolulu and Santiago. He performed principal components analysis on homogeneous series of 50 values (1896–1945) of the seasonal mean pressures at these eight stations and standardized the time series of the coefficients of the first eigenvector. The series were then extended back to 1851 and forward to 1975. The resulting combined series consisting of dimensionless numbers are homogeneous and represent adequately the Southern Oscillation in each season (Wright, 1977; Fleer, 1981). A high index corresponds to high atmospheric pressure in the South-east Pacific Subtropical high and to low pressure in the Malayan-Indonesian low. The data on Wright's index of Southern Oscillation for the season June-July-August (JJA) during the period 1871–1974 have been used in the present study.

(6) *East Equatorial Pacific sea-surface temperature anomalies*

The East equatorial Pacific SST anomaly values, averaged over the area bounded by 0°–10°S and 90°–180°W are available for a considerably long period, 1860–1979 (Angell, 1981). From these series, the data for the season JJA during the period 1871–1979 have been used in the present study.

(7) *Northern Hemispheric surface-air temperature*

The long homogeneous series of Northern Hemispheric surface-air temperature anomalies for the month of January for the period 1871–1985 has been obtained from the study of Jones (1985).

III. CUBIC SPLINE SMOOTHING

The cubic spline smoothing technique, specially designed for use in low-frequency signal detection from long tree-ring data series, is used in the present study. The computer subroutines and algorithms of the cubic spline used are those developed at the Lamont-Doherty Geological Observatory, Columbia University, USA (Cook and Peters, 1981; Peters and Cook, 1981).

The cubic spline is basically a concatenation of cubic polynomial segments that are joined together at their ends or knots. The continuity of the first and second derivatives assures that the segments are joined in a very smooth fashion (Reinsch, 1967; Wold, 1974). When the behaviour of the data series in one region is not much related to its behaviour in the other region the spline smoothing is the best choice, since polynomials and many other mathematical functions possess the property that their behaviour in a small region determines their behaviour everywhere.

The smoothing spline minimizes the total squared curvature,

$$\int_{x_0}^{x_n} [g''(x)]^2 dx, \tag{1}$$

under the constraint

$$\sum_{i=0}^{n} \left[\frac{g(x_i) - Y_i}{\delta Y_i} \right]^2 \leqslant s, \tag{2}$$

where $g(x)$ is the fitting function of the spline, $g''(x)$ is its second derivative, Y_i is the input series, δY_i is a series of weights and S is a scaling parameter. The use of cubic spline as a symmetric low-pass digital filter with a continuous range of frequency response functions along with its time and frequency domain properties are discussed by Cook and Peters (1981), Peters and Cook (1981) and Blasing et al. (1983). The frequency response function of the form

$$u(f) = 1 - \frac{1}{1 + \dfrac{p(\cos 2\pi f + 2)}{6(\cos 2\pi f - 1)^2}} \tag{3}$$

is obtained after Fourier transforming the matrix operations of computing the spline. Here, f is the required frequency and p is computed for a spline which has a 50% response at a specified frequency, using the relation (for $u(f) = 0.5$),

$$p = \frac{6(\cos 2\pi f - 1)^2}{(\cos 2\pi f + 2)} . \tag{4}$$

The frequency response functions are shown in Fig. 1.

A spline is selected for use as a filter based on its frequency response, which is related to the percentage of variance at each frequency that will remain with the filtered series. The frequency at which 50% of the variance is retained in the series and rest of the variance is distributed according to the selected response curve (Fig. 1) is referred to as the 50% variance reduction frequency (50% VRF).

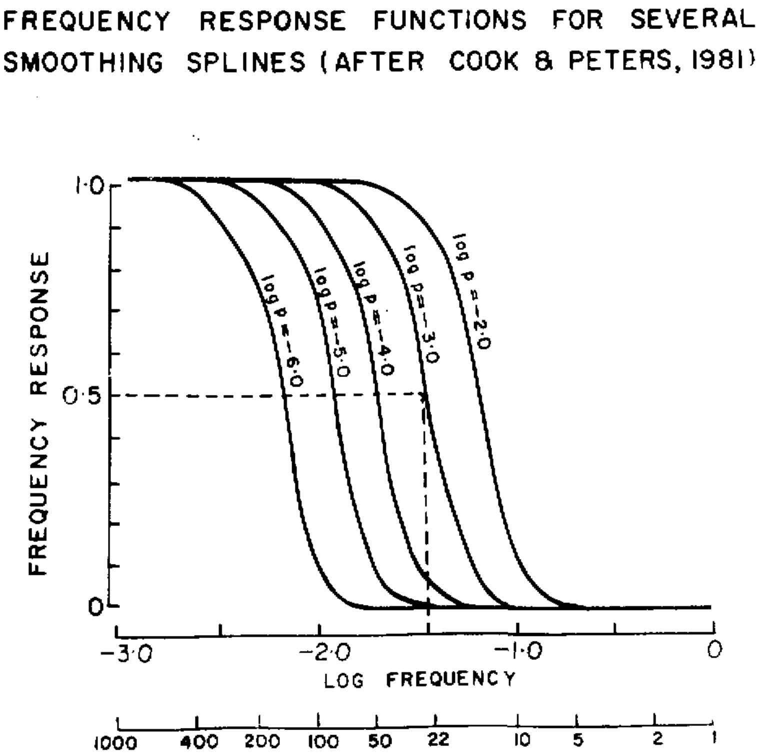


Fig. 1. Frequency response functions for several smoothing splines (after Cook and Peters, 1981).

IV. RESULTS AND DISCUSSION

The low frequency signals of the above mentioned seven data sets have been computed for 50% VRF of one cycle per 10, 20 and 30 years. It is observed that a high degree of smoothing is achieved with a spline having 50% VRF at periods of 30 years and above. Smoothing splines with 50% VRF at a period of 30 years, superimposed on the original series, are presented in Figs. 2 through 8, for all the seven data sets. It can be seen from Fig. 2 that the All India monsoon rainfall series, upon smoothing, clearly shows the 4 distinct epochs, two of excess rainfall (before 1896 and 1932–1963) and two of deficit rainfall (1897–1931 and after 1964). These epochs are similar to those pointed out by Mooley and Parthasarathy (1984a). The smoothed curves of the date of onset of the monsoon (Fig. 3), storms and depressions (Fig. 4) and break monsoon days (Fig. 5) also show an episodic type of variation. These are consistent with the epochs in the All-India summer monsoon rainfall, indicating the presence of a common low frequency mode. Wright's Southern Oscillation Index (Fig. 6) as well as the East equatorial Pacific SST (Fig. 7) show a basically oscillatory nature, but persisting around the mean. The Northern Hemispheric surface-air temperatures (Fig. 8) show the well-known dominant warming during the first half of the 20th century.

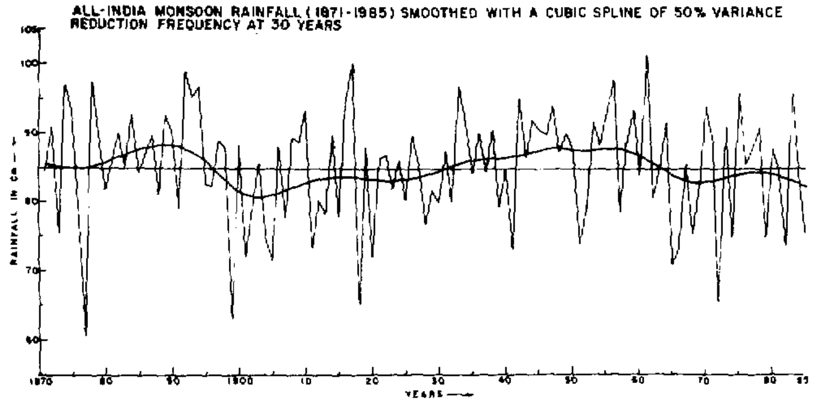


Fig. 2. All-India summer monsoon rainfall (1871–1985) smoothed with Cubic spline of 50% variance reduction frequency at 30 years.

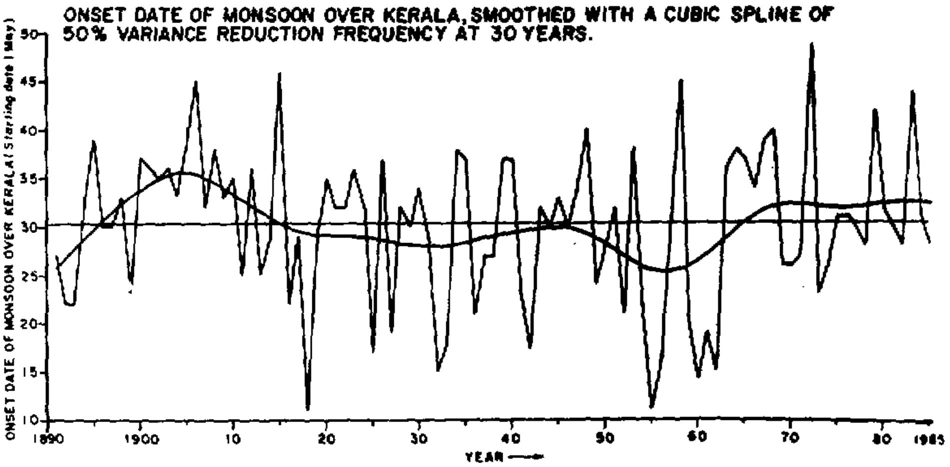


Fig. 3. Onset dates of monsoon over Kerala (1891–1985) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

For a critical examination of the association between the low frequency modes of monsoon rainfall and related parameters, the data sets are divided into two groups. The first group comprises of the time series of the parameters from within the monsoon system; namely, dates of onset of monsoon, number of storms and depressions during monsoon in the Bay of Bengal and Arabian Sea and break-monsoon days in July and August. The second group consists of the parameters with established teleconnections with monsoon but basically outside the monsoon system; they include the Southern Oscillation Index, Northern Hemispheric surface-air temperature anomaly for January and the SST anomaly for the

NUMBER OF STORMS / DEPRESSIONS DURING MONSOON (JUNE - SEPTEMBER) IN ARABIAN SEA AND BAY OF BENGAL, SMOOTHED WITH A CUBIC SPLINE OF 50% VARIANCE REDUCTION FREQUENCY AT 30 YEARS

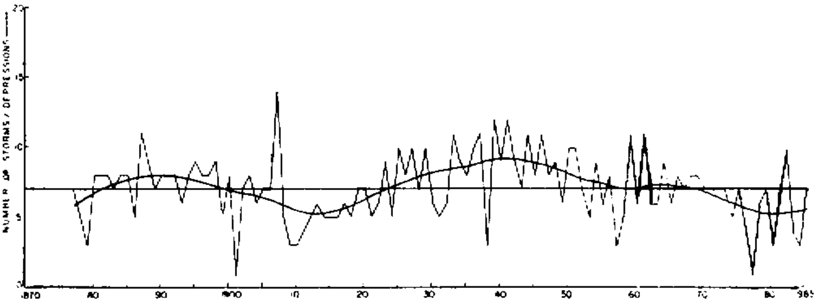


Fig. 4. Number of storms/depressions during monsoon in the Bay of Bengal and Arabian Sea (1877–1985) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

BREAK MONSOON DAYS IN JULY AND AUGUST, SMOOTHED WITH A CUBIC SPLINE OF 50% VARIANCE REDUCTION FREQUENCY AT 30 YEARS.

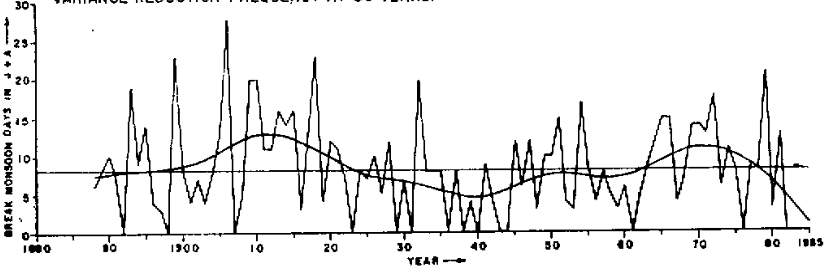


Fig. 5. Number of break-monsoon days in July and August (1888–1985) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

WRIGHT'S SOUTHERN OSCILLATION INDEX (JJA), SMOOTHED WITH A CUBIC SPLINE OF 50% VARIANCE REDUCTION FREQUENCY AT 30 YEARS.

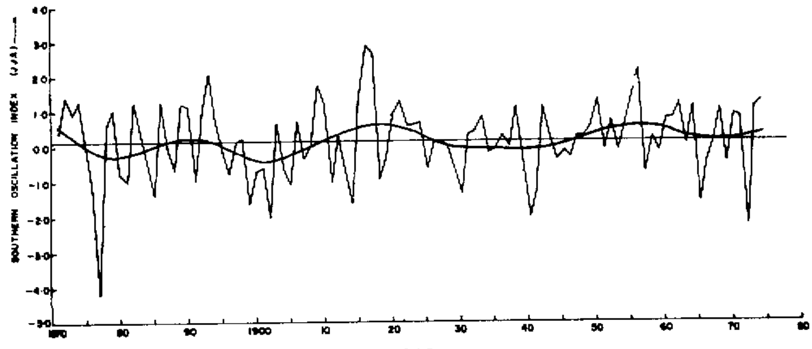


Fig. 6. Wright's Southern Oscillation Index(JJA) (1871–1974) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

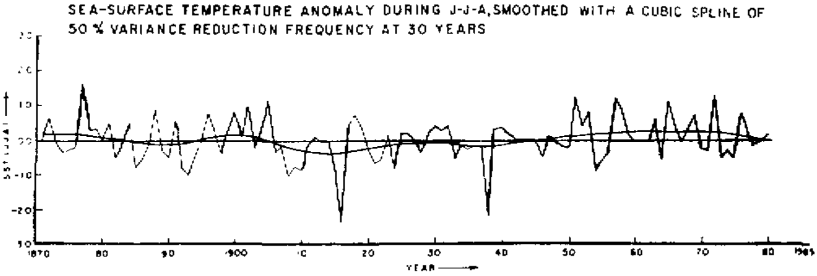


Fig. 7. East equatorial Pacific sea surface temperature (JJA) (1871–1980) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

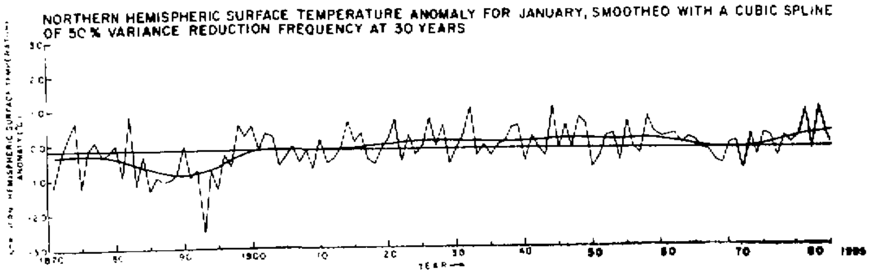


Fig. 8. Northern Hemispheric surface air temperature anomaly for January (1871–1985) smoothed with cubic spline of 50% variance reduction frequency at 30 years.

eastern equatorial Pacific region. The smoothed curves(50% VRF at 30 years) of these parameters are standardized (departure from mean divided by standard deviation) and plotted along with the standardized spline of All-India rainfall, with their zero value lines superimposed. Figs. 9 and 10 show the two groups of the smoothed curves. The excess and deficient All-India rainfall epochs are marked in the curve by shading the areas between its standardized curve and the zero line. An examination of the smoothed parameters and their intercomparison suggests that the removal of the high frequency fluctuations brings out a distinct relationship among the residual low frequency signals. Fig. 9 shows that the excess rainfall epochs are associated with a positive anomaly of number of storms and depressions and a negative anomaly in the onset date of monsoon and break monsoon days; opposite situations are seen for the deficient monsoon rainfall epochs. Joseph (1976) pointed out that the epochs of good and bad monsoon years are associated with distinctly different regional circulation features. A feature of particular interest is that all the curves (Fig. 9) almost simultaneously change their signs before (around 1896) and after (around 1964) one full cycle of poor and good monsoon epochs. This indicates that all these variables have a common slowly varying component. Though these relations are physically consistent and rather obvious, since more storms and depressions, less break days and early arrival of monsoon may bring excess rains, the raw series of data do not exhibit a clear relationship. There are many years when the relations discussed above are opposite and the extremes may not tally on many occasions for individual years.

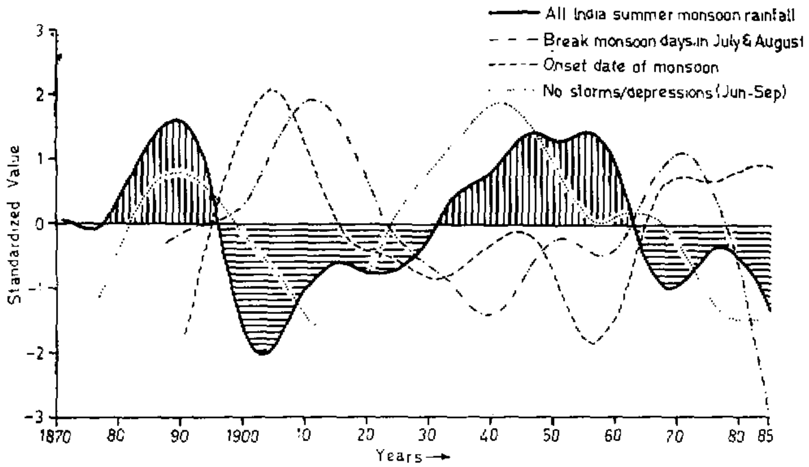


Fig. 9. Standardized low frequency signals in the time series (smoothed with a cubic spline of 50% VRF at 30 years) of monsoon rainfall and related variables within the monsoon system.

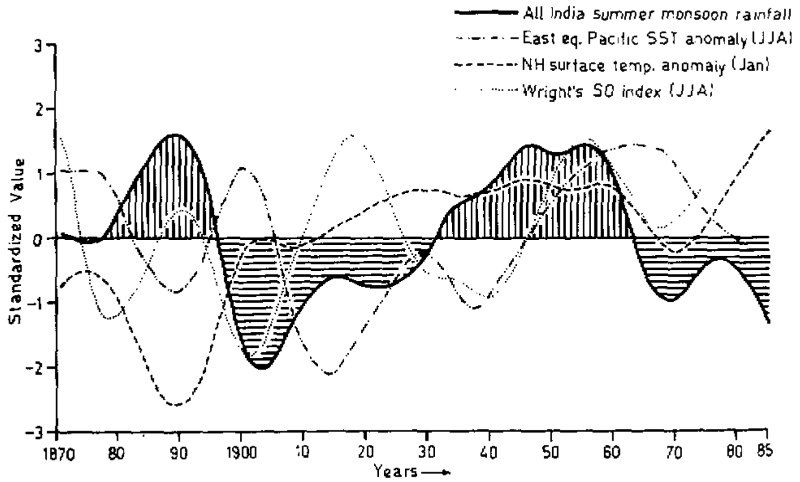


Fig. 10. Standardized low frequency signals in the time series (smoothed with a cubic spline of 50% VRF at 30 years) of monsoon rainfall and related variables outside the monsoon system.

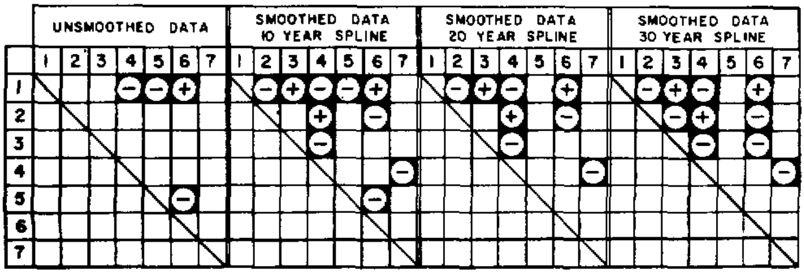
The parameters in the second group, though outside the monsoon system, are known to have significant correlations with the Indian summer monsoon rainfall and are believed to have some predictive capabilities for monsoon rainfall. However, the stability of such relationships over long periods of time has not been encouraging. The low frequency variations in these parameters with reference to those in the rainfall (Fig. 10) also show that the association between them is not consistent over the full period (1871–1975) considered. This is particularly conspicuous in the case of the Northern Hemispheric surface-air temperature anomaly for January, which shows a direct association with rainfall only after 1935. This could be one of the reasons for the high correlations during 1931–1980 and poor correlations during the earlier period, obtained by Verma et al. (1985) between the Indian summer monsoon rainfall and Northern Hemispheric surface-air temperatures of January and February. In this situation, it is useful to study the low frequency signals in the long time series in a stepwise manner, in order to examine the change of phase which reversed the trend of significant correlations.

The correlations among the parameters after successive smoothings are summarized in Fig. 11, in which the correlation values significant at 1% level for the common period 1891–1974 are marked by the sign of the correlation in appropriate locations. For a purely random series, the less significant correlations among the two series are expected to attain significance after smoothing due to increased autocorrelations, but this is not observed as a rule in the present analysis. Many series which are not correlated significantly with unsmoothed data show a significant correlation only for a specific degree of smoothing and for some parameters the significance is lost after certain degree of smoothing. The physical explanation for the behaviour of these series can be located within the time scales of dominant

INTERCORRELATIONS AMONG THE PARAMETERS 1 TO 7
DATA SERIES 84 YEARS (1891–1974)

BOXES WITH SIGNIFICANT CORRELATIONS (AT 1% LEVEL) ARE INDICATED WITH THE SIGN OF CORRELALATION

INDICATOR NUMBER —	PARAMETER
1	ALL INDIA SUMMER MONSOON RAINFALL
2	DATE OF ONSET OF MONSOON OVER SOUTH KERALA
3	NUMBER OF STORMS/DEPRESSIONS IN BAY OF BENGAL & ARABIAN SEA (JJAS)
4	BREAK MONSOON DAYS IN JULY & AUGUST
5	SST ANOMALY OF EAST PACIFIC JJA
6	WRIGHT'S SOUTHERN OSCILLATION INDEX FOR JJA
7	*NORTHERN HEMISPHERIC SURFACE TEMPERATURE ANOMALY IN JANUARY*



	UNSMOOTHED DATA							SMOOTHED DATA 10 YEAR SPLINE							SMOOTHED DATA 20 YEAR SPLINE							SMOOTHED DATA 30 YEAR SPLINE						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1	╲			⊖	⊖	⊕		╲	⊖	⊕	⊖	⊖	⊕		╲	⊖	⊕	⊖		⊕		╲	⊖	⊕	⊖		⊕	
2		╲							╲		⊕		⊖			╲		⊕		⊖			╲	⊖	⊕		⊖	
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Fig. 11. Intercorrelations among monsoon rainfall and related variables with various degrees of smoothing during the period 1891–1974.

variations in these parameters. A logical relationship between the late and early arrival of monsoon with the less or more net rainfall during the season and in the same manner between the number of storms and depressions and the rainfall is conspicuously absent in the unsmoothed data but the correlations become significant after smoothing, thus pointing out that these signals basically refer to the long-term mean monsoon condition. The Wright's Southern Oscillation Index persistently retains the significance of correlations in stepwise smoothing but the correlation coefficient value goes on decreasing, with highest value of +0.58 for the raw data. The correlation between the Southern Oscillation Index and SST anomaly of East equatorial Pacific is −0.62 and its magnitude decreases sharply after smoothing and loses its statistical significance after smoothing with a spline having 50% VRF of 10 years and above. This relationship suggests that the mechanism involved in feedback coupling between the Southern Oscillation, SST and monsoon rainfall is dominating in interannual scale and that the signal may damp out in decadal scale (scale of Southern Oscillation is 3-6 years). The January Northern Hemispheric mean temperature anomaly for 1891–1974 shows poor correlation and the only significant correlations appearing in the smoothed data series is with break-monsoon days in July and August.

V. CONCLUSIONS

The study demonstrates the applicability of cubic spline smoothing to examine the association of the low frequency variations in monsoon rainfall and several local and teleconnected climatic parameters. The results indicate that the parameters generally used to describe the Indian summer monsoon behaviour comprise a common slowly varying component in an episodic manner, as can be seen from the significant association of the low frequency variations of rainfall with those of date of onset, number of storms and depressions and break-monsoon days. However, the physical mechanisms relating the Southern Oscillation and the equatorial Pacific SST and their dynamical links with the Indian monsoon are very complex and not well understood; results of this study may only indicate that these relations may be dominant in the interannual scale. The low frequency variations are found to have significantly contributed to the instability of correlations of monsoon rainfall with the parameters outside the monsoon system over long periods of time. The physical causes underlying these changes may be associated with the interacting land/ocean/atmosphere processes which may unfold only after the ocean-atmosphere coupled models are successfully simulated to the relevant time scales.

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