Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 94, No. 3, November 1985, pp. 199–210.

Relationship between all-India summer monsoon rainfall and southern oscillation/eastern equatorial Pacific sea surface temperature

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MS received 24 November 1983; revised 15 March 1985

Abstract. The interannual variability of all-India summer monsoon (June to September) rainfall and its teleconnections with the southern oscillation index (SOI) and sea surface temperature (SST) anomaly of the eastern equatorial Pacific ocean have been examined for the period 1871–1978 for different seasons (i.e., winter, spring, summer and autumn). The relationship (correlation coefficient) between all-India summer monsoon rainfall and SOI for different seasons is positive and highly significant. Further examination of 10-, 20- and 30-year sliding window lengths' correlations, brings out the highly consistent and significant character of the relationships. The relationship between all-India monsoon rainfall and SST for different seasons is negative and is significant at 1 % level or above. Drought years are characterised by negative anomalies of SOI and positive anomalies of SST and vice versa with flood years. The relationship between SOI and SST is negative and significant at 0.1 % level.

The relationships between all-India summer monsoon rainfall, SOI and SST are expected to improve our understanding of the interannual variability of the summer monsoon.

Keywords. All-India rainfall; southern oscillation; Pacific sea surface temperature; sliding correlation.

1. Introduction

The agricultural economy of India with its large growing population is closely linked with the summer monsoon (June to September) which gives 75 to 90 % of the annual rainfall. The Indian summer monsoon is rightly described as the life and soul of the country because the livelihood of a large part of the country depends upon timely and adequate rains. Monsoon rainfall exhibits considerable year-to-year variations in its occurrence and sometimes produces calamities like droughts and floods. The large-scale behaviour of the monsoon over the Indian sub-continent can be regarded as an important manifestation of a planetary-scale phenomenon. The southern oscillation (SO) is one of the most important single mechanisms, especially in the tropical zone of the Pacific and Indian ocean sectors, responsible for fluctuations of the atmospheric circulation with climatic variations of irregular period about one to five years. Growing interest in understanding and in estimating the monsoon rainfall over India has recently resulted in many studies on the possible relationship between the amount and the distribution of the Indian monsoon rainfall with antecedent regional and global circulation features. A revival of interest in the SO and the related SST, El Nino phenomenon has occurred recently in connection with the identification of climatic regimes and atmospheric teleconnections. In view of this a detailed study has been made between the interannual variations of Indian summer monsoon rainfall and southern oscillation and east equatorial sea surface temperature during the period 1871–1978.

2. Details of data

2.1 *Indian summer monsoon rainfall*

306 stations, one from each of the districts in the plain regions of India and distributed fairly uniformly over the country were selected to form the network of raingauge stations used in this study. The relevant rainfall data for the selected raingauge stations were collected from the records of the Additional Director General of Meteorology (Research), Poona (for details of data refer Mooley *et al* 1981, 1984). These stations have rainfall data from 1871 onwards. The hilly region of the country parallel to the Himalayan mountain range has not been considered in view of meagre raingauge network, and low areal representation of a raingauge in a hilly area. The area considered measures $2{\cdot}88 \times 10^6$ km^2 which is about 90% of the country. Summer monsoon season (June to September) area-weighted rainfall series was prepared for India as one unit (to be referred to as all-India series) by assigning district area as the weight for each raingauge station for the period 1871–1978. These summer monsoon rainfall data series for the period 1871 to 1978 have been utilized in the present study and is shown in figure 1. The mean all-India summer monsoon rainfall is 85·31 cm and it is 78% of the annual amount. The standard deviation of the series is 8·29 cm and coefficient of variation, 9·5%. Swed and Eisenhart's test of runs above and below the median shows that the series is homogeneous. The auto-correlation of the series is −0·116 which is too low to suggest any persistence in the series. Chi-square test indicates that the rainfall series, 1871–1978, is normally distributed (for further details refer Mooley and Parthasarathy 1984; Parthasarathy 1984).

2.2 *Southern oscillation index* (SOI)

The southern oscillation is an important mode (circulation) of the tropical atmosphere generally characterized by the exchange of air between the eastern (predominently land) and western (predominently ocean) hemispheres; the sea level pressure anomalies in the Indonesian–Australian region are negatively correlated with those in the southeast Pacific ocean high pressure belt. The term southern oscillation (SO) was first introduced by Walker and Bliss (1932, 1937). It is an important tropical circulation and is named by Bjerknes (1969) as east-west Walker circulation. A number of studies have been made to explore the relationship between the Indian summer monsoon rainfall and SO by many workers. Some of the noteworthy studies in this direction are Walker (1923, 1924), Troup (1965), Sikka (1980), Angell (1981), Pant and Parthasarathy (1981), Mooley and Parthasarathy (1983b) and Parthasarathy and Pant (1984, 1985).

Wright (1975) devised a pressure index, called the southern oscillation index (SOI), making use of sea level pressure data of eight stations (Capetown, Bombay, Djakarta, Darwin, Adelaide, Apia, Honolulu and Santiago) in the latitude zone of 30°S to 20°N. This index is considered to meet the requirement of an estimator of the tropical east-west circulation (Fleer 1981) and to interpret well the behaviour of the SO in every season for the period 1851 to 1974 and we have made use of this series in the present study.

The monthly SOI series for the period 1871–1974, have been combined into standard seasons relative to Indian summer monsoon, June, July, August and September (JJAS) as

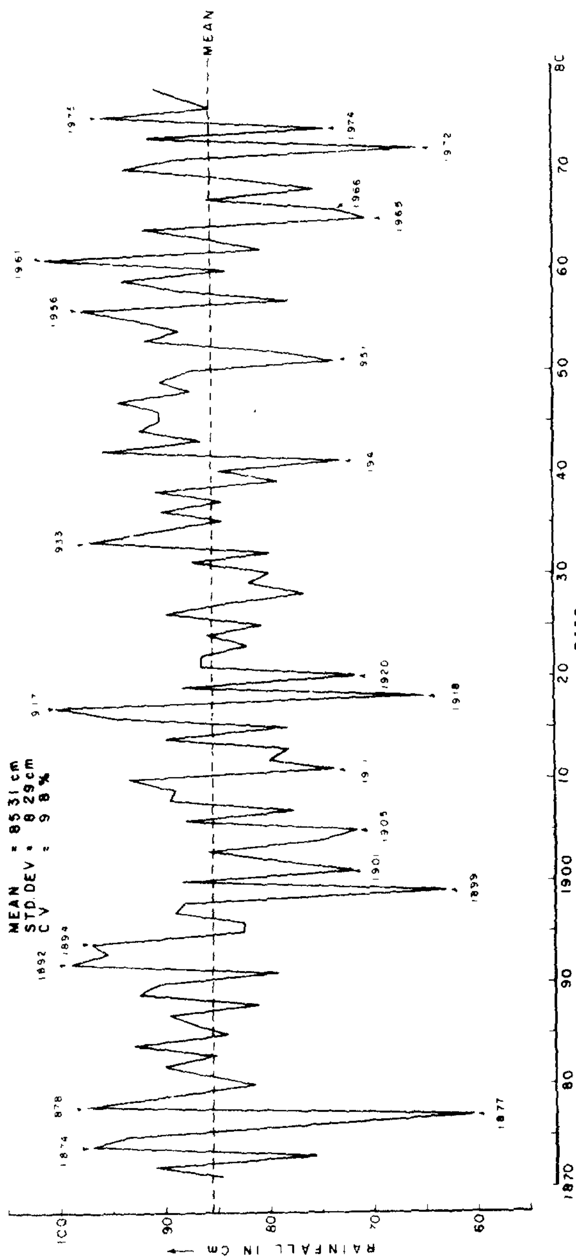

Figure 1. Summer monsoon (June to September) rainfall of India taken as one unit during 1871–1978

follows: (i) the winter season, SOI-DJF, two seasons earlier to monsoon (lag − 2), (ii) the spring season, SOI-MAM, one season earlier to monsoon (lag − 1), (iii) the summer monsoon season, SOI-JJA, concurrent monsoon season (lag 0), (iv) the autumn season, SOI-SON, one season after monsoon (lag + 1) and (v) the succeeding winter season SOI-DJF, two seasons after monsoon (lag + 2). The SOI series i.e. SOI-DJF, SOI-MAM, SOI-JJA and SOI-SON have been examined for homogeneity by Swed and Eisenhart's test and the series are generally found to be homogeneous at 5% level. The auto-correlations of these series do not indicate any persistence.

2.3 *Sea surface temperature (SST) anomalies in the equatorial eastern Pacific ocean*

The interaction between the atmosphere and the sea at the air-sea interface results in the coupling of the circulation systems of the atmosphere and the ocean. Since 70% of the earth's surface is covered with water and changes in SST are much slower compared to the atmospheric fluctuations, it is obvious that the interannual variability of SST may be responsible for the variability of the atmospheric circulation and may reflect well in the rainfall regimes.

Studies by Khandekar (1979), Weare (1979), Joseph (1981), Pisharoty (1981), Anjaneyulu (1981), Ramesh Babu *et al* (1981), Webster (1981), Newell *et al* (1982) and Rasmusson and Carpenter (1982), have brought out the role of SST in tropical and equatorial oceans in modifying the atmospheric circulation and in the distribution of cloudiness and precipitation. Bjerknes (1969), Rowntree (1972), Shukla (1975), Julian and Chervin (1978) and Keshavamurthy (1982), used general circulation models to study the response of the atmosphere to a fixed SST anomaly in the tropical Pacific and have shown that the atmosphere is much more closely coupled to the state of the underlying ocean in the tropics. Therefore, it is proposed to examine the relationship between the all-India summer monsoon and SST anomaly of different seasons for eastern equatorial Pacific ocean.

Angell (1981) has prepared the seasonal SST anomaly values, which are averaged over the wide area of 0–10°S; 180–90°W of the equatorial Pacific ocean and which are available for the long-period from 1860 to 1979. We have utilized these data to examine the relationship with Indian monsoon rainfall. The SST anomaly series for different seasons i.e. SST-DJF, SST-MAM, SST-JJA and SST-SON, for the period 1871–1978 have been examined for homogeneity. These have been found to be homogeneous at 5% level. There is no persistence noticed in the series.

3. Relationship with All-India summer monsoon rainfall

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

Persistence or high auto-correlation in the individual series should be considered while assessing the significance of cross-correlation between concurrent series (Quenouille 1952; Scirremammano 1979). It is already seen from the earlier sections that there is no persistence in any of the series considered and therefore there is no change in the degrees of freedom involved in assessing the significance of correlation coefficient (CC) between the two data series, that is $(N-2)$, where N is the number of years.

3.1 *Southern oscillation*

The CC between all-India rainfall series and SOI for the different seasons are given in table 1. The CC values for all seasons (except for SOI-DJF) are positive and significant at 0·1 % level showing an excellent relationship between the series for the whole period (104 years). This relationship continues to be excellent in the two halves of the series for SOI-JJA and SOI-SON seasons. However, for the SOI-MAM season in the first half of the series i.e. 1871–1922, the CC value is significant at 1 % level, whereas for the second half, 1923–1974 period, the significance is at 5 % level.

Consistency of the relationship for different periods of the series is examined by calculating the variations of the CC by the sliding window method (Bell 1977) using window widths of 10, 20 and 30 years. The highest and lowest CC noticed during different widths are shown in table 2. Sliding CC of 10-year width are highly fluctuating and the highest CC (more than 0·9 for JJA and SON seasons) is generally significant at 5 % or above. 20-year sliding window CC are less fluctuating compared to the 10-year width and highest CC are significant at 1 % level or above. 30-year sliding window length brings out the highly consistent and significant character of the relationships. These curves are shown in figure 2. The CC significant at 1 % level is indicated in the figure by a dashed line. It is seen from figure 2 that the CC for SOI-MAM season during the years 1881–95 period are high and significant at 1 % level. For SOI-JJA the CC are significant at 1 % level during the first half period of the series and oscillatory afterwards. For SOI-SON season the CC are significant at 1 % level or above throughout the period; this indicates the stability of the relationship.

Having seen the consistently significant relationship between SOI and all-India summer monsoon rainfall, it was decided to examine the values of Wright's SOI in extreme years i.e., in years of large-scale drought and flood. In order to identify the years of abnormal performance of the monsoon (i.e. droughts/floods), the criteria based on standard deviate, $t_i = (R_i - \bar{R})/\sigma$ has been adopted (for details of method refer to Mooley and Parthasarathy 1983a, 1984) and used here. It is already shown that all-

Table 1. Correlation coefficient between all-India summer monsoon rainfall and Wright's (1975) SOI for different seasons

SOI season	104 years (1871–1974)	52 years (1871–1922)	52 years (1923–1974)
DJF (lag − 2)	0·046	0·082	−0·293*
MAM (lag − 1)	0·357***	0·412***	0·288*
JJA (lag 0)	0·616***	0·671***	0·525***
SON (lag + 1)	0·694***	0·734***	0·629***
DJF (lag + 2)	0·552***	0·566***	0·523***

***Significant at 0·1 % level; **significant at 1 % level; *significant at 5 % level

Table 2. Highest and lowest CC between all-India summer monsoon rainfall and SOI for different seasons and with different sliding window widths

No. of years		SOI for preceding MAM (lag − 1)		SOI for concurrent JJA (lag 0)		SOI for succeeding SON (lag + 1)		Significant table values at		
		Period	CC	Period	CC	Period	CC	* 5%	** 1%	*** 0·1%
10	Highest	1940–49	+0·746*	1874–83	+0·927***	1874–83	+0·981***	0·63	0·76	0·87
	Lowest	1942–51	−0·529	1944–53	−0·164	1919–28	+0·188			
20	Highest	1905–24	−0·608**	1974–93	+0·862***	1974–93	0·885***	0·44	0·56	0·68
	Lowest	1919–38	−0·030	1919–38	−0·219	1919–38	+0·421			
30	Highest	1888–1917	+0·547**	1874–1903	+0·811***	1871–1900	+0·839***	0·36	0·46	0·57
	Lowest	1923–52	+0·054	1919–48	+0·317	1919–48	+0·496**			

***Significant at 0·1 % level; **significant at 1 % level; *significant at 5 % level

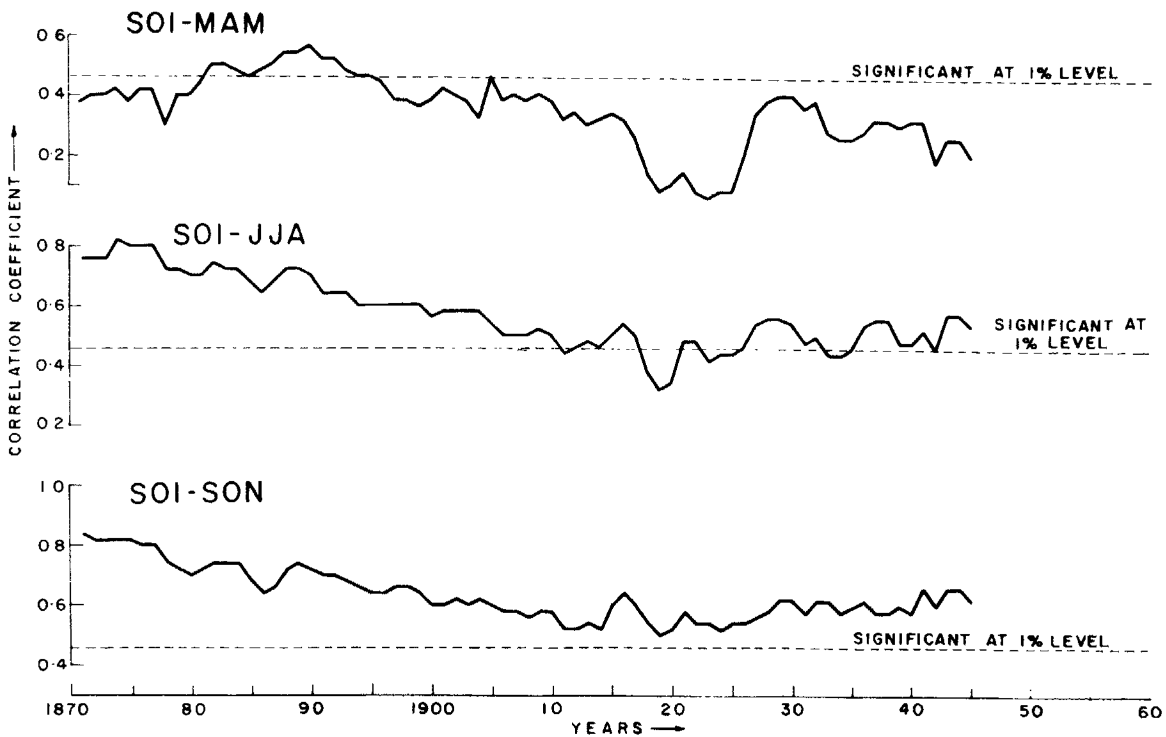

Figure 2. Variation of correlation coefficient between all-India summer monsoon rainfall and Wright's (1975) SOI of different seasons with 30-year sliding window width over the period 1871–1974.

India rainfall series is Gaussian distributed and the t_i values -1.28 and $+1.28$ indicate 10th and 90th percentile of the standard normal (Gaussian) distribution, and $R_i > 1.28$ and $R_i < -1.28$ have been taken as large-scale flood and drought years respectively. With these criteria 13 large-scale drought years and 9 large-scale flood years have been identified during the period 1871–1978. The drought years are 1877, 1899, 1901, 1905, 1911, 1918, 1920, 1941, 1951, 1965, 1966, 1972 and 1974; flood years are 1874, 1878, 1892, 1894, 1917, 1933, 1956, 1961 and 1975. These large-scale drought/flood years are marked suitably on the all-India summer monsoon rainfall curve in figure 1. On examination of SOI values for different seasons, it is seen that in the years of large-scale drought, SOI is invariably negative and in the years of large-scale flood it is positive. The composite means for the groups of large-scale drought (flood) years are given below.

Wright's SOI (composite mean) for different seasons

	SOI values for different seasons				
large-scale	lag − 2 DJF	lag − 1 MAM	lag 0 JJA	lag + 1 SON	lag + 2 DJF
drought years	−0·08	−0·45	−1·00	−0·73	−0·53
flood years	+0·27	+0·76	+1·23	+1·53	+0·78

The contrast for the concurrent and the succeeding seasons is much more than that for preceding seasons.

3.2 *Sea surface temperature (SST) anomalies in the equatorial eastern Pacific ocean*

The CC between all-India monsoon rainfall and SST anomaly series for the whole as well as two halves of the series for different seasons of SST have been calculated and it is found that there is strong negative correlation. These CC values along with significance levels are given in table 3, the main points are (a) the inverse relation between monsoon rainfall and SST anomaly is significant at 0·1 % level for concurrent JJA and succeeding SON seasons for the whole series as well as each of the two halves of the series and (b) the relationship for the preceding MAM season is significant at 5 % level only for the whole series and the first half of the series but not for the second half of the series.

Table 3. Correlation coefficient between all-India summer monsoon rainfall and equatorial Pacific sea surface temperature (SST of Angell 1981)

SST season	108 years (1871–1978)	54 years (1871–1924)	54 years (1925–1978)
DJF (lag − 2)	0·079	0·025	0·132
MAM (lag − 1)	−0·217*	−0·293*	−0·167
JJA (lag 0)	−0·475***	−0·467***	−0·521***
SON (lag + 1)	−0·600***	−0·656***	−0·555***
DJF (lag + 2)	−0·577***	−0·654***	−0·522***

***Significant at 0·1 % level; **significant at 1 % level; *significant at 5 % level

Consistency of the relationship for different periods is examined by calculating the CC by sliding window method of widths 10, 20 and 30 years. The results for the highest/lowest CC are given in table 4. For 10- and 20-year sliding windows the fluctuations are greater compared to the 30-year window. The highest observed CCs are generally significant at 5 % or above. Consistent significant CCs are noticed for 30-year window widths series; these are shown in figure 3. For the SST-MAM series none of the CCs are significant at 1 % level. In the SST-JJA series the CC for the period 1895–1940 are low and not significant. For SST-SON highly significant CC are noticed up to the year 1910 and after 1940.

We have examined the SST anomaly values during large-scale drought/flood years. The mean values for the two groups of years are given in the following table.

Angell's SST (composite mean) for different seasons

	SST values for different seasons				
large-scale	lag − 2 DJF	lag − 1 MAM	lag 0 JJA	lag + 1 SON	lag + 2 DJF
drought years	+0·13	+0·33	+0·48	+0·88	+1·01
flood years	−0·03	−0·36	−0·26	−0·64	−0·61

Table 4. Highest and lowest CC between all-India summer monsoon rainfall and SST for different seasons and with different sliding window widths.

No. of years		SST for preceding MAM (lag − 1) Period	CC	SST for current JJA (lag 0) Period	CC	SST for succeeding SON (lag + 1) Period	CC
10	Highest	1922–31	+0·547	1878–87	0·384	1903–11 1904–12	+0·005
	Lowest	1901–10	−0·698*	1964–73	−0·909***	1936–45	−0·945***
20	Highest	1918–37	+0·009	1917–36	−0·249	1903–22	−0·229
	Lowest	1891–1910	−0·617**	1877–96	−0·698***	1926–45	−0·839***
30	Highest	1921–1950	+0·007	1919–48	−0·246	1889–1918	−0·250
	Lowest	1891–1920	−0·430*	1944–73	−0·654***	1919–48	−0·761***

***Significant at 0·1 % level; **significant at 1 % level; *significant at 5 % level

The anomaly is positive for drought years and the positive value is greater for succeeding seasons than for concurrent and preceding seasons. For the flood years the anomaly is negative, being smaller for the succeeding seasons than for the concurrent and preceding seasons.

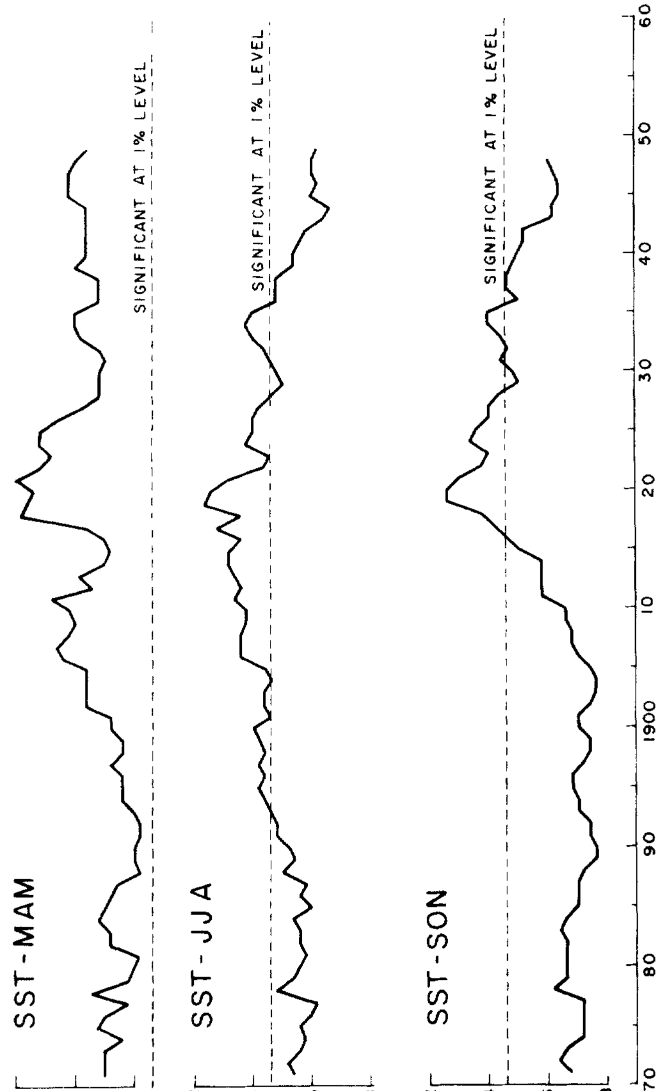

Figure 3. Variation of correlation coefficient between all-India summer monsoon rainfall and SST (Angell 1981) of different seasons with 30-year sliding window width over the period 1871–1978

Table 5. Correlation coefficient between Wright's (1975) SOI and Angelle's (1981) SST for concurrent periods with whole as well as two half periods

Season	104 years (1871–1974)	52 years (1871–1922)	52 years (1923–1974)
DJF (winter)	−0·646***	−0·720***	−0·617***
MAM (spring)	−0·587***	−0·673***	−0·576***
JJA (summer)	−0·617***	−0·653***	−0·587***
SON (autumn)	−0·758***	−0·767***	−0·784***

***Significant at 0·1 % level

Table 6. Correlation coefficient between Wright's (1975) SOI and Angell's (1981) SST for different lags and for the period 1871–1974

SOI \ SST	DJF	MAM	JJA	SON	DJF
DJF	−0·646***	−0·431***			
MAM	−0·566***	−0·587***	−0·501***		
JJA		−0·429***	−0·617***	−0·758***	
SON			−0·558***	−0·758***	−0·767***

***Significant at 0·1 % level

4. Relation between SOI and SST

The association between the different concurrent series of the SOI and SST has also been examined and table 5 gives the CC values. The CC are very high and negative for the whole period as well as the two halves of the series and significant at 0·1 % level. This indicates that SO and SST in the equatorial central Pacific ocean are highly interrelated and related also to the overall evolution of the circulation features of the tropical region. Strong coupling between these features is reflected in the behaviour of the Indian monsoon rainfall.

We have also examined the lag relationships between SOI and SST for the whole period and CC are given in table 6. The relationship is highly significant (0.1 % level) when SOI leads SST by one season.

5. Conclusions

Analysis of all-India summer monsoon rainfall and SOI, SST for the period 1871–1978 has brought out the following results;

(i) The relationship between all-India summer monsoon rainfall with SOI is positive, and that with SST is negative.
(ii) CC between all-India monsoon rainfall and SOI/SST anomaly for JJA and SON seasons for sliding 30-year period show consistency in high significance.
(iii) Drought years are characterised by negative anomalies of SOI and positive anomalies of SST and vice versa for flood years, the values being numerically higher for the concurrent and succeeding seasons.

(iv) SOI and SST are highly interrelated and are also related to the overall evolution of the circulation features of the tropical region.

Acknowledgements

The authors are grateful to Dr Bh V Ramana Murthy, for encouragement and to the Additional Director General of Meteorology (Research), Poona for the rainfall data. They are thankful to Dr J K Angell, NOAA, Air Resources Laboratories, USA for the sea surface temperature anomaly data over the eastern equatorial Pacific ocean. The authors are also thankful to Mr A A Munot and Mr D R Kothawale for help in computations.

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