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Variation in the relationship of the Indian summer monsoon with global factors

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Abstract. Utilizing data for the long period 1871–1990, variation in the relationships between Indian monsoon rainfall (IMR) and tendencies of the global factors. Southern Oscillation Index (SOI) and the sea surface temperature (SST) over eastern equatorial Pacific Ocean has been explored. The periods for which relationships exist have been identified. Tendencies from the season SON (Sept-Oct-Nov) to season DJF (Dec-Jan-Feb) and from DJF to MAM (Mar-Apr-May) before the Indian summer monsoon are indicated respectively by SOIT-2/SSTT-2 and SOIT-1/SSTT-1, current tendency from JJA (June-July-Aug) to SON, by SOITO/SSTTO, tendencies from SON to DJF and DJF to MAM following monsoon, by SOIT1/SSTT1 and SOIT2/SSTT2 respectively.

It is observed that while the relationships of IMR with SSTT-1, SSTTO and SSTT2 exist almost throughout the whole period, that with SOIT-1 exists for 1942–1990, with SOITO for 1871–1921 and 1957–1990 and with SOIT2, for 1871–1921 only. The relationships that exist with SOIT-1, SOIT2, SSTT-1, SSTT2 and with SSTTO (for period 1931–1990) are found to be very good and those that exist with SOITO for periods 1871–1921 and 1957–90 and for SSTTO for the period 1871–1930 are good. It is thus seen that the relationships of SOIT-1, SOITO and SOIT2 with IMR do not correspond well with those of SSTT-1, SSTTO and SSTT2 with IMR respectively, even though SOI and SST are closely related to each other for all the seasons. SOIT-1 and SSTT-1 can continue to be used as predictors for IMR. During the whole period, IMR is found to play a passive, i.e. of being influenced or anticipated by SSTT-1 as well as an active role, i.e. of influencing or anticipating SSTT2. This implies a complex and perhaps non-linear interaction between IMR and SST tendency from DJF to MAM. Possibly, this is a part of the larger interaction between Asian monsoon rainfall and the tropical Pacific. A possible physical mechanism for the interaction is indicated.

Keywords. Indian monsoon rainfall; southern oscillation index; sea surface temperature; correlation coefficient.

1. Introduction

Quinn and Burt (1970) who used Darwin pressure trend for prediction of abnormally heavy precipitation over the equatorial Pacific dry zone found that the Darwin pressure trend could not be used for this purpose during the period 1943–1961 due to breakdown in the relationship.

Ramage (1983) who examined teleconnections, found variation in these over time. He noted breakdown in some of the teleconnections.

Mooley and Parthasarathy (1984a) and Mooley *et al* (1985) studied the variations over time in the relationships of the Indian summer monsoon rainfall (hereafter Indian monsoon rainfall or IMR) with seasonal sea surface temperature (SST) over eastern equatorial Pacific and with seasonal Southern Oscillation Index, SOI (Wright's index) upto two seasons before and after monsoon and for the monsoon season. They considered correlation coefficients for sliding 30-year periods. They found some notable variations in the relationship.

Elliot and Angell (1987) examined the variations in the relationship between IMR and seasonal SOI, as well as that between IMR and seasonal SST over eastern equatorial Pacific. They considered SOI as (i) difference between mean sea level pressures of Santiago and Darwin, and that between mean sea level pressures of Tahiti and Darwin; (ii) individual mean sea level pressures of Darwin, Santiago and Tahiti; (iii) Wright's index based on pressures at 8 stations. They considered correlation coefficients (CCs) between IMR and the different measures of SOI, for different seasons, for two periods, 1884–1984 and 1947–1984. They generally found little evidence for variation in the relationship between IMR and SOI over these periods except for the difference that CC between IMR and Darwin pressure two seasons before monsoon is significant at 5% for the period 1947–84 but not for the whole period. They considered CCs between IMR and seasonal SST for the periods 1884–1915, 1916–1946, 1947–1984 and for the whole period 1884–1984. They found rather large variations in the CCs between IMR and SST for the four seasons preceding the concurrent summer monsoon season and for the monsoon season following the concurrent monsoon season. Even for the concurrent summer monsoon season there is some variation over these periods. But, for the three seasons following the concurrent summer monsoon season there is little variation in the CCs over the different periods.

Elliot and Angell (1988) examined the relationship between Southern Oscillation indices and SST for each of the four seasons for sliding 30-year periods. They found that variations in the CCs occurred and that the CCs were lowest around 1940. They also found that for DJF, MAM and SON seasons the CCs were highly significant but for JJA, the CCs though significant were numerically much smaller.

Parthasarathy *et al* (1991) examined the secular variations in the relationships between Indian monsoon rainfall and the circulation. They considered the trend from DJF (Dec-Jan-Feb) season to MAM (Mar-Apr-May) season before the monsoon in Bombay and Darwin mean sea level pressures as circulation parameters. They found notable variations over time in the CC between IMR and Bombay pressure trend and in the CC between IMR and the Darwin pressure trend. In the case of Bombay pressure trend, there was even a change of sign in the CC around 1900 and 1941. However, the CC with the Darwin pressure trend continued to retain the same sign, CCs being generally not significant at 5% level upto about 1940 and thereafter being highly significant.

The main objective of this study is to examine the variations in the relationships of the Indian monsoon and the two global factors, the Southern Oscillation and the SST over the eastern equatorial Pacific and to locate the periods of good and very good relationship. Shukla and Paolino (1983) who considered Darwins m.s.l. pressure as a measure of SOI have clearly brought out that the Indian monsoon rainfall has a better relationship with SOI tendency from the season DJF to the season MAM than that with SOI for the season MAM. In view of this situation, we propose to use tendencies of the seasonal SOI and of the seasonal SST, instead of the seasonal values.

2. Data

The activity of the Indian summer monsoon is assessed on the basis of the rainfall recorded during the summer monsoon season (1 June to 30 September). This rainfall is the end product of the various physical processes resulting from the monsoon wind circulation and the changes therein that take place in the atmosphere over India and the neighbourhood during the period of the summer monsoon season. In this study, Indian monsoon rainfall has been considered as area-averaged monsoon season rainfall over the plains of India. The series for IMR is the same as that used by Mooley and Parthasarathy (1984b) upto 1978 and updated, thereafter upto 1990. For the details of the preparation of this series, the reader may please see these papers. The series is based on the monthly rainfall data of 306 raingauge stations distributed fairly uniformly over the plains of India which cover about 90% of the total Indian area. The hilly areas, Jammu and Kashmir, hills of northwest U.P. and of Assam were not considered due to very poor raingauge network, particularly before 1900.

It is seen from the study of Elliot and Angell (1987, 1988) that Darwin seasonal m.s.l. pressure has a better relationship with IMR than Tahiti during the period 1947–84, and that Tahiti pressure record for early periods showed a poorer relationship with SST over eastern equatorial Pacific than that with Darwin pressure record. Ropelewski and Jones (1987) who extended backwards Tahiti-Darwin Southern Oscillation Index have pointed out that there are questions about early Tahiti data that make the reconstruction of the SOI less reliable than the post-1935 record. Parthasarathy *et al* (1988) have brought out that Darwin m.s.l. pressure tendency from the season DJF to season MAM is better related to IMR than a similar tendency for Tahiti-Darwin m.s.l. pressure during the period 1951–80. Considering these points, it was decided to consider only Darwin m.s.l. pressure as a measure of SOI.

Darwin monthly mean sea level pressure data are available from 1882 to 1985 in the publication by Bureau of Meteorology (1987), Australia. Allan *et al* (1991) have extended backwards Darwin pressure data upto March 1869. Darwin monthly mean sea level pressure data have been taken from Allan *et al* (1991) for the period 1871 to 1881 and from the publication of the Bureau of Meteorology (1987), Australia and its later issues for the period 1882 to 1990. It was decided to compute the seasonal values of SOI for the seasons December (previous calendar year's) January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). These were computed for each of the years 1871 to 1990 from the monthly mean pressure values. Darwin mean sea level pressure tendencies (DART) considered as Southern Oscillation Index tendencies (SOIT) and as defined below have been computed for all the years.

$$\begin{aligned}
\text{DART0} = \text{SOIT0} &= \text{Concurrent tendency}\\
&= (\text{Darwin pressure})_{\text{FSON}} - (\text{Darwin pressure})_{\text{CJJA}}\\
\text{DART-1} = \text{SOIT-1} &= (\text{Darwin pressure})_{\text{PMAM}} - (\text{Darwin pressure})_{\text{PDJF}}\\
\text{DART-2} = \text{SOIT-2} &= (\text{Darwin pressure})_{\text{PDJF}} - (\text{Darwin pressure})_{\text{PSON}}\\
\text{DART1} = \text{SOIT1} &= (\text{Darwin pressure})_{\text{FDJF}} - (\text{Darwin pressure})_{\text{FSON}}\\
\text{DART2} = \text{SOIT2} &= (\text{Darwin pressure})_{\text{FMAM}} - (\text{Darwin pressure})_{\text{FDJF}}
\end{aligned}$$

Letters P, C, F before the season indicate respectively the season preceding concurrent JJA, concurrent JJA, and the season following the concurrent JJA. The season JJA has been considered as concurrent with the Indian summer monsoon season. If monthly SST values were available, a better measure of concurrent tendency would have been mean for August-Sept-Oct. minus mean for May-June-July. In view of the necessity to define SOITO and SSTTO in the same way, the tendency as defined above has been accepted as concurrent tendency. Standardized values, i.e. anomaly divided by standard deviation (S.D.) of these tendencies have been computed and used in this study of the variation in the relationship between IMR and the global meteorological factor, the Southern Oscillation Index.

The data on seasonal anomalies of SST as compiled by Angell (1981) for the large area of the eastern equatorial Pacific, 0–10°S and 180°W–80°W, and updated by him and used by Angell (1981) and Elliot and Angell (1987) were utilized in the present study. SST tendencies, SSTTO, SSTT-1, SSTT-2, SSTT1 and SSTT2, defined exactly in the same manner as the corresponding SOI tendencies, have been computed for each of the years. These SST tendencies have been standardized (anomaly/S.D). These standardized tendencies are actually used in the study of the variation beween IMR and the global meteorological factor, SST for the eastern equatorial Pacific.

A careful examination of the tendencies showed that the following tendencies are doubtful.

(i) SOIT-1 for 1941 is too low due to SOI for MAM being too low. This value is SOIT2 for 1940.

(ii) SSTT-1 is too high in 1917 and too low in 1941 and 1966, apparently due to SST for DJF in 1917, SST for MAM in 1941 and SST for MAM in 1966 being too low. These values are values of SSTT2 for 1916, 1940 and 1965 respectively.

(iii) SSTTO for 1938 and 1944 are too high, apparently due to SST for JJA for 1938 being too low and SST for SON for 1944 being too high.

In order to understand the influence of the few doubtful tendencies, the analysis was carried out with the whole tendency data as well as with the whole data minus the few doubtful tendencies.

3. Variation in the relationship between IMR and SOIT

To explore the variation in the relationship of these tendencies with IMR during the long period 1871–1990, the relationship as measured by the correlation coefficient (CC) for the whole period is computed in the first instance and examined for statistical significance. Next, relationships are computed for sliding 30-year periods, the first 30-year period commencing on 1871 and the last 30-year period ending on 1990, the first year of the 30-year period sliding forward by one year at a time. This enables one to find out if the relationship over the 30-year component periods, viz., 1871–1900, 1901–1930, 1931–60 and 1961–90 are significant and to locate epochs when notable changes occur in the relationship.

Quenouille (1952) and Sciremammano (1979) have mentioned that while considering statistical significance of CC, persistence in the individual series should be taken into account. For IMR, auto-correlation coefficients with lags 1 to 5 are respectively −0·14, 0·05, 0·11, −0·09 and −0·01 which do not suggest any persistence. Likewise, SOI tendency series do not suggest any persistence. For example, autocorrelation coefficients with lags 1 to 5 for SOIT-1 series are respectively −0·02, −0·09, −0·05, −0·09 and 0·20. Hence while assessing the significance of CCs between IMR and SOIT series, the degrees of freedom between the two data series would be taken as N-2 where N is the number of years of data.

Table 1. Correlation coefficients between Indian monsoon rainfall (IMR) and Southern oscillation index tendencies (SOIT).

	Correlation coefficients of IMR with				
Period	SOIT-2	SOIT-1	SOIT0	SOIT1	SOIT2
1871–1900	−0·41*	−0·12	−0·32	+0·06	+0·55 ~
1901–1930	−0·05	−0·31	−0·17	−0·10	+0·22
1931–1960	+0·16	−0·25 (−0·39*)	−0·07	−0·18	+0·23 (+0·27)
1961–1990	+0·21	−0·59 ~ ~	−0·40*	+0·09	+0·32
1871–1990	−0·13	−0·33 ~ (−0·36 ~ ~)	−0·28 ~	+0·01	+0·33 ~ (+0·34) ~

Note: (i)* denotes significance at 5% level.
~ denotes significance at 1% level.
~ ~ denotes significance at 0·1% level.
(ii) under SOIT-1, the bracketted CCs are for the periods 1931–61 and 1871–1990 without 1941; under SOIT2, the bracketted CCs are for the periods 1931–61 and 1871–1990 without 1940.

Table 1 gives the CCs for the component 30-year periods and for the whole period. Relationship of IMR with SOIT-1, SOIT0 and SOIT 2 for the whole period shows significance at 1% level. SOIT-2 and SOIT1 have no relationship with IMR, and we come to the same conclusion on the basis of CCs for the component 30-year periods. Though the CC of IMR with SOIT-2 for the period 1871–1900 is significant at 5%, it cannot be given any consideration in view of the changing sign of the CCs for the component 30-year periods. It may be seen from table 1 that a notable improvement in CC with SOIT-1 occurs for the 30-year period when 1941 is deleted. In other cases, the deletion of doubtful tendencies results in a small improvement in CC. Figure 1 gives the CCs of IMR with SOIT-1, SOIT0 and SOIT2 for sliding 30-year periods, the CC being plotted against the first year of each period. The continuous curves shows CCs for all sliding 30-year periods and the dots show CCs for 30-year periods on deletion of doubtful tendencies when CC increases by 0·1 or more. Deletion of SOIT-1 for 1941 has resulted in a rather large improvement in the relation between SOIT-1 and IMR. Deletion of SOIT2 for 1940 has resulted in a small improvement only. It may be noted from table 1 that the relationships of IMR with SOIT-1, SOIT0 and SOIT2 are significant for some of the component 30-year periods. From a careful examination of the CCs of IMR with SOIT-1, SOIT0, and SOIT2 for sliding 30-year periods, the relationships for the undermentioneds periods are observed to possess consistency in sign and are significant at 5% or are near this level.

(i) SOIT-1, 1902–40. It may, however, be noted that sliding 30-year periods 1919–49 and 1920–50 show a low numerical value of CC (about −0·25) which is not significant even at 10% level.
(ii) SOIT-1, 1942–90, highly significant.
(iii) SOIT0, 1871–1921 and 1957–1990, with better relationship for the latter period
(iv) SOIT2, 1871–1921 highly significant. 1943–90, significant at 5% for a couple of successive sliding 30-year period contained in this period. It is possible that the relationship may not be significant for the period. 1943–90. But it would be necessary to check in this matter.

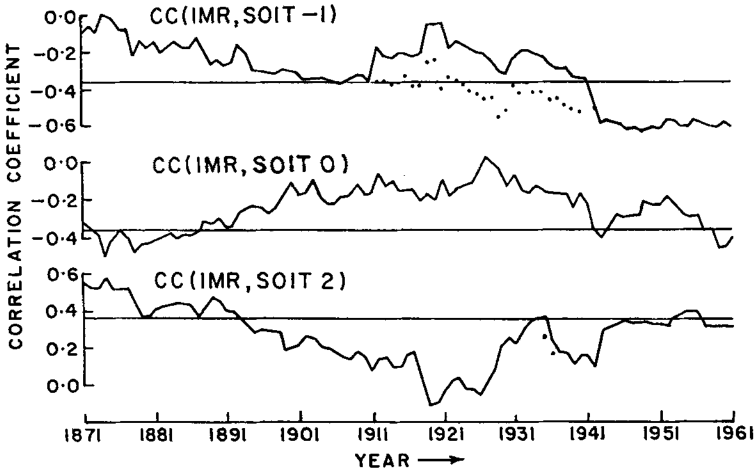

Figure 1. CC between Indian monsoon rainfall (IMR) and SOIT-1/SOIT0/SOIT2 for sliding 30-year periods. CC plotted against the first year of the sliding period. Continuous curve gives CCs when no data are omitted, and dots give CCs on omission of doubtful data when CC changes by 0·1 or more.

To estimate how good the relationships are at (i), (ii), (iii) and (iv) above, the procedure proposed to be adopted is as follows. Let x and y be the variables for which the relationship is being considered. Four groups of values of the variables are obtained. These groups are labelled A, B, C and D. A contains values of y in years of low values of x, B contains values of y in years of high values of x, C contains values of x in years of low values of y and D contains values of x in years of high values of y. The criterion adopted for low and high values of a variable are, about 16% lowest and 16% highest values respectively out of the total values of the variable within the period considered. Generally, for a Gaussian distribution, about 16% of the values of the variable are smaller than or equal to mean minus one S. D. and about 16% are greater than or equal to mean plus one S. D. The variables we are concerned with are Gaussian-distributed. Hence this percentage has been adopted as the criterion for identifying low and high values of a variable. Some times, this percentage may vary slightly in view of some identical values of the variables. If the difference in the levels of the groups A and B, as well as that in the levels of the groups C and D are both significant at least at 5% level, only then can we say that the variable y discriminates well the high and low values of x and vice versa. Therefore, with these stipulated conditions being satisfied, we shall judge relationships to be good or very good, depending on the level of significance attained. For testing the significance of the difference in the levels of the concerned groups, Mann and Whitney (1947) non-parametric test, developed earlier by Wilcoxen (1945), would be used. We briefly indicate how this test is applied. Let x series have m terms and y series, n terms. Mix up the terms of the two series, and arrange the combined series in ascending order of values; and add up separately the ranks of the terms of the x series and the ranks of the terms of the y series, in the combined series in the ascending order. Let R_x and R_y be sums of the ranks of terms of the x and y series respectively, in the combined series. Let R_x be smaller than R_y. The test statistic is U where

$$U = R_x - [m(m+1)/2]$$

U is Gaussian or near-Gaussian for $m, n > 12$. For $m, n \leqslant 12$, values of U significant at the desired level may be obtained from the relevant tables (Fix and Hodges 1955). For $m, n > 12$, $E(U) = mn/2$; Var $U = mn(m+n+1)/12$. Deviation of U from the expected mean in terms of S.D. of

$$U = \left[R_x - \frac{m(m+1)}{2} - \frac{mn}{2} \right] \Big/ \sqrt{\frac{mn(m+n+1)}{12}}.$$

Standardized deviation of U may be referred to tables of standard Gaussian distribution, for judging the significance of U. If U is significant, the difference in the levels of the two groups of values is significant.

Table 2 relating to IMR and SOIT relationships, gives the concerned variables, the concerned period, inference from Mann-Whitney tests regarding the levels of the concerned groups, level of significance of the test statistic U, if any upto 5% and inference about the relationship. In table 2, non-attainment of 5% significance level is indicated by – and below it are indicated U value obtained/U value significant at 5%. It may be noted from this table that the relationship with SOIT-1 for the period 1942–90 and that with SOIT2 for the period 1871–1921 are very good and that with SOIT0 for the periods 1871–1921 and 1957–1990 is good. The relationships with SOIT-1 and SOIT0 are inverse and that with SOIT2 is direct. There is no good

Table 2. Examination of the relationships between Indian monsoon rainfall (IMR) and SOIT-1, SOIT0 and SOIT2.

Variables	Period	Inference from Mann-Whitney test regarding levels of the groups	Level of significance (%)	Inference about relationship
IMR (variable x) and SOIT-1 (variable y)	1902–40	(i) $A \approx B$ (ii) $C > D$	— (26·5/15) 5·0	Not good
IMR (variable x) and SOIT-1 (variable y)	1942–90	(i) $A > B$ (ii) $C > D$	0·1 0·2	Very good
IMR (x) and SOIT0 (y)	1871–1921	(i) $A > B$ (ii) $C > D$	5·0 2·5	Good
IMR (x) and SOIT0 (y)	1957–90	(i) $A > B$ (ii) $C > D$	0·1 5·0	Good
IMR (x) and SOIT2 (y)	1871–1921	(i) $A < B$ (ii) $C < D$	0·5 0·1	Very good
IMR (x) and SOIT2 (y)	1943–90	(i) $A \approx B$ (ii) $C \approx D$	— (35/27) — (36/27)	Apparently no relationship

Notes: (i) Groups A and B contain values of y in years with low and high values of x respectively. Groups C and D contain values of x in years of low and high values of y.
(ii) For the symbols $>$, $<$ and $\approx$ read higher than, lower than, and not significantly different from, respectively.
(iii) Figures within parentheses below—in the penultimate column give the value of Mann-Whitney test statistic, U/value of test statistic significant at 5% level.

Table 3. Values of SOIT-1 in years of low IMR (Group *A*) and of high IMR (Group *B*); Values of IMR in years of low SOIT-1 (Group *C*) and of high SOIT-1 (Group *D*).

Group *A*		Group *B*		Group *C*		Group *D*	
Year	SOIT-1 (Standardized)	Year	SOIT-1 (Standardized)	Year	IMR (Standardized)	Year	IMR (Standardized)
1951	1·82	1942	−1·09	1942	1·27	1946	0·59
1965	0·43	1947	−0·12	1958	0·41	1951	−1·38
1966	0·57	1955	−0·61	1959	1·03	1957	−0·81
1968	0·82	1956	−0·36	1963	0·04	1967	0·09
1972	2·10	1959	−1·79	1964	0·82	1968	−1·18
1974	0·71	1961	0·26	1973	0·72	1969	−0·27
1979	0·09	1970	−0·95	1978	0·67	1972	−2·39
1982	0·09	1975	−1·02	1983	1·24	1976	0·04
1986	0·64	1983	−1·99	1985	−0·78	1981	0·00
1987	0·82	1988	−0·99	1990	0·77	1987	−1·98
Mean	0·81		−0·87		0·62		−0·63

Test statistic *U* for Mann-Whitney test = 2 (significant at 0·1% level)

Test statistic *U* for Mann-Whitney test = 8·5 (significant at 0·2% level)

relationship between IMR and SOIT-1 for the period 1902–40 and there does not appear to be any relationship between IMR and SOIT2 for the period 1943–1990. As an example, table 3 gives for the very good relationship between IMR and SOIT-1 for the period 1942–90, the years under groups *A* and *B* and the corresponding values of SOIT-1, as well as the years under groups *C* and *D* and the corresponding values of IMR. The group means are found to show strong contrast.

4. Variation in the relationships between IMR and SSTT

The variations in these relationships have been explored in the same manner as in the case of the relationships between IMR and SOIT. However, in view of the few doubtful SST tendency values as indicated at the end of section 2, CCs for sliding 30-year periods and for the whole period were computed with as well as without the doubtful tendencies. Auto correlation coefficient with lags 1 to 5 for the SST tendency series do not suggest any persistence, hence, while considering the significance of CCs between IMR and SST tendency series, the degrees of freedom have been taken as N-2 where N is the number of years of data. Table 4 gives CCs between IMR and these SST tendencies for whole data, for whole data minus doubtful data and for the component 30-year periods with as well as without the doubtful tendencies. CCs given within parenthesis are based on data from which doubtful data are excluded. It is observed that exclusion of doubtful data makes a large difference in the CCs of IMR with SSTT-1 and with SSTT0 but little difference in the CCs of IMR with SSTT2. This is clearly brought out in figure 2 which shows the CCs between IMR and SSTT-1/SSTT0/SSTT2 for sliding 30-year periods with as well as without doubtful data. The continuous curves in figure 2 are CCs for sliding 30-year periods when no data are deleted. CCs for sliding 30-year periods when doubtful data are deleted are shown by dots against the commencement year for only those sliding periods for

Table 4. Correlation coefficients between Indian monsoon rainfall (IMR) and sea surface temperature tendencies (SSTT).

	Correlation coefficient of IMR with				
Period	SSTT-2	SSTT-1	SSTT0	SSTT1	SSTT2
1871–1900	0·37*	−0·46 ~	−0·52 ~	−0·31	0·65 ~ ~
1901–1930	−0·31	−0·10 (−0·30)	−0·41*	0·12	0·42* (0·37*)
1931–1960	0·14	−0·08 (−0·44*)	−0·01 (−0·32)	−0·23	0·44* (0·40*)
1961–1990	−0·26	−0·41* (−0·49 ~)	−0·61 ~ ~	0·07	0·51 ~ (0·47 ~)
1871–1990	0·05	−0·29 ~ (−0·38 ~ ~)	−0·36 ~ ~ (−0·47 ~ ~)	−0·11	0·52 ~ ~ (0·52 ~ ~)

Note: (i) Symbols *, ~, ~ ~ mean the same levels of significance as in table 1.
(ii) Under the column SSTT-1, the CCs within parentheses are for periods 1901–31 without 1917, 1931–61 without 1941, 1960–90 without 1966 and 1871–1990 without 1917, 1941 and 1966.
(iii) Under the column SSTT0, the CCs within parentheses are for periods 1930–61 without 1938 and 1944 and 1871–1990 without 1938 and 1944.
(iv) Under the column SSTT2, the CCs within parentheses are for periods 1901–31 without 1916, 1931–61 without 1940, 1960–90 without 1965, and 1871–1990 without 1916, 1940 and 1965.

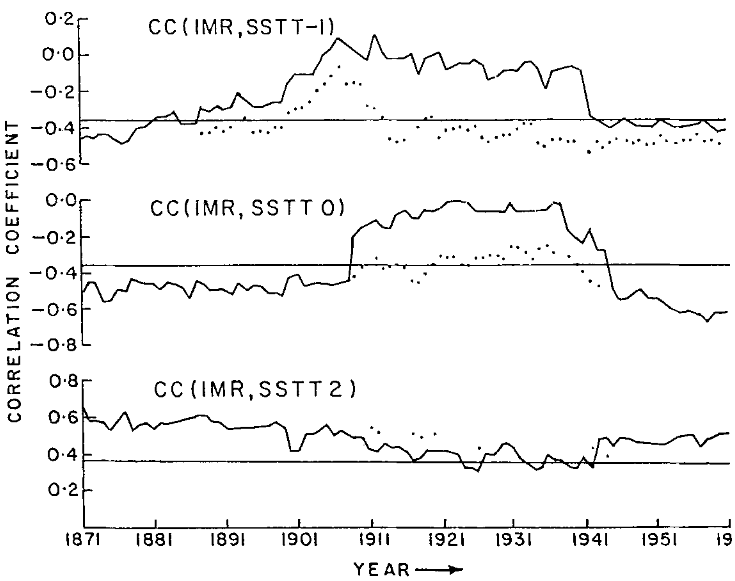

Figure 2. CC between Indian monsoon rainfall (IMR) and SSTT-1/SSTT0/SSTT2 for sliding 30-year periods. CC plotted against the first year of the sliding period. Continuous curve gives CCs when no data are omitted, and dots give CCs on omission of doubtful data when CC changes by 0·1 or more.

which the value of CC has changed by 0·1 or more, to avoid close proximity of the corresponding points on the continuous curve. Figure 2 shows clearly that the CC (IMR, SSTT-1) is strongly vitiated by the data for 1917 and 1941 and moderately vitiated by the data of 1966 and the CC (IMR, SSTT0) is also strongly vitiated by the data of 1938 and 1944, but the absence or presence of data for SSTT2 for 1916, 1940 and 1965 makes little difference to the CC of IMR with SSTT2. In view of this finding, we shall hereafter delete data for these few years only when we consider the relationship of IMR with SSTT-1 and with SSTT0. Table 4 brings out clearly that there is no relationship of IMR with SSTT-2 and SSTT1, the marginally significant CC with SSTT-2 for 1871–1900 being ignored in view of the changing sign of CC for component 30-year periods. It may be noted that CCs of IMR with SSTT-1/SSTT0/SSTT2 for the whole period are all significant at 0·1%. Careful examination of the CCS of IMR with SSTT-1, SSTT0 and SSTT2 for sliding 30-year periods shows that the following relationships which possess consistency in sign are significant at 5% or are near this significance level for the periods indicated.

(i) IMR and SSTT-1 for practically the whole period.
(ii) IMR and SSTT0 for practically the whole period.
(iii) IMR and SSTT2 for the whole period. The relationship for sliding 30-year periods exhibits good stability in significance.

The goodness of these relationships has been tested exactly in the same manner as the goodness of the relationships of IMR with SOIT-1, SOIT0 and SOIT2, by applying Mann-Whitney test. However, since a couple of sliding 30-year periods covering some years before 1930 and some years after 1930 do not have CCs close to 5% significance level in the case of SSTT-1 and SSTT0, goodness of the relationship of IMR with SSTT-1 and with SSTT0 has also been tested for each of the two halves of the whole period. Table 5 gives the results of the test. It is observed from this table

Table 5. Examination of the relationships between Indian monsoon rainfall (IMR) and SSTT-1, SSTT0 and SSTT2.

Variables	Period	Inference from Mann-Whitney test regarding levels of the groups	Level of significance (percentage)	Inference about the relationship	
IMR (x) and SSTT-1 (y)	1871–1990	(i) $A > B$ (ii) $C > D$	0·1 0·1	Very good	(Also very good for each half of whole period)
IMR (x) and SSTT0 (y)	1871–1930	(i) $A > B$ (ii) $C > D$	5·0 5·0	Good	
IMR (x) and SSTT0 (y)	1931–1990	(i) $A > B$ (ii) $C > D$	0·2 0·1	Very good	
IMR (x) and SSTT2 (y)	1871–1990	(i) $A < B$ (ii) $C < D$	0·2 0·1	Very Good	(Also very good for each half of whole period)

Notes: (i) Groups A and B contain values of y in years with low and high values of x respectively. Groups C and D contain values of x in years of low and high values of y respectively.
(ii) For the symbols > and < read higher than; and lower than, respectively.

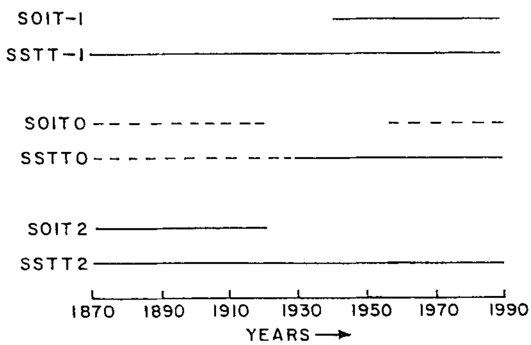

Figure 3. A comparison of IMR-SOIT-1/SOIT0/SOIT2 relationships with IMR–SSTT-1/SSTT0/SSTT2 relationships. ---- shows period of good relationship and ——— shows period of very good relationship.

that the relationships of IMR with SSTT-1, SSTT0 and SSTT2 for the whole period are very good. While the relationship with SSTT-1 for both the halves of whole period is very good, the relationship with SSTT0 is good for the first half and very good for the second half of the whole period. The relationships with SSTT0 and SSTT-1 are inverse and that with SSTT2 is direct.

Figure 3 brings out a comparison of the IMR-SOIT relationships with IMR-SSTT relationships. It may be noted that the two relationships differ substantially in respect of the periods covered by them. SSTT-1 has a very good relationship for the whole period but SOIT-1 has a good relationship in post-World War II period. SSTT0 has a good relationship for the first half and very good relationship for the second half of the whole period, but SOIT0 has a good relationship over the period 1871–1921 and 1957–90. SSTT2 has a very good relationship over the whole period but SOIT2 has a very good relationship during the period 1871–1921 only. It can thus be seen that the relationships of SOIT-1, SOIT0 and SOIT2 with IMR do not respectively correspond well with those of SSTT-1, SSTT0 and SSTT2 with IMR, even though the SOI is strongly related with SST for each of the four seasons. SSTT relationships cover a much wider period than SOIT relationships. For the whole period, CCs with SSTT-1, SSTT0 and SSTT2 are all significant at 0·1% whereas those with SOIT-1, SOIT0 and SOIT2 are significant at 1% level only. SST tendency is observed to have a much stronger relationship with IMR than SOI tendency with IMR. In this connection, it may be mentioned that Mooley and Paolino (1989) have brought out that SST changes over the Pacific Ocean area 0–10°S, 180°W–80°W have a much stronger association with IMR than SOI changes have with IMR.

5. Implications of the relationships of IMR with SOI and SST tendencies

SOIT-1, having a very good inverse relationship with IMR for the past 50 years or so, can be used as a predictor for IMR in future. Below normal tendency of SOI from DJF to MAM before the monsoon season leads to above normal IMR and vice versa. Shukla and Mooley (1987) and Parthasarathy *et al* (1988) have used this as one of the predictors. However, as years roll by a continuing watch has to be kept on this relationship since it is difficult to estimate how long this relationship will continue to be good into the future. Taking into account the complete history of the relationship over the past 120 years, there is every reason to believe that the relationship may start deteriorating from some epoch in future. SOIT-1 can continue to be used as a predictor till the epoch upto which the relationship remains reasonably good.

During the period 1871–1921, IMR plays an active role in that it influences or anticipates SOIT2, i.e. SOI tendency from DJF to MAM after the monsoon season, but does not play the passive role of being influenced or anticipated by SOI tendency from DJF to MAM before the monsoon season. However, during the period 1942–1990, IMR plays only the passive role of being influenced or anticipated by SOIT-1.

IMR has a very good direct relationship with SSTT2 during the whole period 1871–1990, above normal IMR leading to above normal SSTT2, i.e. SST tendency from DJF to MAM following the monsoon season. IMR has also a very good inverse relationship with SST-1 during the whole period i.e. above normal SST tendency from DJF to MAM preceding the monsoon season leading to below normal IMR and vice versa. Thus, IMR plays an active as well as passive role with respect to SST tendency from DJF to MAM over the whole period. The relationship suggests interaction between IMR and SST tendency from DJF to MAM. Let us examine the consequences of this interaction. We suppose that the year y_i gets below normal IMR. This, in view of the very good relationship of IMR with SSTT2 would lead to below normal SST tendency from DJF to MAM after the monsoon of year y_i and preceding the monsoon in the year $y_i + 1$, i.e. the next year. In view of the very good relationship of IMR with SST tendency from DJF to MAM preceding the monsoon season, the below normal SST tendency from DJF to MAM in the year $y_i + 1$ would lead to above normal IMR in the year $y_i + 1$. Thus, through this interaction between IMR and SST tendency from DJF to MAM, below normal IMR in one year leads to above normal IMR in the next year and vice versa. One consequence of this interaction would be negative autocorrelation coefficient of IMR with lag 1. The autocorrelation coefficient of IMR with lag 1 for the whole period is $-0{\cdot}14$ which is close to 10% significance level. Auto-Correlation Coefficient of IMR with lag 1 for sliding 30-year periods is consistently negative for all the sliding 30-year periods within the whole period and is significant at 10% level for a number of 30-yr sliding periods. Elliot and Angell (1987) who studied relationships of IMR with SOI and northern hemispheric land temperature found a suggestion of negative feedback in post-World War II data–an above-average IMR followed by above-average SOI and below-average northern hemispheric land temperature in succeeding winter and this in turn being followed by below-average IMR. They felt that an implied loop as suggested by post-World War II data may be an illusion.

A critical examination of the CC (IMR, SSTT-1) and CC (IMR, SSTT2) would be useful in getting an insight into these relationships. We have considered data of the standardized variables, i.e. deviation from long-period mean divided by standard deviation. When we are dealing with two standardized variables, then

$$\text{Covariance} = (1/n)\ \Sigma \text{ product of standardized variables}$$
$$= \text{Correlation Coefficient}$$

n is the number of years of data of the variables.

We divide the total number n of years into two groups, UN and F. UN is the

Table 6. Examination of the relationships between IMR and SSTT-1 and IMR and SSTT2.

	IMR, SSTT-1 relationship (based on 117 years' data)	IMR, SSTT2 relationship (based on 120 years' data)
i) Percentage of the total number of years under group *F* (i.e. years making contributions favourable to the relationship)	64	72
ii) Sum of the products of the variables for years under group *F*	− 57·79	73·97
iii) Sum of the products of the variables for years under group *UN* (with contribution unfavourable to the relationship)	12·86	− 11·81
iv) Numerical value of ratio of the sum at (ii) to the sum at (iii)	4·5	6·3

group of years for which data are observed to be unfavourable for the relationship and *F* is the group of years for which data are observed to be favourable for the relationship. The number of years under group *F* expressed as a percentage of the total number of years is computed for each of the relationships. Sum of the products of the two standardized variables is obtained for the years under each of the groups *UN* and *F*. Finally, we computed the numerical value of the ratio of the sum of the products of the standardized variables for years in group *F* to that in group *UN*. Table 6 gives for each of the two relationships, the percentage of years under group *F*, sum of the products of the standardized variables for years under each of the groups *F* and *UN* and the ratio of the sum of the product for years under group *F* to that under group *UN*. This table shows that for quite a large percentage of years (about two-thirds of the total number of years) the data are favourable to the relationships, and that for the years for which data are favourable to the relationship, the sum of the products of the two variables i.e. contribution to the relationship, is very large in comparison to the sum of the products of the two variables for the years unfavourable to the relationship, i.e. contribution unfavourable to the relationship. This clearly brings out that the data of a large percentage of the total number of years have contributed to these highly significant relationships, and that we have no reason to believe that such highly significant relationships could have arisen due to random chance.

We need to examine the influence of SSTT-1 on the relationship between SSTT2 and IMR and that of IMR on the relationship between SSTT2 and SSTT-1, i.e. serial correlation with lag one in the SST tendency from DJF to MAM. For this purpose we must obtain $r_{13\cdot 2}$, the partial correlation coefficient of first order between variable no. 1 (SSTT2) and variable no. 3 (IMR) after the influence of the variable no. 2 (SSTT-1) has been eliminated and $r_{12\cdot 3}$, i.e. partial correlation coefficient between SSTT2 and SSTT-1 when the influence of IMR is eliminated.

$$r_{13\cdot 2} = \frac{r_{13} - r_{12}r_{23}}{[(1 - r_{12}^2)(1 - r_{23}^2)]^{1/2}}; \quad r_{12\cdot 3} = \frac{r_{12} - r_{13}r_{23}}{[(1 - r_{13}^2)(1 - r_{23}^2)]^{1/2}},$$

where

r_{12}, r_{13}, r_{23}

are total correlation coefficients (Kendall and Stuart 1961)
Now, $r_{12} = \mathrm{CC(SSTT2, SSTT\text{-}1)} = -0{\cdot}21$
$r_{13} = \mathrm{CC(SSTT2, IMR)} = 0{\cdot}52$
$r_{23} = \mathrm{CC(SSTT\text{-}1, IMR)} = -0{\cdot}38$,
for whole data ($n = 117$)

We obtain $r_{13\cdot 2} = 0{\cdot}487$ which shows a highly significant relationship between SSTT2 and IMR even when the influence of SSTT-1 is eliminated, and $r_{12\cdot 3} = -0{\cdot}015$ which shows no relationship beween SSTT2 and SSTT-1 when the influence of IMR is eliminated or shows that the relationship between SSTT2 and SSTT-1 is due to the influence of IMR. These results bring out very clearly the active role played by IMR.

6. Possible physical mechanism for the interaction between IMR and SST tendency

The physical mechanism which could possibly lead to the interaction may be as follows. Changes in SST over the eastern equatorial Pacific prior to the monsoon result in changes in the intensity and location of Walker Circulation which influence the monsoon circulation and consequently monsoon rainfall over India. Year to year variations in the summer monsoon circulation over India and the neighbourhood result in the variations of the atmospheric processes of cloud and rain formation. Rain which falls to the ground and is measured is the end result of the various atmospheric processes and could be taken as a measure of intensity of these processes. These atmospheric processes lead to liberation of latent energy into the atmosphere over India and the neighbourhood. Variations in this input of latent energy into the atmosphere may lead to variations in the outgoing long-wave radiation from the surface and in the lower troposphere and to consequent changes in the thermal field, and this could result in the variation in circulation over the Pacific. The variations in circulation, particularly at the surface could influence SST over eastern equatorial Pacific through variations in the upwelling off the south American Coast, off Peru. It appears, however, that the whole mechanism of the interaction is too complex to defy a simple explanation.

The interaction between IMR and SST tendency as observed through the inter-relationships can be viewed as a part of the much larger interaction between the Asian summer monsoon on the one hand and the tropical Pacific Ocean and the overlying troposphere on the other hand. Large amounts of latent energy from the ocean area to the south of Asia are transported to south Asia under the influence of the heat low and the extensive trough of low pressure over south Asia resulting from well-marked differential heating of land and sea. A large part of this latent energy is liberated into the atmosphere over south Asia and the adjoining Pacific through the processes of cloud and rain formation. Nowhere else in the world, do we have such a huge area over which in a season of hardly four months, vast amounts of latent heat are released into the atmosphere with rather large inter-annual variations in the release of the latent energy. It is, therefore, quite reasonable to expect that these rather large variations in the releases of the latent heat into the atmosphere would interact with the neighbouring Pacific Ocean through influence on circulation over the Pacific. The interaction is thus unique. The factors which complicate this interaction are the influence of the variations in the activity of the westerly troughs on monsoon, the influence of the variations in the ocean currents on SST in the equatorial Pacific, and the current SST tendency, i.e. SSTT0, and the monsoon influencing each other. The highly complex mechanism may involve non-linear interactions.

7. Concluding remarks

(i) SSTT-1/SSTT0/SSTT2 are much better related to IMR than SOIT-1/SOIT0/SOIT2 respectively. The relationships with SST tendencies cover generally the whole period, but those with SOI tendencies cover only part of the whole period. While SOI and SST are strongly related to each other for each of the seasons, the relationships of SOIT-1/SOIT0/SOIT2 with IMR do not respectively correspond well with the relationships of SSTT-1/SSTT0/SSTT2 with IMR. IMR has an inverse relationship with SSTT-1/SOIT-1 and SSTT0/SOIT0 but direct relationship with SSTT2/SOIT2.
(ii) Taking into account the fact that SOIT-1 was delinked from IMR prior to 1942, the possibility of similar delinking in future cannot be ruled out. SOIT-1 can continue to be used as a predictor of IMR till a reasonably good relationship is maintained. A very good relationship is continuing since 1942.
(iii) During the whole period, SSTT-1, i.e. tendency from DJF to MAM before monsoon, has a very good relationship with the following Indian monsoon rainfall and the latter has a still better relationship with SSTT2, i.e. tendency from DJF to MAM following the monsoon season. These relationships suggest interaction between IMR and SST tendency from DJF to MAM.
(iv) This interaction can be considered as a part of the much larger interaction between the Asian summer monsoon on one hand and the neighbouring Pacific Ocean and the overlying troposphere on the other hand. The mechanism of this interaction appears to be as follows. Variations in SST-1 lead to variations in the tropical circulation including the Walker Circulation which influence monsoon circulation and monsoon rainfall. Enormous amounts of latent heat are released into the atmosphere over Asian summer monsoon area through the processes of cloud formation and rain during a period of hardly four months. The inter-annual variations of these amounts of latent heat are quite large. The variations in the latent energy released into the atmosphere may lead to variations in the out-going long-wave radiation at the surface and in the lower troposphere and to consequent changes in the thermal field. The latter variations could result in changes in circulation over the Pacific. The variations in circulations particularly at the surface would affect SST in equatorial Pacific through variations in the upwelling off Peru coast and the neighbourhood. This interaction appears to be highly complex and may involve non-linear effects.

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