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The response of the Indian monsoon associated with the change in sea surface temperature over the eastern south equatorial Pacific

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सार – ऋतुनिष्ट समुद्री सतह तापमान (एस.एस.टी.) विसंगति और वस्तुपरक कसौटी का उपयोग करते हुए, 1871 - 1984 के दौरान पूर्वदक्षिण भूमध्य प्रशान्त महासागर की उष्मन और शीतलन प्रावस्थाओं का पता लगाया गया है। ग्रीष्म मानसून के दौरान भारत और उसके पड़ोसी देशों पर भारतीय मानसून वर्षा और चक्रवात-जनन का उष्मन और शीतलन प्रावस्थाओं के परिप्रेक्ष्य में परीक्षण किया गया है। ये प्रावस्थाएँ भारतीय मानसून वर्षा के साथ प्रबल रूप और प्रतिलोमी रूप में सम्बद्ध हैं। निम्न दाब प्रणालियों के निर्माण से इनका संबंध प्रतिलोम है और 5 प्रतिशत स्तर पर सार्थक है।

पूर्वदक्षिण भूमध्य प्रशान्त महासागर के उष्मन और सामान्य से कम भारतीय मानसून वर्षा के मध्य संबंध गर्म पूर्वदक्षिण भूमध्य प्रशांत महासागर तथा भारतीय मानसून वर्षा के बीच संबंध की अपेक्षा अधिक प्रबल पाया गया है। जो यह सूचित करता है कि उष्मन प्रावस्था, मानसून परिसंचरण को गर्म पूर्वदक्षिण भूमध्य प्रशान्त महासागर की अपेक्षा अधिक प्रभावित करता है। एल-नीनो और भारतीय मानसून वर्षा के मध्य संबंध यद्यपि काफी महत्वपूर्ण है परन्तु वह उष्मन और सामान्य से कम भारतीय मानसून वर्षा के बीच संबंध की अपेक्षा काफी क्षीण हैं।

दिस. जन. फर. से जून जुलाई अगस्त एस. ओ. आई. प्रवृत्ति के लिए एस. एस. टी. परिवर्तन और दक्षिणी दोलन सूचकांक (एस. ओ. आई.) के मध्य संबंधों का भी परीक्षण किया गया है और उनकी तुलना एस. एस. टी. के परिवर्तनों और भारतीय मानसून वर्षा के बीच संबंधों से की गई हैं। परवर्ती का संबंध पूर्ववर्ती की तुलना में अधिक प्रबल पाया गया है। यह संकेत करता है कि मानसून ऋतु के अन्त में भारतीय मानसून वर्षा पर उष्मन और शीतलन का प्रभाव दक्षिणी दोलन सूचकांक प्रभाव की अपेक्षा अधिक प्रबल होता है।

सतत उल्लेखनीय दक्षिणी दोलन सूचकांक में परिवर्तनों का बढ़ना/कम होना वस्तुपरक कसौटी द्वारा पता लगाया गया जो कि उनके बराबर है जिनका प्रयोग उष्मन/शीतलन का पता लगाने के लिए किया जाता है। दक्षिण दोलन सूचकांक में परिवर्तनों (बढ़ना, थोड़े परिवर्तन, कम होना) और भारतीय मानसून वर्षा के मध्य संबंध की तुलना समुद्री सतह तापमान के परिवर्तनों और मानसून वर्षा के बीच संबंध से की गई। इसके बाद वाला संबंध पहले से अधिक प्रबल पाया गया है जो दक्षिणी दोलन सूचकांक के बढ़ने/कम होने के प्रभाव की अपेक्षा भारतीय मानसून वर्षा पर पूर्वदक्षिण भूमध्य प्रशांत महासागर के उष्मन/शीतलन का अपेक्षाकृत अधिक प्रभाव दर्शाता है।

ABSTRACT. Utilizing the seasonal SST anomaly and the objective criteria, warming and cooling phases of the ESE Pacific are identified during 1871-1984. The Indian monsoon rainfall (IMR) and cyclogenesis over India and neighbourhood during the summer monsoon are examined in relation to warming and cooling phases. These phases are strongly and inversely associated with IMR. Association with the formation of low pressure systems is inverse and significant at 5% level.

The association between warming of ESE Pacific and below normal IMR is found to be far stronger than that between warm ESE Pacific and IMR, suggesting that warming phase influences the monsoon circulation much more than the warm ESE Pacific. The association between *El Nino* and IMR though highly significant is relatively much weaker than that between warming and below normal IMR.

The associations between the SST changes and Southern Oscillation Index (SOI) for JJA and SOI tendency from DJF to JJA are also examined and these are compared with that between the SST changes and IMR. The latter is found to be much stronger than the former, indicating the stronger influence of warming and cooling phases on IMR than on SOI by the end of the monsoon season.

Sustained notable SOI changes, rise/fall, were identified by objective criteria which are equivalent to those used for identifying warming/cooling. The association between SOI changes (rising, small change, falling) and IMR was compared with that between SST changes and IMR. The latter is found to be much stronger than the former, showing stronger influence of warming/cooling of ESE Pacific on IMR than that of rising/falling SOI.

1. Introduction

Southern Oscillation (SO) described by Walker and Bliss (1930) as interannual variations in the exchange of mass between the Indian and Pacific Oceans, has been linked by Bjerknes (1969) to variations in SST in the tropical Pacific through the Walker circulation. SO can be considered as atmospheric response to the interannual variations in the distribution of SST over tropical Pacific and Indian Oceans. Alternatively, in view of the interaction at the ocean-atmosphere interface, variations in the SST distribution over the tropical Pacific and Indian Oceans can be considered as the dynamic response of the ocean to the SO.

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Flohn and Fleer (1975) who made a preliminary survey of climatic anomalies in various tropical regions found that several *El Nino* phenomena were followed by drought conditions during the subsequent monsoon season over India.

On the basis of data for 1925–70, Khandekar (1979) found that mean SST (April-May) at Puerto Chicama, Peru (7°42′S, 79°27′W) is inversely related to Indian monsoon rainfall (June–September). He obtained a correlation coefficient of — 0.36, significant at 5%. He suggested this as a possible physical link between pre-monsoon conditions over the equatorial Pacific and subsequent Indian monsoon rainfall.

Sikka (1980) examined Indian monsoon rainfall in *El Nino* years during the period 1875–1975. He found that out of 22 *El Nino* years during the period, in 12 years there was monsoon failure, but in 7 years there was no monsoon failure at all. He also found that there were 3 years of monsoon failure in which the *El Nino* event did not occur. This investigation brought out an out-of-phase relationship in some years between monsoon rainfall over India and the rain over eastern/central Pacific, suggesting very large-scale teleconnections operating through the displacement of the Walker circulation due to changes in the thermal forcing in equatorial regions on a planetary scale.

Angell (1981) found that the Indian monsoon rainfall is related at high significance levels to the SST anomaly over Eastern Equatorial Pacific (EEP), one to two seasons later. Rasmusson and Carpenter (1983) found a strong tendency for below normal monsoon rainfall over India and Sri Lanka during the 25 moderate/strong warm episodes. For the periods of inadequate ships' observations (1875–1920, 1939–1947) they took the *El Nino* events tabulated as moderate and strong by Quinn *et al.* (1978). For the remaining period they identified these events from Peru-Ecuador coast SST data by the criterion, maximum positive anomaly of + 1° C or more and an anomaly change from the largest negative anomaly of the previous year to the largest positive anomaly of the warm episode year $\geqslant 2.5°$ C. The criteria followed by Quinn *et al.* (1978) are, SST anomaly along Peru-Ecuador coast $\geqslant 3.0°$ C for strong *El Nino* and $\geqslant 2.0°$ C for moderate *El Nino*.

Mooley and Parthasarathy (1983) examined Indian monsoon rainfall in years of *El Nino* events as identified by Quinn *et al.* (1978). They showed that the mean rainfall for the 22 *El Nino* years was 8.5% below normal. They found significant (at 5%) association between *El Nino* and deficient rainfall.

Mooley and Parthasarathy (1984 a) brought out that the highly significant (0.1% level) inverse relationships between Indian monsoon rainfall and SST over EEP for the concurrent JJA season and the following SON and DJF seasons show high stability in significance over 30-year periods, the stability for SON and DJF being higher than that for JJA.

Khandekar and Neralla (1984) showed that the major drought (flood) years are associated with warmer (cooler) than normal eastern equatorial Pacific SST values before, during and after the monsoon season.

Mooley *et al.* (1985) brought out that the difference in the means of SST anomaly in drought and flood years increased successively from MAM through DJF season, the difference for DJF being 1.6° C.

Parthasarathy and Mooley (1985) examined the mean rainfall for strong, moderate, weak and very weak *El Nino* events as identified by Quinn *et al.* (1978) and found that the mean rainfall increased with the decrease in the intensity of the *El Nino* events and that the mean rainfall in the strong *El Nino* years was 14 per cent below the long-term mean.

The SST anomaly changes over the large area, like the eastern south equatorial Pacific Ocean, 0°–10° S, 180°W,/80°W, affect the large-scale oceanic and atmospheric processes over the Pacific and the Indian Ocean, resulting in circulation changes which in turn have an impact on rainfall over large areas. The main objective of this study is to examine the characteristics of the SST anomaly changes over this portion of the eastern equatorial Pacific, the response of the Indian monsoon to these changes and to compare this response with that of Southern Oscillation.

2. Data

The series for the seasonal SST anomaly over the eastern south equatorial Pacific (0°–10°S, 180°–80°W) Ocean (hereafter, ESE Pacific) is obtained from Angell who updated it up to 1985. The series for the area 0°–10°S, 180°–90° W up to 1980 is used earlier by Angell (1981). The updated series obtained from Angell is used for the period 1871–1984 in the present study.

Global Comprehensive Ocean-Atmosphere Data Sets (COADS) which were generated by merging several historical marine data sets are also available. However, as mentioned by Lander and Morrissey (1987), duplicate ships reports remain in COADS products despite the rigorous efforts made to eliminate them. Steurer (1987), in reply to Lander and Morrissey, pointed out that an error existed in the processing scheme of Lander and Morrissey for locating duplicates and that this error overestimates the duplicates by 7%. According to him, for most surface marine applications, the telecom duplicates found by Lander and Morrissey are negligible. Steurer also drew attention to the additional sources of potential duplicates of similar magnitude described by Slutz *et al.* (1985). We have, however, preferred to use the SST anomaly series prepared by Angell (1981) on the basis of the SST series compiled at the Environmental Research Laboratories of NOAA at Boulder, Colorado, and updated by him.

Area-averaged Indian summer monsoon (June through September) rainfall (hereafter, Indian monsoon rainfall, IMR) series for the period 1871–1978 as used by Mooley and Parthasarathy (1984) and updated up to 1984 by Mooley *et al.* (1986) has been used. The series is based on monthly rainfall from a fixed network of 306 raingauges evenly-distributed over the non-hilly regions of India. In addition, area-averaged monsoon rainfall series are prepared for three divisions, *viz.*, north, central and south India (for these areas, *see* Mooley and Shukla 1989, Fig. 4, p. 141) and for the different sub-divisions of India for the period 1871–1984 from the monthly station rainfall data. This study covers the plain region which constitutes 88% of the total Indian area, which will hereafter be referred to as India or the country.

Information in respect of the number of low pressure systems which formed over the Indian region, during the monsoon season in each of the years 1888-1983, is collected from the *Indian Daily Weather Reports* and *Pakistan Daily Weather Reports*.

Darwin (12.4° S, 130.9° E) seasonal mean sea level pressure which is available for a long period has been used as a measure of SOI. These data for the period 1882-1984 were obtained from the National Centre for Atmospheric Research (NCAR).

3. SST changes over ESE Pacific

3.1. *Type of changes considered*

We have considered SST anomaly changes to eliminate the seasonal variation. Hereafter, these would be referred to as SST changes.

An examination of the seasonal SST anomaly of the ESE Pacific shows that there are periods of rise and of fall in the anomaly. In this study, notable changes of a sustained nature are considered since such changes are likely to influence circulation. Since the effect of a change in SST anomaly on the atmospheric circulation is expected to depend not only on the amount of the change in the SST anomaly, but also on the anomaly attained consequent on the change, both the amount of change and the SST anomaly attained are utilized in developing the criteria for sustained notable SST changes.

Quinn *et al.* (1978) adopted the criterion of SST anomaly of $\geqslant 2.0°$ C over the narrow ocean strip off Peru-Ecuador coast (0° to 12° S) for identifying a moderate *El Nino* or warm event. Considering the fact that ESE Pacific is much larger in comparison to the ocean strip off Peru-Ecuador coast, attainment of an SST anomaly of $\geqslant 1°$C or $\leqslant -1°$C would be quite adequate criterion pertaining to the amount of change. It is, however, possible that a numerically smaller SST anomaly attained in combination with a larger magnitude of SST anomaly change may also lead to a notable change in atmospheric circulation. The changes which are proposed to be considered are sustained and notable increase or decrease in SST anomaly of ESE Pacific, and shall be termed warming and cooling phases respectively, during the period 1871-1984.

3.2. *Criteria for warming and cooling phases*

The following criteria are laid down for warming and cooling phases of ESE Pacific :

> *Warming (cooling) phase* — (*i*) Progressive increase (decrease) in SST anomaly over three or more seasons totalling $\geqslant 1°$C and resulting in attainment of SST anomaly of $\geqslant 1°$C ($\leqslant -1°$ C), or, (*ii*) if x, the anomaly attained is $< +1°$C ($> -1°$C), but the increase (decrease) in SST anomaly is $\geqslant 1 + y°$C, where y is the amount by which x falls short of 1°C (exceeds —1°C), thus compensating a numerically smaller SST anomaly attained by a larger SST increase (decrease).

TABLE 1

Years of warming/cooling phases of ESE Pacific during the period 1871-1984

Warming phase years	Cooling phase years
1876, 1877, 1883, 1888, 1896, 1899, 1902, 1904, 1905, 1911, 1913, 1918, 1925, 1930, 1939, 1940, 1941, 1948, 1951, 1957, 1963, 1965, 1968, 1969, 1972, 1976, 1982	1872, 1874, 1878, 1885, 1889, 1892, 1897, 1898, 1900, 1903, 1906, 1908, 1916, 1938, 1942, 1946, 1954, 1955, 1964, 1967, 1970, 1973, 1983

The calendar year in which the highest (lowest) SST anomaly occurs is taken as the year of warming (cooling) phase. When warming (cooling) covers 6 or more seasons, then apart from considering the year of the highest (lowest) SST anomaly, the other year is also considered as warming (cooling) year, if for two consecutive seasons in that year the mean anomaly is $\geqslant +0.5°$C ($\leqslant -0.5°$C).

Examples will make the definition of warming (cooling) clearer. The SST changes over three seasons, from anomaly 0.0 to +1.0°, from —1.1°C to +0.5°C, and from —2.5°C to —0.2°C are all categorized as warming, and those from +0.0°C to —1.0°C, from —0.4°C to —2.1°C, and from 2.5°C to +0.1°C are all categorized as cooling.

3.3. *Years of warming and cooling phases*

Following these criteria objectively, years of warming/cooling phase over ESE Pacific are identified by an examination of the SST anomaly. These years are listed in Table 1; the remaining years are generally found to have small SST changes and will hereafter be referred to as years with small SST change. There are 27 warming years, on an average one per four years. The two successive warming years with the longest interval are 1930 and 1939. The decadal frequency of warming year was mostly 2. The decade 1961-70 had the highest frequency of 4. The number of cooling years is 23, *i.e.*, on an average of one per five years. Two successive cooling years with the longest interval are 1916 and 1938. The decadal frequency of cooling years exhibits high variability. The occurrence of each of the two events is found to be random when tested by Swed and Eisenhart's test.

3.4. *SST anomaly in warming and cooling years*

(*a*) *Mean anomaly* — Fig. 1 shows the mean SST anomaly over ESE Pacific in warming/cooling years for different seasons. The season of warming/cooling year is denoted by 0 in parentheses and of preceding and succeeding year by —1 and +1 in parentheses respectively. It is seen that the mean SST during warming years commences to rise progressively from SON (—1) to DJF (+1), the total rise in the mean being 1.4°C. The mean for the cooling years starts falling progressively from DJF (0) to DJF (+1), the total fall in the mean being 1.4°C. The difference between the means for warming and cooling years increases progressively from 0.3°C in MAM (0) to 1.8°C in DJF (+1).

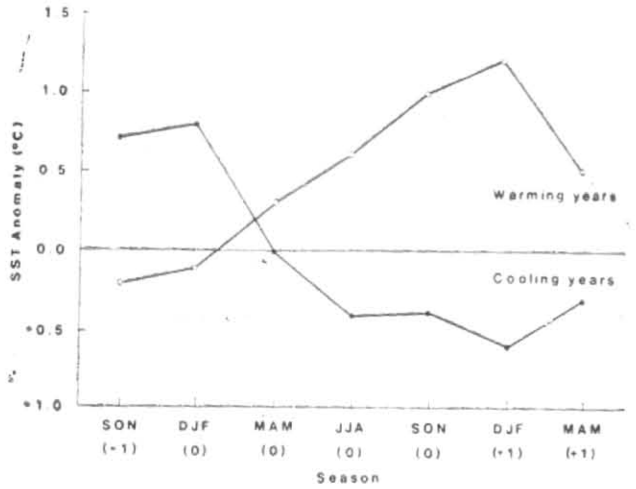

Fig. 1. Mean SST anomaly over ESE Pacific in warming and cooling years. (0) indicates season of warming/cooling year, and (+1)/(−1) indicate season of the following/preceding year

(*b*) *Anomaly in individual years of warming and cooling phases* — SST anomaly is shown separately for warming and for cooling years in Fig. 2 for the seasons DJF (0), MAM (0), JJA (0), SON (0), and DJF (+1). It may be remembered that in some of the years the rise or fall commences from SON (—1) which is not shown in Fig. 2. This figure is primarily designed to bring out the main features of SST anomaly change with season in the two groups of years. It is seen that for warming and cooling years there is a notable change from DJF (0) to MAM (0). In a majority of the warming years, SST changed from negative to positive. The change was exactly reverse, but more marked, for cooling years. After MAM (0), there is a progressive increase in positive anomaly in warming years and in the magnitude of negative anomaly in cooling years. The contrast between the groups of warming and cooling years, on the whole is very good in JJA (0) and SON (0) and is maximum in DJF (+1).

The most spectacular warming and cooling of ESE Pacific occurred in the successive years 1877 and 1878. From DJF 1877 to DJF 1878, SST anomaly rose from 0.3°C to 3.2°C, *i. e.*, a rise of 2.9°C, and from DJF 1878 to JJA 1878, SST anomaly fell from 3.2°C to 0.3°C. These are the steepest rise and the steepest fall in SST anomaly during 1871-1984. SST observations in 1877-78 are far fewer than those in the last 3-4 decades. In this connection, it may be mentioned that Kiladis and Diaz (1986) found that SST observations over the eastern south equatorial Pacific for 1877-78 are highly coherent over the domain used by them, with nearly all data points showing positive anomalies during this period, and that SST anomalies dacayed fast in 1878.

3.5. *Years of warming phase in relation to El Nino years*

Table 2 gives the years of warming of ESE-Pacific as well as *El Nino* years during the period 1871-1984. The *El Nino* years are taken from Quinn *et al.* (1978). In addition, the years classified by Rasmusson and Carpenter (1983) as *El Nino* or warm episode during the periods 1921-38 and 1948 onwards and the widely known *El Nino* year 1982, have also been included.

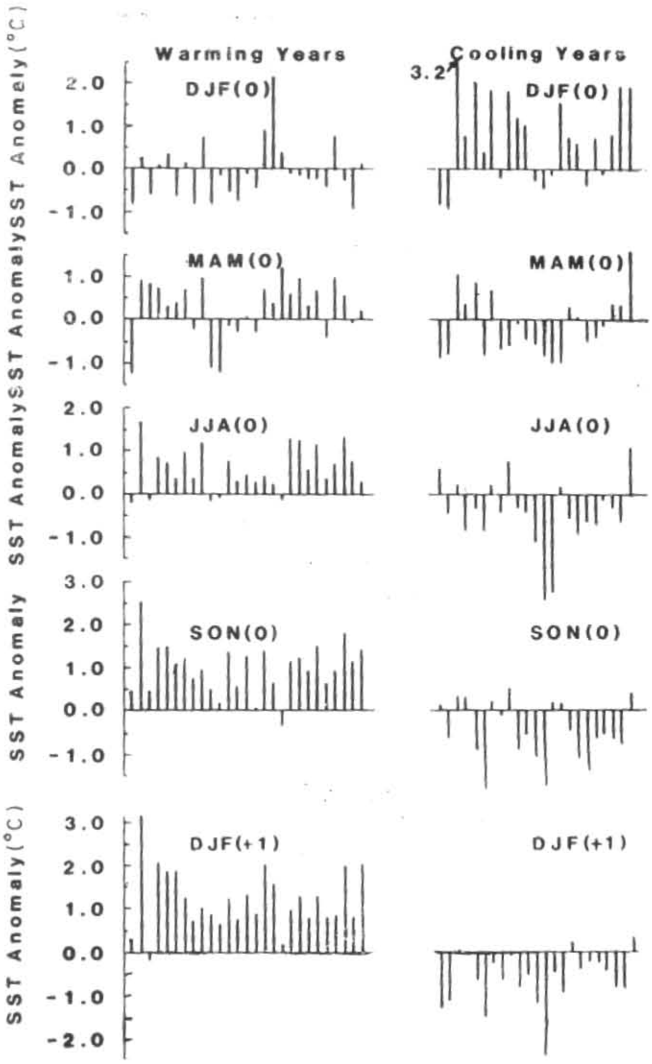

Fig. 2. SST anomaly during warming and cooling years in different seasons. (0) indicates seasons of the warming and cooling years and (+1) indicates season of the following year

TABLE 2

Years of warming of ESE Pacific and years of *El Nino* event during the period 1871-1984

	Warming years	Non-warming years
El Nino years	1877, 1896, 1899, 1902, 1905, 1911, 1918, 1925, 1930, 1939, 1941, 1951, 1957, 1965, 1969, 1972, 1976, 1982	1871, 1880, 1884, 1887, 1891, 1914, 1923, 1929, 1932, 1953
	(18)	(10)
Non-*El Nino* years	1876, 1883, 1888, 1904, 1913, 1940, 1948, 1963, 1968	
	(9)	(77)

Note : Cell frequencies are given within parentheses.

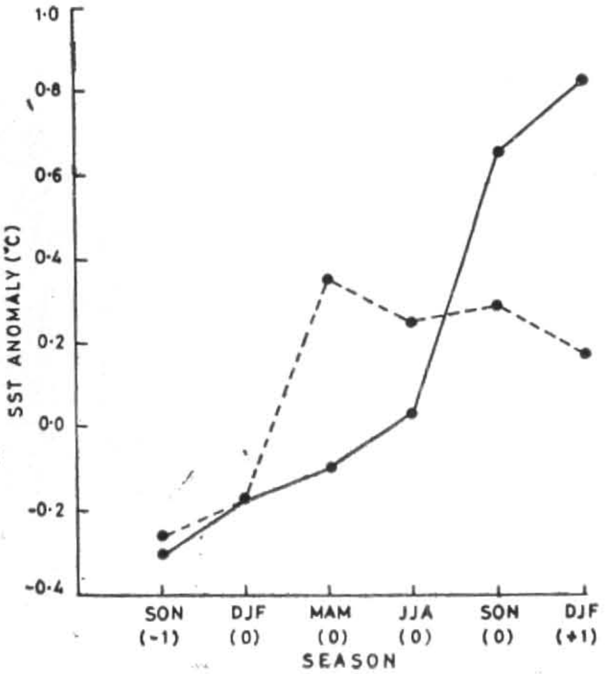

Fig. 3. Mean seasonal SST anomaly of ESE Pacific for 9 warming, but not *El Nino* years (continuous line) and for 10 *El Nino*, but not warming years (broken line)

There are 27 warming years and 28 *El Nino* years. Table 2 shows that there are 18 warming years which are also *El Nino* years, 9 warming years which are not *El Nino* years and 10 *El Nino* years which are not warming years. This brings out that *El Nino* and ESE warming need not go together. Hickey (1975), Barnett (1977) and Rasmusson and Carpenter (1980) showed that the large-scale SST anomalies appearing off Peru coast during *El Nino* event spread westward along the equator. From their comprehensive analysis of the composite SST data from the tropical Pacific for the six warm episode years, 1951, 1953, 1957, 1965, 1969 and 1972, Rasmusson and Carpenter (1982) clearly demonstrated that the large-scale anomalies off Peru coast spread northwestwards and then westwards along the equator to longitude 170°W in 3 to 6 months. From the analysis of the SST anomalies of the equatorial Pacific (4° N-4° S, 120° E-80° W) associated with individual ENSO events during 1940-83, Fu *et al.* (1986) found SST warmer than normal almost everywhere, especially west of 150° W in two events, suggesting absence of westward migration of the positive SST anomalies. *Climate Diagnostic Bulletins* issued by National Met. Centre, Washington D.C., U.S.A., indicate a rather notable change in SST anomaly over the Pacific area (5° N-5° S, 160° E-150° W) from October to January, prior to onset of *El Nino*. It may be noted that in 18 *El Nino* years, the large-scale positive SST anomalies from Peru coast spread westwards to the international dateline, or positive anomalies spread to eastern equatorial Pacific by some other mechanism, resulting in the warming phase of the ESE Pacific. However, in 10 *El Nino* years, the large-scale positive anomalies did not spread to eastern equatorial Pacific. Fig. 3 shows the mean SST anomaly for 10 *El Nino* but non-warming years and also for 9 warming but non-*El Nino* years for different seasons and brings out the appreciable difference between the two sets of years. (0) below the season indicates the seasons of the warming/*El Nino* year and (—1) and (+1) indicate the season of the preceding and following years. After reaching a peak in MAM (0) the mean SST anomaly for non-warming *El Nino* years generally fell from MAM (0) to DJF (+1), suggesting a suppression of the spreading of the positive SST anomalies to ESE Pacific. However, for the non-*El Nino* warming years the SST anomaly continued to rise progressively during the same period. It is reasonable to infer that during the 9 non-*El Nino* warming years, the mechanism of warming must have been different. Barnett (1977) has indicated surfacing of the equatorial undercurrent and meridional shifts in the North Equatorial Countercurrent as mechanisms that could cause SST changes in central Pacific in addition to the westward migration of the SST anomalies from Peru coast.

4. Response of Indian monsoon to changes in SST of ESE Pacific

4.1. *Monsoon rainfall over India*

The influence of ESE Pacific warming/cooling phases has been examined on area-averaged monsoon rainfall of India, on area-averaged monsoon rainfall of three divisions of India, north, central and south India, and area-averaged monsoon rainfall of the meteorological sub-divisions of India.,

To bring out the character of rainfall, the rainfall categories as defined below are used:

	Standardized rainfall anomaly
Drought	⩽—1.28
Deficient	<—0.50 but >—1.28
Normal	⩽+0.50 but ⩾—0.50
Excess	<+1.28 but >+0.50
Flood	⩾+1.28

Standardized anomaly is deviation from the mean divided by standard deviation.

In contingency tables, the rainfall classes used are, below normal which combines drought and deficient rainfall, normal as it is defined above, and above normal which combines excess and flood. These three classes, below normal, normal and above normal, correspond approximately to tercile classes of rainfall distribution.

4.1.1. *Indian monsoon rainfall*

Table 3 gives the normalized rainfall anomaly in years of warming/cooling, the mean anomaly for the two groups of years, and the frequency of each rainfall category. This table clearly brings out that during warming years India does not experience any excess rain or flood and during cooling years the country does not experience drought or deficient rainfall. The means for the two groups of years show a strong contrast. On average, the mean IMR during warming years is 8.7 cm (10.2%) below the long-period mean and that during cooling years, 6.2 cm (7.3%) above the mean. In extreme cases, the rainfall was 24.8 cm (29.1%) below the normal and 13.8 cm (16.2%) above the normal. It may be noted that the mean IMR in the 28 *El Nino* years was 8.2% below the long-period mean. The mean deficiency of rainfall in warming years is 2% more than that in *El Nino* years, indicating the stronger adverse influence

TABLE 3

Normalized anomaly of Indian monsoon rainfall and frequency of each category of Indian monsoon rainfall during years of warming and cooling over ESE Pacific

S. N.	Years of warming event	Normalized rainfall anomaly	Years of cooling event	Normalized rainfall anomaly
1	1876	—0.92	1872	0.70
2	1877	—2.99	1874	1.43
3	1883	—0.04	1878	1.47
4	1888	—0.51	1885	—0.12
5	1896	—0.34	1889	0.90
6	1899	—2.70	1892	1.66
7	1902	—0.73	1897	0.46
8	1904	—1.24	1898	0.34
9	1905	—1.65	1900	0.40
10	1911	—1.43	1903	0.07
11	1913	—0.84	1906	0.37
12	1918	—2.46	1908	0.52
13	1925	—0.59	1916	1.18
14	1930	—0.63	1938	0.67
15	1939	—0.76	1942	1.28
16	1940	—0.02	1946	0.59
17	1941	—1.48	1954	0.40
18	1948	+0.24	1955	0.94
19	1951	—1.39	1964	0.82
20	1957	—0.82	1967	0.08
21	1963	+0.04	1970	1.05
22	1965	—1.75	1973	0.72
23	1968	—1.18	1983	1.29
24	1969	—0.28		
25	1972	—2.40		
26	1976	+0.04		
27	1982	—1.40		
	Mean	—1.05	Mean	+0.75

Frequency of rainfall category		*Frequency of rainfall category*	
Drought	10	Drought	0
Deficient	10	Deficient	0
Normal	7	Normal	8
Excess	0	Excess	10
Flood	0	Flood	5

Note : Long period (1871-1984) normal rainfall 85.2 cm and S.D. 8.3 cm.

of warming of ESE Pacific on Indian rainfall than that of *El Nino*. There are only 3 warming years, 1948, 1963 and 1976 with small positive rainfall anomaly and there is only one cooling year, 1885, with small negative rainfall anomaly. It may be noted that the standardized anomaly of IMR was —2.99 in 1877, the year of steepest rise in SST anomaly and it was +1.47 in 1878, the immediately following year with steepest fall in SST anomaly. There are 11 pairs of successive years of warming followed by cooling and amongst these, the pair 1877-78 has the maximum contrast in IMR. The character of rainfall during the two groups of years as given in Table 3 clearly brings out the strong influence of the changes in ESE Pacific SST on IMR. There is thus a strong tendency for below/above normal monsoon rainfall during warming/cooling years.

TABLE 4

Association between Indian monsoon rainfall and SST changes over ESE Pacific (three classes of rainfall — below normal, normal and above normal; three classes of SST changes — cooling, small change and warming). Period 1871-1984

Type of SST change	Indian monsoon rainfall			Total
	Below normal	Normal	Above normal	
Cooling	0 (6.86)	8 (8.07)	15 (8.07)	23
Small change	14 (19.10)	25 (22.46)	25 (22.46)	64
Warming	20 (8.05)	7 (9.47)	0 (9.47)	27
Total	34	40	40	114

Chi-square = 42.90 (4 d.f.)

Chi-square significant at 0.1% = 18.47 (4 d.f.)

Note : (*i*) Above normal : rainfall normalized anomaly >0.5
Normal rainfall : normalized anomaly between +0.5 and —0.5
Below normal rainfall ; normalized anomaly <—0.5

(*ii*) Cell frequencies in parentheses give frequencies on the null hypothesis of independence

To assess the strength of the association between the changes in ESE Pacific SST and IMR, contingency table is prepared for 3 classes of rainfall (below normal, normal and above normal as indicated earlier) and three classes of changes in SST (warming, small change and cooling) and is tested for strength of association by applying the Chi-square test. Chi-square for the contingency table (Table 4) is 42.90 (4 d.f.). This very high value in comparison to 18.47, the value significant at 0.1% level for 4 d.f. shows a very strong inverse association between the changes in SST over ESE Pacific and the IMR.

For the contingency table with two classes, warming, non-warming for condition of ESE Pacific, and below normal and not below normal for IMR the Chi-square value is 33.13 (1 d.f.), the value significant at 0.1% level being 10.83% (1 d.f.). However, for a similar table with *El Nino* and no *El Nino* and below normal and not below normal rainfall classes, the Chi-square is 16.92 (1 d.f.). Thus the association between warming phase of ESE Pacific and below normal rainfall is much stronger than that between *El Nino* and below normal rainfall.

The association between the thermal condition of ESE Pacific and IMR is also examined. ESE Pacific is defined as warm (cold) if for two consecutive seasons in a year mean SST anomaly is ≥+1.0° C (≤—1.0°C) and for immediately preceding or succeeding season the SST anomaly is positive (negative). With these criteria, the years with warm (cold) ESE Pacific are identified. Using 3 classes of the thermal condition of ESE Pacific, warm small anomaly and cold, and 3 classes of IMR, below, normal, normal, and above normal, a contingency table is prepared. Chi-square for this table is 12.76 (4 d.f.),

TABLE 5

Association between thermal condition of ESE Pacific and IMR (1871-1984)

Thermal condition of ESE Pacific	Indian monsoon rainfall			Total
	Below normal	Normal	Above normal	
Cold	3	2	9	14
Small SST anomaly	19	31	27	77
Warm	12	7	4	23
Total	34	40	40	114

$\chi^2=12.76$ (4 d.f.), $\chi^2_{.05}=9.49$ (4 d.f.)

significant above 5% level. As noted above, Chi-square for a similar table between SST changes and IMR is 42.9 (4 d.f.). Thus the association between SST anomaly changes and IMR is far stronger than that between thermal condition of ESE Pacific and IMR, indicating that SST changes influence the monsoon much more strongly than the thermal condition of ESE Pacific.

Association between the warming of ESE Pacific and low normal IMR is compared with that between warm ESE Pacific and below normal IMR. It is found that the adverse influence of warming of ESE Pacific on IMR is far stronger than that of warm ESE Pacific. Examples of the cooling years, 1878, 1889, 1897, 1942 and 1983 clearly bring this out. In these years, the mean SST anomalies for the period DJF to JJA were 1.50°, 0.90°, 0.95°, 0.90° and 1.6° C respectively and normalized IMR anomalies were 1.47, 0.90, 0.46, 1.28 and 1.29 respectively. Similarly, there are warming years with SST anomalies of —0.50° C or less and below normal IMR. It is the changes in SST anomaly in these years and not the SST anomaly that influenced the Indian monsoon.

A comparison of the association between warming of ESE Pacific and IMR with that between cooling of ESE Pacific and IMR shows that the former association is much stronger (Chi-square 33.13, d.f. 1) than the latter (Chi-square, 11.48, d.f. 1).

4.1.2. *Area-averaged monsoon rainfall of north India, central India and south India*

The influence of warming/cooling over ESE Pacific has been examined for north India, central India, and south India (for these areas, *see* Mooley and Shukla 1989) which respectively cover 27.1%, 40.0% and 32.9% of the Indian area. Examination of the monsoon rainfall over these divisions, in individual years of warming/cooling, shows that for each of these divisions there is no occurrence of flood/drought in warming/cooling year. In a majority of the years of warming, central and south India experienced deficient rainfall or drought and in a majority of the years of cooling, south India experienced excess rainfall or flood. Central India experienced excess rain or flood in 45% of the cooling years. 3×3 contingency tables similar to that for India are prepared for north India, central India and south India to examine the association between monsoon rainfall and SST changes. Chi-square values for these contingency tables are respectively 9.39, 32.05 and 33.43, d.f. being 4 in each case, suggesting strong association (significant above 0.1% level) with monsoon rainfall of central India and south India, and weak association (just significant at 5% level) with monsoon rainfall of north India. As will be noted from Chi-square value, the association with IMR is stronger than that with monsoon rainfall over central India and south India. Thus, the association is strongest for the largest spatial scale of monsoon rainfall.

4.1.3. *Monsoon rainfall of meteorological sub-divisions of India*

The area of the sub-division (Mooley and Shukla 1989) varies from 0.18×10^5 to 2.32×10^5 sq. km, *i. e.*, about one order of magnitude. An examination of the monsoon rainfall anomaly during the warming and cooling years for the different meteorological subdivisions has been made. Rainfall anomaly is found to be chaotic. The rainfall of the sub-divisions appears to be overshadowed by the local factors which strongly influence the rainfall over the smaller sub-divisional areas.

4.2. *On cyclogenesis over India and neighbourhood during the monsoon season*

A large number of low pressure systems (LPS) form over India, adjoining countries, the Bay of Bengal and the Arabian Sea during the monsoon season. In fact, this is the season of maximum cyclogenesis over this area. To find out if the warming and cooling of ESE Pacific exert any influence on the formation of these systems, the difference between the means of LPS formation frequency for warming and cooling years is computed and the same is tested by Student's t-test (2-tailed test). The difference between the two means is 1.7 which is about 13% of the mean frequency of formation of LPS for the period 1888-1983. The variances of the two samples are not significantly different. The value of the test statistic t is 2.26 (d.f. 40) which is significant at 2% level. Application of the Mann-Whitney test also shows that the number of LPS formed in cooling years is higher than that in warming years at a level of significance of 2%. Thus both the tests suggest that there is a significant tendency for frequency of LPS formation to be lower during warming years than that during cooling years. The warming/cooling of ESE Pacific appears to exert an adverse/favourable influence on the cyclogenesis over the India and neighbourhood during the monsoon season.

5. Response of Southern Oscillation (SO) to SST changes over ESE Pacific

5.1. *Type of changes produced in southern oscillation index*

An examination of SOI anomaly during all the periods of warming (cooling) shows that while in a majority of the cases there is an associated progressive rise (fall) of SOI anomaly of 1 to 3 mb over 3 or more seasons, commencing either in the same season, earlier season or later season, in a number of cases there is no rise (fall) corresponding to warming (cooling). It is also noticed that there are cases of similar rise (fall) in SOI anomaly

TABLE 6

Response of SOI anomaly to warming (cooling) of ESE Pacific (1882–1984)

	No. of cases when commencement of rise (fall) in SOI anomaly had a lag of :					No. of cases with no rise (fall) in SOI anomaly	No. of occasions with rise (fall) in SOI anomaly without warming (cooling)
	—2	—1	0	1	2		
	0(1)	3(2)	8(9)	7(3)	1(0)	6(5)	8(9)
Mean rise (fall) in SST anomaly (°C)	(2.3)	1.7(1.8)	1.5(2.0)	1.8(1.7)	1.7	1.4(1.6)	0.25(0.15)
Mean rise (fall) in SOI anomaly (mb)	(3.0)	1.8(1.9)	2.1(2.3)	2.4(2.2)	2.0	0.0(0.1)	1.8(1.9)

Note : Lag 1 means commencement of SOI anomaly rise (fall) one season after the season of commencement of SST anomaly rise(fall)

not associated with warming (cooling). Table 6 shows the response of SOI to warming (cooling) of ESE Pacific and its lag, as well as the number of cases of rise (fall) in SOI anomaly not associated with warming (cooling). Lag in the commencement of response is given in seasons. Lag 1 means response of SOI commences one season later than commencement of warming (cooling). In about 60% of the cases of warming (cooling) SOI anomaly rise (fall) commences either with SST rise (fall) or later. In 19 cases, SOI anomaly rises in response to warming of ESE Pacific and in 15 cases, it falls in response to cooling of the ESE Pacific; however, in 6 cases of warming and in 5 cases of cooling, this type of response in SOI is not produced. It is noteworthy that there are 8 (9) cases of similar rise (fall) in SOI anomaly not associated with warming (cooling) of ESE Pacific. This clearly suggests that apart from warming (cooling), of ESE Pacific, there are other factors which produce this type of rise (fall) in SOI anomaly. Table 6 also gives in the second and third rows respectively the mean rise (fall) in SST in warming (cooling) and the mean rise (fall) in SOI anomaly for the different types of cases as given in the first row. It may be seen from the last and last but one column of Table 6 that for cases of SOI anomaly rise (fall) not associated with warming (cooling) the mean SST change is very small, and for the cases of warming (cooling) not associated with rise (fall) in SOI anomaly, the mean SOI anomaly change is near zero respectively.

5.2. *Association between SOI and SST changes*

We shall first examine the strength of association between SOI anomaly for JJA (0) season and SST changes. JJA season and the monsoon season differ slightly. The three classes of SOI anomaly considered are based on the standardized SOI anomaly, the limits for standardized anomaly being the same as for the three classes for rainfall, *viz.*, <-0.5, -0.5 to $+0.5$ and $>+0.5$. The classes with these limits are referred to as below normal, normal and above normal. The three classes of SST changes are warming, small change and cooling. Table 7 brings out the association between SOI anomaly and SST changes. Chi-square for the table is 23.70 (4d. f.). The association is direct and is significant at 0.1% level. Similar tables for SOI anomaly for the later seasons, SON (0), DJF (+1) and MAM (+1), give Chi-square values of 39.56, 44.31 and 16.88 respectively. It is seen that the strength of the association between SST change and the SOI anomaly increases from JJA (0) to DJF (+1) and thereafter the strength of the association decreases sharply. Even for SOI anomaly for MAM (+1), the association is significant at 1% level. It is worth noting that the association between SST changes and IMR is about as strong as that between SST changes and SOI anomaly for DJF (+1) season, *i.e.*, two seasons after monsoon season. The association of SST changes with IMR is much stronger ($\chi^2=42.90$, Table 4) than that with SOI anomaly for JJA (0) season which differs slightly from the monsoon season; this brings out the stronger influence of SST changes on IMR.

TABLE 7

Association between SST changes and SOI for JJA (0) season (1882–1984)

SST change	SOI			
	Below normal	Normal	Above normal	Total
Cooling	10	8	2	20
Small change	20	26	12	58
Warming	1	8	16	25
Total	31	42	30	103

$\chi^2=23.70$ (4 d.f.), significant at 0.1% level

We shall next examine the association between SST changes and SOI anomaly tendency from DJF (0) to JJA (0). We consider three classes of SOI anomaly tendency based on the same limits of standardized anomaly. Chi-square for the contingency table between SST changes and SOI anomaly tendency is 29.0 (4 d. f.) which is much smaller than that for the contingency table between SST changes and IMR, thus indicating the larger influence of SST changes on IMR. Similar contingency tables for SOI anomaly tendencies from DJF (0) to SON (0) and DJF (0) to DJF (+1) have Chi-square values of 39.79 (4 d.f.) and 35.98 (4 d.f.), showing stronger association between SST changes and SOI tendency from DJF (0) to seasons later than the monsoon season, in comparison to that between SST changes and SOI tendency from DJF (0) to JJA (0). However, these Chi-square values are smaller than that for the association between SST changes and IMR. Thus, the association of SST changes is stronger with IMR than that with SOI tendencies.

The strength of the association between IMR and SST changes is compared to that between SOI/SOI tendency and the same SST changes over the three sub-periods, 1882–1932, 1907–58 and 1933–84 on the basis of Chi-square for the contingency tables for these sub-periods. When we consider these sub-periods, we find that a large majority of the cells in the contingency tables have expected frequency exceeding 3 and only in a few cells the expected frequency lies between 2 and 3. According to Cochran (1952) who examined in detail the applicability of Chi-square test when expected cell frequencies are small, the tabular Chi-square is tolerably accurate provided that all expected cell frequencies exceed 2. Hence, Chi-square can be used to assess the significance of the associations. Presently, our main purpose is to compare the strength of the different associations. Comparability is not likely to be affected by the small size of the expected cell frequencies. The computed Chi-square values show consistently stronger association of IMR with SST changes in comparison to that of SOI/SOI tendency with the same SST changes, over these sub-periods also.

6. Response of Indian monsoon to SOI changes

In this section, we shall consider the response of IMR and of cyclogenesis over India and neighbourhood to the notable and sustained SOI anomaly changes (hereafter, SOI changes) similar in type to the changes in SST considered in earlier sections and compare the same with the response of IMR and of the cyclogenesis to the SST changes. We have seen in sub-section 5.1 that in a majority of the warming/cooling years there is a notable and sustained rise/fall in SOI anomaly. In each of these years of rise/fall in SOI associated with warming/cooling, the amount of rise/fall in SOI and the anomaly attained at the end of rise/fall are noted. Amongst the warming years which are observed to have the associated response of rise in SOI, the warming year 1968 had the lowest SOI rise of 1.4 mb and the lowest SOI anomaly attained, +0.6 mb, at the end of the rise. Taking these values of SOI rise and SOI anomaly attained as the basis of equivalent criteria for notable sustained rise in SOI, and following the principle of compensation of SOI anomaly by SOI change and *vice versa,* as was done in bringing out notable sustained changes in SST, years of notable sustained rise in SOI have been identified from the SOI data for the period 1882–1984. Amongst the cooling years which had the associated response of fall in SOI, the cooling year 1954 has the lowest fall of 1.5 mb in SOI and the SOI anomaly attained, *viz.,* —0.7 mb at the end of the fall, was nearly the highest. These values of SOI fall and of the SOI anomaly attained were taken as the basis of the equivalent criteria for notable sustained fall in SOI and following in a similar way the principle of compensation as mentioned earlier, the years of sustained notable fall in SOI are identified during the period 1882–1984.

TABLE 8

Association between SST changes and SOI changes (1882-1983)

SST changes	SOI changes			
	Falling	Little change	Rising	Total
Cooling	12 (4.08)	7 (11.07)	1 (4.85)	20
Small change	9 (11.83)	44 (32.10)	5 (14.08)	58
Warming	0 (5.10)	6 (13.83)	19 (6.07)	25
Total	21	57	25	103

Chi-square=67.95 (4 d.f.)

Note : Cell frequencies on the hypothesis of independence between SST changes and SOI changes are given within parentheses.

We now have years of rising/falling SOI identified by criteria equivalent to those used in identifying the years of warming/cooling of ESE Pacific. We examine the strength of association between the changes in SST of ESE Pacific (cooling, small change, warming) and these changes in SOI (falling, small change, rising). The contingency table between these changes in SST and in SOI is given under Table 8. It is seen from this table that in 12 years, cooling of ESE Pacific and falling of SOI go together and in 19 years, warming of ESE Pacific and rising of SOI go together. There is no case of warming of ESE Pacific and falling of SOI going together; however, there is one case (1885) of cooling of ESE Pacific and rising of SOI going together. There are some years of warming/cooling of ESE Pacific with little change in SOI, and of rising/falling SOI with little change in SST. Thus, there is no complete equivalence between these two sets of changes. However, the association between these two sets of changes is extremely strong as seen from the Chi-square value of 67.95 (4 d.f.).

6.1. *Indian monsoon rainfall*

In years of rising SOI, the mean rainfall is about 8.2% below the long-period mean and in years of falling SOI, it is 6.2% above the long period mean. Drought occurred over India in 8 years of rising SOI and flood occurred in 5 years of falling SOI. Probability of above/below normal rainfall in years of rising/falling SOI is low, about 10%.

Considering the three classes of SOI changes, falling, small change, rising, and three classes of IMR, below normal, normal and above normal, a contingency table is prepared. Chi-square for this table is 22.72 (4 d.f.) which is significant above 0.1%, bringing out strong association between SOI change and IMR.

6.2. *Cyclogenesis over the Indian region*

The difference between the number of low pressure systems (LPS) forming during the monsoon season, in years of rising SOI and in years of falling SOI is tested for significance by Student's t-test (2-tailed). Variances of the two samples are not significantly different. The value of the test statistic t is 1.68 (d.f. 42) which is not significant at 5% level. Changes in SOI do not appear to influence significantly the number of LPS forming in the monsoon season.

6.3. *Comparison with the response of the Indian monsoon to SST changes*

The measures of response used for comparison are Chi-square values for the contingency tables for the whole period and the three sub-periods 1882-1932, 1907-58 and 1933-1984. The contingency tables are between IMR and the SOI anomaly change and between IMR and SST anomaly change. Table 9 lists these measures. It can be seen from this table that the values of the measures for response of IMR to SST changes are at least 50% higher than the values for response of IMR to SOI changes, bringing out the much stronger influence of SST changes on IMR than that of SOI changes on IMR.

TABLE 9

Response of IMR to changes in SOI anomaly as compared with that of IMR to changes in SST of ESE Pacific

Response of IMR to	Chi-square for contingency table for period			
	Whole period	1882-1932	1907-1958	1933-1984
SOI anomaly changes	22.72	10.21	10.17	14.32
SST anomaly changes	42.90	18.96	23.37	20.18

Note : (*i*) d.f. in each case is 4.

(*ii*) Chisquare values significant at 5%, 1% and 0.1% levels are 9.49, 13.28 and 18.47 respectively.

7. Concluding remarks

On an examination of the association of the SST changes of the ESE Pacific, objectively defined as warming, small change and cooling, with Indian monsoon and with SOI, and also the association of SOI change (equivalently defined as rise, small change and fall) with Indian monsoon, the following conclusion can be drawn :

I. Associations

(a) *Between SST changes and IMR*

(*i*) A strong inverse association exists between SST changes over ESE Pacific and Indian monsoon rainfall. (Warming)/(cooling) of ESE Pacific and (excess rainfall or flood)/(deficient rain or drought) are found to be mutually exclusive events. The association of the SST changes with Indian monsoon rainfall is much stronger than that with the southern oscillation index for JJA season or with SOI tendency from DJF to JJA. It may be advantageous to examine SST anomaly for ESE Pacific for the seasons SON to MAM for any indication of the warming phase and if there is any indication, take this into account while preparing forecast of seasonal monsoon rainfall over India.

(*ii*) Association between warming of ESE Pacific and below normal IMR is much stronger than that between *El Nino* and below normal IMR.

(*iii*) Association between warming of ESE Pacific and below normal IMR is far stronger than that between warm ESE Pacific and below normal IMR, suggesting that the changes in SST influence the monsoon rainfall much more strongly than the warm ESE Pacific.

(*iv*) Association between warming and below normal IMR is far stronger than that between cooling and above normal IMR, showing that warming exerts a much greater influence on IMR than cooling.

(*v*) Associations of the SST changes with monsoon rainfall over the divisions, central India and south India are significant at or above 0.1% level; however, the association with IMR is much stronger. This is apparently due to the large-scale nature of the influence exerted by the SST changes.

(b) *Between SST changes and cyclogenesis over India and neighbourhood during the monsoon*

Warming/cooling tends to decrease/increase the cyclogenesis significantly (above 5% level).

(c) *Between SST changes and SOI anomaly for JJA season/SOI tendency from DJF to JJA*

The association is strong (generally significant above 1% level) for the whole period and the sub-periods; however, the association of IMR with SST changes is far stronger not only for the whole period, but also for the sub-periods.

(d) *Comparison of the association between SST changes and IMR with that between SOI changes and IMR*

Considering the sustained notable changes in SOI, *viz.*, rise and fall, similar in type to warming and cooling and identifying these by criteria equivalent to those used for warming/cooling, the association between these SOI changes (rising, small change and falling) and IMR is compared with that between SST changes and IMR. The latter is found to be much stronger than the former, suggesting that the influence exerted by the warming/cooling of ESE Pacific on IMR is much stronger than that exerted by rising/falling SOI.

II. *Questions raised by the study*

(*i*) What factors prevented the eastern equatorial Pacific warming in 10 *El Nino* years? What caused the warming of the ESE Pacific in 9 years which were not *El Nino* years ? A comprehensive examination of the ocean currents and wind field over a wide area in those years and also in comparison to those in *El Nino* years in which the warming spreads from Peru-Ecuador coast to ESE Pacific might give some clue to the possible cause.

(*ii*) What role is played by the SST over the central and western equatorial Pacific (120°E-160°W) in the interannual variability of the Indian and east Asian monsoon ? Physically, it is likely that the SST over this portion of the Pacific exerts a direct influence over the monsoon and plays an important role. A long SST series for this portion of the Pacific, based on reliable data, needs to be examined with reference to the monsoon (study similar to that of Fu *et al.* 1986).

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