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Recent monsoon variability in the global climate perspective

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सार – पिछले कुछ वर्षों से भारतीय ग्रीष्म मानसून ने काफी अनियमितताएं दिखाई है, संभवत: उसी समय माप की किसी भी अवधि में प्रेक्षित से भी अधिक 1940 के दशक से दशकीय माप माध्य वर्षा निरन्तर कम हो रही है। इसके परिवर्तन के गुणांक के पदों में अभिव्यक्त मानसून वर्षा की परिवर्तनशीलता पिछले तीन दशकों में तुलनात्मक रूप में अधिक रही है। मानसून के सम्बन्धों के परिप्रेक्ष्य में 1982-89 के दौरान, हाल के मानसून के व्यवहार का बड़े पैमाने पर इस शोधपत्र में मुख्य रूप से चर्चा की गई है। विशेष रूप से ENSO-मानसून-सम्बन्ध और 1982-83 एवं 1986-87 के हाल के ENSO घटना पर बल दिया गया है।

ABSTRACT. Over the past few years the Indian summer monsoon has shown large abnormalities, perhaps, more than that observed in any period on the same time-scale. The decadal scale mean rainfall has been continually decreasing since the decade of 1940s. The variability of monsoon rainfall, expressed in terms of its coefficient of variation, has been relatively larger in the last 3 decades. The paper mainly discusses the large-scale behaviour of recent monsoons during 1982-88. In particular, the ENSO-monsoon-linkages *vis-a-vis* the recent ENSO episodes of 1982-83 and 1986-87 are emphasised.

1. Introduction

Some characteristic features of recent variability of monsoon depicting its uniqueness is first presented in Sec. 3 of this study. Elsewhere on the globe, there were equally strong climatic variations. Some of these features are described in Sec. 4. Vital role of the surface boundary forcings is recognised in the interannual and longer-term variability of climate. To support this, in Sec. 5, the relationships of Indian summer monsoon with surface boundary forcings of air temperature, snow-cover and sea surface temperatures are presented. The recent severe ENSO (*El Nino*-Southern Oscillation) episodes of 1982-83 and of 1986-87 have again brought into sharp focus its relevance in global climate variations, in general and monsoon, in particular. An attempt is made in Sec. 6 to bring out some new aspects of ENSO-monsoon-linkages.

2. Data

The all India summer monsoon (June to September) rainfall is the most appropriate climatic index for the large-scale performance of the monsoon. This rainfall series (henceforth called 'Monsoon Index' or MI series) is taken from the long and homogeneous series constructed by Mooley and Parthasarathy (1984) and updated. Northern hemisphere surface air temperature estimates onto a 5° latitude by 10° longitude have come through the most comprehensive study by Jones *et al.* (1986). The homogeneous temperature departure series of monthly mean, which is representative of the land areas of the northern hemisphere, has been constructed objectively. Monthly mean values of the satellite derived Eurasian snow-cover data have been obtained from NOAA/National Earth Satellite Service, Washington, USA. The sea surface temperatures (SST) of global oceans were extracted from the Comprehensive Ocean Atmosphere Data Set (COADS). The Southern Oscillation Index (SOI) data series as computed by Climate Analysis Center (CAC), NOAA/NMC, Washington USA is obtained from the '*Climate Dignostics Bulletin*'.

3. Recent monsoon variability

Fig. 1 presents some of the statistics of the Indian summer monsoon rainfall (MI) since 1901 to date. The decadal mean rainfall has been continually decreasing after it reached the peak ($\approx$89 cm) during the decade 1941-50. Though its negative departure from the long-term mean is not statistically significant, nevertheless the decreasing trend since 1950s may be a cause of concern. Another feature of the monsoon variability of the present decade may be gauged from its value of coefficient of variation (CV). The period 1981-88 shows the second largest CV ($\approx$13) after the 1911-20 decadal value of 13.6. The CV during this century touched its minimum of 4.8 in the decade of 1920s. In a climatic element, like monsoon rainfall, the drastic change in its mean and variability is mainly caused by significant changes in the frequency of occurrence of extremes. An extreme monsoon rainfall is (defined here) when its departure is greater than one standard deviation (σ) in magnitude. Thus, it is a drought when the rainfall departure is $\leqslant -1\,\sigma$ and an excess-monsoon when the rainfall departure is $\geqslant +1\,\sigma$. With these criteria, extremes of both the categories are

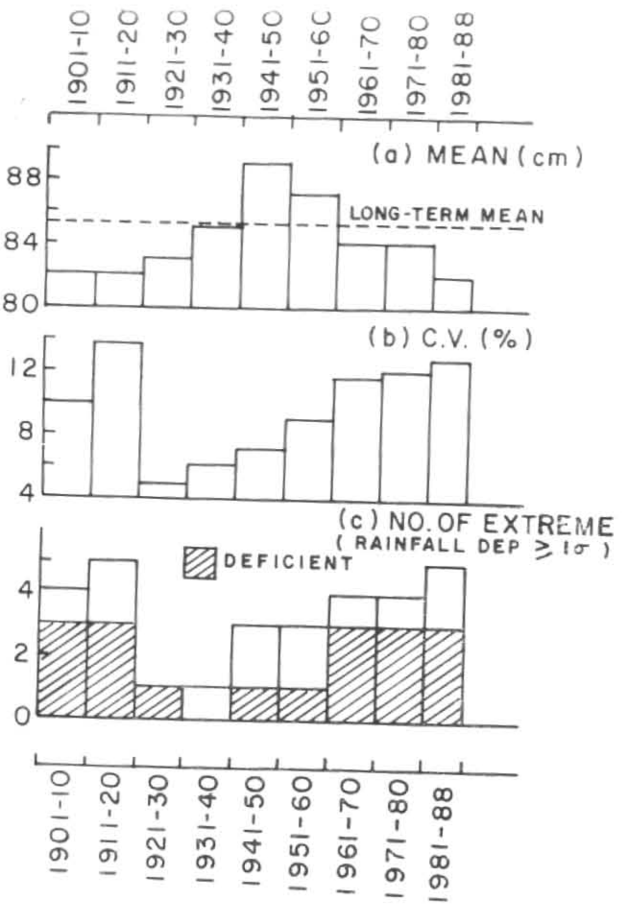

Fig. 1. Decadal variability of Indian summer monsoon rainfall (1901-1988) : (a) Mean in cm, (b) Coefficient of variation and (c) Number of extremes

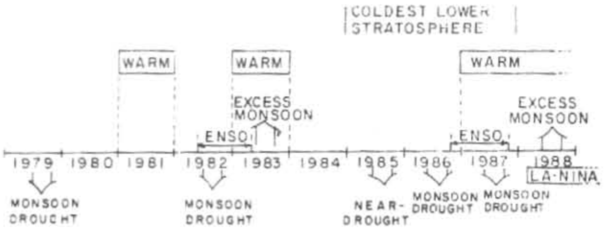

Fig. 2. Some major global climate anomalies (1979-1988)

delineated and frequencies accounted for each decade (*see* Fig. 1). Frequency of extremes touched the lowest value during the two-decadal period of 1921-40 : only one drought and one excess rainfall years. Since then the frequency of extremes (and more so the frequency of droughts) has been increasing. Five out of the last eight years were extreme monsoon years.

4. Recent global climate variability

During the recent past ten years notable anomalies have also been observed over much of the globe. Fig. 2 depicts some of the major events. There had been years of frequent droughts (1979, 1982, 1986 & 1987) over Indian/south Asian regions and years of excessive rains or floods (1983, 1988). Global surface air temperature records reveal that the three most warm years occurred in 1981, 1983 and 1987 with 1987 being the warmest year. The warmth of the 1980s is most evident over the southern hemisphere where seven of the eight warmest years over the land have occurred during the 1980s, with 1987 being the warmest. The warmth is not just a surface phenomenon. The global radiosonde data network, where comparable data are available since 1958, confirms the tropospheric warmth in 1981, 1983 and 1987. Stratospheric temperatures are also monitored, which show that the three coldest years in the lower stratosphere were 1985, 1986 and 1987. However, over the Arctic regions the year 1987 was the coldest since 1972. Severe winter conditions prevailed in 1985 over much of Eurasia.

The most exciting climatological event of 1980s was the 1982-83 *El Nino* Southern Oscillation (ENSO) which was the strongest of the century with unprecedented warm equatorial Pacific Ocean temperatures. This was followed by another strong ENSO episode during 1986-87 which was followed by equally unprecedented cooling of the equatorial Pacific (known as *La Nina*) in 1988 since the previous one occurred in 1975.

5. Influence of global surface boundary conditions on monsoon

The modelling and observational evidences suggest that the slowly varying boundary conditions of surface air temperature, sea surface temperature, soil moisture, sea ice and snow at the earth's surface can influence the interannual variability of atmospheric circulation. Based on numerical experiments with a global GCM, Charney and Shukla (1981) suggested that the Asiatic monsoon is a dynamically stable circulation system and its interannual variability is largely determined by the slowly varying boundary conditions. In this section relationships of monsoon with surface air temperature, SST and snow-cover are presented.

(a) *Relationship of monsoon with NH surface air temperature*

Verma *et al.* (1985) demonstrated a statistically significant positive relationship with a time-lag of about six months between the monsoon rainfall and the averaged NH surface air temperature; maximum correlation being with the preceding January/February temperature anomalies. With the availability of the grid point data (Jones *et al.* 1986) spatial analysis of the relationship became plausible. Using the recent 30-year (1950-79) data, correlation mapping between the Monsoon Index (MI) and the surface air temperature anomalies over NH were carried out. Thirty maps were produced, one for each month from January of the preceding year through June of the following year with respect to the monsoon year. These correlation maps give the spatial distribution of the strength as well as the nature of the relationship of surface air temperature with the monsoon at different time-lags. The correlation maps for January and February for the concurrent or zeroth year with respect to monsoon year are presented in Fig. 3. Regions of higher latitudes over the land-masses of North America and Eurasia show positive correlations ranging from 0.4 to 0.6 (statistically significant at >95% level) during the preceding months of January and February, *i.e.*, cooler winters, particularly in January/February, are associated with poor monsoon over India and *vice-versa*.

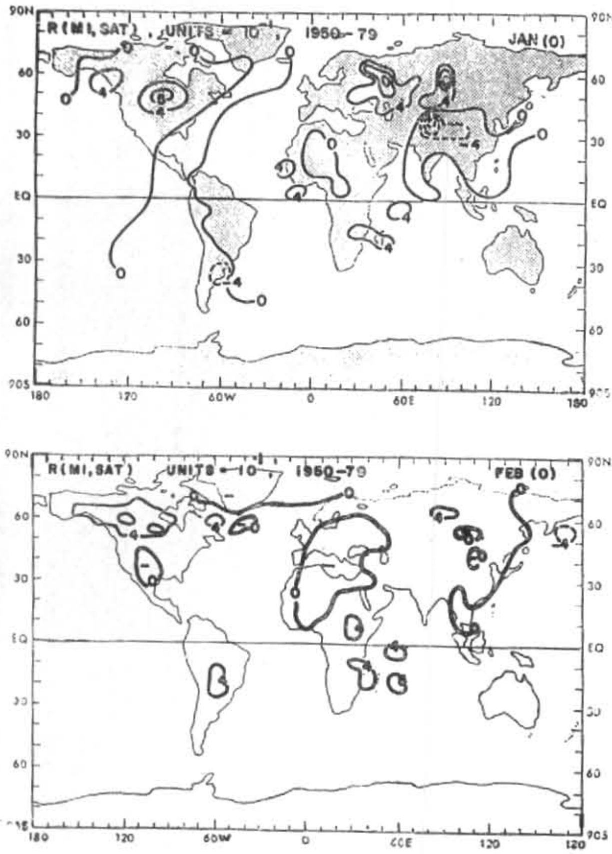

Fig. 3. Correlation (× 10) of the Indian summer monsoon rainfall (MI) with January and February mean surface temperature anomalies over northern hemisphere, concurrent to monsoon-year. Contour interval is 2.0 with negative values dashed. Significant correlations at more than 95% level are numbered. Data period : 1950-1979

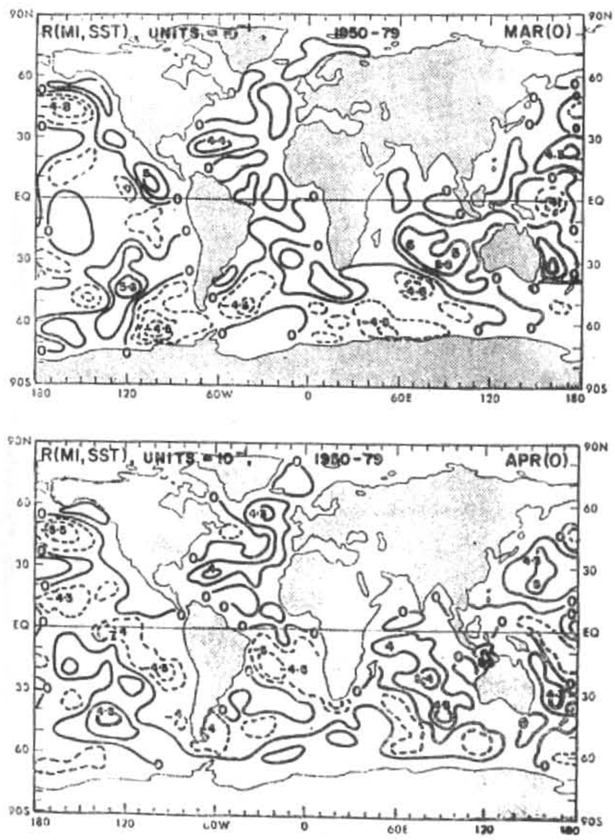

Fig. 4. Correlation (× 10) of the Indian summer monsoon rainfall (MI) with monthly mean sea surface temperature anomaly for March and April of the year concurrent to monsoon-year. Contour interval is 2.0 with negative values dashed. Significant correlations at more than 95% level are numbered. Data period : 1950-1979

(b) *Relationship of monsoon with global sea surface temperature*

COADS data for the period 1950-79 were used to investigate the relationship between the Indian summer monsoon rainfall and the global SST anomalies, particularly the SSTs in the tropical and sub-tropical belts of the Pacific, Indian and the Atlantic Oceans. The analysis delineates some key-regions of the oceans whose temperatures at different time-lags with summer monsoon show statistically significant relationships with its seasonal rainfall. Important relationships revealed are the following :

(*i*) *Positive correlation coefficients with SST anomalies in the central Indian Ocean south of equator during late northern winter and spring just preceding the monsoon* — Correlation maps for March and April, which reveal maximum correlations over the region, are shown in Fig. 4. This relationship is of special interest as it may provide a useful guidance tool for the long-range forecast of monsoon, well in advance.

(*ii*) *Negative correlations with the preceding, concurrent and succeeding months' SST anomalies over the eastern equatorial Pacific* (*El Nino region*) — Since, now it is established that *El Nino* is only a recognisable phase of an ENSO cycle and since ENSO is much greater in space and time scales than monsoon cycle, its significant relationship with monsoon, revealed over the time period which spans from months before the monsoon onset through months after the withdrawal of the monsoon, seems to be physically understandable. Correlation maps for typical months of March/April (preceding to monsoon), July/August (concurrent to monsoon) and November/December (succeeding to monsoon) are depicted in Figs. 4, 5 and 6 respectively.

The relationship suggests that warmer phase of ENSO (*i.e., El Nino*) over east equatorial Pacific is associated with poor monsoon activity and *vice-versa*. The noteworthy point of this relationship revealed through these maps, is that the correlation coefficient values, though statistically significant, are small with SST of months preceding to monsoon and became greater and greater through December.

(*iii*) *Negative correlations with the concurrent and succeeding months' SST anomalies over Arabian Sea and Bay of Bengal* (Figs. 5 and 6) — The relationship suggests that greater cloudiness and precipitation associated with a good monsoon cools down the sea surface The temperature anomaly also persists for few months

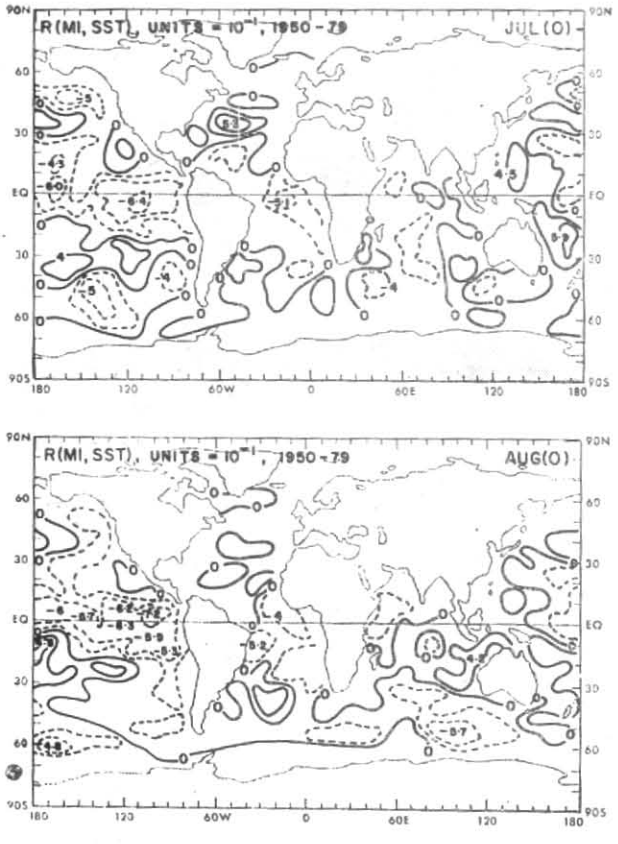

Fig. 5. As in Fig. 4 except for the months, July and August

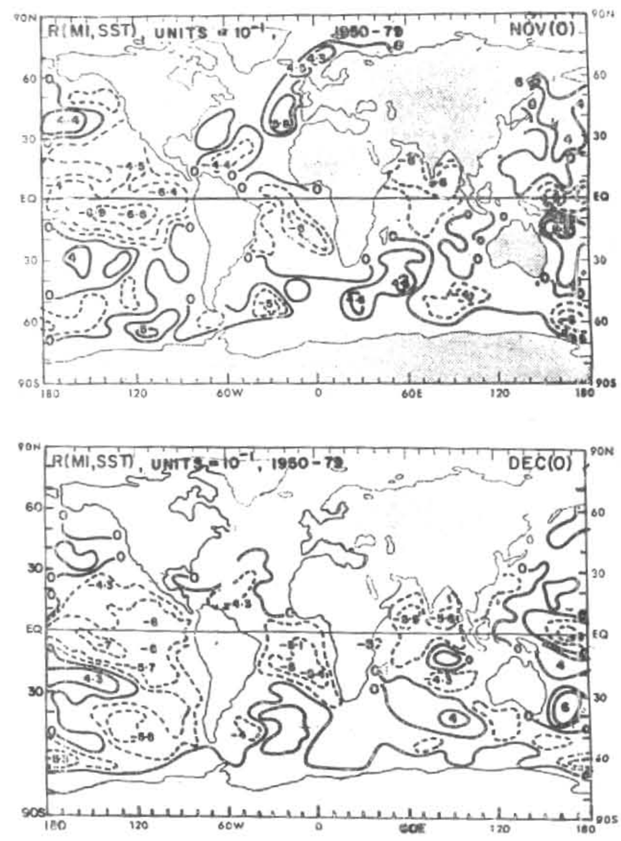

Fig. 6. As in Fig. 4 except for the months, November and December

after the monsoon withdrawal. The opposite holds when there is lesser cloudiness and precipitation associated with a poor monsoon.

(c) *Relationship of monsoon with Eurasian snow-cover*

Continental snow-cover has important climatic impacts on the radiation balance, surface and air temperatures, cloudiness, soil-moisture, water storage and precipitation. Beginning from Blanford (1884), there have been many empirical studies (Hahn and Shukla 1976; Dickson 1984; Yeh *et al.* 1983 etc) showing relationship of Himalayan/Eurasian snow-cover with Indian monsoon. In a more recent study, Barnett *et al.* (1988) performed numerical experiment with a GCM which suggests that large-scale changes in Eurasian snow-cover are coupled to large-scale changes in the global climate system including Asian summer monsoon. Lag-correlations between the Indian summer monsoon rainfall and the continental snow-cover over Eurasia are shown in Fig. 7. The winter-time (DJF) snow-cover is negatively correlated with the monsoon rainfall. The maximum correlation is revealed with December snow-cover (which is statistically significant at 95% level) and the snow-cover anomaly tends to persist through the subsequent months of January and February.

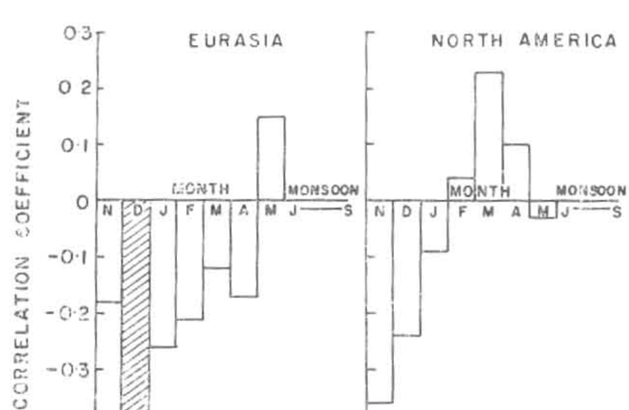

Fig. 7. Lag-correlations between the Indian summer monsoon rainfall (MI) and the monthly mean Eurasian snow-cover. Data period : 1967-1987

6. ENSO monsoon linkages *vis-a-vis* the recent ENSO episodes of 1982-83 and 1986-87

SOI (Southern Oscillation Index) defined as the difference between the standardized sea level pressure anomalies at Tahiti and Darwin is now widely accepted index of ENSO. CAC (Climate Analysis Center, USA) — evaluated monthly mean SOI data from 1935 to 1988 have been used to delineate the ENSO episodes. An ENSO is termed episodic when SOI $\leqslant -.5\sigma$, where σ is the standard deviation of the SOI series. Life of an ENSO episode is taken as more or less a continuous period when SOI remained episodic. Accordingly, there were twelve ENSO episodes since 1935 as listed in Table 1.

TABLE 1

Some characteristic features of recent ENSO episodes : 1935-1988 (CAC data)

S. No.	Year(s)	Life (months) (continuous period of SOI $\leqslant -0.5\,\sigma$)	Av. intensity (SOI/month)	Rank
1	1939-42	32	—1.28	4
2	1946-47	11	—0.95	7
3	1951-52	14	—0.91	9
4	1953	11	—0.85	10
5	1957-59	19	—0.70	11
6	1963-64	8	—0.92	8
7	1965-66	14	—1.10	6
8	1969-70	12	—0.66	12
9	1972-73	11	—1.25	5
10	1977-78	14	—1.34	3
11	1982-83	12	—2.48	1
12	1986-87	12	—1.68	2

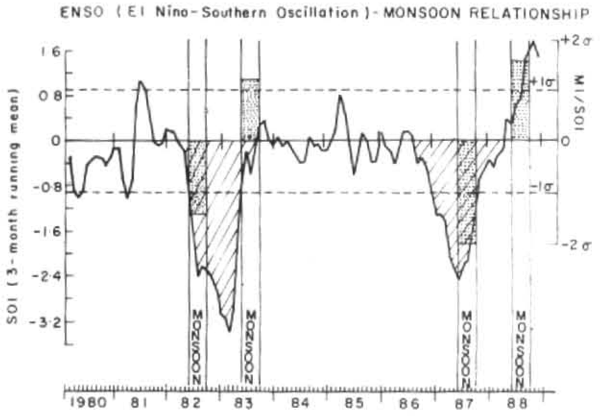

Fig. 8. 3-month running mean SOI (Southern Oscillation Index) from January 1980 through December 1988. Vertical columns on time-axis are drawn to depict monsoons of 1982, 1983, 1987 and 1988 with their standardised rainfall departures (MI). Horizontal dotted lines denote ± 1 σ lines applicable to both SOI and MI. The intense ENSO episodes of 1982-83 and of 1986-87 are shaded.

Fig. 8 depicts the intense ENSO episodes of 1982-83 and of 1986-87 *vis-a-vis* the respective Indian summer monsoons. For this purpose monthly mean SOI values from January 1980 to December 1988 are smoothed by 3-month running mean to filter out random monthly fluctuations. The continuous graph depicts the 3-month running mean SOI. Vertical columns on time-axis are drawn to depict monsoons of 1982, 1983, 1987 and 1988 with their standardized rainfall departures (MI). Horizontal dotted lines denote ± 1σ lines applicable to both SOI and MI. The intense ENSO episodes of 1982-83 and of 1986-87 are shaded.

It is now well established in observational, theoretical/modelling studies that an ENSO episode shifts eastward the convective regimes of the tropical belt. This is the main factor for deficient rains over southeast Asian regions during an ENSO event. A restoring-to-normal phase of ENSO, on the converse, restores the normal circulation patterns creating favourable conditions for a normal/good monsoon. It is, therefore, clear that the influence of ENSO on monsoon will be either adverse or favourable depending upon whether the monsoon is phase-locked with the ENSO or it is out-of-phase with ENSO. It is in this context that Fig. 8 is drawn to appreciate the in-phase or out-of-phase relationship of ENSO-monsoon linkage so far as the ENSO episodes of 1982-83 and of 1986-87 are concerned.

During the summer monsoon-1982 the ENSO was episodic and even intense (SOI $< -1\sigma$). This in-phase locking of monsoon-1982 with ENSO caused shifting of the convective belt away from the monsoon region. The result was a drought and deficient monsoon rainfall over India (MI $= -1.4\sigma$) and over other regions of southeast Asia. After reaching its peak (*i.e.*, largest negative SOI) in the early 1983, the ENSO quickly restored to normal. During the onset and established phase of monsoon-1983, ENSO was in the restoring-to-normal phase and hence the ENSO rather enhanced the meridional circulation over southeast Asian region in which the monsoon circulation is embedded. Therefore, restoring-to-normal phase of ENSO 1982-83 was mainly responsible for the good monsoon of 1983 (MI $= 1.2\sigma$).

A more or less similar ENSO-monsoon configuration occurred during the ENSO episode of 1986-87. The major difference between the episodes of 1982-83 and of 1986-87 was that the latter reached episodic magnitude in November 1986 whereas during the 1982-83 ENSO episode, it was in May 1982. Hence with the reasoning of above, the ENSO episode of 1986-87 which remained intense during the onset and established phase of monsoon-1987, affected it adversely resulting in severe drought conditions and deficient rains over southeast Asia (MI $= -1.9\sigma$). Monsoon-1988 was phased-locked with the restoring-to-normal phase of the ENSO episode of 1986-87 and hence it received heavy precipitation (MI$= +1.6\sigma$).

In Sec. 3, while discussing the decadal variability of monsoon, it was emphasised that the monsoon variability largely depended upon the frequency of extreme monsoons. Also, keeping the fact in view that ENSO is an aperiodic phenomenon which oscillates between 2 and 7 years and the monsoon being a seasonal phenomenon occurs every summer, a particular extreme monsoon may or may not occur in association with an ENSO. Also, as discussed above, the ENSO related extreme monsoon, may be a deficient or an excess rainfall monsoon depending upon its phase-locking with the ENSO. Thus, it is possible to make a simple statistical analysis of all the extreme monsoons occurred during the period 1935-88 *vis-a-vis* ENSO episodes. Such an analysis is projected in Table 2 classifying the deficit and the excess rainfall monsoons as either ENSO-related or ENSO-unrelated. What emerge from this analysis are as follows :

(*i*) 7 out of 11 or about 64% of deficit-monsoons are ENSO-related.

(*ii*) 6 out of 9 or about 66% of excess-monsoons are ENSO (or rather restoring-to-normal phase of ENSO)-related.

TABLE 2

Frequency distribution of extreme monsoons *vis-a-vis* ENSO episodes : 1935-88

Extreme monsoons	ENSO-related	ENSO-unrelated	Total
Deficit-monsoon ($R' \leqslant -1\ \sigma$)	1941, 51, 65, 66, 72, 82, 87 (7)	1968, 74, 79, 86 (4)	11
Excess monsoon ($R' \geqslant 1\ \sigma$)	1942, 47, 59, 70, 83, 88 (6)	1956, 61, 75 (3)	9
Total	**13**	7	20

TABLE 3

Warm-phases (*El Nino*) of ENSO episodes during 1935-88 with climatic characteristics of the following winter/spring over northern hemisphere/Eurasia and the following summer monsoon over India

Warm-phase of ENSO-episode	Following winter, spring of N.H./Eurasia	Monsoon (Standardised value)
1940-41	Warmer 1942	Excess 1942 (+1.3)
1951-52	Warmer 1953	Good 1953 (+0.8)
1957-58	Warmer 1959	Excess 1959 (+1.0)
1965-66	Cooler 1967	Normal 1967 (+0.1)
1969	Warmer 1970	Excess 1970 (+1.0)
1972	Warmer 1973	Good 1973 (+0.7)
1977	Warmer 1978	Good 1978 (+0.7)
1982	Warmer 1983	Excess 1983 (+1.2)
1987	Warmer 1988	Excess 1988 (+1.6)

(*iii*) 13 out of 20 or 65% of the extreme monsoons are ENSO-related.

7. Predictability of ENSO-related good monsoon

The warm phase of an ENSO (*i.e.*, *El Nino*) is often much more pronounced than the cooling phase. It is also revealed that the NH experiences warm anomaly after a lag of 1-2 seasons (Pan and Oort 1983). Discussion on the interannual variability of Indian summer monsoon in relation to the NH surface air temperature in Sec. 5(a) suggested that the warmer winter over NH is statistically correlated with a subsequent good monsoon. If this sequence is generally followed in the nature, it should be possible to predict with greater confidence the occurrence of a good monsoon, preceded by warmer NH which in turn is preceded by the warm phase of ENSO. Such a possibility is examined in the analysis which follows :

Table 3 lists warm phases of all the intense ENSOs during the period 1935-88. Against each of the episodes, nature of the following winter-to-spring of NH (particularly Eurasia) in qualitative term and performance of the following summer monsoon over India along with rainfall departure value are depicted.

All the warm phases of ENSO episodes, with the exception of 1965-66 episode, were followed by warmer winter/spring over NH/Eurasia. All the monsoons subsequent to such combinations were good-to-excess (MI $\geqslant 0.5\sigma$)-rainfall monsoons. Thus, there is distinct possibility to achieve high skill in predicting the ENSO-related good-monsoon by monitoring the ENSO cycle and the NH temperature/Eurasian snow-cover.

8. Conclusions

The following salient points of monsoon variability are brought out in the analysis :

(*i*) Monsoon variability in the recent decade was very large. This was mainly due to ENSO (*El Nino*-Southern Oscillation).

(*ii*) The effect of ENSO on monsoon is such that it may cause drier or wetter monsoons depending on the phase-locking between the two events.

(*iii*) Majority of the extreme monsoons are ENSO-related.

(*iv*) Surface forcings of northern hemisphere temperature and Eurasian snow-cover also play important role in the interannual variability of the Indian summer monsoon.

(*v*) Warmer winter/spring over northern hemisphere, particularly the Eurasian region, caused by warm phase of ENSO, leads to wetter monsoon.

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