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A study on the role of synoptic and semi-permanent features of Indian summer monsoon on it's rainfall variations during different phases of El-Nino

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सार – इस शोध पत्र में वर्ष 1960–98 की अवधि में एल–नीनों के विभिन्न चरणों के दौरान मानसून विक्षोभों (निम्न दाब और अवदाबों), मानसून द्रोणी और तिब्बती प्रति चक्रवात तथा मानसून की अवधि जैसे भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) के विभिन्न सिनाप्टिक अभिलक्षणों और अर्ध स्थायी लक्षणों का अलग – अलग अध्ययन किया गया ताकि यह पता लगाया जा सके कि एल–नीनों की केवल एक ही घटना के दौरान भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) में कमी क्यों आई थी जबकि अन्य वर्षों के दौरान भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) लगभग सामान्य अथवा सामान्य थी। इस अध्ययन के द्वारा एल–नीनों की दुहरी घटनाओं का क्रमशः दो वर्षों में एक बार और दोनों वर्षों में भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) कम होने तथा इसके और अधिक कम होने की जाँच की गई है। बिना किसी एल–नीनों के भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) की कमी के मामलों पर भी विचार–विमर्श किया गया है। भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) की स्थानिक भिन्नताओं पर सिनाप्टिक और अर्ध–स्थायी लक्षणों के प्रभावों पर बल दिया गया है।

इनसे प्राप्त हुए परिणामों से यह पता चलता है कि भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) के लिए सिनाप्टिक के अभिलक्षण और अर्ध–स्थायी लक्षण महत्वपूर्ण थे और वर्ष 1997 के एल–नीनों के बावजूद कुछ वर्षों में सामान्य और सामान्य से अधिक भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) के लिए ये उत्तरदायी थे। एल–नीनों की अनुपस्थिति में भी मानसून–द्रोणी के कम दिनों, निम्न दाब क्षेत्रों ओर अवदाबों तथा कमजोर तिब्बती प्रति चक्रवात के कारण भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) में कमी थी। ला–नीना की अनुपस्थिति में बाढ़ वाले वर्षों में यह स्थिति इसके विपरीत थी। सांख्यिकीय विश्लेषण से भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) के साथ इन सिनाप्टिक और अर्ध–स्थायी लक्षणों के बहुत अधिक सहसंबंध गुणाकों (सी. सी.एस.) का पता चला है। वर्ष 1961 में भारत में अत्याधिक मानसून की वर्षा हुई क्योंकि उस वर्ष भारत में तीव्र मानसून विक्षोभों और मानसून द्रोणी के कुल दिनों की संख्या तथा मानसून की कुल अवधि सबसे अधिक थी। इस अध्ययन से यह पता चला है कि मानसून विक्षोभ और मानसून द्रोणी सिनाप्टिक और अर्ध–स्थायी लक्षणों के सबसे अधिक महत्वपूर्ण घटक है जिससे 1965 और 1966 में भारतीय ग्रीष्मकालीन मानसून वर्षा (आई. एस. एम. आर.) की स्थानिक भिन्नताएँ प्रभावित हुई तथा वर्ष 1961 में कम वर्षा और वर्ष 1994 में भारत के अधिकांश भागों में अत्याधिक वर्षा हुई।

ABSTRACT. Characteristics of different synoptic and semi-permanent features of Indian Summer Monsoon Rainfall (ISMR), such as monsoon disturbances (lows and depressions), monsoon trough and Tibetan anticyclone and duration of monsoon, are studied individually for different phases of El-Nino during the period 1960-98 to understand why during some El-Nino single events, ISMR was deficient while during other years, ISMR was on the positive side of normal or normal. This study examines cases of El-Nino double events with deficient and near deficient ISMR in one of the two years and in both the years respectively. The cases of deficient ISMR without any El-Nino are also discussed. Emphasis has been given on the effects of the synoptic and semi-permanent features on spatial variations of ISMR.

Results show that characteristics of synoptic and semi-permanent features were important for ISMR and these were responsible for producing normal or above normal ISMR during some years in spite of El-Nino such as 1997. Also in the absence of El-Nino, ISMR was deficient because of less number of days of monsoon trough, lows and depressions, and weak Tibetan anticyclone. The reverse happened during flood years when there was no La-Nina. Statistical analysis indicates very high correlation coefficients (CCs) of these synoptic and semi-permanent features with ISMR than those of SST of Nino-3 region. India received highest monsoon rainfall during 1961 because total number of days of intense monsoon disturbances and monsoon trough and the total duration of monsoon over India during the year was the highest. This study shows that monsoon disturbances and monsoon trough are the most important components of synoptic and semi-permanent features, which affected spatial variation of ISMR in 1965 and 1966 with deficient rainfall and in 1961 and 1994 with excess rainfall over a large part of India.

Key words – Indian Summer Monsoon Rainfall (ISMR), El-Nino double/single events, La-Nina, Drought without El-Nino, Duration of monsoon, Monsoon disturbances, Monsoon trough.

1. Introduction

Negative correlation of El-Nino with Indian Summer Monsoon Rainfall (ISMR) is well established by various authors (Rasmusson and Carpenter, 1983; Kiladis and Diaz, 1989 and Mooley and Paolino, 1989). This relation represents a tendency of the ISMR to be below normal during El-Nino epochs over the eastern equatorial Pacific and *vice-versa* during La-Nina conditions. However, characteristics of individual El-Nino events (starting phase, persistence, spatial and temporal variation of SST over east Pacific) differ from one other and its complex relationship with monsoon has already been highlighted by Normand (1953). Apart from irregular periodicity of its occurrence (2 to 5 year's cycle), some El-Nino events continue longer. In the present study, the El-Nino phenomena covering two monsoon seasons are termed as El-Nino double events and others with smaller periods are called El-Nino single events.

It has been observed that characteristics of ISMR differ during El-Nino single and double events. In order to understand the relationship between El-Nino and ISMR correctly, it is essential to examine the characteristics of ISMR during different types of El-Nino events. Data shows that ISMR during El-Nino double events are either deficient or near deficient twice in 1991-92 or once as in 1982 of 1982-83. However, in 1983 *i.e.*, in the second year of El-Nino double event of 1982-83, there was flood. During El-Nino single events in 1965, 1972 and 1987, ISMR was deficient and during 1976 and 1997, ISMR was on the positive side of normal or normal. Why does this anomaly occur in their relationships? Why does during some El-Nino double events, ISMR become deficient only in one of the two years, while in some El-Nino events, ISMR become deficient in both the years? Why does during some years when El-Nino is absent *e.g.* 1966, 1968, 1974, 1979 & 1986, ISMR becomes deficient? It has also been observed that floods have occurred over India during years 1961, 1983 & 1994 when La-Nina conditions were not present and in 1961, the highest seasonal monsoon rainfall occurred over India.

Khole and De (1999) have considered different facets of El-Nino-ISMR relationship from circulation pattern, over Indian region for individual years and concluded that the effect of El-Nino to modify the regional scale circulation pattern over India and interaction between planetary scale and regional scale circulation alterations finally results into the circulation pattern of any year. The rainfall activity is a manifestation of this pattern and hence the effect of El-Nino on ISMR can be studied with this aspect.

Kripalani and Kulkarni (1997), Goswami (1998), Krishnamurthy and Goswami (1998) and Verma (1990) have studied the effect of El-Nino on ISMR in interannual and interdecadal scales. According to Verma (1990), deficiency of ISMR during any El-Nino year depends on whether monsoon season falls on increasing or decreasing tendencies of SST from previous autumn season. Hence, one expected drought during 1982 instead of 1983 because monsoons of 1982 and 1983 fall in the increasing and decreasing tendency of SST respectively. Also, it fails to explain why during other El-Nino years of increasing tendency, India received normal ISMR (1976 and 1997). Krishnamurthy and Goswami (1998) used composite circulation features of interdecadal variability and found that El-Nino - monsoon relationship varies with interannual variation of position of Walker/Hadly circulation with broadly fixed interdecadal one. If both interannual and interdecadal variability are in the same phase, then ISMR is affected depending upon whether both the phases are of El-Nino or La-Nina type *i.e.*, ISMR is deficient during an El-Nino year of a warming decade of east Pacific SST and the reverse happens during La-Nina year. But, if both are in opposite phases, then El-Nino-monsoon relationship becomes complex. It fails to explain the contrasting effect of different individual El-Nino double events on monsoon *i.e.*, why El-Nino double events affected ISMR in both the years during 1991-92 and once during 1982-83, in spite of all these years falling in warming decades.

Based on GCM control experiments, Goswami (1998) inferred that ISMR is also controlled by some other factors which he termed as model internal dynamics apart from slowly varying boundary conditions. Recently, Krishna Kumar *et al*., (1999) have studied El-Nino- ISMR relation in a climatic scale from various different aspects and found that effect of El-Nino on ISMR is becoming insignificant during recent years due to increase of temperature over Eurasia region. But when 1997 is excluded (when major El-Nino have occurred, but ISMR was normal) from the long data period, the relationship does not become so weak (Chang *et al*., 2001).

For finding the cause of normal ISMR during intense El-Nino 1997, various factors such as intraseasonal oscillations, Indian Ocean SST anomalies, Eurasian snow cover, decadal changes in ENSO monsoon coupling and global warming have been examined by various authors (Webster *et al*., 1999; Lau and Wu, 1999; Lau and Wu, 2001; Slingo and Anamalai, 2000; Shen and Kimoto, 1999; Krishna Kumar *et al*., 1999). As yet, there is no conclusive evidence on the relative importance of each factor in to ISMR and how they affect the monsoon-ENSO relationship. Mooley (1997) have studied the effect of El-Nino on spatial variation of ISMR over northwest India by classifying El-Nino years into two categories according to spatial distribution of warm SST over equatorial south east Pacific. Srinivasan and Nanjundiah (2002) have studied ISMR-ENSO relationship for 1983 and 1997 and found that both in 1983 and 1997, the conditions in May were similar to those of a drought year, but the appearance of westward migrating cloud systems in June to the Bay of Bengal changed the course of monsoon which turned out to be above normal. Hence events on time-scales of weeks or intraseasonal oscillations during the evolution of the monsoon have considerable impact on the seasonal rainfall.

Kripalani and Kulkarni (1999) show that in 1979, ISMR was deficient in the absence of El-Nino, since snow depth was dominant. These studies again do not explain why during some El-Nino double events, ISMR was deficient only in one of the two years, while in some El-Nino event, it is deficient in both the years or normal in one year. Also, why during some other drought years *e.g*., 1974, 1979, 1986, ISMR was deficient even though there was no El-Nino, while flood during the years 1961 and 1994 in the absence of La-Nina.

In the present study, different synoptic and semi-permanent features concurrent to the monsoon season are examined for different drought, flood and normal rainfall years during 1960-98 to attempt to answer some of the questions raised earlier pertaining to El-Nino-ISMR relationship. The synoptic and semi-permanent features over India include characteristics of monsoon disturbances, monsoon trough and Tibetan anticyclone and onset, withdrawal dates and duration of monsoon. Effects of these synoptic and semi-permanent features on spatial variation of ISMR are also studied for some individual years to know whether these features have some special characteristics to produce a particular type of spatial distribution according to whether these are very active or weak. After comparative study of characteristics of all of these features for different categories, correlation coefficients (CCs) are also computed between notable features and ISMR.

In section 2, earlier studies on the role of some important synoptic and semi-permanent features are discussed in the context of ISMR. The data used in this study and methodology adopted are given in section 3. Section 4, contains results of analysis of synoptic and semi-permanent features. Role of these synoptic and semi-permanent features in the occurrence of highest ISMR during 1961 is discussed in section 5 followed by, effect of synoptic and semi-permanent features on spatial distribution of ISMR in section 6. CCs of some synoptic and semi-permanent features and SST of Nino-3 region with ISMR are given in section 7. Conclusions are given in section 8.

2. Important synoptic and semi-permanent features

Onset of monsoon rainfall over Kerala and the withdrawal of monsoon from northwest India are very significant events. It is well known that the date of onset of monsoon over Kerala and the date of withdrawal of monsoon from northwest India have no relation with ISMR (Chowdhary *et al*., 1990 and Jenamani and Desai, 1999). But if monsoon onset over the whole of India is too early and the starting of withdrawal from northwest India is also too late *i.e*., if the total duration of monsoon is longer, ISMR may be more.

Intraseasonal monsoon systems over Indian region can be basically divided into two parts; synoptic disturbances of transient characteristics and semi-permanent systems of quasi-permanent characteristics. Role of such intraseasonal oscillations on interannual variation of ISMR have been recently debated by many authors after failure of ENSO-ISMR relationship in 1997 [Krishnamurthy and Shukla, 2000; Lawrence and Webster, 2001; Srinivasan and Nanjundiah, 2002]. In fact, as mentioned earlier, while studying the cause of normal monsoon during recent El-Nino of 1997 from day to day OLR data analysis Srinivasan and Nanjundiah, 2002 have found that presence of such strong intraseasonal oscillation of monsoon in June 1997 over Indian region was responsible for ISMR being normal. However, they did not study the effect of such intraseasonal oscillations on interannual variation of ISMR from day to day synoptic and semi-permanent features evolutions. This has been studied in the present study.

Most important synoptic disturbances during monsoon season over India are monsoon disturbances (lows, depressions and storms) which form mostly over the Bay of Bengal, off-shore troughs along west coast of India and western disturbances over north India. Monsoon disturbances (low pressure area, depression, storms) generally form over Bay of Bengal and move westwards or west northwestwards along monsoon trough and produce large amount of rainfall. Interannual and intraseasonal variations of these characteristics of monsoon disturbances are studied by Jenamani and Dash

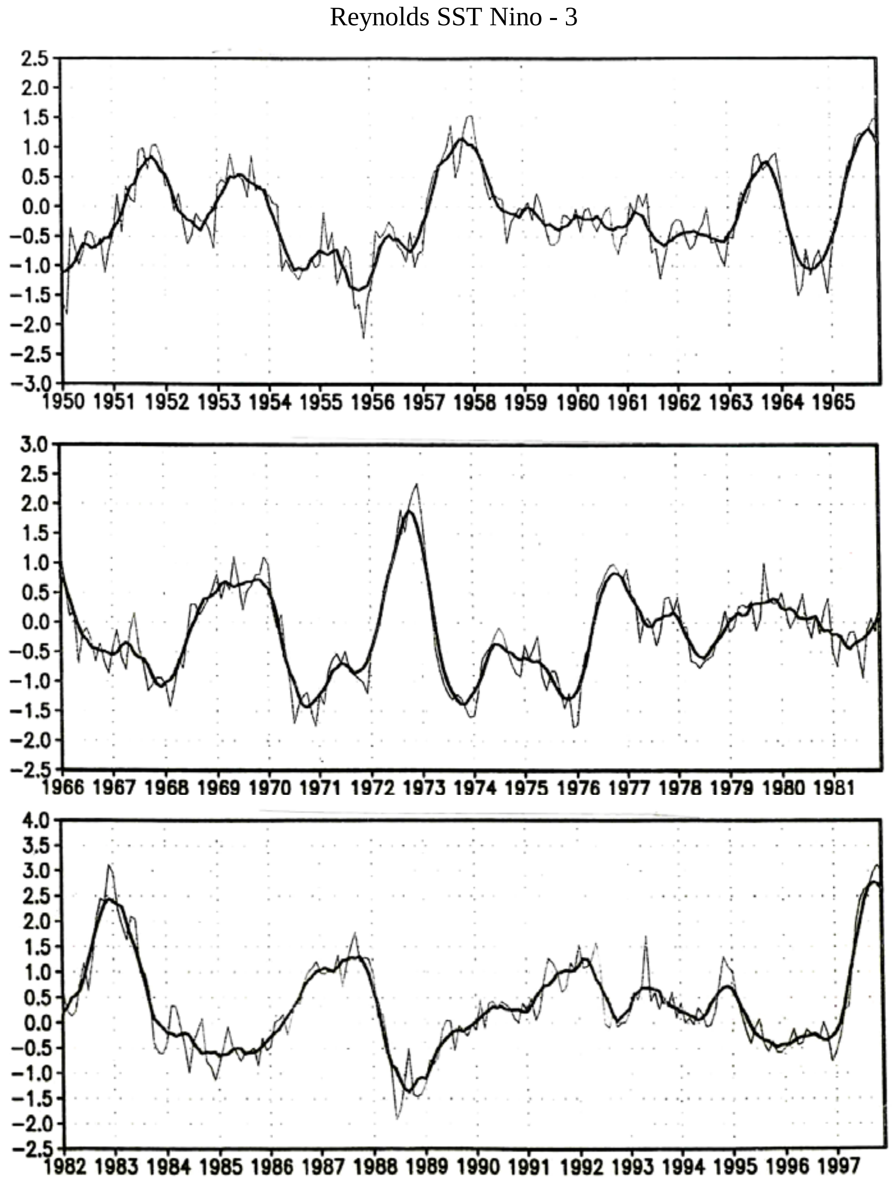


Fig. 1. Monthly SST anomaly (ºC) over Nino - 3 region during 1950-97 (thin line represents monthly mean anomaly values and bold line represents six monthly running means)

(1999) and Jenamani and Desai (1999) from ISMR prospective. Their study on relationship of ISMR with characteristics of monsoon disturbances shows that years of good rainfall have higher number of such disturbance days compared with drought years. In the present study, we have considered their role by taking such characteristic during different phases of El-Nino/La-Nina. Chen and Weng (1999) have also studied interannual and intraseasonal variations of their genesis from predecessors of monsoon disturbances over northwest Pacific and south China sea for some recent El-Nino/La-Nina years.

Out of the remaining synoptic systems, interaction of westerly systems which include western disturbances and middle-latitude westerly troughs at mid or upper troposphere, with monsoon circulation for favouring good/bad ISMR have already been highlighted earlier through different case studies (Rao, 1976 for references). These studies show that interaction between monsoon and westerly systems depends upon prevailing circulation pattern over India in the intraseasonal scale and hence these systems have a mixed role of either enhancing rainfall or suppressing it by producing break in monsoon

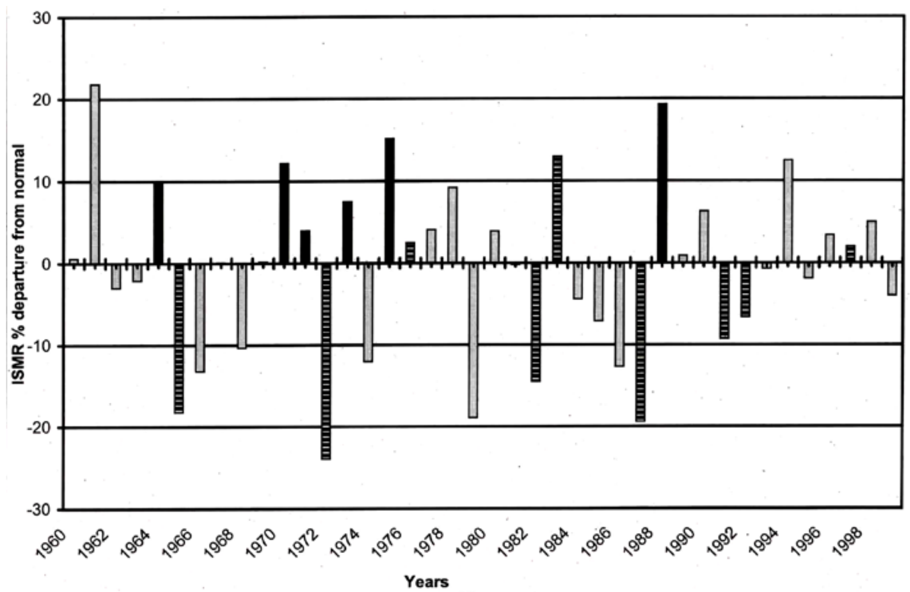


Fig. 2. Percentage departure of ISMR from normal (1960-98)

over India. The other synoptic disturbance, which affects ISMR strongly, is the position of off - shore trough/vortex along west coast of India. George (1956) had examined these features long back. The off-shore trough being a part of monsoon system, is significantly affected by cross equatorial flow or north-south hemispheric pressure gradient. It can also affect activities of ISMR during different phases of El-Nino/La-Nina. However, in the present study, we have neither considered effect of westerly systems nor the effect of off-shore trough on ISMR because of unavailability reliable research quality data for both systems. Though, some of their characteristics are available in "India Daily Weather Summary/India Daily Weather Report (IDWR)", a bulletin prepared from operational data and published by India Meteorological Department (IMD), locations for these two types of systems in these reports are little subjective because these are determined based upon operational data which are sometimes received sparse over the region where these systems are normally observed.

Quasi-permanent systems of synoptic scale that appear over the Indian sub-continent and neighbourhood during start of the monsoon season are called semi-permanent systems. These semi-permanent systems are important components of regional features. Monsoon Trough (trough of low from northwest India to Bay of Bengal through central India) is one of the components of these semi-permanent systems. The others are heat low at the surface over Pakistan and adjoining Afghanistan and Rajasthan, an east-west oriented Tibetan anticyclone over Tibetan region in mid and upper troposphere and tropical easterly jet of strong easterly winds at upper troposphere with jet core at peninsular India. Characteristics of these systems and their role in monsoon are studied by several authors. A brief review is available in Rao (1976). Krishnamurthy and Bhalme (1976) studied these semi-permanent systems and found a quasi-bi-weekly low frequency oscillation. Jenamani and Desai (1999) have considered characteristics of all these semi-permanent systems simultaneously for examining their role in controlling interannual variation of ISMR. The study found that these characteristics (position and intensity) of semi-permanent systems fluctuate and the monsoon trough and the Tibetan anticyclone, are highly responsible for interannual variability of monsoon rainfall over India. In this study, characteristics of monsoon trough and Tibetan anticyclone are examined during different phases of El-Nino/La-Nina.

3. Data and methodology

For classification of El-Nino/La-Nina, SST anomalies in Nino-3 region of eastern equatorial Pacific (area covering 150º W to 90º W and 5º S to 5º N) is considered in the present study. The SST anomalies in Fig. 1, is based on, monthly 2º × 2° grided Reynolds SST data for January, 1950 to May, 1998. In this study, an event is said to be El-Nino (La-Nina) if SST anomalies in Nino - 3 region during monsoon ≥ + 7° C (≤ -7° C). An El-Nino event is said to be double El-Nino event, if warm SST anomaly persists till the next monsoon season even though it is weakened, otherwise it is called single El-Nino event. Cumulative area weighted ISMR percentage departure from normal for recent years of 1960-98 plotted in Fig. 2. These are updated ISMR data from IMD. ISMR is defined as deficient or drought when ISMR percentage departure from normal ≤ -10%, near deficient when

TABLE 1

Categorisation of El-Nino & ISMR relationship

S. No.	Categories	Years	ISMR percentage departure from normal	Status of ISMR
1	Drought once in double El-Nino event	1982	-14.5	Deficient
		1983	13	Flood
2	Drought twice in double El-Nino event	1991	-9.3	Near deficient
		1992	-6.6	Near deficient
		1965	-17.2	Deficient
3	El-Nino drought	1972	-23.9	Deficient
		1987	-19.4	Deficient
4	El-Nino normal	1976	2.5	Normal
		1997	2	Normal
5	Drought near deficient without El-Nino	1966	-13.2	Deficient
		1968	-10.3	Deficient
		1974	-12	Deficient
		1979	-18.9	Deficient
		1985	-7.1	Near deficient
		1986	-12.6	Deficient
6	La-Nina flood	1970	12.2	Flood
		1975	15.2	Flood
		1988	19.3	Flood
7	Flood without La-Nina	1961	21.8	Flood
		1983	13	Flood
		1994	12.5	Flood

departure > -10% but ≤ -7 %, positive side of normal or normal when departure > 0 and above normal or flood when departure ≥ +10%. We classify El-Nino-ISMR relationships in to four categories based on Figs. 1 and 2 and listed in Table 1 as categories 1 to 4 for the period 1960-98.

We have also considered all flood/drought years with respect to all El-Nino/La-Nina during 1960-98 according to definition given above and classified those into another three categories 5 to 7 in Table 1. All of these classifications are based on earlier established ENSO-ISMR relationships *i.e.*, "El-Nino drought" and "La-Nina flood" and years which do not obey such relationships *i.e.*, years when El-Nino was present but normal rainfall occurred over India named as "El-Nino normal", years when El-Nino was not there but drought or near deficient rainfall occurred over India named as "drought without El-Nino" and La-Nina was not there but flood have occurred over India named as "flood without La-Nina". It may be noted that not a single drought has occurred during any La-Nina year. Droughts are only associated with El-Nino or without El-Nino events of eastern Pacific. Hence we have classified all droughts as "El-Nino droughts or drought without El-Nino". Since there is not a single example of occurrence of flood in two consecutive years during 1960-98, we have not considered any La-Nina double events.

Onset and withdrawal dates for 1960-98, are collected from Monsoon Summaries published in the Journal "Mausam" and weekly weather report publish from IMD, Pune. The duration of monsoon is calculated by subtracting the date when monsoon covered the whole of India from the date of first withdrawal from west Rajasthan in the extreme north-west India.

For studying role of monsoon disturbance days which include total days of cyclonic storms (CS), depressions and lows on ISMR during different phases of El-Nino/La-Nina, frequency of the number of CS (includes intensity of CS and above) and depressions for monsoon season over Indian region for the period 1960-98, are collected from the "Tracks of Depressions and Storms in the Bay of Bengal and Arabian Sea" published by IMD (1979) and IMD (1996). Similar data for recent years (1991-98) are collected from India daily weather report and Monsoon Summaries prepared by IMD. However, for finding frequency of lows which are relatively weak systems, no other documented data source except Mooley and Shukla (1987) is available readily for referring seasonal frequency of low pressure areas. Mooley and Shukla (1987) have prepared an exhaustive document of all monsoon disturbances which includes well marked lows and lows for Indian region and the area under consideration is 60° E to 100° E and 5° N to 35° N. This area includes north Indian Ocean and adjoining Indian sub-continent. Further, the data source of Mooley

TABLE 2

Period of break monsoons

Year	July	August	July - August	Total no. of days
1960	16-21	-	-	6
1961	-	-	-	-
1962	-	18-22	-	5
1963	10-13; 17-21	-	-	9
1964	14-18	-	28-3	12
1965	6-8	4-15	-	15
1966	2-11	23-27	-	15
1967	7-10	-	-	4
1968	-	25-27	-	3
1969	25-28	18-20	-	7
1970	12-16; 22-24	-	-	7
1971	-	-	-	-
1972	19-30	-	-	12
1973	-	-	24-1	9
1974	-	-	-	-
1975	25-27	-	-	3
1976	-	-	-	-
1977	-	12-17	-	6
1978	-	-	-	-
1979	-	19-31	-	13
1980	18-20	-	-	3
1981	-	24-26	-	3
1982	-	-	-	-
1983	-	22-26	-	5
1984	21-24	-	-	4
1985	-	23-26	-	4
1986	-	24-26	-	3
1987	29-31	-	-	3
1988	4-6	13-15; 25-27	-	9
1989	29-31	-	-	3
1990	-	-	-	-
1991	-	-	-	-
1992	-	-	-	-
1993	-	-	-	-
1994	-	-	-	-
1995	-	12-15	-	4
1996	1-5	-	-	5
1997	-	-	-	-
1998	16-25	-	-	10
1999	-	-	-	-
2000	-	1-4	-	4

and Shukla (1987) is Indian Daily Weather Report for the period 1888-1983 published by IMD.

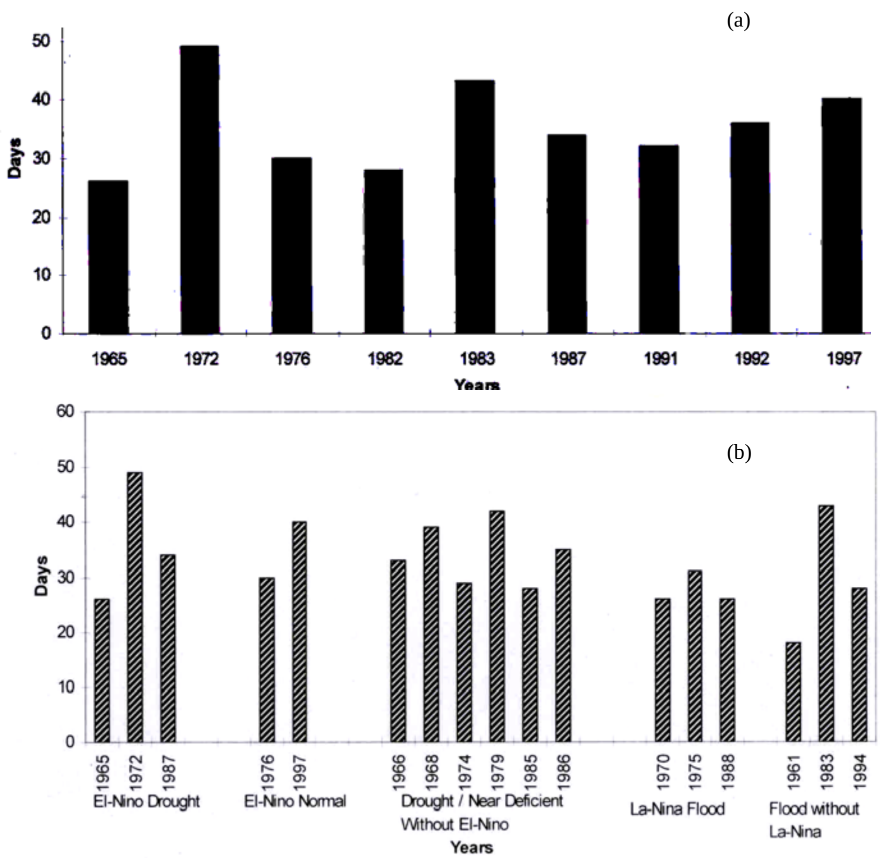
Surface charts with isobaric analysis of 0300 UTC for Indian region are also available in this daily IMD report and while finalising the frequency or tracks of lows from these IMD source, respective authors have followed a stringent method. Details of such method are available in the report of Mooley and Shukla (1987) published by COLA USA and subsequently in an article published in the journal "Mausam" by Mooley and Shukla (1989a).

Since in Mooley and Shukla (1987), synoptic systems such as lows, depressions & CS which are not feeble and have life period of 2 days or more have been considered for counting their number and duration, we have only consider those monsoon disturbances including CS and depressions which has satisfied these conditions. If the synoptic systems continue from one month to the next month then it is considered to belong to that month during which system lies on more number of days. Number of days of cyclonic storm and depression are counted from the days, when the said synoptic system was a low pressure area. Hence low days are also included in the disturbance days in case system intensified into a cyclonic storm. Total disturbance days are the sum of days of cyclonic storm, depression and low days.

When the axis of monsoon trough is seen from west Rajasthan to north Bay both in 0300 and 1200 UTC surface chart, at least for two days, then that day is taken as the date of establishment of monsoon trough and towards the second half of the season, the date from which the trough over this normal position is continuously not seen is taken as its date of less marked. Monsoon trough days are the difference of both of these dates. The "break" is defined, when monsoon trough on the surface chart, lies over the foot hills of Himalayas as defined by Ramamurthy (1969). Break monsoon dates are also collected for the period 1960-2000 are listed in Table 2. From 1960 till 1967, same break monsoon dates as published by Ramamurthy (1969) are listed. Afterwards, for determination of dates of break monsoon, Ramamurthy (1969) conditions of break monsoon have been exactly followed *i.e.*, dates of July and August, when monsoon trough on the surface chart, lies over the foot hills of Himalayas continuously for at least 3 days or more, have been considered for updating break monsoon dates till 2000. Break monsoon dates based on same conditions for the period 1979-98 are published already earlier by present author in Jenamani and Thapliyal (1999). It may be noted that there is not much difference of these dates with that of break monsoon dates of De *et al.*, (1998) except inclusion of some more break monsoon days in the later one from the month of June and September.

The seasonal mean characteristics (position and intensity) of Tibetan anticyclone are determined from daily surface and upper air grided NCEP re-analysed data available in CD ROM for 1976-96 (Kalnay *et al.*, 1996).

Two different types of figures are given for each of the above synoptic and semi-permanent features; one type of figures is given for all the El-Nino double/single events, others are for selected years of "El-Nino drought"



Figs. 3(a&b). Number of days after 1 May when the monsoon onsets over Kerala (MOK) during years of (a) El-Nino double/single events (b) El-Nino drought, El-Nino normal, drought without El-Nino, La-Nina flood and flood without La-Nina

(El-Nino with deficient ISMR, as in 1965,1972 & 1987), "El-Nino normal" (El-Nino years when ISMR percentage departure from normal is on higher positive side as in 1976 & 1997), "drought without El-Nino" (drought or near deficient years when there was no El-Nino as in 1966, 1968, 1974, 1979, 1985 & 1986), "La-Nina flood" (as in 1970, 1975 & 1988) and "flood without La-Nina" (flood years when there was no La-Nina as in 1961, 1983, & 1994).

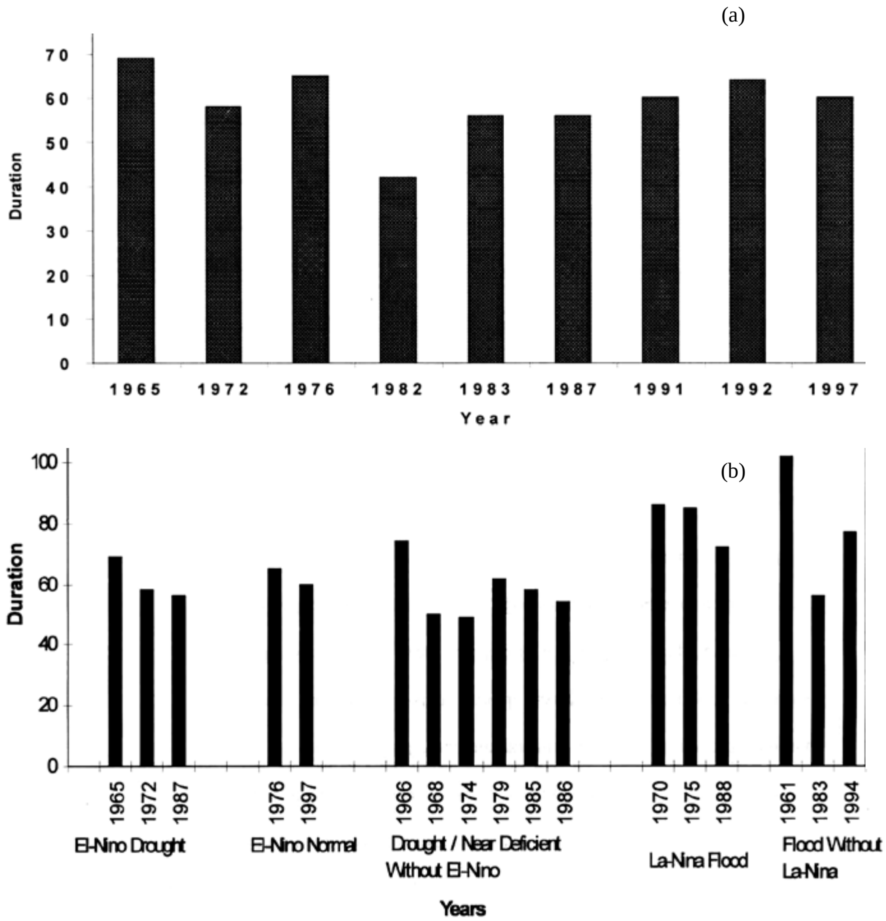
After comparative study of characteristics for each of above mentioned features under different categories, CCs are also calculated between those features with ISMR which have significant role on variation of ISMR for years given in Table 1. This also includes CC of Nino-3 SST with ISMR. All CCs are calculated by using data of 21 years listed in Table 1.

4. Synoptic and semi-permanent features of Indian Summer Monsoon

4.1. *Variation of dates of onset, withdrawal and duration of monsoon over India*

Figs. 3(a&b) show dates of onset of monsoon over Kerala (MOK) in May and June during the cases classified earlier. It is seen that the MOK was early during the El-Nino single event of 1965 (which had deficient rainfall) compared to the El-Nino single event of 1976 (which had normal rainfall) and second year of El-Nino double event 1982-83 (which was a flood year). Similarly, MOK was late during El-Nino normal year 1997 compared to 1965, 1991 and 1992 which were deficient or near deficient rainfall years. Hence MOK has no relation with occurrence of drought during double/single El-Nino events or drought without El-Nino and flood during other years. Similarly it has been seen that the date when monsoon covers complete India and withdrawal date of monsoon from extreme northwest India have no relation with the ISMR during different phases of El-Nino consider for the present study.

Figs. 4 (a&b) show duration of monsoon over India for all the years of study. It may be mentioned here that the duration of monsoon has been computed from the date of prevalence of monsoon over the whole of India up to the date of first date of withdrawal from extreme northwest India. It is seen that in most of the years of El-Nino double/single events and years without El-Nino

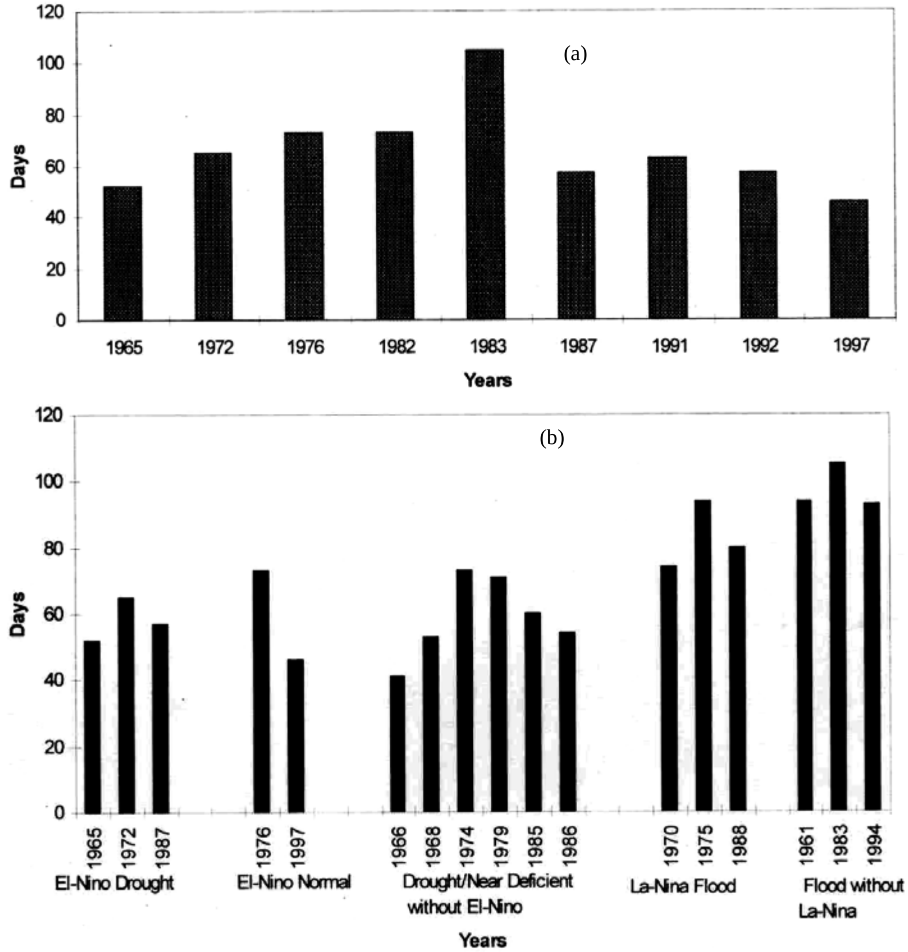


Figs. 4(a&b). Duration of monsoon during years of (a) El-Nino double/single events and (b) El-Nino drought, El-Nino normal, drought without El-Nino, La-Nina flood and flood without La-Nina

when ISMR was deficient or near deficient, duration of monsoon over India was less than La-Nina flood/ flood without La-Nina or El-Nino normal years. In fact, duration of monsoon over India was the longest during flood without La-Nina year of 1961. However, in the deficient year of 1966, it was higher than the duration of monsoon during flood years 1983 & 1988. Similarly during the drought year without La-Nina *i.e.*, 1979, the duration of monsoon was higher than the normal rainfall year of 1997. Thus in general, the duration of monsoon has a positive relation with ISMR, with some exceptions. The above regional features are sometimes responsible for drought or near deficient rainfall when there was no El-Nino, normal rainfall during El-Nino year or flood during years when there was no La-Nina. Hence durations of monsoon is longer (shorter) during most of the flood (drought) years irrespective of the presence or absence of El-Nino/ La-Nina.

4.2. *Variation of characteristics of synoptic features*

Figs. 5(a&b) show the total number of monsoon disturbance days (lows and depression and storms days) during different years. The lowest number of disturbance days amongst all the years of study is found to be during 1966 which is one of the severe drought years when no El-Nino was observed. The highest number of disturbance days is found to be in 1983 which was a flood year in the absence of La-Nina. In fact, it was the second year of El-Nino double event in 1982-83. From Fig. 5(a), it is seen that the number of disturbance days is less during other years of El-Nino double/single events when ISMR was affected. During El-Nino of 1976 and 1983, ISMR was normal or above normal and also low and depression days are higher than other El-Nino drought years. So ISMR is not affected during El-Nino single event of 1976 and during the second year of El-Nino double event in 1982-83. However during El-Nino year 1997, the number of disturbance days is less in comparison with many other deficient years. It may be mentioned that during 1997, the second lowest number of monsoon disturbances was observed amongst all the years of study. During 1997, though less number of low and depression days were observed, it is seen that the number of days of cyclonic circulations and monsoon troughs days were more and hence the ISMR was not affected by El-Nino. During



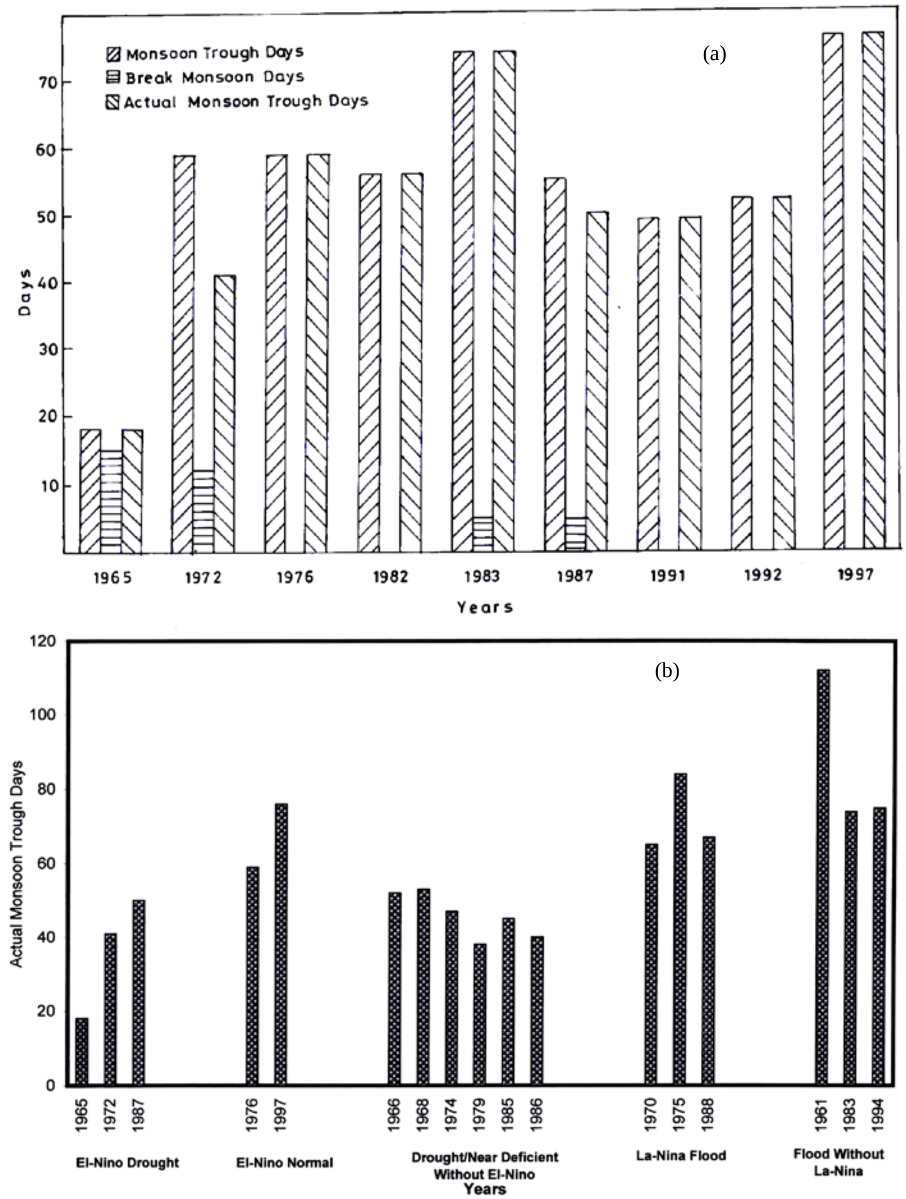
Figs. 5(a&b). Number of monsoon disturbances days during years of (a) El-Nino double/single events and (b) El-Nino drought, El-Nino normal, drought without El-Nino, La-Nina flood and flood without La-Nina

1982, though slightly more days of monsoon disturbances were observed, due to weak monsoon trough, their formation was sporadic and hence ISMR was less. Thus the influence of the number of monsoon disturbance days during the season is very important so as to produce good rainfall during El-Nino years. If the number of these synoptic disturbances days is very much above normal, ISMR is observed to be high in spite of absence of La-Nina.

From Fig. 5(b), it is seen that the disturbance days are also very less during drought years of 1966, 1968, 1979 and 1986 and El-Nino drought years of 1965, 1972, 1987 compared with El-Nino normal years of 1976, La-Nina flood years of 1970, 1975, 1988 or flood years of 1961, 1983, 1994 . In near deficient rainfall years without El-Nino in 1985, the monsoon disturbance days were also less. In 1974 and 1979, though the number of monsoon disturbance days was comparable with 1976, due to weak monsoon trough during most of the days of the season, the disturbances did not produce much rainfall. Thus it may be stated that due to the absence (presence) of sufficient number of monsoon disturbances formation and their movement along monsoon trough, drought (flood) occurred during years when El-Nino (La-Nina) were absent. Hence, the days of monsoon disturbances in a particular year also affect ISMR significantly in spite of presence/absence of El-Nino/La-Nina.

4.3. *Variation of characteristics of semi-permanent features*

Fig. 6(a) shows the total monsoon trough days for different years of El-Nino double/single events. From Fig. 6(a), it is seen that monsoon trough days are less during El-Nino double event in 1991-92, when India received deficient or near deficient rainfall in both the consecutive years, during 1982 of 1982-83, when India



Figs. 6(a&b). (a) Number of monsoon trough and break monsoon days during years of El-Nino double/single events and (b) Actual monsoon trough days for years of El-Nino drought, El-Nino normal, drought without El-Nino, La-Nina flood and flood without La-Nina

received deficient rain once and during El-Nino single events of 1965 and 1987 when India received deficient rainfall. 1972 was an exception. In the year of El-Nino double event in 1982-83, when there was flood, the number of monsoon trough days was more. During single El-Nino events of 1976 and 1997, when ISMR was normal, monsoon trough days were also very high.

During break monsoon conditions (Ramamurthy, 1969) over India, significant decrease of rainfall takes place over most parts of India. Monsoon trough is normally not seen or it runs close to foot hills of Himalayas during break monsoons. Year-wise total break monsoon days over India taken from Table 2, for main monsoon months of July and August during all El-Nino double/single events and plotted in Fig. 6(a) for establishing relationship with ISMR. It is seen that total break monsoon days in 1983 which is flood year is more than 1982 which is a drought year and no break monsoon days were observed in 1991 & 1992 which are near deficient years respectively. Hence the number of break monsoon days over India a has no relationship with ISMR.

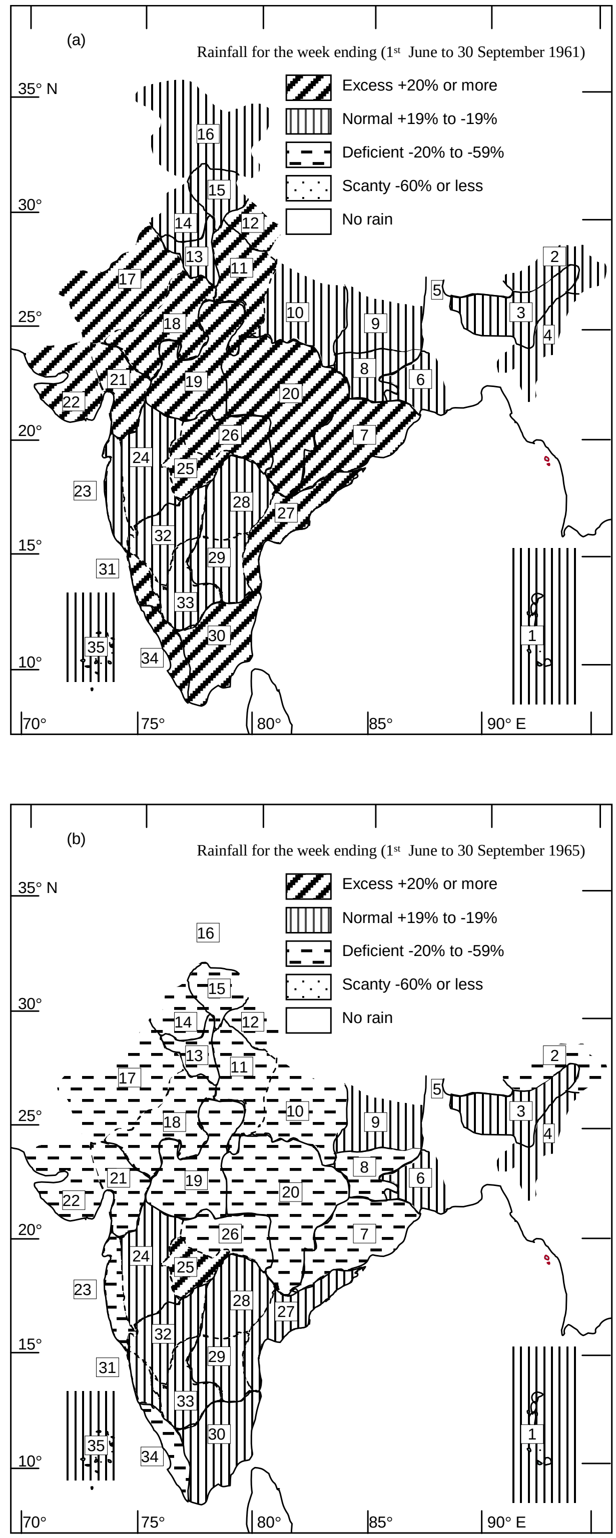
TABLE 3

Characteristics of Tibetan anticyclone

Years	Centre of Tibetan anticyclone (at 500 hPa) (---- indicates centre is not defined)	
	Lat. (° N)	Long. (° E)
1976	26	94
1979	26	94
1982	26	95
1983	26	----
1985	27.5	91
1986	26	91
1987	26	94
1988	27	91
1991	26	92
1992	26	94
1994	28	----

Monsoon trough days in the present study as given in Fig. 6(a) are calculated from the date of establishment of monsoon trough till it becomes less marked, without considering the break monsoon days occurred in between. Thus, it will be more appropriate if all of these break monsoon days when monsoon trough was observed at foot hills of Himalayas between the date of establishment of monsoon trough till it becomes less marked, are subtracted from the total monsoon trough days given in Fig. 6(a) before. We have defined this as the actual monsoon trough days when monsoon trough is mostly active and given in Fig. 6(b) for years of El-Nino drought or near deficient, drought without El-Nino and flood over India with or without La-Nina.

From Fig 6(b), it is seen that actual monsoon trough days are also very less during drought or near deficient years of 1966, 1968, 1974, 1979, 1985 & 1986 compared with flood years and El-Nino normal years including 1972. In fact the number of actual monsoon trough days (112) is the highest in 1961 when there was no La-Nina and India received the highest rainfall. In Fig. 6(b), it may also be noted that during drought year of 1972 when monsoon trough days were found higher, actual monsoon trough days is very less because it's break monsoon days is very high. In other words, ISMR depends on the combination of break monsoon days and monsoon trough days calculated from the date of establishment till it becomes less marked. Both the factors together control ISMR. If monsoon trough establishes early and becomes less marked later on, then persistence of longer days of break monsoon will not affect ISMR (*e.g.*, year 1998, when break monsoon days



Figs. 7(a&b). Spatial distribution of ISMR during (a) 1961 and (b) 1965

were very high, but ISMR was normal) since the actual monsoon trough days will be still high compared with drought years. But, if break monsoon days are very high then the actual monsoon trough days will be less in comparison to good rainfall years (as in drought year of 1972). Hence, ISMR depends more on the actual monsoon trough days in the season compared with other regional features discussed earlier. If monsoon trough is not active (is active) during most of the days of the season, then ISMR will be less(high) as was during 1974, 1979, 1985 & 1986 (1961, 1976, 1983, 1994 & 1997) in spite of the absence of El-Nino (La-Nina) types of boundary conditions. So the actual days of monsoon trough is one of the most important factors responsible for normal rain during El-Nino and drought or near deficient rainfall over India without El-Nino and flood over India without La-Nina types of boundary condition.

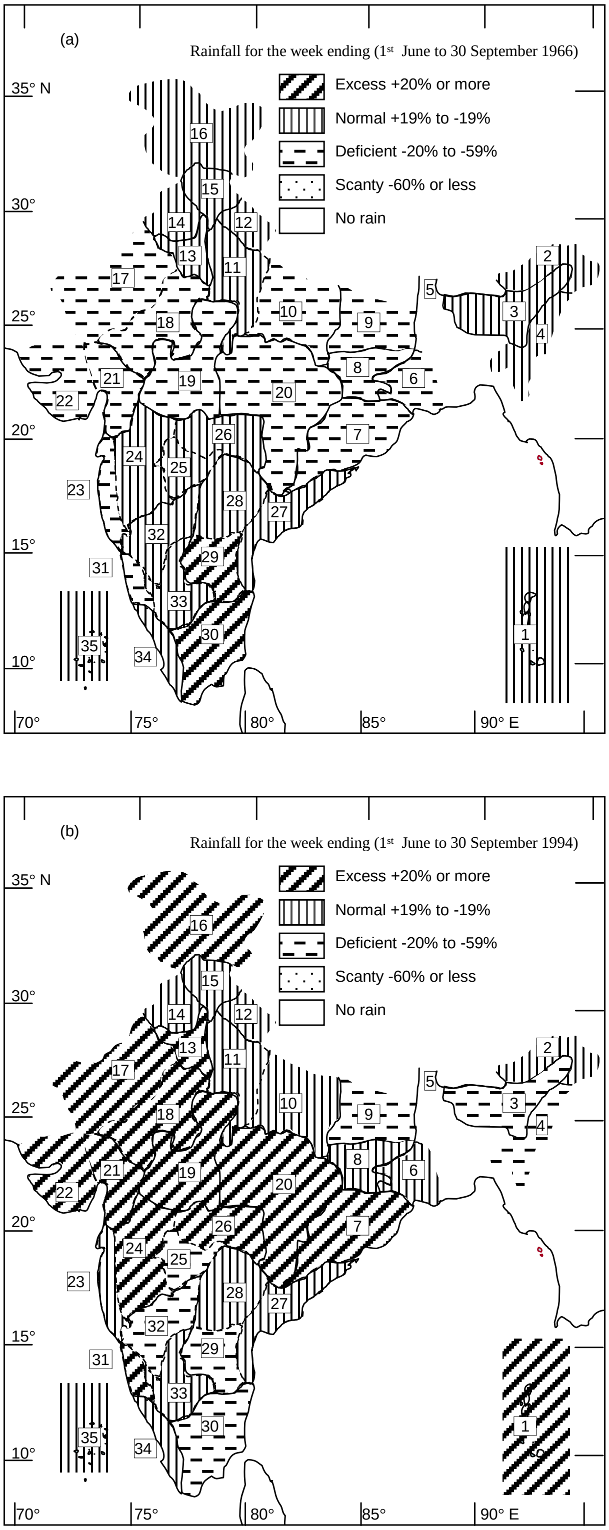
Table 3, shows the approximate positions of the centre of seasonal mean of Tibetan anticyclone at 200 hPa during different years. From Table 3, it is seen that during flood years 1988 and 1994, Tibetan anticyclone was to the north of its normal position and active and during drought without El-Nino as in 1979, 1982, 1986, 1987, 1991 & 1992, it was to the south of it's normal position and weak. But during the second year of El-Nino double event of 1982-83 *i.e*., in 1983, when ISMR was above normal, the Tibetan anticyclone was also very weak compared with 1985. Similarly, during good rainfall year of El-Nino single event of 1976, Tibetan anticyclone was also very weak and to the south of its position in 1985. So mean seasonal position of Tibetan anticyclone has very weak relationship with ISMR during different phases of El-Nino and La-Nina. However according to Jenamani and Desai (1999), ISMR also depends upon the date of establishment of Tibetan anticyclone and number of days of it's presence in it's normal position. Study of operational daily upper air data for 1987-98 also confirmed this result. Thus one may infer that during El-Nino double/single events and flood without La-Nina years (drought without El-Nino years), if the Tibetan anticyclone prevailed for more (less) number of days in its favourable position, the ISMR is on the positive side of normal or there is flood(near deficient or drought).

5. Role of synoptic and semi-permanent features in occurrence of the highest ISMR during 1961

In 1961, India received the highest monsoon rainfall during the period 1960 to 1998 with +21.8 percentage departure. Also in 1961, both the date of monsoon onset over Kerala (18 May) and the date of monsoon covering the complete India (21 June) were earliest, the starting date of withdrawal of monsoon from extreme north-west India was very late (1 October) and duration of monsoon was of longest duration (101 days) compared to other years of study. Since there was no break monsoon days in 1961 [Fig. 7(b)] and monsoon trough established very early and it was present till the end of September, hence the number of actual number of monsoon trough days was highest (113 days). However, the number of monsoon disturbance days was not the highest (94 days). The highest number of disturbance days was observed (105 days) in 1983. During 1961 & 1975, the second highest number of monsoon disturbances days (94 days) were observed. However, number of intense monsoon disturbance days *i.e*., number of depression and cyclonic storm days, were significantly higher in 1961 (75 days) compared with 1975 (50 days), 1983 (34 days). Also in 1961, five monsoon disturbances moved from the Bay of Bengal to the extreme west Rajasthan. Though higher number of monsoon disturbance days occurred in 1983, none of these systems had long westward travel like 1961. During other good rainfall years of 1975 & 1983, numbers of monsoon disturbance days was also high, however, the numbers of actual monsoon trough days was much less (84 & 74 days respectively) as compared to 1961 (113days). Due to low activity of monsoon trough in 1975 & 1983 compared to 1961, these disturbances might not have produced as much rainfall as in 1961. In 1961, all the important synoptic and semi-permanent features such as number of depression and storm days and number of monsoon trough days and duration of monsoon were highest amongst all the years of study and monsoon trough and disturbances were active during most of the days of the season and hence there was the highest ISMR in spite of no La -Nina.

6. Role of synoptic and semi-permanent features on spatial variation of ISMR during different phases of El-Nino

Out of all the synoptic and semi-permanent features discussed in this paper, active off-shore trough produces good rainfall over sub-divisions of west coast of India and active monsoon trough and monsoon disturbances normally produce good rainfall over areas along central India. Thus, the spatial distribution of seasonal rainfall is critically examined for finding the role of these three main features. The role of off-shore trough in producing a particular type of spatial distribution of rainfall could not be established for the period of 1960-98 due to unavailability of good quality data for locating this system. However, it has been seen that spatial distribution of rainfall during 1961, 1965, 1966 and 1994 have affected by formation, intensification, movement, life period, etc. of monsoon disturbances and intensities of monsoon trough during the season. During 1961 and 1994, the number of days of monsoon trough were very high (113 days, 75 days) and active compared with all other years of study except in 1997 and 1975. In 1975 &



Figs. 8(a&b). Same as Figs. 7(a&b) but for (a) 1966 and (b) 1994

1997, the actual monsoon trough days were 76 and 84 respectively which were higher than 1994. The number of monsoon disturbance days was very less during 1997 compared to 1994 and hence could not affect spatial distribution of ISMR during 1997 as was in 1994. In 1975, though almost equally higher number of monsoon disturbances days (94) was seen compared with 1994, only five monsoon disturbances have moved to northwest India after forming over Bay during 1975, while 9 such monsoon disturbances have moved during 1994. Similarly, except comparable number of actual monsoon trough days during 1983 with 1994, though monsoon disturbance days in 1983 was also higher than in 1961 and 1994, these disturbances during 1983 were having very less west ward movement. Hence these disturbances during 1983 gave rainfall over the Bay during most of the days by persisting over the same area without entering into the land along the monsoon trough compared to 1961 and 1994. Hence during 1975 and 1983, the spatial distribution of ISMR was not as varied as in 1961 and 1994. Due to long west ward movement of higher number of monsoon disturbances along the monsoon trough which is also active for higher days during 1961 & 1994, a large belt of excess rainfall activities were observed during both years around area through which monsoon trough normally passes. In contrast, during 1965 and 1966, actual monsoon trough days were of very lower value (18 days, 52 days) and weak compared with all other years of study except bad rainfall years of 1986, 1987 and 1991, when though monsoon trough days are less, number of monsoon disturbances days were more. Similarly, analysis from characteristics of monsoon disturbances for these contrasting years show that cyclogenesis over Bay was very weak, monsoon disturbances days were very less (52 and 41 days respectively) and these disturbances were having very less westwards movements during 1965 and 1966 compared with all other years of study. These regional features during 1965 & 1966 are just of reversed characteristics compared with their characteristics in 1961 and 1994.

Figs. 7 and 8 show sub-division wise spatial distribution of ISMR in 1961, 1965, 1966 and 1994. Due to the above contrasting characteristics of monsoon disturbances and monsoon trough during these years, a large area covered by deficient rainfall are seen from Orissa on east coast of India to Rajasthan in the north-west India during 1965 and 1966 in Figs. 8(b) and 7(a) and *vice versa* in Fig. 8(a) and Fig.7(b) for 1961 and 1994 respectively. It may be noted that normally this is the region of monsoon trough and over this region, monsoon disturbances pass. So variation of characteristics (*e.g.* formations, movements, life period etc.) of monsoon disturbances and intensity of monsoon trough from day to day in the season are the most important components of synoptic and semi-permanent features of monsoon which can affect spatial variation of ISMR significantly.

TABLE 4

CCs of synoptic and semi-permanent features and Nino-3 SST with ISMR

Parameters	CC with ISMR
Duration of monsoon over the whole of India	0.68
Monsoon disturbance days	0.7
Actual monsoon trough days	0.84
SST in Nino-3 region	-0.49

7. CCs of synoptic and semi-permanent features and SST of Nino-3 region with ISMR

To make quantitative representations and to understand the most important feature favourable for ISMR, the CCs of all these parameters and Nino-3 SST with ISMR have been computed and given in Table 4. Interestingly, the highest CC has been obtained between ISMR and the actual monsoon trough days followed by monsoon disturbances days. Hence, Table 4 also confirms results of our comparative study done in section 4 that synoptic and semi-permanent features *e.g.*, characteristics of monsoon trough and monsoon disturbances and duration of monsoon may help in producing normal/excess rainfall over India during some years of El-Nino events and flood in the absence of La-Nina. Whether these regional features are the effect of El-Nino or other slowly boundary conditions *e.g.*, snow cover over Eurasia, northern hemispheric surface temperature etc. or independent of El-Nino, remains a challenging question, which is beyond the scope of the present study.

8. Conclusions

This study leads to following main conclusions ;

(*i*) The duration of monsoon over the whole of India are found to be higher (less) during most of the flood (drought) years particularly in the years of flood without La-Nina (drought without El-Nino).

(*ii*) It is seen that the monsoon trough was established early and stayed for more number of days at it's favourable position and the number of monsoon disturbance days were higher during the second year of El-Nino double event in 1982-83 and El-Nino single events of 1976 and 1997 when ISMR was normal. The same synoptic and semi-permanent features were also found to be responsible for flood in the absence of La-Nina over Pacific ocean in 1961 & 1994.

(*iii*) Establishment of Tibetan anticyclone and it's position as seen from operational data seem to indicate its association with occurrence of drought (flood) with or without El-Nino (La-Nina).

(*iv*) The importance of the same synoptic and semi-permanent features in ISMR has been studied for 1961 which had the highest rainfall during the period of study 1960 to 1998. The present study shows number of days of monsoon trough and intense monsoon disturbances were the highest and also the duration of monsoon was the longest during 1961 compared to other years.

(*v*) This study also shows that the number of monsoon disturbances days and monsoon trough are the most important components of monsoon which affect the spatial variation of ISMR. Statistical analysis shows that ISMR has the highest CC with the actual monsoon trough days followed by monsoon disturbances days and then duration of monsoon, Nino-3 SST in that order.

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