J. Ind. Geophys. Union ( January 2014 )
**v.18, no.1, pp:127-140**

# South Indian Convergence Zone Model: A new approach to seasonal forecasting of summer monsoon rainfall in India Part V: Relative roles of major oscillations in Pacific and Indian Oceans in inter-annual variability of Indian summer monsoon rainfall

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**ABSTRACT**

El Nino Southern Oscillation (ENSO), which affects the weather over the globe, is considered as one of the major factors in the inter-annual variability of Indian Summer Monsoon (ISM) Rainfall (ISMR). Studies on ISM by the authors have identified an important role of the annual oscillation of the equatorial troughs in Indian Ocean (IO), as monitored in satellite observed cloud data, in inter-annual variability of ISMR. Quantification of the activity of equatorial troughs in Indian ocean during the period January-May in relation to rainfall over India during June-September, i.e., ISMR, and development of a Long Range Forecast (LRF) model, referred to as South Indian Convergence Zone (SICZ) model, have been discussed in Part I of the paper. Verification of real time LRF for the past 22 years (1990-2011) for India as a whole, i.e., ISMR, as well as in meteorological sub-divisions of India ( numbering 36 ), as discussed in Pt II and Pt III of the paper respectively, have shown that SICZ model has produced reasonably good forecasts of summer monsoon rainfall for more than 2 decades now. In this part of the paper we have examined the relative roles of major oscillations in Pacific and Indian Oceans in inter-annual variability of ISMR. It has been shown that SST anomalies in Nino 3.4 region ( 5°S- 5°N, 120°W -170° W ) could provide good LRF of ISMR during 'normal' monsoon years. However, all extreme seasons ('excess' / 'drought' ) could not be foreshadowed. On the other hand, SICZ model, has been able to foreshadow not only 'normal' monsoons but the extreme seasons also during the past 22 years. This has indicated a dominant role of Indian Ocean in the development of ISM and its inter-annual variability. The relative roles of Pacific and Indian Oceans in the inter-annual variability of ISMR are discussed in this part of the paper.

## INTRODUCTION

The relationship between the activity of South Indian Convergence Zone (SICZ) during the period January-May and the activity of Indian Summer Monsoon (ISM) during June-September has been discussed in Pt I of the paper (Prasad, Singh and Prasad,2010b). Quantification of the activity of SICZ in relation to ISMR by assigning an activity index, referred to as SICZ Activity Index (SAI), ranked from 1 to 20 covering the range of ISMR between 25% above normal to 35% below normal, development of linear regression equations between SAI and rainfall for India as a whole for the summer monsoon months of June, July, August and September, bi-monthly periods of June+ July, July+ August and August+ September and for the season as a whole ( June-September), i.e., ISMR and verification of forecasts had been discussed in Pt II of the paper ( Prasad and Singh, 2012). Similarly, development of regression equations between SAI and rainfall during monsoon months, bi-monthly periods and season as a whole for meteorological sub-divisions of India ( numbering 36) and verification of forecasts, has been discussed in Pt III ( Prasad and Singh,2013a). Role of ongoing changes in Equatorial Pacific Ocean (EPO) in intra-seasonal changes in ISMR have been discussed in Pt IV ( Prasad and Singh,2013b). Verification of real time forecasts for the period 1990-2011 (Prasad and Singh, 2012,2013a) have shown that SICZ model has produced reasonably good forecasts of ISMR for more than 2 decades. There were three droughts in the past decade, i.e., in the years 2002, 2004 and 2009. All the three droughts had also been foreshadowed by the model. It may be mentioned here that none of the models, statistical or dynamical, could foreshadow any of these droughts. There was no excess monsoon during the period 1990-2011 except that the ISMR was 10% above normal in 1994.

Inter-annual variability in ISMR attracts the attention of researchers all over the world. Sea Surface Temperature (SST) and land surface processes (snow mass, ground wetness) have been recognized, as two important factors that govern the inter-annual variability of summer monsoon. Experiments conducted by Yang and Lau (1998) have shown that SST anomalies cause a more significant change in the Asian summer monsoon as compared to land surface processes: In their experiments, May-September monsoon rainfall averaged within 10°-25° N , 50°-120° E was about 1 mm/day due to warm SST anomalies and 0.2 mm/day because of increased ground wetness. Both Walker circulation and local Hadley circulation became weaker than normal with warm SST anomalies. Consequently, the amount of atmospheric water vapor transported into tropical Asia also reduced. ISMR tends to be deficient during El Nino years, more particularly during the second half of the season, i.e., August-September (Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983; Webster and Yang, 1992). ENSO being a major factor, affecting weather in different regions of the globe, is considered to remotely affect the ISM also. Inter-annual variability in ISMR in relation to ENSO has been studied mainly by linking SST anomalies in central and eastern Equatorial Pacific Ocean and anomalies in rainfall. The motivation for such studies has been to find a tool for Long Range Forecasting (LRF) of ISMR. In spite of an important role of the Pacific Ocean SST anomalies in inter-annual variability of summer monsoon, ENSO alone could not explain all the inter-annual variability of ISMR: The years 1914, 1963, 1976, 1983 and 1997 did not experience deficiency in ISMR in spite of occurrence of strong El Nino events. Severe all India droughts in the years 2002 and 2009 occurred when El Nino was weak (Kalsi et al; 2004). Weakening of the relationship between ENSO and ISMR has been reported by some workers (Webster et al.,1998; Kumar et al.,1999). Some of the recent studies (Gadgil, et al., 2007; Ihara et al.,2007, 2008) have concluded that inter-annual variability of ISMR could be better explained by considering the indices of Pacific and IO together. Inter-annual variability in ISM as studied in cloud data from the IO region by Prasad et al. (1988), De et al. (1991), Gupta and Prasad (1991,1992,1993), Prasad and Singh (2010a,b; 2012,2013a,b) have demonstrated that the annual oscillation of the equatorial troughs in IO appears to better explain the inter-annual variability of ISMR. This conclusion is based on the performance of SICZ model in producing reasonably good forecasts of ISMR for more than 2 decades (1990-2011). SICZ model makes use of the features related to this oscillation in formulating long range forecasts. The activity of SICZ during the period January-May, contains signals which are precursors of ISM. This result appears to be an important step forward in furthering our understanding about development of ISM and its inter-annual variability. Inter-annual variability of ISMR is also related to several other factors: Eurasian winter/spring snow cover (Hahn and Shukla, 1976; Dey and Bhanu Kumar, 1982; Vernekar, Jhou and Shukla,1996; Kriplani, Singh, Vernekar and Thapliyal, 1996; Bamzai and Shukla,1999; Kriplani, Kulkarni and Sabade, 2003), the northern hemisphere temperature in winter (Verma, Subramaniam and Dugam,1985), Sea surface temperatures around Northern Australia and Indonesia (Nicholls, 1983,1995), surface air temperatures over northwest Europe and Eurasia (Chang, Harr and Ju,2001), inter-decadal variability ( Kriplani and Kulkarni,1997). These factors and major oscillations in Pacific and Indian Ocean are not necessarily independent. In this study we aim at examining the relative roles of major oscillations in EPO and IO in inter-annual variability of ISMR.

Use of satellite observed cloud data in the study of summer monsoon began with the studies of Sadler (1969) and Saha (1972). Another aim of the present study is to inform the scientific community about the important role played by satellite observed cloud data in improving our understanding about the development of ISM and how a simple technique developed, making use of cloud data has been able to produce reasonably good long range forecast of ISMR rainfall for more than two decades now.

## DATA USED AND METHOD OF ANALYSIS

As the discussions in the sections to follow shall show, oscillation in the EPO associated with the development of El Nino- ENSO neutral- La Nina and vice-versa as monitored in SST anomalies, and the activity of SICZ as monitored in cloudiness over IO region only could be used to prepare LRF of ISMR. Accordingly, 3-months running mean SST anomalies in Nino 3.4 region and ISMR for a period of 62 years (1950-2011) and data on the activity of SICZ for a period of 40 years (1972-2011) have been used in the study. Cloud data were not available before 1972. Three months running mean SST anomalies of Nino-3.4 region have been taken from Climate Prediction Centre's web site (www.cpc.ncep.noaa.gov). For the analysis of cloud data, assigning of SICZ Activity Index (SAI) and SICZ model forecast of ISMR reader is referred to Pt II of the paper (Prasad and Singh,2012). In the discussions to follow, summer monsoon has been categorized into 5 categories based on the percentage departures of ISMR from its normal (100 %), namely, 'excess' ( % departure of ISMR ≥ 11%), 'active' ( between 5% and 10%), 'normal' (between 4% and -4%), 'weak' (between -5% and -10%) and 'drought'(% departure ≤ -11%).

## EL NINO SOUTHERN OSCILLATION (ENSO)

Compared to other Nino regions, SST anomalies in Nino 3.4 region show stronger relationship with ISMR. In an effort to find existence of a pattern, if any, in the evolution of SST anomalies in Nino 3.4 region and its relationship with Indian Summer Monsoon Rainfall, we have examined the anomalies for the past 62 years (1950-2011). It may be mentioned here that pattern recognition in weekly mean cloudiness from the IO region formed the basis of the new approach to LRF of ISMR. For the sake of comparison of the relative roles of both the oceans in inter-annual variability in ISMR, years have been grouped into five, corresponding to five categories of ISM as mentioned above, i.e., excess, active, normal, weak and drought. The salient features of the evolution of SST anomalies in each group in relation to anomalies in ISMR have been discussed below.

Three months running mean of SST anomalies for the years in different categories of monsoon are given in Tables 2-4. However, for the sake of easy comparison, the means of anomalies for all categories have been put at one place and shown in Table 1. The exceptions are 1974 from drought years (Table 2); 1991 and 1992 from weak monsoon years (Table 2); 1994 from active monsoon years (Table 3) and 1983 from excess monsoon years (Table 3). The anomalies in these years were opposite to the anomalies of the remaining years of their group and hence they have not been considered for obtaining mean anomalies of their respective group. In case of normal monsoon (Table 4), there were several such exception years and hence they have not been excluded for obtaining the mean anomalies. It is interesting to note that the mean anomalies show a distinct pattern of their evolution for each category of monsoon: During drought years anomalies are negative and small in magnitude in the beginning

**Table – 1.** Evolution of mean of 3-months running means of SST anomalies in Nino 3.4 region for different categories of Indian summer monsoon

| Monsoon category | No. of years | Mean ISMR | Mean of 3-month running means of SST anomalies(°C) in Nino 3.4 region | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DJF | JFM | FMA | MAM | AMJ | MJJ | JJA | JAS | ASO | SON | OND | NDJ |
| Drought | 11 | -18 | -0.2 | -0.1 | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.1 | 1.3 | 1.4 | 1.4 |
| Weak | 5 | -8 | -0.7 | -0.7 | -0.2 | -0.4 | -0.3 | -0.2 | -0.1 | -0.1 | -0.1 | 0.1 | 0.1 | -0.1 |
| Normal | 26 | 0 | -0.2 | -0.2 | -0.2 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 | -0.1 | -0.2 |
| Active | 9 | 8 | 0.7 | 0.5 | 0.2 | 0.0 | -0.2 | -0.2 | -0.2 | -0.4 | -0.5 | -0.7 | -0.7 | -0.5 |
| Excess | 7 | 15 | 0.3 | 0.2 | 0.1 | 0.0 | -0.1 | -0.4 | -0.6 | -0.7 | -0.9 | -0.9 | -1.0 | -1.1 |

Note: **Bold figures**, **Positive/Negative,** in this table as well Tables 2-4 below, indicate **El Nino** /**La Nina** conditions respectively.

**Table – 2.** Evolution of 3-months running mean SST anomalies in Nino 3.4 region during 'drought' and 'weak' Indian summer monsoon years.

| S. No. | Year | ISMR | 3-months running mean SST anomalies (°C) in Nino 3.4 region | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DJF | JFM | FMA | MAM | AMJ | MJJ | JJA | JAS | ASO | SON | OND | NDJ |
| 'drought' | | | | | | | | | | | | | | |
| 1 | 1951 | -19 | **-1.0** | **-0.9** | **-0.6** | -0.3 | -0.2 | 0.2 | 0.4 | **0.7** | **0.7** | **0.8** | **0.7** | **0.6** |
| 2 | 1965 | -18 | **-0.8** | -0.4 | -0.2 | 0.0 | 0.3 | **0.6** | **1.0** | **1.2** | **1.4** | **1.5** | **1.6** | **1.5** |
| 3 | 1972 | -24 | **-0.7** | -0.4 | -0.0 | 0.2 | **0.5** | **0.8** | **1.0** | **1.3** | **1.5** | **1.8** | **2.0** | **2.1** |
| 4 | 1982 | -15 | 0.0 | 0.1 | 0.1 | 0.3 | **0.6** | **0.7** | **0.7** | **1.0** | **1.5** | **1.9** | **2.2** | **2.3** |
| 5 | 1986 | -13 | -0.5 | -0.4 | -0.2 | -0.2 | -0.1 | 0.0 | 0.3 | **0.5** | **0.7** | **0.9** | **1.1** | **1.2** |
| 6 | 2002 | -19 | -0.1 | 0.1 | 0.2 | 0.4 | **0.7** | **0.8** | **0.9** | **1.0** | **1.1** | **1.3** | **1.5** | **1.4** |
| 7 | 2004 | -14 | 0.4 | 0.3 | 0.2 | 0.2 | 0.3 | **0.5** | **0.7** | **0.8** | **0.9** | **0.8** | **0.8** | **0.8** |
| 8 | 2009 | -22 | -0.8 | -0.7 | -0.5 | -0.1 | 0.2 | **0.6** | **0.7** | **0.8** | **0.9** | **1.2** | **1.5** | **1.8** |
| 9 | 1987 | -19 | **1.2** | **1.3** | **1.2** | **1.1** | **1.0** | **1.2** | **1.4** | **1.6** | **1.6** | **1.5** | **1.3** | **1.1** |
| 10 | 1966 | -13 | **1.2** | **1.0** | **0.8** | **0.5** | 0.2 | 0.2 | 0.2 | 0.0 | -0.2 | -0.2 | -0.3 | -0.3 |
| 11 | 1979 | -21 | -0.1 | 0.0 | 0.1 | 0.1 | 0.1 | -0.1 | 0.0 | 0.1 | 0.3 | 0.4 | 0.5 | 0.5 |
| 12 | 1974 | -12 | **-1.9** | **-1.7** | **-1.3** | **-1.1** | **-0.9** | **-0.8** | **0.6** | **0.5** | **-0.5** | **-0.7** | **-0.9** | **-0.7** |
| 'weak' monsoon | | | | | | | | | | | | | | |
| 1 | 1952 | -8 | 0.3 | 0.1 | 0.1 | 0.2 | 0.1 | -0.1 | -0.3 | -0.3 | -0.2 | -0.2 | -0.1 | 0.0 |
| 2 | 1968 | -10 | **-0.7** | **-0.9** | **-0.8** | **-0.7** | -0.3 | 0.0 | 0.3 | 0.4 | 0.3 | 0.4 | **0.7** | **0.9** |
| 3 | 1985 | -7 | **-0.9** | **-0.8** | **-0.7** | **-0.7** | **-0.7** | **-0.6** | **-0.5** | **-0.5** | **-0.5** | -0.4 | -0.3 | -0.4 |
| 4 | 2000 | -8 | **-1.6** | **-1.4** | **-1.0** | **-0.8** | **-0.6** | **-0.5** | -0.4 | -0.4 | -0.4 | **-0.5** | **-0.6** | **-0.7** |
| 5 | 2001 | -8 | **-0.6** | **-0.5** | -0.4 | -0.2 | -0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.0 | -0.1 | -0.1 |
| 6 | 1991 | -9 | 0.4 | 0.3 | 0.3 | 0.4 | **0.6** | **0.8** | **1.0** | **0.9** | **0.9** | **1.0** | **1.4** | **1.6** |
| 7 | 1992 | -7 | **1.8** | **1.6** | **1.5** | **1.4** | **1.2** | **0.8** | **0.5** | 0.2 | 0.0 | -0.1 | 0.0 | 0.2 |

**Table – 3.** Evolution of 3-months running mean SST anomalies in Nino 3.4 region during 'Active' and 'excess' Indian summer monsoon years.

| S. No. | Year | ISMR | 3-months running mean SST anomalies (°C) in Nino 3.4 region | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DJF | JFM | FMA | MAM | AMJ | MJJ | JJA | JAS | ASO | SON | OND | NDJ |
| 'active' monsoon | | | | | | | | | | | | | | |
| 1 | 1955 | 10 | **-1.0** | **-0.9** | **-0.9** | **-1.0** | **-1.0** | **-1.0** | **-1.0** | **-1.0** | **-1.4** | **-1.8** | **-2.0** | **-1.9** |
| 2 | 1964 | 10 | **0.8** | 0.4 | -0.1 | **-0.5** | **-0.8** | **-0.8** | **-0.9** | **-1.0** | **-1.1** | **-1.2** | **-1.2** | **-1.0** |
| 3 | 1973 | 8 | **1.8** | **1.2** | **0.5** | -0.1 | **-0.6** | **-0.9** | **-1.1** | **-1.3** | **-1.4** | **-1.7** | **-2.0** | **-2.1** |
| 4 | 1978 | 9 | 0.7 | 0.4 | 0.0 | -0.3 | -0.4 | -0.4 | -0.4 | -0.4 | -0.4 | -0.3 | -0.2 | -0.1 |
| 5 | 2003 | 5 | **1.2** | **0.9** | **0.5** | 0.1 | -0.1 | 0.1 | 0.4 | -0.5 | -0.6 | -0.5 | -0.6 | -0.4 |
| 6 | 2007 | 6 | 0.8 | 0.4 | 0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.4 | -0.7 | -1.0 | -1.1 | -1.3 |
| 7 | 1990 | 6 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 |
| 8 | 1953 | 10 | 0.2 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 9 | 1958 | 10 | **1.7** | **1.5** | **1.2** | **0.8** | **0.6** | **0.5** | 0.3 | 0.1 | 0.0 | 0.0 | 0.2 | 0.4 |
| 10 | 1994 | 10 | 0.2 | 0.2 | 0.3 | 0.4 | **0.5** | **0.5** | **0.6** | **0.6** | **0.7** | **0.9** | **1.2** | **1.3** |
| 'Excess' monsoon | | | | | | | | | | | | | | |
| 1 | 1956 | 14 | **-1.3** | **-0.9** | **-0.7** | **-0.6** | **-0.6** | **-0.6** | **-0.7** | **-0.8** | **-0.8** | **-0.9** | **-0.9** | **-0.8** |
| 2 | 1975 | 15 | **-0.6** | **-0.6** | **-0.7** | **-0.8** | **-0.9** | **-1.1** | **-1.2** | **-1.3** | **-1.5** | **-1.6** | **-1.7** | **-1.7** |
| 3 | 1988 | 19 | **0.7** | **0.5** | 0.1 | -0.2 | **-0.7** | **-1.2** | **-1.3** | **-1.2** | **-1.3** | **-1.6** | **-1.9** | **-1.9** |
| 4 | 1970 | 12 | 0.5 | 0.3 | 0.2 | 0.1 | 0.0 | -0.3 | **-0.6** | **-0.8** | **-0.9** | **-0.8** | **-0.9** | **-1.1** |
| 5 | 1961 | 22 | -0.2 | -0.2 | -0.2 | -0.1 | 0.1 | 0.2 | 0.0 | -0.3 | -0.6 | -0.6 | -0.5 | -0.4 |
| 6 | 1959 | 14 | 0.4 | 0.5 | 0.4 | 0.2 | 0.0 | -0.2 | -0.4 | -0.5 | -0.4 | -0.3 | -0.2 | -0.2 |
| 7 | 1983 | 13 | **2.3** | **2.0** | **1.5** | **1.2** | **1.0** | **0.6** | 0.2 | -0.2 | -0.6 | -0.8 | -0.9 | -0.7 |

**Table – 4.** Evolution of 3-months running mean SST anomalies in Nino 3.4 region during 'normal' Indian summer monsoon years.

| Sl. No | Year | ISMR | 3-months running mean SST anomalies (°C) in Nino 3.4 region | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DJF | JFM | FMA | MAM | AMJ | MJJ | JJA | JAS | ASO | SON | OND | NDJ |
| 1 | 1950 | 4 | **-1.7** | **-1.5** | **-1.3** | **-1.4** | **-1.3** | **-1.1** | **-0.8** | **-0.8** | **-0.8** | **-0.9** | **-0.9** | **-1.0** |
| 2 | 1971 | 4 | **-1.3** | **-1.3** | **-1.1** | **-0.9** | **-0.8** | **-0.8** | **-0.8** | **-0.8** | **-0.8** | **-0.9** | **-1.0** | **-0.9** |
| 3 | 1999 | -4 | **-1.4** | **-1.2** | **-0.9** | **-0.8** | **-0.8** | **-0.8** | **-0.9** | **-0.9** | **-1.0** | **-1.1** | **-1.3** | **-1.4** |
| 4 | 1954 | 3 | 0.5 | 0.3 | -0.1 | **-0.5** | **-0.7** | **-0.7** | **-0.8** | **-1.0** | **-1.2** | **-1.1** | **-1.1** | **-1.1** |
| 5 | 1989 | 1 | **-1.7** | **-1.5** | **-1.1** | **-0.8** | **-0.6** | -0.4 | -0.3 | -0.3 | -0.3 | -0.3 | -0.2 | -0.1 |
| 6 | 2008 | -2 | **-1.4** | **-1.4** | **-1.1** | **-0.8** | **-0.6** | -0.4 | -0.1 | 0.0 | 0.0 | 0.0 | -0.3 | -0.6 |
| 7 | 1976 | 2 | **-1.6** | **-1.2** | **-0.8** | **0.6** | **0.5** | -0.2 | 0.1 | 0.3 | **0.5** | **0.7** | **0.8** | **0.7** |
| 8 | 2011 | 2 | **-1.3** | **-1.2** | **-0.9** | **-0.6** | -0.2 | 0.0 | 0.0 | -0.2 | -0.4 | **-0.7** | **-0.8** | **-0.9** |
| 9 | 1962 | -3 | -0.4 | -0.4 | -0.4 | -0.5 | -0.4 | -0.4 | -0.3 | -0.3 | **-0.5** | **-0.6** | **-0.7** | **-0.7** |
| 10 | 1984 | -4 | -0.4 | -0.2 | -0.2 | -0.3 | -0.5 | -0.4 | -0.3 | -0.2 | -0.3 | **-0.6** | **-0.9** | **-1.1** |
| 11 | 1967 | 0 | -0.4 | -0.4 | -0.6 | -0.5 | -0.3 | 0.0 | 0.0 | -0.2 | -0.4 | -0.5 | -0.4 | -0.5 |
| 12 | 1960 | 0 | -0.3 | -0.3 | -0.3 | -0.2 | -0.2 | -0.2 | -0.1 | 0.0 | -0.1 | -0.2 | -0.2 | -0.2 |
| 13 | 1993 | 0 | 0.3 | 0.4 | 0.6 | 0.7 | 0.8 | 0.7 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 0.2 |
| 14 | 1980 | 4 | 0.5 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 | 0.2 | 0.0 | -0.1 | -0.1 | 0.0 | -0.1 |
| 15 | 1981 | 0 | -0.3 | -0.5 | -0.5 | -0.4 | -0.3 | -0.3 | -0.4 | -0.4 | -0.3 | -0.2 | -0.1 | -0.1 |
| 16 | 2006 | -1 | -0.7 | -0.6 | -0.4 | -0.1 | 0.1 | 0.2 | 0.3 | **0.5** | **0.6** | **0.9** | **1.1** | **1.1** |
| 17 | 1963 | -2 | **-0.6** | -0.3 | 0.0 | 0.1 | 0.1 | 0.3 | **0.6** | **0.8** | **0.9** | **0.9** | **1.0** | **1.0** |
| 18 | 1997 | 2 | -0.4 | -0.3 | 0.0 | 0.4 | **0.8** | **1.3** | **1.7** | **2.0** | **2.2** | **2.4** | **2.5** | **2.5** |
| 19 | 1957 | -2 | **-0.5** | -0.1 | 0.3 | **0.6** | **0.7** | **0.9** | **0.9** | **0.9** | **0.9** | **1.0** | **1.2** | **1.5** |
| 20 | 2005 | -1 | **0.7** | **0.5** | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | -0.2 | -0.1 | -0.4 | -0.7 |
| 21 | 1977 | 4 | **0.6** | **0.5** | 0.2 | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | **0.5** | **0.6** | **0.7** | **0.7** |
| 22 | 1996 | 3 | **-0.7** | **-0.7** | **-0.5** | -0.3 | -0.1 | -0.1 | 0.0 | -0.1 | -0.1 | -0.2 | -0.3 | -0.4 |
| 23 | 1995 | -2 | **1.2** | **0.9** | **0.7** | 0.4 | 0.3 | 0.2 | 0.0 | -0.2 | **-0.5** | **-0.6** | **-0.7** | **-0.7** |
| 24 | 2010 | 2 | **1.7** | **1.5** | **1.2** | **0.8** | 0.3 | -0.2 | **-0.6** | **-1.0** | **-1.3** | **-1.4** | **-1.4** | **-1.4** |
| 25 | 1998 | 4 | **2.3** | **1.9** | **1.5** | **1.0** | **0.5** | 0.0 | **-0.5** | **-0.8** | **-1.0** | **-1.1** | **-1.3** | **-1.4** |
| 26 | 1969 | 0 | **1.0** | **1.0** | **0.9** | **0.7** | **0.6** | **0.5** | 0.4 | 0.4 | **0.6** | **0.7** | **0.8** | **0.7** |

of the year. They show increasing tendency, become zero during February-March-April (FMA) and then remain higher than +0.6° C from May-June-July (MJJ) till the end of the year. In other words El-Nino conditions prevailed from MJJ till the end of these years. The opposite conditions prevailed during excess monsoon years. The anomalies were positive, small in magnitude in the beginning of the year, reduced to zero in March-April-May (MAM) and La Nina conditions prevailed during monsoon. During weak monsoons, anomalies were large negative in the beginning, increased during pre-monsoon and monsoon months and were close to zero but still negative at the end of the season. Opposite to this, the anomalies were large positive in the beginning of active monsoon years, showed decreasing trend becoming zero during MAM and negative ( -0.2° C to -0.4° C) during the monsoon season. Normal monsoons were characterized by small negative anomalies in the beginning of the year, showed very slow increase and remained zero during the season. The distinct pattern, as seen in the mean of SST anomalies, for each category of monsoon may appear to be helpful in formulating a LRF of ISMR based on the SST anomalies alone. However, an examination of the evolution of anomalies in individual years, as discussed below in brief, shall show that there are limitations in doing so.

**Table – 5.** Forecast ISMR (FISMR) based on (i) mean SST anomalies during JAS in Nino 3.4 region (ii) the activity of SICZ during January-May and ISMR. Figures in brackets pertain to % departure of FISMR / % departure of ISMR.

| FISMR based on | | ISMR | | | | |
|---|---|---|---|---|---|---|
| | Monsoon category | Excess<br>Active | | Normal | Weak<br>Drought | |
| mean SST anomalies (°C) during JAS in Nino 3.4 region | Excess | 1975(13/12)<br>1988(12/18) | 1973(12/7) | | | |
| | Active | | 1998(10/6)<br>2007(5/5) | 1999(10/-4)<br>2010(10/2) | 1985(5/-10) | |
| | Normal | 1983(1/12) | 1978(4/9)<br>1990(-2/6)<br>1994(-4/10)<br>2003(-3/5) | 1976(-2/0) 1977(-3/0)<br>1980(0/0) 1981(3/4)<br>1989(4/1) 1993(2/0)<br>1995(2/0) 1996(2/3)<br>2005(-2/-1) 2006(-<br>4/-1) 2008(1/-2)<br>2011(2/2) | 1984(2/-8)<br>1992(-1/-8)<br>2000(4/-8)<br>2001(0/-9) | 1974(4/-15)<br>1979(-1/-21)<br>1986(-2/-14) |
| | Weak | | | | 1991(-8/-9) | 1982(-9/-14)<br>2002(-8/-19/)<br>2004(-7/-13)<br>2009(-7/-23) |
| | Drought | | | 1997(-18/2) | | 1972(-12/-24)<br>1987(-15/-18) |
| the activity of SICZ during January-May. | Excess | 1975(13/12)<br>1988(15/18) | | | | |
| | Active | 1983(10/12) | 1978(5/9)<br>1990(5/6)<br>1994(8/10)<br>1998(5/6)<br>2003(8/5)<br>2007(8/5) | 1973(8/4) 1980(5/0)<br>1996(5/3) 1999(10/-4)<br>2006(5/-1) 2008(5/-2)<br>2010(3/2) | | |
| | Normal | | | 1976(1/0) 1977(3/0)<br>1981(-2/4) 1989(3/1)<br>1993(1/0) 1995(-<br>2/0) 1997(1/2)<br>2011(0/2) | | |
| | Weak | | | 2005(-9/-1) | 1985(-9/-10)<br>2001(-9/-9) | |
| | Drought | | | | 1984(-12/-8)<br>1991(-12/-9)<br>1992(-14/-8)<br>2000(-12/-8) | 1972(-21/-24)<br>1974(-15/-15)<br>1979(-16/-21)<br>1982(-12/-14)<br>1986(-16/-14)<br>1987(-19/-18)<br>2002(-16/-19)<br>2004(-12/-13)<br>2009(-19/-23) |

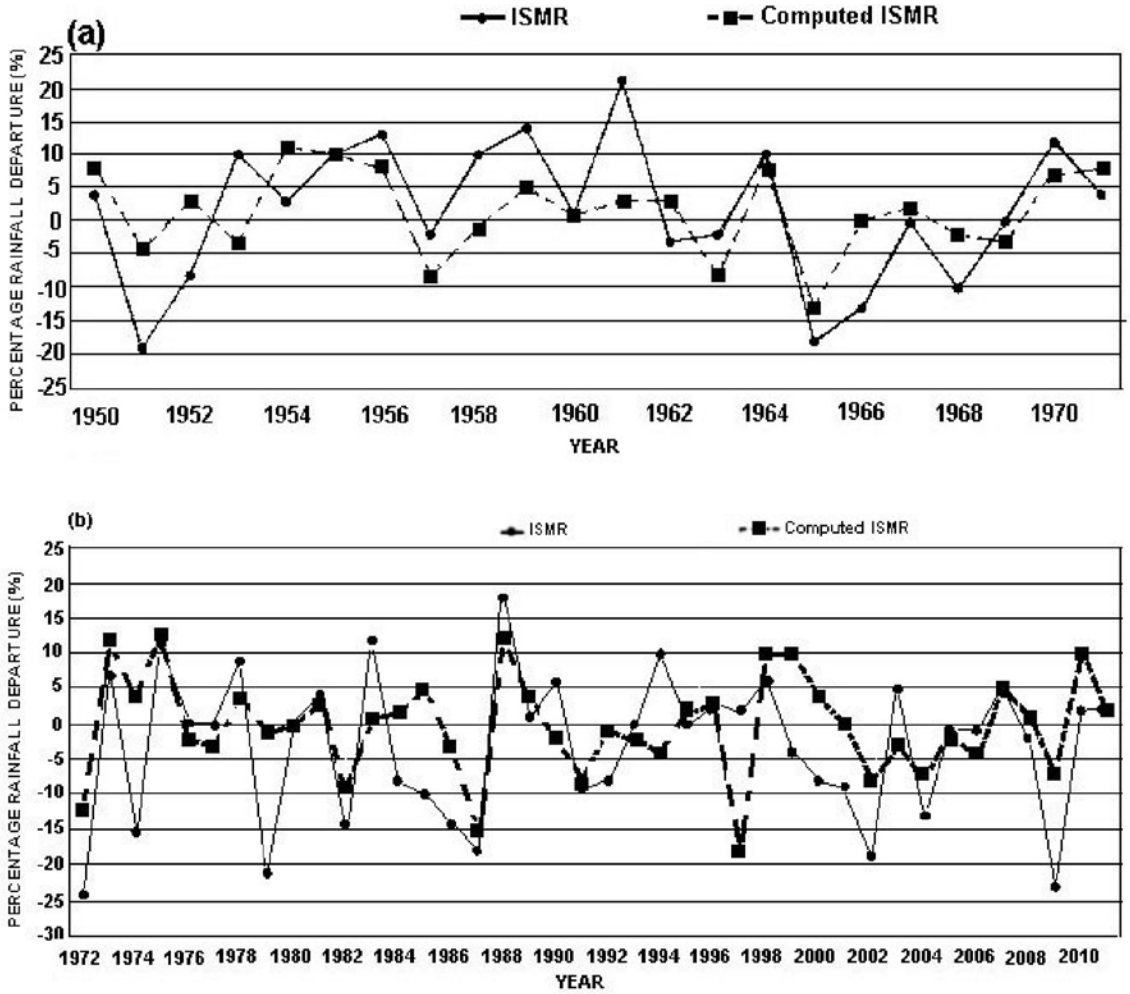


**Figure 1.** Outline of India showing the regional distribution of hot springs (shaded regions) in the Indian landmass. [Modified from GSI (1991)]

There were 12 drought years during the period 1950-2011 (Table 2). The pattern of evolution of anomalies as noted in the mean of anomalies was not seen in 3 years, i.e., 1966, 1974 and 1979. In the year 1974, anomalies remained below -0.5° C, i.e., La Nina conditions prevailed, throughout the year. There were 7 years when ISMR was in weak category (Table 2). In 1991 and 1992, the anomalies during pre-monsoon months were indicative of development of a drought. There were 7 years of excess ISMR during the period 1950-2011 (Table 3). The year 1983 was an exception here as El Nino conditions continued from the beginning of the year till MJJ. Though the anomalies showed a decreasing trend beginning from the 3-months period of JFM, but they became negative only during July-August-September (JAS). Thus the anomalies prevailing before the commencement of the season were not indicative of an excess monsoon in 1983. Out of 10 years of active monsoon, anomalies in the years 1958 and 1994 were not indicative of active monsoon to follow. They were rather indicative of weak monsoon /drought. The pattern seen in the mean of the anomalies for normal group of years, is not seen in several years of normal monsoon (Table 4): La Nina prevailed from (i) the beginning till the end of the year in 1950,1971,1999, and (ii) from MAM till the end of the season in 1954. El Nino conditions prevailed from pre-monsoon months till the end of the season in the years 1957 and 1997. El Nino conditions prevailed up to April-May-June (AMJ) in 1969 and 1998.

It follows from the discussions in this section that the exceptions in the evolution of SST anomalies in Nino 3.4 region are common to all the categories of monsoon. Thus an element of uncertainty shall be inclusive in the forecast of each category of monsoon prepared on the basis of the evolution of SST anomalies. This imposes a limitation on the use of SST anomalies in EPO in preparing LRF of ISMR. In spite of these limitations, the strong relationship between the SST anomalies in Nino 3.4 region during the period JAS and ISMR could still be used for preparing LRF of ISMR provided that accurate forecast of SST anomalies from this region are available in May from ENSO forecast models.

**INDIAN OCEAN OSCILLATION**

The studies relating to the link between the state of IO and inter-annual variability of ISMR appear to have begun in 1970s ( Saha,1970) only, i.e., much later compared to similar studies involving the state of EPO. Indian Ocean Oscillation (IOO) has been studied in sea surface temperature, cloudiness and very recently in equatorial zonal wind also. Results of these studies linking the state of IO with inter-annual variability of ISMR are briefly discussed below.

**SEA SURFACE TEMPERATURE**

Saha (1970) studied the effect of SST in equatorial IO upon monsoon circulation. Shukla and Paolino (1983) suggested that ISMR is correlated more strongly with Pacific SST anomalies than with IO SST. Rao and Goswami (1988) showed the existence of a homogeneous region in southeast Arabian Sea where the March-April SST anomalies were significantly correlated with seasonal ( June-September ) rainfall over India. Krishnamurti et al. (1989) have emphasized the importance of SST anomalies over the equatorial IO, which influenced ISMR adversely during 1987 El-Nino. Rajeevan et al. (2002) analyzed monthly SST data from IO region to examine the relationship between IO SST anomalies with ISMR. In a recent study Sadhuram and Ramana Murthy (2008) have shown high correlation (0.51; significant at 99% level) between SSTA over southeastern Arabian Sea in the preceding January and ISMR. Significant positive correlation (0.61: significant at 99% level) was also reported with SSTA over northwest of Australia in the preceding February. The combined SSTA index has shown a very high correlation of 0.71 with ISMR. They have developed a multiple regression model using the combined SSTA index of the two regions as one parameter and East Asia sea-level pressure ( averaged during February and March over the region 35°-45°N;120°-130°E having CC of 0.62 with ISMR) as another parameter. Their simple multiple regression model could successfully predict the droughts of 2002 and 2004.

Studies of SST anomalies from Indian Ocean region by Saji et al. (1999) and Webster et al. (1999) showed existence of a dipole mode, known as Indian Ocean Dipole (IOD). The Dipole Mode Index (DMI), also referred to as SSTDMI, represents SST anomalies averaged in the western Indian Ocean box minus SST anomalies averaged in the Eastern Indian Ocean (EIO) box. The positive phase of dipole mode is associated with easterly winds over the EIO and vice versa. An IOD event tends to start developing in May-June, peaks in September-October and tapers off thereafter. IOD has been studied using data for a longer period of time (1881-1998) by Ihara et al. (2007). IOD is influenced by the ENSO state. IOD index tends to be in positive phase during El Nino years and in the negative phase during La Nina years. The simultaneous Correlation Coefficient (CC) of IOD index with ISMR is -0.16 indicating that the connection between the two is weak. The CC of IOD index with ISMR based on the data for a period of 40 years (1972-2011) for the months of January to September are .09, -.10, -.14, -.15, -.09, -.05, -.10, -.16, and -.17 respectively. This shows a weak relationship between IOD index and ISMR and that the IOD index for pre-monsoon months could not be used to prepare a LRF of ISMR. Ihara et al. (2008) studied July droughts over homogeneous Indian monsoon regions (as defined by the Indian Institute of Tropical Meteorology: www.tropmet.res.in) and their relationship with IOD during El Nino events. They noted that in the years of severe drought in homogeneous regions, SSTDMI does not tend to start developing in May, the month when SSTMDI usually begins to develop. May-July SSTDMI values tend to be smaller in severe drought years than in the years which were free from droughts in homogeneous regions. The severe drought years tend to be associated with smaller SSTDMI values prior to July compared to normal and above normal July rainfall years in homogeneous regions. It seems that the evolution of SSTDMI during El Nino is important, specifically, the evolution of the IOD-mode event, which usually starts around May, is delayed when July precipitation over homogeneous regions of India is abnormally low.

As an IOD event starts developing in May-June and peaks in September-October, information contained in SSTDMI during the period January-May could be of little use in formulating a LRF of ISMR based on this factor alone. However, as mentioned above, the evolution of IOD event contains some useful information on inter-annual variability of ISMR in some of the years, and the same could be used as an addition factor in the preparation LRF of ISMR.

## EQUATORIAL WIND (EQWIN)

As mentioned above, the positive phase of IOD mode is associated with easterly winds over the EIO and vice versa. The oscillation between the two states has been referred to as Equatorial Indian Ocean Oscillation (EQUINOO). An index of EQUINOO based on the anomalies of the surface zonal wind at the equator (60°-90°E, 2.5° S- 2.5° N, Gadgil et al. (2007) and 62°-90°E and 4°N-4°S, Ihara et al. (2007)) referred to as EQWIN has been studied for its relationship with ISMR. It was found that in addition to ENSO, the phase of EQUINOO makes a significant contribution to the inter-annual variability of ISMR. ENSO and EQWIN together were able to explain droughts that occurred in the absence of El Nino, or in the presence of weak El Nino and excess ISMR when ENSO was unfavorable (Gadgil et al., 2007; Ihara et al.,2007). Worst droughts were associated with unfavorable phases of both. This was further confirmed by the results of Ihara et al. (2007) who used data for a longer period (1881-1998). However, simultaneous CCs of EQWIN with ISMR was found to be -0.15. Thus EQWIN is weakly related with ISMR. Gadgil et al. (2007) had attempted to use EQWIN and ENSO indices before the season for prediction, but found very little information about the rainfall for the forthcoming season in the May values of EQWIN and ENSO indices. In view of these results, EQWIN alone could not be used for preparing LRF of ISMR.

## CLOUDINESS

Satellite observed cloudiness has been extensively used in the study of Indian summer monsoon during the past 4 decades ( Sadler, 1969; Saha,1972; Prasad et al.,1978,1981,1983,1988; Sikka and Gadgil, 1980; Yasunari, 1980,1981; De et al. 1991 and several others). Studies using cloud data by Prasad et al. (1978,1981,1983,1988) had identified an, in general, inverse relationship between the activity of SICZ and the performance of summer monsoon over India. The inverse relationship was also found to be present during the pre-monsoon months of April-May ( Gupta and Prasad,1991). Results of the studies by Prasad and his collaborators formed the basis for proposing SICZ model for LRF of ISMR ( Gupta and Prasad, 1992,1993). Satellite observed cloud data from the IO region during pre-monsoon months of April-May for a period of 16 years (1972-1989, except 1978 and 1981) only, available at that time, had been used to develop the model during the period 1987-1989.Verifications of the real time forecasts for some of the years had been reported earlier by Prasad (1993,2000,2001). With the availability of cloud data for about 4 decades now, significant improvements have been made in the model ( Prasad, Singh and Subramanian,2010a; Prasad, Singh and Prasad, 2010b; Prasad and Singh, 2012,2013a,b). Experience of preparing LRF of monsoon rainfall with SICZ model for the past 22 years beginning from 1990, suggests that the precursors to southwest monsoon start appearing in the activity of SICZ from the beginning of the year, i.e., from January itself. Beginning from the year 2009, SICZ model uses weekly mean cloudiness and cloud anomalies data from IO region for the period January-May to prepare LRF of ISMR in two stages: (i) a qualitative forecast by the end of March and (ii) a detailed quantitative forecast by the end of May.

It follows from above discussions that IOO, as monitored in the activity of SICZ, alone could be used to prepare LRF of ISMR. Though evolution of SSTDMI and EQWIN provide useful information on inter-annual variability of ISMR, none of these two indices could be used to prepare LRF of ISMR. Accordingly we discuss the forecasts of ISMR based on SST anomalies of Nino 3.4 region alone and SICZ activity alone for the past 40 years (1972-2011).

## LONG RANGE FORECAST OF ISMR

It has emerged from the discussions in the previous sections that SST anomalies from Nino 3.4 region of EPO for the period JAS alone, as available in May from ENSO forecast models, and the precursors available in SICZ activity during the period January-May alone, could be used to prepare LRF of ISMR before the commencement of the season, i.e., in May. SICZ model is based on the premise that southwest monsoon, which could be categorized in a number of categories, has a typical rainfall distribution, in space and time, over Indian subcontinent associated with each monsoon category. Once the category for the coming monsoon has been estimated based on the characteristic features of cloudiness over equatorial regions of Indian Ocean during the period January-May, the rainfall distribution pertaining to that category becomes the forecast. Had the cloud data been available for a large number of years, say 100 years or so, then there was every likelihood of a previous year's cloud pattern being available which could be used as an analogue and the rainfall of that year as the forecast rainfall for the given year. Satellite observed cloud data are available for a limited temporal extent, as compared to rainfall data. This does not allow us to find years with matching characteristics of equatorial cloud features pertaining to various categories of monsoon. It was, therefore, necessary to assign an index to cloud features, so that correlation coefficient between the index and ISMR and linear regression equation relating them could be worked out and used to compute forecast rainfall. This has been discussed in Pt II of the paper.

Mean SST anomaly data from Nino 3.4 region ( 5°N- 5°S, 120°-170° W) are available for a period of 62 years (1950-2011) (www.cpcncep.noaa.gov). CCs between SST anomalies and ISMR and linear regression constants between them have been worked out for a period of 22 years (1950-1971) and forecast verified for the remaining period of 40 years (1972-2011). The 40 years' period (1972-2011) of verification has been chosen to match with the period for which SICZ model forecasts are also available. The CC between SST anomalies in Nino 3.4 and ISMR is 0.17 for the 3-months period of December of the previous year-January-February (DJF) of the current year. CC starts decreasing from January-February-March (JFM) and becomes inverse and insignificant (-0.07) during the 3-months period of March-April-May (MAM).The inverse relationship strengthens, becomes strongest during JAS (CC = -0.58, significant at 99% level, with linear regression constants, a= -9.24 and b=100.57) and again starts weakening thereafter. Observed ISMR and ISMR computed from the linear regression equation for the period 1950-1971 are shown in Fig. 1a. During this period there were 4 excess (ISMR > 10% of normal) monsoons (1956,1959,1961 and 1970). In none of these years, the computed rainfall was in the excess category. However, the computed rainfall in all these four years was on the higher side of normal and the difference between the computed rainfall and ISMR was within ±6 % in two years, i.e., in 1956 and 1970. There were 3 droughts ( ISMR < 10% of normal) years (1951,1965 and 1966). The computed rainfall was in drought category in 1965 only. There was no indication of drought in the years 1951 and 1966. Thus compared to droughts, the computed rainfall was closer to realized rainfall in excess monsoon years. There were 15 normal monsoons (ISMR within ± 10% of normal). Out of 15 normal years, rainfall was on the higher side of normal in 8 years, on the lower side of normal in 5 years and just normal in 2 years. The computed rainfall was in normal category in 20 years and in excess category in 1 year (11% above normal in 1954). ISMR in 1954 was 3% above normal. The difference between the observed and computed ISMR was within ±6% in as many as 10 normal monsoon years. Except for droughts, computed rainfall was reasonably good during normal and excess monsoon years.

The computed rainfall and observed ISMR for the period of verification (1972-2011) are shown in Fig.1b. The graph of computed ISMR has a good resemblance with the graph of observed ISMR during this 40 years period except in drought years and in the years 1984-85,1994 and 1997. There were 3 excess monsoon years (1975, 1983 and 1988).The computed ISMR was in excess category and also close to ISMR in 1975 and 1988. In the excess monsoon year 1983, the computed ISMR was close to normal (1% above normal). Out of 9 drought years, the computed ISMR was in drought category in 2 years, i.e., 1972 and 1987, only. In the remaining 7 drought years, i.e., 1974, 1979, 1982, 1986, 2002, 2004 and 2009 the computed ISMR was in the range of normal monsoon. The computed ISMR using SST anomalies of Nino 3.4 region alone did not give any hint about the deficiency in rainfall in the majority of drought years. Thus it may be concluded that, for the entire period of 62 years (1950-2011), computed rainfall was good during excess and normal monsoon years but not so during drought years. As mentioned earlier, the forecast of ISMR prepared using SST anomalies for the period JAS are based on the assumption that such accurate SST anomalies were available in May from ENSO forecast models ( Cane et al 1986). Any uncertainty in forecast SST anomalies shall have similar effect on forecast ISMR.

Forecasts based on SST anomalies in Nino 3.4 region alone and the activity of SICZ alone are now compared by grouping them in 5 categories, i.e., excess (ISMR ≥11% of normal), active (5-10% ), normal (within ±4%), weak(-5 to -10%) and deficit/ drought (≤ -11). Table 5 shows both the forecasts grouped in these categories. Out of 9 years of 'drought', forecast based on SST anomalies was in 'drought' category in 2 and it was in 'weak' monsoon category in 4 years. Forecast could not give any hint about the 'drought' in the years 1974, 1979 and 1986. Out of 3 excess monsoons (1975,1983 and 1988) forecast rainfall was in excess category in 2 and in normal category in 1. Out of 6 years of 'weak' monsoon, forecast was in 'weak' category in only one year, i.e., 1991. It may be concluded here that even with the observed SST anomalies in Nino 3.4 region for the 3-months period of JAS, it could not be possible to foreshadow 'excess' monsoons in some of the years and drought in the majority of the years. In addition, forecast for a severe drought in 1997 could not be realized. These results indicate that perhaps ENSO does not play the primary role in inter-annual variation in ISMR.

During the year 1978, cloud data were not available after 16th March. However, the activity of SICZ during the period 1 January-15 March 1978 had already displayed features of an active southwest monsoon. Therefore, SICZ model forecast for ISMR-1978 has been taken as active monsoon (5% above normal). This has been done to remove the one year gap during 1978 in SICZ forecast. As mentioned earlier also, the forecasts based on the activity of SICZ during the period January-May, have been taken from Part II of the paper ( Prasad and Singh, 2012) and included in Table 5. Out of 3 excess monsoons during the 40 years period (1972-2011), forecast rainfall was also in excess category in 2 and in active category in 1, i.e., in 1983. Here also the difference between ISMR and forecast ISMR was small. Out of 6 years of active monsoons, the forecast ISMR was also in the same category. Out of 16 years of normal ISMR, forecast ISMR was normal in 9, active in 6 and weak in 1 year, i.e., in 2005. There were 6 weak monsoons. Forecast ISMR was weak in 2 years and drought in the remaining 4 years. However, the differences of the percentage departure between ISMR and forecast ISMR in these 4 years were within the forecast error of the model, i.e., within ± 5%. There were 9 drought years, and forecast ISMR was also in the same category in these years. It follows from the discussions in this section that the forecasts prepared using the activity of SICZ alone, were closer to ISMR. This implies that the predictive potential of IOO is higher compared to that of ENSO. This may be considered as an important result relating to long range forecasting of monsoon rainfall in India and more particularly in foreshadowing its extreme seasons (excess/drought). It may be concluded that reliable LRF of ISMR could be prepared by taking into account the oscillation in the Indian Ocean alone, as monitored in the activity of SICZ during the period January-May.

In-spite of reasonably good real time forecast of ISMR by SICZ model for the past 22 years, the difference between forecast ISMR and ISMR was larger than the model error of ± 5% in the years 1992, 1999, 2005 and 2010. Summer monsoon circulation system over Indian sub-continent witnessed large intra-seasonal changes in these years: While there was a significant strengthening in monsoon circulation during the second half of the season (August-September) in the year 1992 and to some extent in 2005 also, monsoon circulation weakened considerably during the second half of the season in 1999. Monsoon circulation showed weakening during June-July 2010 also. Results of a study of the intra-seasonal changes during SWM-2010 reported in Pt IV of the paper (Prasad and Singh,2012c) has shown that the intensification of SICZ for 2 weeks in June- and also in July-2010 occurred as a result of westward propagation of positive SST anomalies in EWPO resulting in intensification of SICZ in South-East Indian Ocean (SEIO). Development of enhanced convection over Indonesia and SEIO was a result of this change. The changes in SST anomalies in EWPO were related to the demise of El Nino and development of ENSO-Neutral condition/La Nina there. Thus the impact of ongoing changes in EPO on the activity of SICZ and thereby on the performance of the monsoon was clearly seen during southwest monsoon-2010. Intra-seasonal changes in other years, i.e., 1992, 1999 and 2005, are being investigated and the results shall be reported in the concluding part of the paper (Part VI).

**CONCLUSIONS**

i. Three months running mean SST anomalies in Nino 3.4 region have shown a distinct pattern of their evolution for each category of Indian summer monsoon: During drought years, anomalies were negative and small in magnitude in the beginning of the year. They showed increasing tendency, becoming zero during FMA and then remained higher than +0.6° C from MJJ till the end of the year. The opposite conditions prevailed during excess monsoon years. During weak monsoons, anomalies were large negative in the beginning, increased during pre-monsoon and monsoon months and were close to zero but still negative at the end of the season. Anomalies opposite to this prevailed during active monsoon years. The normal monsoons were characterized by small negative anomalies in the beginning of the year, showed very slow increase and remained close to zero during the season.

ii. Exceptions in the evolution of SST anomalies in Nino 3.4 region were common to all the categories of monsoon.

iii. There are limitations in foreshadowing extreme seasons using SST anomalies from Nino 3.4 region alone. Even with the observed SST anomalies in Nino 3.4, some of the excess monsoon seasons and majority of the droughts could not be foreshadowed.

iv. Though evolution of SSTDMI and EQWIN could provide useful information on inter-annual variability of ISMR, none of these two indices could be used to prepare LRF of ISMR.

v. The signals available in the activity of SICZ during the period January-May are intimately related with the inter-annual variability of ISMR. However, these alone are also not able to forecast the total variability in ISMR in some of the years. It would be of an additional advantage to take into account the forecast based on the forecast SST anomalies in Nino 3.4 for the period JAS while formulating the forecast of ISMR based on SICZ model, more particularly when SICZ model indicates development of an extreme season.

In-spite of reasonably good real time forecast of ISMR by SICZ model for the past 22 years, the difference between forecast ISMR and ISMR was larger than the model error of ± 5% in the years 1992, 1999, 2005 and 2010, i.e., in about 18% cases. Summer monsoon circulation system over Indian sub-continent witnessed large intra-seasonal changes in these years: While there was a significant strengthening in monsoon circulation during the second half of the season (August-September) in the year 1992 and to some extent in 2005 also, monsoon circulation weakened considerably during the second half of the season in 1999. Monsoon circulation showed weakening during June-July 2010 also. Results of a study of the intra-seasonal changes during SWM-2010 reported in Pt IV of the paper (Prasad and Singh,2012c) has shown that the intensification of SICZ for 2 weeks in June- and also in July- 2010 occurred as a result of westward propagation of positive SST anomalies in Equatorial West Pacific Ocean resulting in intensification of SICZ in South-East Indian Ocean (SEIO) . Development of enhanced convection over Indonesia and SEIO was a result of this change. The changes in SST anomalies in EWPO were related to the demise of El Nino and development of ENSO-Neutral condition/La Nina there. Thus the impact of ongoing changes in EPO on the activity of SICZ and thereby on the performance of the monsoon was clearly seen during southwest monsoon-2010. Intra-seasonal changes in other years, i.e., 1992, 1999 and 2005, are being investigated and the results shall be reported in the concluding part of the paper (Part VI).

**ACKNOWLEDGEMENT**

The authors thank the reviewers for their valuable suggestions**.** One of the authors (OP) would like to record his sincere gratitude to his Ph. D. supervisor, Prof. P. N. Belov and his colleagues at the Department of Meteorology and Climatology, Moscow State University, Moscow (Russia) for their keen interest in the study of Indian monsoons.

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