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Predictive relationships between Indian Ocean sea surface temperatures and Indian summer monsoon rainfall

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सार - इस शोध पत्र में भारतीय ग्रीष्म मानसून वर्षा (आई.एस.एम.आर.) सहित हिंद महासागर में एस. एस. टी. की विसंगतियों के संबंधों की जाँच करने तथा आई.एस.एम आर. के दीर्घावधि पूर्वानुमानों के लिए उपयोगी पूर्वसूचकों का पता लगाने के लिए 49 वर्षों (1950-98) के मासिक समुद्र सतह तापमान (एस.एस.टी) के आँकड़ों का विश्लेषण किया गया है। नवंबर से जनवरी माह के दौरान तथा मई माह में भी अरब सागर में उत्पन्न हुई आई.एस.एम.आर.और एस.एस.टी की विसंगतियों के मध्य उल्लेखनीय रूप से सकारात्मक संबंध पाया गया है। फरवरी से मार्च माह के दौरान दक्षिण पूर्वी हिंद महासागर तथा मई माह में उत्तरी प्रशांत महासागर में पाई गई एस.एस.टी. की विसंगतियाँ भी आई.एस.एम.आर. के साथ सकारात्मक रूप से परस्पर संबंधित पाई गई है। संयुक्त विश्लेषण करने से यह पता चला है कि गैर एनसों के सूखा वाले वर्षों (1966, 1968, 1974 और 1979) में फरवरी माह से दक्षिणी हिंद महासागर में एस.एस.टी. की विसंगतियाँ नगण्य पाई गई हैं। जिनमें बाद मे महीनों में भूमध्य रेखा की तरफ धीरे धीरे बढ़ोतरी होती है। मानसून ऋतु के दौरान विद्यमान एस.एस.टी. की ये नगण्य विसंगतियाँ आई.एस.एम.आर. के माडूलन में विशेषकर गैर एनसो के वर्षों में महत्वपूर्ण भूमिका निभा सकती है।

आइ.एस.एम.आर. के दीर्घावधि पूर्वानुमानों के लिए उपयोगी पूर्व सूचकों के रूप में हमने दो अभिसूचकों ए.आर.बी.एस.एस.टी (अरब सागर में 15° उ. - 25° उ., 50° पू. - 70° पू. तथा नवंबर-दिसंबर-जनवरी माह में एस.एस.टी की औसतन विसंगतियाँ) तथा एस.आई.ओ.एस.एस.टी (दक्षिणी हिंद महासागर में 15°द. - 30°द., 70°पू. - 110°पू. तथा फरवरी और मार्च माह में एस.एस.टी की औसतन विसंगतियाँ) का पता लगाया गया है। आई.एस.एम.आर. के साथ ए.आर.बी.एस.एस.टी और एस.आई.ओ.एस.एस.टी के सहसंबंध गुणांक (1950-98 की अवधि में) क्रमशः 0.45 और 0.46 पाया गया है जिसका 99.9% स्तर पर साँख्यिकीय रूप से महत्व है। एस.आई.ओ.एस.एस.टी. के सूचकांक आई.एस.एम.आर. के साथ मिलकर निरंतर रूप से स्थायी संबंध को दर्शाते हैं। तथापि आई.एस.एम.आर. के साथ ए.आर.बी.एस.एस.टी. के सूचकांक से महत्वपूर्ण परस्पर संबंध का पता 1976 के पश्चात् ही चला है।

ABSTRACT. Monthly sea surface temperature (SST) data of 49 years (1950-98) have been analysed to examine the relationship of SST anomalies in the Indian Ocean with Indian summer monsoon rainfall (ISMR) and to derive useful predictors for long-range forecasts of ISMR. There is significant positive relationship between ISMR and SST anomalies over the Arabian Sea during November to January and also in May. SST anomalies over southeast Indian Ocean during February to March and over North Pacific during May are also positively correlated with ISMR. The composite analysis revealed that in Non-ENSO drought years (1966, 1968, 1974 and 1979) negative SST anomalies are observed over south Indian Ocean from February which slowly spread towards equator during the subsequent months. These negative SST anomalies which persist during the monsoon season may be playing an important role in modulating ISMR especially in non-ENSO years.

We have derived two indices, ARBSST (SST anomalies in Arabian Sea averaged over 15° - 25° N, 50° -70° E and November-December-January) and SIOSST (SST anomalies over south Indian Ocean averaged over 15° -30° S, 70° -110° E and February and March) as useful predictors for the long-range forecasts of ISMR. The correlation coefficient (for the period 1950-98) of ARBSST and SIOSST with ISMR is 0.45 and 0.46 respectively which is statistically significant at 99.9 % level. SIOSST index has shown consistently stable relationship with ISMR. However the ARBSST index showed significant correlation with ISMR only after 1976.

Key words – Indian monsoon, Sea surface temperature, Indian Ocean, Long range forecasting.

1. Introduction

The Indian summer monsoon rainfall is known to have considerable inter-annual variability. This inter-annual variability is generally attributed to the slowly varying boundary conditions of sea surface temperature, soil moisture and snow cover *etc.* (Charney and Shukla 1981). However the intra-seasonal variability may also affect substantially the seasonal monsoon rainfall of any particular year (Sikka and Gadgil, 1980;Webster *et al*. 1998; Ferranti *et al*. 1997; Shen and Kimoto, 1999 and several others). For example, Shen and Kimoto (1999) suggested that it was the intra-seasonal variability of the monsoon system that brought the above normal rainfall over India in 1997, which was a major El-Nino year.

The relationship between Indian summer monsoon rainfall (ISMR) and sea surface temperature (SST) anomalies over the equatorial east Pacific ocean associated with the ENSO phenomenon is well documented (Sikka, 1980; Keshavamurty, 1982; Rasmusson and Carpenter, 1983; Mooley and Parthasarathy, 1983; Ropelewski and Halpert, 1987; Kane, 1997 and Thapliyal *et al*. 1998). During the El-Nino events, Indian monsoon rainfall tends to decrease due to large-scale subsidence and weakened moisture supply. However there is no one to one correspondence between El Nino and ISMR.

The role of the sea surface temperature over the Arabian sea on the southwest monsoon over India has been a subject for a long time (Pisharoty, 1965; Saha and Bhavadekar,1973; Shukla and Misra 1977; Weare, 1979; Joseph and Pillai, 1984). Seasonal variations of the SST over this region are very large, but the inter-annual variations are very weak. Rao and Goswami (1988) have reexamined the relationship between the Arabian Sea SST and monsoon rainfall by removing the large amplitude high frequency noise and very low frequency long-term trends. They have found that there exists a homogeneous region in the south-eastern Arabian sea where the March-April (MA) SST anomalies are significantly correlated with the seasonal (June-September) rainfall over India.

There are not many studies addressing the relationship of SST over south Indian ocean and ISMR. Verma (1990) has addressed the relationship of SSTs over south Indian ocean with Indian summer monsoon rainfall. Krishnamurti *et al*. (1989) emphasized the importance of SST anomalies over the equatorial Indian Ocean, which influenced ISMR adversely during the 1987 El-Nino. The study by Shukla and Paolino (1983) suggested that Indian monsoon rainfall is correlated more strongly with Pacific SST anomalies than with Indian ocean SST anomalies. There are also some model studies on the relationship between SST anomalies over the Indian Ocean with Indian monsoon rainfall (Shukla, 1975; Ju and Slingo, 1995; Chandrasekhar and Kitoh, 1998; Yang and Lau, 1998). Meehl (1997) explained the tropospheric biennial component or Tropical Biennial Oscillation (TBO) of the Asian monsoon based on air-sea negative feedback mechanism in which SSTs in the Indian Ocean play an important crucial role.

In this paper, we have analysed the monthly SST data of 49 years (1950-98) to examine the role of SST anomalies over Indian Ocean on the inter-annual variability of ISMR. Another purpose of this study is also to explore the possibility of identifying some useful predictors for empirical prediction of ISMR. Empirical prediction of ISMR has been performed using many climatic parameters (Gowariker *et al*. 1989; Hastenrath, 1987; Parthasarathy *et al*. 1988, Thapliyal, 1997 and Thapliyal *et al*. 1998). However, none of these models make use of Indian Ocean sea surface temperatures as predictors.

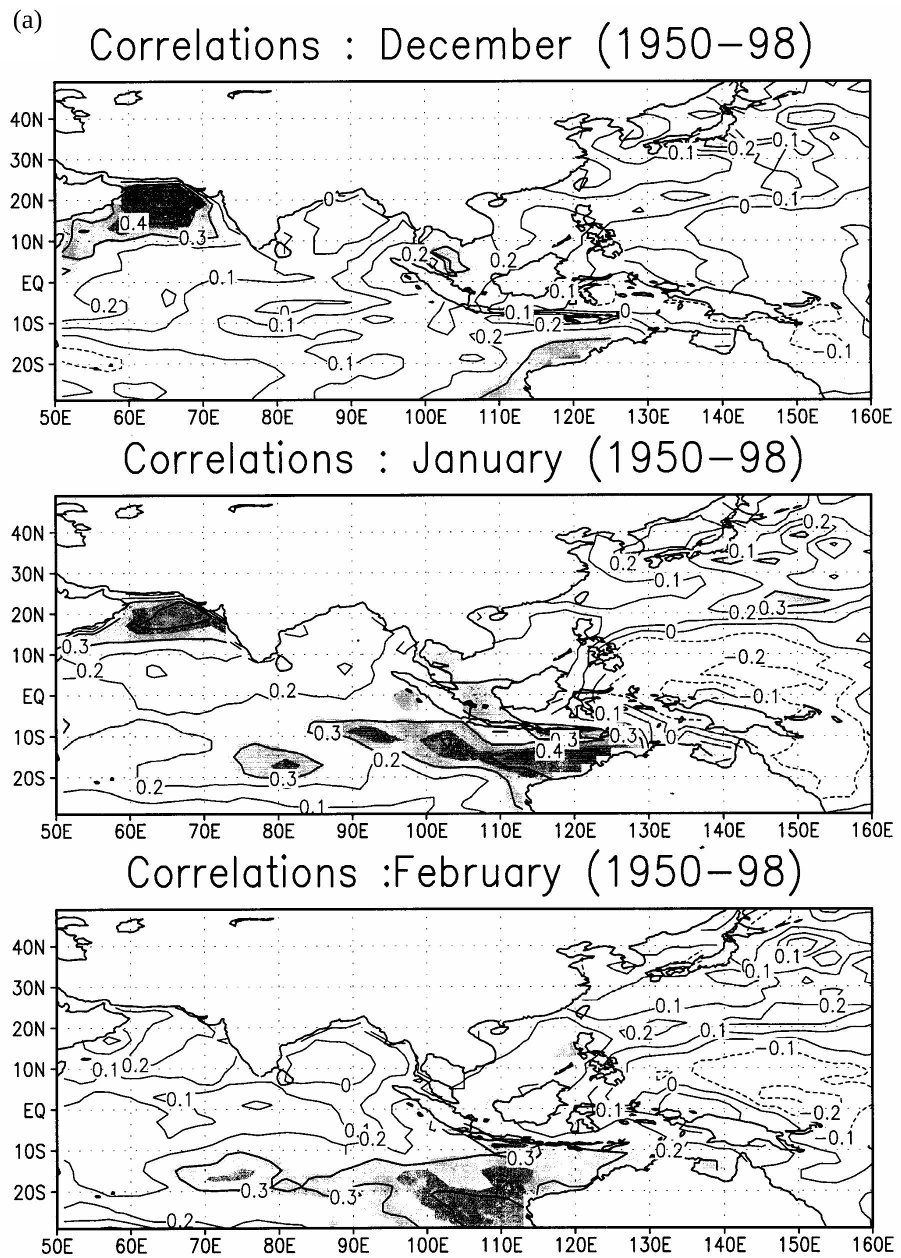
In section 2, the data used and the method of study are given. In section 3, the results are discussed and in section 4, conclusions are drawn.

2. Data and method of study

For this study, we have used the reconstructed historical sea surface temperature data (Smith *et al*. 1996) which are available from January 1950 to December 1998 as 2.0° × 2.0° Lat. / Long. gridded monthly sea surface temperature values. Although the high resolution SST analysis (Reynolds and Smith 1994) is satisfactory for climate studies, this can not be maintained before November 1981 due to the lack of satellite data. Longer periods of SSTs have come from traditional analysis of *in situ* SST observations alone. In the study of Smith *et al*. (1996), a new interpolation method was developed using spatial patterns from Empirical Orthogonal Functions (EOF) to improve analysis of SST anomalies from 1950 to 1981. The method uses the more accurate OI analysis from 1982 to 1993 to produce the spatial EOFs. The dominant EOF modes are used as basis functions and are fit in a least square sense to the *in situ* data to determine the time dependence of each mode. A complete field of SST anomalies is then reconstructed from these spatial and temporal modes. In the global EOF analysis, the first mode (EOF1) accounted 24% of variance and the second mode (EOF2) 8%. Over the tropical Indian Ocean, they have used 16 modes, which together explain 81% of variance to reconstruct the SST anomalies. The use of EOF basis functions produces an improved *in situ* SST analysis that more realistically represent sparsely sampled large – scale structure than traditional analyses. The results show that the reconstructed fields generally have lower root mean square differences than the traditional *in situ* only analyses relative to the OI. In general, the EOF construction gives a more spatially coherent field of SST anomalies.

Monthly SST anomalies have been calculated at each grid by subtracting monthly SST values from the long-term mean (1961-90). Further, the anomaly time series

(a)



Correlations : December (1950–98)

Correlations : January (1950–98)

Correlations :February (1950–98)

Fig.1(a). Correlation coefficients of Indian summer monsoon rainfall (ISMR) with SST anomalies from December to February Period : 1950-98. Grids with 95% (99%) significance level are shaded light (dark). Contour interval : 0.1

has been de-trended by removing the linear trend estimated by linear regression.

In addition, monthly data of sea level pressure and surface winds from the NCEP/NCAR reanalyses (Kalnay *et al.* 1996)for the period 1958-98 also have been used in this study. These data are on a resolution of 2.5° Lat. × 2.5° Long.

Indian Summer Monsoon (June-September) Rainfall (ISMR) time series has been prepared as the area weighted average rainfall over 35 meteorological sub-divisions during the monsoon season. Long period (1875-1996) data for ISMR are available in literature (Thapliyal 1997). ISMR is said to be normal if the rainfall percentage departure is within ± 10% of long-period mean (1901-70). Drought is defined if the rainfall departure is less

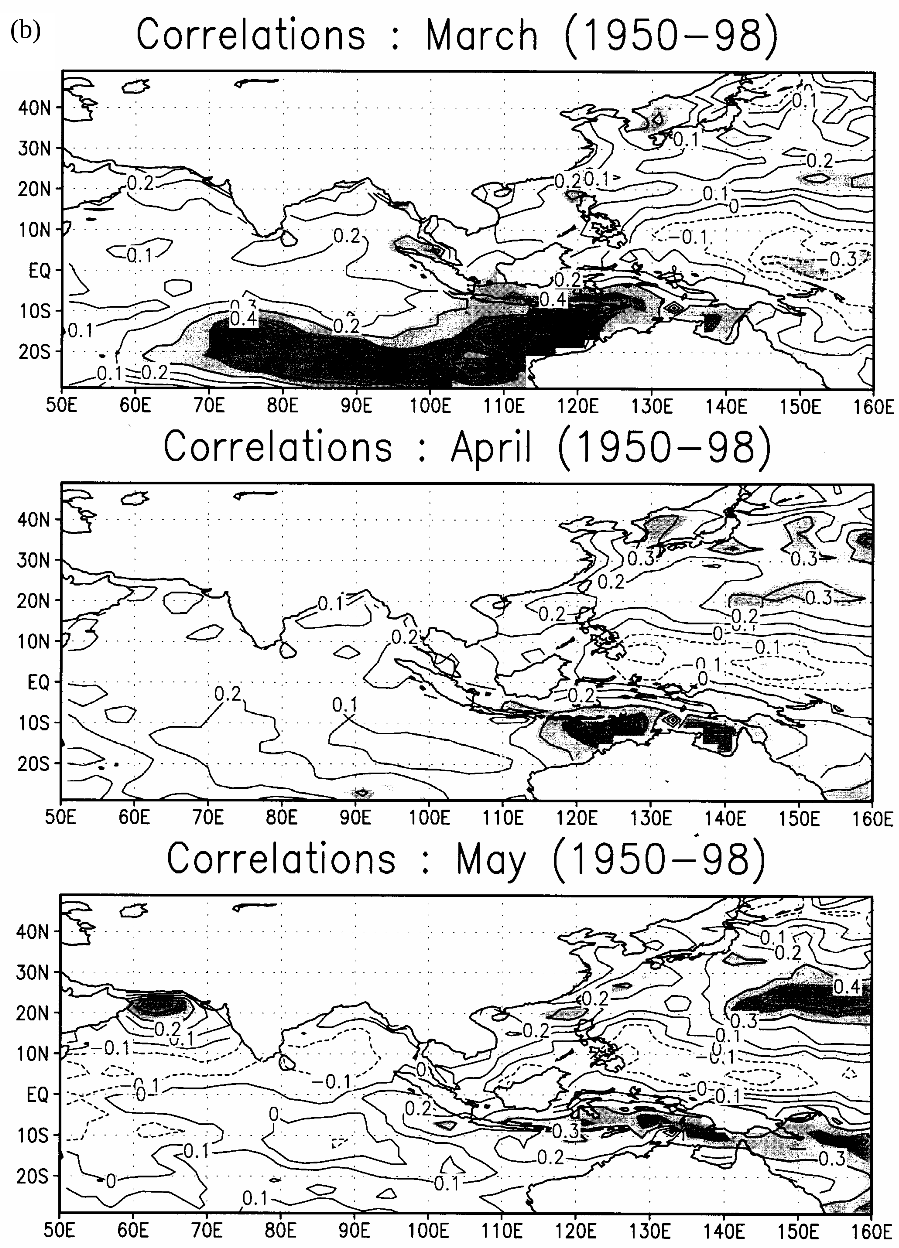


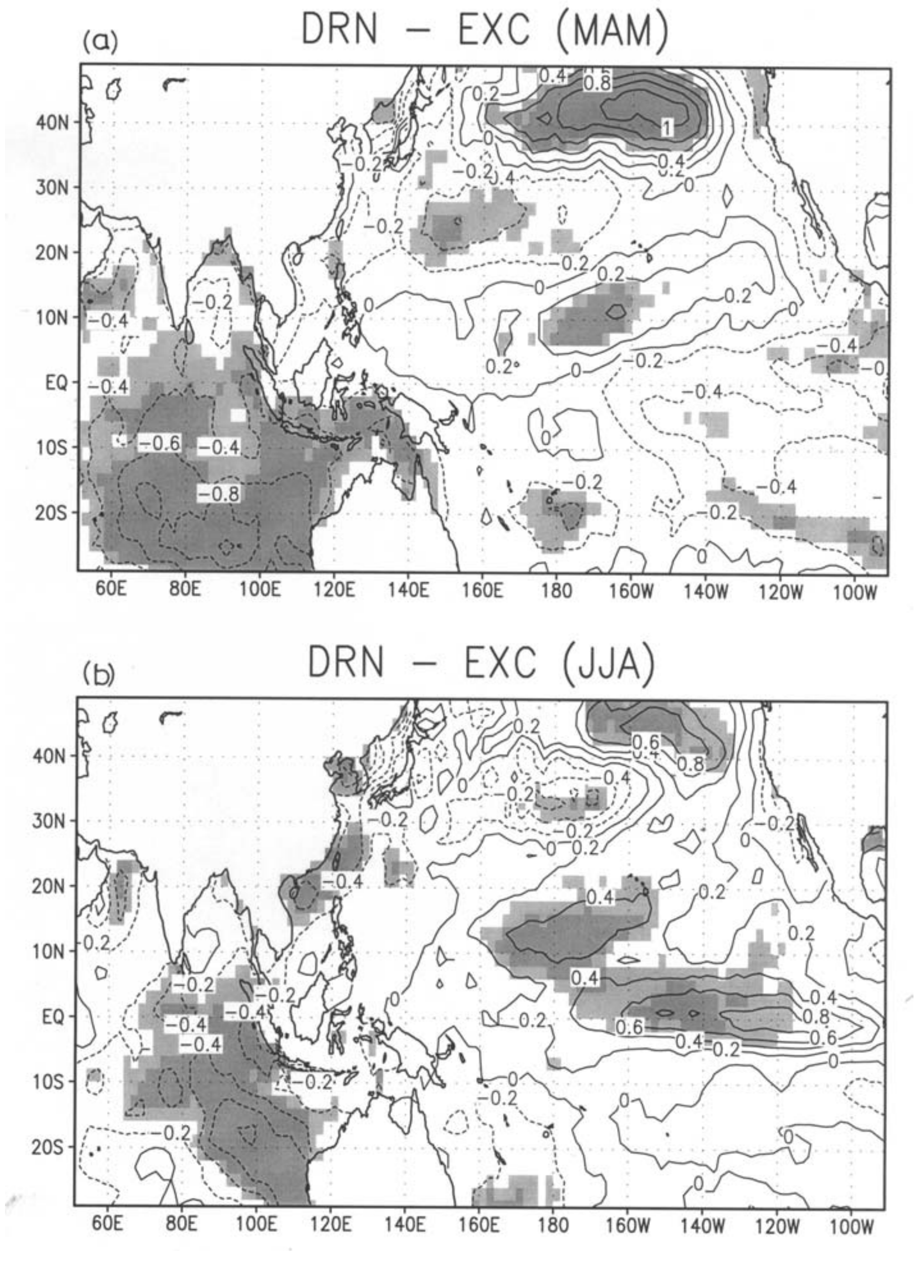
Fig.1(b). Correlation coefficients of Indian summer monsoon rainfall (ISMR) with SST anomalies from March to May. Period : 1950-98. Grids with 95% (99%) significance level are shaded light (dark). Contour interval : 0.1 °C

than 10%. Similarly, the excess monsoon is defined if the rainfall departure is more than 10 %. The present analysis has been carried out by the correlation and composite techniques. For preparing the composite maps of SST anomalies, three cases have been considered. They are (*i*) Drought years (ISMR < –10%) associated with El-Nino [DRE (El)] (1951, 1965, 1972, 1982 and 1987 (*ii*) Excess monsoon years (ISMR >10%) (EXC) (1959, 1961, 1970, 1975, 1983 and 1988) and (*iii*) Drought years (ISMR <–10%) which are not associated with ENSO (DRN) (1966, 1968, 1974, 1979 and 1986).

3. Results and discussion

3.1. *Correlation patterns*

The correlation coefficients between ISMR and monthly SST for each month from previous December to



Figs. 2(a&b). SST anomaly composite of the difference between non-ENSO drought Years (DRN) and Excess Years (EXC) for (a) MAM season and (b) JJA season. The grids where the difference is statistically significant at 95% (99%) level are shaded light (dark). Contour interval : 0.1°C

May have been calculated using the data of 1950-98. The results are shown in Fig. 1. Correlation Coefficient significant at 95% (99%) level is shaded light (dark).

During December and January, significant (at 95% level) positive correlations are observed over west Arabian Sea north of 10° N. By March, however, these correlations became insignificant. In December, significant (at 95% level) positive correlations are also observed over southeast Indian Ocean west of Australia. During the next three months it spreads towards west with larger magnitudes. However, these positive correlations become insignificant by the month of May. The maximum spread and magnitude are found in the month of March. Over west Arabian sea, positive correlations are again observed in the month of May. During April and May, significant positive correlations are observed over west Pacific, north of Australia. These positive correlations are previously documented by Nicholls (1983,1995). Positive correlations are also observed during March to May (highest in May) over north Pacific around 155° E, and also over north Arabian sea, which has the highest correlation (0.50) in December.

The composite results are discussed in the next section.

3.2. *Composite analysis*

As mentioned in section 2, we have made composite SST anomalies for two seasons (MAM and JJA) for four cases. We however, did not find any significant difference in the SST anomalies over Indian Ocean in El Nino years. We therefore discuss only the cases of non-ENSO droughts (DRN) years and excess years.

The difference of composite SST anomalies between the DRN years and the EXC years are shown in Fig. 2(a). The student's *t*-test (WMO, 1966) has been used to test the significance of the differences in the anomaly pattern between the two cases. The most significant feature is the anomaly pattern over the south Indian Ocean and north Pacific ocean around 140° E. During the DRN years, SST anomalies over south Indian Ocean were cooler than the anomalies of EXC years by 0.4 to 0.8° C while they are warmer by same amount over north Pacific ocean. These differences over the south Indian Ocean and north Pacific ocean are significant at 99% significance level. Over west Arabian sea, north of 10° N also significant differences are noticed. Therefore a cooler south Indian Ocean and warmer north central Pacific during MAM are associated with deficient monsoon rainfall over India.

During the JJA period [Fig. 2(b)] the differences between the DRN and EXC years are again significant over the south Indian Ocean. The cooler SST anomalies observed during MAM associated with DRN years persist during the JJA period. The month-latitude variation of SST anomalies averaged for the DRN years is shown in Fig. 3. Large negative SST anomalies are first observed near 25° S during February and March which subsequently spread towards equator by April and May. During the monsoon season, negative SST anomalies persist over the south Indian ocean between 10° - 25° S.

In the next section, we shall discuss the derivation of SST indices and further examine their usefulness as the predictors for long-range forecasting of ISMR.

3.3. *Sea surface temperature indices*

In the earlier section, we have seen that positive correlation with ISMR is observed over west Arabian Sea north of 10° N, and over south Indian Ocean. We have averaged SST anomalies over these two regions, over west Arabian sea (15° -25° N, 50°-70° E), and over south Indian ocean (15° -30° S, 70°-110° E). With these indices we have examined the monthly variation of correlations with ISMR. The correlation coefficient with ISMR is calculated for 18 months, staring from June of previous year to December of the same year. The results are shown in Fig. 4. The 99% significance level is shown as a horizontal dashed line. The Arabian Sea SST is positively correlated with ISMR from June of previous year. But they become statistically significant (at 99 % level) only from November to January. Afterwards its magnitude decreases and becomes negative after the monsoon season. The positive correlation of south Indian ocean SST with ISMR steadily increases from previous December and becomes significant in February and March. Subsequently, its magnitude decreases and remains close to zero during the remaining months.

TABLE 1

Correlation of ARBSST and SIOSST with 3 month averaged Nino-3 Index Period: 1950-1998

Season	ARBSST	SIOSST
DJF	0.21	0.19
MAM	0.45	0.50
JJA	0.49	0.53
SON	0.51	0.59

We have derived two SST indices averaged (*i*) over Arabian Sea (15°-25° N, 50°-70° E) for November, December and January (ARBSST) and (*ii*) over south Indian ocean (15°-30° S, 70°-110° E) for February and March (SIOSST). We have further examined their usefulness as predictors for long-range forecasts of ISMR. The yearly variation of these indices is shown in Fig. 5. The correlation coefficient (for the period 1950-98) of ARBSST and SIOSST with ISMR is 0.45 and 0.46 respectively which is statistically significant at 99.9 % level. The ARBSST index was large negative in 1951, 1965, 1968 and 1987, all major drought years. It was also negative successively for four years from 1984, during which ISMR was also on negative side of the normal. Since 1988, this index is positive except in 1997. During the period, 1951-98, ARBSST was negative in 18 years. In those 18 years, ISMR was on negative side of the normal in 15 years. It can be seen that the SIOSST index was large negative in all the non-ENSO drought (DRN) years (1966, 1968, 1974 and 1979). Also in some of ENSO years like 1951, 1965 and 1982, this index was negative. But in El Nino years like 1972 and 1987, this

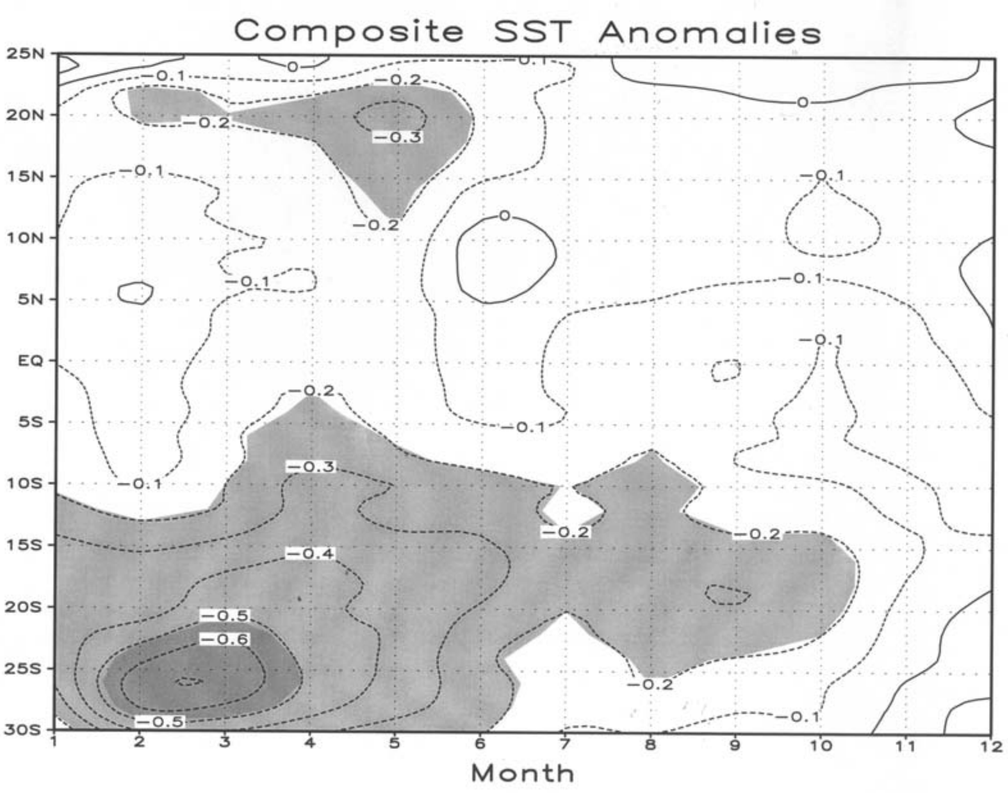


Fig. 3. Month-Latitude variation of composite SST anomalies in DRN years averaged for the longitudes between 50° E and 120° E. Contour interval : 0.1° C

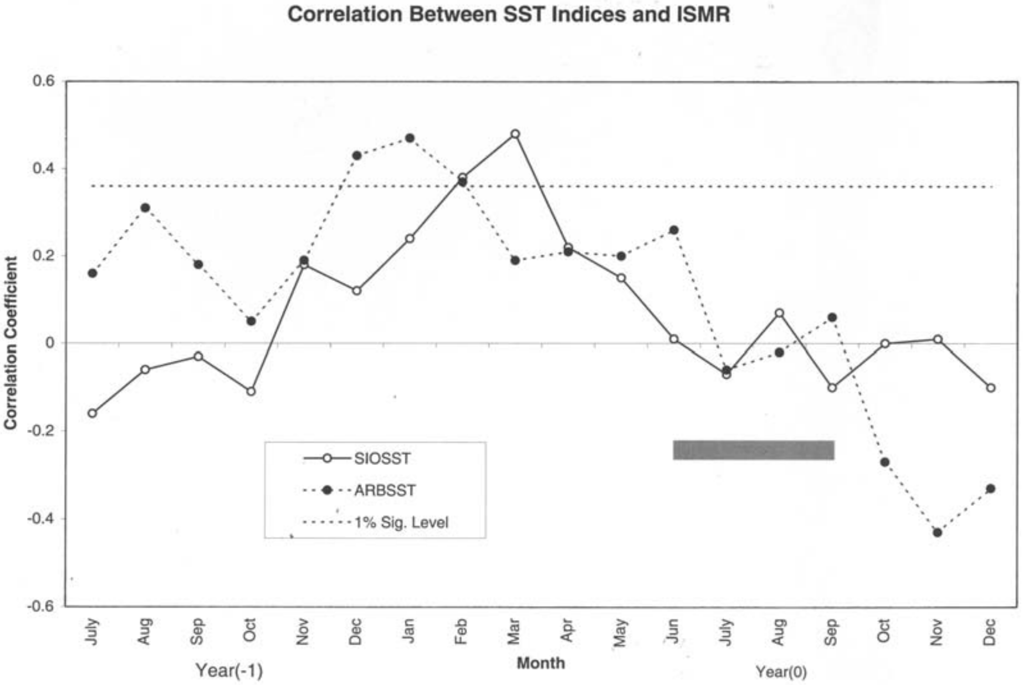
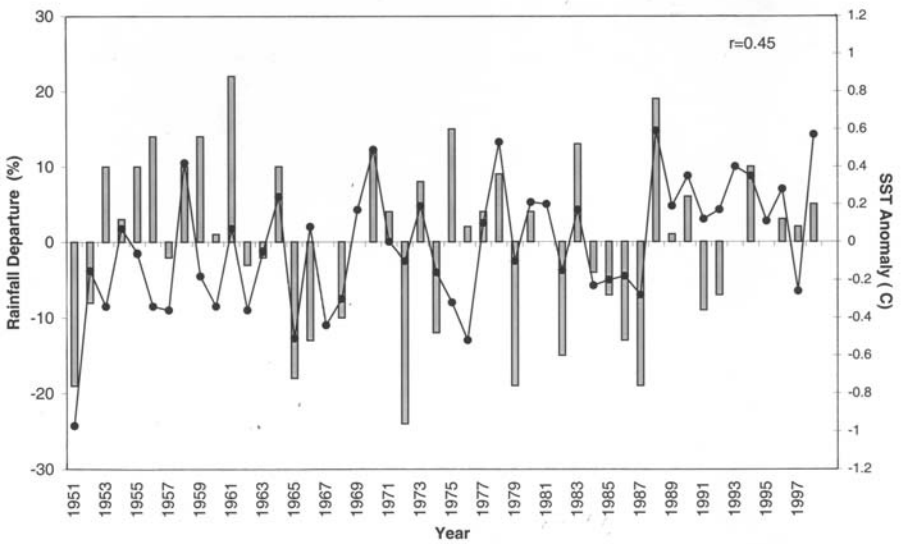
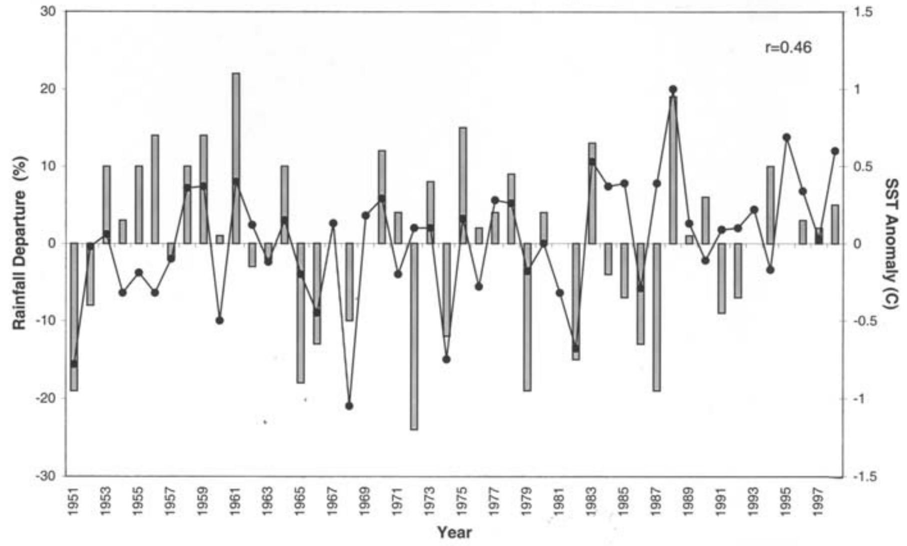


Fig. 4. Monthly variation of correlation between ARBSST (filled circles), and SIOSST (open circles) indices and ISMR. Period: 1950-98. The 99% significance level is shown as the horizontal dashed line

(a) Variation of Arabian Sea SST Anomalies and ISMR Departures



(b) Variation of South Indian Ocean SST Anomalies and ISMR Departures



Figs. 5(a&b). Variation of (a) ARBSST index (continuos line) and ISMR (vertical bars) and (b) SIOSST index (continuos line) and ISMR (vertical bars). Period : 1950-98

index was positive. Therefore the SST anomaly over south- east Indian ocean may be playing an important role in modulating ISMR especially in non-ENSO years.

Further, we have examined the relationship of these indices with ENSO index. Table 1 show correlation of these SST indices with the 3 month averaged Nino-3 index. The ARBSST index has insignificant correlation with Nino-3 index during DJF. But, it is positively and significantly correlated with the Nino-3 index one to three seasons later. The SIOSST index is also significantly correlated with Nino-3 index from MAM season onwards.

The secular variation of the relationship of these indices with ISMR is further investigated by calculating the 21year sliding correlations. The results are shown in Fig. 6. The SIOSST is consistently showing significant correlation with ISMR throughout the period. On the other hand, the correlation of ARBSST index with ISMR has become significant only after 1976. It has become stronger further during the recent years. The shift in relationship with ISMR after 1976 may be because of the climate shift observed in the Indian Ocean after 1976 (Nitta and Yamada 1989, Wang 1995). The Indian Ocean has undergone the greatest warming after 1976. Terray

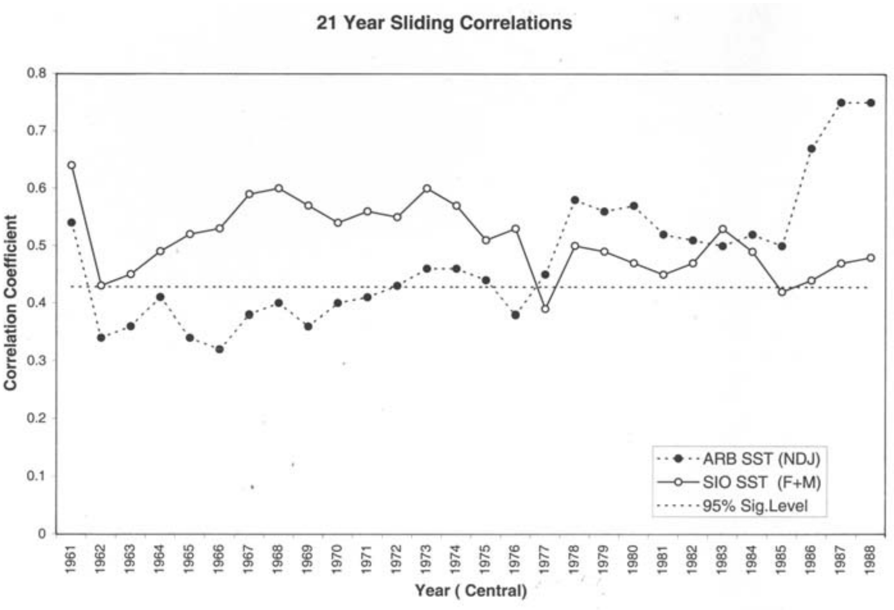


Fig. 6. 21 Year sliding correlation of ARBSST (filled circles) and SIOSST (open circles) indices with ISMR. The 95% significance level is shown as a horizontal dashed line

(1994) also reported sudden warming of SST after 1976 corroborating the evidence of a climatic change in the Indian Ocean after 1976.

3.4. *Regression analysis*

We have further carried out a regression analysis to examine the utility of these indices as predictors for long-range forecasting of Indian summer monsoon rainfall. We have used the data of 25 years (1971-95) for model development and 6 years (1996-2001) for verifications. Two linear multiple regression models were developed. The first model was developed with ARBSST and SIOSST as the predictors. For the second model, we have used two prominent predictors, the minimum temperature anomaly over NW India for the month of May and Nino-3 SST anomaly. For Nino-3 SST, we have used its tendency from winter to spring seasons (MAM-DJF). May minimum temperature represents the intensity of heat low and Nino-3 SST anomaly represents the monsoon-ENSO relationship. The comparative performances of the two models are given in Table 2. Model–2 has higher multiple correlation coefficient (0.64) compared to that of Model-1 (0.46) during the model development period. However, the Model-1 with SIOSST and ARBSST as the predictors performed much better during the independent period (verification period). During the independent period, the Model–1 has the root mean square error (RMSE) of only 3.3 %, while the Model–2 has the root mean square error as 11.3 %. The actual and forecast monsoon rainfall during the verification period are also

TABLE 2

Comparative performance of two multiple regression models

(i) Model statistics

	Model –1	Model-2
Predictors	SIOSST, ARBSST	May Min Temp, Nino-3 SST
Model Development Period	1971-95	1971-95
Multiple Correlation Coefficient (MCC)	0.46	0.64
RMSE during the model development period (1971-95)	10.6 %	9.01%
RMSE during the verification period (1996-2001)	3.3%	11.3%

(ii) Performance during the verification period (1996-2001)

Year	Actual (%)	Forecast (%) Model – 1	Forecast (%) Model – 2
1996	103	102 (1)	109 (-6)
1997	102	97 (5)	99 (3)
1998	105	108 (-3)	120 (-15)
1999	96	97 (-1)	107 (-11)
2000	92	97 (-5)	101 (-9)
2001	92	94 (-2)	109 (-17)

Error is given in bracket

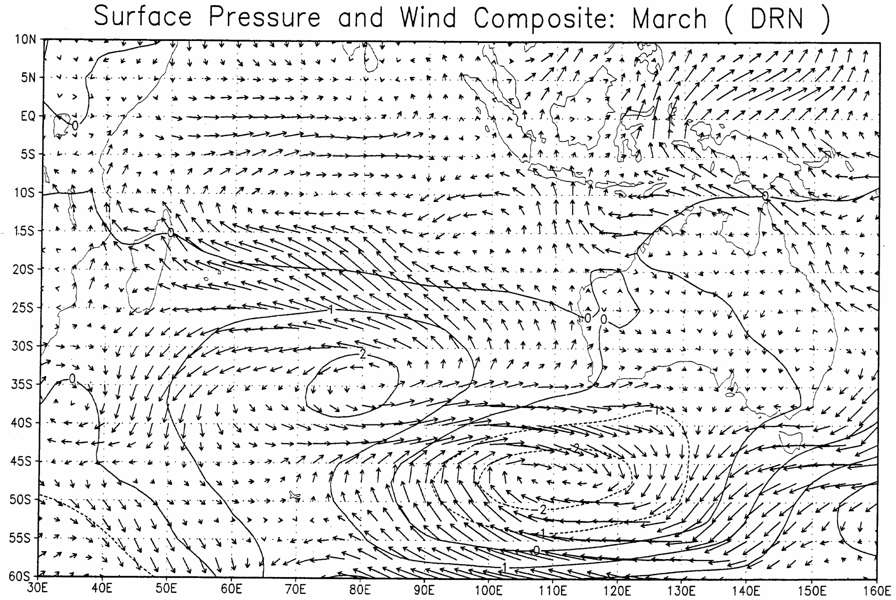


Fig. 7. Composite sea level pressure and surface winds for the month of March averaged for 5 negative SIOSST index years (1966, 1968, 1974, 1982 and 1986)

shown in Table 2. It can be seen that the hindcasts from the Model–1 with ARBSST and SIOSST were much closer to the observed rainfall than the Model-2. Further, the relationship of these predictors with ISMR anomalies has been found to be stable during the recent years as shown in Fig. 6. Thus it can be concluded that both the ARBSST and SIOSST are two promising predictors for long-range forecasts of Indian summer monsoon rainfall.

3.5. *Physical linkage*

At present, we do not understand fully the physical linkage of the SST anomalies over the south Indian ocean with Indian summer monsoon. SST anomalies over south Indian ocean can be caused in association with sea level pressure and surface wind anomalies over that region (Behera and Yamagata, 2001). To examine the associated sea level pressure and surface wind anomalies, we have made the composites of sea level pressure and surface wind anomalies for 5 years when SIOSST index was negative (1966, 1968, 1974, 1979 and 1986). NCEP/NCAR data have been used to calculate these composites. The anomalies have been calculated from the mean for the period 1958-98. The composite diagram of sea level pressure and surface winds for the month of March is shown in Fig. 7. It can be seen that over the region of negative SST anomaly, anomalous SE winds prevail. These stronger SE winds are associated with the stronger pressure gradient between the anomalous sub tropical high around 35° S, 75° E and the trough of low pressure along the west-coast of Australia. The stronger SE trades can induce negative SST anomalies through excess evaporation (Behera and Yamagata, 2001). Further, surface wind anomalies in the S.H. are aligned so that the S.H. equatorial trough becomes stronger along around 10° S. It may be mentioned that the activity of the S.H. equatorial trough during March-April-May period is inversely related to Indian summer monsoon rainfall (De *et al.* 1995). South Indian Ocean is very crucial in maintenance of the Indian summer monsoon circulation. During the spring season, trade wind circulation over the south Indian ocean is quite intense and plays a dominant role in the regulation of the cross equatorial flow over the Bay of Bengal and the Arabian Sea which is a vital component of Indian summer monsoon. During the monsoon season the cross equatorial flow from the southern hemisphere originates from the outflow of the Mascerene High situated in the south Indian ocean. Further, Mohanty *et al.* (1996) found that during pre-monsoon of good monsoon years, latent heat flux was more than normal over south Indian ocean. The positive SST anomalies observed over the south-east Indian ocean may be playing an important role in contributing the positive latent heat flux anomaly observed during the pre-monsoon season of good monsoon years. However, more elaborate study (both data analysis and numerical model simulation) will be required to establish the complete physical linkage of SST anomalies over south Indian ocean and Indian summer monsoon rainfall.

4. Conclusions

We have analysed 49 years of monthly SST data of Indian ocean to examine the role of SST anomalies over Indian Ocean on Indian summer monsoon rainfall and also to derive same predictive relationships. There is significant positive relationship between the ISMR and SST anomalies over the Arabian sea during the winter season and also in May. SST anomalies over southeast Indian ocean during the February-March season also are positively correlated with ISMR. The composite analysis further revealed that in non-ENSO drought (DRN) years, SST anomalies over the south Indian ocean are negative from February to September. Relationship over the Arabian sea during winter is observed almost 6 months in advance. The SST index derived over Arabian sea and south Indian ocean have been found to be promising predictors for long-range forecasts of Indian summer monsoon rainfall. We have also explored the physical linkage of SST anomalies over south Indian ocean and ISMR anomalies.

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