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# Relationship between surface fields over Indian ocean and monsoon rainfall over homogeneous zones of India

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**सार** - इस शोध-पत्र में हिन्द महासागर और उसके समीपवर्ती समुद्रों में कम, सामान्य और अधिक वर्षा वाले वर्षों के दौरान मानसून परिसंचरण की विशेषताओं, समुद सतह तापमान (एस.एस.टी.), समुद्र सतह दाब, धरातल पवन बल और अंतनिहित उष्मा प्रवाह की विशिष्टताओं की जाँच करने के लिए, 1948-1998 की अवधि के वायुमंडलीय क्षेत्रों के मासिक माध्य और धरातल से संबंधित एन.सी.ई.पी./एन.सी.ए.आर. के पुनः-विश्लेषित प्राचलों का अध्ययन किया गया है। भारत और अलग-अलग प्रेक्षित मौसमी माध्य वर्षा के आधार पर पाँच अन्य समरूपी क्षेत्रों को कम, सामान्य और अधिक वर्षा वाले वर्षों में इस अध्ययन की समूची अवधि को वर्गीकृत किया गया है। धरातलीय स्थानों की माध्य विशेषताओं के आधार पर हिन्द महासागर और उसके समीपवर्ती समुद्रों के अंतर्गत आने वाले महासागरीय क्षेत्रों को चार आंचलिक भागों में बाँटा गया है। विभिन्न साँख्यिकी माध्यों का उपयोग करते हुए चार आंचलिक भागों के धरातलीय क्षेत्रों और भारतीय भूभाग के पाँच समरूपी क्षेत्रों में हुई मानसून वर्षा के बीच पाए गए संबंध की जाँच की गई है। इस शोध -पत्र में कुछ ऐसे धरातलीय प्राचलों की पहचान करने का प्रयास किया गया है जिनका उपयोग समूचे भारत और कुछ अन्य समरूपी क्षेत्रों में हाने वाली मौसमी मानसून माध्य वर्षा के लिए पूर्वसूचकों के रूप में किया जा सकेगा।

**ABSTRACT.** The monthly mean atmospheric fields and surface parameters of NCEP/NCAR reanalysis for the period 1948-1998 have been studied to examine the characteristics of monsoon circulation features, sea surface temperature (SST), sea level pressure, surface wind stress and latent heat flux over the Indian Ocean and nearby seas during deficient, normal and excess rain years. The entire period of study has been classified into deficient, normal and excess rain years for all India as well as for each of the five homogeneous zones separately based on the observed seasonal mean rainfall. On the basis of the mean characteristics of the surface fields, the oceanic region covering the Indian Ocean and adjacent seas has been divided into four regional sectors. Using various statistical means the relation between the surface fields over the four regional sectors and the monsoon rainfall over five homogeneous zones of Indian landmass has been examined. Attempt have been made to identify some surface parameters which can be used as predictors for seasonal mean monsoon rainfall over the entire India and also over some homogeneous zones.

**Key words** – Monsoon rainfall, Homogeneous zones, Sea surface temperature, Deficient, normal and excess rain years, Interannual variation, Wind stress, Latent heat flux.

## 1. Introduction

Characteristics of sea surface fields represent the interaction between the atmosphere and the ocean. This is especially true in the tropics where the ocean serves as the main reservoir of heat for the genesis and the maintenance of atmospheric circulation patterns, of which Indian monsoon is a spectacular one. Numerous studies (Walker, 1928; Normand, 1953; Yusunary, 1991; Webster and Yang, 1992; Palmer *et al*. 1992 and Fenessy *et al*. 1994) have indicated the important role of the Pacific Ocean in Indian monsoon rainfall variability. Oceanic regions close to the Indian monsoon area such as the Arabian Sea, the Bay of Bengal, the South China Sea and the Southern Indian Ocean within 30° E-120° E and 30° S-0° are also extremely important in supplying necessary heat, moisture and momentum for the monsoon circulation. Understanding the characteristics of the surface fields and their seasonal changes over Indian Ocean and adjacent seas is very essential for the complete understanding of the Indian monsoon and its variability.

Investigators have tried to study the characteristics of surface fields over the Indian Ocean in relation to Indian monsoon activity. Findlater (1969 a & b, 1971; Krishnamurti *et al*. 1976) demonstrated that the low level cross equatorial jet over Kenya was closely associated with the intertropical convergence zone over the Arabian Sea and Western India, and variation in the strength of surface stress were related to the rainfall over western India during southwest monsoon. Furthermore, Findlater indicated that the low level jet begins to move northwestward in February and reaches the East African high lands by June. This jet is most intense during the summer monsoon season and the axis of the jet down stream from the Somalia coast splits into two branches during southwest monsoon period. Fu *et al*. (1983), based on 110 years of surface marine data over the Indian and West Pacific regions revealed that the monsoon current coming from the southern hemisphere has three branches: (1) Arabian Sea, (2) Bay of Bengal and (3) South China Sea. These branches are distinct in their characteristics and influence the rainfall in South Asia.

Surface fields over the Indian Ocean were examined by Mohanty and Ramesh (1993) using 30 years (1950-1979) of COADS data. This study showed that SST and sea level pressure do not show significant variability over the Arabian Sea and Bay of Bengal, but significant variability is observed over southern hemisphere in association with monsoon activity over India. Dash *et al*. (1995) emphasised that the annual cycle of SST and its northward propagation in the northern Indian Seas play significant role in monsoon variability. Variability of the surface fields over the Indian Ocean was also examined (Mohanty and Dash, 1995) using European Centre for Medium Range Weather Forecasts (ECMWF) analyses for 1985 and 1986. The results of this study indicate that branching is also reflected in the latent heat flux and mean sea level pressure in addition to the wind field as noted by Fu *et al*. (1983) earlier. Dash and Mohanty (1997) have examined the characteristics of surface fields such as SST, mean sea level pressure, zonal and meridional components of wind, wind stress and pseudostress, latent and sensible heat fluxes during summer (June, July, August, September) and winter (December, January, February) monsoons over the years 1985 to 1990. Three zones of maxima over Arabian Sea, Bay of Bengal and South China Sea recognised as three branches of the monsoon prominently appear in surface wind, wind stress and pseudo stress both during summer and winter monsoon months. Sea level pressure and latent heat flux exhibit regionality in their characteristics over the three branching regions. Arabian Sea is dominant in strength and variability of the surface fields during summer monsoon season while South China Sea is prominent during winter monsoon season. Land-sea heating contrast appears to be the primary mechanism for the above branching phenomenon. The study reveals that in addition to solar forcing and its seasonal reversal, local processes also contribute significantly to the seasonal cycle in each oceanic region.

It is well known that monsoon rainfall over India has a significant temporal as well as spatial variability (Mooley and Parthasarathy, 1984; Parthasarathy *et al*., 1995). India as a whole is too large to be treated as a single unit. Even in early days, Walker (1924) suggested that rainfall anomalies over several sub-divisions of India should be grouped together to define areal averages for large homogeneous regions on the basis of uniformity of correlation coefficients between the anomalies and geographical distant atmospheric parameters. It is not uncommon to find some areas of excessive rainfall even with the worst all-India monsoon performance. Therefore, it is always desirable to consider some homogeneous zones of Indian monsoon rainfall and then to find out their association with the regional/global scale circulation features or boundary forcing rather than taking All-India rainfall alone.

In this study the composites of seasonal mean surface fields such as SST, sea level pressure and surface fluxes of momentum and latent heat have been examined over the Indian Ocean and adjacent seas during excess and deficient rain years to identify the zones of maximum activity. The composites of seasonal mean monsoon winds at 850 hPa and 200 hPa, stream function at 200 hPa and temperature at 500 hPa are also examined to validate the reanalysis data of National Centre for Environmental Prediction / National Centre for Atmospheric Research (NCEP/NCAR). Using various statistical means, the relationship between the surface fields over the Indian Ocean regional sectors and the monsoon rainfall over All India (hereafter referred to as AI) and five homogeneous zones of Indian land mass has been examined. Attempts have been made to identify some new oceanic parameters as predictors for seasonal mean monsoon rainfall over AI and some homogeneous zones.

Section 2 deals with the data used and the observed seasonal mean rainfall and its interannual variability over AI and five homogeneous zones. The contrasts in some of important monsoon circulation features and sea surface parameters between excess and deficient rain years are examined in Section 3. Statistically meaningful relationship between the surface fields and seasonal rainfall over AI and its homogeneous zones is examined in

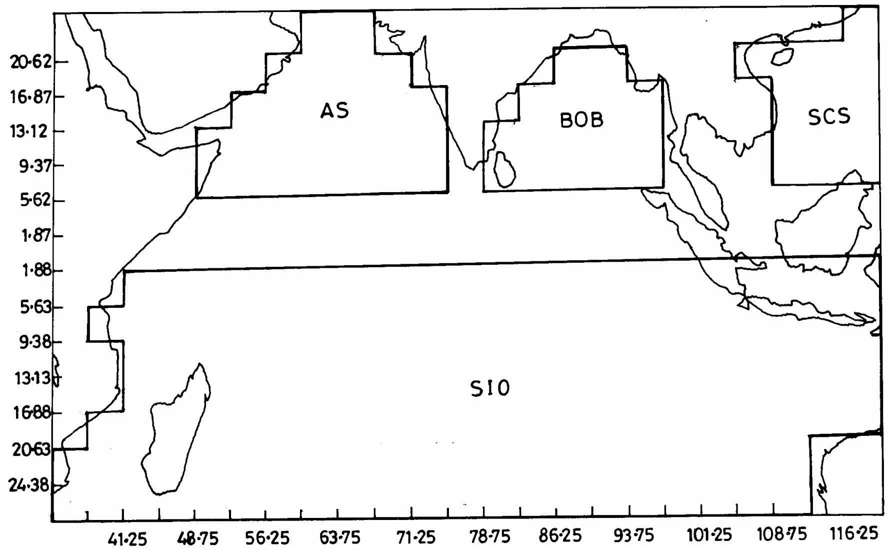



**Fig. 1.** Four regional sectors of the Indian Ocean

Section 4. Some new oceanic parameters are identified for seasonal mean rainfall over AI and three of its homogeneous zones and multiple regression (MR) equations are established in Section 5. Conclusions are given in Section 6.

## 2. Data

The monthly mean NCEP/NCAR reanalysed winds at 850 hPa and 200 hPa stream function at 200 hPa, SST, surface wind, sea level pressure, surface fluxes of momentum and latent heat for the period 1948-1998 are used in this study. These reanalyses were undertaken with fixed state-of-the-art data assimilation/analysis methods to provide multi-year global data sets for a range of investigations of many aspects of climate, particularly interannual variability. The large spurious effects present in operational analysis arising from changes in assimilation systems are absent from the reanalysed data set. These data provide a much more homogeneous time series, although there are still effects from the varying observational database (WCRP, 1998). Major efforts in reanalysis were carried out by the ECMWF, the NCEP in collaboration with NCAR and National Aeronautics and Space Administration (NASA)/Goddard Space Flight Centre (GSFC), Data Assimilation Office. Studies (WCRP 1998) indicate that the reanalysis has provided much improved, consistent and more homogeneous global fields of a range of key parameters such as surface fluxes, diabatic heating and other components of hydrological cycle. The NCEP/NCAR surface fluxes are derived (Kalnay *et al.* 1996) solely from the model fields forced by the data assimilation to remain close to the atmosphere. Goswami *et al.* (1998) have compared the NCEP/NCAR wind stress with those of Florida State University (FSU) and concluded that reanalysis does not have any major systematic bias on the monthly and interannual time scales arising from the analysis system (including the physical parameterization schemes used in the model). The oceanic area covering the Indian Ocean and adjacent seas has been divided into four regional sectors (Fig. 1) namely Arabian Sea (5° N-25° N, 47° E-75° E), Bay of Bengal (5° N- 21° N, 78° E-98° E), South China Sea (5° N-25° N, 100° E - 120° E) and Southern Indian Ocean (30° S-0°, 30° E-120° E); hereafter referred to as AS, BOB, SCS and SIO respectively. SIO mentioned in this study covers a large area with the objective of including the effects of the trade wind and the Mascarene High on the monsoon.

Fig. 2 shows five homogeneous zones into which the country has been divided by Parthasarathy *et al.* (1995). These zones are northwest India (NWI), west central India (WCI), central northeast India (CNI), northeast India (NEI) and south peninsular India (SPI). They considered 306 well distributed rain gauge stations and collected the relevant monthly rainfall data over the stations for the period 1871 to 1994 for preparing the five homogeneous rainfall zones. These regions cover AI rainfall consisting

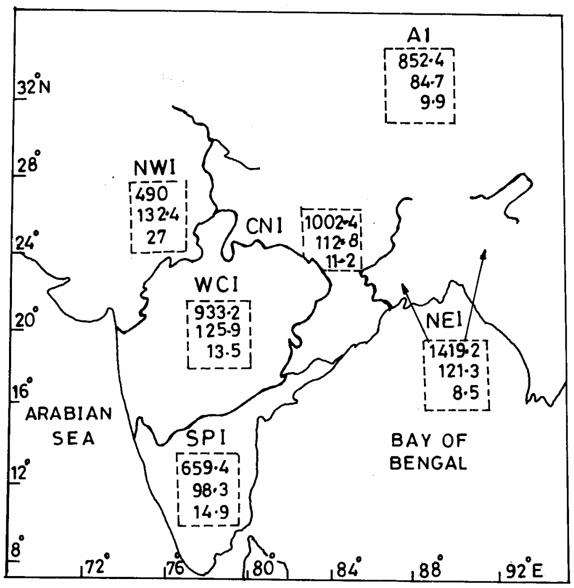



**Fig. 2.** Five homogeneous zones of India. The numbers in each zone represent mean monsoon rainfall (mm); standard deviation (mm) and coefficient of variation (%) from top to bottom respectively

of 29 sub-divisions. The monthly rainfall data over the meteorological sub-divisions have been obtained from India Meteorological Department (IMD). NWI consists of six meteorological sub-divisions 13, 14, 17, 18, 21 and 22 as defined by IMD. WCI consists of 8 meteorological sub-divisions such as 19, 20, 23, 24, 25, 26, 28 and 32. CNI consists of 5 sub-divisions numbering 7 to 11. NEI consists of 4 sub-divisions numbering 3 to 6. Similarly, SPI consists of 6 meteorological sub-divisions of IMD bearing numbers 27, 29, 30, 31, 33 and 34. Basically Parthasarathy *et al.* (1995) divided the homogeneous regions on the basis of similarity in rainfall characteristics and association of sub-divisional rainfall with regional/global circulation parameters. They did not include six subdivisions numbered 1, 2, 12, 15, 16 and 35 sub-divisions because of their inadequate rain gauge network and limited representativeness. In this study the monthly mean values of Eurasian snow cover have been obtained from Climate Diagnostics Bulletin of the Climate Prediction Center, USA.

Fig. 2 also shows the seasonal mean rainfall, standard deviation and coefficient of variation of seasonal monsoon rainfall of AI and five rainfall regions considered. The information given in the figure support the fact that AI rainfall series is not the true representative of rainfall over every part of the country. This is indicated by the relatively low standard deviation and coefficient of variation of AI rainfall compared to five other homogeneous zones. The coefficient of variation is the largest for the sub-divisions in NWI with the value 132, primarily because of the fact that the amount of rainfall is small there. The amount of seasonal mean rainfall in NEI is quite large with 1419 mm and the standard deviation is relatively small (8.5 mm) giving rise to the low value (121) of coefficients of variation. Grouping of the homogeneous zones appears to be adequate since there is large rainfall variability observed amongst these zones. Based on observed rainfall, the entire period of 51 years has been divided into excess, normal and deficient rain years for AI as well as for five homogeneous zones separately. The years with seasonal mean rainfall less than ($r$-$\sigma$) for a particular region are termed as deficient rain years for that zone. Here $r$ is the mean rainfall and a is the standard deviation. Similarly the years with seasonal mean rainfall greater than ($r$+$\sigma$) are classified as excess rain years. Finally the years with seasonal mean rainfall between ($r$-$\sigma$) and ($r$+$\sigma$) are termed as normal rain years. Thus the characteristics of the excess monsoon over AI are based on the mean of the years 1956, 1959, 1961, 1970, 1975, 1983, 1988 and 1994. Similarly the characteristics of the deficient monsoon over AI are obtained based on the mean of the years 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1986 and 1987. Rest of the period are considered as normal monsoon years for AI. As shown in Fig. 3, the identification of excess, normal and deficient monsoon years on the basis of AI seasonal rainfall does not hold good in most of the homogeneous zones indicative of inadequate representatives of AI rainfall. For example, even in 1988 when AI monsoon performance is very good, CNI rainfall is normal with 0.95% departure. Similarly in 1987, the year of worst AI monsoon performance, NEI records rainfall in excess from the 1ong term mean. Fig, 3 shows many such disparities.

## 3. Contrast in circulation features and surface fields between excess and deficient rain years

It is well known that the monsoon circulation is established due to the differential heating between the landmass in the north and Indian Ocean to the south. The north-south differential heating is reflected in the temperature field up to 500 hPa level in the vertical. Also the Indian Ocean and the adjacent seas such as AS, BOB and SCS are the main source of moisture for rainfall over India during the monsoon season (JJAS). The interhemispheric pressure gradient between the Mascarene High and the low pressure area over Afghanistan, Pakistan and North India is one of the main driving forces for this moisture to enter into the land area. Southwest trade wind and the subsequent Somali jet carry this moisture into the Indian region through AS and across the Western Ghats. In addition, the monsoon disturbances found over the

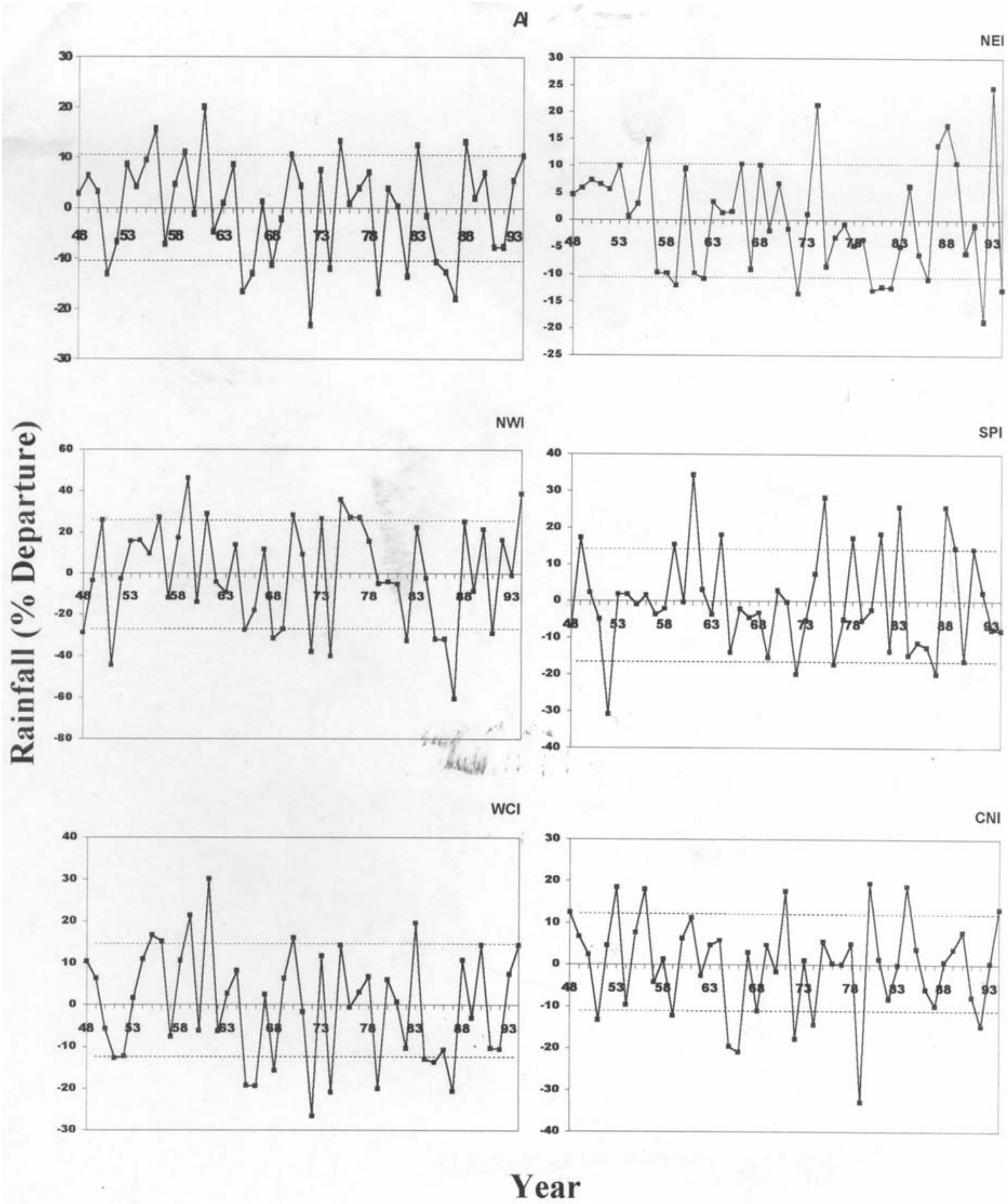
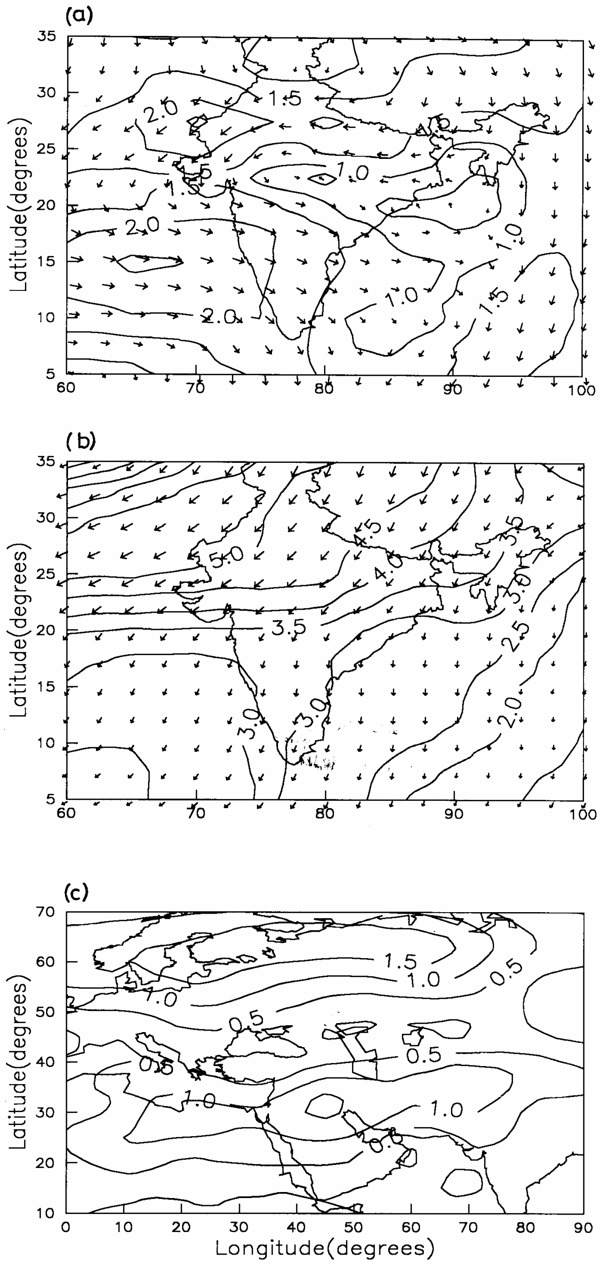



**Fig. 3.** Percentage departure of rainfall over All India (AI) and its five homogeneous zones based on the observed data of IMD for the period 1976 to 1994. The upper and lower horizontal dotted lines on each figure represent the cutoff departure for excess and deficient rainfall over each zone respectively

BOB move in the north-northwest direction and produce copious rainfall over India. Thus the importance of the Indian Ocean and adjoining seas in the performance of monsoon circulation and subsequent rainfall during




**Figs. 4(a-c).** Difference wind fields (m/s) at (a) 850 hPa, (b) 200 hPa and (c) Difference temperature field (°C) at 500 hPa. The difference fields are obtained by deducting the mean of deficient rain years from the mean of excess rain years

different years is well known. Strong southeast trade wind, strong cross-equatorial flow, strong Somali jet, strong surface wind and more evaporation over the Indian Ocean and the adjacent seas give rise to strong monsoon circulation, abundant supply of moisture and hence more rain during the excess monsoon. The reverse occurs during the deficient monsoon.

In this section, the NCEP/NCAR reanalysed data for the period 1948 to 1998 have been analysed to examine some of the important seasonal (JJAS) mean characteristics of the Indian summer monsoon circulation such as maximum strength of Somali jet at 850 hPa, strength of easterly jet at 200 hPa, strength and position of the Tibetan anticyclone at 200 hPa, temperature at 500 hPa, surface pressure, SST, surface wind stress and latent heat flux. This study emphasises on the difference in the strength of the circulation features and surface fields between composites of excess and deficient rain years. Results show that the maximum strength of Somali jet during the excess rain years is about 17.5 m/s whereas its value during the deficient rain years is 15.0 m/s. During the normal monsoon years the strength of Somali jet is 16.0 m/s. Similarly the strengths of easterly jet at 200 hPa during excess and deficient rain years are 24.0 m/s and 21.0 m/s respectively. The strength of Tibetan anticyclone at 200 hPa during the excess monsoon rain years is $130\times10^5$ $m^2/s$ as against $90\times10^5$ $m^2/s$ during the deficient rain years. During the normal monsoon years its value is $125\times10^5$ $m^2/s$. The contrast in the strengths of wind at 850 hPa [Fig.4(a)] and at 200 hPa [Fig. 4(b)] between the excess and deficient AI rain years is very good in consonant with the thermal contrast at 500 hPa [Fig. 4(c)]. It is observed that, the temperature at 500 hPa to the north of Indian landmass is higher during the excess monsoon years than in the deficient rain years with maxima of 1.5° C at 30° N and 60° N latitudes. The strength of the Somali jet at 850 hPa, the strength of the easterly jet at 200 hPa and the strength of the Tibetan anticyclone at 200 hPa are more during the excess rain years than the respective values in the deficient years. These results show that the NCEP/NCAR reanalysed data is good enough to study the variability of monsoon features during excess and deficient rain years.

The difference in the strengths of the monsoon circulation features and surface fluxes between excess and deficient rain years for each of the homogeneous zones are given in Table 1. It is seen that all the five zones do not behave in the same way as AI when the strength of the monsoon circulation is concerned. The contrast in the maximum wind values at the lower and upper levels between excess and deficient rain years is very good in all the zones with slight variations. Except in NEI, the contrast in the strength of Tibetan anticyclone is also good. The difference in the latent heat flux between the excess and deficient rain years is also very good over all the four oceanic zones AS, BOB, SCS and SIO. However, NEI rainfall behaves in opposite phase with rest of the zones. Another noticeable feature is the BOB latent heat flux difference in case of CNI rainfall. BOB latent heat flux is more during the deficient rain years than the excess rain years in CNI. It is necessary to conduct some

**TABLE 1**

**Difference of seasonal (JJAS) mean monsoon circulation features and surface fluxes between excess and deficient rain years for All-India (AI) and five homogeneous zones separately**

| Region | Wind (m/s) | | Tibetan anticyclone 200 hPa strength ($10^5$ $m^2$/s) | Latent heat flux (W/$m^2$) | | | | Surface wind stress ($10^{-2}$ N/$m^2$) | |
|---|---|---|---|---|---|---|---|---|---|
| | Maximum strength of Somali jet (850 hPa) | Maximum strength of easterly jet (200 hPa) | | AS | BOB | SCS | SIO | AS | SIO |
| Al | 2.6 | 3.0 | 40 | 17.0 | 14.0 | 7.0 | 19.0 | 2.0 | 3.0 |
| NWI | 2.9 | 3.5 | 25 | 13.0 | 12.0 | 12.0 | 22.0 | 4.5 | 10.5 |
| WCI | 2.7 | 2.5 | 45 | 17.0 | 14.0 | 11.0 | 19.0 | 2.5 | 3.0 |
| CNI | 2.0 | 2.9 | 50 | 14.0 | -14.0 | 6.0 | 12.0 | 3.5 | 2.5 |
| SPI | 2.0 | 1.9 | 30 | 10.0 | 20.0 | 12.0 | 24.0 | 2.5 | 8.0 |
| NEI | 2.6 | 2.5 | -3 | -10.0 | -16.0 | -8.0 | 6.0 | 1.5 | 2.5 |

**TABLE 2**

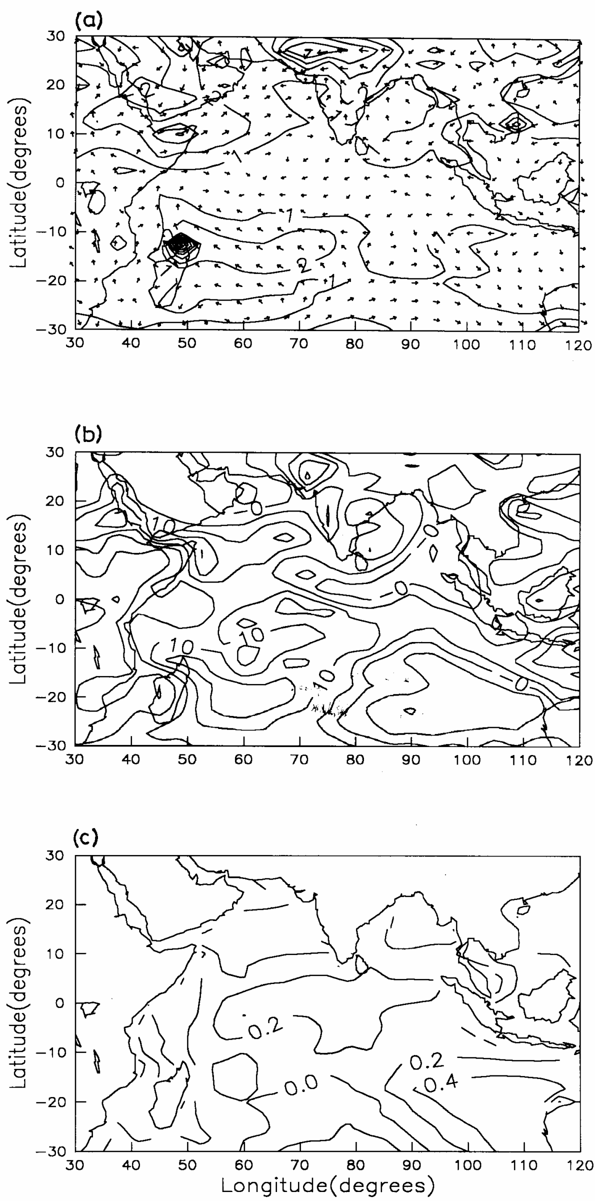
**Correlation coefficients between different oceanic parameters and percentage departure of rainfall anomaly (Numbers given in the brackets denote the percentage of significant levels)**

| Anomaly fields | Region | Antecedent season | Homogeneous rainfall regions | | | | |
|---|---|---|---|---|---|---|---|
| | | | AI | WCI | CNI | SPI | NEI |
| | AS | DJF | 0.46 (5) | 0.52 (2) | – | 0.50 (5) | – |
| | BOB | MAM | – | – | – | 0.46(5) | – |
| SST | SCS | DJF | – | – | – | 0.57(1) | – |
| | | MAM | – | – | – | 0.47(5) | – |
| | SIO | DJF | – | – | – | 0.61(1) | – |
| | | MAM | – | – | – | 0.55(2) | – |
| LHTFL | AS | MAM | 0.50 (5) | 0.52 (2) | – | – | – |
| | BOB | DJF | – | 0.43 (5) | – | – | 0.43 (5) |
| UVFLUX | AS | MAM | – | – | 0.51(5) | – | – |
| SNOW COVER | EURASIA | DJF | – | – | -0.44(5) | – | – |

modelling studies to examine such exceptional behaviour. However, the results of this section definitely indicate that the NCEP/NCAR reanalysed data are good enough to confirm the conventional hypothesis that upper and lower level monsoon winds, the Somali jet, the cross equatorial flow are stronger during excess rain years than during deficient rain years.

Earlier study (Mohanty and Dash, 1995) has shown four zones of maximum concentration of surface features such as fluxes of momentum and latent heat over AS, BOB, SCS and SIO. Also these zones exhibit different types of interannual variability. In the present study, the Indian Ocean has been divided into the same four zones as shown in Fig. l. In this study the monthly mean values of fluxes of momentum (UVFLUX) and latent heat (LHTFL), SST and sea level pressure have been analyzed for all the years from 1948 to 1998.

Fig. 5(a) shows that surface wind stress over SIO is stronger during the excess AI rain years, which leads to stronger southwest monsoon wind. Similarly, the evaporation [Fig. 5(b)] over SIO is stronger during the excess than the deficient rain years. However the difference in the SSTs during the excess and deficient rain years is negligibly small as shown in Fig. 5(c).




**Figs. 5(a-c).** Same as in Fig. 4 except for (a) surface wind stress ($10^{-2}$ N/m$^2$), (b) surface latent heat flux (W/m$^2$ ) and (c) SST (°C)

## 4. Correlation between surface fields over Indian Ocean regional sectors and homogeneous rainfall zones

The basic purpose of this section is to examine and establish some significant relationship between the rainfall over five homogeneous zones and AI and sea surface parameters over the four oceanic zones adjacent to India. Time series of SST, LHTFL, UVFLUX anomalies over AS, BOB, SCS and SIO and Eurasian Snow Cover during December to May are correlated with the following seasonal mean (JJAS) summer monsoon rainfall over the homogeneous zones. The seasonal mean of all these parameters averaged over 19 years (1976-1994) are calculated. The seasonal anomalies of SST, LHTFL, UVFLUX and Eurasian Snow Cover are obtained by subtracting seasonal data from respective 19 year mean values.

Here lag Correlation Coefficients (CCs) of seasonal SST, LHTFL and UVFLUX anomalies over AS, BOB, SCS and SIO during December, January, February (DJF) and March, April, May (MAM) and Eurasian Snow Cover anomalies during DJF and MAM are computed with the percentage departure of southwest monsoon rainfall in JJAS over NWI, WCI, CNI, SPI, NEI and AI.

Since, the objective is to form regression equations separately for each homogeneous region of India, as a first step, significant predictors are obtained from correlation method over each homogeneous region. Table 2 presents the CCs along with their significant levels between different surface parameters such as seasonal SST, LHTFL, UVFLUX and snow cover anomalies and percentage departure of rainfall over AI, WCI, CNI, and NEI. Only those correlations, which are significant during antecedent seasons, have been presented in Table 2. CCs between these anomaly fields and the seasonal mean rainfall over NWI are very small except those of MAM LHTFL over BOB and SCS which are 0.36 and 0.38 respectively. Hence these values are not given in Table 2.

It is seen from Table 2 that AI monsoon rainfall has strong and direct association with antecedent DJF LHTFL and DJF SST anomaly of AS with CCs of 0.50 (at 5% level) and 0.46 (at 5% level) respectively. It is found that significant and direct correlations are obtained between seasonal mean rainfall departure of WCI and antecedent DJF SST and MAM LHTFL anomaly of AS both with CCs of 0.52 significant at 2% level. DJF LHTFL anomaly of BOB has CC of 0.43 significant at 5% level with WCI rainfall departure. As far as CNI rainfall is concerned, antecedent MAM UVFLUX of AS and DJF Eurasian snow cover has CCs of 0.51 at 5% level and – 0.44 (at 5% level) respectively. SPI rainfall departure has CCs of 0.50 at 5% level, 0.57 at 1% level and 0.61 at 1% level with antecedent DJF SST anomalies of AS, SCS and SIO respectively. MAM SST anomaly over BOB, SCS and SIO has direct and significant CC of 0.46 (at 5% level), 0.47 (at 5% level) and 0.55 (at 2% level) respectively with the rainfall departure of SPI. The seasonal mean rainfall departure of NEI has positive CC of 0.43 (at 5% level) with the LHTFL anomaly of BOB only.

It is interesting to note that AI rainfall has significant positive correlation with antecedent DJF LHTFL and SST

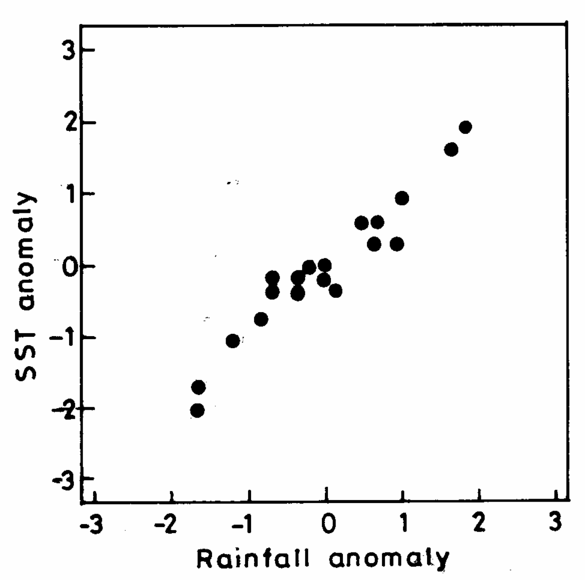



**Fig. 6.** Standardised scatterplot of AI rainfall anomaly *vs* DJF SST anomaly of AS

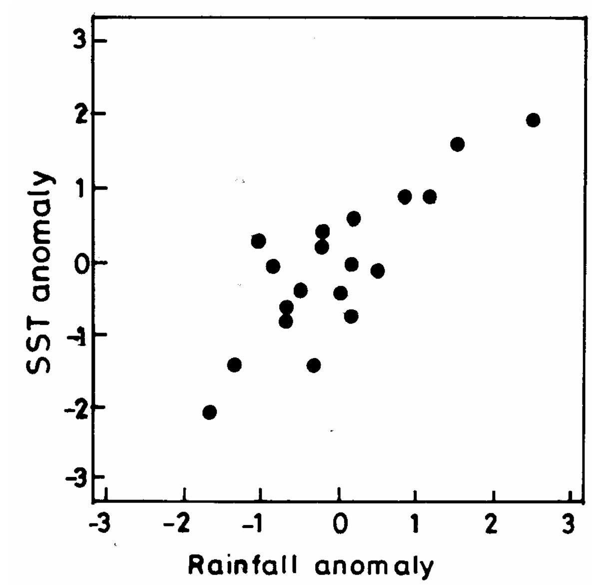



**Fig. 8.** Standardised scatterplot of SPI rainfall anomaly *vs* DJF SST anomaly of SIO

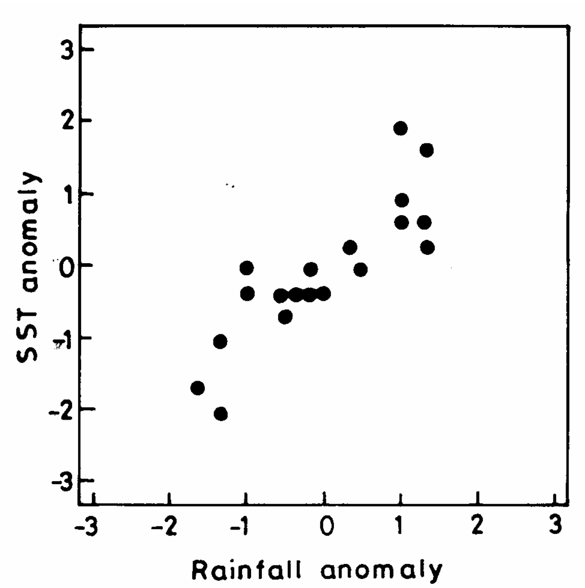



**Fig. 7.** Same as Fig. 6 except for WCI rainfall

anomalies of AS only, whereas SPI has significant and positive correlation with DJF SST anomalies of AS, SIO, SCS and MAM SST anomalies of BOB, SIO and SCS. Similarly seasonal mean rainfall departure of WCI has significant positive correlation with DJF SST anomaly of AS, DJF LHTFL anomaly of BOB and MAM LHTFL anomaly of AS.

## 5. Multiple regression model

Gowariker *et al.*, (1991) developed 16 parameter power regression model for long range forecast of southwest monsoon rainfall over All India. This model has been successfully used by IMD for operational seasonal monsoon forecast. Their 16 parameters include EI-Nino, four surface temperatures of Northern Hemisphere, North India, East coast of India and Central India, wind at 500 hPa, 50 hPa and 10 hPa, SOI and surface pressure of Northern Hemisphere and Darwin, Eurasian Snow Cover *etc*. None of these parameters represent the sea surface conditions of the Indian Ocean and adjacent seas except the Indian Ocean equatorial pressure from January to May, In this section, the significant parameters shown in Table 2 are used to develop MR models separately for AI and three homogeneous regions of India such as WCI, CNI and SPI on the basis of 15 year data (1976-1990) and forecast has been given for the next four years from 1991 to 1994. NEI is not considered because there is only one possible predictor *i.e.* BOB LHTFL. Results show that in case of AI, the highest value of multiple CC is 0.53 and the standard errors (which measure the accuracy of prediction of dependent variable, here AI rainfall) in 1991, 1992, 1993 and 1994 are 9.93, 10.02, 9.63 and 9.43 respectively. The corresponding F-ratios (measures the strength of regression) are 1.45, 1.16, 1.37 and 1.49. The best fit regression is found between AI rainfall anomaly and antecedent DJF SST anomaly of AS as shown in the scattered diagram (Fig. 6).

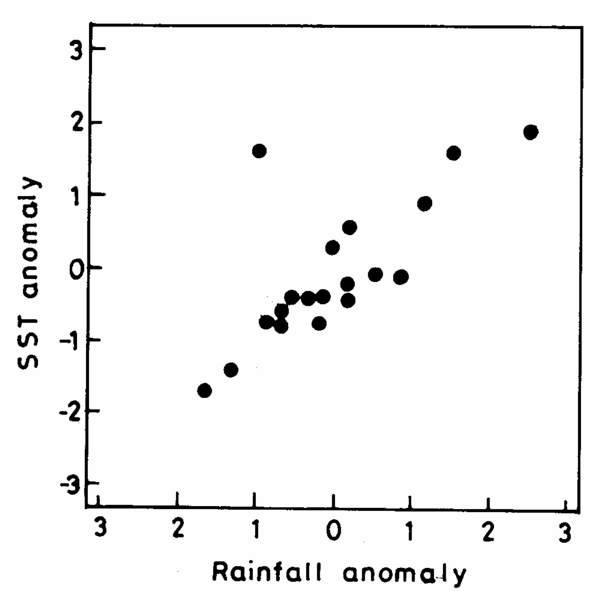



**Fig. 9.** Same as Fig. 8 except for MAM SST anomaly

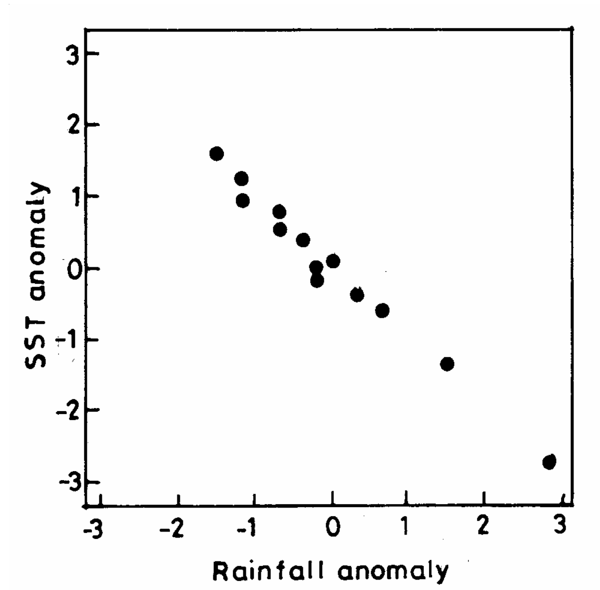



**Fig. 10.** Standardised scatterplot of CNI rainfall anomaly *vs* MAM Eurasian Snow Cover anomaly

For WCI the highest multiple CC is 0.68. Standard errors and F-ratios in 1991, 1992, 1993 and 1994 are 10.37 & 3.31, 11.18 & 2.09, 10.86 & 2.28 and 10.52 & 2.72 respectively. WCI rainfall anomaly and DJF SST anomaly of AS show reasonably good fit as shown in Fig. 7.

For SPI, the highest value of multiple CC is 0.76, Standard errors and F-ratios are 14.69 and 1.7, 13.85 and 2.11, 13.19 and 2.32 and 13.23 and 2.12 respectively. The best fit of regression is found between SPI rainfall anomaly and antecedent DJF SST and MAM SST anomaly of SIO as shown in Figs. 8 and 9 respectively.

For CNI, highest value of multiple CC is 0.6. Standard errors and F-ratios are 10.66 & 3.39, 10.87 & 2.88, 11.17 & 2.57 and 10.79 & 3.43 respectively. The best fit is found between CNI rainfall anomaly and Eurasian Snow Cover anomaly as shown in Fig. 10.

From the above statistical values it is noted that the highest value of multiple correlation and F-ratios are found for SPI followed by WCI, CNI and AI. Also the regression fit on scatter plot shows that best result is obtained for SPI (Fig. 9). Skill scores for the period 1991 to 1994 based on climatological mean of 19 years (1976-1994) over AI, WCI, CNI and SPI have been computed using the formula

$$SS = (R-R_{cli})/(R_{obs} - R_{cli})* 100$$

Here R is the model predicted rainfall, $R_{cli}$ is the climatological rainfall and $R_{obs}$ is the observed rainfall amount. Results indicate that out of four rainfall regions, only SPI has positive skill score for all the four years with 73%, 39%, 24% and 12% in 1991, 1992, 1993 and 1994 respectively. WCI shows positive skill of 22%, 39% and 12% in 1992, 1993 and 1994. CNI and AI have positive skill during 1993-1994 and 1991 & 1993 respectively. This study indicates that regression parameters for SPI and WCI have good potential for prediction and have positive skill for seasonal mean monsoon rainfall prediction over these zones. With a view to examine the advantage of using the new sea surface parameters in the long range forecast of rainfall over India, MR model has been used to give the forecast for the above four years (1991-1994) by using (a) some of the well known and dominant parameters used in Gowariker *et al.* (1991) and (b) the parameters in (a) plus the new parameters identified in this paper.

Comparison of statistics show that DJF SST anomaly over AS is a good parameter for seasonal monsoon rainfall over AI whose inclusion enhances the R square value from 76.4 to 76.9. Similarly the inclusion of the parameter DJF SST anomaly over SIO enhances the R square value from 87.3 to 91.3 for the SPI. Inclusion of other parameters cause marginal improvements.

## 6. Conclusions

In this study the NCEP/NCAR reanalysed data for the period 1948-1998 have been examined to study the contrast in the characteristics of monsoon circulation features over India and sea surface parameters over the Indian Ocean and adjacent seas between the excess and deficient monsoon years. The 50 years of study consists of 8 excess rain years and 10 deficient rain years over India.

Results show that the NCEP/NCAR reanalysed data is good enough to show that the monsoon circulation features such as the Somali jet at 850 hPa, the easterly jet at 200 hPa, Tibetan anticyclone at 200 hPa, temperature at 500 hPa and sea surface wind stress and latent heat flux over the Indian Ocean and nearby seas are stronger in excess rain years than during deficient rain years over India. This indicates that the NCEP/NCAR reanalysed data is of good quality to study the interannual variability of monsoon.

Attempts have been made here to examine the possible relationship between the seasonal mean monsoon rainfall over all India and its five homogeneous zones and the sea surface parameters such as SST, momentum flux and latent heat flux over AS, BOB, SCS and SIO. Results indicate that AI rainfall has significant positive correlation with antecedent DJF latent heat flux and SST anomalies of AS only. However, the peninsular India has significant and positive correlation with DJF SST anomalies of AS, SIO and SCS and MAM SST anomalies of BOB, SIO and SCS. Similarly seasonal mean rainfall departure of WCI has significant positive correlation with DJF SST anomaly of AS, DJF latent heat flux anomaly of BOB and MAM latent heat flux anomaly of AS.

The 16 parameter model of IMD does not consist of any parameter which represent the sea surface conditions of the Indian Ocean and adjacent seas directly except the Indian Ocean equatorial pressure. In the present study, efforts have been made to identify new sea surface parameters of the Indian Ocean which may be used as predictors for seasonal mean monsoon rainfall over AI and five homogeneous zones. Multiple regression models have been used. Results show that DJF SST anomaly over AS is a good parameter to be considered for seasonal mean monsoon rainfall prediction over AI. Similarly DJF SST anomaly over SIO will serve as additional good predictor for the seasonal mean monsoon rainfall over SPI. There are other sea surface parameters, which in this study, show marginal impact on the seasonal prediction. It is necessary to use these Indian Ocean parameters in the IMD operational model and conduct some more studies in order to reconfirm the practical utility of the new parameters in the prediction of seasonal monsoon rainfall.

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**List of Acronyms**

| | |
|---|---|
| AI | All India |
| AS | Arabian Sea |
| BOB | Bay of Bengal |
| CC | Correlation Coefficient |
| CNI | Central Northeast India |
| COADS | Comprehensive Ocean Atmospheric Data Set |
| DJF | December, January and February |
| ECMWF | European Centre for Medium range Weather Forecasts |
| ENSO | El-Nino Southern Oscillation |
| FSU | Florida State University |
| GSFC | Goddard Space Flight Centre |
| IMD | India Meteorological Department |
| JJAS | June, July, August and September |
| LHTFL | Latent Heat Flux |
| MAM | March, April and May |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Centre for Atmospheric Research |
| NCEP | National Centre for Environmental Prediction |
| NEI | Northeast India |
| NWI | Northwest India |
| SCS | South China Sea |
| SIO | Southern Oscillation Index |
| SST | Sea Surface Temperature |
| TOGA | Tropical Ocean Global Atmosphere |
| WCI | West Central India |
| SPI | South Peninsular India |