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The effect of ENSO/Anti ENSO on northeast monsoon rainfall

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सार — दक्षिणी प्रायद्वीपीय भारत में होने वाली वर्षा पर पड़ने वाले एल निनो दक्षिणी दोलनों/प्रति एल निनो दक्षिणी दोलनों के प्रभाव का पता लगाने के लिए भारत के पांच मौसम वैज्ञानिक उपखंडों की उत्तरी पूर्वी मानसून वर्षा के 1901से 1997 तक की अवधि के आंकड़ों का विश्लेषण किया गया है । एल निनो दक्षिणी दोलनों प्रति/एल निनो दक्षिणी दोलनों वाले वर्षों का चयन मौसमी दक्षिणी दोलनों के आधार पर किया गया है। इन विश्लेषणों से यह पता चला कि एल निनो दक्षिणी दोलनों वाले वर्षों में प्रायः उत्तरी पूर्वी मानसून वर्षा में वृद्धि हुई है जबकि प्रति एल निनो दक्षिणी दोलनों वाले वर्षों के दौरान वर्षा में कमी आई है । प्रति ई एन एस ओ वर्षों में वर्षा की कमी तमिलनाडु (0.1 प्रतिशत तक), केरल (1 प्रतिशत तक), और दक्षिणी प्रायद्वीपीय भारत में (1 प्रतिशत तक) उल्लेखनीय रही है । 22 ई एन एस ओ वर्षों में से 18 वर्ष या तो बाढ़ वाले वर्ष अथवा वर्षा वाले वर्ष पाए गए हैं जबकि 15 प्रति ई एन एस ओ में से 11 वर्ष सूखा वाले वर्ष अथवा कम वर्षा वाले वर्ष पाए गए हैं ।

ई एन एस ओ वर्षों के दौरान अक्तूबर से दिसम्बर के महीनों में बंगाल की खाड़ी एवं अरब सागर दोनों में ही समुद्र सतह तापमान विसंगतियाँ सामान्य थीं जबकि प्रति ई एन एस ओ वर्षों में स्थिति इसके बिल्कुल विपरीत थी । मध्य-पूर्व अरब सागर में तथा बंगाल की खाड़ी के मध्य-उत्तर के क्षेत्रों और उत्तरी पूर्वी मानसून वर्षा एवं समुद्र सतह तापमान के बीच सहसंबंध उल्लेखनीय रूप से सामान्य पाए गए हैं ।

प्रति ई एन एस ओ वर्षा की तुलना में ई एन एस ओ वर्षों के दौरान चक्रवात अपेक्षाकृत निम्न अक्षांशों पर बनते देखे गए हैं । ये चक्रवात पश्चिमी दिशा की ओर और आगे बढ़ते हुए पाए गए हैं, जिन्होंने तमिलनाडु औंर दक्षिणी आंध्र प्रदेश के तट को पार किया जिसके कारण ई एन एस ओ वर्षों के दौरान प्रायद्वीपीय क्षेत्र में अपेक्षाकृत अधिक वर्षा हुई है । प्रति ई एन एस ओ वर्षों में रिज लाइन 200 hPa पर अवस्थित थी जबकि ई एन एस ओ वर्षों के दौरान तुलनात्मक रूप से यह 3° दक्षिण में स्थित थी ।

ABSTRACT. Northeast monsoon precipitation data of 5 meteorological sub-divisions in India, spanning the period 1901-97, were analysed to identify the effect of ENSO/Anti ENSO events on the rainfall over southern peninsular India. ENSO/Anti ENSO years were selected on the basis of seasonal Southern Oscillation Index (SOI). The analysis revealed that ENSO years were generally associated with enhanced northeast monsoon precipitation while there was reduced precipitation during Anti ENSO years, the reduction in Anti ENSO years being significant for Tamil Nadu (at 0.1% level), for Kerala (at 1% level) and for South Peninsular India (at 1% level). Of 22 ENSO years, 18 years were found to be either flood or wet years, while 11 years out of 15 Anti ENSO years were found to be either drought or dry years.

During ENSO years, the Sea Surface Temperature (SST) anomalies both over the Arabian Sea and the Bay of Bengal were positive during the months October to December, while the reverse was the case during Anti ENSO years. A concurrent significant positive correlation was noted between SST over east central Arabian Sea and the northcentral Bay regions and northeast monsoon rainfall.

The cyclonic systems were observed to form relatively at lower latitudes during ENSO years as compared to those during Anti ENSO years. These systems were also found to move in a more westerly direction, hit Tamil Nadu and south Andhra coast, thus giving more rain over peninsula during ENSO years. The ridge line at 200 hPa level during ENSO years was located 3° south as compared to its location during Anti ENSO years.

Key words — Northeast monsoon, ENSO, Anti ENSO, Southern Oscillation Index, Rainfall.

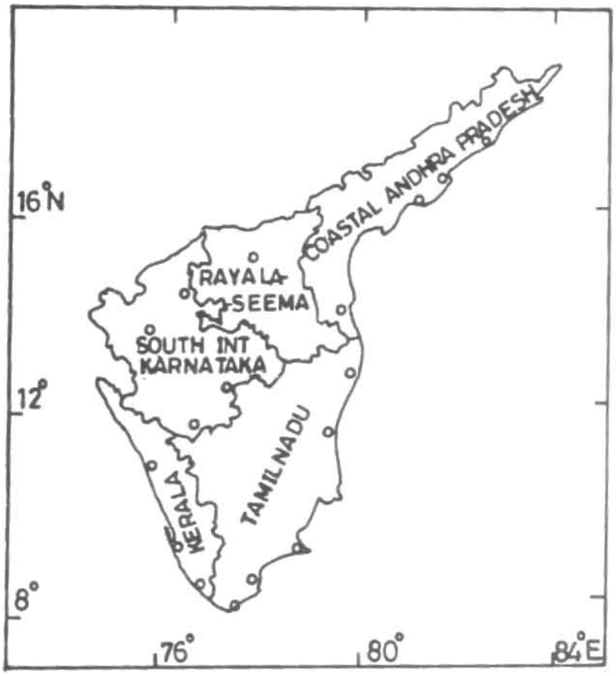


Fig. 1. Locater map

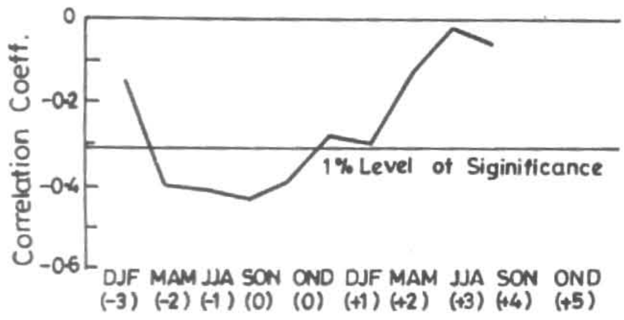


Fig. 2. Correlation analysis of northeast monsoon rainfall and seasonal SOI. (–) indicates previous season, (0) indicates congruent season and (+) indicates succeeding season

1. Introduction

"El-Nino" is the term that is used for an oceanographic phenomenon: an extensive warming of the upper ocean in the equatorial eastern Pacific lasting three or more seasons. The negative or cooling phase of El-Nino is called La Nina. El-Nino events are linked with a change in atmospheric pressure known as the Southern Oscillation (SO). This is characterized by a see-saw in the atmospheric pressure between the western and central regions of the Pacific Ocean, with one centre of action located in the vicinity of Indonesia and the other centre located over the central Pacific Ocean. The index that measures the magnitude of the SO is known as the Southern Oscillation Index (SOI). As the SO and El-Nino are so closely linked with each other, they are collectively known as El-Nino Southern Oscillation, or "ENSO". The system oscillates between warm (El-Nino) to neutral (or cold) conditions with a natural periodicity of roughly 3-4 years between El-Nino events.

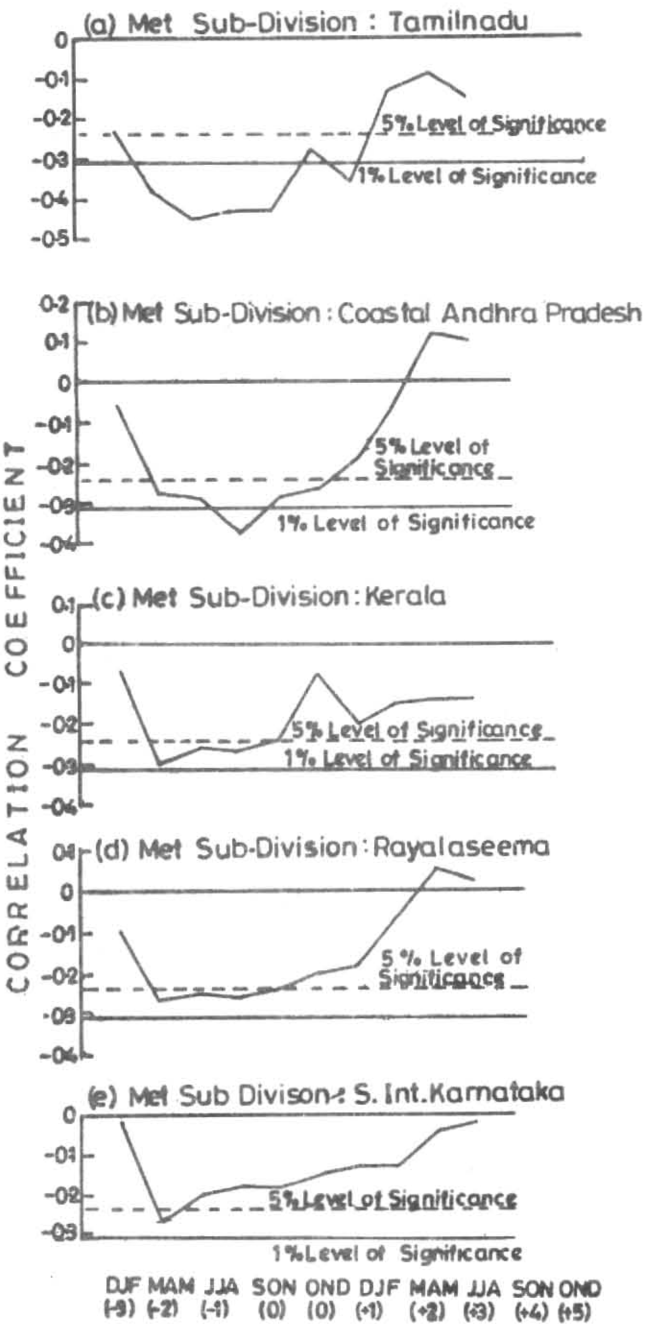
1997 was one of the severest ENSO events of the century, but southwest monsoon rainfall over the country was 102% of long term average, while the 5 southern sub-divisions received 498.0 mm rain during northeast monsoon season which is 124% of long term median value. This has raised many scientific questions. The paper's aim is to examine the long term behaviour of northeast monsoon and rainfall over southeast peninsular India during ENSO and Anti ENSO years.

Many studies have documented the relationship between SO and Indian summer rainfall across the Indian subcontinent (Sikka1980; Rasmusson and Carpenter 1983; Shukla and Paolino 1983; Parthasarthy and Pant 1985; Mooley 1997). Though the SOI is not the only factor influencing monsoon precipitation over the Indian subcontinent (Hastenrath 1987; Shukla and Mooley 1987), a close association between summer monsoon rainfall and SO is clearly evident in the precipitation distribution. The relationship between SO and northeast monsoon rainfall has not received much attention as compared to the summer monsoon. However, strong SOI precipitation relationship has also been found across extreme south India and Sri Lanka during October to December season (Ropelewski and Halpert 1987).

In India, the term northeast monsoon is often used to describe the period October to December. This is the period of major rainfall for particularly the eastern half of southern peninsular India. The coastal districts of Tamil Nadu receive 60%, while the interior districts get 40-50% of their annual rainfall during this period. Meteorological sub-divisions such as Tamil Nadu, Coastal Andhra Pradesh, Rayalaseema, South Interior Karnataka and Kerala experience the northeast monsoon (Srinivasan and Ramamurthy 1973a). The main objective of this study is to examine the modulation of northeast monsoon rainfall with the changes of SOI.

2. Data and methodology

The annual cycle of the pressure at each station, Darwin and Tahiti, is removed by forming anomalies from long term monthly averages. These monthly anomalies are then normalized by appropriate monthly standard deviation to produce the monthly standardized index. The difference of these standardized values: Standardized Tahiti minus Standardized Darwin is itself standardized. These data are obtained from Climate Analysis Centre (CAC), USA, and monthly climate data of the world published by National Climate Data Centre, NOAA, Asheville.



Figs. 3(a-d). Correlation analysis of northeast monsoon rainfall and seasonal SOI (–) indicates previous season, (0) indicates congruent season and (+) indicates succeeding season

Monthly rainfall data for the period October-December for 5 meteorological sub-divisions (Fig. 1) of the southern peninsular India for the period 1901-97 have been obtained from India Meteorological Department, Pune. With the help of these monthly rainfall data, the area weighted average rainfall series was prepared.

Different authors have selected the ENSO/Anti-ENSO events based on a number of factors, *e.g.*, Sea Surface Temperature Anomaly (SSTA) over eastern Pacific (Quinn *et al.* 1978; Rasmusson and Carpenter 1982) and Southern Oscillation Index (SOI) [Halpert and Ropelewski (1992)]. Therefore, a disagreement prevails among the scientists about the ENSO/Anti-ENSO years (Chattopadhyay and Bhatla 1996 ; Mooley and Paolino 1989). Hence, in this study ENSO/Anti-ENSO years are identified with the help of seasonal SOI. According to Caviedes (1985) SOI is the best parameter to identify the inception, maturity and decline of ENSO events.

3. Identification of ENSO/Anti-ENSO years

Usually ENSO/Anti ENSO event is a long duration (12-18 months) phenomenon. Yang and Webster (1990) defined El-Nino and La-Nina winters as the three months of December to February. In the present study the winter is defined as December to February.

3.1. *Correlation between seasonal SOI and northeast monsoon precipitation*

To identify the appropriate season to define ENSO/Anti ENSO years, a correlation analysis of the combined area weighted rainfall of five meteorological subdivisions during the period October to December is first done with the seasonal SOI series starting from previous winter December to February (DJF) to succeeding post monsoon season October - December (OND) as shown in Fig. 2. The analysis has been done on the basis of 1933 to 1996 data. The significant correlation can be observed from the previous premonsoon season, March to May [(MAM) (-2)] till the concurrent OND(O) (Fig. 2). The maximum correlation -0.43 (significant at 1% level) is observed during the simultaneous season September to November [(SON)(0)]. The simultaneous significant correlation shows that ENSO will have some impact if and only if it continues during the post monsoon season. It might have started since the previous premonsoon and continued during the post monsoon or it might have developed during the post monsoon season only but in the latter case it should continue till December.

Chattopadhyay and Bhatla (1996) using the same Tahiti-Darwin SO index found similar type of relationship between SOI and the Indian summer monsoon rainfall. In their study the maximum correlation 0.54 is noted between the Indian summer monsoon rainfall and the SOI during the succeeding season September to November. However, significant correlation 0.44 and 0.40 are also observed by them for the season July-September and June-August respectively. This shows that SOI for the season September - November is not only significantly correlated with northeast monsoon rainfall but also with the summer monsoon rainfall. Only difference is that in the case of northeast monsoon rainfall the correlation is negative, while for the summer monsoon rainfall the correlation is positive.

TABLE 1

ENSO and Anti ENSO years

	ENSO years	
1902	1905	1911
1914	1918	1923
1925	1930	1932
1939	1940	1946
1953	1957	1963
1965	1972	1976
1977	1982	1987
1997		
	Anti ENSO years	
1909	1915	1917
1924	1928	1942
1947	1955	1964
1970	1973	1975
1983	1988	1995

TABLE 2

Mann whitney rank statistics for precipitation amount during ENSO and Anti ENSO years

Meteorological sub-division	Mean rainfall		R_1	U_1	Z_1	Level of significance of Z_1
	ENSO years	Anti ENSO years			Standardized U_1	
Southern Peninsular India	410	306	515	262	3.00	1%
Tamil Nadu	581	398	549	296	4.05	0.1%
Coastal Andhra Pradesh	369	296	468	215	1.54	Not significant at 5%
Kerala	610	471	504	251	2.66	1%
Rayalaseema	244	190	471	218	1.64	Not significant at 5%
South Interior Karnataka	258	206	477	224	1.83	Not significant at 5%

Note : $E(U_1) = 165$; S.D. $(U_1) = 32.32$

3.2. *Correlation between seasonal SOI and northeast monsoon rainfall of individual meteorological sub-divisions*

The correlation analysis of the seasonal SOI with the area-weighted rainfall of individual met. sub-division affected by northeast monsoon is presented in Figs. 3(a-e).

Significant correlation between seasonal SOI and the area- weighted precipitation has been observed for the meteorological sub-division Tamil Nadu and Coastal Andhra Pradesh (Figs. 3a and 3b respectively). These relationships are found to be progressively decreasing as we go inland *viz.* met. sub-divisions of Rayalaseema and South Interior Karnataka (Figs. 3d and 3e respectively). The correlation again increases for Kerala (Fig. 3c). This shows that the effect of the SOI on northeast monsoon precepitation is more pronounced for the met. sub-division situated near the coast.

3.3. *Criteria for identification of ENSO and Anti ENSO years*

In the present study the ENSO and Anti ENSO years are selected on the basis of seasonal SOI during the period SON (-1) to SON (0). SON (-1) indicates the previous post monsoon season, while SON (0) indicates the congruent post-monsoon season. It has been observed that seasonal SOI varies from year to year and from season to season. The standard deviation of the seasonal SOI is found to be on an average 1.5 hPa. We have already seen that the maximum correlation between the seasonal SOI and the northeast monsoon precipitation occurred for the congruent season September to November [SON (0)]. Hence the criteria for the ENSO and the Anti ENSO event, has been fixed on the basis of SOI of SON (0). For the ENSO year, SOI of SON(0) must be negative and reverse will be the case for Anti ENSO year, provided that the seasonal SOI should progressively fall (rise) for atleast three consecutive seasons and the total fall (rise) should be less than (greater than) one standard deviation which is 1.5 hPa. On the basis of this criteria, years have been identified as ENSO/Anti ENSO years (Table 1).

Years, thus identified as ENSO/Anti ENSO years, are in good agreement with the years identified by Ropelewski and Halpert (1987); Chattopadhyay and Bhatla (1996); Van Loon and Shea (1985) and Mooley and Paolino (1989). This confirms that the criteria, chosen for identification of ENSO and Anti ENSO years, is based on a sound scientific footing.

3.4. *Variation of seasonal SOI during ENSO and Anti ENSO years*

Fig. 4. shows the mean seasonal SOI during the ENSO/Anti ENSO years. It can be seen that during the ENSO year the mean seasonal SOI starts decreasing from the season DJF(0). It continues its decreasing phase till the

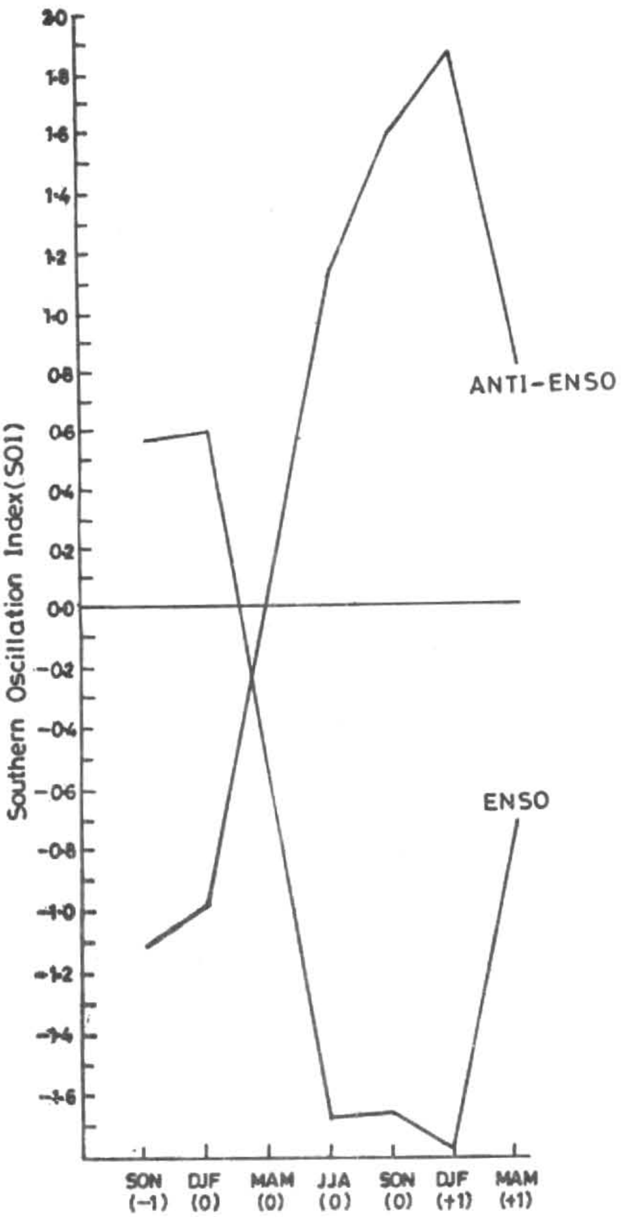


Fig. 4. Mean SOI, in ENSO and Anti ENSO years. (0) indicates season of ENSO/Anti ENSO years, and (+1)/((-1) indicate season of the following/preceding year

DJF(+1). The total fall succeeding the seasonal SOI from DJF(0) to DJF(+1) is found to be 2.4 hPa. Reverse pattern is observed for the Anti ENSO years and total rise from DJF(0) to DJF(+1) is found to be about 2.8 hPa. Though the total rise of the seasonal SOI during the Anti ENSO years is comparatively more than the total fall of the seasonal SOI during the ENSO years, there is rapid fall of SOI during the initial season of the ENSO year than that of Anti ENSO years.

4. Northeast monsoon precipitation-distribution

Rainfall data of October to December for the period 1901 to 1997 of 5 meteorological sub-divisions under study and the southern peninsula as a whole are subjected to normality test by using Fisher's g_1 and g_2 statistics (Fisher, 1930) and comparing them with their standard error. It was found that the rainfall series of all 5 meteorological sub-divisions under study and southern peninsula as a whole are more or less normally distributed.

4.1. *Area average northeast monsoon precipitation distribution*

In order to examine the influence of the SO on the precipitation, a non-parametric test "Mann-Whitney Rank Statistics" test has been applied to the area-weighted rainfall series associated with ENSO and Anti ENSO years of 5 meteorological sub-division and the southern peninsular India. Test statistics U is given by

$$U_1 = R_1 - \frac{n_1 (n_1 + 1)}{2}$$

or

$$U_2 = R_2 - \frac{n_2 (n_2 + 1)}{2}$$

Where,

U_1 = test statistics of the ENSO years;

U_2 = test statistics of the Anti ENSO years;

n_1 = no. of observations of ENSO years' precipitation;

n_2 = no. of observations of Anti ENSO years' precipitation;

R_1 = sum of the ranks of precipitation during ENSO years in combined sample;

R_2 = sum of the ranks of precipitation during Anti-ENSO years in combined sample.

According to Keeping (1962), when n_1 and n_2 are moderately large (9 or more), the sampling distribution of U_1 and U_2 are approximately normal. In the present study, $n_1 = 22$ and $n_2 = 15$, hence the distribution of U_1 and U_2 can be taken to be near normal. Statistical texts, (Keeping 1962), state $E(U_1)$ = Mean of $U_1 = \frac{1}{2}\, n_1 \; n_2$; Variance of $(U_1) = \frac{(n_1\, n_2)}{12} \; (n_1 + n_2 + 1)$; Z_1 = Standardized $U_1 = \frac{[U_1 - E\ (U_1)]}{S.D.\ of\ U_1}$; If Z_1 numerically exceeds 1.96, 2.58, 3.29 and is positive then the rainfall of the ENSO years is higher than that of Anti-ENSO years at 5%, 1% and 0.1% levels of significance respectively.

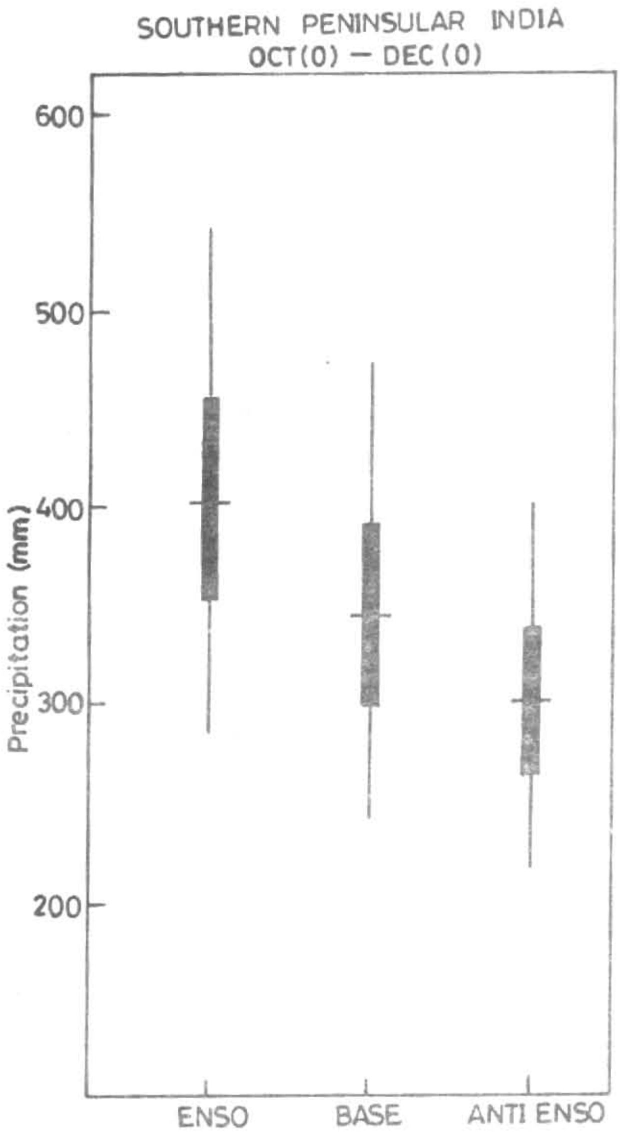


Fig. 5. Precipitation distribution for (from left to right) ENSO episodes, the base period, and Anti ENSO episodes for northeast monsoon. The horizontal line on each solid box represents median (50th percentile) precipitation amounts, each solid box delineates the 70th (top) and 30th (bottom) precipitation percentiles. The end points of the vertical line delineates the 90th and 10th percentile values

The results of the test applied to U_1 are presented in Table 2. This table brings out clearly that while the level of northeast monsoon rainfall for south Peninsular India and for each of its five component sub-divisions is higher in ENSO than that in Anti-ENSO, the level is significantly higher for Tamil Nadu (significant at 0.1%) and Kerala (at 1%), the two southernmost sub-divisions of India, and for south Peninsular India (at 1%). The significance for south Peninsular India is apparently due to high significance for Tamil Nadu and Kerala.

The mean precipitation of 410 mm for south Peninsular India for ENSO years is found to be higher by 104 mm than that for Anti-ENSO years. This shows a shift towards wetter condition in association with ENSO year (Fig. 5).

Similar results were reported by Ropelewski and Halpert (1996) in the precipitation of Sri Lanka and neighbouring southeast Indian Peninsula during the northeast monsoon.

A shift towards the wetter condition during ENSO years and towards the drier condition during Anti-ENSO years is noticed in the case of meteorological sub-divisions *viz.*, Tamil Nadu, coastal Andhra Pradesh and Kerala (Figs. 6(a-c) and Table 2), while for the meteorological sub-divisions Rayalaseema and South Interior Karnataka, the influence of the extreme SO is comparatively weaker than that for the other 3 meteorological sub-divisions (Figs. 6d & 6e).

4.2. *Relationship between ENSO/Anti ENSO events and abnormal northeast monsoon rainfall*

If the flood year/wet year is considered as a year of having precipitation amount greater than 90th percentile/less than 90th percentile but greater than 70th percentile of the rainfall distribution respectively, it is observed that out of 22 ENSO events, 7 years (32%) are associated with floods, while 4 years (18%) are associated with wet years. Whereas, in the case of Anti ENSO events, not a single year is found to be a flood year and only one (7%) is associated with wet for the southern peninsular India (Table 3).

Similarly if the year having the precipitation amount less than 10th percentile/greater than 10th percentile but less than 30th percentile of the rainfall distribution is considered as a drought/dry year respectively, it is observed that during the ENSO year not a single year is found to be associated with drought and only three years (14%) were associated with dry years.

In the case of Anti ENSO event, 3 years (20%) are associated with drought years, while 5 years (33%) are associated with dry years (Table 3).

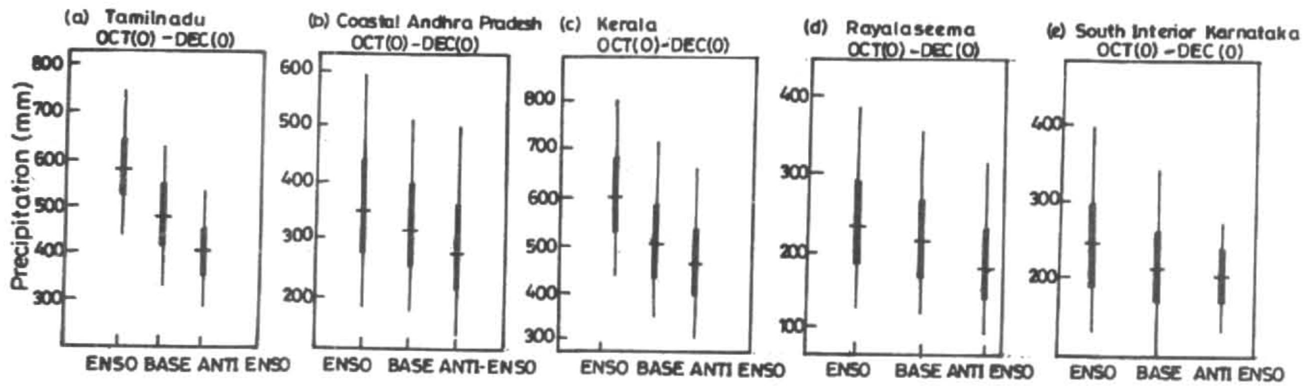
Hence it may be inferred that ENSO years are usually associated with flood and wet years, while Anti ENSO years are associated with drought and dry years, flood/wet and drought/dry years being as defined above.

4.3. *Spatial pattern*

The relationship of SO and precipitation has been shown by the examination of the precipitation distribution as presented in Section 4.2. However, spatial pattern of SO related precipitation shift is observed with the help of the analysis of the precipitation data of the individual stations. The median precipitation amount associated with ENSO (Anti ENSO) years are computed for the season October (0) - December (0) for each station in the met. sub-division under study. These median amounts are then compared with the individual station precipitation amount for the entire period, normally 1901-92, and the difference in the median

TABLE 3
Probability of occurrence of abnormal rainfall years

Region	ENSO events				Anti ENSO events			
	Flood year (%)	Wet year (%)	Drought year (%)	Dry year (%)	Flood year (%)	Wet year (%)	Drought year (%)	Dry year (%)
Southern Peninsular India	32	18	0	14	0	7	20	33
Tamil Nadu	41	14	0	4	7	0	20	40
Coastal Andhra Pradesh	14	32	14	4	0	33	20	7
Kerala	23	36	4	4	0	20	13	27
Rayalaseema	14	32	9	9	7	7	7	27
South Interior Karnataka	27	23	9	9	0	13	7	7

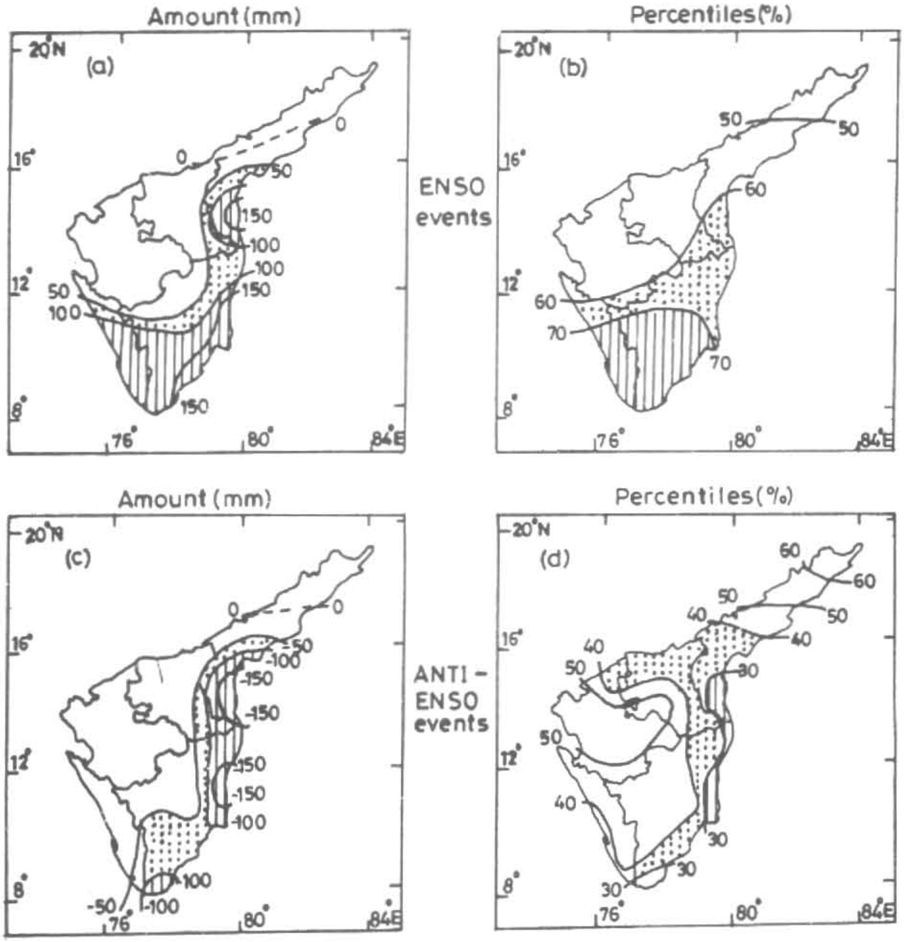


Figs. 6(a-e). Precipitation distribution for (from left to right) ENSO episodes, the base period, and Anti ENSO episodes for northeast monsoon. The horizontal line on each solid box represents median (50th percentile) precipitation amounts, each solid box delineates the 70th (top) and 30th (bottom) precipitation percentiles. The end points of the vertical line delineates the 90th and 10th percentile values

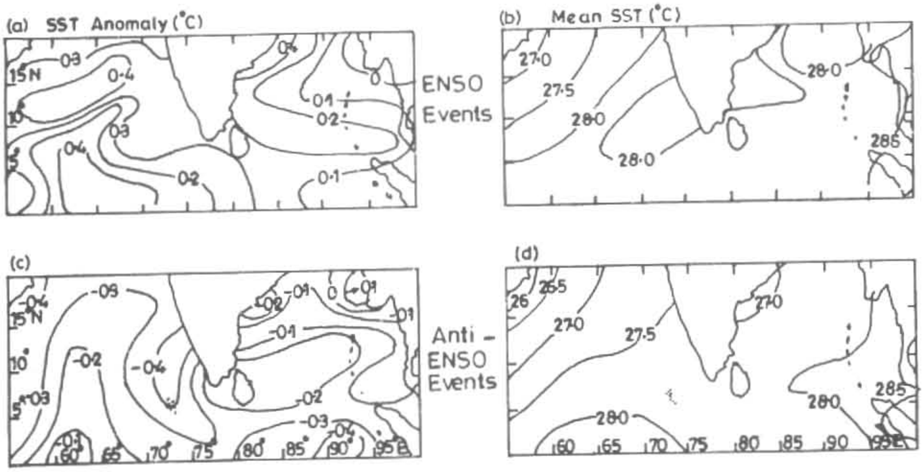
amount is plotted. In addition, for each station SO related median is expressed as a percentile value with respect to base period distribution. This may be interpreted as precipitation percentile *i.e.* expected with SO episode. One advantage of this analysis is that percentile shift, in SO precipitation relationship are more spatially coherent than the actual rainfall anomalies. Thus for the quantification of the spatial shift in the SO related precipitation, probability distribution based on the historical record may be useful tool for those interested in SO precipitation relationship as an aid to long range weather forecast. Fig. 7 shows the spatial distribution pattern. It has been noted that in association with ENSO (low SOI) condition, median precipitation amount ranges from 18-175 mm greater than the normal for October (0) - December (0) season. This pattern may also be interpreted as ENSO conditional climatology for October through December season. Analysis shows large shifts in median precipitation towards Tamil Nadu coast as well as south Coastal Andhra Pradesh. During ENSO event (low SOI) larger areas of south Tamil Nadu and Kerala show more than 100 mm increase in the median precipitation (Fig. 7a). Southern parts of Coastal Andhra Pradesh also show an increase of 150 mm compared to median precipitation. In the case of met. sub-division, South Interior Karnataka, Rayalaseema and northern portion of Coastal Andhra Pradesh, the increase in the median precipitation is small. Furthermore, at the extreme northern part of the Coastal Andhra Pradesh, the precipitation amount instead of increasing actually decreased, compared to the long term average. The largest ENSO episode related increase in the median (to 70th percentile) occurs over the southern part of India (Fig. 7b). During the Anti ENSO year (high SOI) over the large portion of the east coast covering Tamil Nadu and south Coastal Andhra Pradesh, there is a decrease of 150 mm in the median precipitation (Fig. 7c). Decrease in median precipitation (to 30th percentile) also occurs over the same area. Similarly northern parts of Coastal Andhra Pradesh, increase in the precipitation amount compared to base period has been observed. The above analysis indicates that the spatial effect of ENSO/Anti ENSO related precipitation is mostly confined to the parts of the met. sub-divisions Tamil Nadu, Kerala and southern parts of Coastal Andhra Pradesh, while no significant relationship of increase/decrease of the median precipitation associated with extreme SO has been observed over South Interior Karnataka and Rayalaseema.

5. Sea surface temperature (SST) over the Indian seas during extreme SO conditions

A link between interannual variation in Indian SST and the intensity of the Indian summer monsoon circulation and the associated rainfall has been examined by the number of authors (Saha 1970, 1974; Shukla and Misra 1977;



Figs. 7(a-d). Shifts in the median precipitation associated with the southern oscillation for the peninsular India October(0) - December(0) (upper-panels) in association with ENSO (low SOI) condition expressed as (a) amounts (mm) and (b) shifts in the median precipitation expressed as percentile of the base-precipitation distribution and (lower-panels) in association with Anti ENSO (high SOI) conditions expressed as (c) anomalous amount (mm) and (d) shifts in the median precipitation expressed as a percentile of the base period distribution



Figs. 8(a-d). SST(°C) and its anomaly for the months October (0) to December (0) during ENSO/Anti ENSO events

TABLE 4
Number of cyclonic systems

	Bay of Bengal				Arabian Sea			
	Dep.	C.S.	S.C.S.	Total	Dep.	C.S.	S.C.S.	Total
ENSO Years[21]	35	24	22	81 (3.8)	12	6	8	26 (1.2)
Anti ENSO years[14]	23	15	21	59 (4.2)	4	2	2	8 (0.6)

NOTE : Figures in [ ] show the number of cyclonic systems per year.

Raghavan *et al.* 1978). In order to find out the cause of enhancement of the precipitation related with extreme SO, monthly SST of October to December for the period 1950-80 at 5°×5° grid in the domain of 0°-20°N and 55°- 100°E has been used for computing SST normal. With the help of this normal the composite SST anomaly patterns for ENSO and Anti ENSO year have been studied. The composite SST during ENSO and Anti ENSO year as well as SST anomaly are presented in Fig. 8. It can be seen that during the ENSO year SST anomalies over Arabian Sea and Bay of Bengal are positive during the months October to December. The maximum anomaly 0.4°C is noticed over central Arabian Sea, while over Bay of Bengal warming of SST of the order of 0.4°C can be observed near Andhra coast (Fig. 8a). These anomalies are found to be more than 1 S.D. over those areas. During the Anti ENSO year SST anomaly is found to be negative over both the Arabian Sea and the Bay of Bengal. The maximum negative anomaly -0.4°C occurred over southeast Arabian Sea while over Bay of Bengal the maximum negative anomaly (-0.4°C) is noticed over near the equator (Fig. 8c).

In order to see the further relationship of the SST with the rainfall, the correlation analysis between SST and southern peninsular Indian rainfall during the months October to December has been done and presented in Fig. 9. The significant positive correlation (significant at 5% level of significance) is noticed over east-central Arabian Sea and the north central Bay regions. The maximum correlation (0.40) is noted over these areas (Fig. 9). Shukla and Misra (1977) also found the positive and significant correlation coefficients between SST during July and rainfall over central and western India during August. Joseph and Pillai (1984) found that monsoon rainfall is negatively correlated with SST of the following post monsoon season at Selected Representative Areas (SRA), A (11.0°N, 59.5°E), B (14.0°N, 71.5°E) and C (11.0°N, 83.5°E). These SRA almost coincide with the areas of the significant correlation found in this study. Negative correlation found by Joseph and Pillai (1984) indicates that a poor monsoon, which is generally associated with ENSO events, warms significantly the Arabian Sea and the Bay of Bengal. Thus the positive SST anomalies as observed during ENSO events agree well with that of Joseph and Pillai (1984). Joseph *et al.* (1994) also inferred that the warm SST anomaly over

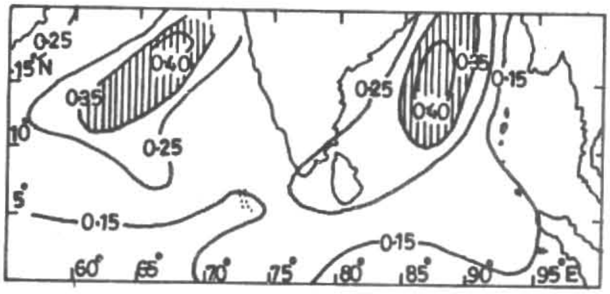


Fig. 9. Correlation analysis of SST anomaly and the rainfall of southern peninsular India during October-December. (Shaded area shows correlation significant at 5% level of significance)

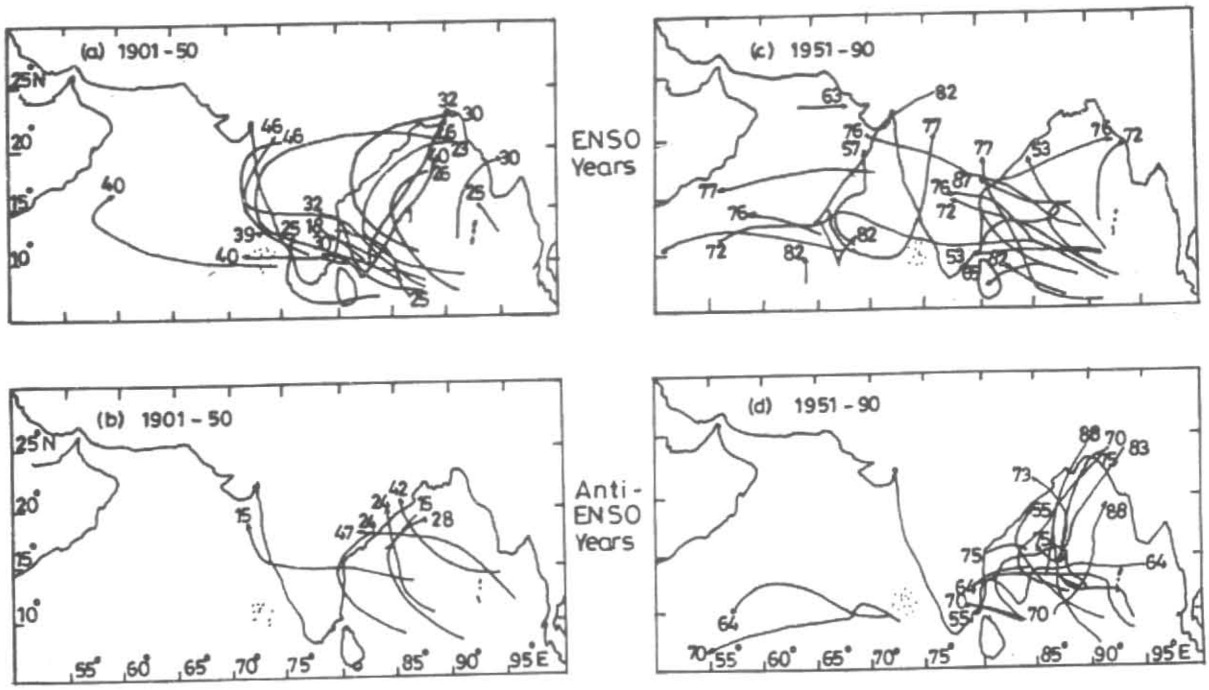
India and Pacific Ocean associated with El-Nino years either in congruent or succeeding year or in both cause the interannual variability of the monsoon onset over Kerala through the action affecting the time of northwestward movement of the Equatorial Convective Cloudiness Maximum (ECCM). They also found that the SST anomaly over the area bounded by 6°N - 18°N, 52°E - 76°E has a significant negative correlation (-0.21) with the monsoon onset over Kerala. According to them the warm SST anomaly is likely to be associated with delay of monsoon.

Mooley and Paolino (1989) concluded that the warming/cooling of equatorial southeast Pacific may appear to exert an adverse/favourable influence on the cyclogenesis over India and neighbourhood during monsoon season. De and Joshi (1997) also observed that the minimum number of cyclonic disturbances occurred during the decade 1911-20 and the frequent failure of monsoon occurred as a result of El-Nino. They noticed that maximum number of cyclonic disturbances occurred during the decade 1941-50 when in general the impact of the El-Nino on monsoon rainfall was the least.

6. Cyclogenetic activity over Indian Seas during ENSO and Anti-ENSO years

So far, it has been observed that during the ENSO years the precipitation pattern over the southern peninsular India shifts towards the wetter condition. The reverse is the case during the Anti ENSO years.

The frequency of cyclonic activity over the Indian Seas during the ENSO/Anti ENSO years, has been obtained from



Figs. 10(a-d). November tracks of cyclonic systems during ENSO/Anti ENSO years

"Tracks of Depression and Tropical Cyclonies over India" for the period (1901-90), published by India Meteorological Department and presented in Table 4.

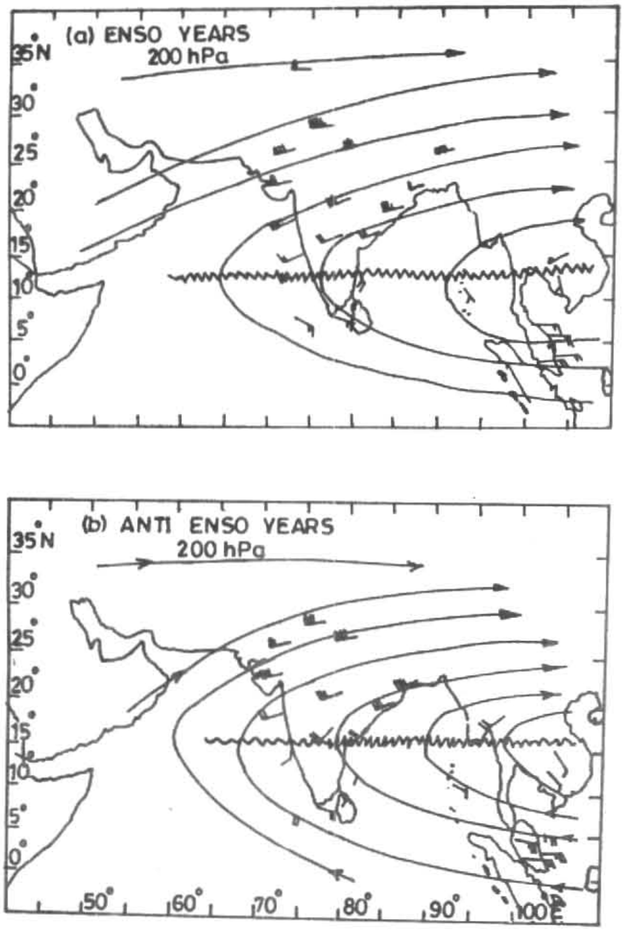
The long term normal of the number of cyclonic systems formed over the Bay of Bengal during October to December is 3.5 per year (Srinivasan and Ramamurthy 1973b). This long term normal over Arabian Sea is 0.5 per year. It is seen that, in all 81 systems formed over the Bay of Bengal during 21 ENSO years with a average number of systems formed 3.8 per year. During 14 Anti ENSO years 59 systems formed over the Bay and its average value per year is 4.2. This shows that the average cyclonic system during the Anti ENSO years is more than that of ENSO years. This is in conformity with findings of De and Joshi (1997). The reduction of cyclonic systems during ENSO years follows the same pattern as that observed in other parts of the World like Australian region (Nicholls 1985), northwest Pacific (Atkinson 1977) and north Atlantic (Gray 1984, 1988). It is noticed that during the ENSO year, number of cyclonic systems is same as the long term normal (3.5 per year) while during the Anti ENSO year there is a clear- cut increase of cyclonic systems compared to long term normal.

Over the Arabian Sea the picture is completely reversed. During the ENSO year 26 cyclonic systems formed with an average of 1.2 per year. This figure is more than twice the long term normal value (0.5), while during the Anti ENSO year, the average number of cyclonic systems per year is the same as that of the long term normal (Table 4). This shows that during the ENSO year the Arabian Sea is cyclogenetically more active than during normal year.

Number of cyclonic systems over the Bay of Bengal during October to December does not indicate the reduction/enhancement of the precipitation over southern peninsular India during Anti ENSO/ENSO years. But examination of the tracks of these systems during ENSO/Anti ENSO years clearly shows that during the ENSO years cyclonic systems follow more westerly path and cross Tamil Nadu and south Andhra coast (Fig. 10), thus giving an enhancement in the precipitation. This finding is in good agreement with Gupta and Muthuchami (1991). They observed that 87% cyclonic storms during El-Nino years crossed south of 17°N *i.e.* south Andhra Pradesh - Tamil Nadu coast. However, they have not studied the tracks of storm associated with Anti ENSO years.

In case of Anti ENSO year tracks of cyclonic systems follow more northerly direction and often recurved and hit West Bengal or Bangladesh coast (Fig. 11).

This can be further substantiated with the help of the three monthly composite flow patterns (OND) at 200 hPa level. This composite flow pattern for ENSO/Anti ENSO events has been prepared by taking five ENSO years (1972, 1976, 1977, 1982 and 1987) and five Anti ENSO years (1970, 1973, 1975, 1983 and 1988). These flow patterns are depicted in Fig. 11. During ENSO years, the ridge line at



Figs. 11(a&b). Composite wind pattern at 200 hPa level for October to December during (a) ENSO years (b) Anti ENSO years

200 hPa level is found to be at more southern latitutde (*i.e.* at 13°N) than that during Anti ENSO years (*i.e.* at 16°N).

So far the relationship of northeast monsoon rainfall over the peninsular India has been discussed. A question may arise what is the effect of SO over these areas during monsoon months June - September.

7. Summer monsoon precipitation over southern peninsula related with SO

The southern peninsula comprising of 5 meteorological sub-divisions receives 55% of the annual rainfall during summer monsoon season. The possible existence of a relationship between Indian summer monsoon rainfall and the phases of the ENSO has long been recognised and has been extensively studied (Bhalme and Mooley1980; Rasmusson and Carpenter 1983; Shukla and Paolino 1983; Yasunari 1990;. Webster and Yang 1992). Drought years over India are often but not always related to warm SST anomalies in the equatorial central and east Pacific and wet years with abnormally low SST. In other words weak monsoons were related to ENSO condition and strong monsoons to Anti ENSO conditions.

It has already been demonstrated that northeast monsoon precipitation is enhanced during ENSO years, while drier conditions are associated with Anti ENSO years. This suggests that there exists an inverse relationship between summer monsoon rainfall and northeast monsoon rainfall in these meteorological sub-divisions. In order to find out this inverse relationship the correlation analyses between summer monsoon precipitation and northeast monsoon precipitation of 5 meteorological sub-divisions have been done, both for ENSO and Anti ENSO years. These analyses show that significant (at 5% level) inverse relationship (CC, -0.50) during ENSO years exists for Coastal Andhra Pradesh only. During Anti ENSO years, significant inverse relationship (CC, -0.45) between summer monsoon rainfall and the northeast monsoon rainfall exists for Tamil Nadu only.

8. Conclusions

The following conclusions may be drawn from the above study.

(*i*) Significant negative correlation exists between seasonal SOI index and northeast monsoon rainfall over the southern peninsular India.

(*ii*) ENSO year is associated with enhanced northeast monsoon precipitation, while Anti ENSO year is associated with reduced precipitation. 50% of the wet/flood years are found to be associated with ENSO events, while 53% of the dry/drought years are associated with Anti ENSO events.

(*iii*) Significant positive correlation is observed between SST over east central Arabian Sea and the northcentral Bay and south peninsular Indian northeast monsoon rainfall.

(*iv*) The frequencey of cyclonic systems formed is smaller during the ENSO years compared to that during Anti ENSO years. However, during ENSO years these cyclonic systems follow more westerly path and cross Tamil Nadu and south Andhra Coast, thus giving an enhanced precipitation, while during Anti ENSO years, these cyclonic systems move in a more northerly direction and often recurve and hit either West Bengal or Bangladesh coast.

(*v*) Significant inverse relationship exists between summer monsoon and the northeast monsoon rainfall for coastal Andhra Pradesh only during ENSO years and for Tamil Nadu only during Anti ENSO years.

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