

## Relation between southern oscillation index and Indian northeast monsoon as revealed in antecedent and concurrent modes

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**सार** — इस षोडश-पत्र में तमिलनाडु के वर्ष 1901 से 2004 तक 104 वर्षों के मासिक/मौसमी माध्य एस. ओ. आई. और मासिक/मौसमी वर्षा आंकड़ों पर आधारित पूर्वगामी तथा समवर्ती प्रणालियों में दक्षिणी दोलन सूचकांक (एस. ओ. आई.) तथा भारतीय उत्तर पूर्व मानसून के बीच के संबंधों का अध्ययन किया गया है। इस अध्ययन से ज्ञात हुआ है कि एस. ओ. आई. और भारतीय उत्तर पूर्व मानसून के पूर्वगामी तथा समवर्ती प्रणालियों के बीच एक अच्छा ऋणात्मक संबंध रहा है जिसमें पूर्ववर्ती परवर्ती से अधिक प्रबल रहा है। समवर्ती प्रणाली में मौसम के आरंभ में प्रबल ऋणात्मक संबंध कायम रहता है जो मौसम के अग्रसर होने के साथ बदलता रहता है और मौसम के अंतिम समय में यह धनात्मक हो जाता है। इस प्रकार के संबंध में परिवर्तन की व्याख्या 200 हेक्टापास्कल उपोष्ण कटक (एस. टी. आर.) भूमध्य रेखीय द्रोणी के अक्षांशीय स्थितियों में भिन्नता और उत्तर पूर्व मानसून से लाभान्वित क्षेत्रों की स्थितियों के आधार पर की गई है। ऐसा देखा गया है कि धनात्मक (ऋणात्मक) एस. ओ. आई. पूरे वर्ष के दौरान एस. टी. आर. उत्तर (दक्षिण) की तरफ परिवर्तित होता रहा है। एस. टी. आर. की अक्षांशीय स्थिति और भारतीय उत्तर पूर्व मानसून वर्षा (एन. एम. आर.) के बीच के संबंध मौसम के आरंभ में ऋणात्मक रहते हैं और मौसम के अंतिम समय के दौरान धनात्मक हो जाते हैं। ऊपरी क्षोभमंडलीय पवन/तापमान की विभिन्नताओं और एन. एम. आर. के आपसी संबंधों से भी इसी प्रकार के सदृश संबंधों में परिवर्तन का पता चलता है। अक्टूबर माह में पश्चिमी पवन और ऋणात्मक तापमान में विभिन्नताओं का जनवरी माह में पूर्वी पवन और धनात्मक तापमान विभिन्नताओं में परिवर्तित होने की प्रक्रिया बहुत हद तक उत्तर पूर्व मॉनसून सक्रियता के अच्छे संकेत हैं। जैसे-जैसे मौसम आगे बढ़ता है एस. टी. आर. और एन. एम. आर. की अक्षांशीय स्थितियों के संबंधों में उत्क्रमण होता जाता है जिसे भ्रमिलता समीकरण के झुकावदार पद द्वारा सैद्धांतिक विचारों के आधार पर आंशिक रूप से प्रदर्शित किया गया है। इस प्रकार दक्षिणी दोलन सूचकांक से स्पष्ट हो जाता है कि भारतीय उत्तर पूर्व मॉनसून वर्षा एस. टी. आर. की अक्षांशीय स्थितियों में उतार-चढ़ाव के कारण होती है। श्रीलंका और दक्षिण पूर्व एशिया के कुछ स्टेशनों के षरद ऋतु के दौरान हुई वर्षा आंकड़ों का आस्ट्रेलियाई "रेनमैन" सॉफ्टवेयर के आधार पर विप्लेषण करने पर उनके संबंधों की प्राकृतिक परिवर्तनशीलता प्रमाणित होती है। एस. ओ. आई. के संबंध में भारतीय उत्तर पूर्व मॉनसून के आगमन तथा वापसी की तिथियों के अध्ययन से यह पता चला है कि सितम्बर माह में एस. ओ. आई. का सतत ऋणात्मक मान मानसून के बहुत जल्दी और अचानक वापसी को दर्शाता है। ऋतु समाप्ति के अंतिम चरण के दौरान एस. ओ. आई. का धनात्मक मान मॉनसून के बार-बार अधिक समय तक अर्थात् अगले वर्ष के जनवरी तक प्रभावी रहने का संकेत देता है।

**ABSTRACT.** The relation between Southern Oscillation Index (SOI) and Indian northeast monsoon has been studied in antecedent and concurrent modes based on monthly/seasonal mean SOI and monthly/seasonal rainfall data of Tamil Nadu for the 104 year period, 1901 to 2004. It has been found that a good negative relationship exists between the SOI and Indian northeast monsoon in antecedent and concurrent modes, the former being stronger than the later. In the concurrent mode, a strong negative relationship exists during the beginning of the season which changes as the season advances and turns positive during the fag end of the season. Such a changing nature of relationship is explained through the variation of latitudinal positions of 200 hPa Sub Tropical Ridge (STR) / Equatorial Trough (ET) and the location of these with reference to the latitudinal location of the area benefited by the northeast monsoon. It has been shown that a positive (negative) SOI shifts the STR north(south)wards throughout the year. The relationship between latitudinal position of STR and the Indian northeast monsoon rainfall (NMR) is negative during the beginning of the season and turns positive during the fag end of the season, which is similar to the relationship between SOI and NMR. The relation between upper tropospheric wind/temperature anomalies and NMR also shows a similar change in relationship. Westerly wind and negative temperature anomalies in October changing to easterly wind and positive temperature anomalies in January are by and large associated with good northeast monsoon activity. The reversal in the relationship between latitudinal position of STR and NMR as the season advances has also been partly explained based on theoretical considerations by invoking the tilting term of the vorticity equation. Thus the SOI appears to manifest itself on Indian northeast monsoon rainfall by way of modulating the latitudinal positions of STR. An analysis based on Australian

“Rainman” software on winter monsoon rainfall of some Sri Lankan and southeast Asian stations has substantiated the changing nature of relationship. A study of dates of onset and withdrawal of Indian northeast monsoon in relation to SOI has revealed that negative (positive) SOI in September is associated with early (late) onset. But, continuation of negative SOI throughout the season favours early and abrupt withdrawal. Positive SOI during the fag end of the season is frequently associated with extension of the monsoon into January of the next year.

**Key words** – Northeast monsoon, India, Tamil Nadu, ENSO, SOI, 200 hPa level, Sub Tropical Ridge, Equatorial Trough, Vorticity, Onset, Withdrawal, Correlation, Conditional mean.

## 1. Introduction

The Indian northeast monsoon is a small scale monsoon confined to parts of southern Indian peninsula, during the period October to December. It is characterised by seasonal reversal of surface and lower tropospheric winds from southwesterlies during the southwest monsoon season of June – September to northeasterlies which set in over the Indian region in October (IMD 1973 a&b). In a broader perspective, it is also associated with the northern hemispheric winter circulation dominated by a strong surface anticyclone (high) over Siberia, a primary low over eastern equatorial Pacific region and secondary shallow lows over the north Indian ocean. The winter monsoon circulation is characterised by a primary Hadley circulation feature between the Siberian high and the primary low over eastern equatorial Pacific region along with a secondary circulation feature between the Siberian high and the shallow lows over the north Indian ocean (Das, 1986). The onset of easterlies over the Indian region induces the northeast monsoon rainfall activity over the meteorological sub divisions of Tamil Nadu, Kerala, Coastal Andhra Pradesh (CAP), Rayalaseema and South Interior Karnataka of the southern peninsula (Raj, 1992). A synoptic/climatological overview is given in IMD (1973 a&b).

The Indian southwest monsoon is perhaps the best defined monsoon of the world. The inter annual variation of this monsoon and its relation with various global scale features such as El Nino and Southern Oscillation Index (SOI), together known as ENSO, have been studied extensively. Whereas detailed studies have been undertaken on the relation between Indian southwest monsoon and ENSO parameters in both antecedent and concurrent modes (Gowariker *et al.*, 1989 & 1991), similar studies on the smaller scale Indian northeast monsoon have started emerging in the last decade. The present study is aimed at further exploring the relationship that is known to exist between the ENSO parameters and the Indian northeast monsoon. The nature of relationship in the concurrent mode is studied in detail so that a broader and deeper understanding of the relationship between ENSO and Indian northeast monsoon could be established.

## 2. Relation between ENSO parameters and Indian southwest/northeast monsoons - Results from past studies

### 2.1. ENSO parameters

El Nino refers to abnormal increase of the sea surface temperature (SST) off the Peru coast of South America. The SST is monitored over four regions of the Pacific referred as Nino1+2, Nino 3, Nino 3.4 and Nino 4. Of the four Nino indices, Nino 3.4 is the most widely used index for studying the relation between El Nino and the Indian southwest monsoon. The SOI is taken as the see-saw like pressure oscillation between the eastern equatorial Pacific ocean and the south Indian ocean. The most widely used SOI is the standardised anomaly of the m.s.l. pressure difference between Tahiti (17° S, 150° W), an island located in the eastern equatorial Pacific and Darwin (15° S, 130° E), located in northern Australian coast. The m.s.l. pressures of these two stations are 180° out of phase. El Nino and SOI are highly negatively inter related.

### 2.2. Relation between ENSO and Indian southwest monsoon

Several studies have established that anti-ENSO events, *viz.*, negative SST anomalies over the Nino regions, also referred as La Nina, and positive SOI during March-September are associated with good Indian southwest monsoon rainfall (ISMR). Whereas ENSO events, *viz.*, positive SST anomalies over the Nino regions and negative SOI are associated with poor ISMR. The relationship however is comparatively stronger in the concurrent mode *i.e.*, between SOI (JJAS) and ISMR. But, in the antecedent mode, *i.e.*, relation between SOI (MAM) and ISMR is not that strong.

### 2.3. Relation between ENSO and Indian northeast monsoon

The following are some of the important studies hitherto undertaken on the inter annual variation of Indian northeast monsoon rainfall (NMR) with ENSO events :

**TABLE 1(a)**

**Monthly / seasonal normal rainfall of five southern Indian sub-divisions influenced by northeast monsoon**

Sub-division	Normal rainfall (mm) during					CV (OND) in %
	Oct	Nov	Dec	OND	Jan	
CAP	194.0	113.1	22.4	329.2	10.1	38.0
RS	122.4	78.1	24.1	224.8	7.0	39.6
SIK	150.9	60.0	14.2	225.0	3.6	36.0
TN	191.8	197.5	98.5	488.3	30.6	27.1
KER	297.6	179.1	46.8	523.8	14.8	27.5

(based on data of 1901-2000)

CAP: Coastal Andhra Pradesh; RS : Rayalaseema; SIK : South Interior Karnataka;  
 TN : Tamil Nadu; KER: Kerala; CV : Coefficient of Variation

**TABLE 1(b)**

**Mean January rainfall of some coastal districts of Tamil Nadu averaged over 23 years during 1901-2000 when the northeast monsoon season extended beyond first week of January**

District	Thiruvallur	Chennai	Cuddalore	Thanjavur	Thiruvarur	Nagapatnam	Ramanathapuram	Tuticorin
Rainfall (mm)	59.5	47.5	114.8	106.5	132.9	147.6	102.9	69.9

Sridharan and Muthuchami (1990) studied the variation of NMR in relation to El Nino using 114 year data (1875-1988) and have shown that normal to above normal rainfall is realised over Tamil Nadu during 93% of occasions of El Nino years. Jayanthi and Govindachari (1999), based on data of 1901-1996, have shown that Tamil Nadu received above normal rainfall in about 80% of El Nino years and in the remaining 20% years, rainfall recorded was well within the normal range. They have reported a correlation coefficient (CC) of 0.66 between northeast monsoon rainfall of Tamil Nadu and annual SST anomalies over the Nino 3.4 region, based on data of 1978-97. De and Mukhopadhyay (1999) have reported a simultaneous relation with a CC value of -0.43 (1% LS) between SOI and NMR during September to November. Khole & De (2003) have studied the variation of NMR of southern peninsula with El Nino and have shown that NMR is 11% higher than Long Period Average (LPA) during El Nino years and 6% lower than LPA during La Nina years.

*2.4. Relation between Indian southwest and northeast monsoons*

It has also been established that ISMR and NMR exhibit some sort of negative relationship, with the meteorological features that favour the former, by and large, not favouring the later and *vice-versa*. Hence, performance of southwest monsoon over India can

provide some pre indication of the ensuing northeast monsoon performance (Dhar and Rakheja, 1983 and Raj *et al.*, 2004).

**3. Scope of the present study**

While the studies listed in Section 2 clearly indicate that the ENSO phenomenon does have a bearing on NMR, there are other intriguing questions - such as (a) How the meteorological feature(s) prevailing during the northeast monsoon season over India are affected by the ENSO events and (b) Is the effect of the ENSO event uniform throughout the season – these are required to be looked into, in order to have a better understanding of the effect of ENSO on NMR. The present study is aimed at understanding the influence of ENSO parameters on the temporal variations (inter annual and intra seasonal) of NMR in both antecedent and concurrent modes with a lookout for a possible physical cause behind such a variation. The influence of ENSO during the onset and withdrawal phases of the Indian northeast monsoon is also studied.

**4. Data**

*4.1. Sub-divisional rainfall data*

Time series of sub-divisional rainfall of Tamil Nadu during October – January for 104 years (1901-02 to

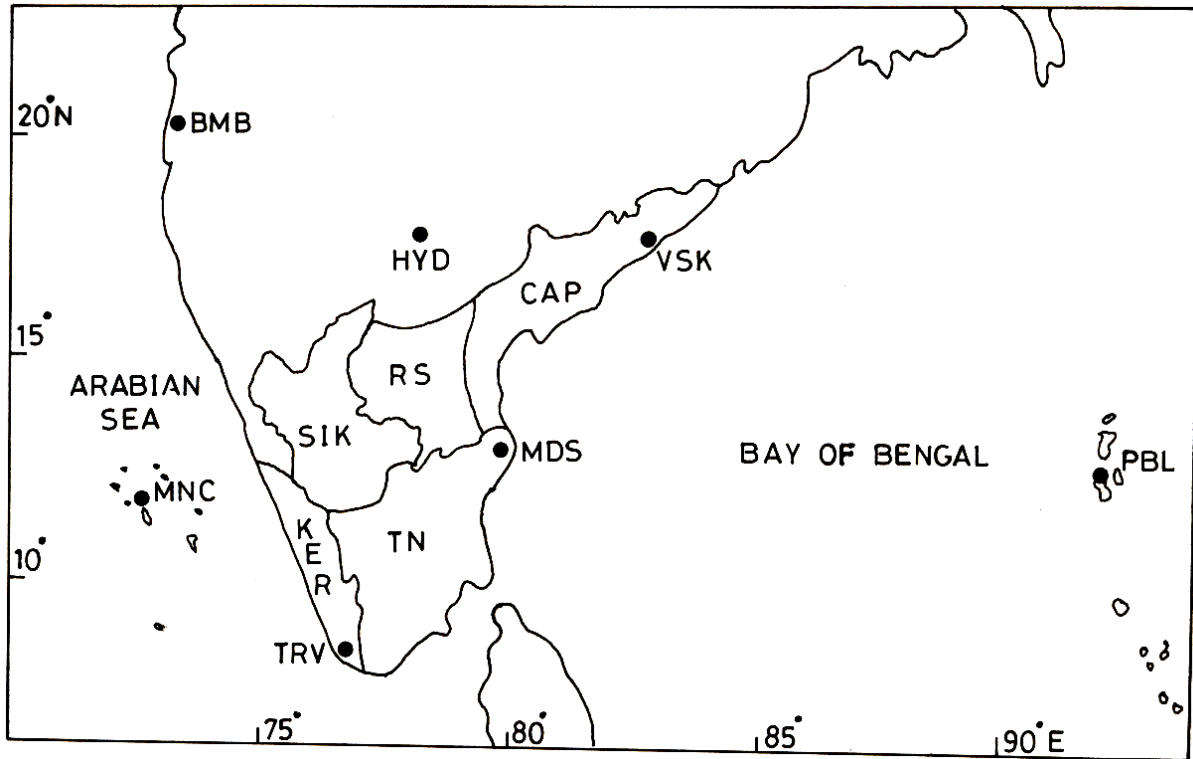


Fig. 1. Southern Indian sub-divisions influenced by northeast monsoon

2004-05) was utilised for the study. For the years from 1901 to 2003, homogeneous rainfall series prepared by the National Climate Centre, India Meteorological Department (IMD), Pune were used. Data for the years 2004 and 2005 were taken from the National Data Centre (NDC), IMD, Pune.

#### 4.2. Onset and withdrawal dates

Dates of onset and withdrawal of northeast monsoon over Tamil Nadu as determined in (Raj 1992, 1998 & 2003) have been taken for the period 1901-2000. For the years from 2001 to 2004, they have been independently determined by following the same criteria.

#### 4.3. SOI data

The most frequently used ENSO indices are the Nino 3.4 SST anomalies and the SOI. In the present study, the SOI is taken to represent the ENSO phenomenon. The monthly mean SOI data for the period 1901-2005 were taken from the SOI archives downloaded from the website of Australian Bureau of Meteorology, viz., [www.bom.gov.au/climate/current/soihtm1.shtml](http://www.bom.gov.au/climate/current/soihtm1.shtml). The SOI has been computed as,  $\frac{\text{m.s.l. pressure (Tahiti)} - \text{m.s.l. pressure (Darwin)}}{\text{standard deviation}}$  to

normalise the difference and multiplied by 10 to express it in full digits. Based on this definition, the SOI ranges from -35 to +35. Further details about the methodology of computation could be found in the above referred website.

#### 4.4. Upper air data over India

The 200 hPa level monthly mean temperature and wind data for the period 1963 to 2001 for each month and year of 14 upper air observatories of India (Delhi, Jodhpur, Lucknow, Guwahati, Ahmedabad, Nagpur, Bhubaneswar, Mumbai, Hyderabad, Visakhapatnam, Chennai, Port Blair, Minicoy and Thiruvananthapuram) were obtained from NDC, IMD Pune for subsequent analysis.

### 5. Methodology and analysis

#### 5.1. Normal NMR over the southern Indian Peninsula

Table 1(a) presents the mean and coefficient of variation of rainfall realised during the northeast monsoon season of the five major sub divisions of peninsular India (Fig. 1) influenced by the northeast monsoon activity. The

statistics have been generated from the sub divisional rainfall data of 100 years (1901-2000) archived by NDC, IMD, Pune. These statistics reveal that the rainfall activity is not uniform throughout the season with more than 80% of the seasonal rainfall realised during the period October - November itself in all the sub-divisions except for Tamil Nadu, where the rainfall continues in December and January also especially over the coastal regions.

In about one third of the years (36 out of 100 years during 1901- 2000), the northeast monsoon season spilled over to the month of January of the next calendar year (Raj, 2003). Even though the rainfall normal for Tamil Nadu in January is modest, coastal stations receive a normal rainfall of 7.5 to 11 cm. During the years when the season spills over to January of the next year, the realised rainfall in January in coastal Tamil Nadu is quite substantial. Table 1(b) presents mean rainfall (mm) received by selected coastal districts of Tamil Nadu averaged over the 23 years during 1901-2000 when the northeast monsoon season extended beyond the first week of January. It can be seen that the mean rainfall for January for such years for most of these coastal districts is as much as 10 to 15 cm.

Thus, Tamil Nadu is the major beneficiary and is the only sub division that receives rainfall throughout the season amongst the five sub-divisions influenced by northeast monsoon activity. The October-December rainfall of the southern region and Tamil Nadu are closely related with high CC of 0.87 (Raj *et al.*, 2004). The features of northeast monsoon are clearly defined over Tamil Nadu compared to other areas. The sub-divisional rainfall of Tamil Nadu is frequently taken as the index that well represents the northeast monsoon activity over the southern Indian peninsula. Therefore, in this paper, we will be using the time series of northeast monsoon rainfall of Tamil Nadu (NRT) only to study the inter annual and intra seasonal variation of this monsoon and the influence SOI exercises over such features.

5.2. *Relation between SOI and NRT in antecedent and concurrent modes*

The northeast monsoon seasonal/monthly rainfall of Tamil Nadu for 104 years (1901-02 to 2004-05) was correlated with seasonal/monthly SOI data in the antecedent and concurrent modes. The important results are presented in Table 2. It can be seen that SOI (JJAS) is significantly negatively correlated with NRT (OND) with a CC value of -0.38 as already reported by the earlier workers. Thus, SOI during the antecedent southwest monsoon season gives some pre-indication of the performance of the ensuing northeast monsoon.

TABLE 2

CCs between SOI and NRT in antecedent and concurrent modes

SOI (period)	NRT (period)	CC
JJAS	OND	-0.38**
Oct	Oct	0.00
Nov	Nov	-0.21*
Dec	Dec	-0.03
ND	ND	-0.24*
OND	OND	-0.33**
JF	JF	0.19 <sup>#</sup>
Oct	OND	-0.42 **
Oct	ND	-0.47 **
Oct	Nov	-0.44**
Oct	Dec	-0.18 <sup>#</sup>
Jan	Jan	0.18 <sup>#</sup>

(based on 104 year data from 1901-02 to 2004-05)  
 SOI: Southern Oscillation Index  
 NRT: Northeast monsoon rainfall of Tamil Nadu  
 CC: Correlation coefficient; \*\* : significant at 1% level;  
 \* : significant at 5% level; <sup>#</sup> : significant at 10% level

In the concurrent mode, the negative relationship between SOI(OND) and NRT(OND) is significant with a CC value of -0.33. Even though, the antecedent relationship between SOI (JJAS) and NRT (OND) is good, still higher CCs of -0.42, -0.47 & -0.44 are obtained between SOI (Oct) and NRT of OND, ND and November respectively testifying to the important role played by SOI (Oct) in modulating NRT. However, an examination of month by month relationship in the concurrent mode reveals that while there is little relationship between SOI and NRT in October, a modest negative CC of -0.21 is obtained for November. The relationship becomes insignificant in December (CC = -0.03) and then turns positive in January with a CC of 0.18 significant at 10% level. Even though only modest CCs are obtained in the month by month analysis, the striking feature that emerges is that the negative concurrent relationship existing between SOI and NRT during the beginning of the season does not continue throughout the season. The intensity of the relation decreases as the season advances and finally the relation turns positive towards the fag end of the season.

To get a better and further insight into the type of the relation that exists between SOI and NRT, we resort to computation of conditional means (CMs) of rainfall for various ranges of SOI. Such a simple analysis is capable of bringing out the non-linearity in the relationship as

TABLE 3

Conditional means of NRT for various SOI intervals in antecedent and concurrent modes

SOI Month/season	NRT Month/season	CC	Conditional means of NRT (PDN) for SOI intervals				
			<-10	-10 to -5	-5 to 5	5 to 10	>10
JJAS	OND	-0.38**	19	15	-3	-6	-19
Oct	Oct	0.00	0	3	-1	1	-3
Nov	Nov	-0.21*	3	23	-1	-16	-12
Dec	Dec	-0.03	-5	-1	19	-26	-7
OND	OND	-0.33**	14	14	-2	-10	-8
Oct	OND	-0.42**	22	3	-3	-11	-12
Oct	ND	-0.47**	37	3	-5	-19	-18
Jan	Jan	0.18 <sup>#</sup>	-48	-19	-9	29	34

PDN : Percentage departure from normal; SOI, NRT, CC, \*\*, \*, <sup>#</sup> : as defined in Table 2

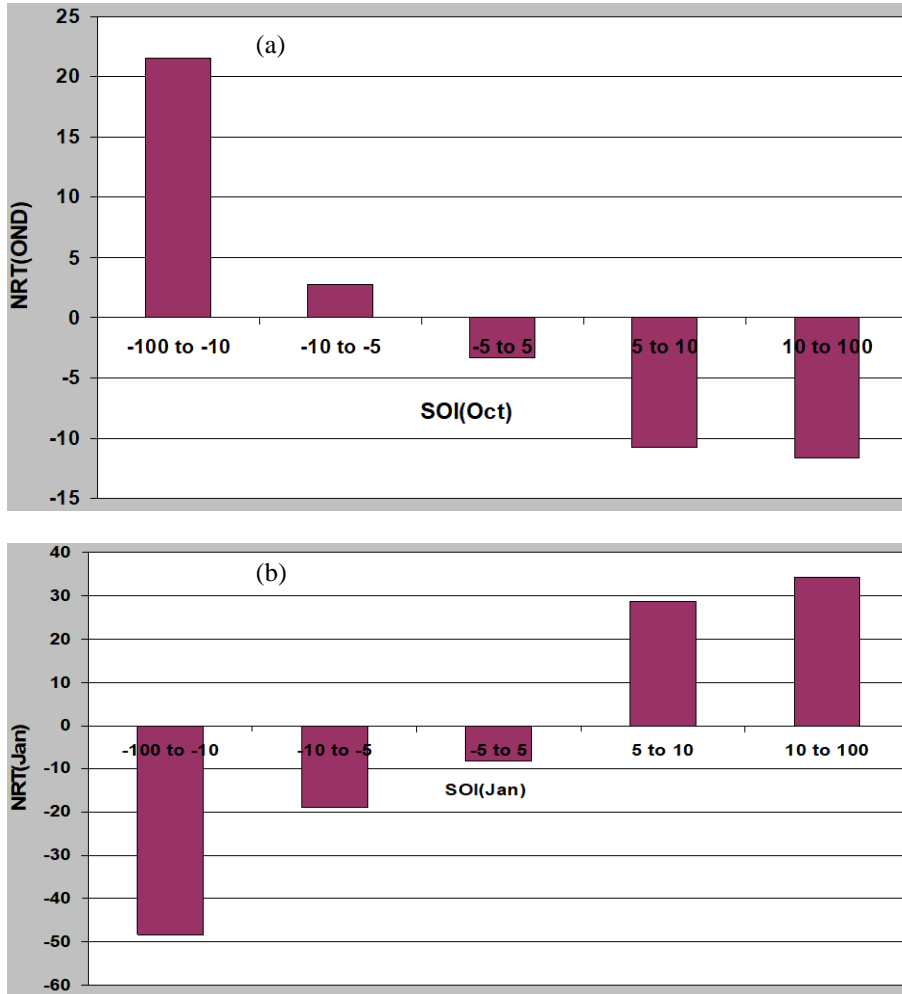
well. The CMs of the NRT as seasonal/monthly percentage anomalies were computed for the SOI intervals  $< -10$ ,  $-10$  to  $-5$ ,  $-5$  to  $5$ ,  $5$  to  $10$  and  $>10$ . Important results are shown in Table 3. It can be seen that very good antecedent negative relationship exists between SOI (JJAS) and NRT (OND); and also a good concurrent negative relationship between SOI (OND) and NRT (OND). Monthly analysis in the concurrent mode reveals that while SOI (Oct) does not give any signal on October rainfall, SOI  $< -10$  in October is associated with good positive departures of NRT (ND) and NRT (OND). During the months of November and December the highest conditional means of NRT have values of 23 and 19% (as percentage anomalies) respectively which are associated with SOI values of  $-10$  to  $-5$  in November and  $-5$  to  $+5$  in December. In January, the conditional means of NRT indicate clearly that good rainfall activity in January is associated with positive SOI. The CMs are 29 and 34% when SOI (Jan) lies in the interval  $5$  to  $10$  and  $>10$  respectively. This pattern based on computation of CMs bring out the changing nature of relationship between SOI and NRT much more clearly than the analysis based on linear correlation. Thus, it is shown that a pattern of SOI, whereby negative SOI in October slowly increasing and changing into positive in January, is more favourable for a good and sustained NMR rather than the pattern of negative SOI continuing throughout the season.

A plot of conditional means of NRT (OND) given SOI (Oct) and NRT (Jan) given SOI (Jan) for the various intervals of SOI presented in Figs. 2 (a&b) clearly bring out the reversal of relationship between SOI and NRT in the concurrent mode as the season advances from October to January.

### 5.3. Possible physical causes for the reversal of relationship between SOI and NRT in the concurrent mode

The analysis of section 5.2 has clearly brought out the changing nature of relationship between the SOI and NRT from significantly negative to slightly positive with the advancement of the season. The possible physical causes behind such a reversal could be of considerable scientific interest. SOI being a global atmospheric parameter with wider ramification, its variation is likely to be felt in the atmospheric flow pattern over the Indian region as well. The Sub Tropical Ridge (STR) at 200 hPa level which separates the mid-latitude westerlies in the north and the tropical easterlies in the south and the Equatorial Trough (ET) in the lower troposphere are two important features of the the tropospheric wind flow over India. Both these features are persistent over India throughout the year and their normal latitudinal movement during the year is in concert with the movement of the Sun.

When the Sun is at its northern most position with respect to the earth ( $23\frac{1}{2}^{\circ}$  N latitude in June), the STR at 200 hPa level is also located at about  $30^{\circ}$  N latitude. During the southward march of the Sun, the STR also moves southwards and is located at around  $8^{\circ}$  N in December/January when the Sun is at its southern most position ( $23\frac{1}{2}^{\circ}$  S latitude). By March/April, the northward march begins. Though the normal position of STR follows a specific pattern in relation to the Sun, there is significant inter annual variability owing to variations in the controlling atmospheric features.



**Figs. 2(a&b).** Conditional means of (a) NRT (OND) given SOI (Oct) and (b) NRT (Jan) given SOI (Jan) (NRT expressed as percentage anomaly)

It has been shown in Raj *et al.*, (2004) that positive temperature anomalies, negative zonal wind anomalies and northward location of the STR at 200 hPa level over India during the preceding months/seasons are associated with good southwest/poor northeast monsoons and the complement of the above with poor southwest/good northeast monsoons. It has also been shown that a southward location of the STR from its normal position, in October, favours a good northeast monsoon. These results compliment the well known concepts that, seasonal latitudinal movement of ET is in concert with the movement of STR and the zone of rainfall over India is governed by the latitudinal position and movement of ET.

A noteworthy feature of the climatology of movement of STR at 200 hPa level over India during the northeast monsoon season is its position in relation to the location of Tamil Nadu or other sub-divisions that benefit

from northeast monsoon rainfall. The monthly mean latitudinal positions of STR at 77.5° E for each year of 1963-2001 were derived in the present study by following the same methodology as elaborated in Raj *et al.*, (2004). The positions of the STR for the period 2002-2005 were obtained from the NCEP/NCAR reanalysis data for 200 hPa level from the website of NOAA. A 43 year data set *i.e.*, 43 × 12 matrix of monthly mean latitudinal positions of STR over India for 1963-2005 was thus generated. From this data set, the normal latitudinal position of STR for each month was computed and the values are given in Table 4.

The monthly normal latitudinal positions of the ET off the east coast of India were extracted from IMD (2003) which presents grid point values of normal wind vectors over the north Indian ocean sea surface. The normal latitudinal positions of the STR and ET thus

TABLE 4

CCs between SOI and latitudinal position of STR at 200 hPa level over India

SOI (month/season)	STR			CC
	Month/ season	Normal latitudinal position (°N)	S.D. (°Lat.)	
Jan	Jan	8.7	2.5	0.63**
Feb	Feb	8.5	2.7	0.67**
Mar	Mar	7.4	2.7	0.26
Apr	Apr	7.2	3.2	0.52**
May	May	14.3	2.3	0.37*
Jun	Jun	24.4	2.2	0.47**
Jul	Jul	33.5	2.4	0.31*
Aug	Aug	33.1	2.1	0.33*
Sep	Sep	24.5	1.7	0.41**
Oct	Oct	16.5	2.0	0.64**
Oct	OND			0.46**
Nov	Nov	12.7	1.5	0.37*
Dec	Dec	9.7	2.5	0.46**
JF	JF	8.8	1.7	0.68**
MAM	MAM	9.4	2.3	0.56**
JJAS	JJAS	28.4	1.5	0.57**
JJAS	OCT			0.66**
OND	OND	12.8	1.3	0.58**

(based on 43 year data from 1963-2005)

STR: Sub Tropical Ridge; S.D: Standard Deviation  
SOI, CC, \*\*, \* : as defined in Table 2

obtained for the period from October to January are presented in Fig. 3. As seen, the STR shifts from 16.5° N in October to 8-9° N in January/February and during this period the ET shifts from 13.8° N to near equator. By and large, the ET is located 3-4° latitude south of the STR on any given month.

At the time of normal northeast monsoon onset, *i.e.*, during the third week of October, the STR is located north of Tamil Nadu and the ET is located along the north Tamil Nadu latitudes. As the season advances, both the STR and the ET pass through the latitudes of Tamil Nadu and during the fag end of the season *i.e.*, during December/January, they are located south of Comorin (Fig. 3). Hence, during October when the STR is normally to the north of Tamil Nadu, its southward location is bound to be favourable for northeast monsoon rainfall activity over Tamil Nadu. However, during December/January when the normal position of STR is already

TABLE 5

Important CCs between monthly/seasonal NRT and the latitudinal position of STR at 200 hPa level

STR	NRT	CC
Oct	Oct	-0.14
Oct	Nov	-0.45**
Oct	OND	-0.39
Nov	Nov	0.13
Dec	Dec	0.36*
Jan	Jan	0.19
Jan	JF	0.24

(based on 42 year data from 1963-2004)

NRT, CC, \*\*, \* : as defined in Table 2

STR: as defined in Table 4

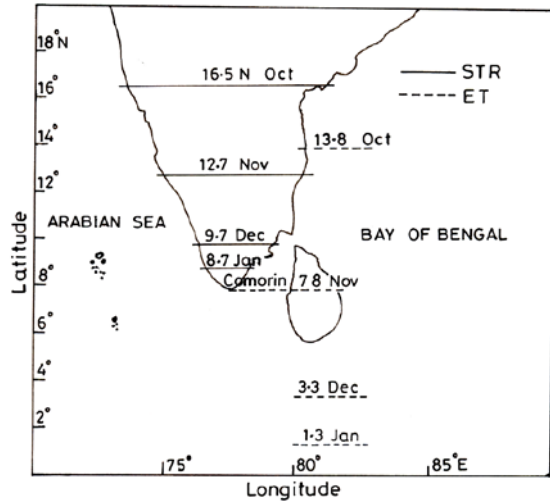
located south of Comorin, a further southward shift of it would not be conducive for rainfall activity over Tamil Nadu but a northward shift would be conducive. To connect such a pattern with the changing nature of relationship between SOI and NRT, relation between SOI and latitudinal position of STR needs to be analysed.

We now look into as to how the SOI modulates the transposition of STR over India and how STR is related to NRT. The CCs between monthly/seasonal latitudinal positions of STR with SOI for the period 1963-2005 in antecedent and concurrent modes were computed and details are presented in Table 4. It can be seen that significant positive CCs are obtained in the concurrent mode for almost all the months/seasons throughout the year. The CCs corresponding to the seasons vary between 0.56 to 0.66. Table 5 presents the important CCs between NRT and STR for the period 1963-2004. While good negative CC (-0.45) is obtained between STR (Oct) and NRT (Nov), the CC turns positive as the season advances yielding a significant value of 0.36 between STR (Dec) and NRT (Dec).

#### 5.4. Interpretation of changing relationship between SOI and NRT

The relationship as revealed in the previous two sections, when viewed together, provide us with a plausible physical reasoning for the changing nature of relationship between SOI and NRT in the form of modulations in the position of STR (& ET) under the influence of SOI. A southward shift of STR (& ET) associated with negative SOI in the beginning of the season (October/November) brings the convective zone of ET over Tamil Nadu. As the season advances





**Fig. 3.** Normal latitudinal movement of Sub Tropical Ridge at 200 hPa level over 77.5E and surface Equatorial Trough off the east coast of India during October-January

(November/December) and when the ET is located over Tamil Nadu, neither a southward nor a northward shift is conducive and hence, a normal SOI ranging between -5 and 5 is favourable for good rainfall activity (Table 3). But, during the fag end of the season (December/January) a slightly northward shift associated with positive SOI in January becomes favourable for good NRT.

Thus, the manifestation of SOI on Indian northeast monsoon appears to be by way of modulating the position of STR & ET. The SOI influences Indian northeast monsoon by either bringing the convective zone of ET over Tamil Nadu thereby leading to good rainfall or moving it away from the Tamil Nadu latitudes and causing a deficient rainfall.

**5.5. Relation between NMR and upper tropospheric temperatures and winds over India**

The upper tropospheric features that evolve over India in relation to ISMR and NMR in antecedent, concurrent and succeeding time lags were studied in Raj *et al.* (2004) and it has been shown that westerly zonal wind and negative temperature anomalies in October are associated with good northeast monsoon. In the context of the changing nature of concurrent relationship between SOI/STR and NRT as elucidated in the previous section, CCs between upper tropospheric temperature/wind at 200 hPa level and NRT in the concurrent mode were computed using 39 year data (1963-2001) after averaging the values of the parameters of 14 stations for which data were collected and deriving a single value for India for each month/season and year. Table 6 presents significant CCs between 200 hPa upper tropospheric temperatures/winds and NRT.

**TABLE 6**

**CCs between upper tropospheric parameters at 200 hPa level averaged over India and NRT**

<i>TT</i>		Month of NRT	CC
Month	Mean (°C)		
Oct	-52.6	Nov	-0.52**
Oct	-52.6	OND	-0.36*
Jan	-54.0	Jan	0.43**
<i>U</i>		Month of NRT	CC
Month	Mean (m/sec)		
Oct	5.8	Nov	0.33*
Oct	5.8	OND	0.40*
Jan	26.2	Jan	-0.22

(based on 39 year data from 1963-2001)

*TT* : Temperature; *U* : Zonal wind; NRT,CC,\*,\*\*,: as defined in Table 2

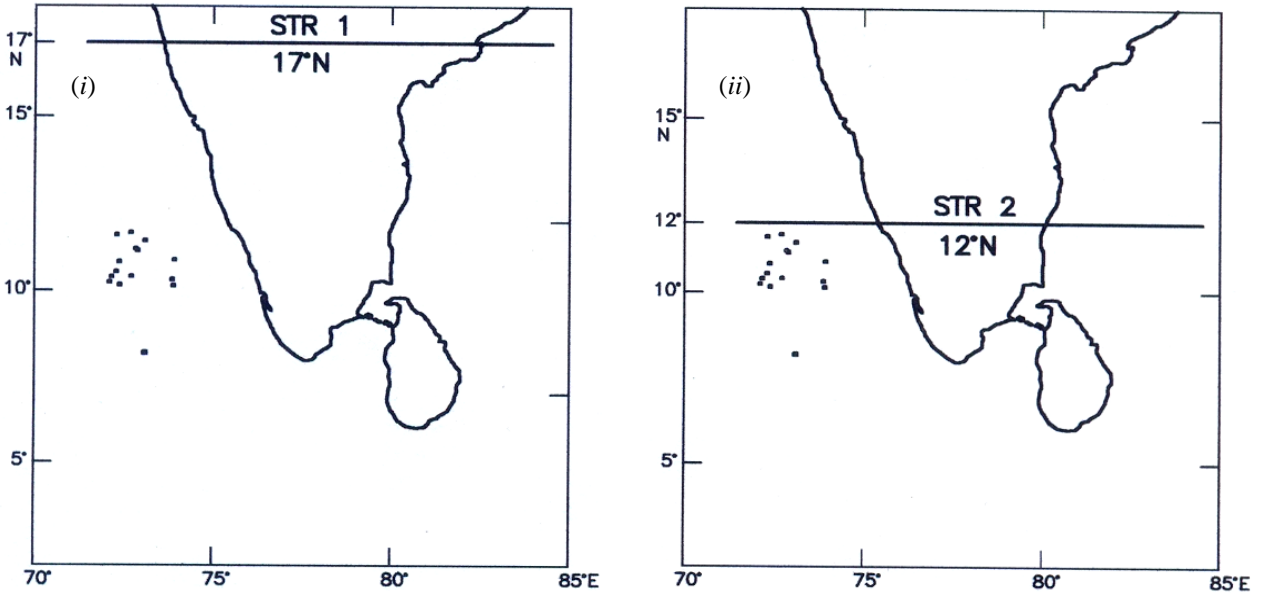
While significant negative CCs (-0.52 and -0.36) are obtained between October upper tropospheric temperatures and NRT (Nov) / NRT (OND), the CCs turn to positive (0.43) between January temperature and NRT (Jan). Similarly significant positive CCs (0.33 and 0.40) are obtained between October zonal wind and NRT (Nov)/ NRT (OND). The CC between January zonal wind and NRT (Jan) is modestly negative (-0.22). The positive relationship between October zonal wind and NRT decreases as the season advances and turns negative in January.

A colder (warmer) upper troposphere over India tends to shift the STR southwards (northwards). Also, strengthening of westerly winds in the beginning and easterly winds towards the fag end of the season in the upper troposphere favour a good northeast monsoon. Thus colder temperatures and westerly wind anomalies, in the upper troposphere, during the beginning of the season slowly changing to warmer temperatures and easterly anomalies during the fag end of the season favour a good northeast monsoon rather than the former features persisting throughout the season. These results, based on upper tropospheric temperature and winds clearly authenticate the results based on relation between SOI and STR derived in the previous sections.

**5.6. Role played by tilting term of vorticity equation in the reversal of relation between NRT and STR**

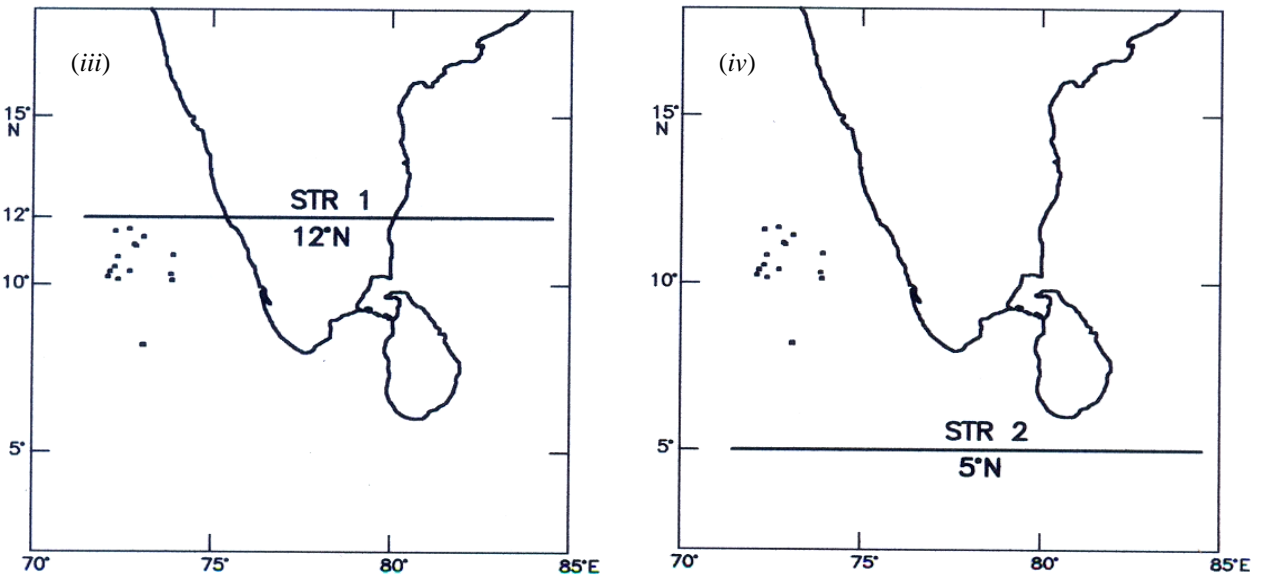
In a detailed study on Indian northeast monsoon, Rao (1963) brought out the crucial role played by the 500 hPa STR over India in modulating northeast monsoon rainfall. He has shown that the tilting term in the vorticity equation

(a) Oct/Nov- Initial phase of northeast monsoon :  $\partial u/\partial z > 0$  &  $\partial w/\partial y > 0$



$$\begin{aligned} (\partial u/\partial z)_1 &< (\partial u/\partial z)_2 \\ \xi_1' &< \xi_2' \end{aligned}$$

(b) Dec/Jan – Final phase of northeast monsoon :  $\partial u/\partial z > 0$  &  $\partial w/\partial y < 0$



$$\begin{aligned} (\partial u/\partial z)_1 &< (\partial u/\partial z)_2 \\ \xi_1' &< \xi_2' \end{aligned}$$

**Figs. 4(a&b).** Illustration of north/south ward location of STR at 500 hPa level and associated variation in vertical shear of zonal wind and vertical velocity during the (a) initial [(i) & (ii)] and (b) final [(iii) & (iv)] phases of northeast monsoon ( $\xi_1' < \xi_2'$  : Vorticity due to tilting term of vorticity equation corresponding to STR<sub>1</sub> and STR<sub>2</sub>)

plays an important role in generating vorticity, positive or negative corresponding to the different patterns of vertical variation of wind vector obtained in the mid troposphere over the southern Indian region. In what follows, we set out to show that the tilting term also plays a role in explaining the reversal of relation between NRT and STR at 500 hPa.

### 5.6.1. The tilting term

The tilting term, say  $\partial\xi_T/\partial t$ , of the vorticity equation which provides an expression for  $\partial\xi/\partial t$  is given by, (Holton, 1979) (symbols have the usual meaning)

$$\frac{\partial\xi_T}{\partial t} = -\left(\frac{\partial w}{\partial x}\right)\left(\frac{\partial v}{\partial z}\right) + \left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right) \quad (1)$$

We denote the second term of the above expression by  $\xi'$ , *i.e.*,

$$\xi' = \left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right) \quad (2)$$

The first factor of  $\xi'$  is the latitudinal variation of vertical velocity  $w$ , whereas the second factor is the vertical variation of zonal wind  $u$ . After the northeast monsoon has set in, the easterly wind speed decreases with height *i.e.*, the zonal wind increases with height up to 500 hPa over the southern peninsula above the friction layer. Thus, by and large,

$$\frac{\partial u}{\partial z} > 0 \quad (3)$$

The contrasting roles played by  $\xi'$  during the initial and final phases of northeast monsoon are now discussed.

### 5.6.2. During the initial phase

In October, during the initial phase of northeast monsoon, the ET is located along 12-13° N (Fig. 3). Invoking the reasonable assumption that vertical velocity  $w$  at a given level decreases from north to south in the lower troposphere over the southern region, we get

$$\frac{\partial w}{\partial y} > 0 \quad (4)$$

Using Eqn. (3) and Eqn. (4) in Eqn. (2) we obtain

$$\xi' = \left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right) > 0$$

thus resulting in  $\xi'$  contributing to increase of prevailing relative vorticity with respect to time at all the levels of lower troposphere.

We now introduce two different positions of the STR at 500 hPa level, *viz.*, STR<sub>1</sub> and STR<sub>2</sub>, STR<sub>1</sub> located north of STR<sub>2</sub> (Fig. 4). Let  $(\partial u/\partial z)_1$  and  $(\partial u/\partial z)_2$  denote the values of  $(\partial u/\partial z)$  corresponding to STR<sub>1</sub> and STR<sub>2</sub>. In case of STR<sub>2</sub>, westerlies penetrate to lower latitudes at 500 hPa level whereas the low level winds remain as easterlies. We therefore have,

$$\left(\frac{\partial u}{\partial z}\right)_1 < \left(\frac{\partial u}{\partial z}\right)_2 \quad \text{and so}$$

$$\left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right)_1 < \left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right)_2 \quad \text{as } \left(\frac{\partial w}{\partial y}\right) > 0$$

which can be written as

$$\xi'_1 < \xi'_2. \quad (5)$$

From Eqn. (5), it is evident that a southerly position of STR favours increased generation of positive vorticity and so increased northeast monsoon activity in the beginning of the season.

### 5.6.3. During the final phase

In December/January, the ET is located closer to equator (Fig. 3) and so by and large

$$\left(\frac{\partial w}{\partial y}\right) < 0 \quad \text{and} \quad \xi' < 0 \quad (6)$$

implying that the tilting term contributes to decrease of prevailing relative vorticity. Based on the same arguments as advanced in Sec.5.6.2, we have,

$$\left(\frac{\partial u}{\partial z}\right)_1 < \left(\frac{\partial u}{\partial z}\right)_2 \quad \text{and so}$$

$$\left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right)_1 > \left(\frac{\partial w}{\partial y}\right)\left(\frac{\partial u}{\partial z}\right)_2 \quad \text{as } \left(\frac{\partial w}{\partial y}\right) < 0$$

Therefore,

$$\xi'_1 > \xi'_2. \quad (7)$$

which implies that the tilting term contributes to sharper decrease of relative vorticity in the second case

TABLE 7(a)

## Relation between SOI and dates of onset and withdrawal of northeast monsoon

	Parameter		Month of SOI	CC	Mean No. of days from normal for various SOI intervals				
	Normal date	SD (days)			<-10	-10 to -5	-5 to 5	5 to 10	>10
Easterlies onset	14 <sup>th</sup> Oct	7	Sep	0.23*	-3	-2	1	1	2
Northeast monsoon onset	20 <sup>th</sup> Oct	7-8	Sep	0.23*	-2	-2	1	1	2
Northeast monsoon withdrawal	27 <sup>th</sup> Dec	13-14	Dec	0.13	-8	-2	1	-1	3

(based on 104 year data from 1901-02 to 2004-05)

SOI, CC,\* : as defined in Table 2

SD: as defined in Table 4

TABLE 7 (b)

## No. of years corresponding to early / late onset and withdrawal of northeast monsoon associated with various SOI intervals

Type of Onset/withdrawal	Month of SOI	n	SOI interval				
			<-10	-10 to -5	-5 to 5	5 to 10	>10
Early onset (on or before 12 <sup>th</sup> Oct)	Sep	15	1	6	3	5	0
Late onset (on or after 28 <sup>th</sup> Oct)	Sep	14	0	2	4	5	3
Early withdrawal (on or before 15 <sup>th</sup> Dec)	Oct	23	5	5	8	2	3
	Nov	23	4	5	9	2	3
Late withdrawal (on or after 8 <sup>th</sup> Jan)	Dec	23	1	3	8	5	6
	Jan	23	1	4	6	8	4

(based on 104 year data from 1901-02 to 2004-05)

n: No. of years ; SOI: as defined in Table 2

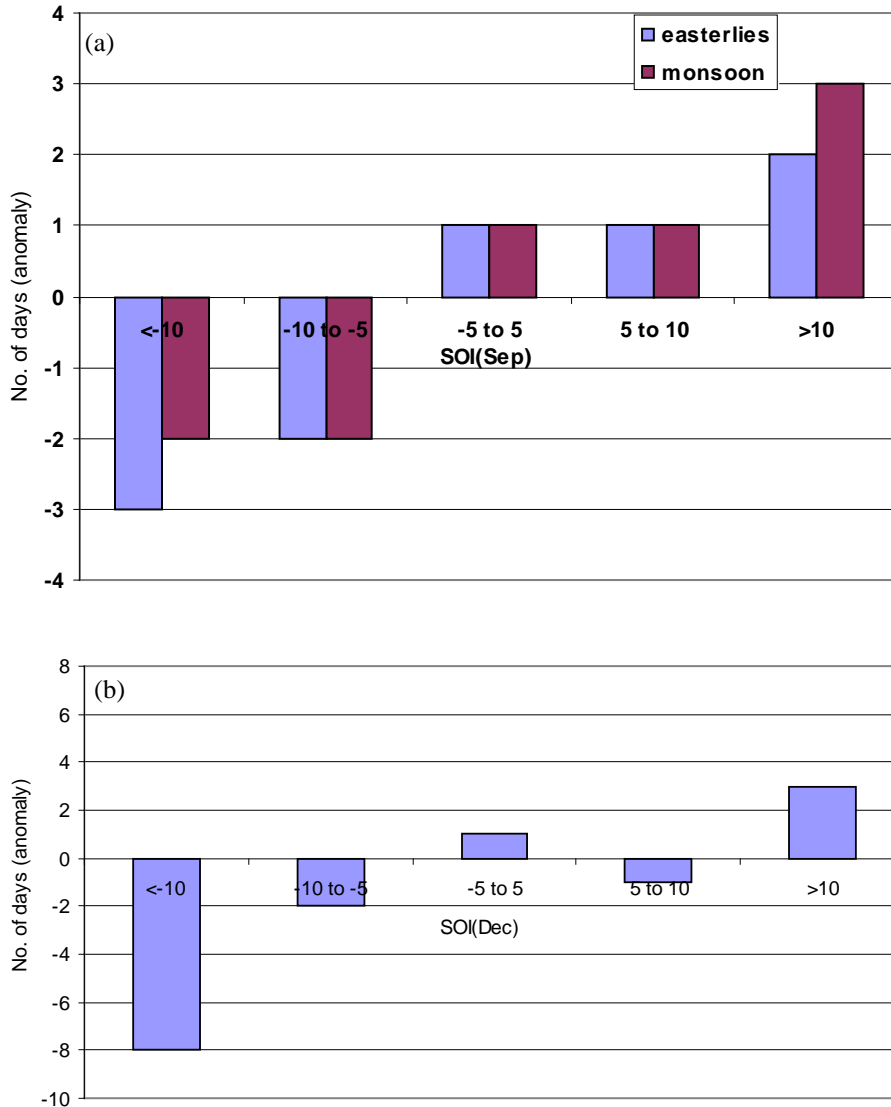
when STR is located south as compared to the first when STR is located north. We can therefore conclude that the first case is more conducive for good northeast monsoon activity than the second.

5.6.4. The deductions in the previous section which are some what similar in style to the deductions made in Rao (1963), lend some theoretical support to the empirical results derived in this paper in the earlier sections based on actual data. The change of sign of  $\xi'$  from positive to negative as the season advances is also consistent with the temporal decrease of normal rainfall [Table 1(a)] during the same time frame over the peninsular India.

It must be pointed out that the empirical results have been based on the STR of 200 hPa whereas the theoretical derivations are based on the STR of 500 hPa. As moisture extends upto 500 hPa level only during northeast monsoon, it is adequate to study the relative vorticity

profiles upto that level. However, in order to compare the empirical results based on 200 hPa STR and the theoretical results based on 500 hPa STR, we have generated the latitudinal positions of STR at 500 hPa level also at 77.5° E. The CCs between the latitudinal positions of 200 and 500 hPa level STR (based on 43 year data generated from NCEP reanalysis datasets) have been found to be 0.69, 0.69, 0.56 and 0.58 for the months of October, November, December and January respectively and are significant at 0.1% level. Thus, by and large, the STR anomalies at 500 hPa level behave in the same way as the STR anomalies in 200 hPa level which should be adequate for us to compare both the results.

The authenticity of the assumptions expressed in Eqns. (3), (4) and (6) were verified by generating long term means of  $u$  and  $w$  over Indian region at 850, 700 and 500 hPa levels for the months of October, November, December and January from NCEP reanalysis datasets.

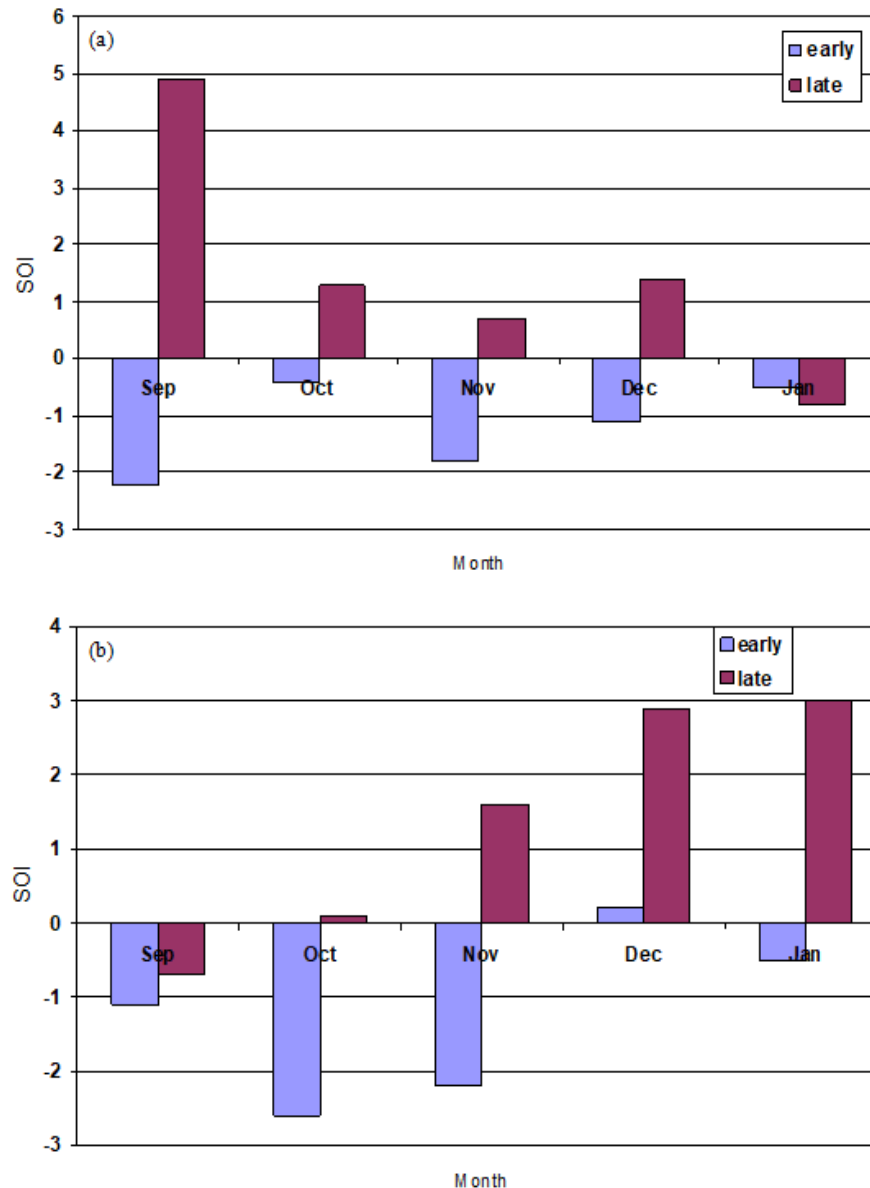


**Figs. 5(a&b).** Conditional means of anomalies of dates of (a) onset of easterlies/northeast monsoon for various SOI intervals and (b) withdrawal of northeast monsoon for various SOI intervals

The relations were found to be valid for November, December and January in the case of zonal wind and for all the four months in the case of vertical velocity. For October, these relations held true for the period commencing from the normal date of onset that falls in the third week of October. The profiles of vertical variation of zonal wind over Chennai during various types of northeast monsoon activities have been presented in Raj (1996), which also authenticates Eqn. (3). That the zonal winds increase with height is also consistent with the thermal wind concept with the northern parts of India getting gradually colder than the southern parts as the season advances.

### 6. Relation between SOI and the dates of onset and withdrawal of NMR

The onset of northeast monsoon over the southern peninsula is a well defined event that succeeds the withdrawal of southwest monsoon from the entire India and the consequent establishment of low level easterlies over the peninsula during mid October. The withdrawal, which takes place by December end, is less well defined. Both the processes of onset and withdrawal are clearly marked in the coastal Tamil Nadu region only. We define early/late onset/withdrawal if the concerned event takes



**Figs. 6(a&b).** Mean monthly SOI profile associated with early and late (a) onset of northeast monsoon and (b) withdrawal of northeast monsoon

place one standard deviation earlier/later from the normal dates of 20<sup>th</sup> October and 27<sup>th</sup> December for onset and withdrawal respectively. With this definition, the benchmark dates for early/late onset are 12<sup>th</sup> and 28<sup>th</sup> October respectively and for early/late withdrawal are 15<sup>th</sup> December and 8<sup>th</sup> January respectively, all dates inclusive [Tables 7(a&b)].

The relation between SOI and the events of onset/withdrawal of northeast monsoon has been studied

as per the following methodology. The CCs between SOI and onset dates of easterlies, northeast monsoon onset/withdrawal dates and the conditional means of these parameters for the various SOI intervals have been computed. Important results are presented in Table 7(a). For early/late onset/withdrawal of northeast monsoon, the frequencies (in years) corresponding to various SOI intervals based on 104 year data (1901-02 to 2004-05) have been derived. These details are presented in Table 7 (b) and Figs. 5(a&b). The mean monthly SOI

**TABLE 8**

**Monthly mean SOI profile for various types of northeast monsoon onset/withdrawal and for extreme monsoon performance**

Northeast monsoon parameter	Mean duration of northeast monsoon (days)	SOI					NRT (PDN)	
		Sep	Oct	Nov	Dec	Jan	OND	Jan
Early onset	75	-2.2	-0.4	-1.8	-1.1	-0.5	13.4	19.6
Late onset	54	4.9	1.3	0.7	1.4	-0.8	-18.1	0.8
Early withdrawal	51	-1.1	-2.6	-2.2	0.2	-0.5	-6.0	-32.7
Late withdrawal	87	-0.7	0.1	1.6	2.9	3.0	6.2	129.0
NRT(OND) >30%	75	-6.4	-8.4	-3.5	-3.2	-2.1	40.1	-1.1
NRT(OND) <-30%	59	4.4	2.4	2.0	3.7	0.1	-39.7	-23.3

SOI, NRT : as defined in Table 2; PDN: as defined in Table 3; Early / late onset and withdrawal: as defined in Table 7(b).

profiles for each month between September and January associated with early/late onset/withdrawal have been derived and are presented in Table 8 and Figs. 6(a&b). The results are discussed below.

Modest CCs of 0.23 and 0.23 significant at 5% level, are obtained between SOI (Sep) and the date of onset of earterlies/northeast monsoon over Tamil Nadu respectively. The profiles of conditional means indicate that SOI (Sep) < -5 is associated with an early onset by 2 days and SOI (Sep) >10 with a late onset by 2 days. The CCs between dates of withdrawal and SOI of various months are not significant. However, the conditional means suggest that SOI (Dec) does have a bearing on the withdrawal. If SOI (Dec) is <-10, withdrawal takes place 8 days earlier than normal and if >10, 3 days later.

Early onset has occurred during 15 years out of which 10 are associated with negative to normal SOI (Sep) [Table 7(b)] with a mean value of -2.2 (Table 8). During the 14 years of late onset, 8 and 4 years are associated with positive and normal SOI (Sep) respectively with a mean of 4.9. The 23 years with early withdrawal are mostly associated with negative or normal SOI during October and November with a mean of -2.6 & -2.2 respectively. The 23 years of late withdrawal are mostly associated with normal or positive SOI during December and January with a mean of 2.9 and 3.0 respectively. Thus, there is a clear indication of occurrence of late onset with prevalence of positive SOI in

September and occurrence of late withdrawal with prevalence of positive SOI in December/January.

The mean monthly SOI profile for the period between September and January associated with early onset and early withdrawal are almost identical, the values are well within the normal range, but remain slightly negative throughout the season (Table 8). However the profiles in respect of late onset/withdrawal are well defined. Late onset is associated with a SOI profile commencing with a positive value (4.9) in September which decreases gradually as the season advances and becomes slightly negative (-0.8) in January. In contrast, late withdrawal is associated with an SOI profile that starts with a slightly negative value (-0.7) in September but increases gradually and becomes positive (3.0) in January.

The above analysis based on early/late onset/withdrawal of northeast monsoon also clearly reinforces the changing nature of relationship between SOI and northeast monsoon with the advancement of the season. Whereas a negative SOI in September seems to favour early onset, a positive SOI towards the end of the season prolongs the monsoon activity.

To further bring out the association between SOI and NRT, the mean SOI profile for each month from September to January when NRT was substantially excess

or deficient, *i.e.*, when NRT (OND)  $>30\%$  and  $< -30\%$  were derived. These profiles are also presented in Table 8. As seen, during the excess years, SOI remains strongly negative in September and October ( $-8.4$ ) and then increases to  $-2.1$  in January. In contrast, during deficient years, the SOI is modestly positive in September ( $4.4$ ) and then decreases to  $0.1$  in January.

## 7. Analysis based on Australian “Rainman” software

“Rainman” is a graphical user interface software developed by the Australian Bureau of Meteorology for International Agricultural Research (Clewett *et al.*, 2002). Climatological rainfall data for a large number of stations of the world have been archived for the period from late 19<sup>th</sup> century upto 1990. It contains an extensive package to extract rainfall data and to study the relationship between SOI and rainfall of a given station in concurrent and antecedent modes.

For the present study, the Rainman software was used to study the relation between SOI and northeast/winter monsoon rainfall of stations located in the (a) Eastern and western coastal belts of south India and (b) A few Sri Lankan & southeast Asian stations. The results are furnished below:

(i) In CAP, stations located north of  $15^\circ$  N (Kalingapatnam, Visakhapatnam and Machilipatnam) manifested no clear relationship, either concurrent or antecedent, between SOI and NMR.

(ii) In CAP, stations located south of  $15^\circ$  N, showed a slightly discordant negative concurrent relationship between SOI and NRT(OND).

(iii) In the coastal belt of Tamil Nadu (CTN), above normal or excess NRT (OND) was associated with negative SOI (*i.e.*) SOI (OND)  $< -5$  and NRT (Jan) with SOI (Jan)  $> 5$ . In fact, typical northeast monsoon stations like Nagapattinam, Vedaranyam and Adiramapatnam in the latitudinal belt of  $10-11^\circ$  N gave a clear indication of gradual change of relationship as the season advanced. Good rainfall during OND was associated with SOI (OND)  $< -5$ . But, good rainfall in December was associated with  $-5 < \text{SOI (Dec)} < 5$  and in January, it was associated with SOI(Jan)  $> 5$ .

(iv) Along the western coastal belt, Thiruvananthapuram showed a relationship very similar to that of the CTN stations. Other stations considered and located north of Thiruvananthapuram, *viz.*, Kozhikode, Mangalore, Karwar, Honavar and Goa did not show any clear relationship.

(v) For the Sri Lankan stations in the latitudinal belt of  $8.5$  to  $6^\circ$  N (Triconamalee, Colombo and Galle) good rainfall during OND was associated with SOI (JAS)  $< -5$  and SOI (OND)  $< -5$ . But during JF, normal SOI (*i.e.*)  $-5 < \text{SOI (JF)} < 5$  was found to be favourable for good rainfall activity.

(vi) The same analysis was carried out for some stations located in the Indo China and Malaysian regions in the latitudinal belt of  $8^\circ$  N to  $2^\circ$  N (Nakhon-si Thammarat ( $8^\circ$  N,  $100^\circ$  E) – Indo China; Sitiawan Met. ( $4^\circ$  N,  $101^\circ$  E), Kuala Lumpur ( $3^\circ$  N,  $102^\circ$  E), Malaka ( $2^\circ$  N,  $102^\circ$  E) – Malaysia. Good rainfall during OND was found to be associated with SOI (OND)  $< -5$ . But, good rainfall in JF was associated with  $-5 < \text{SOI (JF)} < 5$ .

In view of existence of good positive CC between SOI and STR at 200 hPa level, throughout the year, the above results lead to the following inferences:

(i) The northern CAP stations are located far away from STR and ET during the northeast monsoon season. As such OND rainfall has not shown any relationship with SOI.

(ii) For the CTN stations in the latitudinal belt of  $8$  to  $14^\circ$  N, a southerly position of STR from its normal position during OND but a northerly position of STR in January are favourable for good concurrent rainfall activity.

(iii) The Sri Lankan and Malaysian stations located south of  $8^\circ$  N also show a trend similar to that of CTN stations, but, only normal position of STR in January rather than a northerly position is associated with good monsoon.

Thus a very clear profile of the latitudinal variation of relation between SOI and winter monsoon rainfall emerges substantiating the results obtained.



## 8. Discussions

SOI has been reported to influence the Indian southwest monsoon in a significant way. The relationship starts to build up from the preceding pre monsoon season and gets stronger during JJAS. The antecedent SOI of MAM serves as a predictor for ISMR. However, in the case of NMR, antecedent seasonal SOI (JJAS) seems to be related strongly than the concurrent seasonal SOI (OND). When we focus on concurrent relationship, SOI (Oct) accounts for almost all the relation that exists between NRT and SOI (OND).

This pattern of relationship between SOI and NMR holds some implication for the Long Range Forecasting (LRF) of NMR based on ENSO parameters. Inclusion of these in deriving empirical models for the LRF of ISMR has been in vogue in India (Gowariker *et al.*, 1989 & 1991). Of late, similar works on modelling of LRF of NMR have emerged using antecedent SOI of JJAS/October as potential predictors (Kumar, 2006). Some amount of discretion may have to be exercised in using such schemes in view of the changing nature of the relationship between SOI and NMR. Forecasts based on antecedent SOI are likely to have better validity for the first phase of the northeast monsoon season (Oct/Nov) than for the final phase of the season (Dec/Jan). If SOI (Dec/Jan) could be predicted in September/October, better estimates of NRT (Dec/Jan) could be obtained based on the concurrent relationship between SOI and NRT. Univariate prediction models of SOI using the internal dynamics of the series and based on techniques such as canonical correlation and CLIPER have been developed (Barnston & Ropelewski, 1992 and Knaff & Landsea, 1997) and have shown good skill. If such estimates for NRT (Dec/Jan) are assimilated with the forecasts for NRT (Oct/Nov), the composited forecast for the whole season will be expected to carry a higher skill than forecasts solely based on antecedent SOI. These aspects must be preferably factored into the SOI based LRF models for NMR/NRT.

The results on relation between SOI and the onset/withdrawal process of northeast monsoon (Sec.6) are on the expected lines and lend further support to the results derived in Sec.5. The onset of northeast monsoon is closely associated with the movement of ET over the peninsula that is in harmony with the movement of STR at 200 hPa which is related to the SOI phase. The withdrawal of northeast monsoon is not associated with any major discernable synoptic feature but as has been shown, SOI,

through STR and ET controls to some extent, the process of withdrawal as well. The phenomenon of northeast monsoon spilling over to the next calendar year could thus be partly comprehended through SOI. The results of Tables 7(a&b) also could be used to qualitatively forecast the onset/withdrawal or to understand the physical process responsible for early/late onset/withdrawal.

It is well known that low pressure systems that originate over the ET zone of Bay of Bengal and cross the lower latitudes of southern Indian peninsula are important synoptic features contributing towards the seasonal rainfall total (IMD, 1973b). During October, November and December, the normal latitudinal positions of formation of low pressure systems in Bay of Bengal (derived from the database on Cyclones and Depressions formed over North Indian Ocean available at Regional Meteorological Centre, Chennai) are approximately 14.1° N, 10.4° N and 8.4° N respectively (IMD, 1979 & 1996). These systems normally move west/northwest/northwards along the periphery of the anticyclone at 200 hPa level. During October/November when the 200 hPa level STR is located north of 14° N, prevalence of negative SOI shifts STR/ET southwards. During this period, a low pressure system forming in southern latitude has a greater chance of moving westwards and cross the southeastern coast thereby causing more rainfall in the peninsular India. But, in December, when the STR at 200 hPa level is already south of Comorin, its further southward shift will result in penetration of upper tropospheric westerlies to lower latitudes that will cause steering of the low pressure systems towards east/northeast and move them away from the Indian region. However, a northward shift of the STR associated with positive SOI phase, ensures presence of upper tropospheric easterlies over the lower latitudes of the southern peninsula and Bay of Bengal, which can steer low pressure systems towards the Indian peninsula and increase rainfall activity along the southeastern coastal districts.

It is interesting to note that good northeast monsoon activity is associated with westerly zonal wind anomalies at 200 hPa level in October, but, with easterly zonal wind anomalies in January. However good/active northeast monsoon spells are characterised by the presence of strong easterlies at the lower levels, say at 850 hPa, throughout the season, from October to January save for the occasions when tropical cyclones form and move over Bay of Bengal as verified from NCEP reanalysis data. A subtle change in the low level wind flow pattern however can be

discerned, which is that in October the ET shifts from north to south at the time of onset (Raj *et al.*, 2007) and also during active northeast monsoon conditions. In December/January, the ET shifts from south to north in association with active northeast monsoon conditions, a fact already mentioned in IMD (1973b).

The above discussions reveal that the relationship that SOI exhibits with Indian northeast monsoon as derived in this paper are consistent with known climatological features associated with active/weak northeast monsoon conditions and also with the tropical cyclone climatology of Indian seas. As a matter of abundant caution and discretion, it also must be pointed out that there are a few years in which SOI has failed to convincingly explain exceptionally poor and good northeast monsoon performances. SOI must be only one of the many parameters that influence northeast monsoon and hence cannot solely explain the inter annual and intra seasonal rainfall variation. Despite this, the Southern Oscillation, which represents a global phenomenon, exhibits significant and time tested relationship with Indian northeast monsoon and as reported in a few recent works, this relationship has been strengthening of late (Kumar, 2006). Considering its robustness and global nature, SOI should remain as one of the important parameters to understand and prognosticate the inter annual and intra seasonal variation of northeast monsoon rainfall.

## 9. Conclusions

The results of the study are summarised herein below:

(i) Relation between SOI of JJAS/OND and northeast monsoon rainfall of October-December of southern Indian peninsula is negative. However, the relation is stronger in the antecedent mode and slightly weaker in the concurrent mode. This is in contrast to the existence of positive relationship between SOI and the Indian southwest monsoon rainfall during JJAS which builds up in March-May and becomes stronger in the concurrent mode.

(ii) An analysis of seasonal/monthly northeast monsoon rainfall in relation to seasonal/monthly SOI based on linear correlation and conditional means in the antecedent and concurrent modes has revealed that the good negative relationship existing between SOI and Indian northeast monsoon rainfall at the beginning of the season (October/November) does not continue throughout the

season. The magnitude of negative relationship decreases with the advancement of the season. During November/December no clear relationship exists. In January, the relationship turns modestly positive.

(iii) Such a changing nature of relationship between SOI and Indian northeast monsoon rainfall is shown to be associated with the modulation in the latitudinal position of the STR at 200 hPa level and the surface ET .

(iv) The SOI and the latitudinal position of STR are positively correlated throughout the year which implies that a positive (negative) SOI shifts the STR/ET northwards (southwards) through out the year.

(v) The Indian northeast monsoon rainfall especially that of November is negatively correlated with the latitudinal position of the STR (Oct). But, the December rainfall is correlated positively with the STR (Dec) *i.e.*, a southward shift of STR in October and northward shift in December are associated with good northeast monsoon rainfall activity. There is no correlation between November position of the STR and the November rainfall.

(vi) During October/November when STR/ET is to the north of Tamil Nadu, negative SOI shifting them southwards is conducive for good rainfall activity. During November/December, when the ET is right over the Tamil Nadu latitudes, neither a northward shift nor a southward shift of STR/ET, but a normal position is favourable for enhanced monsoon activity. In December/January, when the STR/ET has moved south of Comorin, positive SOI shifting the STR/ET northwards is favourable for good northeast monsoon.

(vii) An analysis of upper tropospheric (200 hPa level) temperatures and winds over India in relation to seasonal/monthly northeast monsoon rainfall based on linear correlation has also revealed a changing nature of relationship. While colder temperatures and strengthening of westerly winds in October are associated with good rainfall especially during November, warmer temperatures and stronger easterly winds in January are associated with good rainfall in January.

(viii) The changing nature of relationship between STR at 200 hPa level and northeast monsoon rainfall as the season advances has been shown to be consistent with the contribution of the tilting term in the vorticity equation.

The vertical wind structure upto the mid troposphere and the latitudinal variation of vertical velocity together convincingly explain the reversal of the relationship thus lending some theoretical support to the empirically proven relationship.

(ix) An analysis of the onset and withdrawal dates of the Indian northeast monsoon in relation to SOI has revealed that negative SOI in September leads to normal or slightly earlier onset. But, continuation of negative SOI throughout the season leads to an early and abrupt withdrawal of the monsoon in December. Positive SOI in September leads to a late onset and prevalence of the same in December/January, leads to extension of the monsoon into January of the next year.

(x) Based on Australian "Rainman" software, an analysis of relationship between SOI and northeast monsoon rainfall of a few stations of eastern/western coastal peninsular India and some Sri Lankan/southeast Asian stations was carried out. The results further substantiated the changing nature of relationship.

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