MAUSAM, **65**, 3 (July 2014), 407-416

551.526 : 551.463.6 (540.63, 540.65)

Impact of eastern equatorial Indian ocean during positive tropical dipole on regions over Tamilnadu and coastal Andhra Pradesh

U. K. CHOUDHARY, G. P. SINGH*, O. P. SINGH** and A. K. SRIVASTAVA

India Meteorological Department, *Banaras Hindu University*, *Varanasi, India*

**Department of Geophysics*, *Banaras Hindu University*, *Varanasi, India*

***India Meteorological Department*, *New Delhi, India*

(*Received 9 April 2013*, *Modified 4 July 2013*)

e mail : gpsinghbhu@hotmail.com

सार – इस शोध पत्र का मुख्य उद्देश्य, वर्ष 1980-2009 की अवधि में मुख्य रूप से तमिलनाडु और तटीय आंध्र प्रदेश में क्षेत्रीय ग्रीष्मकालीन मॉनसून वर्षा पर सकारात्मक उष्णकटिबंधीय हिंद महासागर द्विध्रुव (PTIOD) की घटनाओं के दौरान पूर्वी समुद्र सतह तापमान (SST) की विसंगतियों के प्रभाव की जाँच करना है। इस अध्ययन के दौरान 7 प्रबल PTIOD की घटनाएं अभिलेखित की गई जो भारत में मौसमी ग्रीष्मकालीन मॉनसून वर्षा के साथ उल्लेखनीय रूप से बढ़ी हुई देखी गई। अप्रैल, मई, जून में EQ.ESIO (भूमध्यरेखीय पूर्वी दक्षिणी हिंद महासागर) में औसत समुद्र सतह तापमान (SST) की विसंगतियों से पता चला है कि अप्रैल, मई, जून (AMJ), में अतिशीत (उष्ण) EQ.ESIO और सकारात्मक TIOD की घटनाएं तमिलनाडु और तटीय आंध्र प्रदेश में ग्रीष्मकालीन मॉनसून वर्षा की कम होती हुई (संवर्धित) प्रवृत्ति के साथ संबंधित थी। सांख्यिकीय विश्लेषण से तमिलनाडु और तटीय आंध्र प्रदेश में AMJ,SST विसंगतियों और वर्षा के मध्य क्रमश: 0.59 और 0.76 के सहसंबंध सहगुणांक का पता चला है। नकारात्मक AMJ SSTA के साथ PTIOD वर्षों के दौरान पवन की विसंगतियों ने दक्षिण पश्चिमी बंगाल की खाड़ी (SWBOB) की ओर सुमात्रा-जावा से दूर शीत अपवेल्ड समुद्री धारा को वाहित किया है जिसके कारण इस क्षेत्र में विसंगत SST शीतलन की स्थिति बनी। इस प्रकार अप्रैल मई जून (AMJ) के दौरान SWBOB में पहुँचने वाली निम्नस्तरीय दक्षिणी पवन से अधिकतम सौर सूर्यातप के महीने में उस क्षेत्र में अतिशीत समुद्री सतह तापमान बना और इस प्रकार दक्षिण पूर्वी/उत्तरी बंगाल की खाड़ी (BOB) की ओर संवहनी गतिविधियों के खिसकने के साथ कमजोर उष्मीय प्रवणता देखी गई। इसके साथ-साथ मॉनसून पूर्व, ऋतु में क्षेत्र में SWBOB क्षेत्र में कम संवहनी गतिविधियों के साथ कम आर्द्रता वाले संवहन से जून, जुलाई, अगस्त और सितम्बर (JJAS) में तमिलनाडु और तटीय आंध्र प्रदेश उपखंडों में सामान्य से कम वर्षा हुई।

इस क्षेत्र में उच्च बहिर्गामी दीर्घतरंग विकिरण (OLR) क्षीण निम्न स्तर अभिसरण और मेघ बनने के साथ संबद्ध था। वर्षा वाले वर्षों में बड़े नकारात्मक OLR सूचकांक रहे जबकि बिना वर्षा वाले वर्षों में तुलनात्मक रूप से अधिक मान रहे। निम्न क्षोभमंडल में महासागर-वायुमंडल तापन युग्मन के कारण SWBOB क्षेत्र में स्थूलता विसंगतियां बनी जो मूलाधार समुद्र सतह तापमान विसंगतियों के समान रहीं। वर्ष 1994 (बिना वर्षा वाला वर्ष) में जुलाई-अगस्त के दौरान निम्नतम नकारात्मक स्थूलता विसंगति पाई गई। SWBOB में विसंगत शीत (उष्ण) SST से नकारात्मक (सकारात्मक) स्थूलता विसंगति बनती है, जिसका शुष्क (आर्द्र) मामलों में भारत के निचले पूर्वी तट तक विस्तार रहता है। तापीय प्रवणता के क्षीण (तीव्र) होने से संबद्ध तापीयपवनों का SWBOB में मौसमी पवनों पर बहुत प्रभाव पड़ता है जिससे गुप्त उष्मा क्षति में कमी (वृद्धि) होती है। ऊष्मा बजट घटक गुप्त ऊष्मा अभिवाह में परिवर्तिता का विश्लेषण करने से SWBOB के क्षेत्र में वर्ष 1994 के शुष्कतम वर्ष में मई के दौरान 20-40 w/m^2 की रेंज की सकारात्मक LHF विसंगति पाई गई। PTIOD वर्षों जैसे 2007 के दौरान EQ. ESIO में ऊष्ण AM JSSTA, निम्न स्तर संवर्धित पश्चिमी पवन तापीय विपर्यास के कारण मध्य BOB तक पहुँचने के फलस्वरूप इस क्षेत्र में तीव्र संवहन हुआ। इस सबके परिणामस्वरूप संवहनीय मेघ का विस्तृत बैंड बना जिससे भारत के पूर्वी घाट में अत्यधिक वर्षा हुई।

ABSTRACT. The main objective of the present work is to investigate the influence of eastern Sea surface temperature (SST) anomalies during the Positive Tropical Indian Ocean dipole (PTIOD) events on regional summer monsoon rainfall especially over Tamilnadu and Coastal Andhra Pradesh (A. P.) for the period of 1980-2009. There were 7 strong PTIOD events recorded during the period of study which are accompanied by significant increase in the seasonal summer monsoon rainfall over India. Averaged SST anomalies (SSTA) over the EQ.ESIO (Equatorial Eastern South Indian Ocean) during AMJ (April, May, June) shows that colder (warmer) EQ.ESIO during AMJ and positive TIOD events were associated with the decreasing (increasing) tendency of summer monsoon rainfall over Tamilnadu and coastal A.P. The statistical analysis shows the correlation coefficient of 0.59 and 0.79 between AMJSST anomalies and the rainfall over Tamilnadu and Coastal A. P. respectively. Wind anomalies during PTIOD years with negative AMJSSTA, transports the cold upwelled oceanic current off Sumatra-Java towards the South West Bay of Bengal (SWBOB) and caused anomalous SST cooling in the region. Thus, the low level southerly wind reaching over the SWBOB during AMJ enforced the colder oceanic surface temperature of the region during the month of maximum solar insolation and thereby weak thermal gradient was observed with the shifting of the convective activity towards the south-east/northern Bay of Bengal (BOB). Moreover, less moisture advection with less convective activity in SWBOB region during pre-monsoon season may be the caused of the below-normal rainfall over Tamilnadu and coastal A. P. sub-divisions during June, July, August and September (JJAS).

Higher outgoing longwave radiation (OLR) in this region was associated with the weak low level convergence and cloud formation. The wet years have large negative OLR Indices whereas dry years have relatively higher values. Due to ocean-atmosphere thermal coupling in the lower troposphere, thickness anomalies developed over the SWBOB region with the same sign as the underlying SST anomalies. The lowest negative thickness anomaly during July-August has been found in 1994 (dry year). Anomalous cold (warm) SST leads to negative (positive) thickness anomalies over the SWBOB, extending over the lower eastern coast of India in dry (wet) cases. Thermal winds associated with the weakening (intensifying) of thermal gradient have greater impact on seasonal winds over the SWBOB leading to decrease (increase) in the latent heat loss. On analyzing the variations in the heat budget component latent heat flux (LHF), positive LHF anomaly in the range of 20-40 w/m^2 was found during May in the driest year of 1994 over the domain of the SWBOB. Warm AMJSSTA over the EQ. ESIO during PTIOD years, like 2007, low level enhanced westerly wind reached over the central BOB due to thermal contrast caused strong convection in the region and resulting huge band of convective cloud formation leads to high rainfall over the Eastern Ghats of India.

Key words – Sea surface temperature, Tropical Indian Ocean dipole, Solar insolation, Thermal wind.

1. Introduction

The Indian summer monsoon (ISM) is one of the main components of the large-scale Asian summer monsoon system. It is regulated by the thermal contrast between land and ocean and large availability of moisture from the Indian Ocean. Summer monsoon rainfall over India is influenced by the Sea surface temperatures (SST). Due to major landmasses surrounding the Indian Ocean, it is one of the most important components of the earth climate system, having profound impact on the ecosystem, agriculture and economic performance of the several tropical countries. In the ocean-atmosphere dynamics, the basic idea behind the process of air-sea interaction is; the wind drives the sea and latter changes the balance of energy by releasing or absorbing the enormous amount of heat. The sea surface temperature anomalies (SSTA) generally alter the latent heat and sensible heat fluxes from ocean to atmosphere and hence affecting the atmospheric circulations.

Several authors have attempted to correlate the SSTA of different sectors of the Indian Ocean with the Indian summer monsoon rainfall (ISMR) on both shorter and longer time scales. In order to understand the summer monsoon in detail, it is necessary to consider the mechanisms of the formation of pre-monsoonal SST anomalies. The importance of the SST anomalies in modulating the regional climate was recognized recently by several scientists working in this area. There are several mechanisms working on Sea surface by which Indian Ocean variability modulates the regional rainfall. Shukla and Misra (1977), Weare (1979), Joseph and Pillai (1984) and Rao and Goswami (1988) mainly in their observational studies have focused on the relationship between the tropical Indian Ocean (TIO) SST and ISM. On the other hand, Yamazaki (1988), Chandrasekar and Kitoh (1998) and Meehl and Arblaster (2002) have shown the impact of Indian Ocean on ISMR in their modeling studies. The annual cycle of SST over the Indian Ocean is crucial for a realistic simulation of the Indian summer monsoon (Shukla and Fennessy, 1994). The influence of the equatorial SSTA on the ISMR has been extensively studied by Navarra *et al.*, (1999), Lau and Nath (2000), Kinter *et al.*, (2002) and they have found in their studies that the Indian summer monsoon and El Niño-Southern Oscillation (ENSO) are negatively correlated.

Saji *et al.*, (1999) and Webster *et al.*, (1999) investigated the Tropical Indian Ocean dipole (TIOD) as an important mode of variability over the Indian Ocean and suggested the teleconnection between the equatorial Indian Ocean SST variability and the ISMR. SSTA over the equatorial Indian Ocean causes the emergence of Tropical Indian ocean dipole which results in widespread changes in regional climate of nearby landmasses. Behera *et al.*, (1999) have pointed out that the anomalous moisture transport from the southeastern tropical Indian Ocean (SETIO) during TIOD events is conducive for enhanced monsoon precipitation over the Bay of Bengal (BOB) and the Indo-Gangetic plains. Later, Ashok *et al.*, (2001) and Li *et al.*, (2003) argued that the positive TIOD events enhance the ISMR. In particular, Ashok *et al.*, (2001) argued that the TIOD influenced the meridional circulation cell over the Indian sector in summer. Li *et al.*, (2003) found that a strong ISM seems to be able to damp the original TIOD event. Loschnigg *et al.*, (2003) and Meehl *et al.*, (2003) have also suggested a relationship between positive Indian Ocean dipole mode (IODM) events and dry conditions over the Indian subcontinent. Later, Ashok *et al.*, (2004) from his model experiments have confirmed that the positive (negative) Indian Ocean dipole events may reduce the influence of an El Niño (La Niña) event on the Indian monsoon. Gadgil *et al.*, (2004) have reported that the inter-annual variability of ISMR is significantly related to the equatorial Indian Ocean oscillation (EQUINOO), which is the atmospheric component of TIOD and it is represented as a normalized index of the near-equatorial surface zonal wind anomaly. Non uniform warming trends in the Indian Ocean have been described by Ihara *et al.*, (2008). Abram (2008) has also noted some variability in the tropical Indian Ocean. Sea surface temperature anomalies in the Ocean coupled with the variability in the atmosphere can help in understanding the links between Indian Ocean sea surface temperature (IOSST) and regional climate. The ocean-atmosphere coupled interactions in the Indian Ocean together with the Tropical Indian Ocean dipole phenomenon have established the importance of Indian Ocean (IO) dynamics on the regional climate variability (Saji *et al.*, 1999; Webster *et al.*, 1999; Behera *et al.*, 1999; Murtugudde *et al.*, 2000; Gualdi *et al.*, 2003; Kripalani *et al.*, 2005). The development of TIOD events as the SST anomalies in the region of EQ.ESIO (Equatorial eastern south Indian Ocean) and EQ.WSIO (Equatorial western south Indian Ocean) in opposite character evolve through boreal summer and attain peak amplitude in autumn. Ashok *et al.*, (2001, 2004) further noted that the positive TIOD events can counteract the effects of El Niño and hence alter the ISMR variability. The summer monsoon of 1997 is a good example that illustrates this point. During this period, the Indian subcontinent experienced above-normal monsoon precipitation despite the evolution of a very intense El-Niño in the Pacific. Slingo and Annamalai (2000) showed that the strong suppression of convection over EQ.ESIO and the Maritime Continent during 1997 played a key role in altering the local monsoon Hadley circulation in a manner so as to favour above normal precipitation over India.

We are mainly concerned to study the regional impact of eastern equatorial Indian Ocean due to formation of TIOD. Positive TIOD and its connectivity with the Indian rainfall have been examined by Behera *et al.*, (1999), Gadgil *et al.*, (2004) and Ummenhofer *et al.*, (2009), but its impact over India on regional basis is yet untouched. One of the objectives of this work is to investigate the influence of the TIOSST anomalies during positive TIOD events on the rainfall of Tamilnadu and Costal A. P.

2. Data and methodology

1º × 1º monthly gridded SSTA obtained from Smith and Reynolds, so called National Oceanic and Administrative Agency/National Climatic Data Centre (NOAA/NCDC) and extended restructured sea surface temperature (ERSST) v2. SST anomaly is averaged of April, May and June months (AMJ). The climatology is defined as the mean SST during the period of 1979-2008 to address the state of the Indian ocean SST. Methods for the reconstructions of the ERSST by Smith and Reynolds are used by separating low and high frequency variability and reconstructing the high frequency variability by the projection method. The OLR, LHF and Wind anomaly datasets from NCEP/NCAR (National Center for Environment Prediction/National Center for Atmospheric Research, USA) reanalysis dataset has been used in the present study. Time series of seasonal rainfall for the regions considered has been taken from the IITM dataset generated from the station rainfall data of the India Meteorological Department (IMD). The domains examined in this study are approximately 10° S - Equator, 90° E-110° E (EQ.ESIO) for SST anomalies, 5° N-13° N, 79° E-89° E (SWBOB) for OLR, LHF, SST and wind anomalies. The main domain of TIOD developed over the Indian Ocean has been shown in Fig. 1 [as two blocks-west (10° S-10° N) and east (10° S-0)].

Daily thickness data (six hourly) at 850 hPa between 500-1000 hPa levels have been taken from the NCEP/NCAR reanalysis and averaged to get the monthly and seasonal series. Normalized thickness anomalies have been computed for the months of July and August during the period of 1979-2008. Measured thickness indicates the vertical depth of a layer in the atmosphere bounded by two constant-pressure surfaces and related to the average temperature in the column. Higher the average temperature of the layer, the thicker it is, which in turn describes the instability of the atmosphere.

3. Results and discussion

The analysis shows 7 strong positive TIOD events (1982, 1991, 1994, 1997, 2006, 2007 and 2008) during 1980-2009, out of which 6 events (except 1982) were accompanied by the significant increase in ISMR over India. To investigate the actual effect of the evolution of positive TIOD, SSTA during April, May and June (AMJ) has been considered. When the SSTA during AMJ were averaged over the EQ.ESIO, it was observed that negative averaged AMJSSTA have shown adverse impact on the rainfall over Tamilnadu and coastal Andhra Pradesh during JJAS season. The other point of discussion is the pattern of OLR and SST anomalies associated with the eastern coastal sub-divisional rainfall conditions.

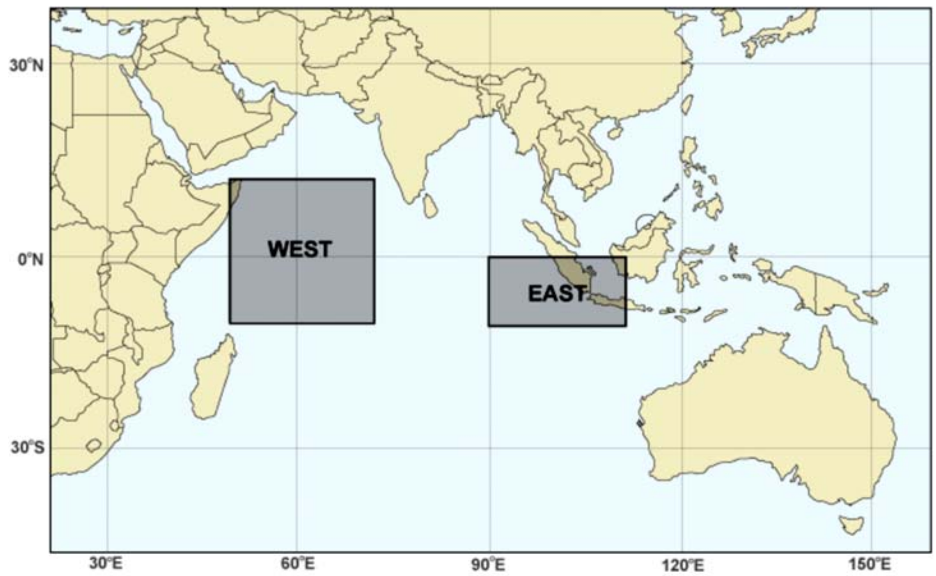


Fig. 1. Location of two blocks over the equatorial Indian Ocean

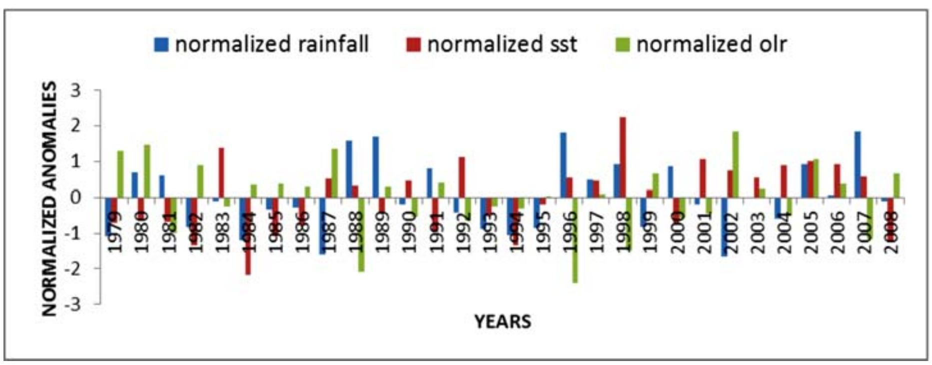


Fig. 2. Normalized rainfall (blue line), sea surface temperature (red line) and outgoing longwave radiation (green line) anomalies over the Coastal A.P. from 1979-2008

Normalized south west Bay of Bengal outgoing longwave radiation (SWBOBOLR), equatorial eastern south Indian Ocean sea surface temperature (EQ.ESIOSST) and Coastal A.P. rainfall indices were calculated relative to the climatology (1979-2008) and has been shown in Fig. 2. Here, it is observed that the OLR indices are relatively higher/lower to the SST and rainfall indices in the cold/warm AMJSST conditions during positive TIODs (we call PTIOD latter). This is the verification of the fact that the higher values of OLR are indicative of no cloud/thin band of clouds over the region. In the year 2007, which has warm AMJSST and above normal rainfall, OLR and rainfall curves were out of phase with low OLR and excess rainfall. The year 2008 was cold year and has shown opposite relationship between OLR and rainfall (Fig. 2). In addition to 1982, 1994 and 2008, cases of 1984 and 1985 are the non-TIOD years having strong negative SSTA (cooler) EQ.ESIO and SD < -1. Both the years have shown the same characteristics of positive OLR and negative rainfall.

The correlation coefficients (CCs) between AMJSSTA and rainfall over Tamilnadu and Coastal Andhra Pradesh were found to be 0.59 and 0.76 (significant at 0.1% level) respectively. The colder (warmer) of EQ.ESIO during AMJ in PTIOD years caused decrease (increase) in tendency of rainfall over Tamilnadu and coastal A.P. PTIOD year of 1994 is an interesting example which shows above normal rainfall over the North Central India, Peninsular India and also west coast of India, but scanty rainfall over Tamilnadu and coastal A. P. Due to anomalous east-west circulation cell along the equatorial region during PTIOD event, Gujarat and Kutch & Saurastra received 57.4% and 46.0% excess

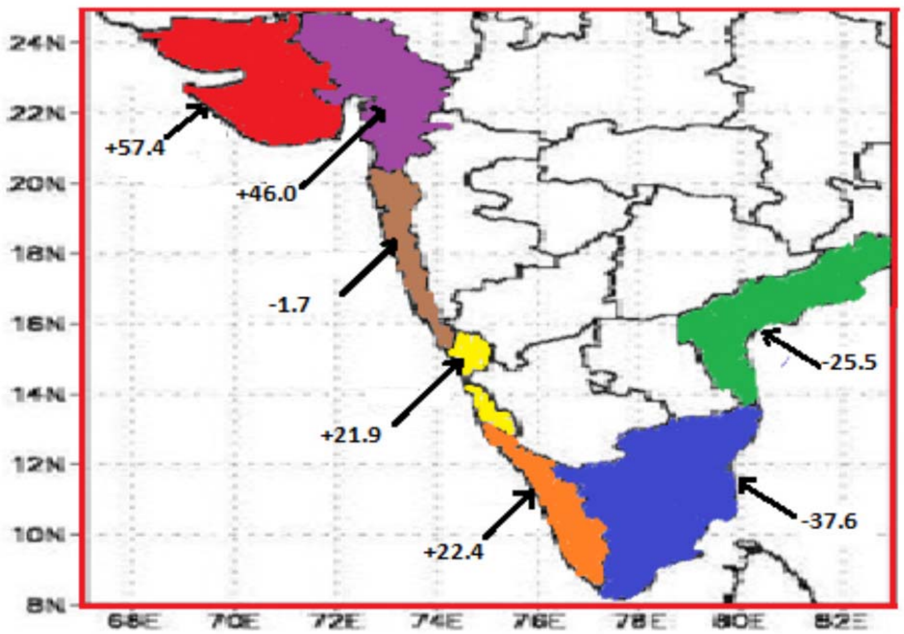


Fig. 3. Positive and negative rainfall conditions over the west coast, coastal A.P. and Tamilnadu in 1994

rainfall respectively while the Coastal A.P. and Tamilnadu received - 25.5% and - 37.6% less rainfall from the climatological average (1980-2009) (Fig. 3). It is interesting to note the tendency of rainfall over the two regions during the strong and warm ENSO (we call ENSO later) years with PTIOD in 1982 and 1997. In 1982, Tamilnadu and Coastal A.P. received 39% and 26% below normal rainfall respectively while in 1997, there was normal rainfall. Our concern is AMJSST anomaly in PTIOD years which changes the atmospheric linkage to the nearby ocean and ultimately seasonal rainfall activity over the concerned regions. EQ.ESIO has negative AMJSSTA in 1982, while it has positive in 1997. Similarly, the years 2007 and 2008 having La Nina event in Pacific Ocean with PTIOD have shown opposite nature in rainfall activities. These regions have received excess rainfall in 2007, while below normal rainfall in 2008. It clearly indicates that the rainfall variations in the two concerned regions are not mainly affected by the ENSO event, but warming/cooling during AMJ months over the EQ.ESIO is the major factor for climate variability in these regions. Wind anomaly during cold AMJSSTA (1994), transports the cold upwelled oceanic current off Sumatra-Java towards the SWBOB and caused anomalous SST cooling in the region. Thus, low level southerly wind reaching SWBOB during AMJ enforced the colder oceanic surface temperature of the region during the months of maximum solar insolation and thereby less thermal gradient observed with shifting of the convective activity towards the south-east/northern BOB. Thus, less moisture advection with less convective activity over SWBOB region during pre-monsoon season is the reasons behind the below-normal rainfall over Tamilnadu and coastal A.P. during JJAS. In contrast, warm AMJSSTA (2007) caused enhance low level westerly reaching over the central BOB due to thermal contrast and thereby strong convection in the region resulting huge band of convective cloud formation and hence enhancement in rainfall over the Eastern Ghat of India. This is similar to the high rainfall over the Western Ghats in response to increased evaporation by the warm SST anomalies over the western Indian Ocean and moisture transport toward the west coast of India (Shukla, 1975).

As far as south Peninsular India is concerned, it is found that the PTIOD event affects its rainfall even Indian monsoon interacts with the ENSO. Due to orographic structure, the south Peninsular India received high rainfall because of cooling of wind due to ascent. During ENSO years, south Peninsular India received below normal rainfall (negative departure), but PTIOD+ENSO years have excess rainfall (positive departure) in the range of 40% to 50% (Fig. 4). The cases 1982, 1991, 1994, 1997 and 2006 were PTIOD+ENSO years and have received above normal rainfall of the order of 15%, 47%, 56%, 40% and 44% respectively. The positive effect of PTIOD event on ISMR overrides the negative effect of ENSO event.

It is understandable fact that the PTIOD have enhancement its effect on the monsoon current due to anomalous east - west thermal contrast and high rainfall

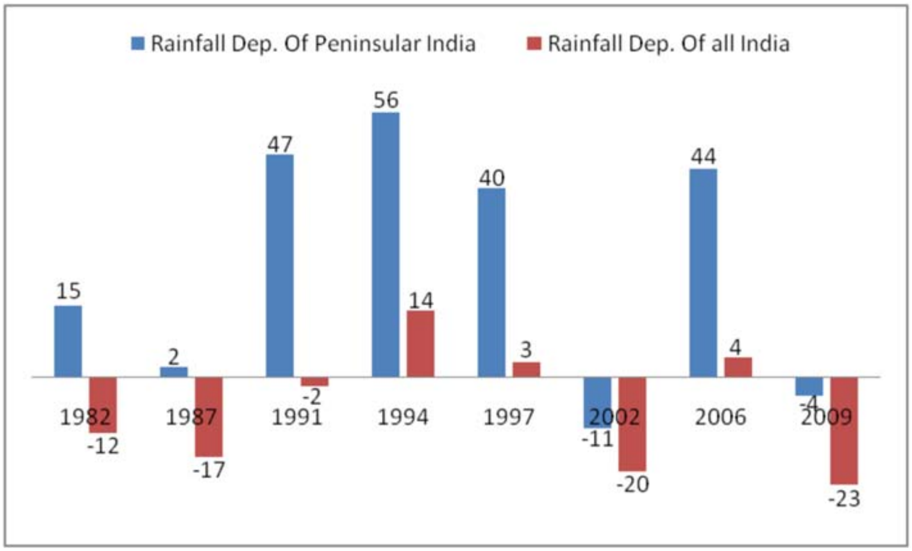


Fig. 4. Rainfall departure over all India and peninsular India (Tropical Indian Ocean Dipole counteracting the effect of warm ENSO)

TABLE 1

Rainfall departure over all India and south peninsular India during different ENSO and ENSO +TIOD cases over the Indian Ocean

Years	Rainfall departure (in %)		Events in Ocean
	All India	South peninsular region	Pacific + Indian
1982	- 12	+15	ENSO +TIOD
1987	-17	+02	Only ENSO
1991	-02	+47	ENSO + TIOD
1994	+14	+56	ENSO + TIOD
1997	+03	+40	ENSO + TIOD
2002	-20	-11	Only ENSO
2006	+04	+44	ENSO + TIOD
2009	-23	-09	Only ENSO

over the west coast. During ENSO non-TIOD years like 1987, 2002 and 2009, India received 17%, 20% and 23% below normal rainfall respectively while mixed years received normal to above normal rainfall except in 1982. During 1997 (strong ENSO event of the century), the ISMR was normal. Thus, PTIOD tends to minimize the affect of ENSO and it produced more effectively positive impact on the rainfall over India as well as over the south Peninsula than that of negative impact of ENSO over the Pacific Ocean (Table 1) and it supports the study of Ashok *et al*. (2004).

Indian monsoon has its own identity with strong precipitation received during early June over the western part of India and during July-August over large parts of India. Generally, large precipitation tends to occur due to large availability of moisture from the Indian Ocean in conjunction with the strong low level convergence. It is important to recognize that the off-equatorial easterly anomalies over the EQ.ESIO during JJAS extend upto nearly 15° S over the northern flanks of Australian High (AH). The positive tropical dipole with the anomalous easterly wind due to SLP anomaly enhances the SW monsoon current and moisture supply to the Indian subcontinent. With the intensification of the monsoonal wind, surface water cools down and the thermal contrast in the Indian Ocean helps to induced winds. A wind in turn enhances the evaporation which intensifies the temperature gradient. Emergence of PTIOD produces anomalous east west winds which enhance the cross equatorial flow in the summer monsoon season. Swapna and Krishnan (2008) have shown that the transient EUCs (Equatorial under current) tend to be relatively stronger when TIOD events co-occur with intensified summer monsoons.

In fact, a majority of positive dipole events were associated with the above-normal summer monsoon precipitation over the west coast and central north India and intensified the monsoon circulation due to the favourable SSTA pattern in the Northern Hemisphere. But forced colder SSTA over the SWBOB during pre-monsoon season creates unfavourable condition for monsoon current moving ahead in this region. Here, we

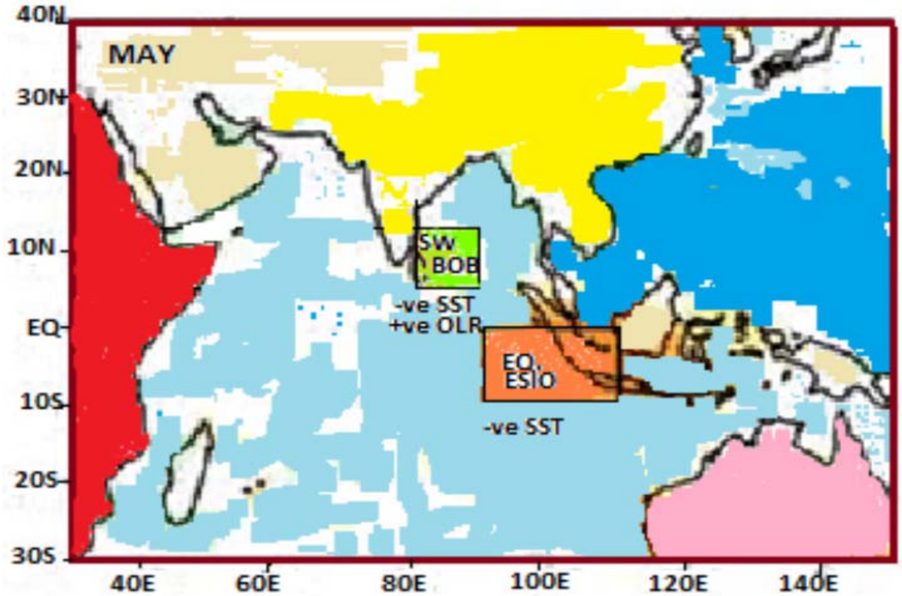


Fig. 5. Sea surface temperature anomaly over the EQ.ESIO during May

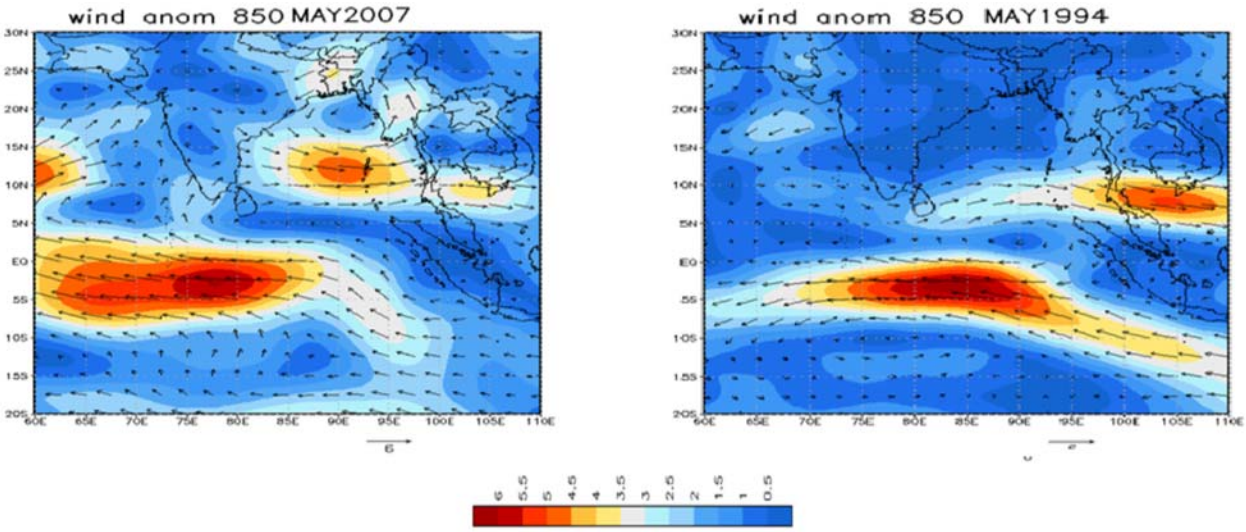
TABLE 2

Excess and deficient rain years during TIOD years over all India and coastal Andhra Pradesh

Surplus monsoon Years (Normal rainfall)		Deficient monsoon Years (Normal rainfall)	
All India	C.A.P	All India	C.A.P
1994 (+1.94)	1991(+0.86)	1982 (-1.17)	1982 (-0.83)
1997 (+0.54)	1997(+0.48)	1991 (-0.54)	1994 (-1.07)
2006(+0.52)	2006(+0.07)		2008 (-0.11)
2007 (+1.34)	2007(+1.85)		
2008 (+0.73)			

have focused on its negative impact over the east coast of India particularly over the Coastal A.P. and Tamilnadu (Table 2). Table 2, clearly shows that the years 1994 and 2007 were two extreme monsoon years among all PTIODs cases. The SST over negative end of dipole modulates the other meteorological parameters persisting over the SWBOB regions. We have also studied the OLR and LHF anomalies, atmospheric thickness and surface wind for these two cases of extreme years in detail. Over BOB, convection is sustained due to strong low level convergence with large availability of moisture from Indian Ocean. The nature of Surface temperature of EQ.ESIO has been conveyed to nearby SWBOB and it influences the rainfall activities over the landmasses (Fig. 5). Fig. 5 shows the same SSTA condition (colder) during the month of May in 1982, 1994 and 2008 over both the regions; namely EQ.ESIO and SWBOB and its impact on rainfall over Tamilnadu and Coastal Andhra Pradesh was seen to be deficient. The analysis of OLR anomalies over the southwest Bay of Bengal (SWBOB; 5º N-13º N, 79º E-89º E) have shown that all PTIOD years with negative AMJSST have either positive or very low negative OLR anomalies during summer monsoon season, indicating less convective activities and weak low level convergence over the region. The OLR conditions during different years have been already shown in Fig. 2. It is found that the wet years have large negative OLR values whereas dry years have relatively higher values. Negative (positive) OLR indicates enhanced (reduced) weather activities over the region.

Due to ocean-atmosphere thermal coupling in the lower troposphere, thickness anomalies develop over the SWBOB region with the same sign as the underlying SST anomalies (Table 3). The lowest negative thickness anomaly during July-August months has been found in 1994 (dry year). Anomalous cold (warm) SST leads to negative (positive) thickness anomalies over the SWBOB, extending over the lower eastern coast of India in the dry (wet) cases. All the negative (positive) AMJSST anomalies over the EQ.ESIO have conveyed almost the same pattern as in the 1000 and 500 thickness anomalies during July (not shown). A reduction (increase) in the meridional SST gradient drives a corresponding response in the atmospheric thickness gradients and result an



Figs. 6(a&b). Wind anomaly at 850 hPa during (a) 2007 and (b) 1994

TABLE 3

Sea surface temperature anomalies (SSTA) during AMJ over the SWBOB /EQ.ESIO and thickness anomalies at 850 hPa during July/August over the SWBOB

TIOD Years	SSTA (AMJ)	Thickness Anomalies
	SWBOB /EQ.ESIO	July /August
1982	-0.03/-0.19	-0.30/-0.38
1991	+0.44/+0.18	+0.88/0.00
1994	-0.18/-0.33	-0.71/-1.52
1997	+0.24/+0.24	+1.46/+1.43
2006	+0.07/+0.26	+1.15/+0.29
2007	+0.04/+0.24	+0.88/+0.73
2008	-0.19/-0.31	-0.07/-0.38

anomalous dry (wet) conditions over Tamilnadu and Coastal A.P. When the seasonal thickness is analyzed during JJA, the analysis showed that the year 1994 (dry year) has lowest thickness while 2007 (wet year) has the highest thickness and difference in thickness between two years is significantly found to be 12.47 m.

Rainfall activities depend on moisture availability in addition to the atmospheric instability. Wind speed/ direction decide the moisture advection in the region. Figs. 6(a-b) show the anomalous east-west equatorial wind current during PTIOD which helps to enhance the south-west cross equatorial flow emerging from the Mascerene High (MH). Since TIOD mode is a seasonal locked activity and its emergence starts during April or May, it has been also observed that that the strong PTIOD years are associated with the normal Indian monsoon over Kerala indicating its direct relationship with the monsoon current. Fig. 6(b) shows a weak monsoon circulation in 1994 over entire east coast of India and weak low level convergence over the concerned region can be also seen. But in 2007, strong convective activities (with strong SST gradient) favour the monsoonal circulation over the regions [Fig. 6(a)]. Thermal winds associated with the weakening (intensifying) of the thermal gradient have large impact on the seasonal winds over the SWBOB leading to decrease (increase) in latent heat loss.

On analyzing the variation of the heat budget component LHF, positive LHF anomaly in the range of 20-40 w/m^2 was observed in the month of May during the driest year of 1994 over the region of SWBOB. Similar pattern of less latent heat loss and less evaporation is also found during August with positive LHF anomaly of the order of 10-20 w/m^2. But in the wet year of 2007, both the months May and August have shown significant negative LHF anomalies means enhanced evaporation with increased latent heat loss.

4. Conclusion

Based on above study, strong association between SST anomaly over the eastern end of tropical dipole and Indian monsoon rainfall over Eastern Coast has been found. It is established fact that PTIOD events caused excess rainfall over India during summer monsoon season, but in this paper, it has been attempted to explain the possible cause of large deficit/excess rainfall over Tamilnadu and Coastal Andhra Pradesh and its teleconnection with the colder /warmer EQ.ESIO regions. The seasonal rainfall over the Tamilnadu and Coastal Andhra Pradesh is below normal during the negative AMJSSTA and the positive TIOD years. In the emerging stage of dipole, cooling of EQ.ESIO weakens the southeasterly trade winds reaching towards southwest Bay of Bengal and decreases the strength of this monsoonal branch. Shifting of convective activity towards the east/north over the BOB has been observed. Significant changes were also observed in the meridional wind, OLR, SST over different parts of the eastern equatorial Indian Ocean. The positive anomaly of OLR over the SWBOB indicates the less convection over this region. Weak northerly winds in the region are observed due to colder SSTA between EQ.ESIO and SWBOB and weak thermal contrast may be the reason of less northward transport of moisture. Thermal winds associated with the weakening (intensifying) of thermal gradient have greater impact on seasonal winds over the SWBOB leading to decrease (increase) in latent heat loss. Also a reduction (increase) in the meridional SST gradient drives a corresponding response in the atmospheric thickness gradients and results anomalous dry (wet) conditions over Tamilnadu and Coastal A. P.

PTIOD has its own physical identity in the Indian Ocean and it is not associated with ENSO. Moreover, PTIOD co-occurred with the ENSO overrides in terms of impact on Indian monsoon rainfall. All the ENSO without PTIOD years caused adverse impact on Indian rainfall, but all ENSO years co-occurred with PTIOD produce normal to above normal rainfall. Best example is the year 1997 over the south Peninsular India when rainfall was normal. South peninsula has extensive orographic structure, but it received low rainfall in every ENSO years. However, it received 40% to 50% excess rainfall when ENSO co-occurred with the PTIOD. The AMJSST anomalies over the EQ.ESIO during PTIOD years change the atmospheric linkage nearby the ocean and ultimately rainfall activity. In 1982 (an ENSO + PTIOD year), Tamilnadu and Coastal A.P. received 37.6% and 25.5% below normal rainfall respectively while in 1997, another ENSO + PTIOD year, received almost normal rainfall. EQ.ESIO has negative AMJSSTA in 1982, while it has positive in 1997. Thus, emergence of positive TIOD over Indian Ocean pushed up the tendency of Indian summer monsoon, but significant variations during May in the anomalies of low level winds, OLR and SST over the equatorial east southern Indian Ocean and southwest Bay of Bengal provide some indication of the behaviour of rainfall activity over Tamilnadu and Coastal Andhra Pradesh during June to September.

However, it is important to explore the SST condition over the EQ.ESIO region using climate model and identify the physical mechanisms for above relationships. We plan to study the sensitivity of SST over different sectors of the Indian Ocean to Indian summer Monsoon Rainfall.

Acknowledgment

The authors want to acknowledge to the Department of Science and Technology, Government of India for using the computer facility under the project No.SR/AS/05/2008. We also want to acknowledge India Meteorological Department (IMD) who facilitated the work and provided a platform of receiving suggestions from scientists from time to time. We are also thankful to reviewers for their insightful comments which helped to improve the quality of the paper.

References

Abram, 2008, "Recent intensification of tropical climate variability in the Indian ocean", *Nature Geosci.*, **1**, 849-853.

Ashok, K., Guan, Z. and Yamagata, T., 2001, "Impact of the Indian Ocean Dipole on the decadal relationship between the Indian monsoon rainfall and ENSO", *Geophys. Res. Lett.*, **28,** 4499-4502.

Ashok, K., Guan, Z., Saji, N. H. and Yamagata, T., 2004, "Individual and combined influences of ENSO and the Indian Ocean Dipole on the Indian summer monsoon", *J. Climate*, **17,** 3141-3155.

Behera, S. K., Krishnan, R. and Yamagata, T., 1999, "Unusual ocean-atmosphere onditions in the tropical Indian Ocean during 1994", *Geophys. Res. Lett.*, **26,** 3001-3004.

Chandrasekar**,** A. and Kitoh, A., 1998, "Impact of localised sea surface temperature anomalies over the equatorial Indian ocean on the Indian summer monsoon", *Journal of the meteorological society of Japan*, **76**, 841-853.

Gadgil, Sulochana, Vinayachandran, P. N., Francis, P. A. and Gadgil, Siddhartha, 2004, "Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation", *Geophysical Res. Letters*, **31,** L12213.

Gualdi, S., Guilyardi, E., Navarra, A., Masina, S. and Delecluse, P., 2003, "The interannual variability in the tropical Indian Ocean as simulated by a CGCM", *Climate Dyn.*, **20,** 567-582.

Ihara, C., Kushnir, Y. and Cane, M. A., 2008, "Warming trend of the Indian ocean SST and Indian ocean Dipole from 1880 to 2004", *J. Climate*, **21**, 2035-2046.

Joseph, P. V. and Pillai, P. V., 1984, "Air-sea interaction on a seasonal scale over north Indian Ocean, Part-I: Interannual variations of sea surface temperature and Indian Summer monsoon rainfall", *Mausam*, **35**, 323-330.

Kinter III, J. L., Miyakoda, K. and Yang, S., 2002, "Recent changes in the connection from the Asian monsoon to ENSO", *J. Climate*, **15,** 1203-1215.

Kripalani, R. H., Kulkarni, A. and Sabade S. S., 2005, "South Asian monsoon precipitation variability : coupled climate model projections under IPCC AR4.", *CLIVAR Exchanges*, **10**, 3, 13-15.

Lau, N. C. and Nath, M. J., 2000, "Impact of ENSO on the variability of the Asian–Australian monsoons as simulated in GCM experiments", *J. Climate*, **13,** 4287-4309.

Li, T., Wang, B. Chang, C. P. and Zhang, Y. S., 2003, "A theory for the Indian Ocean Dipole-zonal mode", *J. Atmos. Sci.*, **60,** 2119-2135.

Loschnigg, J., Meehl, G. A., Webster, P. J., Arblaster, J. M. and Compo, G. P., 2003, "The Asian monsoon, the tropospheric biennial oscillation, and the Indian Ocean zonal mode in the NCAR CSM", *J. Climate*, **16,** 1617-1642.

Meehl, G. A. and Arblaster, J. M., 2002, "GCM sensitivity experiments for the Indian monsoon and tropospheric biennial oscillation transition conditions", *J. Climate*, **15**, 923-944.

Meehl, G. A., Arblaster, J. and Loschnigg, J., 2003, "Coupled ocean–atmosphere dynamical processes in the tropical Indian and Pacific Oceans and the TBO", *J. Climate*, **16,** 2138-2158.

Murtugudde, R. G., McCreary, J. P. and Busalacchi, A. J., 2000, "Events in the Indian Ocean with relevance to 1997-1998", *J. Geophys. Res.*, **105,** 3295-3306.

Navarra, A., Ward, M. N. and Miyakoda, K., 1999, "Tropical-wide teleconnection and oscillation, I: Teleconnection indices and type I/type II states", *Quart. J. Roy. Meteor. Soc.*, **125,** 2909-2935.

Rao, K. G. and Goswami, B. N., 1988, "Interannual variations of sea surface temperature over the Arabian Sea and the Indian monsoon: A new perspective", *Mon. Wea. Rev.* **116**, 558-568.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401**, 359-363.

Shukla, J., 1975, "Effect of Arabian Sea-surface temperature anomaly on Indian summer monsoon: A numerical experiment with the GFDL model", *J. Atmos. Sci.*, **32,** 503-511.

Shukla, J. and Misra, B., 1977, "Relationship between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India", *Mon. Weather Rev.*, **105,** 998-1002.

Shukla, J. and Fennessy, M. J., 1994, "Simulation and predictability of monsoons", Proc. Int. Conf. on Monsoon Variability and Prediction, Tech. Rep. WCRP-84, Geneva, Switzerland, World Climate Research Program, 567-575.

Slingo, J. M. and Annamalai, H., 2000, "1997 : The El Niño of the century and the response of the Indian Summer Monsoon", *Mon. Weath. Rev.*, **128**, 1778-1797.

Swapna, P. and Krishnan, R., 2008, "Equatorial undercurrents associated with Indian Ocean Dipole events during contrasting summer monsoons", *Geophys. Res. Lett.*, **35**, L14S04.

Ummenhofer, Caroline C.**,** Sen Gupta, Alexander**,** Taschetto, Andréa S.**,** and Matthew H. England, 2009, "Modulation of Australian precipitation by meridional gradients in East Indian ocean sea surface temperature", *Journal of Climate*, **22**, 5597-5610.

Weare, B. C., 1979, "A statistical study of the relationships between ocean surface temperatures and the Indian monsoon", *J. Atmos. Sci*., **36**, 2279-2291.

Webster, P. J., Moore, A. M., Loschnigg, J. P. and Leben, R. R., 1999, "Coupled ocean-atmosphere dynamics in the Indian ocean during 1997-98", *Nature*, **401**, 356-360.

Yamazaki, K., 1988, "Influence of sea surface temperature anomalies over the Indian Ocean and Pacific Ocean on the tropical atmospheric circulation: A numerical experiment", *J. Meteor. Soc. Japan*, **66,** 797-806.