MAUSAM, **66**, 2 (April 2015), 287-298

551.553.21 : 551.526 (267)

Impact of changes in sea surface temperature over southern equatorial Indian ocean on Indian summer monsoon : A model study

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(*Received 29 July 2013, Modified 1 May 2014*)

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सार - इस शोध पत्र में 2009-1980 तक उपउष्णकटिबंधीय हिंद महासागर द्विध्रुव (STIOD) की घटनाओं के दौरान विशेषकर भारत के तटीय क्षेत्रों में भारतीय ग्रीष्मकालीन मॉनसून वर्षा (ISMR) पर समुद्र सतह तापमान (SST) की विसंगतियों के प्रभावों का अध्ययन किया गया है। इस अध्ययन के दौरान 6 प्रबल सकारात्मक और 8 नकारात्मक द्विध्रुव घटनाओं को अभिलेखित किया गया है। उपउष्णकटिबंधीय हिंद महासागर (IO) में बर्हिगामी दीर्घतरंग विकिरण (OLR) से सम्बद्ध याम्योतरी SST प्रवणता और गहन संवहन के मध्य प्रेक्षित संबंधों और ISMR पर उनके प्रभाव का विश्लेषण किया गया। हमने प्रबल SST द्विध्रुवों के दौरान दक्षिणी हिंद महासागर में SST की विविधताओं से सम्बद्ध उपउष्णकाटिबंधी OLR और पवन क्षेत्र के सामान्य अभिलक्षणों को दर्शाया है। यह देखा गया है कि विभिन्न चरणों में द्विध्रुव की घटनायें दक्षिणी भूमध्यरेखीय हिंद महासागर (SEIO) के अलग-अलग क्षेत्रों में उष्णता उत्पन्न करते हैं जिससे विशेषकर तटीय क्षेत्रों में ISMR पर उल्लेखनीय रूप से प्रभाव पड़ता है। सकारात्मक उपउष्णकटिबंधीय हिंद महासागर द्विध्रुव (PSTIOD) के कारण दक्षिण मध्य भूमध्यरेखीय हिंद महासागर (SCEIO) में उष्णता उत्पन्न हुई जिसकी वजह से भारत के पश्चिमी तट (ऊपरी पूर्वी तट) में वर्षा में उल्लेखनीय रूप से कमी (वृद्धि) हुई जबकि नकारात्मक उपउष्णकटिबंधीय हिंद महासागर द्विध्रुव (NSTION) के कारण दक्षिण पश्चिमी भूमध्यरेखीय हिंद महासागर (SWEIO) में उष्णता उत्पन्न हुई जिसकी वजह से पश्चिमी तट (ऊपरी पूर्वी तट) में वर्षा में वृद्धि (कमी) हुई। द्विध्रुव अवस्थाओं का प्रभाव प्रायद्वीप और दक्षिण प्रायद्वीपीय भारत की वर्षा पर भी उल्लेखनीय रूप से पड़ा NSTION (PSTIOD) अवस्थाओं के दौरान प्रायद्वीपीय वर्षा में वृद्धि (कमी) SEIO क्षेत्र में गहन संवहन के अंतरण पर निर्भर करती है। ISMR का अनुकरण करने के लिए राष्ट्रीय वायुमंडलीय अनुसंधान केंद्र (NCAR) के नवीनतम रूपांतरण क्षेत्रीय जलवायु मॉडल (CMS से संबंधित) का उपयोग किया गया। RegCM3 ने हिंद महासागर के तटीय क्षेत्रों और आस-पास के समुद्री क्षेत्रों में वर्षा का सफलतापूर्वक अनुकरण किया है। ग्रीष्मकालीन मॉनसून प्रसरण और ISMR पर RegCM3 में 0.5° से द्वारा SEIO पर SST में बढ़ोतरी के प्रभाव का अध्ययन किया किया। SST (उष्ण) परीक्षण, उड़ीसा (UR) और पश्चिमी बंगाल के गांगेय क्षेत्र (GWB) में वर्षा में वृद्धि किंतु भारत के पश्चिमी तट में मॉनसून की वर्षा में कमी सहित उस क्षेत्र में संवर्धित गहन संवहन के साथ SCEIO की उष्णता उत्पन्न करता है। PSTIOD वर्षों में पश्चिमी उपउष्णकटिबंधीय हिंद महासागर (WSTIO) में OLR पश्चिम दक्षिणी हिंद महासागर (WSIO, 0 - 20° द, 50° - 60° पू (में माध्य समुद्र तल दाब (MSLP) के साथ (-0.81) उल्लेखनीय रूप से नकारात्मक ढंग से सहसंबंधित था। जब OLR, PSTIOD वर्षों में WSTIO में बढ़ा (कम) हुआ उस समय WSIO क्षेत्र में दाब कम (बढ़ा) हुआ है।

ABSTRACT. The influence of Sea Surface Temperature (SST) anomalies on Indian Summer Monsoon Rainfall (ISMR), especially over coastal regions of India during Subtropical Indian Ocean Dipole (STIOD) events from 1980-2009 has been studied. 6 strong positive and 8 negative dipole events were recorded during the period of study. The observed relationship between the meridional SST gradient and deep convection in relation to Outgoing Longwave Radiation (OLR) in the subtropical Indian Ocean (IO) and their impact on ISMR has been analyzed. We have demonstrated the common characteristics of the subtropical OLR and wind field in association with SST variations in the southern Indian Ocean during the strongest SST dipoles. It has been observed that the dipole events in different phases induce warming over different regions of the Southern Equatorial Indian Ocean (SEIO) which produces significant impact over ISMR, particularly over the coastal regions. Positive Subtropical Indian Ocean Dipole (PSTIOD) causes warming over the South Central Equatorial Indian Ocean (SCEIO) resulting in remarkable reduction (enhancement) in rainfall over the west coast (upper east coast) of India whereas Negative Subtropical Indian Ocean Dipole (NSTIOD) causes warming over the South Western Equatorial Indian Ocean (SWEIO) resulting in enhancement (reduction) in rainfall over the west coast (upper east coast). The impact of dipole phases is also significant on rainfall over Peninsular and south Peninsular India. Increase (decrease) of peninsular rainfall during NSTIOD (PSTIOD) phases depends on the shifting of deep convection over the SEIO region. The Regional Climate Model (RegCM3), a recent version of National Center for Atmospheric Research (NCAR) has been used to simulate the ISMR. RegCM3 successfully simulates the rainfall over Indian coastal regions and its surrounding sea areas. The influence of increase in SST over SEIO by 0.5 °C in RegCM3 on the summer monsoon circulation and ISMR has been studied. The SST (warm) experiment produces warming of SCEIO with increased deep convection over the region with increase in rainfall over Orissa (UR) and Gangetic West Bengal (GWB), but reduced monsoon precipitation over the west coast of India. OLR over the West Subtropical Indian Ocean (WSTIO) during PSTIOD years is significantly negatively correlated (-0.81) with the mean sea level pressure (MSLP) over West Southern Indian Ocean (WSIO, 0 - 20° S, 50° E - 60° E). When OLR is enhanced (reduced) over WSTIO during PSTIOD years, pressure is reduced (enhanced) over the WSIO region.

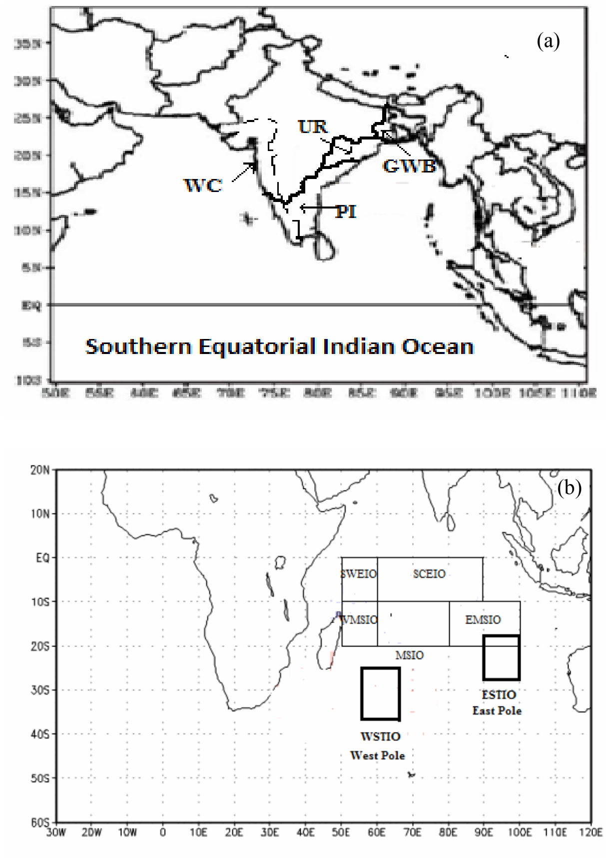
Key words – Deep convection, Subtropical Indian Ocean dipole, Sea surface temperature, Outgoing longwave radiation, Precipitation, Mean sea level pressure.

1. Introduction

Various important SST modes in different Oceans have been extracted by the use of empirical orthogonal function (EOF) analysis. The first mode in the Pacific accounts for about 40% of the total SST variance and corresponds to the El Nino phenomenon. Barber (1983) and Timmermann *et al.* (1999) found Pacific Ocean as an important key area for research by virtue of its size. Compared to the Pacific Ocean, the role of Indian Ocean (IO) in influencing the regional climate patterns has not attracted much attention. After recent works of Reason (1998 & 1999); Reason and Mulenga (1999); Yu and Rienecker (1999, 2000); Webster *et al.* (1999); Anderson (1999); Saji *et al.* (1999) and Behera and Yamagata (2001), more investigators are now focusing their attention to investigate the linkages between atmospheric circulation and rainfall anomalies in this region. Saji *et al.* (1999) defined a dipole in SST field over the equatorial IO which has linkage with precipitation anomalies in eastern Africa, Indonesia and Indian region. Murtugudde and Busalacchi (1999) showed that most of the significant SST anomalies in the East Subtropical Indian Ocean (ESTIO) are typically associated with SSTA of the opposite sign in the WSTIO. More recently, Behera and Yamagata (2001) dealt with the subtropical SST dipole in the southern IO. The largest correlation between SST and ISMR indices has been found in the subtropical IO (Goswamy, 1997) and the largest SST change in the southern IO (Reason 1999; Yu and Rienecker, 2000; Behera and Yamagata, 2001). Several investigators, like, Yamagata and Masumoto (1992); Yasunari and Seki (1992); Reason and Mulenga (1999) have shown that the interannual and interdecadal variations in the atmosphere may result from the air-sea interaction in subtropical regions. At present, tropical and subtropical SST dipoles are proposed but the interannual-interdecadal variability in the IO as well as their linkages with the monsoon circulation and precipitation anomalies surrounding the ocean and Indian subcontinent are not well known and required more studies.

The prominent mode of subtropical interannual variability that influences the SIO is STIOD [Behera and Yamagata (2001) and Suzuki *et al*. (2004)]. Domains preferred for WSTIO and ESTIO are 55° E-65° E, 37° S-27° S and 90° E-100° E, 28° S-18° S respectively (as considered by Behera and Yamagata, 2001). They have described an independent climate signal as the subtropical dipole mode events that generally evolve during the austral summer with opposite polarity in the SST anomalies of the subtropical region. The evolution of SST anomalies during subtropical dipole events is found to be linked with the strengthening/weakening of the atmospheric subtropical high normally observed in the sea level pressure. The mechanism for cooling in the eastern pole during a positive mode are strengthened southeasterly trade winds and resultant enhanced ocean surface evaporation and mixing, while the western warm pole develops concurrently with increased poleward Ekman transport of warm SST from tropical latitudes combined with decreased equatorward cold air advection and ocean surface evaporation (Reason, 1999; Venzke *et al*., 2000; Behera and Yamagata, 2001; Qian, 2002; Hermes and Reason, 2005; Chiodi and Harrison, 2007; Huang and Shukla, 2007b). In negative mode, the SSTA poles are generally reversed with cold air advection and equatorward Ekman pumping occurring over the SWIO in conjunction with more frequent cold frontal passages while warm air advection is located more frequently over the southeastern part of the basin.

Anomalous latent heat flux (LHF) plays an important role for the formation of STIOD. This flux anomaly is caused by the anomaly in wind field which in turn is associated with a pressure anomaly in the central region of the SIO (Suzuki *et al*., 2004). Since the flux anomaly starts developing during austral fall in the year previous to the event peak and develops for the next 9 months, air-sea interaction plays an active role in the formation of STIOD. Different field changes occur during subtropical dipole SST mode in SIO. The dipole events in its different phases have significant impact over tropical IO with warming in



Figs. 1(a&b). (a) Location the southern equatorial Indian Ocean (SEIO) where the warm SST of 0.5 °C is applied in the sensitivity experiment and (b) Location map of the different blocks in the Indian Ocean

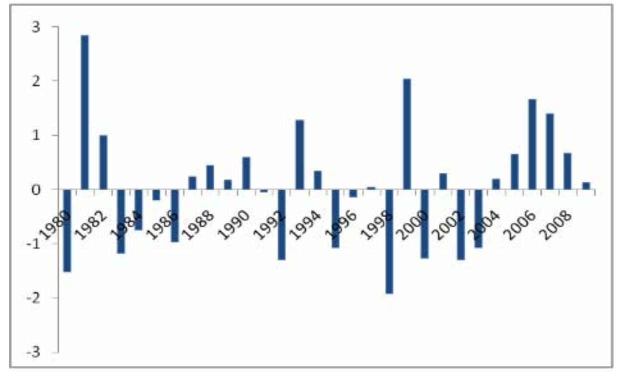


Fig. 2. Normalized subtropical dipole index (blue line) from 1979-2008

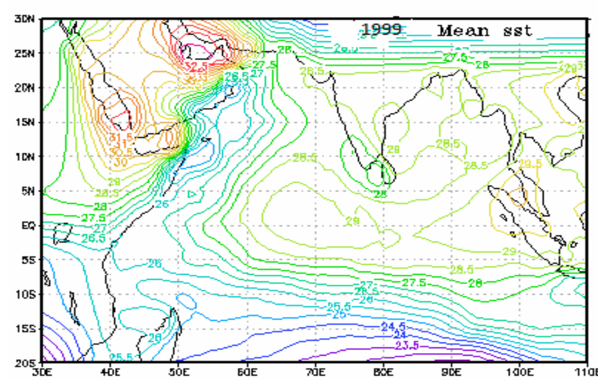


Fig. 3. Mean SST (1981-2010) in 1999 over the southern equatorial Indian Ocean

one region and cooling in another region. An experiment with RegCM3 has been conducted by imposing positive SST anomaly over the SEIO region to examine its impact on rainfall. Indian monsoon rainfall shows increasing and decreasing trend in response to northward shift of ITCZ. A dipole event over STIO influences the regional position of ITCZ. The main objective of this study is to examine the impact of SST gradients across IO on seasonal variations in precipitation over India.

2. Data and methodology

Monthly 1° Lat. × 1° Long. gridded SST anomalies obtained from Smith and Reynolds, National Oceanic and Administrative Agency/National Climatic Data Centre (NOAA/NCDC) and Extended Restructured Sea Surface Temperature (ERSST) v2. SSTA were averaged for December-January-February (DJF) months. The climatology was defined as the mean SST during the period of 1980-2009 to address the state of the Indian Ocean. The OLR and wind anomaly data sets from National Center for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis have been used in the present study. Time series of seasonal rainfall for the regions under consideration have been taken from Indian Institute of Tropical Meteorology (IITM) data set generated from the station rainfall data of the India Meteorological Department (IMD). The domains examined in this study are 10° S-Equator, 50° E-60° E (SWEIO), 10° S-Equator, 60° E-90° E (SCEIO) for SST and OLR anomalies, 20° S-10° S, 50° E-60° E (WMSIO) and 20° S-10° S, 90° E-100° E (EMSIO) for OLR, pressure and wind anomalies [Fig.1(b)]. The terrain height and land use data were generated from the Global Land Cover Characterization (GLCC) global 2 min resolution terrain and land use data from NCEP/NCAR Reanalysis Product Version 2.

The modified version of RegCM3 used in the present study was originally developed by Giorgi *et al*. (1993 a & b) and then augmented and described by Giorgi and Mearns (1999) and Pal *et al*. (2000). The dynamical core

TABLE 1

Seasonal polarities of OLR in DJF and MAM and monthly MSLP polarities in May over WSTIO during Positive Subtropical Indian Ocean Dipole (PSTIOD) years

PSTIOD years	DJF (Austral summer)	MAM (pre-monsoon season)	
	OLR		MSLP (May)
	WSTIO	WSTIO	WSTIO
1981	positive	negative	negative
1982	negative	negative	negative
1993	negative	negative	negative
1999	positive	negative	negative
2006	positive	negative	negative
2007	positive	positive	negative

TABLE 2

Same as in Table 1 but for Negative Subtropical Indian Ocean Dipole (NSTIOD) years

PSTIOD years	DJF (Austral summer)	MAM (pre-monsoon season)	
	OLR		MSLP (May)
	ESTIO	ESTIO	WSTIO
1980	negative	negative	positive
1983	negative	positive	positive
1992	negative	negative	negative
1995	positive	positive	positive
1998	positive	negative	positive
2000	positive	negative	positive
2002	negative	negative	positive
2003	negative	positive	positive

of the RegCM3 is similar to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model MM5 (Grell *et al*., 1994). In all experiments, the central longitude and central latitude is centered at 80° E and 16° N respectively. The model domain covers the area bounded between 48° E to 112° E and 40° N to 10° S with a horizontal grid distance of 50 km. The grid is defined on a Normal Mercator (NORMER) projection. The details about RegCM3 can be found in Singh and Oh (2007).

3. Results and discussion

Two contrasting years 1998 and 1999 are considered to link the variation of rainfall with the variation of deep convection over the subtropical IO. In the sensitivity study, a warm SST of 0.5 °C was superimposed over Southern Equatorial Indian Ocean (Equator - 10° S and 48° E - 112° E) [Fig. 1(a)] in the model domain and all other features of the model were kept the same, as in the control (CTL) experiments. There were six strong positive SST dipoles during study period (1980-2009) with dipole Index (STIODI) ≥1 SD when averaged in Austral summer and eight strong negative SST dipoles with dipole Index (STIODI) ≤ -1 SD (Fig. 2). STIODI was computed from SST anomaly difference between western (55° E-65° E, 37° S-27° S) and eastern (90° E-100° E, 28° S-18° S) subtropical Indian Ocean.

OLR over the ESTIO is negatively correlated with OLR over the WSTIO. Surface pressure and OLR are positively correlated. We also find the subtropical level pressure and the zonal (west-east) component of the surface wind are consistent with the OLR anomalies.

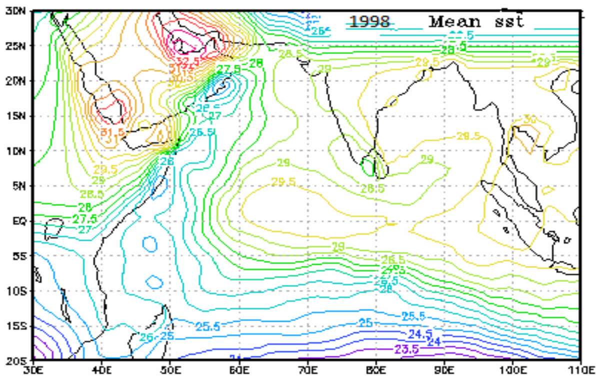


Fig. 4. Same as in Fig. 3 except for 1998

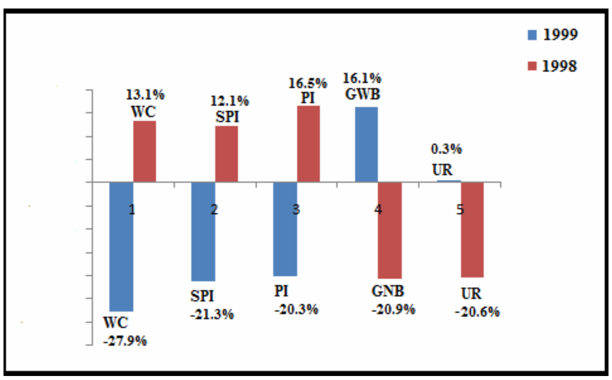


Fig. 5. % Departure of observed rainfall over peninsular, south peninsular India, Gangetic west Bengal and Orissa during 1998 and 1999

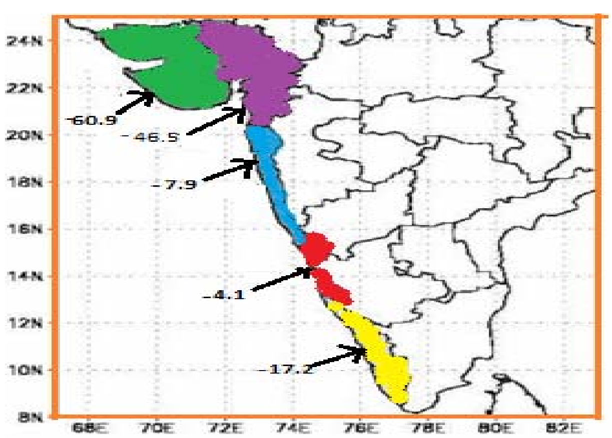


Fig. 6. % Departure of observed rainfall over the west coast of India in 1999

Thus, when deep convection is enhanced over the WSTIO and reduced over the ESTIO, the pressure is reduced over the western part and enhanced over the eastern part. Surface pressures between two poles are oppositely correlated (-0.55) during PSTIOD years. The anomalous pressure gradient (with pressure increasing from west to east) is associated with easterly anomalies in the zonal wind. On the other hand, when deep convection is enhanced over the eastern part, westerly anomalies are found in the zonal wind at the subtropical Indian Ocean. We call the oscillation between these two states as the Subtropical Indian Ocean Oscillation (STINOO). We usean index of the STINOO, based on the anomaly of the zonal component of the surface wind at the subtropics (60°-80°E, 25°S-30°S) which is positively correlated (+0.34) with the difference between OLR of WSTIO and ESTIO. The Sub-Tropical Zonal Wind Index (STWIN) is taken as negative of the anomaly (to make quantitively positive to easterly zonal wind). However, the correlation between STWIN and subtropical dipole mode index (STDMI) is higher than that of correlation between STWIN and OLR Index. While the zonal wind from the west coast of Australia has an important role in establishing SST dipole over subtropical IO, OLR pattern at the western pole is significant in circulation changes and precipitation. This aspect has been discussed below with the help of a numerical experiment with RegCM3.

The association between STWIN and ISMR is stronger than that between STDMI and ISMR. In every season with large positive (negative) STWIN, the ISMR anomaly was negative (positive). As far as OLR is concerned, a positive polarity of DJFSST of WSTIO induces a negative polarity of MAMOLR during PSTIOD years (Table 1). Among 6 PSTIOD years, 5 years showed negative OLR when averaged for MAM months. Since the location of the subtropical high is near WSTIO region, the polarities of MAMOLR over WSTIO are significant. A negative MAMOLR creates a low pressure area over the region. MSLP polarity in the month of May has been shown in Table 1. Surface pressure (May) and STDMI are highly negatively correlated. High SST over WSTIO induces low surface pressure and causes high rainfall over coastal South African countries and Indian Ocean (IO). During 8 years of negative STIOD, 5 years showed negative OLR polarity over ESTIO (Table 2). SST polarities of DJF (Austral summer) are correlated with OLR polarities of MAM (pre-monsoon season) in both STIODs (positive or negative). This also indicates that subtropical dipole starts in Austral summer and persists mostly till boreal summer and even monsoon season. It is seen that SSTAs in MAM months have the same sign as in DJF months (Table 3). Table 3 also shows that STDMI reached its maximum value in MAM months. Thus, SSTA anomaly for dipole phases starts during austral summer in the year previous to the event peak and develops for the next 6 months. Subtropical dipole phases are perhaps not influenced by the ENSO phases over Pacific Ocean as they could develop during years of La Nina (-ENSO), El Nino (+ENSO) and even during ENSO neutral (Table 3).

TABLE 3

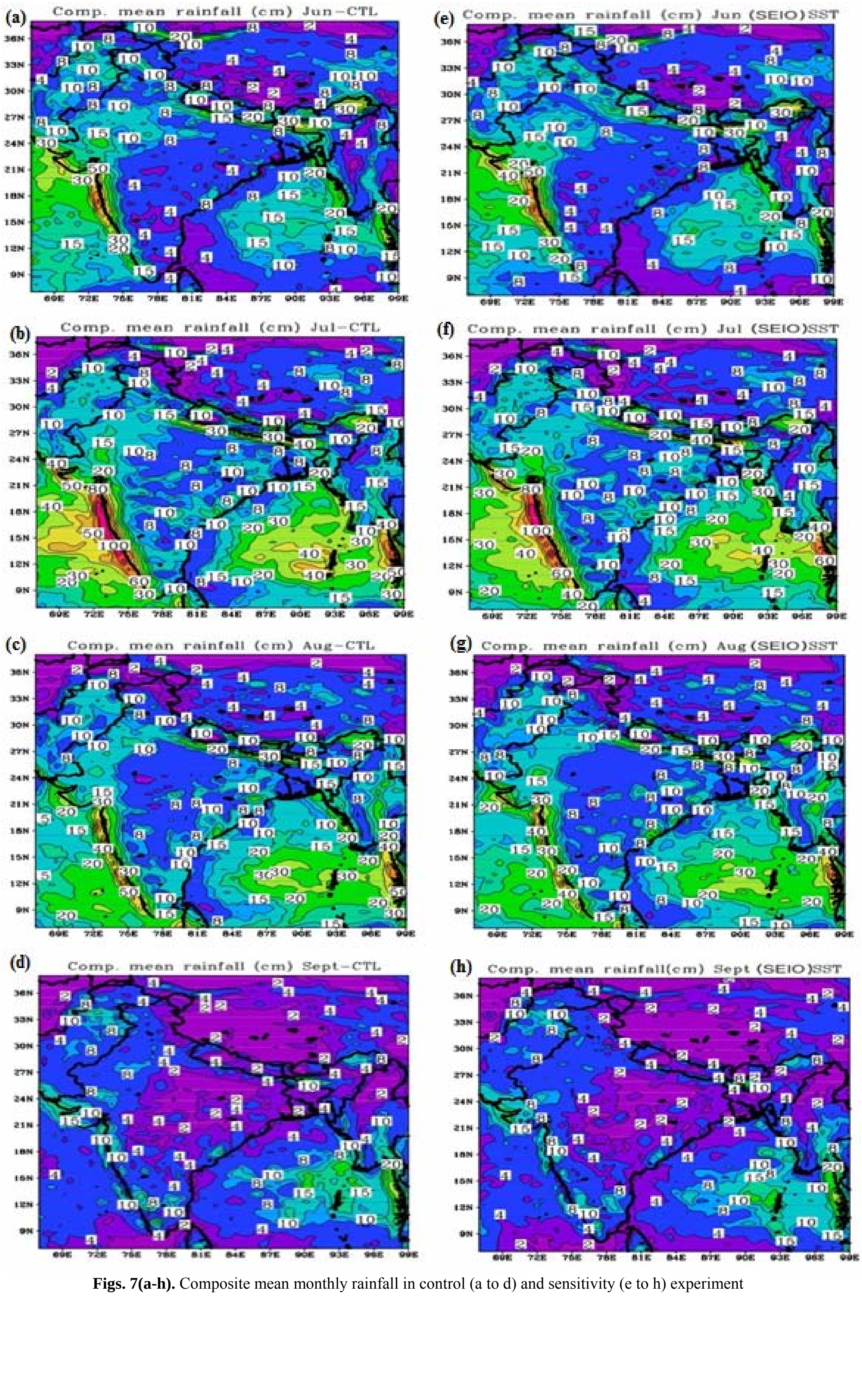
Mean MAM SSTA and month of higher STDMI during dipole phases over the Indian Ocean and ENSO phases over the Pacific Ocean

Years	Subtropical phases	Mean SSTA (MAM)	Month with higher STDMI	ENSO phase over Pacific Ocean
1980	negative	-0.41	March	Neutral
1981	positive	+1.01	March	Neutral
1982	positive	+1.41	March	+ ENSO
1983	negative	-0.30	April	- ENSO
1992	negative	-0.44	April	+ ENSO
1993	positive	+0.84	May	+ ENSO
1995	negative	-0.74	March	- ENSO
1998	negative	-1.54	March	- ENSO
1999	positive	+0.79	March	- ENSO
2000	negative	+1.24	April	- ENSO
2002	negative	-0.93	May	+ ENSO
2003	negative	-0.16	May	Neutral
2006	positive	+1.28	March	+ ENSO
2007	positive	+1.08	March	- ENSO

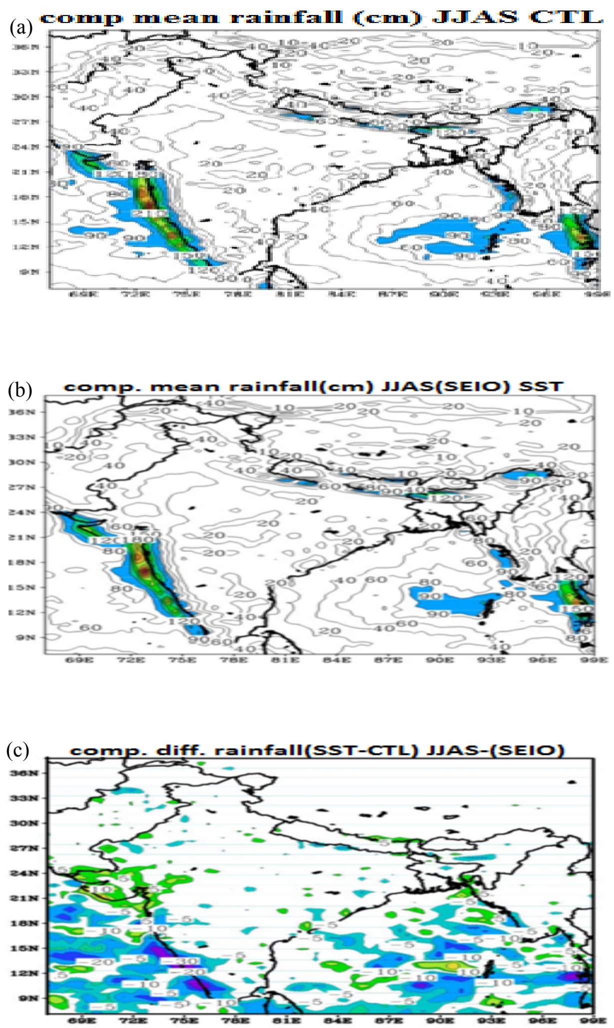
It is observed that SCEIO has warming trend in comparison to SWEIO during PSTIOD events and the thermal contrast over SEIO is shifted towards east (Fig. 3). During NSTIOD event, whole SEIO tends to have warmed up, but its thermal gradient is towards west with warmer SWEIO (Fig. 4). It is warmer with average 0.5 °C during negative dipole. Thus deep convection and low pressure near Somali coast cause enhancement of cross equatorial flow reaching Arabian Sea. The impact of this anomalous wind flow during PSTIOD (NSTIOD) event, is seen in rainfall over west coast of India. Also the enhancement (reduction) of rainfall over Gangetic W.B. and Orissa is due to excess (less) monsoon flow into BOB during PSTIOD (NSTIOD). The two subtropical dipole years 1998 (NSTIOD) and 1999 (PSTIOD) with La-Nina years (1998 was moderate and 1999 was strong La-Nina (www.cpc.ncep.noaa.gov./)) were chosen for this study. Percentage departure of rainfall of these two regions during 1998 and 1999 has been shown in Fig. 5. GWB received more rainfall (+16.1%) in 1999 whereas less rainfall (-20.9%) in 1998. Similar pattern of rainfall were observed over Orissa. Less amount of rainfall (although positive) over Orissa in 1999 was due to the deficient rainfall in September. Out of six PSTIODs, 4 years recorded positive rainfall in GWB and Orissa whereas out of eight NSTIODs, 6 years received negative rainfall. It is also observed that coastal Karnataka and Kerala subdivisions received significantly low rainfall of 4.9% and 17.2% respectively in 1999 whereas they received positive rainfall of 16.9% and 10.9% respectively in 1998 (Fig. 6). Anomalous negative rainfall (-27.9%) in 1999 and positive rainfall (+13.1%) in 1998 was observed over WC (Fig. 5).

RegCM3 model has been used for conducting control and sensitivity experiments in simulating the seasonal monsoon circulation and precipitation over Indian subcontinent. In the sensitivity experiment, we have increased the SST by 0.5 °C over the Southern Equatorial Indian Ocean (SEIO). The aim of the sensitivity experiment is to study the response of SST warmer by 0.5 °C over SEIO on seasonal monsoon circulation and precipitation over coastal India and its surrounding seas. RegCM3 results indicate that the model successfully simulates the low level (850 hPa) westerly and some anomalous circulations due to warming of SCEIO. Also the zone of low and high precipitation simulated by RegCM3 is close to the observational rainfall patterns. Thus PSTIOD event at subtropics accorded the SST warm results on seasonal circulations and rainfall anomalies.

Composite analysis of monthly rainfall for control and sensitivity experiments over SEIO has been shown in Figs. 7(a-h) and seasonal (JJAS) mean rainfall and difference (SST-control) has been shown in Figs. 8 (a-c).



Figs. 7(a-h). Composite mean monthly rainfall in control (a to d) and sensitivity (e to h) experiment



Figs. 8(a-c). Composite mean seasonal rainfall in JJAS (a) control, (b) warm SST and (c) difference between warm SST and control

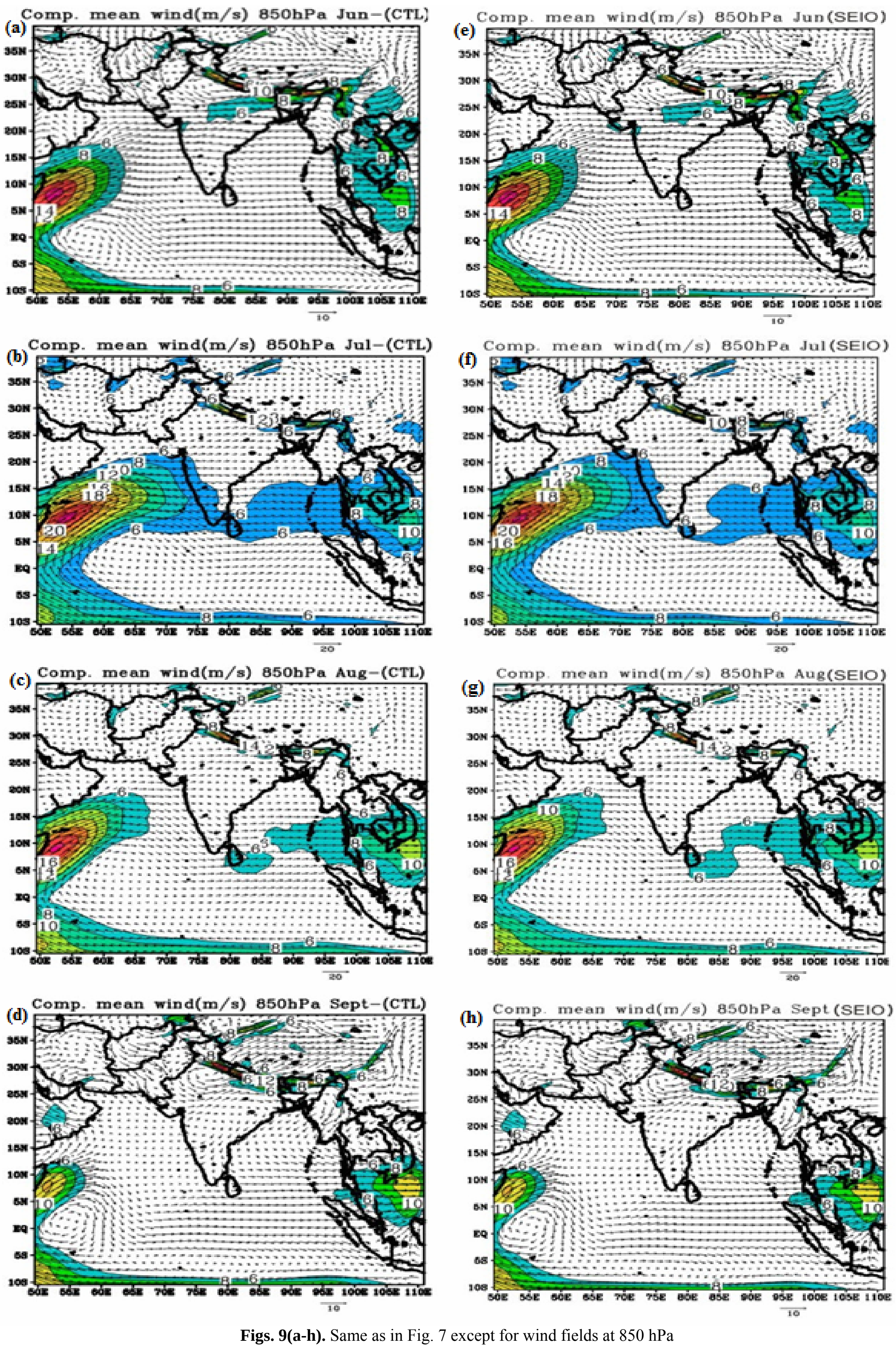
It is observed that warm SST has major impact over Arabian Sea and west coast of India. Figs. 8(a-c) shows that entire Arabian Sea and west coast of India except Gujarat region subdivision received deficient monthly rainfall in warm SST experiment. Percentage increase or decrease of rainfall [100* ($Rain_{SST}$ – $Rain_{CTL}$) / $Rain_{CTL}$] was calculated. The maximum decrease in rainfall is observed over Coastal Karnataka (-20%) and Kerala (-16.7%). Also deficient precipitation can be seen over adjacent Arabian Sea, central and eastern Bay of Bengal in the warm SST experiment. The enhancement of rainfall over Orissa and Gangetic west Bengal shown by the model is in agreement with the result shown by the PSTIOD event over subtropical IO. This might be due to the enhance flow of moist air into BOB during the warming of SCEIO.

Figs. 9(a-h) show the monthly and Figs. 10 (a&b) show the seasonal mean wind field in control and warm SST experiments while Fig. 10(c) shows difference in seasonal mean wind fields between warm SST and control experiments respectively. The above figures show that an anticyclonic circulation is centered near the coastal region of Konkan area and large amount of moisture entering into Gujarat. That is why a positive rainfall is simulated by the model. Also these figures show a cyclonic circulation south of equator centered over SCEIO under the influence of warm SST. The difference wind field at 850 hPa [Fig. 10(c)] is stronger by 0.5 m/s in this region and wind converges from both side of the equator. Thus deep convection over SCEIO and rainfall over west coast of India and surrounding seas simulated by the model in warm SST experiment are in accordance with the observed deep convection and atmospheric changes with rainfall during PSTIOD event. The mean state of SEIO is that the eastern IO is warmer than western IO.

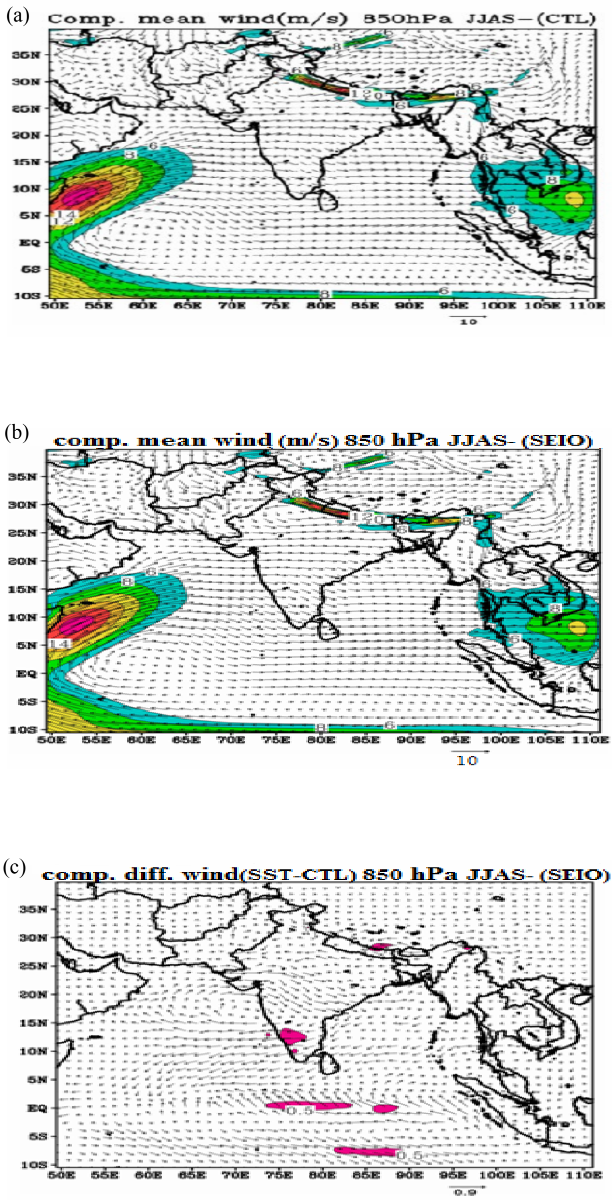
Socotra region from where Somali Jet enters Arabian Sea plays an important role in deciding the mass cross equatorial flows. In RegCM model with SST warm experiment, the monthly and seasonal monsoon circulation entering in this region is weaker comparison to the northern Arabian Sea as shown in Fig. 10 due to the reduction of flow in western AS. Lesser convection and evaporation over SWEIO region is expected in both SST warm experiment of RegCM model and observational analysis. In 1999, the whole west coast of India received significantly decreased rainfall (Fig. 6). Negative anomaly of rainfall over west coast during PSTIOD years might be the reason behind low seasonal rainfall over India.

During PSTIOD years, SST gradient over adjacent northern region weakens leading to change of seasonal atmospheric circulation with anomalous northeasterly winds (higher positive STWIN value) towards southern African coast. The northward movement of ITCZ during PSTIOD phase induces warming of SCEIO rather than SWEIO. During a NSIOD phase, the anomalous southwesterly winds (higher negative STWIN value) are observed towards the Australian coast. The regional convection is now located near the northern flank of Western Australia. This convection shifts westwards with northward movement of ITCZ seasonally. Atmospheric circulation with positive STWIN (negative STWIN) during PSTIOD (NSTIOD) favours the warming of SCEIO (SWEIO) regions and causes reduction (enhancement) of rainfall over west coast and enhancement (reduction) of rainfall over northern flank of east coast of India.

The impact of dipole phases over subtropical Indian Ocean is seen significantly on peninsular rainfall. During



Figs. 9(a-h). Same as in Fig. 7 except for wind fields at 850 hPa



Figs. 10(a-c). Same as in Fig. 8 except for wind fields

NSTIOD years, OLR over WMSIO are positively correlated with peninsular rainfall whereas OLR over EMSIO are highly negative correlated (-0.73). NSTIODs in general cause enhancement of deep convection over ESTIO and it penetrates up to EMSIO region. Those years like 1983, 1992, 1998 and 2000 which had negative OLR over EMSIO received above normal rainfall. Interestingly there is significant reduction of rainfall over PI and SPI during PSTIOD (Fig. 5). Percentage rainfall departure over SPI is +12.1% (-21.3%) and over PI is +16.5% (-20.3%) in 1998 (1999). This is because deep convection is shifted towards SWEIO (SCEIO) during NSTIOD (PSTIOD) resulting in flow of moisture towards AS (BOB). The RegCM3 result in warm SST experiment is also consistent with the observational result. An anticyclonic wind field instead of southwesterlies persists over the Peninsular India. Due to the continuous low pressure area centered over SCEIO in the warm SST experiment, Figs. 9 and 10 show weaker wind arriving over the Peninsular India. Thus reduction of rainfall occurred over Peninsular India in RegCM3 warm experiment and PSTIOD event. 1992 and 1993 (NSTIOD and PSTIOD year respectively) have also the same pattern of rainfall over the regions in warm ENSO in Pacific Ocean and no Tropical Indian Ocean dipole (TIOD) in Indian Ocean. PSTIOD (NSTIOD) causes enhancement (decrease) of rainfall over Gangatic West Bengal and Orissa as described earlier. Patterns of rainfall over Peninsular India, GWB, Orissa and east-west coastal region during 1998 and 1999 is in agreement with the impact of deep convection over either end of the dipole.

4. Conclusions

(*i*) The association between SST and OLR anomalies over subtropical IO persists from Austral summer to boreal summer-monsoon season.

(*ii*) The effect of deep convection at western end of the subtropical dipole seems to be more on surface pressure at MSIO. OLR (DJF) over WSTIO during PSTIOD years is negatively correlated (-0.81) with MSLP (MAM) over WSIO (0-20° S, 50°-60° E).

(*iii*) The thermal gradient over Southern Equatorial Indian Ocean region is established in the direction of east (west) during PSTIOD (NSTIOD) phases and this causes more monsoonal flow in BOB (AS) respectively. The impact of this anomalous wind flow during PSTIOD (NSTIOD) event, negative (positive) rainfall is observed over west coast of India.

(*iv*) It is observed that coastal Karnataka and Kerala received low and significantly low rainfall of 4.9% and 17.2% respectively in 1999 (an year of PSTIOD and strong La Nina year) whereas they received positive and significantly high rainfall of 16.9% and 10.9% respectively in 1998 (an year of NSTIOD and moderate La Nina year).

(*v*) There is a significant impact on rainfall over Peninsular India, Gangetic W.B and Orissa. Reduction (enhancement) of rainfall over peninsular India, but enhancement (reduction) of rainfall over GWB and Orissa was observed during PSTIOD (NSTIOD) events.

Acknowledgment

The authors acknowledge the support of Department of Science and Technology, Government of India by providing computer facility under the project No. DST/CCP/NMSKCC/10. We also acknowledge India Meteorological Department (IMD) for facilitating the work by providing a platform for receiving suggestions from their scientists from time to time.

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