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The Indo-Pacific climate dynamics and teleconnections with a special emphasis on the Indian summer monsoon rainfall

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सार – भारत प्रशांत क्षेत्र में जलवायु गतिकी अंतः वार्षिक जलवायु परिवर्तनशीलता की अनेक प्रणालियाँ प्रबल है। एलनीनो दक्षिणी दोलन (ENSO) को भूमंडलीय जलवायु प्रणाली में जलवायु परिवर्तनशीलता की प्रबल प्रणाली के रूप में प्रमाणिक तौर पर देखा गया है। यह भारतीय ग्रीष्मकालीन मानसून ऋतु (ISMR) के साथ-साथ पूरे विश्व के मौसम और जलवायु पर प्रत्यक्ष अप्रत्यक्ष रूप से प्रभाव डालती है। उष्णकटिबंधीय हिंद महासागर में ENSO से उत्पन्न बेसिन वाइड प्रणाली संधारित्र की भाँति पश्चिम विलंब पश्चिमी प्रशांत और एशिया के समीपवर्ती भूक्षेत्र की जलवायु परिवर्तनशीलता पर संधारित्र की भाँति विलंब से प्रभावित होती है। हाल ही में हिंद महासागर द्विध्रुव (IOD) की पहचान अन्य प्रभावी जलवायु प्रणाली के रूप में हुई है जो कि भारतीय ग्रीष्मकालीन मानसून वर्षा सहित मौसम और जलवायु को विश्व व्यापी रूप से प्रभावित करती है। इसके अलावा, संभवतः भूमंडलीय उष्णीकरण प्रक्रिया से हाल ही के दशकों में ENSO की विशेषताओं में परिवर्तन हुआ है और ENSO मोडोकी नामक महासागरीय - वायुमंडलीय युग्मित मोड उभर कर आएगा। ENSO मोडोकी के संकेत मध्य प्रशांत महासागर में स्थित देखे गए हैं जो बेसिनों के दोनों ओर से विपरीत ध्रुवीय संकेत दे रहे हैं। ENSO भिन्न ENSO मोडोकी से संबद्ध टेलिकनेक्शन विश्व के अनेक भागों में देखा जा सकता है। इसके अतिरिक्त उष्णकटिबंधीय जलवायु मोड भारत प्रशांत क्षेत्र में भी उपउष्णकटिबंधीय जलवायु मोड है जो स्थानीय वायु समुद्र अन्योन्य क्रिया से संबद्ध है। विशेषकर हिंद महासागर उपउष्णकटिबंधीय द्विध्रुव (IOSD) में वर्षा परिवर्तनशीलता दक्षिणी अफ्रीका, आस्ट्रेलिया, भारत और यहाँ तक की दक्षिणी चीन में विशेष रूप में दिखाई देते हैं। हाल ही में तटीय वायु समुद्र अन्योन्य क्रिया मोड के अनेक मोडों की खोज की गई है। उनमें से सबसे दिलचस्प आस्ट्रेलिया के पश्चिमी तट से परे निंगालू निनो / निंगालू हैं। तटीय निनो का प्रबल प्रभाव न केवल तटीय पारिस्थितिकी की प्रणाली पर पड़ता है बल्कि आस्ट्रेलिया में क्षेत्रीय जलवायु परिवर्तनशीलता के ऊपर भी पड़ता है।

ABSTRACT. The climate dynamics in the Indo-Pacific sector is dominated by several modes of interannual climate variations. The El Niño/Southern Oscillation (ENSO) is historically recognized as the dominant mode of climate variations in the global climate system. It affects the weather and climate all over the world including Indian summer monsoon rainfall (ISMR) through direct and indirect pathways. Also, the ENSO-induced basin-wide mode of the tropical Indian Ocean is shown to have a delayed effect, like a capacitor, on the climate variations of the western Pacific and the adjacent land regions of Asia. The Indian Ocean Dipole (IOD) is recently recognized to be the other dominant climate mode that has worldwide impacts on weather and climate including ISMR. In addition, perhaps related to the global warming processes, the characteristics of the ENSO have changed in recent decades and a new ocean-atmosphere coupled mode called ENSO Modoki has emerged. The ENSO Modoki signals are seen centered in the central Pacific with opposite polarity signals appearing on both sides of the basin. Different from ENSO, the ENSO Modoki associated teleconnections can be seen in many parts of the world. Besides the tropical climate mode, the Indo-Pacific sector also has subtropical climate modes related to local air-sea interactions. Particularly, the Indian Ocean subtropical dipole (IOSD) is shown to have a significant correlation with the rainfall variability in southern Africa, Australia, India and even southern China. Several modes of coastal air-sea interactions modes are also discovered recently. The most interesting of them is the Ningaloo Niño/Ningaloo Niña off the western coast of Australia. This coastal Nino has a strong influence not only on the coastal ecosystem but also the regional climate variability in Australia.

Key words – ENSO, ISMR, ENSO Modoki, IOD.

1. Introduction

Climate dynamics of the Indo-Pacific sector has a significant effect on the monsoon rainfall variability of the Indian sub-continent. This in turn has a paramount impact on the socioeconomic conditions of the region, which is one of the densely populated regions of the world. Several societal sectors are dependent on the seasonal monsoon rainfall, during the summer months of June-September (JJAS). In particular, the summer crops in India are very

much dependent on the seasonal rainfall since more than half of the farm-lands are rain-fed. Therefore, the seasonal JJAS rainfall, which is about 70% of the annual rainfall, is vital for the agriculture-dependent economy. Any serious variations in the seasonal mean could not only jeopardise a large part of the farming system but also increase the risk to other associated economic sectors affecting the growth of Gross Domestic Product (GDP) of India. Gadgil and Gadgil (2006) have found that the impact of severe droughts has remained between 2 and 5% of GDP despite a substantial decrease in the contribution of agriculture to GDP over the decades.

Climate variability in the tropical Pacific, in particular the El Niño/Southern Oscillation (ENSO) has been historically linked to the deficiencies in Indian summer monsoon rainfall (ISMR) and associated droughts. The Southern Oscillation (SO) was discovered by Walker (1924) while trying to find a cause for the monsoon failures and devastating Indian famines of the 19th century. Subsequently, the ISMR was linked to the oceanic counterpart El Niño (Wyrtki, 1975) of the coupled ENSO (Bjerknes, 1969). Based on the analysis of the sub-divisional rainfall data from India and Sri Lanka, Rasmussen and Carpenter (1983) have suggested a strong tendency of the summer monsoon to be below normal during the El Niño years. That relationship has been extensively studied over the years by many researchers (Sikka, 1980; Barnett, 1983; Keshavamurthy, 1982; Mooley and Parthasarathy, 1984; Ropelewski and Halpert, 1987; Ju and Slingo, 1995; Kripalani and Kulkarni, 1997; Soman and Slingo, 1997; Krishna Kumar et al., 1999; Krishnamurthy and Goswami, 2000; Kane, 2005; Annamalai and Liu, 2005; Rajeevan and Pai, 2007; Li and Lin 2016).

ISMR is generally deficient in the El Niño years but there were occasions when ISMR was either normal or above normal during an El Niño year. Therefore, the ENSO-ISMR relationship is not perfect giving rise to the possibilities to explore other modes of climate variations to understand the ISMR variability. Even the impact of the tropical Pacific on ISMR varies based on the source region of the impact. For example, Krishna Kumar et al. (2006) found that the warm SST anomalies in the central equatorial Pacific are more effective in producing droughts over India than the warm SST anomalies in the eastern equatorial Pacific seen in El Niño years. They have suggested that it is better to use an index with the SST pattern rather than the Nino3 index to predict the ISMR using statistical models.

The central Pacific warming is seen to be associated with the El Niño Modoki phenomenon (Ashok et al., 2007; Weng et al., 2007). Different from canonical El Niños, the El Niño Modokis are characterized by warm SST anomalies in the central Pacific but with cold anomalies in eastern and western sides of the tropical Pacific. The opposite phase of El Niño Modoki is the La Niña Modoki when cold SST anomalies prevail in the central Pacific and warm anomalies prevail in eastern and western Pacific, which is analogous to La Niña phase of ENSO. Typical cases of El Niño Modoki and La Niña Modoki were seen in the boreal summer of 2004 and the boreal winter of 2000-2001, respectively. Similar to ENSO, ENSO Modoki refers to both phases of Modoki events. The Modoki events are also discussed as Trans-Niño (Trenberth and Stephaniak, 2001), Dateline El Nino (Larkin and Harrison, 2005), Central Pacific El Niño (Kao and Yu, 2009; Yeh et al., 2009) and Warm Pool El Nino (Kug et al., 2009). ENSO Modoki is seen in both boreal summer and winter and it causes global teleconnections different from those of the canonical ENSO (Ashok et al., 2007; Cai and Cowan, 2009; Kim et al., 2012; Pradhan et al., 2011; Taschetto and England, 2009; Wang and Hendon, 2007; Weng et al., 2007, Weng et al., 2009a; Weng et al., 2009b).

In recent years, the role of the Indian Ocean is discussed not only for the association with ISMR but also other modes of climate variations in the Indo-Pacific domain. The dominant mode of the SST variability in the tropical Indian Ocean is seen as a basin-wide mode (Cadet, 1985; Klein et al., 1999; Wallace et al., 1998; Venzke et al., 2000; Behera et al., 2003) with the loadings of warm/cold temperatures generally associated with El Nino/La Nina. Called as the Indian Ocean basin mode (IOBM), the mono-pole mode in a Principal Component analysis is shown to cause an enhancement of the western North Pacific subtropical high and the South Asian high (Wu et al., 2000; Terao and Kubota, 2005; Yang et al., 2007; He et al., 2015). Wu et al. (2000) suggested that a low-level anomalous cyclone induced by the warm SST anomaly by a warm IOBM, can enhance southerlies and promote deep convective precipitation to the east of IOBM. This in turn causes an anomalous anti-cyclonic circulation over the tropical Northwest Pacific and South Asia prolonging the influences of ENSO through the effects of charging and discharging (Yang et al., 2007) of the IOBM, like a capacitor in an electronic circuit. The IOBM effect on the tropical Northwest Pacific anomalous anticyclone is also confirmed by model simulation experiments (Li et al., 2008; Huang et al., 2010; Wu et al., 2010; Chowdary et al., 2011; Hu and Duan, 2015). Some studies find that the baroclinic Kelvin wave associated with the tropical Indian Ocean warming induces suppressed convection and an anomalous anticyclone over the tropical Northwest Pacific (Xie et al., 2009; Wu et al., 2009). Other studies suggested that the inter-basin interaction between the tropical Northwest Pacific
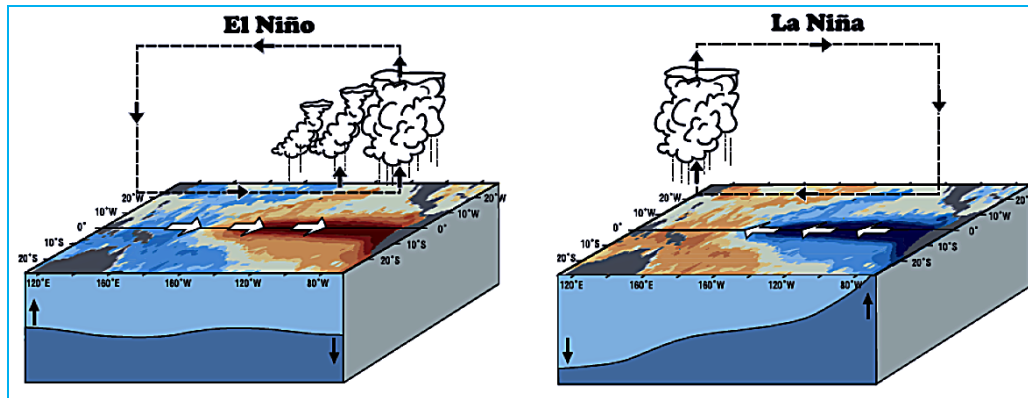
Fig. 1. Schematics of atmospheric and oceanic conditions associated with El Niño and La Niña

anomalous anticyclone and the north Indian Ocean warming (Du *et al*., 2009; Kosaka *et al*., 2013) could sustain the IOBM for extended period.

The Indian Ocean has another interesting mode of variability (Saji *et al*., 1999; Webster *et al*., 1999; Behera *et al*., 2003; Yamagata *et al*., 2004) known as the Indian Ocean Dipole (IOD). The IOD is a coupled ocean-atmosphere mode inherent to the Indian Ocean. During a positive phase of the IOD, the eastern Indian Ocean cools down owing stronger south easterlies and associated upwelling, advection and evaporation near Sumatra. That in turn suppresses the seasonal convection over there and feeds back to upwelling in a positive-feedback process. The resulting anomalous moisture transport positively influence the ISMR (Behera *et al*., 1999; Ashok *et al*., 2001; Ashok *et al*., 2004; Behera and Ratnam 2018) and the frequent occurrences of IODs in recent decades have weakened the ENSO-ISMR relationship (Krishna Kumar *et al*., 1999; Ashok *et al*., 2001; Loschnigg *et al*., 2003; Gadgil *et al*., 2004; Anil *et al*., 2016) as well as the Indian Ocean-East Africa short rains (Nakamura *et al*., 2009).

Coastal ocean circulations around India vary among the seasons. Their role in the local climate is not so well-understood. However, the circulation variations off western Australia and associated air-sea interactions give rise to a coastal phenomenon called Ningaloo Niño that influences the coastal ecosystem as well as the regional climate. Predictability of such a narrow coastal phenomenon is a challenge and need to be addressed.

Since these climate modes of Indo-Pacific sector affect the rainfall and temperature of many regions of the world, it is important to develop seasonal prediction systems that can reliably predict these climate modes. Over the last several decades much emphasis is given to the ENSO prediction. As a result, the ENSO predictability has been improved dramatically among these climate

modes. It is now time to focus more on the other modes of climate variability and their predictability that directly or indirectly influence the periodicity, evolution and strength of ENSO.

2.   ENSO and ENSO Modoki

The ocean-atmosphere variability in the tropical Pacific gives rise to seasonal warm pool in the western Pacific and cold tongue in the eastern Pacific. Anomalous events evolve sometimes, however, owing to an imbalance between the equatorial winds and the east-west slope in the thermo clines giving rise to the modes of climate variations: ENSO and recently found ENSO Modoki.

2.1. *The ENSO*

ENSO is certainly the dominant mode of climate variations in the tropical Pacific. The El Niño, which is the warm phase of ENSO, develops when large amounts of warm water, from the western Pacific warm pool, accumulates off the coast of Peru (Fig. 1). This helps to enhance the atmospheric convection in the eastern Pacific, east of the datelines and bring copious amounts of rainfalls over most of the neighboring landmass. In the opposite phase of the phenomena, called the La Niña, the equatorial cold tongue and the coastal cold waters are enhanced owing to the strengthened trade winds (Fig. 1). The warm/cold oceanic state combined together with the respective atmospheric condition is known as the ENSO, which is explained by a simple mechanism proposed by Bjerknes (1969). The positive ocean-atmosphere feedback of Bjerknes type amplifies, for example, initial warm perturbations in the eastern Pacific into large anomalies through ocean-atmosphere interactions and eventually develops an ENSO event. The ENSO variability and its impact on the rainfall variability over the Indian subcontinent, particularly the ISMR, has already been discussed in many previous studies. Therefore, in the

followings, I will focus most of my discussions on ENSO Modoki, the other newly identified mode of climate variations in the tropical Pacific.

2.2. *The ENSO Modoki and its impacts*

Different from canonical El Niños, the El Niño Modokis (Ashok *et al*., 2007) are characterized by warm anomalies in the central Pacific flanked by cold anomalies on both sides of the basin (Fig. 2). This phenomenon, also known as "Dateline El Niño" [Larkin and Harrison, 2005], "Warm Pool El Niño" (Kug *et al*., 2009) or "Central Pacific El Niño" (Kao and Yu, 2009), typically lasts from boreal summer through boreal winter and cause large-scale world-wide impacts, different from that of the canonical El Niño (Ashok *et al*., 2007; Ashok and Yamagata, 2009; Weng *et al*., 2007, 2009a, 2009b; Wang and Hendon, 2007; Cai and Cowan, 2009; Taschetto and England, 2009, Pradhan *et al*., 2011; Kim *et al*., 2012; Behera and Yamagata, 2018). Ashok *et al*. (2007) based on EOF and composite analysis showed that the ENSO Modoki (dominantly a second EOF mode) events are not necessarily related to the conventional ENSO (dominantly a first EOF mode) events. Therefore, they formulated a new index to define the ENSO Modoki events. The index called the ENSO Modoki index (EMI) is derived from the area averaged SST anomalies of three regions in the tropical Pacific.

$$EMI = \ [SSTA]_{CP} - 0.5*[SSTA]_{WP} - 0.5*[SSTA]_{EP}$$

The square brackets in the above equation represents the area-averaged SST anomaly over the regions CP (165° E-140° W, 10° S-10° N), WP (110° W-70° W, 15° S-5° N) and EP (125° E-145° E, 10° S-20° N), respectively.

The geographical domains of these three poles are different compared to other ENSO indices and three poles together make EMI unique in the sense that it captures a completely different variability in the SST anomalies of the tropical Pacific (Behera and Yamagata, 2018). Niño 3.4 index shares considerable parts of the central box of EMI and hence it mixes up two different types of variations in the tropical Pacific represented by ENSO and ENSO Modoki (Weng *et al*., 2007).

The physical processes associated with ENSO Modoki events are characterised by interactions among surface wind, SST and subsurface anomalies that remain confined in the central Pacific throughout the event cycle (Ashok *et al*., 2007; Kao and Yu, 2009; Kug *et al*., 2009). Ashok *et al*. (2007), using a lead/lag correlation between the EMI and satellite derived sea surface height (SSH) anomalies as well as a regression of the EMI with the
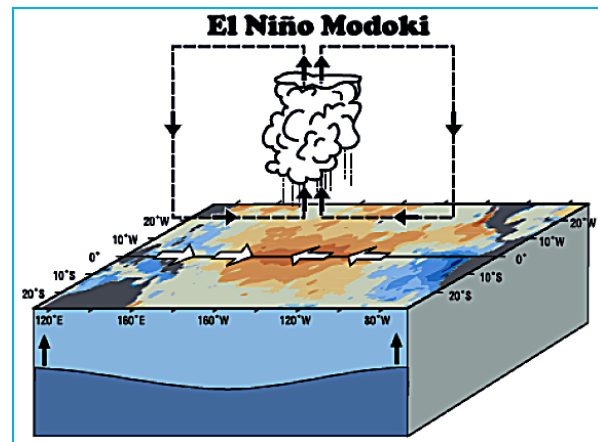

Fig. 2. Schematics of the atmospheric and oceanic conditions associated with El Niño Modoki. The conditions are reversed during La Niña Modoki

wind anomalies, have shown that the warm signal is excited by westerly wind anomalies in the western Pacific during the El Niño Modoki evolution. The westerly wind anomalies help to transport the warm water from the off-equatorial regions to the equator through the down welling equatorial Kelvin waves that subsequently deepen the thermocline in the central Pacific (Fig. 2). In the following months, SSH anomalies build-up in a positive feedback-process until the peak phase of the event. At this time, anomalous down welling Ross by waves propagate westward from the central tropical Pacific region. Together with the weakening of westerlies in the western Pacific following the peak phase, these down welling Rossby waves reduce the cold anomaly in the western Pacific and eventually cause the termination of the El Niño Modoki events. The process is basically opposite during the La Niña Modoki evolution.

The ENSO Modoki impact on the SSH variation is also evident in the decadal sea-level variation in the basin. In the recent decades, it is manifested by higher than normal sea levels in the central Pacific flanked by lower than normal sea levels on either side of the basin. The abnormal condition is evidently aided by frequent occurrences of El Niño Modoki events and associated wind convergence to the dateline during 2000-2004 (Behera and Yamagata, 2010). The sea level rise in the central Pacific succeeded a phase of lower than normal sea level associated with La Niña Modoki events during 1995-1999. The influence can even be seen in remote regions such as the coasts of California and Mauritius through atmospheric teleconnections.

The atmospheric teleconnections of El Niño Modokis are quite different from that of El Niños. For example, the persistent summer drought in the western
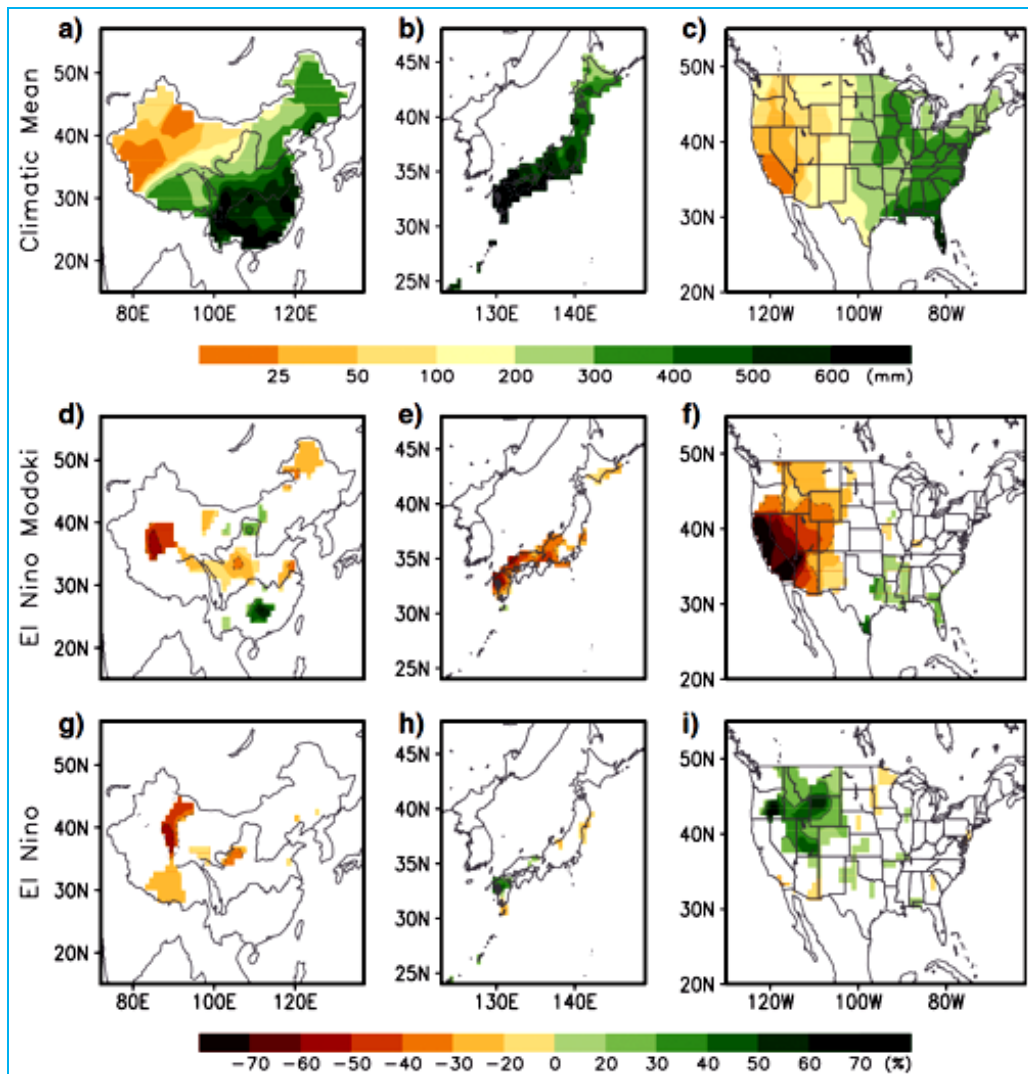
Figs. 3(a-i). Summer time rainfall climatology (1979-2005) for (a) China, (b) Japan and (c) the USA. Composite anomalies of summer rainfall in percentage departures to normal (%) for the three largest El Niño Modoki events are shown in (d) China, (e) Japan and (f) the USA. The corresponding composite percentage anomalies for the three largest El Niño events are shown in (g), (h) and (i). Adapted from Weng *et al.* (2007)

of the USA is caused not only by below-normal rainfall but also by above-normal temperature associated with El Niño Modoki summers (Weng *et al.*, 2007). The surface air temperature related to El Niño Modoki is warmer than normal in the western states, while it is cooler than normal in the central and eastern states. However, the El Niño-related temperature in most areas of the USA, except for the southeastern and northwestern states, is basically cooler than normal (Weng *et al.*, 2007).

In the western North Pacific, El Niño Modoki is associated with a positive Pacific-Japan pattern, enhanced western-north Pacific summer monsoon and weakened East Asian summer monsoon, which causes droughts in

most parts of Japan and the central eastern China, while flood in southern China (Weng *et al.*, 2007; Weng *et al.*, 2009b; Wang and Wang, 2013). The tropical storm activities near Japan and the southeastern USA may be enhanced during El Niño Modoki events [Figs. 3(a-i)]. Furthermore, a recent study indicated that concurrent occurrence of El Niño Modoki and positive Indian Ocean dipole (IOD) events can generate more cyclones over northwest Pacific (Pradhan *et al.*, 2011). The cooling associated with the Modoki events may lead to heat waves over coastal eastern India (Ratnam *et al.*, 2016).

The Indian summer monsoon is seen to be strongly affected by El Niño Modoki. Ratnam *et al.* (2010) and
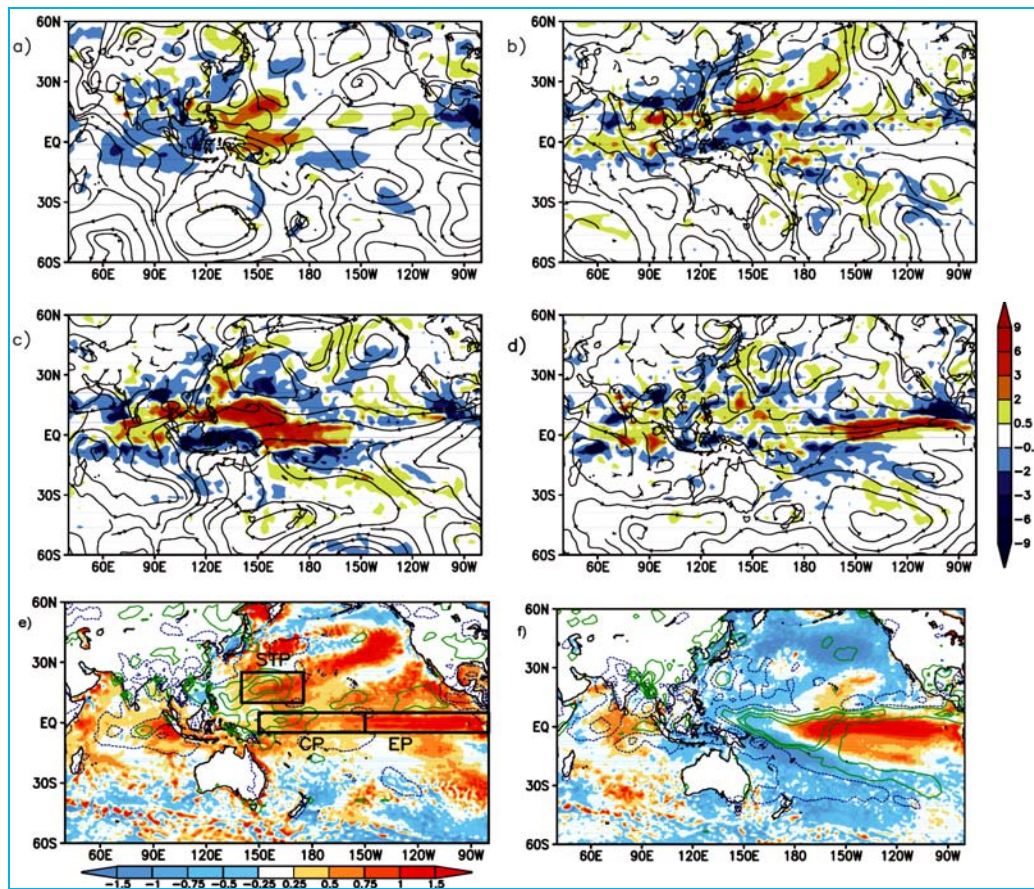
Figs. 4(a-f). Observed and model simulated precipitation anomalies (in mm/day; shaded) and wind anomalies at 850 hPa (streamlines) for June-September 2009. (a) Observed anomalies, (b) model simulated anomalies for STP (shown in e), (c) simulated anomalies for CP [shown in (e)] and (d) simulated anomalies for the EP [shown in (e)] perturbation experiments. SST anomalies (shaded) for (e) 2009 and (f) 1987 in °C. Adapted from Ratnam *et al.* (2009)

Ratnam *et al.* (2012) extensively studied the impact of the central Pacific warming, associated with the El Nino Modoki, on the ISMR of that year. Using observations and atmospheric general circulation model experiment results, they have shown that the central Pacific warming of that year caused a teleconnection to the subtropical northwest Pacific and that in turn suppressed the rainfall over India causing one of the severest droughts over the region [Figs. 4(a-f)]. By separating the influences arising from the SST anomalies in the different regions of the equatorial Pacific, they have found that the anomalous central Pacific warming generated a regional Walker circulation with updraft near the central Pacific and downdraft near the western Pacific. The downdraft in the western Pacific suppressed the atmospheric convection and the seasonal rainfall there. At this time, due to interaction between the strong low-level westerlies observed near the western Pacific and the suppressed convection, regions of low and high rainfall were observed from the equatorial western Pacific to subtropical north-western Pacific [Fig. 4(a-f)]. That enhanced precipitation region in the subtropical north-western Pacific caused rising motion there and sinking motion over the Indian longitudes, similar to the one discussed by Krishna Kumar *et al.* (2006). In a study Wang and Wang (2013) suggested that the difference in the rainfall anomalies in southern China could be associated with two types of El Niño Modokis. The El Niño Modoki I, which is characterised by symmetric SST anomaly distribution about the equator with the maximum warming in the equatorial central Pacific in their classification, cause anomalously higher rainfall in southern China owing to higher moisture transport around the anomalous anticyclone in the Philippine Sea associated with that type of Modoki event. In case of the El Niño Modoki II, characterised by an asymmetric distribution with the warm SST anomalies extending from the northeastern Pacific to the equatorial central Pacific, an anomalous cyclone resides east of the Philippines bringing northerly wind anomalies & causing a decrease in seasonal rainfall over southern China.
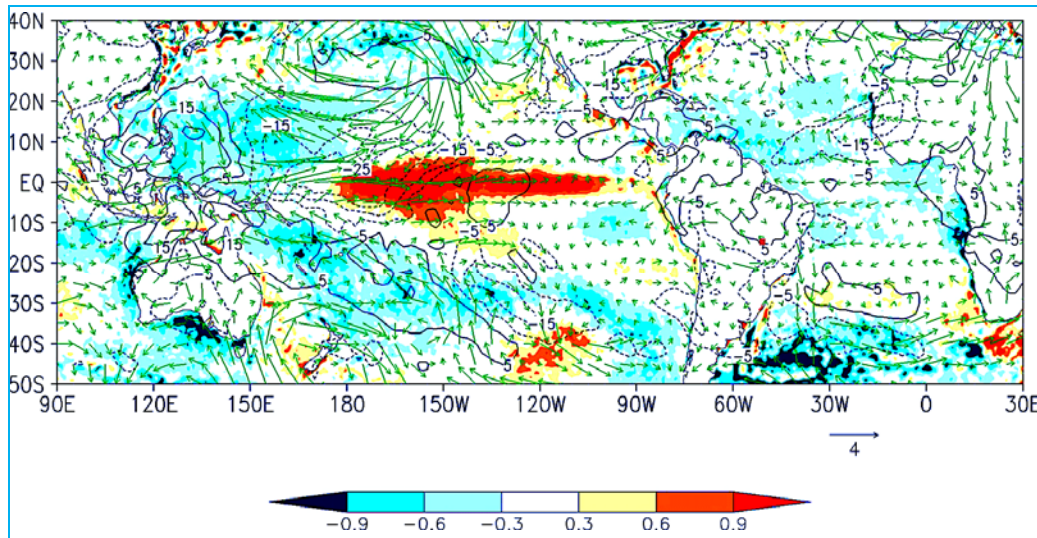
Fig. 5. Composite anomalies of SST (shaded), wind and OLR (contour) during austral summer season for all extremely low stream-flow events of Paranaíba River. Unit for SST is °C, for wind is m s^{-1} and for OLR is w/m^2. Values above 95% confidence level from a two-tailed Student's t test are shown. The red dot mark in the figure shows the location of the stream flow gauge station. Adapted from Sahu *et al*. (2014)

In the Southern Hemisphere, southern Africa experiences significantly below normal precipitation during El Niño events compared to El Niño Modoki events (Ratnam *et al*., 2014). The anomalous Matsuno-Gill response in the Indian Ocean and the anomalous tropospheric stationary wave response in the southern mid-latitudes are intense during El Niño events, causing drought over southern Africa. These processes are weaker during El Niño Modoki events. Over Australia, while classical El Niños are associated with a significant reduction in rainfall over northeastern and southeastern Australia, Modoki events appear to drive a large-scale decrease in rainfall over northwestern and northern Australia (Taschetto and England, 2009) causing distinct impacts on the wheat yield in the region (Yuan and Yamagata, 2015). In addition, rainfall variations during March-April-May are more sensitive to the Modoki SST anomaly pattern than the conventional El Niño anomalies there. The Modoki events are also linked to stream flows in Brazil. Ninety percent of extremely low-discharge events of the Paranaíba River in northern Brazil are associated with El Niño Modoki (Fig. 5) during the austral summer season (Sahu *et al*., 2014). It is suggested that the low-level convergence in the central Pacific associated with warm anomalies of El Niño Modoki gives rise to subsidence over most parts of the Amazon and Paranaíba catchments leading to reduced local rainfall and low river discharges there. Contrary to a general belief, not a single low-discharge event is found to be associated with canonical El Nino.

3. The IOD

In recent times, the Indian Ocean has come into the limelight following the introduction of the IOD (Saji *et al*., 1999) based on the analysis of the abnormal condition of the fall Yoshida-WyrtkiJet in 1994 (Vinayachandran *et al*., 1999) and the associated anomalies in the moisture transport to the Indian region affecting the ISMR (Behera *et al*., 1999). For a long time, the Indian Ocean was considered a passive element in the tropical system essentially controlled by El Niño through an atmospheric bridge (Cadet, 1985; Klein *et al*., 1999; Alexander *et al*., 2002; Lau and Nath, 2000; 2003). However, the discovery of the IOD has changed that viewpoint.

The SST dipole appears as the second dominant mode in the tropical Indian Ocean with cold SST anomalies off Sumatra and warm SST anomalies off Somali (as shown schematically in Fig. 6) during a positive IOD (and vice versa in a negative IOD). The SST dipole being affected by surface fluxes does not last for more than a couple of seasons; the event develops in late spring matures in early fall and terminates thereafter. Due to this short longevity, it appears lower in the order when SST anomalies for the whole year are separated into EOF modes. However, at the subsurface the ocean variation in response to the equatorial winds is dramatic. Portrayed in the SSH anomalies, the dipole appears as the dominant mode of variability in the subsurface (Rao *et al*., 2002). This subsurface dipole provides a basis of the delayed oscillator mechanism, which is required to reverse the
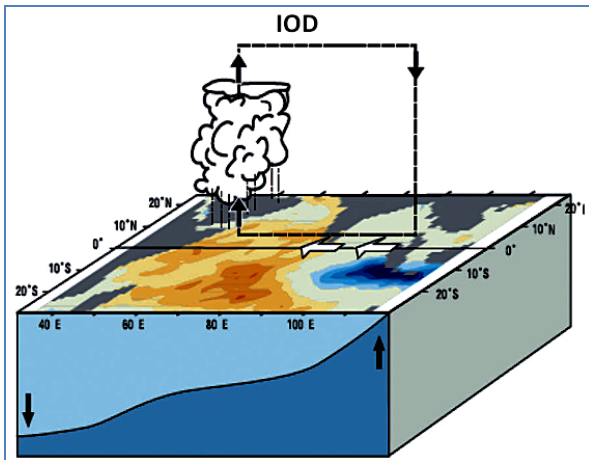
Fig. 6. Schematic of the atmospheric and oceanic conditions associated with a positive IOD event

phase of the surface SST dipole in the following year. The associated mechanism is related to the propagation of oceanic Rossby/Kelvin waves seen in observed data (Rao *et al.*, 2002; Feng and Meyers, 2003). Xie *et al.* (2002) suggested that those coupled Rossby waves are dominantly forced by ENSO, whereas Yamagata *et al.* (2004) and Rao and Behera (2005) have distinguished regions influenced by IOD and ENSO. The wind stress curl associated with the IOD forces the westward propagating down welling long Ross by waves north of 10° S. In contrast, the ENSO influence dominates over the upwelling dome south of 10° S in the southern Indian Ocean as suggested by Xie *et al.* (2002).

The non-linear interaction among ENSO, IOD and monsoon is very complex and the interactions between IOD and ENSO not only affect their amplitudes but also the periodicity of their inherent variations. Based on the results of a model sensitivity experiment, Behera *et al.* (2006) found that the interannual IOD variability is dominantly biennial when the ENSO variability is suppressed in the globally coupled SINTEX-F GCM [Fig. 7(a)]. In a parallel experiment, in which the ocean and atmosphere are decoupled in the tropical Indian Ocean to suppress IOD, the ENSO periodicity is protracted to a periodicity of 5-6 years [Fig. 7(b)]. Several other modeling studies also demonstrate the importance of the intrinsic processes within the basin for the IOD development (Iizuka *et al.*, 2000; Yu *et al.*, 2002; Gualdi *et al.*, 2003; Yamagata *et al.*, 2004; Lau and Nath, 2004; Cai *et al.*, 2005).

3.1. *IOD Impacts*

Like ENSO, IOD can exert its influence on the global climate by way of atmospheric teleconnection
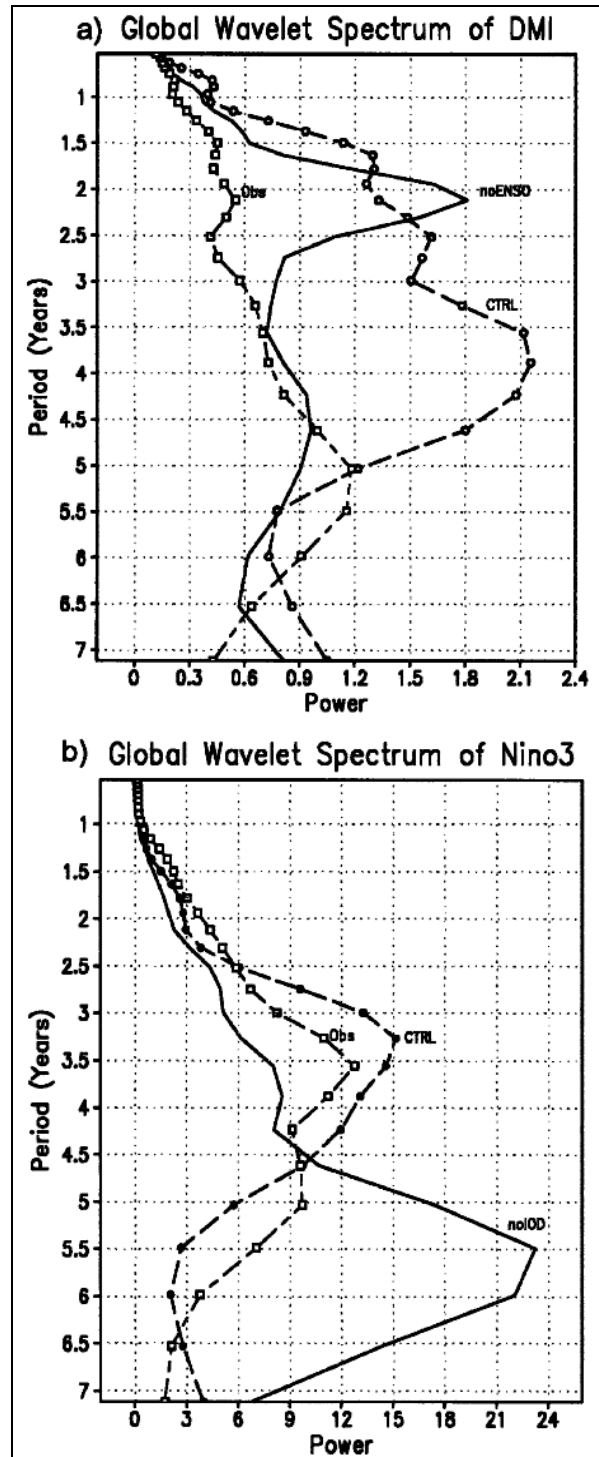
Figs. 7(a&b). Global wavelet spectrum of the DMI derived from SINTEX-F coupled model experiment when ENSO variability is suppressed (solid line), control experiment (dashed line marked by circles) and observation (dashed line marked by squares). (b) Same as in (a), but for Niño-3 index except for the solid line, which is for the experiment in which IOD variability is suppressed
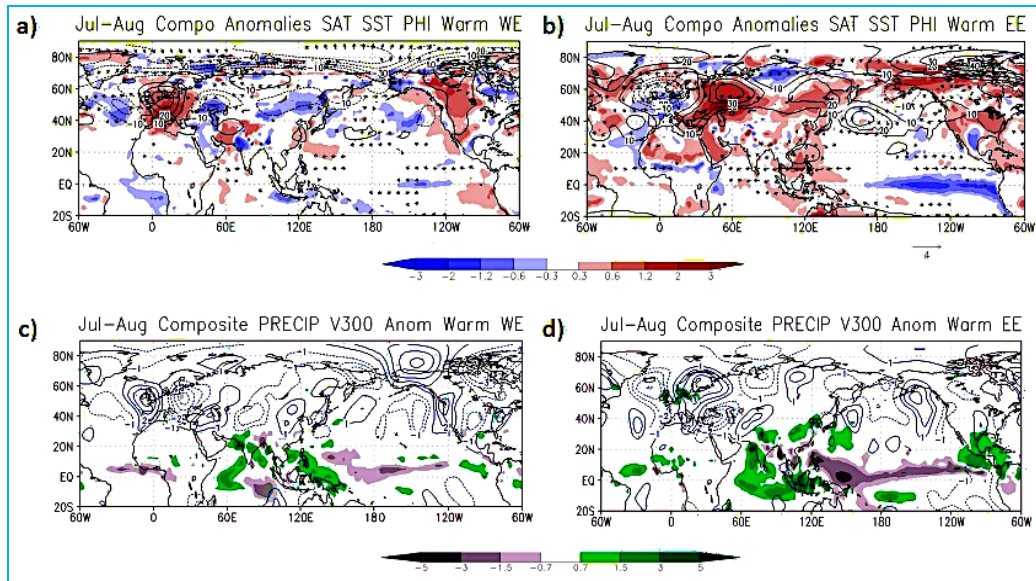
Figs. 8(a-d). (a) July-August composite anomalies of surface temperature (shaded), 850 hPa wind and geopotential height (contour) for the 4 extreme summers of Western Europe as given in Behera *et al.* (2012). (b) The corresponding composites of rainfall (shaded) and 300 hPa meridional wind anomalies. (b) and (d) same as (a) and (c) but for anomalies related to 4 extreme events of Eastern Europe. Values shown are above 85% level of statistical confidence from a 2-tailed t-test. Adapted from Behera *et al.* (2012)
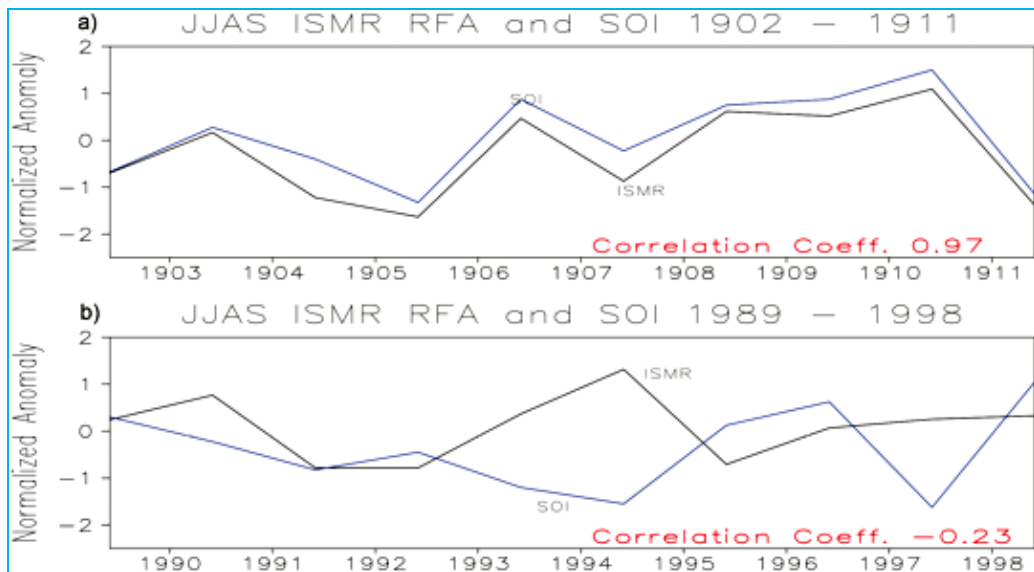
Figs. 9(a&b). The time series of Southern Oscillation Index (SOI) and Indian summer monsoon rainfall (ISMR) for (a) first and (b) last decades of the 20th century. Adapted from Behera (2018)

(Saji and Yamagata, 2003) and by interacting with other modes of climate variability. Through changes in the atmospheric circulation, IOD influences the Southern Oscillation (Behera and Yamagata, 2003), the ENSO (Izumo *et al*., 2010), rainfall variability during the Indian summer monsoon (Behera *et al*., 1999; Ashok *et al*., 2001; Ashok *et al*., 2003; Cherchi *et al*., 2007), the summer climate condition in East Asia (Guan and Yamagata,

2003; Guan *et al*., 2003), the African rainfall (Black *et al*., 2003; Clark *et al*., 2003; Behera *et al*., 2005; Manatsa *et al*., 2008; Manatsa and Behera, 2013), the Sri Lankan Maha rainfall (Zubair *et al*., 2003), the Australian rainfall (Ashok *et al*., 2003; Ummenhofer *et al*., 2008; Ummenhofer *et al*., 2013) and the Brazil rainfall (Chan *et al*., 2008). The precipitation over the northern part of India, the Bay of Bengal, Indochina and the southern part

of China was enhanced during the 1994 positive IOD event (Behera *et al*., 1999; Guan and Yamagata, 2003; Saji and Yamagata, 2003). Recently, Behera *et al*. (2012) have shown that IOD induced circum-global Ross by wave trains influence the summer conditions particularly in late July and early August over Western Europe: Some of the extreme summers of Western Europe are actually associated with the positive IODs [Figs. 8(a&c)]. The extreme summers over Eastern Europe are associated with negative IOD and La Niña [Figs. 8(b&d)]. Similarly, recent studies have shown the relatively stronger impacts of IOD on the stream flows in western part of Indonesia (Sahu *et al*., 2012; Behera, 2016). Sahu *et al*. (2012) have found that the extreme low-stream-flow events of Citarum River are related to positive IOD events though extreme high-stream flows were associated with La Nina. The cold anomalies in eastern Indian Ocean associated with the positive IOD induce anomalous low-level divergence and reduce the normal seasonal rainfall over that region.

3.2. *IOD Impacts on monsoon*

The Indian monsoon, generally represented by ISMR, is historically linked to the ENSO. For example, the droughts of 1790 to 1796 that caused severe famine, widespread civil unrest and socioeconomic turmoil in India occurred during the great El Niño of the late 18th century, which was felt worldwide (Grove, 2007). The relationship was reported to be strong even in the 20th century (Rasmussen and Carpenter, 1983). However, the relationship is shown to have weakened [(Figs. 9(a&b)] in recent decades (Krishna Kumar *et al*., 1999; Behera, 2018).

It has been revealed that the influence of the ENSO on the monsoon is complemented by the IOD (Behera *et al*., 1999). The IOD phenomenon modulates the meridional circulation in the region by inducing anomalous convergence patterns over the Bay of Bengal and strengthening of the monsoon trough over central India as seen in the typical IOD year of 1994. This relationship between IOD and ISMR was firmly established with long records of observational data and atmospheric model experiments (Ashok *et al*., 2001; Ashok *et al*., 2004). It is found that during positive IOD years, such as that in 1997, when the ENSO co-occurred with the positive phase of the IOD, the ENSO-induced anomalous subsidence is neutralized by the anomalous IOD-induced convergence over the Bay of Bengal. This explains why India recorded a near-normal seasonal rainfall during that summer in spite of a record breaking El Niño in 1997-98. The IOD-ISMR link is generally stable irrespective of the period of initiation and the lifetime of IOD events. Comparing the variability in the phases of their evolutions, a recent study suggested that an

early IOD also plays a significant role, like normal and prolonged IOD, in enhancing ISMR even though the strengths of those IODs are generally weaker compared to other IODs (Anil *et al*., 2016). The excess evaporation from the Arabian Sea and the stronger cross-equatorial flow in those early positive IOD years help the monsoon rainfall in those years.

These findings based on recent instrumental records and model experiments are further corroborated by the proxy data. Based on 100-yr of coral record, Nakamura *et al*. (2009) confirmed the recent shift in ENSO-monsoon and IOD-monsoon relationships. Analyzing their coral IOD index in the context of East African short rains they suggested that the relationship between the ENSO and Indian summer monsoon rainfall (ISMR) is weakened when IODs frequently occurred (e.g., in the1990s) leading to the strengthening of the IOD and ISMR relationship. The coral IOD index also correlates well with the East African short rains (EASR) that follow the Indian summer monsoon. The latter is explained by IOD's dominant influence on the short rains (Behera *et al*., 2005). The coral index, which represents the EASR variability, exhibits an intensification of the IOD events in recent decades as discussed in Abram *et al*. (2008). It, therefore, represents an enhanced coupling with the Indian summer monsoon. On the other hand, ENSO-ISMR correlation was significantly high during early part of the 20th century. That was the time when the IOD variability was lower than recent decades. This could be a reason for the discovery of the Southern Oscillation by Walker (1924) while trying to understand the monsoon failures and famines of the late 19th century. Compared to the 19th and 18th century, however, mega-droughts and famines are not seen in recent times mainly because of frequent occurrences of IODs.

These previous studies discussed above have studied the influence of the IOD on the Indian monsoon, in the light of diminishing ENSO impacts on ISMR. While these studies reported a general IOD-ISMR relationship, the regional variability and the impacts of opposite phases of IOD were not investigated. In a recent study the regional asymmetries arising from both phases of IOD teleconnections to India are discussed by Behera and Ratnam (2018). The ISMR variability related to opposite phases of the IOD is investigated by picking eight positive IOD (1982, 1994, 1997, 2003, 2007, 2008, 2012, 2015) and five negative IOD events (1992, 1996, 1998, 2013, 2016) since the satellite era of 1982. They have found that the ISMR response may not necessarily be spatially coherent to both phases of IOD as one would logically conclude based on the studied ISMR response to opposite phases of ENSO. The region of seasonal monsoon trough in central-western part of India showed a symmetric
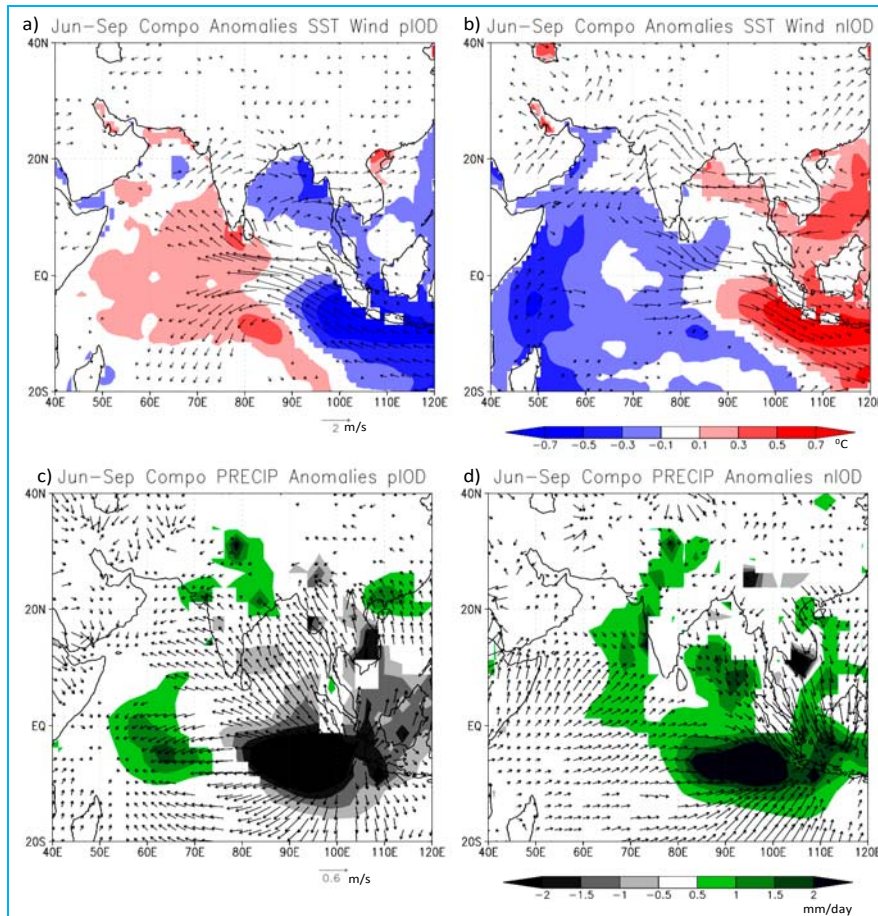
Figs. 10(a-d). June-September composite anomalies of SST (shaded) and 850 hPa wind for (a) pIOD and (b) nIOD. The corresponding anomalies for rainfall and 850 hPa divergent wind are shown in (c) and (d). Shown values exceed 90% of confidence level using a 2-tailed *t*-test. Adapted from Behera and Ratnam (2018)

response with above normal rainfall in both phases of the IOD [Figs. 10(a-d)]. However, asymmetric responses are seen south and east of that region. These symmetric and asymmetric responses arise due to the nature of teleconnection and moisture distributions over India during two phases of IOD. The anomalous moisture transports to India associated with positive IOD strengthen the monsoon trough as discussed in earlier studies (Behera *et al*., 1999; Ashok *et al*., 2001; Anil *et al*., 2016). This gives rise to abundant rainfall around the monsoon trough through an intensified monsoon-Hadley circulation but below normal rainfall to the south and to the north of the trough. The distinct regional variation in the IOD teleconnection gives rise to a distinct meridional tripolar pattern in the rainfall anomalies over India.

The situation is different in negative IOD cases when the atmospheric responses and the moisture distribution favour moisture divergence in the eastern part of India but moisture converge to the western part. This gives rise to a zonal dipole in the rainfall anomalies with abundant rainfall on the western part and scanty rainfall on the eastern part. The resulted regional asymmetry is a unique feature associated with the ISMR response to IOD. However, Behera and Ratnam (2018) have found that this asymmetric response is not simulated well by coupled GCMs. By using a series of regional model experiments with different physical parameterization schemes, they have found a few combinations of the schemes that could realistically reproduce the asymmetric response to the two phases of IOD. Further studies are necessary to formulate identical physical schemes to simulate the responses to both phases of IOD.

The IOD also influences the Eurasian snow cover. In the positive IOD years without El Niño, abundant moisture supplies from Bay of Bengal lead to more precipitation and snow cover over the Tibetan plateau
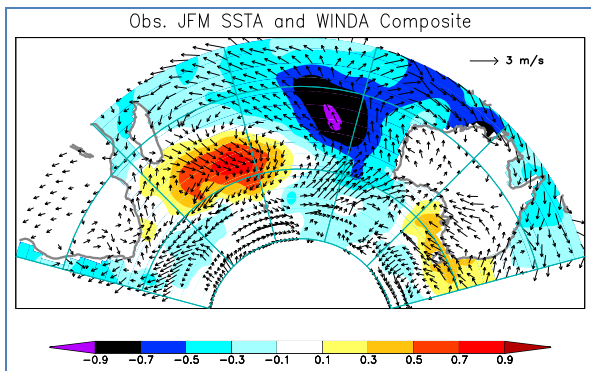
Fig. 11. SST and wind anomalies associated with a typical positive
IOSD event during January-March

(Yuan *et al*., 2009). ENSO is found to be irrelevant to the spring/early summer Tibetan snow cover. The IOD-induced snow cover anomalies can persist long from the early winter to the subsequent early summer. In other monsoon regions of Asia, the positive IOD and El Niño have opposite influences in the Far East, including Japan and Korea (Saji and Yamagata, 2003). Positive IOD events give rise to warm and dry summers in East Asia for example that of 1961 and 1994 (Guan and Yamagata, 2003; Yamagata *et al*., 2003, 2004). IOD-induced diabatic heating around India excites a long atmospheric Rossby wave and links IOD to Mediterranean region through the monsoon-desert mechanism (Rodwell and Hoskins, 1996). The westerly Asian jet then acts as a waveguide for the eastward propagating tropospheric disturbances to connect the circulation change around the Mediterranean Sea with the anomalous circulation changes over East Asia. This mechanism seemed to be related closely to the "Silk Road process" discussed by Enomoto *et al*. (2003). In another study, Pourasghar *et al*. (2012) found that the positive IOD gives rise to excess rainfall during the first part (October-November) of the local rainy season in the southern part of Iran owing to associated anomalous moisture transports from the Arabian Sea, the Red Sea and the Persian Gulf.

3.3 *IOD initiation and termination*

The IOD predictability, particularly the triggering and termination phases, are affected by several processes. Luo *et al*. (2010), using a state-of-the art coupled model, demonstrated that improving the seasonal forecast of the Indian Ocean climate variability may lead to more skillful El Niño forecast and *vice versa*. Process-based studies indicate the presence of a favorable mechanism in the eastern Indian Ocean that triggers IOD events. For example, in case of the positive IOD event, cold SST anomalies, anomalous south easterlies and suppression of convection work together in a feedback loop (Saji *et al*.,

1999; Behera *et al*., 1999) to trigger an event. There are a few alternative mechanisms also. Some studies suggested that atmospheric pressure variability in the eastern Indian Ocean (Gualdi *et al*., 2003; Li *et al*., 2003), favourable changes in winds in relation to the Pacific ENSO and the Indian monsoon (Annamalai *et al*., 2003), oceanic conditions of the Arabian Sea related to the Indian monsoon (Prasad and McClean, 2004) and influences from the southern extratropical region (Lau and Nath, 2004) could provide the triggering mechanism. There is also observational evidence that wind and subsurface temperature hold signals that lead the SST variations associated with IOD (Hastenrath and Polzin, 2004; Horii *et al*., 2008; Doi *et al*., 2017).

The intraseasonal oscillations (ISOs)/Madden Julian Oscillations (MJOs) originating from the tropical Indian Ocean play a significant role in the IOD terminations. Strong 30-60-day oscillations of equatorial zonal winds are detected prior to the termination of IOD events (Rao and Yamagata, 2004; Rao *et al*., 2007). Also, the anomalously high ISO activity in the northern summer of 1974 might explain the aborted IOD event in that year (Gualdi *et al*., 2003). As suggested by Rao *et al*. (2007), the strong westerlies associated with the ISO excite anomalous down welling Kelvin waves that terminate the coupled processes in the eastern Indian Ocean by deepening the thermo cline in the east.

4. The IOSD

The interannual SST variability in the southern Indian Ocean is frequently associated with a northwest-southeast oriented dipole of SST anomalies in the subtropical basin (Fig. 11), called Indian Ocean Sub-tropical Dipole (IOSD; Behera and Yamagata, 2001). The SST anomalies associated with IOSD typically develop in austral summer owing to latent heat flux anomalies linked with variations in the Mascarene High (Behera and Yamagata, 2001; Fauchereau *et al*., 2003). The important role of the latent heat flux anomalies was demonstrated by several studies (Suzuki *et al*., 2004; Hermes and Reason, 2005), but by considering the effect of mixed-layer variations, Morioka *et al*. (2010, 2012) have recently provided generation mechanism of the IOSD in more detail.

El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO) are suggested to somehow contribute to the interannual variations of the subtropical high responsible for the IOSD (Behera and Yamagata, 2001; Fauchereau *et al*., 2003; Hermes and Reason, 2005). This was further explored using the SINTEX-F coupled GCM. By suppressing the interannual variation in each tropical basin in the model experiment, Morioka *et al*. (2013, 2014) suggested that the subtropical dipole occurs
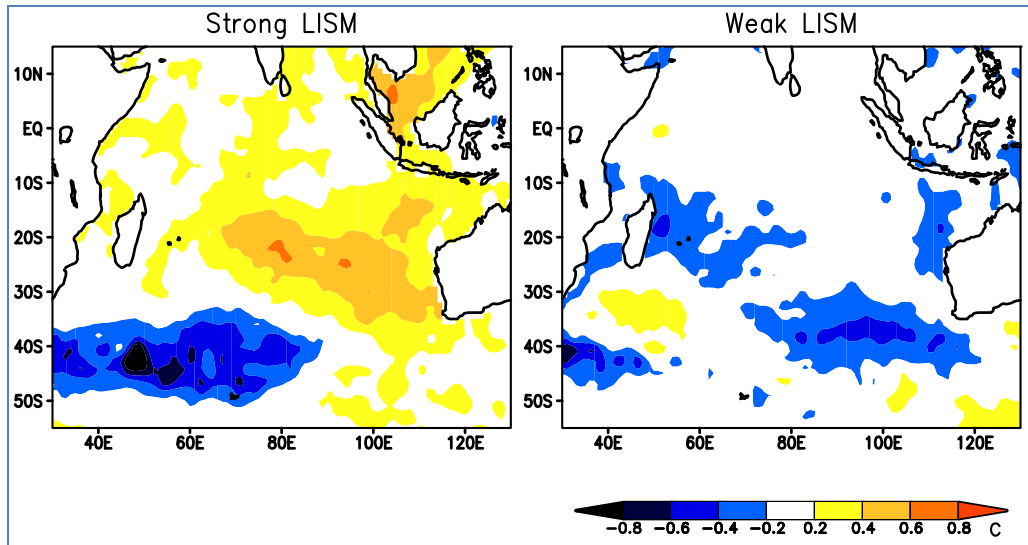
Fig. 12. February-March composite of SST anomalies for strong (left) and weak (right) late-summer (August-September) monsoon years. The late-summer monsoon years are based on Terray *et al.* (2003). The strong (weak) years used in the composite are 1958, 1961, 1970, 1973, 1975, 1983 and 1988 (1965, 1966,1968, 1972, 1979, 1986 and 1991)

in association with the strengthening of the subtropical high in its southern part. The occurrence frequency and amplitude of the IOSD did not significantly change even after suppressing the coupled variability in each tropical basin. However, the variation in the subtropical high is found to be strongly related to the AAO. Their results imply that even in the absence of the tropical climate phenomena such as ENSO, the AAO induces the variation in the subtropical high and hence can influence the IOSD. Understanding a generation mechanism of the subtropical dipole will lead to a better prediction of the phenomenon. For this better prediction, it is necessary to accurately represent climate phenomena in the higher latitudes of the Southern Hemisphere, as well as in the tropics (Yuan *et al.*, 2014).

IOSD is shown to have large impacts on the rainfall variability in southern African and Western Australia (Behera and Yamagata, 2001; Reason, 2001; Reason, 2002; Suzuki *et al.*, 2004; Reason *et al.*, 2005; Washington and Preston, 2006; Muller *et al.*, 2008; Dieppois *et al.*, 2016). It is suggested that IOSD could influence the rainfall variations through the modulation of synoptic atmospheric disturbances (Walker, 1990). Using atmospheric GCM experiments, Reason (2001) has found that increased evaporation that occurs over the warm pole of the positive IOSD in the southwest Indian Ocean causes moist air to move over to Mozambique and eastern South Africa and help the seasonal rainfall there. Furthermore, Reason (2002) has suggested that the model results are sensitive to the proximity of the southwest Indian Ocean pole to southeastern Africa, particularly for the rainfall anomaly over low-latitude southern Africa.

Strong/weak events of ISMR rainfall in August-September are shown to be preceded by significant positive/negative SST anomalies in the south eastern subtropical Indian Ocean, off Australia linked to IOSD events of austral summer (Fig. 12). Terray *et al.* (2003) have found that the SST anomalies in the subtropical Indian Ocean highly persistent and affect the north-westward translation of the Mascarene High from austral summer to boreal summer. The south eastward (north westward) shift of Mascarene High associated with cold (warm) SST anomalies off Australia causes a weakening (strengthening) of the whole monsoon circulation through a modulation of the local Hadley cell during the August-September. The Mascarene High maintains its anomalous position through a positive dynamical feedback mechanism with the underlying SST anomalies. Those SST anomalies explain the monsoon rainfall during the transition from an El Niño to a La Niña in boreal spring (Terray *et al.*, 2005). An El Niño event, usually associated warm SST anomalies in the south eastern Indian Ocean during boreal winter, may play a key role in the development of a strong monsoon season by strengthening the local Hadley circulation during the late season of August-September. Therefore, the SST anomalies of the eastern pole of the IOSD is a potential predictor for the ISMR (Rajeevan *et al.*, 2007).

The IOSD is also shown to affect the Asian monsoon region of China (Jia and Li, 2005). Significant diabatic heating anomalies associated with the peak phase of the IOSD could not only cause the anomalies of the tropical-extra tropical circulation in southern Indian Ocean, but also cause the anomalies in the a larger-scale flow pattern
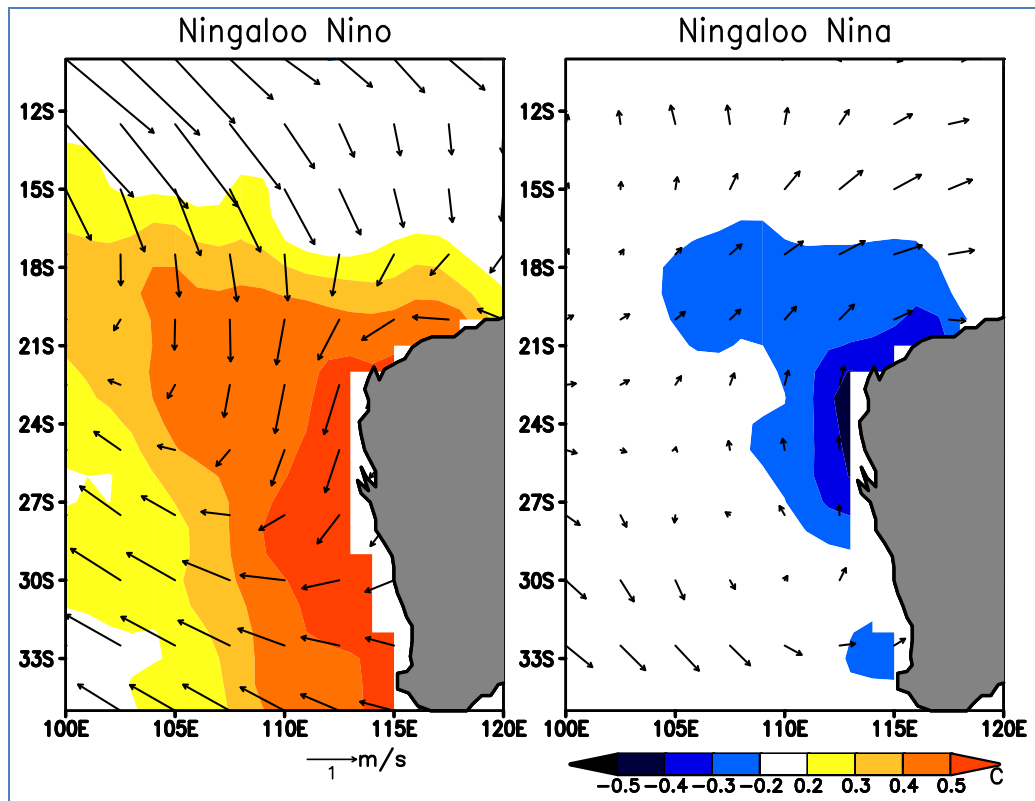
Fig. 13. December-February composite anomalies of SST and wind for typical Ningaloo Niño (left) and Ningaloo Niña (right) events. The years used in the composites of Ningaloo Niño are 1960/61, 1961/62, 1962/63, 1966/67, 1973/74, 1979/80, 1982/83, 1996/97 and 1999/00 and for Ningaloo Niña are 1976/77, 1986/87, 1990/91, 1991/92, 1992/93, 2003/04, 2004/05 and 2005/06, respectively

at low latitudes in South Asia and East Asia. Yang (2009) has shown that the IOSD could influence the climate over mid and high latitudes in East Asia through the low-frequency wave train generated by the tropical-extra tropical interaction. He suggested that a southwestern (northeastern) wind anomaly appears over southeastern China to the south of an anomalous cyclone (anticyclone) circulation during boreal winter when a positive (negative) IOSD event occurs; such a wind anomaly is associated with a strong ascending (descending) motion. As a result, rainfall anomalies in the south of the Yangtze River and northern China tend to be increased (decreased). The impacts of the IOSD on the China climate during winter are very different from those of ENSO and the difference of the geographical regions for dry/wet conditions in China influenced by IOSD and ENSO is significant during winter season.

In another study, Cao *et al*. (2014) found that the summer rainfall variations over the low-latitude highlands of China are affected by IOSD-like pattern. They link the rainfall anomalies to a mechanism through which IOSD influences the lower-tropospheric divergence over the

tropical Indian Ocean and convergence over the subtropical southwestern Indian Ocean and Arabian Sea during a positive IOSD. The convergence over the Arabian Sea can influence the circulation in the Bay of Bengal and weaken the normal season water vapor flux to the northern part of the Bay. This in turn causes anomalous water vapor divergence and less precipitation over the low-latitude highlands. The situation is basically opposite during a negative IOSD.

The IOSD is also shown to be associated with the tropical cyclone trajectories in the southwestern Indian Ocean. By employing hierarchical cluster analysis to group cyclone trajectories by their initial and final positions, Ash and Matyas (2012) found that both ENSO and IOSD are significantly associated with different types of southwestern Indian Ocean cyclone trajectories. Furthermore, they found that significant interactions of ENSO and IOSD phases influence certain types of cyclone tracks. Tropical cyclones in the southwestern Indian Ocean tend to follow more southward or southeastward tracks during concurrent events of El Niño and negative IOSD. However, they tend to take a more

westward trajectories during La Niña and positive IOSD. Therefore, they suggested to use of an IOSD index, besides the ENSO index, in statistical models to predict tropical cyclone activities in the southwestern Indian basin. On the other hand, considering its large impact on the climate of southern Africa, the IOSD has been used in societal application related projects (Yuan *et al*., 2014; Ikeda *et al*., 2017; Behera *et al*., 2018).

5.   Coastal ocean variability in the Indian Ocean

The coastal ocean around India exhibit interesting circulation features varying seasonally. The regional SST also has some interesting spatio-temporal variations but the role of local SST on the regional rainfall is not studied well. However, seasonal and interannual variations in the coastal circulations are investigated using observations and model simulation results. Based on hydrographic observations, Shetye *et al.* (1990) suggested a shallow equator ward surface flow and a northward undercurrent along the west coast of India during the summer monsoon season. A northward current is observed along the eastern coast of India (Cutler and Swallow, 1984) at that time as well as during the pre-monsoon period of February-April (Shetye *et al*., 1993). Following the work of Yu *et al*. (1991) and McCreary *et al*. (1993); Behera and Salvekar (1998) found that the currents along the east coast of India are mostly driven by the remote forcing from the equatorial regions and partly owing to the local forcing inside the Bay of Bengal (McCreary *et al*., 1996). However, the equator ward flow off the western coast of India during summer monsoon months are caused mostly because of the local wind forcing rather than the remote forcing and the propagation of Kelvin waves from the east coast.

On the western side, the upwelling region off Somalia and Oman is well-known for its interactions with monsoon and its importance for the ecosystem in the region. Influenced by the summer monsoon winds, the upwelling in that region peaks during boreal summer. Izumo *et al*. (2008) suggested that a decrease in upwelling strengthens monsoon rainfall along the west coast of India by increasing the SST along the Somalia-Oman coasts and thus local evaporation and water vapor transport toward the Western Ghats.

The upwelling zones off Java-Sumatra in the eastern Indian Ocean are also very active in terms of air-sea interactions and marine ecosystem. The air-sea interactions in that region not only affect the local rainfall but also the monsoons and the modes of tropical climate variations of IOD and ENSO by modulating the inter-basin mass and heat exchanges *via* the Indonesian Throughflow (Meyers, 1996; Yamagata *et al*., 2004; Ogata and Masumoto, 2010; Hood *et al*., 2015).
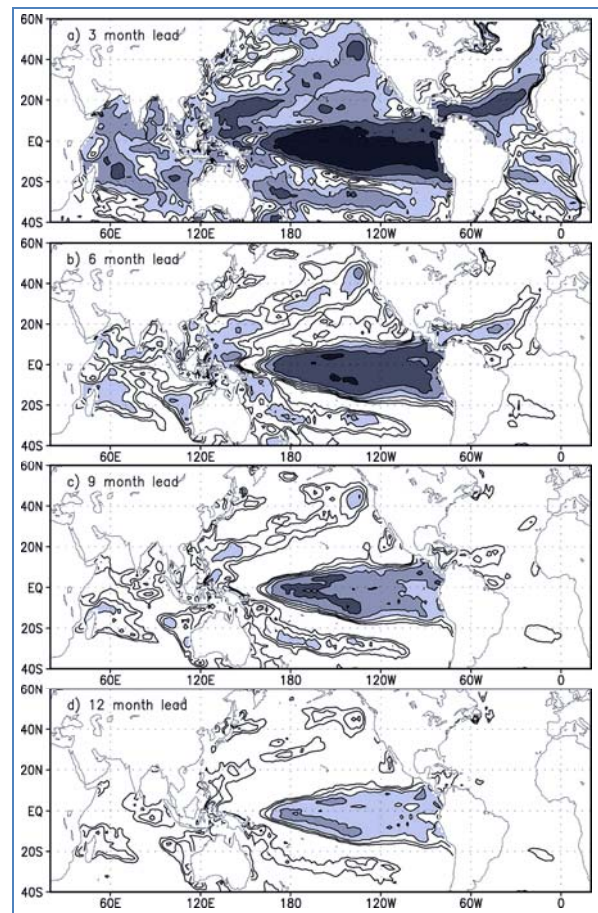
Figs. 14(a-d). SINTEX-F CGCM skill scores (anomaly correlation between prediction and observation) of global SST predictions at (a) 3, (b) 6, (c) 9 and (d) 12 month lead times. Contour interval is 0.1 and regions with values above 0.6 are shaded. Adapted from Luo *et al.* (2005a)

Another interesting mode of coastal air-sea interactions called Ningaloo Niño (Feng *et al*., 2013; Kataoka *et al*., 2014) is discovered off Western Australia recently. There are two types of Ningaloo Niño/Ningaloo Niña; one is locally amplified and the other is non-locally amplified. The locally amplified Niño (Niña) evolves with an anomalous low (high) aloft warm (cold) SST anomalies along the western coast of Australia (Fig. 13). The associated northerly (southerly) wind anomalies induce anomalous coastal down welling (upwelling) as well as less (more) evaporative cooling to develop the warm (cold) SST anomalies (Kataoka *et al*., 2014) there (Fig. 13). The non-locally amplified events are generally associated with ENSO. The ENSO related through flow water pass along the Western Australia, from western Pacific, as coastal Kelvin waves known as the Clarke-Meyers effect, to induce the non-locally amplified Ningaloo Niño/Ningaloo Niña.
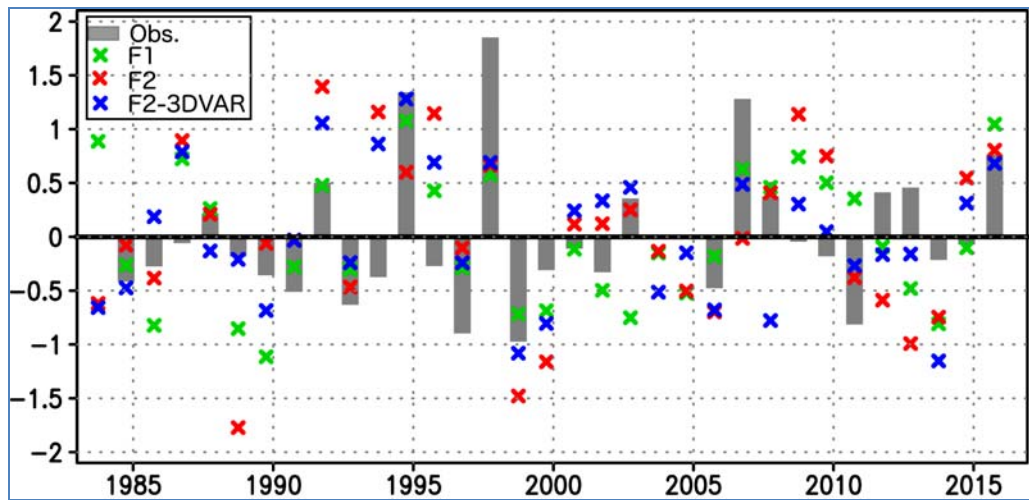
Fig. 15. Time series of September-November DMI (°C) from observation (grey bar), the ensemble mean prediction from the June 1st initialization with the SINTEX-F1 system (green x-mark), the SINTEX-F2 system (red x-mark) and the SINTEX-F2-3DVAR system (blue x-mark). Adapted from Doi *et al*. (2017)

The influence of Ningaloo Niño/Niña on the precipitation over Australia is different between the locally and non-locally amplified events. These results suggested by Kataoka *et al.* (2014) based on observations have been recently confirmed by AGCM experiments of Tozuka *et al*. (2014). In general, positive rainfall anomalies are seen along the Western Australia for the locally amplified Ningaloo Niño when the offshore sea level pressure anomaly is in opposite phase with that of the onshore sea level pressure. For the non-locally amplified mode, the warmer SST brings more rainfall in general with the additional support of the stronger than normal summer monsoon. However, in the south western part experience draughts due to drier easterly wind anomalies. The influence of both types of Ningaloo Niñas is essentially opposites of the Ningaloo Niños.

6. Climate predictability

The ISMR is influenced by tropical and extra-tropical climate variations, particularly the IOD and the ENSO as discussed in earlier sections. Therefore, model predictions are evaluated for their skills to predict ENSO and IOD. Though most models have difficulties to realistically predict the regional variations of the ISMR (Kulkarni *et al*., 2012), some of them are doing quite well to predict the mean ISMR for the whole country perhaps owing to realistic predictions of ENSO and IOD. The dynamical oceanic processes, such as the Rossby and Kelvin waves (Behera *et al*., 2013) and associated basin-wide ocean adjustment can trigger tropical climate anomalies, which rapidly grow *via* vigorous ocean-atmosphere interactions and hence provide key precursors for the climate predictions in the region (Luo *et al*., 2011;

Luo *et al*., 2015). The SINTEX-F1 system based in JAMSTEC (Luo *et al*., 2003; Masson *et al*., 2005; Behera *et al*., 2006) is a leading coupled GCM in the world that has successfully predicted the tropical SST variability at 3- to 6-months lead time [Figs. 14(a-d)]. Connected with that kind of high predictability, most of past IOD events were well-predicted by the model (Luo *et al*., 2005a&b; 2007; 2008a&b; 2015) in addition to the ENSO events. Since IOD plays a key role in ISMR predictability, it is nice to see that several models reported good skills in predicting the IOD (Wajsowicz, 2005; 2007; Song *et al*., 2008; Zhao and Hendon, 2009; Hendon and Wang, 2009; Shi *et al*., 2012; Yang *et al*., 2015; Zhu *et al*., 2015; Liu *et al*., 2016; Doi *et al*., 2016). Unlike the ENSO-forced signals in the Indian Ocean that show high predictability on good lead times, the IOD predictability is limited mostly to a few months of lead time (Wajsowicz, 2005; Luo *et al*., 2005a, 2008b). This is because air-sea coupling related to IOD is usually weak and more localized compared to ENSO. Several scales of phenomena, most prominently the intra-seasonal oscillations affect the basin. Moreover, negative IOD events do not appear to evolve into strong air-sea coupled modes of climate variation in the Indian Ocean. Therefore, their peak magnitudes are generally weak with lower predictability compared to positive IODs (Luo *et al*., 2007).

The ENSO predictability is affected by several factors though it is in general better than that of the IOD. Spring-time barrier is often cited as a factor for low ENSO predictability. However, the SINTEX-F1 model has shown the possibility to successfully predict ENSO across the first spring barrier (Luo *et al*., 2005b) perhaps owing to the correct prediction of subsurface signals in the

equatorial Pacific. Several ENSO events are predicted at lead times of up to 1.5-2 years (Luo *et al*., 2008a). The model has also shown similar skills to El Niño Modoki events such as that of 2002/03 at 2-year lead suggesting the possibility of extending ENSO and ENSO Modoki predictability beyond spring barriers.

Although the SINTEX-F1 system has been successful in predicting most ENSO and IOD events at least one or two seasons ahead, like other coupled GCMS it has shown some shortcomings particularly related to the initiation and terminations of some of the events. A new high-resolution version with a dynamical sea-ice model, called SINTEX-F2 model has shown better skills in the prediction of subtropical and mid-latitude climates (Doi *et al*., 2016). However, absence of subsurface data assimilation in the model predictions has led to some difficulties to predict IOD. Doi *et al*. (2017) report better predictions of the IOD by introducing a new three-dimensional variational ocean data assimilation (3DVAR) method in the SINTEX-F2 prediction system (Fig. 15).

Among two types of Ningaloo Niño, Doi *et al*. (2013) found that the non-locally amplified modes could be predicted well by the SINTEX-F1, though there are difficulties in capturing the strong amplitude of the events like that of 2011 event. It is very challenging to capture and predict such a local climate phenomenon, as most coupled GCMs do not have such fine resolution and necessary physics to capture the local oceanic and atmospheric processes.

7. Summary

The focus of tropical climate research over large part of past few decades has been mostly on the understanding of El Niño-related processes and their predictability. With the discovery of other tropical climate modes such as the IOD, the focus of climate research has shifted a bit to the Indian and other ocean basins. These new modes have turned out to have significant direct impacts on our climate and their predictability. Particularly, the IOD is seen to influence the ISMR, rainfall variability over Maritime Continent, East Africa and even La Plata. IOD is also linked to extreme stream flows of Citaram river and the teleconnection is seen to be associated with extreme heat waves over Europe and Japan (Akihiko *et al*., 2014). The intensified activity of IOD, perhaps associated with the global warming (Behera *et al*., 2008; Abram *et al*., 2008), will play a stronger role in the evolution of El Niño (Cai *et al*., 2013). The large-scale changes in the basic state of our climate system will also be affecting the ocean circulations and modes of climate variations. Frequent occurrences of El Niño Modoki in recent decades (Ashok and Yamagata, 2009) perhaps are

associated with the weakened Walker circulation in the Indo-Pacific domain.

Besides these tropical climate variations, it has been shown that the subtropical and other regional climate variations are important for local weather and climate. For example, the subtropical dipole of the southern Indian Ocean is important for the regional rainfall variations over southern Africa (Morioka *et al*., 2012; Yuan *et al*., 2014) and Australia. It is also shown that the IOSD influences the late monsoon rainfall over India during August-September and early monsoon rains over southern China. Being on the pathway of southern extra tropics and northern subtropical regions, the IOSD will be an important phenomenon to understand and predict.

The regional climate variations are sometimes exhibited as coastal phenomena. Ningaloo Niño/ Ningaloo Niña is one such phenomenon recently discovered off the Western Australia. Ningaloo Niño affects the coral and the marine ecosystem off the coast of Western Australia. In particular, the record-breaking Ningaloo Niño of 2011 caused huge damages to the coastal marine ecosystem. Next generation dynamical prediction system must resolve these coastal ocean-atmosphere coupled processes to satisfy regional societal needs.

Global coupled GCMs are showing a lot of promise in predicting ENSO, ENSO Modoki and IOD. The SINTEX-F system discussed here has excellent skill for the ENSO prediction even at long lead times of up to 2-years. On the other hand, skillful IOD prediction is limited to a few seasons. Further, most models, have sometimes difficulties in predicting the initiation and termination phases of these phenomena. Therefore, it is important to continue to understand the physical processes and scale interactions among various phenomena to improve the predictability of these phenomena for reliable societal applications.

References

Abram, N. J., Gagan, M. K., Cole, J. E., Hantoro, W. S. and Mudelsee, M., 2008, "Recent intensification of tropical climate variability in the Indian Ocean", *Nature Geoscience*, **1**, 849-853.

Akihiko, T., Morioka, Y. and Behera, S. K., 2014, "Role of climate variability in the heatstroke death rates of Kanto region in Japan", *Sci. Rep.*, **4**, 5655.

Alexander, M. A., Blade, I., Newman, M., Lanzante, J. R., Lau, N. C. and Scott, J. D., 2002, "The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans", *J. Climate*, **15**, 2205-2231.

Anil, N., Ramesh Kumar, M. R., Sajeev, R. and Saji, P. K., 2016, "Role of distinct flavours of IOD events on Indian summer monsoon", *Natural Hazards*, **82**, 2, 1317-1326.

Annamalai, H. and Liu, P., 2005, "Response of the Asian summer monsoon to changes in El Niño properties", *Q. J. R. Meteorol. Soc.*, **131**, 805-831.

Annamalai, H., Murtugudde, R., Potemra, J., Xie, S. P., Liu, P. and Wang, B., 2003, "Coupled dynamics over the Indian Ocean: Spring initiation of the zonal mode", *Deep-Sea Res. II*, **50**, 2305-2330.

Ash, K. D., Matyas, C. J., 2012, "The influences of ENSO and the subtropical Indian Ocean dipole on tropical cyclone trajectories in the southwestern Indian Ocean", *Int. J. Climatol.*, **32**, 41-56.

Ashok, K. and Yamagata, T., 2009, "Climate change: The El Niño with a difference", *Nature*, **461**, 481-484.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H. and Yamagata, T., 2007, "El Niño Modoki andits possible teleconnection", *J. Geophys. Res.*, **112**, C11007, doi:10.1029/2006JC003798.

Ashok, K., Guan, Z. and Yamagata, T., 2001, "Impact of the Indian Ocean Dipole on the relationship between the Indian Monsoon rainfall and ENSO", *Geophys. Res. Lett.*, **26**, 4499-4502.

Ashok, K., Guan, Z. and Yamagata, T., 2003, "Influence of the Indian Ocean dipole on the Australian winter rainfall", *Geophys. Res. Lett.*, **30**, 1821, doi:10.1029/2003GL017926.

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", *Geophys. Res. Lett.*, **26**, 4499-4502.

Barnett, T. P., 1983, "Interaction of the monsoon and Pacific trade wind system at interannual time scales. part I: The equatorial zone", *Mon. Weather Rev.*, **111**, 756-773.

Behera S. K., Brandt, P. and Reverdin, G., 2013, "The tropical ocean circulation and dynamics", Ocean Circulation and Climate – A 21 Century Perspective Ed. Gerold Siedler, Stephen Griffies, John Gould, John Church, Elsevier. Academic Press, 385-404

Behera, S. K., 2018, "Variability and predictability of climate linked to extreme events", *World Scientific Series on Asia-Pacific Weather and Climate*, **10**, 17-32.

Behera, S. K., Ratnam, J. V., Masumoto, Y. and Yamagata, T., 2012, "Origin of Extreme Summers in Europe - The Indo-Pacific Connection", *Climate Dynamics*, **41**, 3-4, 663-676.

Behera, S. K. and Ratnam, J. V., 2018, "Quasi-asymmetric response of the Indian summer monsoon rainfall to opposite phases of the IOD", *Sci. Reports*, DOI:10.1038/s41598-017-18396-6.

Behera, S. K. and Salvekar, P. S., 1998, "Numerical investigation of coastal circulation around India", *Mausam*, **49**, 345-360.

Behera, S. K. and Yamagata, T., 2001, "Subtropical SST dipole events in the southern Indian Ocean", *Geophys. Res. Lett.*, **28**, 327-330.

Behera, S. K. and Yamagata, T., 2003, "Influence of the Indian Ocean Dipole on the Southern Oscillation", *J. Meteor. Soc. Japan*, **81**, l69-177.

Behera, S. K. and Yamagata, T., 2010, "Imprint of the El Niño Modoki on decadal sea level changes", *Geophys. Res. Lett.*, **37**, L23702.

Behera, S. K. and Yamagata, T., 2018, "Climate Dynamics of ENSO Modoki Phenomenon", *Oxford Research Encyclopedia of Climate Science*, DOI: 10.1093/acrefore/ 9780190228620. 013.612.

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

Behera, S. K., Luo, J. J. and Yamagata, T., 2008, "The Unusual IOD Event of 2007", *Geophy. Res. Letter*, **35**, L14S11.

Behera, S. K., Luo, J. J., Masson, S., Delecluse, P., Gualdi, S., Navarra, A. and Yamagata, T., 2005, "Paramount impact of the Indian Ocean Dipole on the East African short rain: A CGCM study", *J. Climate*, **18**, 4514-4530.

Behera, S. K., Luo, J. J., Masson, S., Rao, S. A., Sakuma, H. and Yamagata, T., 2006, "A CGCM study on the interaction between IOD and ENSO", *J. Climate*, **19**, 1688-1705.

Behera, S. K., Morioka, Y., Ikeda, T., Doi, T., Ratnam, J., Nonaka, M., Tsuzuki, A., Imai, C., Kim, Y., Hashizume, M., Iwami, S., Kruger, P., Maharaj, R., Sweijd, N. and Minakawa, N., 2018, "Malaria incidences in South Africa linked to a climate mode in southwestern Indian Ocean", *Env. Dev.*, **27**, 47-57.

Behera, S. K., Rao, S. A., Saji, H. N. and Yamagata, T., 2003, "Comments on 'A cautionary note on the interpretation of EOFs'", *Journal of Climate*, **16**, 7, 1087-1093.

Bjerknes, J., 1969, "Atmospheric teleconnections from the equatorial Pacific", *Mon. Wea. Rev*, **97**, 163-172.

Black, E., Slingo, J. and Sperber, K. R., 2003, "An observational study of the relationship between excessively strong short rains in coastal East Africa and Indian Ocean SST", *Mon. Wea. Rev.*, **31**, 74-94.

Cadet, D. L., 1985, "The Southern Oscillation over the Indian Ocean", *J. Climatol.*, **5**, 189-212.

Cai, W. and Cowan, T., 2009, "La Niña Modoki impacts Australia autumn rainfall variability", *Geophys. Res. Lett.*, **36**, L12805, doi:10.11029/12009GL037885.

Cai, W., Hendon, H. and Meyers, G., 2005, "Indian Ocean dipole-like variability in the CSIRO Mark 3 coupled climate model", *J. Climate*, **18**, 1449-1468.

Cai, W., Zheng, X. T., Weller, E., Collins, M., Cowan, T., Lengaigne, M., Yu, W. and Yamagata, T., 2013, "Projected response of the Indian Ocean Dipole to greenhouse warming", *Nature Geoscience*, **6**, 12, 999-1007.

Cao, J., Yao, P., Wang, L. and Liu, K., 2014, "Summer precipitation variability in Low Latitude Highlands of China and Subtropical Indian Ocean Dipole", *J. Clim.*, 27:880-892

Chan, S., Behera, S. and Yamagata, T., 2008, "The Indian Ocean Dipole teleconnection to South America", *Geophys. Res. Lett.*, **35**, L14S12, doi:10.1029/2008GL034204.

Cherchi, A., Gualdi, S., Behera, S., Luo, J. J., Masson, S., Yamagata, T. and Navarra, A., 2007, "The influence of tropical Indian Ocean SST on the Indian summer monsoon", *J. Climate*, **20**, 3083-3105.

Chowdary, J. S., Xie, S. P., Luo, J. J., Hafner, J., Behera, S., Masumoto, Y. and Yamagata, T., 2011, "Predictability of Northwest Pacific climate during summer and the role of the Tropical Indian Ocean", *Climate Dynamics*, DOI: 10.1007/s00382-009-0686-5.

Clark, C. O., Webster, P. J. and Cole, J. E., 2003, "Interdecadal variability of the relationship between the Indian Ocean zonal mode and East African coastal rainfall anomalies", *J. Climate*, **16**, 548-554.

Cutler, A. N. and Swallow, J. C., 1984, "Surface currents of the Indian Ocean", *Institute of Oceanographic Sciences, Rep.*, **187**, p8, 36 charts.

Dieppois, B., Pohl, B., Rouault, M., New, M., Lawler, D. and Keenlyside, N., 2016, "Interannual to interdecadal variability of winter and summer southern African rainfall and their teleconnections", *Journal of Geophysical Research: Atmospheres*, **121**, 6215-6239.

Doi, T., Behera, S. and Yamagata, T., 2013, "Predictability of the Ningaloo Niño/Niña", *Scientific Report*, **2**, 2892, doi:10.1038/srep02892

Doi, T., Behera, S. K. and Yamagata, T., 2016, "Improved seasonal prediction using the SINTEX-F2 coupled model", *J. Adv. in Modeling Earth Systems*, DOI: 10.1002/2016MS000744.

Doi, T., Storto, A., Behera, S. and Yamagata, T., 2017, "Improved the Indian Ocean Dipole Mode prediction by initializing subsurface ocean observation", *J. Climate*, **30**, 7953-7970, DOI: 10.1175/JCLI-D-16-0915.1

Du, Y., Xie, S. P., Huang, G. and Hu, K. M., 2009, "Role of air-sea interaction in the long persistence of El Niño-induced North Indian Ocean warming", *J. Climate*, **22**, 2023-2038, doi: 10.1175/ 2008JCLI2590.1.

Enomoto, T., Hoskins, B. J. and Matsuda, Y., 2003, "The formation of the Bonin high in August", *Quart. J. Roy. Meteor. Soc.*, 587, 157-178.

Fauchereau, N., Trzaska, S., Richard, Y., Roucou, P. and Camberlin, P., 2003, "Sea-surface temperature co-variability in the southern Atlantic and Indian Oceans and its connections with the atmospheric circulation in the Southern Hemisphere", *Int. J. Climatol.*, **23**, 663-677, doi:10.1002/joc.905.

Feng, M. and Meyers, G., 2003, "Interannual variability in the tropical Indian Ocean: A two-year time scale of IOD", *Deep-Sea Res. II*, **50 (12/13)**, 2263-2284.

Feng, M., McPhaden, M. J., Xie, S. and Hafner, J., 2013, "La Niña forces unprecedented Leeuwin Current warming in 2011", *Sci. Rep.*, **3**, 1277. doi:10.1038/srep01277.

Gadgil, S. and Gadgil, S., 2006, "The Indian monsoon, GDP and agriculture", *Econ. Polit. Weekly*, XLI, 4887-4895

Gadgil, S., Vinayachandran, P. N., Francis, P. A. and Gadgil, S., 2004, "Extremes of the Indian summer monsoon rainfall: ENSO and equatorial Indian Ocean Oscillation", *Geoph. Res. Lett.*, **31**, L12213, doi:10.1029/2004GLO19733.

Grove, R., 2007, "The Great El Nino of 1789 93 and its global consequences: Reconstructing an extreme climate event in world environmental history", *Mediev. Hist. J.*, **10**, p75. doi:10.1177/097194580701000203.

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.

Guan, Z., Ashok, K. and Yamagata, T., 2003, "Summer-time response of the tropical atmosphere to the Indian Ocean dipole sea surface temperature anomalies", *J. Meteor. Soc. Japan*, **81**, 531-561.

Guan, Z. and Yamagata, T., 2003, "The unusual summer of 1994 in East Asia : IOD Teleconnections", *Geophys. Res. Lett.*, **30**, 10.1029/2002GL016831.

Hastenrath, S. and Polzin, D., 2004, "Dynamics of the surface wind field over the equatorial Indian Ocean", *Quart. J. Roy. Meteor. Soc.*, **130**, 503-517.

He, C., Zhou, T. J. and Wu, B., 2015, "The key oceanic regions responsible for the interannual variability of the western North Pacific subtropical high and associated mechanisms", *J. Meteor. Res.*, **29**, 562-575, doi: 10.1007/s13351-015-5037-3.

Hendon, H. H. and Wang, G., 2009, "Seasonal prediction of the Leeuwin Current using the POAMA dynamical seasonal forecast model", *Climate Dyn.*, **34**, 1129-1137, doi:10.1007/ s00382-009-0570-3.

Hermes, J. C. and Reason, C. J. C., 2005, "Ocean model diagnosis of interannual coevolving SST variability in the South Indian and South Atlantic Oceans", *J. Climate*, **18**, 2864-2882.

Hood, R. R., Bange, H. W., Beal, L., Beckley, L. E., Burkill, P., Cowie, G. L., D'Adamo, N., Ganssen, G., Hendon, H., Hermes, J., Honda, M., McPhaden, M., Roberts, M., Singh, S., Urban, E. and Yu, W., 2015, "Science Plan of the Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program", Scientific Committee on Oceanic Research, Newark, Delaware, USA.

Horii, T., Hase, H., Ueki, I. and Masumoto, Y., 2008, "Oceanic precondition and evolution of the 2006 Indian Ocean dipole", *Geophys. Res. Lett.*, **35**, L03607, doi:10.1029/ 2007GL032464.

Hu, J. and Duan, A. M., 2015, "Relative contributions of the Tibetan Plateau thermal forcing and the Indian Ocean sea surface temperature basin mode to the interannual variability of the East Asian summer monsoon", *Climate Dyn.*, **45**, 2697-2711, doi: 10.1007/s00382-015-2503-7.

Huang, G., Hu, K. M. and Xie, S. P., 2010, "Strengthening of tropical Indian Ocean teleconnection to the Northwest Pacific since the mid-1970s: An atmospheric GCM Study", *J. Climate*, **23**, 5294-5304.

Iizuka, S., Matsuura, T. and Yamagata, T., 2000, "The Indian Ocean SST dipole simulated in a coupled general circulation model", *Geophys. Res. Lett.*, **27**, 3369-3372.

Ikeda T., Behera, S., Morioka, Y., Minakawa, N., Hashizume, M., Tsuzuki, A., Maharaj, R. and Kruger, P., 2017, "Seasonally lagged effects of climatic factors on malaria incidence in South Africa", *Scientific Reports*, **7**, 2458, doi:10.1038/s41598-017-02680-6

Izumo, T., Montegut, C. D. B., Luo, J. J., Behera, S. K., Masson, S. and Yamagata T., 2008, "The role of the western Arabian Sea upwelling in Indian Monsoon rainfall variability", *J. Climate*, **21**, 5603-5623.

Izumo, T., Vialard, J., Lengaigne, M., Masson, S., Cravatte, S., Montégut, C. B., Luo, J. J., Behera, S. K. and Yamagata, T., 2010, "Influence of the state of the Indian Ocean Dipole on the following year's El Niño", *Nature Geosciences*, **3**, 168-172.

Jia, X. L. and Li, C. Y., 2005, "Dipole oscillation in the southern Indian Ocean and its impacts on climate", *Chinese Journal of Geophysics*, **48**, 1323-1335.

Ju, J. and Slingo, J., 1995, "The Asian summer monsoon and ENSO", *Quarterly Journal of the Royal Meteorological Society*, **121**, 1133-1168.

Kane, R. P., 2005, "Unstable ENSO relationship with Indian regional rainfall", *Int. J. Climatol.*, **26**, 771-783.

Kao, H. Y. and Yu, J. Y., 2009, "Contrasting eastern-Pacific and central-Pacific types of ENSO", *Journal of Climate*, **22**, 615-632.

Kataoka, T., Tozuka, T., Behera, S. K. and Yamagata, T., 2014, "On the Ningaloo Nino/Nina", *Climate Dynamics*, **43**, 5-6, 1463-1482.

Keshavamurthy, R. N., 1982, "Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the Southern Oscillation", *J. Atmos. Sci.*, **39**, 1241-1259.

Kim, J. S., Kim, K. Y. and Yeh, S. W., 2012, "Statistical evidence for the natural variation of the central Pacific El Niño", *J. Geophysc. Res.*, **117**, C06014.

Klein, S. A., Soden, B. J. and Lau, N. C., 1999, "Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge", *J. Climate*, **12**, 917-932.

Kosaka, Y., Xie, S. P., Lau, N. C. and Vecchi, Gabriel A., 2013, "Origin of seasonal predictability for summer climate over the northwestern Pacific", *Proc. Natl. Acad. Sci. U. S. A.*, **110**, 7574-7579.

Kripalani, R. H. and Kulkarni, A., 1997, "Climatic impact of El Niño/La Niña on the Indian monsoon: A new perspective", *Weather*, **52**, 39-46.

Krishna Kumar, K., Rajagopalan, B. and Cane, M., 1999, "On the weakening relationship between the Indian monsoon and ENSO", *Science*, **284**, 2156-2159.

Krishna Kumar, K., Rajagopalan, B., Hoerling, M., Bates, G. and Cane, M., 2006, "Unraveling the mystery of Indian monsoon failure during El Nino", *Science*, **314**, 115-119.

Krishnamurthy, V. and Goswami, B. N., 2000, "Indian monsoon-ENSO relationship on interdecadal timescale", *Journal of Climate*, **13**, 579-595.

Kug, J. S., Jin, F. F. and An, S. I., 2009, "Two types of El Niño events: cold tongue El Niño and warm pool El Niño", *Journal of Climate*, **22**, 1499-1515.

Kulkarni, M. A., Acharya, N., Kar, S. C., Mohanty, U. C., Tippett, M. K., Robertson, A. W., Luo, J. J. and Yamagata, T., 2012, "Probabilistic prediction of Indian summer monsoon rainfall using global climate models", *Theor. Appl. Climatol.*, **107**, 3-4, 441-450.

Larkin, N. K. and Harrison, D. E., 2005, "On the definition of El Niño and associated seasonal average U.S. weather anomalies", *Geophys. Res. Lett.*, **32**, L13705.

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

Lau, N. C. and Nath, M. J., 2003, "Atmosphere-ocean variations in the Indo-Pacific sector during ENSO episodes", *Journal of Climate*, 16, 3-20.

Lau, N. C. and Nath, M. J., 2004, "Coupled GCM simulation of atmosphere-ocean variability associated with zonally asymmetric SST changes in the tropical Indian Ocean", *Journal of Climate*, **17**, 245-265.

Li, C. W. and Lin, X., 2016, "Dynamics of changing impacts of tropical Indo-Pacific variability on Indian and Australian rainfall", *Scientific Reports*, **6**, 31767.

Li, S. L., Lu, J., Huang, G. and Hu, Kaiming, 2008, "Tropical Indian Ocean basin warming and East Asian summer monsoon: A multiple AGCM study", *Journal of Climate*, 21, 6080-6088.

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

Liu, H., Tang, Youmin, Chen, Dake and Lian, Tao, 2016, "Predictability of the Indian Ocean Dipole in the coupled models", *Climate Dynamics*, **48**, 5-6, 2005-2024.

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", *Journal of Climate*, **16**, 1617-1642.

Luo , J. J., Masson, S., Behera, S. K., Delecluse, P., Gualdi, S., Navarra, A. and Yamagata, T., 2003, "South Pacific Origin of the Decadal ENSO-like Variation as Reproduced by a Coupled GCM", *Geophy. Res. Letter*, **30**, 2250, DOI: 10.1029/2003GL018649.

Luo, J. J., Behera, S. K., Masumoto, Y. and Yamagata, T., 2011, "Impact of Global Ocean Surface Warming on Seasonal-to-Interannual Climate Prediction", *Journal of Climate*, **24**, 1626-1646.

Luo, J. J., Behera, S. K., Masumoto, Y., Sakuma, H. and Yamagata, T., 2008a, "Successful prediction of the consecutive IOD in 2006 and 2007", *Geophys. Res. Lett.*, **35**, L14S02.

Luo, J. J., Lee, J. Y., Yuan, C., Sasaki, W., Masson, S., Behera, S. K., Masumoto, Y. and Yamagata, T., 2015, "Current status of intraseasonal-seasonal-to-interannual prediction of the Indo-Pacific Climate", Ch. 3, World Scientific Series on Asia-Pacific Weather and Climate, **Vol. 7**, Ed. S. Behera, T. Yamagata

Luo, J. J., Masson, S., Behera, S. K. and Yamagata, T., 2007, "Experimental forecasts of Indian Ocean Dipole using a coupled OAGCM", **20**, 2178-2190.

Luo, J. J., Masson, S., Behera, S. K. and Yamagata, T., 2008b, "Extended ENSO predictions using a fully coupled ocean-atmosphere model", *Journal of Climate*, **21**, 84-93.

Luo, J. J., Masson, S., Behera, S. K., Shingu, S. and Yamagata, T., 2005a, "Seasonal climate predictability in a coupled OAGCM using a different approach for ensemble forecasts", *Journal of Climate*, **18**, 4474-4494.

Luo, J. J., Masson, S., Roeckner, E., Madec, G. and Yamagata, T., 2005b, "Reducing climatology bias in an ocean-atmosphere OGCM with improved coupling physics", **18**, 2344-2360.

Luo, J. J., Zhang, R., Behera, S. K., Masumoto, Y., Jin, F. F., Lukas, R. and Yamagata, T., 2010, "Interaction between El Niño and Extreme Indian Ocean Dipole", *Journal of Climate*, **23**, 726-742.

Manatsa, D. and Behera, S. K., 2013, "On the epochal strengthening in the relationship between rainfall of East Africa and IOD", *Journal of Climate*, **26**, 5655-5673.

Manatsa, D., Chingombe, W. and Matarira, C. H., 2008, "The impact of the positive Indian Ocean dipole on Zimbabwe droughts", *Int. J. Climatol.*, **28**, 2011-2029.

McCreary, J. P., Han, W., Shankar, D. and Shetye, S. R., 1996, "Dynamics of the East India Coastal Current: 2. Numerical solutions", *J. Geophys. Res.*, **101**, 13993-14010.

McCreary, J. P., Kundu, P. K. and Molinari, R. L., 1993, "A numerical investigation of the dynamics, thermodynamics and mixed-layer processes in the Indian Ocean", *Prog. Oceanogr.*, **31**, 181-244.

Meyers, G., 1996, "Variation of Indonesian Throughflow and the El Niño-Southern Oscillation", *J. Geophys. Res.*, **101**, 12255-12263.

Mooley, D. A. and Parthasarathy, B., 1984, "Indian summer monsoon and El Nino", *Pure Appl. Geophys.*, **121**, 339-352.

Morioka, Y., Masson, S., Terray, P., Prodhomme, C., Behera, S. K. and Masumoto, Y., 2014, "Role of Tropical SST Variability on the Formation of Subtropical Dipoles", *Journal of Climate*, **27**, 4486-4507.

Morioka, Y., Tozuka, T. and Yamagata, T., 2010, "Climate variability in the southern Indian Ocean as revealed by self-organizing maps", *Climate Dynamics,* **35***, 1059-1072.

Morioka, Y., Tozuka, T. and Yamagata, T., 2013, "How is the Indian Ocean Subtropical Dipole excited?", *Climate Dynamics*, **41**, 1955-1968.

Morioka, Y., Tozuka, T., Masson, S., Terray, P., Luo, J. J. and Yamagata, T., 2012, "Subtropical dipole modes simulated in a coupled general circulation model", *Journal of Climate*, **25**, 4029-4047.

Muller, A., Reason, C. and Fauchereau, N., 2008, "Extreme rainfall in the Namib Desert during late summer 2006 and influences of regional ocean variability", *Int. J. Climatol.*, **28**, 1061-1070.

Nakamura, N., Kayanne, H., Iijima, H., McClanahan, T. R., Behera, S. K. and Yamagata, T., 2009, "Mode shift in the Indian Ocean climate under global warming stress', *Geophys. Res. Lett.*, **36**, 23, L23708.

Ogata, T. and Masumoto, Y., 2010, "Interactions between mesoscale eddy variability and Indian Ocean dipole events in the Southeastern tropical Indian Ocean-case studies for 1994 and 1997/1998", *Ocean Dynamics*, **60**, 717-730.

Pourasghar, F., Tozuka, T., Jahanbakhsh, S., Sarraf, B. S., Ghaemi, H. and Yamagata, T., 2012, "The interannual precipitation varaiability in the southern part of Iran as linked to large-scale climate modes", *Climate Dynamics*, **39**, 2329-2341.

Pradhan, K. P., Ashok, K., Preethi, B., Krishnan, R. and Sahai, A. K., 2011, "Modoki, IOD and Western North Pacific typhoons: Possible implications for extreme events", *J. Geophys. Res.*, **116**, D18108.

Prasad, T. G. and McClean, J. L., 2004, "Mechanisms for anomalous warming in the western Indian Ocean during dipole mode events", *J. Geophys. Res. Ocean*, **109**, C2, C02019.

Rajeevan, M. and Pai, D. S., 2007, "On the El Nino-Indian monsoon predictive relationships", *Geophys. Res. Lett.*, **34**, L04704.

Rajeevan, M., Pai, D. S., Anil Kumar, R. and Lal, B., 2007, "New statistical models for long-range forecasting of southwest monsoon rainfall over India", *Climate Dynamics*, **28**, 7-8, 813-828.

Rao, S. A. and Behera, S. K., 2005, "Sub-surface influence on SST in the tropical Indian Ocean structure and interannual variabilities", *Dyn. Atmos.Oceans*, **39**, 103-135.

Rao, S. A. and Yamagata, T., 2004, "Abrupt termination of Indian Ocean dipole events in response to intraseasonal disturbances", *Geophys. Res. Lett.*, **31**, L19306. doi:10.1029/2004GL020842.

Rao, S. A., Behera, S. K., Masumoto, Y. and Yamagata, T., 2002, "Interannual variability in the subsurface tropical Indian Ocean with a special emphasis on the Indian Ocean Dipole", *Deep-Sea Res. II*, **49**, 1549-1572.

Rao, S. A., Masson, S., Luo, J. J., Behera, S. K. and Yamagata, T., 2007, "Termination of Indian Ocean dipole events in a general circulation model", *Journal of Climate*, **20**, 3018-3035, doi:10.1175/JCLI4164.1.

Rasmussen, E. M. and Carpenter, T. H., 1983, "The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka", *Monthly Weather Review*, **110**, 354-384.

Ratnam, J. V., Behera, S. K., Masumoto, Y. and Yamagata, T., 2014, "Remote Effects of El Niño and Modoki Events on the Austral Summer Precipitation of Southern Africa", *Journal of Climate*, **27**, 3802-3815.

Ratnam, J. V., Behera, S. K., Masumoto, Y., Takahashi, K. and Yamagata, T., 2010, "Pacific Ocean origin for the 2009 Indian summer monsoon failure", *Geophys. Res. Lett.*, **37**, L07807, doi:10.1029/2010GL042798.

Ratnam, J. V., Behera, S. K., Masumoto, Y., Takahashi, K. and Yamagata, T., 2012, "Anomalous climatic conditions associated with the El Niño Modoki during boreal winter of 2009", *Clim. Dyn.*, **39**, 1-2, 227-238. DOI: 10.1007/s00382-011-1108-z.

Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M. and Yamagata, T., 2016, "Anatomy of Indian heatwaves", *Sci. Reports*, **6**, 24395.

Reason, C. J. C., 2001, "Sub-tropical Indian Ocean SST dipole events and southern African rainfall", *Geophysical Research Letters*, **28**, 11, 2225-2227. https://doi.org/10.1029/2000GL012735.

Reason, C. J. C., 2002, "Sensitivity of the southern African circulation to dipole sea-surface temperature patterns in the south Indian Ocean", *International Journal of Climatology*, **22**, 377-393.

Reason, C. J. C., Hachigonta, S. and Phaladi, R. F., 2005, "Interannual variability in rainy season characteristics over the Limpopo region of southern Africa", *Int. J. Climatol.*, **25**, 1835-1853.

Rodwell, M. J. and Hoskins, B. J., 1996, "Monsoons and the dynamics of deserts", *Q. J. R. Meteorol. Soc.*, **122**, 1385-1404.

Ropelewski, C. F. and Halpert, M. S., 1987, "Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation", *Monthly weather review*, **115**, 1606-1626.

Sahu, N., Behera, S. K., Ratnam, J. V., Da Silva, R. V., Parhi, P., Yamashiki, Y., Takara, K. and Yamagata, T., 2014, "El Niño Modoki connection to extremely-low stream flow of the Paranaíba River in Brazil", *Clim. Dynamics*, **42**, 5-6, 1509-1516.

Sahu, N., Behera, S. K., Yamashiki, Y., Takara, K. and Yamagata, T., 2012, "IOD and ENSO impacts on the extreme stream-flows of Citarum river in Indonesia", *Climate Dynamics*, **39**, 7-8, 1673-1680, doi 10.1007/s00382-011-1158-2.

Saji, N. H. and Yamagata, T., 2003, "Possible impacts of Indian Ocean Dipole Mode events on global climate", *Climate Res.*, **25**, 151-169.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T., 1999, "A dipole mode in the tropical Indian Ocean", *Nature*, **401**, 360-363.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S., Almeida, A. M. and Santanam, K., 1990, "Hydrography and circulation off the west coast of India during the Southwest Monsoon 1987", *J. Marine Res.*, **48**, 359-378.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S. and Nampoothiri, G., 1993, "The western boundary current of the seasonal subtropical gyre in the Bay of Bengal", *J. Geophys. Res.*, **98**, 945-954.

Shi, L., Hendon, H. H., Alves, O., Luo, J. J., Balmaseda, M. and Anderson, D., 2012, "How predictable is the Indian Ocean dipole?", *Mon. Wea. Rev.*, **140**, 3867-3884, doi:10.1175/ MWR-D-12-00001.1.

Sikka, D. R., 1980, "Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters", *Proc. Indian Acad. Sci. Earth Planet Sci.*, **89**, 179-195.

Soman, M. K. and Slingo, J., 1997, "Sensitivity of the Asian summer monsoon to aspects of SST anomalies in the tropical Pacific Ocean", *Q. J. R. Meteorol. Soc.*, **123**, 309-336.

Song, Q., Vecchi, G. A. and Rosati, A. J., 2008, "Predictability of the Indian Ocean sea surface temperature anomalies in the GFDL coupled model", *Geophy. Res. Lett.*, **35**, L02701, doi:10.1029/2007GL031966.

Suzuki, R., Behera, S. K., Iizuka, S. and Yamagata, T., 2004, "Indian Ocean subtropical dipole simulated using a coupled general circulation model", *J. Geophys. Res.*, **109**, C09001, doi:10.1029/2003JC001974.

Taschetto, A. S. and England, M. H., 2009, "El Ninop Modoki impacts on Australian rainfall", *Journal of Climate*, **22**, 3167-3174.

Terao, T. and Kubota, T., 2005, "East-west SST contrast over the tropical oceans and the post El Niño western North Pacific summer monsoon", *Geophys. Res. Lett.*, **32**, L15706, doi:10.1029/2005GL023010.

Terray, P., Delecluse, P., Labattu, S. and Terray, L., 2003, "Sea surface temperature associations with the late Indian summer monsoon", *Climate Dynamics*, **21**, 593-618.

Terray, P., Dominiak, S. and Delecluse, P., 2005, "Role of the southern Indian Ocean in the transitions of the monsoon-ENSO system during recent decades", *Climate Dynamics*, **24**, 169-195.

Tozuka, T., Kataoka, T. and Yamagata, T., 2014, "Locally and remotely forced atmospheric circulation anomalies of Ningaloo Niño/Niña", *Climate Dynamics*, **43**, 7-8, 2197-2205.

Trenberth, K. E. and Stepaniak, D. P., 2001, "Indices of El Niño Evolution", *Journal of Climate*, **14**, 1697-1701.

Ummenhofer, C. C., England, M. H., McIntosh, P. C., Meyers, G. A., Pook, M. J., Risbey, J. S., Sen Gupta, A. and Taschetto, A. S., 2008, "What causes southeast Australia's worst droughts?", *Geophys. Res. Lett.*, **36**, L04706, doi:10.1029/2008GL036801.

Ummenhofer, C. C., Schwarzkopf, F. U., Meyers, G. A., Behrens, E., Biastoch, A. and Böning, C. W., 2013, "Pacific Ocean contribution to the asymmetry in eastern Indian Ocean variability", *Journal of Climate*, **26**, 1152-1171.

Venzke, S., Latif, M. and Villwock, A., 2000, "The coupled GCM ECHO-2. Part II: Indian Ocean response to ENSO", *Journal of Climate*, **13**, 1371-1387.

Vinayachandran, P. N., Saji, N. H. and Yamagata, T., 1999, "Response of the equatorial Indian Ocean to an anomalous wind event during 1994", *Geophys. Res. Lett.*, **26**, 1613-1616.

Wajsowicz, R. C., 2005, "Potential predictability of tropical Indian Ocean SST anomalies", *Geophys. Res. Lett.*, **32**, L24702, doi:10.1029/2005GL024169.

Wajsowicz, R. C., 2007, "Seasonal-to-interannual forecasting of tropical Indian Ocean sea surface temperature anomalies: Potential predictability and barriers", *Journal of Climate*, **20**, 3320-3343. doi:10.1175/ JCLI4162.1.

Walker, G. T., 1924, "Correlations in seasonal variations of weather IX", *Mem.*, India Meteorological Department, **24**, 4, 275-332.

Walker, N. D., 1990, "Links between South African summer rainfall and temperature variability of the Agulhas and Benguela current systems", *J. Geophys. Res.*, **95**, 3297-3319.

Wallace, J. M., Rasmusson, E. M., Mitchell, T. P., Kousky, V. E., Sarachik, E. S. and von Storch, H., 1998, "On the structure and evolution of ENSO-related climate variability in the tropical Pacific", *J. Geophys.*, **103**, C7, 14241-14259.

Wang, C. and Wang, X., 2013, "Classifying El Niño Modoki I and II by different impacts on rainfall in Southern China and typhoon tracks", *Journal of Climate*, **26**, 1322-1338.

Wang, G. and Hendon, H. H., 2007, "Sensitivity of Australian rainfall to inter-El Nino variations", *Journal of Climate*, **20**, 4211-4226.

Washington, R. and Preston, A., 2006, "Extreme wet years over southern Africa: role of the Indian Ocean sea surface temperatures", *J. Geophys. Res.*, **111**, D15104. https://doi.org/10.1029/ 2005JD006724.

Webster, P. J., Moore, A., Loschnigg, J. and Leban, M., 1999, "Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997-98", *Nature*, **40**, 356-360.

Weng, H., Ashok, K., Behera, S. K., Rao, S. A. and Yamagata, T., 2007, "Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific Rim during boreal summer", *Climate Dynamics*, **29**, 113-129.

Weng, H., Behera, S. K. and Yamagata, T., 2009a, "Anomalous winter climate conditions in the Pacific rim during recent El Niño Modoki and El Niño events", *Climate Dynamics*, **32**, 663-674.

Weng, H., Wu, G., Liu, Y., Behera, S. K. and Yamagata, T., 2009b, "Anomalous summer climate in China influenced by the tropical Indo-Pacific Oceans", *Climate Dynamics*, **36**, 3-4, 769-782, DOI 10.1007/s00382-009-0658-9.

Wu, B., Li, T. and Zhou, T. J., 2010, "Relative contributions of the Indian Ocean and local SST anomalies to the maintenance of the western North Pacific anomalous anticyclone during the El Niño decaying summer", *J. Climate*, **23**, 2974-2986, doi: 10.1175/ 2010JCLI3300.1.

Wu, B., Zhou, T. J. and Li, T., 2009, "Seasonally evolving dominant interannual variability modes of East Asian climate", *Journal of Climate*, **22**, 2992-3005, doi: 10.1175/2008 JCLI2710.1.

Wu, G. X., Liu, P., Liu, Y. M., Li, W. P., 2000, "Impacts of the sea surface temperature anomaly in the Indian ocean on the subtropical anticyclone over the western pacific-Two-stage thermal adaptation in the atmosphere", *Acta Meteor. Sinica*, **58**, 513-522 (in Chinese).

Wyrtki, K., 1975, "El Niño-the dynamic response of the equatorial Pacific ocean to atmospheric forcing", *Journal of Physical Oceanography*, **5**, 572-583.

Xie, S. P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G. and Sampe, T., 2009, "Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Niño". *J. Climate*, **22**, 730-747.

Xie, S. P., Annamalai, H., Schott, F. and McCreary, J. P., 2002, "Structure and Mechanisms of South Indian Ocean climate variability", *J. Climate*, **15**, 864-878.

Yamagata, T., Behera, S. K., Luo, J. J., Masson, S., Jury M. R. and Rao, S. A., 2004, "The coupled ocean- atmosphere variability in the tropical Indian Ocean. Earth's climate: The ocean-atmosphere interaction", *Geophys. Monogr.*, **147**, AGU, 189-211.

Yamagata, T., Behera, S. K., Rao, S. A., Guan, Z., Ashok, K. and Saji, H. N., 2003, "Comments on "Dipoles, temperature gradient and tropical climate anomalies", *Bull. Amer. Meteor. Soc.*, **84**, 1418-1422.

Yang, J. L., Liu, Q. Y., Xie, S. P., Liu, Z. Y. and Wu, L. X., 2007, "Impact of the Indian Ocean SST basin mode on the Asian summer monsoon", *Geophys. Res. Lett.*, **34**, L02708, doi: 10.1029/ 2006GL028571.

Yang, Q., 2009, "Impact of the Indian Ocean subtropical dipole on the precipitation of east China during winter monsoons", *J. Geophys. Res.*, **114**, D14110. doi: 10.1029/2008JD011173.

Yang, Y., Xie, S. P., Wu, L., Kosaka, Y., Lau, N. C. and Vecchi, G. A., 2015, "Seasonality and Predictability of the Indian Ocean Dipole Mode: ENSO Forcing and Internal Variability", *Journal of Climate*, **28**, 8021-8036, doi: 10.1175/JCLI-D-15-0078.1.

Yeh, Sang Wook, Kug, J., Dewitte, B., Kwon, Min-Ho, Kirtman, P. and Jin, F. F., 2009, "El Niño in a changing climate", *Nature*, **461**, 511-514, doi:10.1038/nature08316.

Yu, J. Y., Mechoso, C., McWilliams, J. and Arakawa, A., 2002, "Impacts of the Indian Ocean on the ENSO cycle", *Geophys. Res. Lett.*, **29**, 8, 1204, 46-1-46-4, doi:10.1029/2001GL014098.

Yu, L., O'Brien, J. J. and Yang, J., 1991, "On the remote forcing of the circulation in the Bay of Bengal", *J. Geophys. Res.*, **96**, 20449-20454

Yuan, C. and Yamagata, T., 2015, "Impacts of IOD, ENSO and ENSO Modoki on the Australian Winter Wheat Yields in Recent Decades", *Sci. Rep.*, **5**, 17252, doi:10.1038/srep17252

Yuan, C., Tozuka, T., Landman, W. A. and Yamagata, T., 2014, "Dynamical seasonal prediction of southern African summer precipitation", *Climate Dynamics*, **42**, 3357-3374.

Yuan, C., Tozuka, T., Miyasaka, T. and Yamagata, T., 2009, "Respective Influences of IOD and ENSO on the Tibetan Snow Cover in Early Winter", *Climate Dynamics*, **33**, 509-520, DOI 10.1007/s00382-008-0495-2.

Zhao, M. and Hendon, H. H., 2009, "Representation and prediction of the Indian Ocean dipole in the POAMA seasonal forecast model", *Quart. J. Roy. Meteor. Soc.*, **135**, 337-352, DOI:10.1002/qj.370.

Zhu, J., Huang, B., Kumar, A. and Kinter III, J. L., 2015, "Seasonality in Prediction Skill and Predictable Pattern of Tropical Indian Ocean SST", *Journal of Climate*, **28**, 7962-7984, DOI: 10.1175/JCLI-D-15-0067.1.

Zubair, L., Rao, S. A. and Yamagata, T., 2003, "Modulation of Sri Lankan Maha rainfall by the Indian Ocean Dipole", *Geophys. Res. Lett.*, **30**, 2, 1063, doi:10.1029/2002GL015639.