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

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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 (IOD) 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 Niño 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).

ISMNR 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-ISMNR 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 Stepihania, 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

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; 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.

\[
EMI = \frac{1}{3} \left( \text{SSTA}_{CP} - 0.5 \times \text{SSTA}_{WP} - 0.5 \times \text{SSTA}_{EP} \right)
\]

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. 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 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 Rossby 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
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
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.
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 Niño.

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
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 Rossby 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. 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)
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 circumpolar 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 20th 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-ISMIR 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 Rajam (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
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.
(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 McLean, 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 Subtropical 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.

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).

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.
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 extratropical 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.

Acknowledgement

I am thankful to Prof. Toshio Yamagata for his guidance and I dedicate the article to late Prof. D. R. Sikka who helped me in my early career.

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

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