The Indo-Western Pacific climate variability and the impacts on Indian summer monsoon: Two decades of advancement in India

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सार – इंडो-पैसिफिक इंडो-पैसिफिक क्षेत्र में अंतर वर्षीय जलवायु परिवर्तन अल नीनो दक्षिणी दोलन (ENSO), हिंद महासागर डिपोल (IOD), उपोष्णकटिबंधीय उत्तरपश्चिमी प्रशांत परिसंचरण और इंडो-पैसिफिक महासागर संधारित्र (IPOC) मोड पर हावी हैं। वर्तमान लेख में हिंद महासागर, पश्चिमी उत्तर प्रशांत और भारतीय ग्रीष्मकालीन मानसून वर्षा (ISMR) पर एक विशेष प्रभाव डालने के साथ मौसम और जलवायु परिवर्तनशीलता पर हमारी प्रयोगशाला में किए गए कार्यों की समीक्षा और सारांश प्रस्तुत करता है। यहां हमने हिंद महासागर के मॉडल्स, भौतिक प्रक्रियाओं, मॉडलों में पूर्वाग्रह, प्रशांत महासागर के प्रभाव, भारतीय ग्रीष्मकालीन मानसून वर्षा पर उनके प्रभाव और कुछ महत्वपूर्ण तंत्रों को भी बताया है। उष्णकटिबंधीय हिंद महासागर (TIO) के उपसतह तापमान में परिवर्तनशीलता का एक नया मोड हाल ही में रिपोर्ट किया गया है और क्षेत्रीय जलवायु परिवर्तनशीलता पर इसका प्रबल प्रभाव देखा गया है। हमने वहीं पर प्रेक्षण, पुनर्विश्लेषण, महासागर मॉडल और युग्मित महासागर वायुमंडल मॉडल का उपयोग करके इसके निर्मित होने की प्रक्रिया को भी प्रदर्शित किया है। इस शोध पत्र में एल नीनो और हिंद महासागर डिपोल के सह-घटना के वर्षा के दौरान सघन बेसिन में व्यापक उष्णकटिबंधीय हिंद महासागरीय (TIO) वार्मिंग और इस वार्मिंग को बनाए रखने के पीछे गतिशील प्रक्रियाओं का पता लगाया गया है। हमने पहली बार दिखाया है कि अल-नीनो और हिंद महासागर डिपोल (IOD) एक साथ होने वाले वर्षा के दौरान विषुवतीय आंचलिक वायु विसंगतियों से प्रेरित रॉबी तरंगों के बहाव से उत्पन्न बैरियर लेयर्स के ढलान के माध्यम से उपसतह वार्मिंग के साथ उप-प्रस्तर वार्मिंग का एक स्पष्ट रूप से पश्चिम दिशा में प्रसार होता है। समुद्री सतह तापमान में उष्णता और बैरियर लेयर के बीच एक मजबूत सकारात्मक प्रतिक्रिया पश्चिमी टीआईओ पर समुद्री हवा के प्रभाव में बदलाव के लिए विकसित हुई है, जो भारतीय ग्रीष्मकालीन मानसून वर्षा के पूर्वानुमान और MJO के विकास के लिए महत्वपूर्ण क्षेत्र है। एन्सो (ENSO) और गैर-एन्सो की भारतीय ग्रीष्मकालीन मानसून वर्षा के साथ के संबंधों की समझ की ओर इंगित करने वाले कई विज्ञान के कई प्रश्न अल नीनो और इंडो-वेस्टर्न प्रशांत महासगर संधारित्र (IPOC) मोड और पैसिफिक जापान (PJ) पैटर्न के क्षय चरण पर अधिक जोर देते हैं। हमने भारतीय ग्रीष्मकालीन मानसून वर्षा (ISMR) पर प्रशांत-जापान पैटर्न (PJ) के प्रभाव का भी पता लगाया है और युग्मित (महासागरीय-वायुमंडलीय) और अयुग्मित (वायुमंडलीय) मार्गों के माध्यम से संभावित भौतिक संबंधों पर प्रस्ताव प्रस्तुत किया है और दिखाया है कि PJ पैटर्न के जवाब में दक्षिणी भारत में वर्षा पश्चिमोत्तर विस्तारित पश्चिमी उत्तर प्रशांत प्रति चक्रवात के दक्षिणी फ्लैंक में निचले स्तर के अभिसरण द्वारा रोसबी तरंगों को पश्चिमोत्तर प्रसार के कारण बढ़ाता है। दूसरी ओर, यह पाया गया है कि पश्चिमी उत्तर प्रशांत क्षेत्र पर दबे हुए संवहन से प्रेरित नमी की प्रतिक्रिया के रूप में वायुमंडलीय ठंडी रॉस्बी लहर का पश्चिम की ओर फैलाव, मानसून गर्त क्षेत्र पर नकारात्मक वर्षा विसंगतियों को बनाए रखने के लिए IPOC मोड और डाउनवर्ड मोशन से जुड़े नमी विचलन महत्वपूर्ण भूमिका निभाता है। हिंद महासागर बेसिन मोड के बीच युग्मित प्रभाव, टीआईओ, उत्तर-पश्चिमी प्रशांत परिसंचरण आदि में असममित मोड ने मानसून के सुदूर संबंधों को नए सिरे से समझ के लिए मार्ग प्रशस्त किया है। हमने हिंद महासागर की परिवर्तनशीलता, भारतीय ग्रीष्मकालीन मानसून वर्षा (ISMR) परिवर्तनशीलता और दूर-संचार के लिए जिम्मेदार प्रक्रियाओं को समझने के लिए कई महासागर मॉडल और युग्मित मॉडल सिमुलेशन और संवेदनशीलता प्रयोगों का पता लगाया है। भारत में मानसून के पूर्वानुमान के लिए उपयोग किए जाने वाले युग्मित मॉडल में महासागरीय पूर्वाग्रहों को समझने के लिए भी प्रयास किए गए। युग्मित मॉडल में महासागर की स्थिति की जांच करते हुए, हमने पाया किया कि वे उष्णकटिबंधीय हिंद महासागरीय (TIO) पर बहुत अधिक सतह शीतलन और उपसतह में उष्णता का प्रदर्शन करते हैं। पहली बार हमारे काम से पता चला है कि क्षैतिज धाराओं के मजबूत ऊर्ध्वाधर झुकाव के द्वारा वर्धित वर्टीकल मिश्रण मुख्य रूप से उष्णकटिबंधीय हिंद महासागरीय (TIO) उपसतह वार्मिंग के लिए जिम्मेदार है और युग्मित मॉडल में सतह ठंडा करने के लिए पुन: पोषण देता है। मानसून के पूर्वानुमान मॉडल में एन्सो- मानसून टेलीकनेक्शन और एन्सो-हिंद महासागर के टेलीकनेक्शन की गलत व्याख्या को भी पूर्वानुमान प्रणाली के साथ जोड़कर देखा जाता है। हमने दिखाया है कि मुख्य रूप से अल नीनो / ला नीना से जुड़े एसएसटी वार्मिंग / कूलिंग के अवास्तविक पश्चिमी विस्तार के कारण अधिकांश मॉडल एन्सो- मानसून टेलीकोनेक्शनों का

प्रतिनिधित्व करने में विफल रहे हैं WNP परिसंचरण और TIO SST प्रतिक्रिया में परिवर्तन के कारण जलवायु परिवर्तनशीलता की ओर यह योगदान युग्मित मॉडल और तात्कालिक प्रदर्शन के आगे के विकास के लिए उपयोगी हो सकता है। परिवर्तनशीलता के नए साधनों सहित क्षेत्रीय जलवायु का पूर्वानुमान देने की समझ विकसित करना अनुसंधान समुदाय के लिए एक बड़ी चुनौती है और हमारे पिछले दो दशकों के योगदान इन पहलुओं के प्रति उदासीन थे।

ABSTRACT. Interannual climate variations over the Indo-Pacific region are mostly dominated by El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), subtropical Northwest Pacific circulation and Indo-Pacific Ocean Capacitor (IPOC) Mode. The present manuscript reviews and summarizes the work mostly carried out *in our lab* on the weather and climate variability with a special emphasis on Indian Ocean, western north Pacific and Indian Summer Monsoon Rainfall (ISMR). Here we have provided a synthesis on the Indian Ocean modes, physical processes, biases in models, interaction with Pacific, and their impact on ISMR and also unraveled some important mechanisms. A new mode of variability in the Tropical Indian Ocean (TIO) subsurface temperature was recently reported and which is found to have strong impact on the regional climate variability. We have also demonstrated the formation mechanism using in situ observation, reanalysis, ocean models and coupled ocean atmosphere models. Intense basin wide TIO warming during El Niño and IOD co-occurrence years and the dynamic processes behind maintaining this warming are explored. We have shown for the first time that a pronounced up-westward propagation of subsurface warming along the sloping mean thermocline and westward propagation of Barrier Layers corroborated by downwelling Rossby waves excited by equatorial zonal wind anomalies during El Niño-IOD co-occurring years. A robust positive feedback between SST warming and Barrier Layer development lead to changes in air-sea interactions over the western TIO, which is a region crucial for ISMR prediction and development of MJO. Several science questions leading to the understanding of ENSO and non-ENSO teleconnections to ISMR with more emphasis on decay phase of El Niño and the Indo-western Pacific Ocean capacitor (IPOC) mode and Pacific Japan (PJ) pattern are addressed. We have also explored the influence of the Pacific-Japan pattern (PJ) on ISMR and proposed the possible physical linkages through coupled (ocean-atmospheric) and uncoupled (atmospheric) pathways and showed that in response to the PJ pattern the rainfall over the southern India enhances due to northwestward propagating Rossby waves corroborated by low level convergence in the southern flank of westward extended western north Pacific (WNP) anticyclone. On the other hand, it is found that westward propagating atmospheric cold Rossby wave as a response to suppressed convection over the western north Pacific region induced moisture divergence associated with IPOC mode and downward motion play important role in maintaining negative rainfall anomalies over the monsoon trough region. The coupled interaction between Indian Ocean basin mode, asymmetric mode in the TIO, northwest Pacific circulation etc. paved way for renewed understanding of monsoon teleconnections. We have carried out several ocean model and coupled model simulations and sensitivity experiments to understand the processes responsible for the Indian Ocean variability, the ISMR variability and the teleconnections. The efforts were also made to understand the ocean biases in the coupled model used for monsoon forecast in India. While examining ocean state in coupled models, we noted that they exhibit too much surface cooling and subsurface warming over the TIO. Our work for the first time revealed that the enhanced vertical mixing by strong vertical shear of horizontal currents is primarily responsible for TIO subsurface warming and feeds back to surface cooling in coupled models. The misrepresentation of ENSO-monsoon teleconnection and ENSO-Indian Ocean teleconnection in the monsoon forecast model is also addressed in detail with a view to improve the forecasting system. We have shown that most of the models failed to represent ENSO-Monsoon teleconnections, mainly due to unrealistic westward extension of SST warming/cooling associated with El Niño/La Niña, changes in WNP circulation and TIO SST response. These contributions towards climate variability would be useful to further development in coupled models and improvisations. Developing a predictive understanding of regional climate including the new modes of variability is a grand challenge for research community and our two decades of contributions were nailing towards these aspects.

Key words – ENSO, IOD, ISMR, TIO, IPOC, SST.

1. Introduction

The Sea Surface Temperature (SST) variations associated with El Niño Southern Oscillation (ENSO) have significant impact on the weather and climate over several parts of the globe, including the South and East Asian regions. The ENSO imprints on the Indian Summer Monsoon (ISM) Rainfall (ISMR) are very significant though with some fluctuations from one epoch to another. The Niño indices (e.g., Niño3.4) are highly correlated with ISMR and so the current understanding of the ISMR variability is heavily dependent on the ENSO variability. Surprisingly, this is quite evident in the current forecasting systems for ISMR as well. In fact, most of the current coupled models are over predicting ENSO and its teleconnections with ISMR. It has then been a big

challenge for the forecasting agencies across the world to address this issue. It is believed that the ENSO-monsoon relationship is modulated through changes in the large scale Walker circulation over the tropical Indo Pacific region, though the active role of Indian Ocean is generally undermined. This challenging problem has been attempted and addressed in many of our studies, including the one showing the role of double Walker cell structure over the tropical Indian Ocean (Deshpande *et al.*, 2014) in modulating the teleconnections. Many recent studies (e.g., Chakravorty *et al.*, 2016; Chowdary *et al.*, 2019; Srinivas *et al.*, 2018b) have highlighted the role of Indian Ocean and its impact on ISMR and Indo-Pacific climate variability mainly by modulating the other climate modes such as the Pacific Japan pattern and Indo-Pacific Ocean Capacitor (IPOC) mode etc. (e.g., Xie *et al.*, 2016 and

Kosaka *et al.*, 2013). The Indian Ocean-Western Pacific variability therefore plays an important role especially in the regional climate.

The Indian Ocean was a data sparse ocean, especially up to 2005 and so the studies prior to 2005 were either based on point observations or only focusing on the surface variability retrieved mainly from satellite observations. The subsurface variability studies prior to 2005 were mainly based on either ocean model simulations or reanalysis products. Very limited data from subsurface observations were used in the reanalysis prior to 2005 and so the reanalysis subsurface data prior to 2005 also may be tagged with some uncertainty. However, the scenario has totally changed with the advent of Array of Real time Geostrophic Oceanography (Argo) and more than 3800 Argo floats are currently profiling the upper 2000 m of the global ocean (please visit http://www.argo.ucsd.edu/ for details). So, any findings of the ocean subsurface variability based on reanalysis data need to be re-examined with observations such as ARGO data. We were one of the first to utilize the ARGO observations for Indian Ocean process studies (Chowdary *et al.*, 2005; Thompson *et al.*, 2006a). Chowdary *et al.* (2005) studied the Arabian Sea water mass properties using the first Argo floats deployed there and Thompson *et al.* (2006a) provided observational evidence for the formations of temperature inversions in the northern Bay of Bengal and their role on the Arabian Sea warm pool formation. The present manuscript reviews work on the variability of the Indo-Western Pacific Climate and focused on TIO surface and subsurface modes in observations and models, biases in coupled models, interactions with Pacific Climate and impacts on ISMR. Rest of the paper is organized as follows. Details of data used in this article is provided in Section 2. Tropical Indian Ocean surface and subsurface variability and modes are discussed in Section 3. Inter-basin interactions and their impact on ISMR are provided in Section 4, Section 5 discusses TIO biases in coupled climate models and their influence on the predictability of ISMR. Section 6 provides a discussion. Summary is provided in Section 7.

2. Data used

Centennial *In-situ* Observation Based Estimates of the Variability of SST and Marine Meteorological Variables (COBEv2) (Hirahara *et al.*, 2014), The National Centers for Atmospheric Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) winds (Kalnay *et al.*, 1996) are used. Observed subsurface ocean temperatures for the period from 1979 to 2015 is obtained from HadEN4 (Good *et al.*, 2013) and sea level data during 1958-2002 is taken from the

Ocean Reanalysis System 4 (ORAS4) (Balmaseda *et al.*, 2013). ORAS4 employs the variational ocean data assimilation system NEMOVAR using Nucleus for European Modelling of the Ocean (NEMO) version 3.0 ocean model. Temperature and salinity profiles as well as along-track altimeter sea level anomalies (SLA) are assimilated in NEMOVAR. ORAS4 is forced by daily surface fluxes of heat, momentum and fresh water from ECMWF atmospheric reanalysis.

The global ocean-atmosphere fully coupled model used in this study is SINTEX-F CGCM (Luo *et al.*, 2005). Nine-member ensemble retrospective forecasts for 12 target months from the first day of each month during 1983-2006 is performed. The nine members are generated on the basis of three different coupling physics (*i.e.*, three different models) with three different initial conditions for each model (Luo *et al.*, 2008a,b). Model results are compared with the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis Interim (ERA-Interim; Dee *et al.*, 2011) sea level pressure (SLP), 850 and 200 hPa winds, Reynolds *et al.* (2002) SST and the Center for Climate Prediction merged analysis of precipitation (CMAP; Xie and Arkin, 1997).

3. Tropical Indian Ocean surface and subsurface variability and modes

The Indian Ocean was believed to be responding passively to Pacific forcing until Indian Ocean Dipole (IOD, Saji *et al.*, 1999; Webster *et al.*, 1999), the coupled mode of interannual variability in the Indian Ocean, was invented. So very minimal efforts were made to understand the Indian Ocean especially on the regional climatic impacts. IOD is an east-west mode of variability in TIO SST. The recent studies have shown that IOD (e.g., Ashok *et al.*, 2001) and oscillations in the equatorial winds (Gadgil *et al.*, 2004; Gadgil, 2018) have strong impact on ISMR. El Niño induced subsidence over the Indian Ocean warms the Indian Ocean basin during winter (the period of El Niño peak) and the following spring. In contrast La Niña forces a basin wide cooling of the Indian Ocean. This El Niño (La Niña) induced basin wide warming (cooling) is reported to be the dominant interannual variability in the Indian Ocean SST (e.g., Klein *et al.*, 1999; Alexander *et al.*, 2002; Chowdary *et al.*, 2006; Chowdary and Gnanaseelan, 2007; Singh *et al.*, 2013). This is also evident in the leading mode of variability (first EOF) of SST in the tropical Indian Ocean [TIO; Fig. 1(a)]. Figs. 1(a-d) show the first two leading modes of variability in TIO SST and thermocline. The first leading mode shows a basin wide warming (or cooling) [Fig. 1(a)] and the second mode shows an east-west mode with opposite polarity [Fig. 1(b)]. In contrast to the SST variability, the subsurface temperature displays a
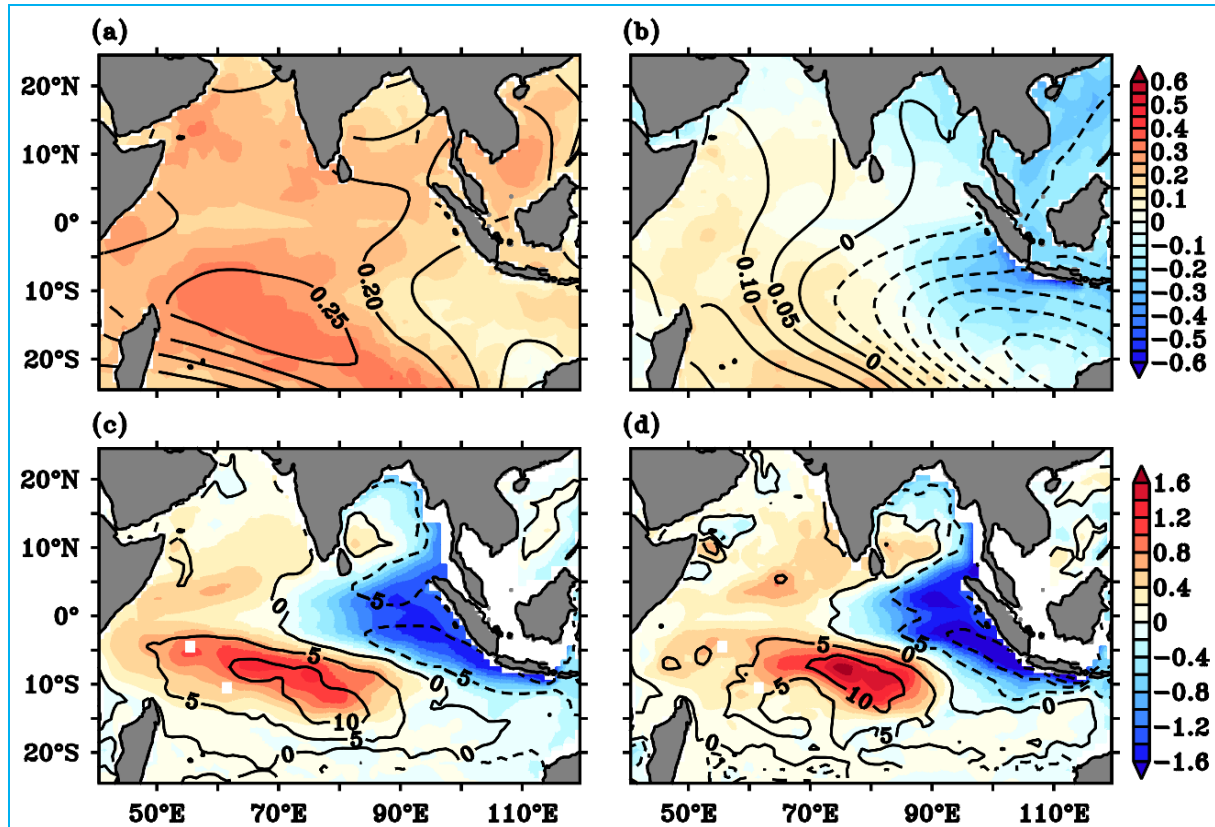
Figs. 1(a-d). (a) EOF 1 and (b) EOF 2 of detrended SST anomalies using SODA 2.1.6 (1958 to 2008; shaded) and ERSST (1950 to 2016; contours); (c) EOF 1 of detrended 100 m temperature anomalies (shaded) and d20 anomalies (contours) using SODA 2.1.6 (d) same as (c) but for September-November season

north south mode of variability forced by IOD and ENSO [Fig. 1(c)] and is found to strengthen even after the IOD forcing ceases. This strongly suggests the existence of possible coupled processes associated with this mode. The basin scale Indian Ocean warming has a prominent role in modulating the rainfall anomalies over Asia (e.g., Yang *et al.*, 2007; Izumo *et al.*, 2008; Xie *et al.*, 2009) and so has been considered as an important mode of variability. However, as the total attribution of this basin scale warming was to El Niño, the Pacific occupied the centre stage even in the context of Indian Ocean basin scale warming. Chowdary and Gnanaseelan (2007) on the other hand showed that the ocean dynamics too plays an important role in the basin wide warming, especially on the western Indian Ocean warming, during the years when El Niño co-occur with positive IOD. This in fact adds to our previous understanding that the basin wide warming (cooling) was just a mere response to El Niño (La Niña) induced large scale subsidence (convection) and the associated changes in the surface heat fluxes. The role of Indian Ocean dynamics on TIO warming was further evidenced by Chakravorty *et al.* (2014a). We in fact have shown in Chakravorty *et al.* (2014a) that Indian Ocean basin scale interannual warming persisted for several

seasons especially after the 1970's climate shift. It was also demonstrated that such persistence is possible only through active ocean dynamics in the Indian Ocean. The dominant role of ocean dynamics on the basin scale Indian Ocean response strongly suggests the existence of possible thermocline SST coupled interaction in the TIO (e.g., Chowdary *et al.*, 2009). So, understanding the evolution of such interaction is crucial for predicting the basin scale warming and the IOD events. The potential predictors of IOD in the form of off equatorial and southern TIO biannual Rossby waves and their formation mechanisms are demonstrated in Gnanaseelan *et al.* (2008) and Gnanaseelan and Vaid (2010). Argo observations (Chowdary *et al.*, 2009) showed a pronounced up-westward propagation of subsurface warming along the sloping mean thermocline due to downwelling Rossby waves over the southern TIO during the El Niño and IOD co-occurrence years [Figs. 2(a-e)]. Most importantly co-propagation of a westward propagating Barrier Layer with downwelling Rossby wave is a new aspect to the dynamical Rossby wave formation reported. The downwelling Rossby wave helps form a Barrier Layer by deepening the isothermal layer and increasing precipitation. The warming along the Rossby
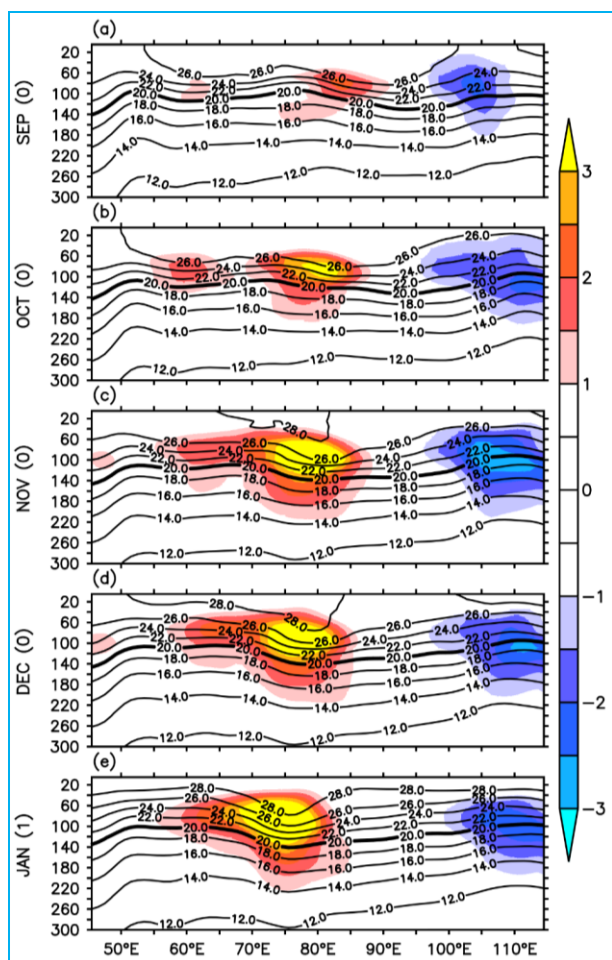
Figs. 2(a-e). Depth-longitude sections of composite (1982-1983, 1994-1995, 1997-1998, 2006-2007) subsurface temperature anomalies (shaded in °C), superimposed on mean temperature (the 20 °C isotherm thickened) at 10° S from September to January based on EN4 data. Fig. is updated based on Chowdary *et al.* (2009)

wave path increases precipitation, favoring Barrier Layer formation in the region west of 75° E and Barrier Layer strengthens the surface warming by shielding the surface from the influence of colder thermocline water in the tropical Southwest TIO. This aspect with a positive feedback between SST warming and Barrier Layer development adds a new dimension to the dynamical Rossby wave forming and its thermocline feedback in the southwestern TIO (e.g., Chakravorty *et al.*, 2014b; Sayantani and Gnanaseelan, 2015; Kakatkar *et al.*, 2019) and the thermocline ridge region of the Indian Ocean (Jayakumar *et al.*, 2011). The dynamically dominant southwestern TIO and its interannual temperature variability play an important role in the air-sea coupled processes in the region at intraseasonal (e.g., Jayakumar *et al.*, 2011; Jayakumar and Gnanaseelan, 2012) to

interannual (e.g., Chakravorty *et al.*, 2014b) time scales. The IOD is found to be the second dominant mode of SST variability in the TIO, however almost half of the IOD events co-occur with El Niño in the Pacific suggesting that El Niño could be playing some role in driving IOD. Moreover, the mechanisms for the IODs formed without El Niños were not clearly understood. So whether IOD is forced by El Niño or is evolved independently is still an unresolved scientific problem. In Sayantani *et al.* (2014), we showed that the evolution of Arabian Sea SST anomalies from the pre-monsoon period onwards and the associated large scale atmospheric dynamics are primarily responsible for the initiation of equatorial easterlies, which in fact is one of the essential component for the IOD formation. So, the role of Arabian Sea processes and the associated air-sea coupled processes in the IOD formation is highlighted.

Sayantani and Gnanaseelan (2015) recently found a new mode of variability in the TIO subsurface which is north south oriented in contrast to the traditional east west surface mode, they also showed strong association of this subsurface mode with the other surface modes in the TIO and is driving the recharge discharge processes in the Indian Ocean, a process which is maintaining heat balance in the north Indian Ocean. The possibility of this mode actively driving the recharge discharge processes in the Indian Ocean is an unexplored topic. This highlights the importance of this subsurface mode in the subsurface surface interaction and thereby the air-sea interactions. The subsurface mode in the coupled models and ARGO observation is studied in Kakatkar *et al.* (2019). This study highlighted that the coupled models in general fail to represent the four dimensional structure of this mode though the initial stages of the evolution of the mode is similar to the observation. This could partially be due to the unrealistic ENSO-Indian Ocean teleconnections in the coupled models (such as CFSv2), a serious problem most of the current coupled models generally suffer from. Major issue with the current coupled models is their inability to maintain the subsurface mode for several months (or capture its persistence), which is in contrast to the observations (Kakatkar *et al.*, 2019). It is important to note from Fig. 3 that the coupled model CFSv2 captures the formation of this mode very well and the leading mode of variability in the model 100 m temperature compares very well with that of ARGO observation and reanalysis ORAS4. Deepa *et al.* (2018) showed the evolution of similar north south pattern of variability in the sea level of TIO as well, strongly suggesting the coupled nature of the subsurface mode. Fig. 4(a) shows the leading mode of variability in the sea level anomalies (SLA) in ORAS4 (shaded) and altimeter (contour). It is also highlights the potential regional impacts as the signals associated with this variability are
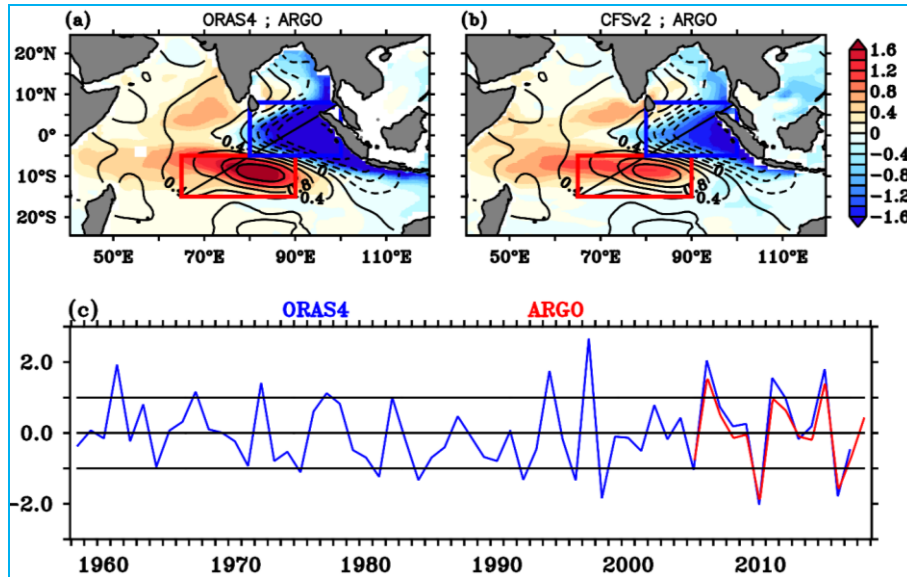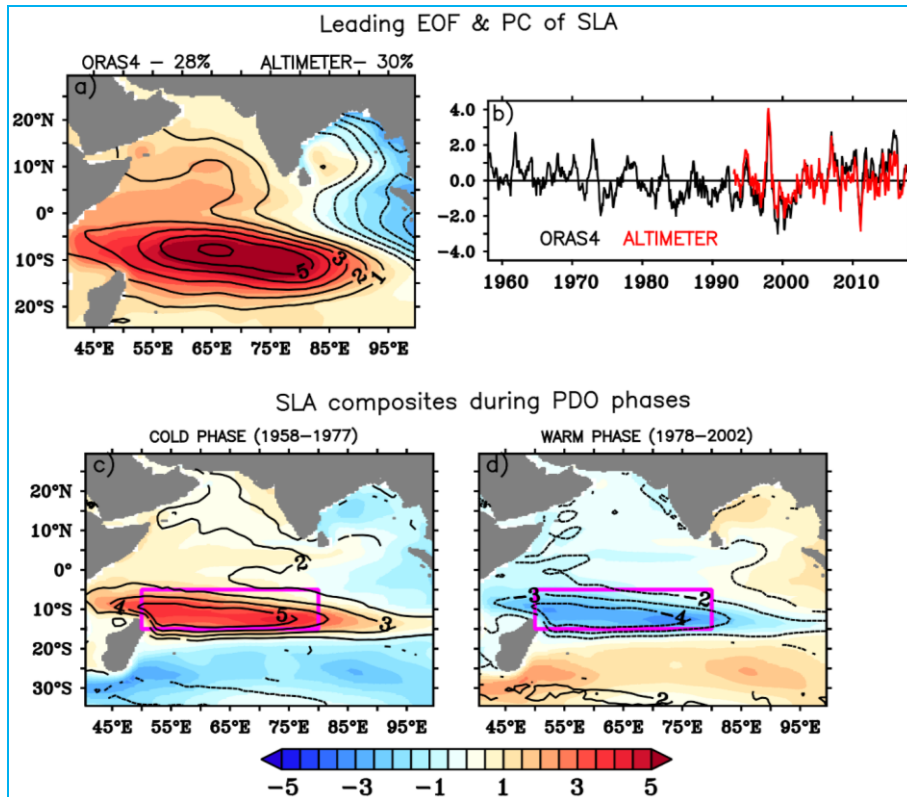
Fig. 3(a-c). EOF1 of detrended 100 m temperature anomalies using (a) ORAS4 (1958 to 2017; shaded) and ARGO (2005 to may 2019; contours); (b) CFSv2 free run (59 years; shaded) and ARGO (contours); (c) PC1 corresponding to EOF1 shown in (a). This figure is reproduced from Kakatkar *et al.* (2019).


Figs. 4(a-d). (a) The leading interannual EOF (EOF-1) patterns of SLA in ORAS4 for the period of 1958 to 2017 (shaded) and altimeter for the period of 1993 to 2017 (contours) and (b) the corresponding principal components of ORAS4 (black line) and altimeter (red line). SLA decadal composite (cm) from ORAS4 (shaded) and CTL significant at 95% confidence level based on two-tailed Student's *t*-test (contours) during (c) cold phase and (d) warm phase of PDO. This figure is reproduced from Deepa *et al.* (2018) and Deepa *et al.* (2019)

spread along the coasts of Bay of Bengal, which may in turn impact the coastal regions around the Bay of Bengal (e.g., Sreenivas *et al.*, 2012b). The above modes of variabilities are simulated in the ocean general circulation model (OGCM) as well and are consistent with ORAS4 (the best reanalysis product over the TIO, Karmakar *et al.*, 2018) and altimeter/ARGO (Figs. 3&4). This in fact makes it an important tool for process studies associated with the subsurface mode in the TIO through sensitivity experiments.

The equatorial Indian Ocean and north Indian Ocean are undergoing climate variability in the interannual (e.g., Thompson *et al.*, 2006b; Gnanaseelan *et al.*, 2012; Sreenivas *et al.*, 2012b; Deshpande *et al.*, 2014; Gnanaseelan and Deshpande, 2018), intraseasonal (e.g., Sreenivas *et al.*, 2012a; Deshpande *et al.*, 2017; Jayakumar *et al.*, 2011; Jayakumar and Gnanaseelan, 2012; Vialard *et al.*, 2012; Jayakumar *et al.*, 2013) and epochal (Rahul and Gnanaseelan, 2016) time scales and long term changes (Rahul and Gnanaseelan, 2013; Rahul and Gnanaseelan, 2016; Thompson *et al.*, 2008; Pratik *et al.*, 2019). These are believed to have strong impact on the regional climate variability. Thompson *et al.* (2006b) demonstrated the existence of strong interannual variability in circulation and salinity associated with IOD using an OGCM and defined an index based on salinity for the first time to explain the coupled nature of IOD. The salinity index is found to evolve very similar to that of dipole mode index (DMI) defined by Saji *et al.* (1999). The coupled nature of IOD evolution is very important in the context of understanding its regional impacts (e.g., Deshpande *et al.*, 2014, 2017). In fact, in Deshpande *et al.* (2014), we defined new IOD indices based on the coupling strength and explained various coupled processes through which IOD evolution actually takes place. We also showed that only strong IOD events with enhanced positive feedback have any significant impacts on ISMR and these results have strong implications on monsoon forecast. The climatic impact of IOD was generally questioned due to its shorter life cycle compared to the similar variability in the Pacific El Niño. Several studies examined the causes of the shorter life cycle of IOD. Thompson *et al.* (2009) showed the role of ocean dynamics in the IOD termination using ocean model simulation and demonstrated the complexity of termination processes. These results have strong prediction values and so need to be highlighted. The evolution of double celled Walker circulation over the tropical Indian Ocean with the western one influencing the African rainfall as well is also reported (Deshpande *et al.*, 2014). The coupled nature of IOD and ENSO is evident in the context of similar evolution of surface winds and currents (e.g., Gnanaseelan *et al.*, 2012). Sreenivas *et al.* (2012b) showed that the equatorial Indian

Ocean sea level responds to these interannual wind forcing and brought out its possible impacts on the Bay of Bengal dynamics and cyclogenesis. The interannual sea level response in the equatorial Indian Ocean as a response to IOD and ENSO is therefore projected as the major driving force for the Bay of Bengal circulation and sea level. It also contributes considerably on the eddy formation in the Bay of Bengal, a topic which needs further scrutiny. The upwelling and downwelling Kelvin waves as a response to equatorial wind forcing propagate along the equator and after reaching the eastern boundary, they propagate as coastal Kelvin waves along the coasts of Bay of Bengal and often the signals propagate up to Arabian Sea. So, the impact of the equatorial variability through coastally trapped waves is evident up to Arabian Sea. Thompson *et al.* (2006b) and Gnanaseelan *et al.* (2012) demonstrated the interannual equatorial surface currents associated with IOD and El Niño induced surface wind forcing and their close association with the persistence of IOD. The evolution of surface winds and circulation has strong association with the evolution of sea surface salinity as well [Figs. 5(a&b)]. In addition to that, Thompson *et al.* (2006b) and Gnanaseelan and Deshpande (2018) explained the role of equatorial undercurrents in feeding the IOD and strengthening the thermocline SST interaction in the eastern equatorial Indian Ocean. The equatorial undercurrents over the Indian Ocean are relatively less studied features mainly because of their transient nature. However, during the strong IOD years, they are semi-permanent in nature and show stronger magnitudes during summer and fall periods in contrast to the weaker or no undercurrents during this period in the normal years. This highlights the importance of understanding the undercurrents in the evolution and maintenance of IOD and the associated coupled variability. The contrasting structures of surface and subsurface current anomalies associated with strong and weak IODs [Figs. 5(a-d)] emphasize the coupled nature of these dynamical features.

Recently lot of emphasis has been given on the transport of warm waters from the Pacific to Indian Ocean through Indonesian Through Flow (ITF) especially in the global warming hiatus period. Many studies attributed this and the associated heat transport to the Indian Ocean through ITF to the decadal variability in the Pacific such as Interdecadal Pacific Oscillation (IPO) or Pacific Decadal Oscillation (PDO) (e.g., Lee *et al.*, 2015; Nieves *et al.*, 2015). However, a clear picture on which latitudes of the Indian Ocean are getting affected by ITF is not yet understood in detail. The role of oceanic pathways from the Pacific to Indian Ocean in the interannual (e.g., Vaid *et al.*, 2007; Rahul and Gnanaseelan, 2016; Deepa *et al.*, 2018) and decadal (Rahul & Gnanaseelan, 2016;
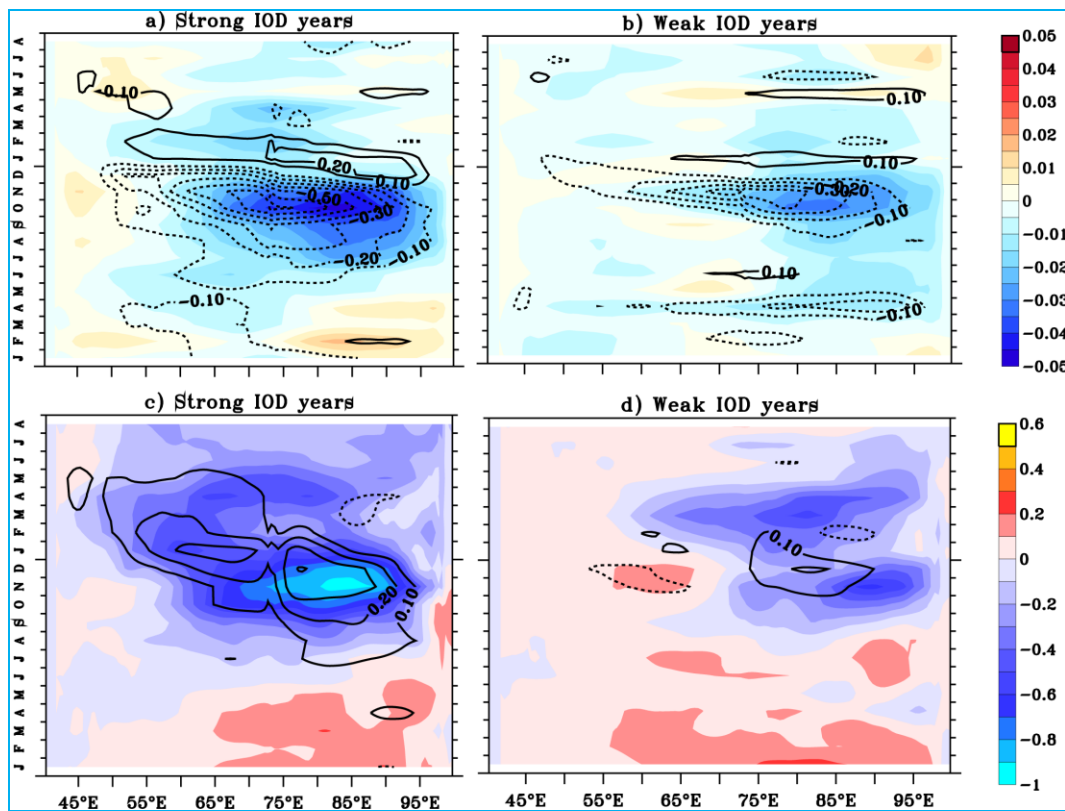
Figs. 5(a-d). Composite evolution of zonal windstress anomalies (shaded; Nm^{-2}) and surface (15 m depth) zonal current anomalies from model (contours; m/s) during (a) Strong IOD years and (b) Weak IOD years. Composite evolution of sea surface salinity anomalies (shaded) and subsurface (depth averaged) zonal current anomalies (contours; m/s) from model during (c) Strong IOD years and (d) Weak IOD years. All the fields are averaged over 1.5° S-1.5° N. This figure is reproduced from Deshpande *et al.* (2017)

Deepa *et al.*, 2019) time scales are studied to quantify the impact of Pacific changes on Indian Ocean variability. It is found that the Pacific influence through ITF is mainly in the region south of 15° S in the Indian Ocean in decadal time scales. However, the region north of 15° S is influenced by ITF in the interannual time scales (Vaid *et al.*, 2007; Deepa *et al.*, 2018).

Though it is evident that ITF has no significant influence in the TIO north of 15° S in the decadal time scale, contrasting patterns of decadal oscillation in sea level is found during the opposite phases of PDO especially in the thermocline ridge region of the Indian Ocean (TRIO; 50° E - 80° E; 15° S - 5° S). Epochal mean sea level rise is observed over the TRIO region (Deepa *et al.*, 2019) during the cold phase of PDO (1958-1977), whereas epochal mean sea level fall is observed during the warm phase of PDO (1978-2002) [Figs. 5(c&d)]. The winds and wind stress curl variations associated with these large scale circulation changes are primarily inducing the observed regional decadal sea level variability over TRIO (Deepa *et al.*, 2019). The decomposed winds (into the rotational and divergent components) are used to explore

the forcing mechanisms (Deepa *et al.*, 2019). Anomalous easterlies in the equatorial region are seen in the cold phase of PDO, whereas westerlies are observed during the warm phase [Figs. 6(a&b)] (Deepa *et al.*, 2019). Anticyclonic circulation is evident in the rotational wind component during the cold phase around 12° S - 8° S region in the TRIO region [Fig. 6(a)]. Instead, a cyclonic circulation is observed in the same region during the warm phase [Fig. 6(b)] thereby imposing a symmetric response to the opposite phases of PDO (Deepa *et al.*, 2019). Detailed analysis reveals that the decadal variability in the sea level pattern in the TRIO region is in accordance with the PDO phase shifts and is primarily caused by changes in the surface forcing over the Indian Ocean as a response to PDO (Deepa *et al.*, 2019). Analysis is carried out using altimeter data for the period 1993-2012 (1993-2002 comes under the long PDO warm phase of 1978-2002 and 2002-2012 is the cold phase following the long warm phase) [Figs. 7(a&b)]. The signals after detrending, shows similar pattern, though it is slightly shifted to south. This shift is present in ORAS4 sea level pattern as well for the recent period, may be arising due to the short period of analysis and dominating influences of interannual events such as
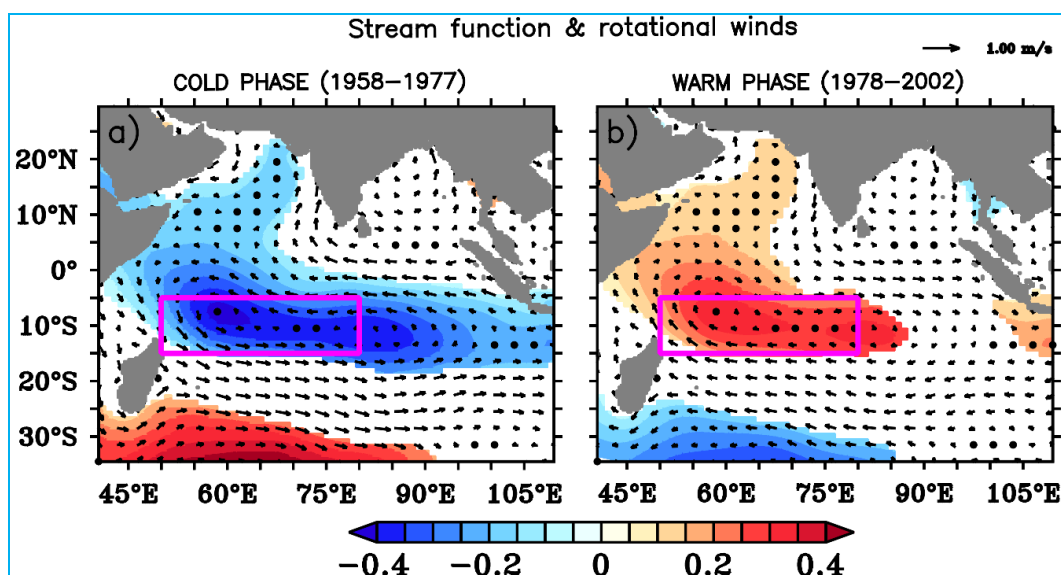
Figs. 6 (a&b). Composite of stream function (s⁻¹, shaded) and rotational components of winds (m/s) overlaid as vectors (a) cold phase (b) warm phase. Composites are significant at 90% confidence level based on two-tailed Student's *t*-test. This figure is reproduced from Deepa *et al.* (2019)
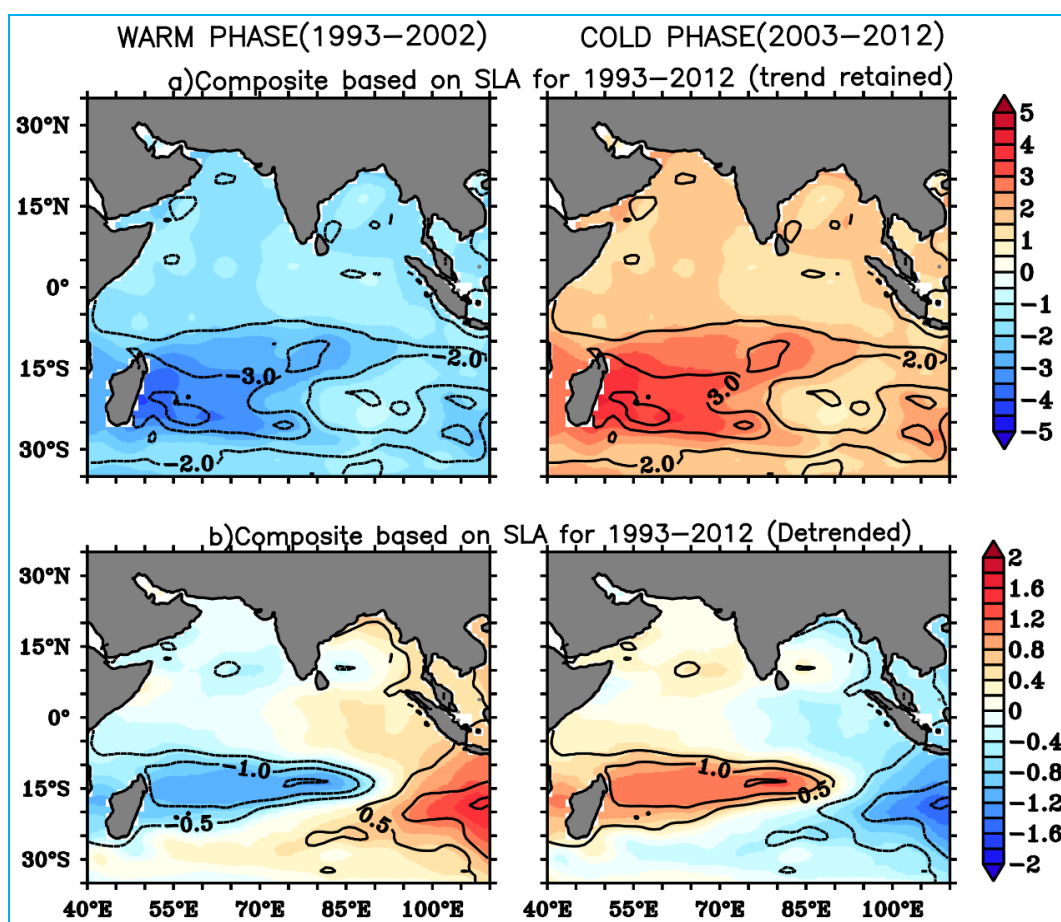
Figs. 7(a&b). Sea level anomaly composite (cm) based on Altimeter data (shaded) and ORAS4 data (contours) for the period 1993-2012 during warm phase (1993-2002, first column) and cold phase (2003-2012, second column). (a) composites with SLA trends retained (b) composites based on detrended SLA. This figure is reproduced from Deepa *et al.* (2019)
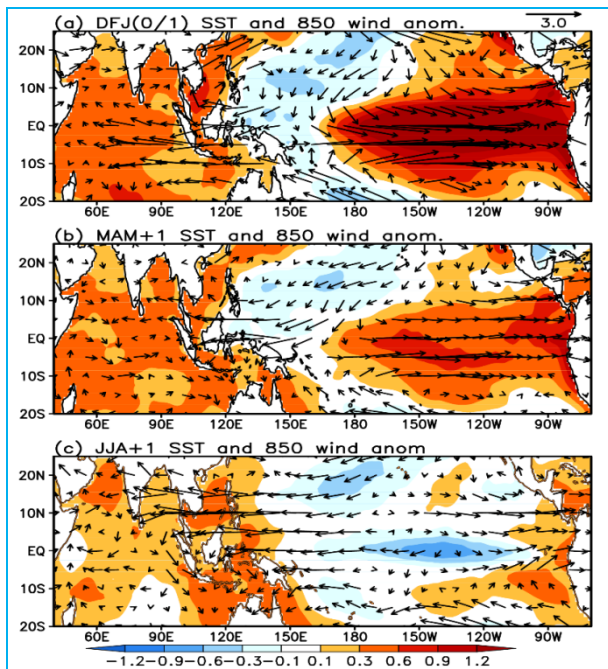
Figs. 8(a-c). Composite of El Niño years from DJF (0/1) to JJA+1 based on COBA SST (°C, shaded) and NECP/NCAR 850 hpa winds (m/s; vectors) anomalies

ENSO, the impact of which in the Indian Ocean mainly is mostly to the south of 15° S. As suggested by previous studies, warming trends in Indian Ocean are dominant in the recent period and hence the SLA pattern shift during the recent PDO phases is clearer only after the trends have been removed. Several studies in the recent years reported excess heat transport from the Pacific to the Indian Ocean through ITF. So, in order to understand the contribution of signal transmission through oceanic pathways from Pacific Ocean, we have carried out OGCM experiments by modulating forcing fields over the Pacific Ocean. The model sensitivity experiments reveal that the oceanic channel is not really playing any major role in controlling the sea level pattern in the TRIO on decadal time scale (Deepa *et al.*, 2019). Moreover, the decadal signals are found originating west of 100° E, suggesting that these signals are not part of remote forcing from the Pacific Ocean through oceanic pathways.

4. Interaction between Tropical Indian Ocean and western north Pacific: Impacts on ISM rainfall

## 4.1. *TIO Basin-wide warming and asymmetric mode*

As discussed in the previous section, ocean dynamics such as Ekman process and oceanic Rossby waves and heat flux variations associated with El Niño through atmospheric bridge mainly induce TIO basin-wide warming (e.g., Chowdary and Gnanaseelan, 2007). This

warming over TIO generally persists for the next two seasons (*i.e.*, until boreal summer) (Xie *et al.*, 2009; Chakravorty *et al.*, 2013). At the same time warm SST anomalies in the eastern Pacific associated with El Niño weakens or are terminated by late boreal spring (e.g., Chowdary *et al.*, 2016a). Persistent TIO warming exerts strong impact on South Asian, East Asian and western north Pacific monsoon rainfall and circulation during the El Niño decaying summers (e.g., Xie *et al.*, 2016; Chowdary *et al.*, 2015a). During the decay phase of El Niño, ISMR is generally normal/above normal (Chowdary *et al.*, 2014, 2017), whereas rainfall is below normal over the northwest Pacific (e.g., Xie *et al.*, 2016). It is important to note that the rainfall over both regions are highly influenced by TIO warming. This indeed suggests their close association.

Surface wind and SST anomalies over the Indo-Pacific region during the peak phase of El Niño (winter; DJF (0/1)), spring (MAM+1) and JJA+1 are depicted in Fig. 8. '0' refers to the El Niño years and '1' and '+1' refer to the following years. During the peak phase of El Niño zonal extension of near equatorial SST anomalies, convergence of surface winds over central and eastern Pacific and western north Pacific anticyclone are seen. At the same time, TIO basin-wide warming and negative SST anomalies over the western north Pacific and easterly wind anomalies over the equatorial Indian Ocean are apparent in observations [Fig. 8(a)]. During MAM+1 spring asymmetric wind pattern over the TIO with northeasterlies in the north of the equator and northwesterlies south of the equator and basin-wide warming are observed (e.g., Chakravorty *et al.*, 2013) [Fig. 8(b)]. On the other hand, weak SST and wind anomalies over the central and eastern Pacific are noted in MAM+1 as compared to DJF (0/1). The anomalous TIO basin-wide warming, western Pacific anticyclone, asymmetric wind pattern over TIO are also seen during JJA+1 even after the decay of El Niño [Fig. 7(c)]. This strongly suggests the close association between them.

4.2. *Impact of TIO warming on ISM during El Niño decay phase*

Composite anomalies of SST and atmospheric parameters over the TIO region for the observations and SINTEX-model during the decay phase of El Niño summers are illustrated in Figs. 9(a-d) (1983, 1998 and 2003). It is noted that the TIO basin-wide warming is apparent during the decay phase of El Niño. Observations show low level northeasterly wind anomalies in the north Indian Ocean (NIO) [Fig. 9(a)] and these wind anomalies support the persistence of basin-wide warming by reducing the surface latent heat flux loss. In response to TIO warming, precipitation anomalies are positive over
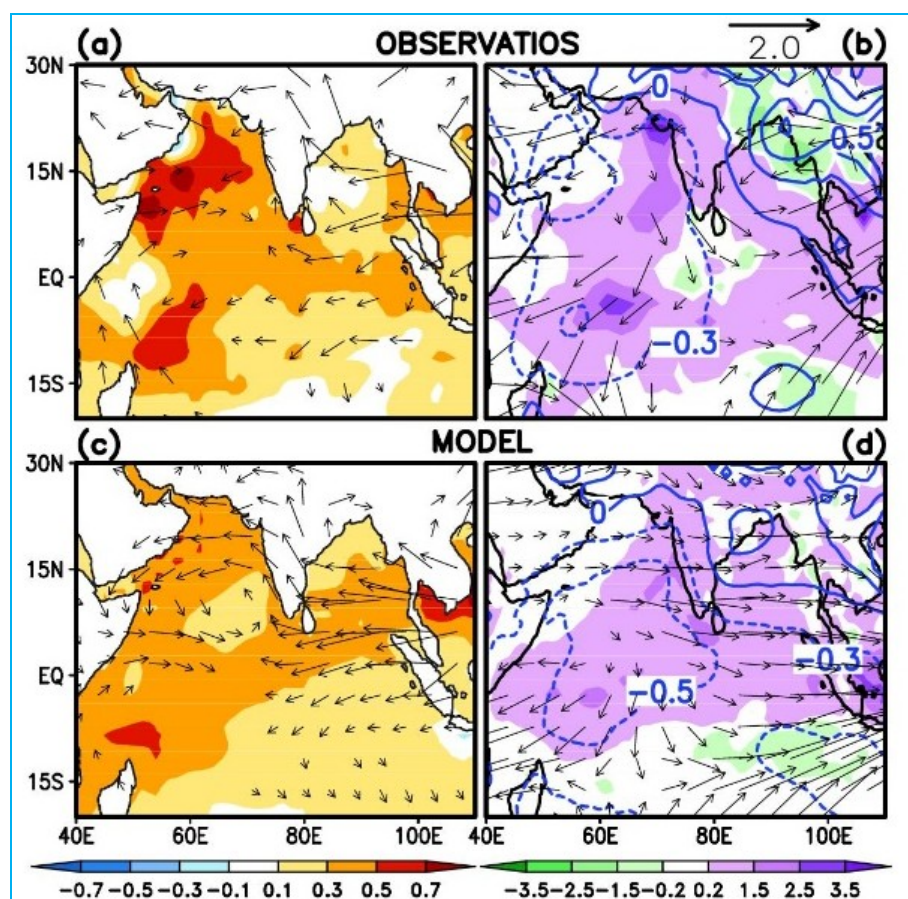
Figs. 9(a-d). JJAS composite anomalies (a) SST (shaded; °C) and 850 hPa winds (vectors; m/s), (b) precipitation (shaded; mm/day), SLP (contours; hPa) and 200 hPa wind (vectors; m/s) during decaying phase of El Niño. (c) and (d) as in (a) and (b) but for model 1-month lead prediction

most of the TIO and parts of Indian subcontinent. Despite having weak monsoon circulation, the stronger low-level moisture transport and reduced moist stability associated with the warm TIO enhances monsoon rainfall (Yang *et al.*, 2007; Park *et al.*, 2010; Chowdary *et al.*, 2015a, 2017). This is also supported by negative SLP anomalies over the Arabian Sea and western parts of Indian subcontinent. However, negative precipitation anomalies are seen over the north eastern parts of the Indian subcontinent corroborated by high SLP extending from western north Pacific (e.g., Chowdary *et al.*, 2013). Overall, SINTEX model showed prominent skill in predicting JJAS rainfall over ISM region during the decaying phase of El Niño including TIO basin-wide warming. It is apparent from the observations and model that ISM rainfall during the decay phase of El Niño is near normal or excess over most parts of India as pointed out in previous studies (e.g., Chowdary *et al.*, 2015a, 2017; Tao *et al.*, 2015).

Some studies suggested that the El Niño progression differs from case to case due to the changes in the decaying phases and influence the climate over various regions (e.g., Chen *et al.*, 2012, 2016). Li *et al.* (2007) noted that strong El Niños are associated with rapid and short decaying phase, while the moderate El Niños are characterized by slow and long decaying phase. The above studies suggest that it is important to examine the variations in the decay phases of El Niño and their impact on rainfall and circulation over the Indo-Western Pacific region including ISM region. In Chowdary *et al.* (2017) we examined the influence of El Niño decay variations on ISM rainfall and circulation based on re-analysis data for the period of 142 years (1871 to 2012). El Niño decay phases are first classified into three types with respect to summer monsoon season, namely early decay (ED), Mid-summer decay (MD) and (3) no summer decay (ND). We found that in case of ED, El Niño completely decays by boreal spring, whereas in MD El Niño related SST anomalies decay around mid-summer. On the other hand, there is no significant cooling in the eastern Pacific from summer to the end of the calendar year in ND case. Rainfall analysis reveals that all ISMR is excess, normal
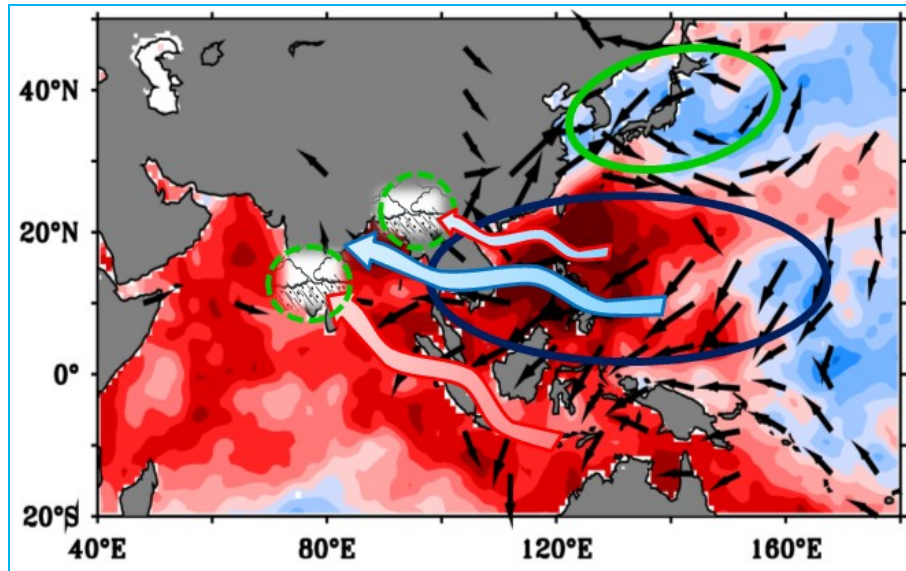
Fig. 10. Schematic diagram that shows pathways associated with the impact of the PJ pattern on ISM rainfall. Ellipse with thick blue (green) line indicates anomalous anticyclone (cyclonic) circulation over the tropical (midlatitude) WNP and vectors represent broad low level circulation associated with PJ pattern. Thick red (blue) arrow represents westward extension of warm (cold) Rossby wave and red (blue) shading in the Indo-Western Pacific Ocean region indicates warm (cold) SST anomalies. Dashed green circles indicates centers of convection. This Fig. is Updated/modified version of Srinivas *et al.* (2018b)

and deficit during ED, MD and ND years respectively. Further, strong sub-seasonal variability in ISM rainfall is reported in decaying El Niño years, indicating that the decay phases have profound influence on the sub-seasonal monsoon rainfall variability. We further pointed out that circulation and rainfall anomalies over ISM are highly influenced by warm TIO SST and La Niña conditions in Pacific during ED years. In case of MD years, it is suggested that southwesterlies from Arabian Sea and northeasterlies from Bay of Bengal converge and lead to positive rainfall over most part of the Indian subcontinent from August onwards. During ND years due to persisting El Niño related warm SST anomalies over the Pacific, weak monsoon circulation and negative rainfall anomalies are seen throughout the summer season. It is important to note that northeasterlies over the Bay of Bengal in summer following El Niño years are induced by anomalous Western North Pacific (WNP) anticyclone or the Pacific-Japan (PJ) Pattern (Nitta 1987; Kosaka and Nakamura 2006).

The PJ pattern is the dominant mode of climate variability in the WNP during boreal summer (June, July and August) and features a meridional dipole structure in lower tropospheric circulation and precipitation anomalies with the tropical and mid-latitude WNP (Nitta, 1987; Kosaka and Nakamura, 2006). The positive PJ pattern is significantly correlated with the decay phase of El Niño (e.g., Sun *et al.*, 2010; Xie *et al.*, 2016). This PJ pattern

over WNP region develops even in the absence of El Niño influence. Recently Srinivas *et al.*, (2018b) examined the impact of the PJ pattern on ISM rainfall variability. The leading EOF (EOF-1) of the 850 hPa relative vorticity over the WNP region represents PJ pattern. They noted that the partial correlation of the PJ index (after removing the influence of ENSO) with precipitation anomalies shows significantly positive correlation over the Maritime Continent and southern and northern parts of India (Fig. 10). The enhanced convection in southern peninsular India is due to the response of deep convection over the Maritime continent through northwestward propagation of warm Rossby waves (Fig. 10). Enhanced deep convection over the Maritime Continent is associated with tropical WNP anomalous anticyclone as a part of the PJ pattern. In conjunction with this, they suggested that the east-west overturning circulation cell with ascending motion corroborated by low level convergence and upper level divergence over the Indian subcontinent and strong subsidence over the WNP region indicates the influence of the PJ pattern on ISM rainfall. It is found that positive rainfall band over north India is due to anomalous low level moisture convergence in the northwestern edge of the westward propagating atmospheric cold Rossby wave as a response to suppressed convection over the tropical WNP region associated with the PJ pattern. This highlights the importance of atmospheric pathway of the PJ influence on ISM rainfall (Fig. 10).
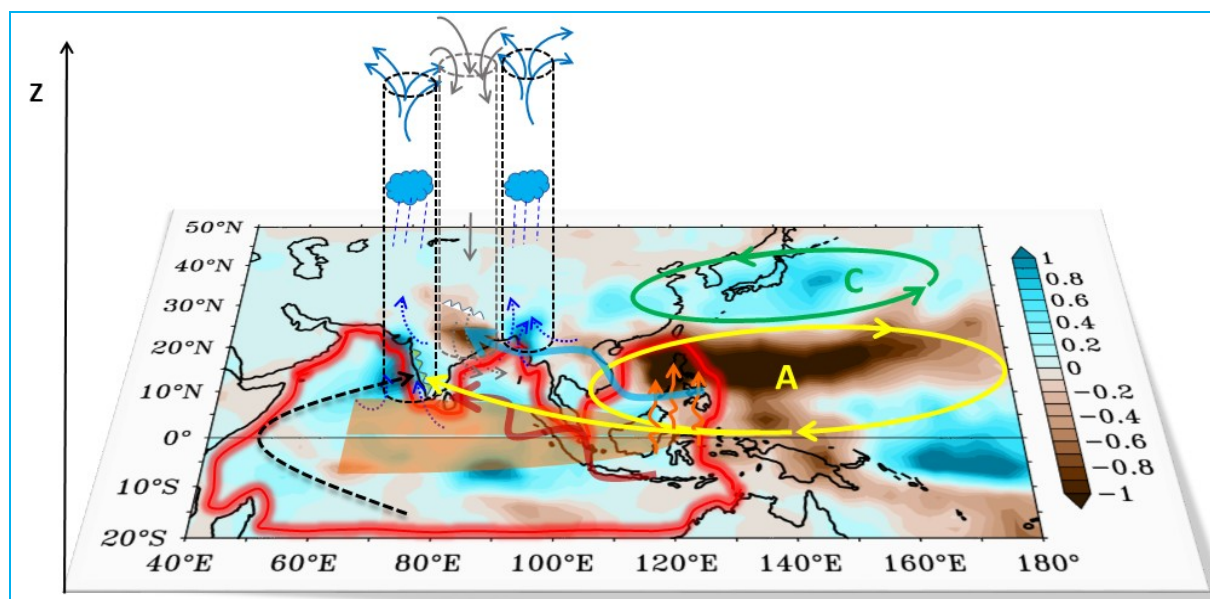
Fig. 11. Schematic diagram of the mechanisms through which IPOC mode influences Indo-Pacific region in JJA. Shaded region with cyan (brown) colour represents positive (negative) anomalies. Area bounded by red thick closed contour indicates strong positive SST anomalies. Thick yellow (green) ellipse displays anomalous anticyclonic ('A') (cyclonic ('C')) circulation over tropical (midlatitude) WNP region is part of PJ pattern. Extension of WNP anticyclone to Northern Indian ocean is shown by curved thick yellow arrow. Thick transparent brown (Blue) arrow represents atmospheric warm (cold) Rossby wave. Orange coloured thin upward arrows indicate deep convection process over Maritime continent. Black and grey coloured dashed cylindrical figures over ISM region denote the tripole precipitation pattern. And small arrows at the top of black (grey) cylinders show upper level divergence (convergence) whereas at the bottom of cylinders reversed low level processes. Mean southwesterly cross-equatorial flow over Arabian Sea is marked by dashed thick black curved arrow. Wedge shaped transparent orange coloured frame over equatorial Indian ocean displays atmospheric warm Kelvin wave. Thin white (Green) filled wavy pattern denote Western Ghats hills (Himalaya range). This figure is prepared based on Chowdary *et al.* (2019)

During JJA+1 TIO warming supports deep convection and enhances the Tropospheric Temperature (TT). Previous studies (e.g., Xie *et al.*, 2009, 2016, Kosaka *et al.*, 2013) showed that this NIO/TIO SST warming excites an atmospheric equatorial warm Kelvin wave, by enhancing TT, which propagates to the western Pacific and suppresses convection over the tropical WNP via surface Ekman divergence, thereby exciting the PJ pattern/WNP anticyclone (Fig. 11). At the same time, the PJ pattern induces strong easterlies over the NIO and causes warming. This suggests the inter-basin feedback between PJ from WNP and warm SSTs over TIO/NIO. This coherent evolution of TIO warming and WNP anticyclone/PJ pattern and their co-variability are collectively referred to as the Indo-western Pacific Ocean capacitor (IPOC) mode (Xie *et al.*, 2016) and the schematic of which is shown in Fig. 11. El Niño is known to excite IPOC mode by prompting the TIO SST warming and WNP cooling as initial perturbations. Kosaka *et al.* (2013) showed, using coupled model experiments, that the IPOC mode can get excited in summer even in the absence of ENSO forcing. This suggests that the IPOC mode mechanism is also independent of ENSO but ENSO can modulate this mode especially in its decay phase (Kosaka *et al.*, 2013; Xie *et al.*, 2016).

Impact of this IPOC mode on ISM rainfall is studied recently by Chowdary *et al.* (2019). From the observations we found that the IPOC mode induces anomalous tripole pattern in the precipitation anomalies over the ISM region with strong positive rainfall anomalies over the eastern Arabian Sea-western Ghats of India and Sundarbans region and negative precipitation anomalies over the monsoon trough region (Fig. 11). This tripole pattern is mainly contributed by anomalous WNP anticyclone/PJ pattern and TIO warming, which are the two components of IPOC mode. The coupled model sensitivity experiments further indicated that the TIO warming is responsible for the positive rainfall anomalies over the western Ghats region contributing to about 80% of rainfall associated with the IPOC mode, which is due to the enhanced convergence corresponding to local SST warming. Enhanced rainfall over the Sundarbans region and reduced rainfall over the monsoon trough region (about 75%) is mainly contributed from WNP anticyclone. The results suggest that the IPOC mode can exert strong impact on regional summer rainfall variability over South Asian/Indian land region *via* TIO warming and WNP anticyclone. Impact of WNP climate on ISM provides a new predictive information especially
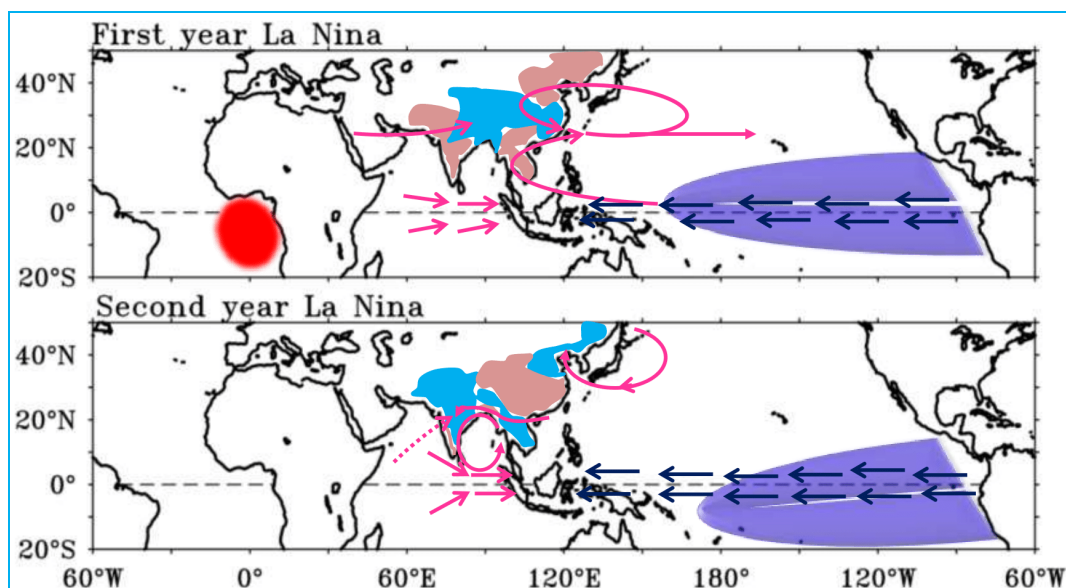
Fig. 12. Schematic diagram that shows summer rainfall, circulation and SST patterns over South Asia, East Asia and Pacific region during Multi-Year La Niña events. Lavender colour show SST cooling associated with La Niña and red colour over Atlantic indicate SST warming related to Atlantic Niño. Blue and brown shading over South and East Asian region indicates positive and negative rainfall pattern respectively. Different coloured thick (dashed) arrows and curves indicate strong (weak) 850 hPa wind anomalies. This figure is prepared based on Raj Deepak *et al.* (2019). Also see https://sciencetrends.com/multiyear-la-Niña-events-effects-on-south-and-east-asian-summer-monsoon-rainfall/

during non-ENSO years when the predictability of ISM rainfall tends to be low.

In general, El Niño events tend to decay rapidly by the following summer, but La Niña events can persist through the year and re-intensify during the subsequent winter, thus occurring as multiple-year events. Studies showed that the cold SST anomalies associated with La Niña over the east equatorial Pacific Ocean favors an above normal monsoon rainfall over the south Asian region. Raj Deepak *et al.* (2019) examined two consecutive summer teleconnections after the first peak phase of La Niña. In this we analyzed the summers after two consecutive La Niña peaks and referred to as the first and second years. An Atlantic Niño like pattern (Yadav *et al.*, 2018) was evident in the first year summer, but not in the second. Analysis of observations reveals distinct evolution of atmospheric teleconnections to the south and east Asian precipitation anomalies during the multiyear La Niña events. In the first year, moisture convergence supported by low-level circulation to the north of Bangladesh and central India results the positive rainfall anomalies over those regions (Fig. 12). The negative Vertically Integrated Moisture (VIM) anomalies (the columnar moisture content) over the rest of the subcontinent are closely related to the negative rainfall anomalies. In case of the second year, anomalous low-level anti-clockwise (cyclonic) circulation over central

Bay of Bengal enhanced the moisture transport into the Indian subcontinent and hence resulted in the positive rainfall anomalies. In the east Asian region, the second year's tri-pole like structure in the VIM supported the similar rainfall anomalies. The same was not true during the first year, although, anomalous negative VIM over Cambodia and Thailand were consistent with the negative rainfall anomalies during the same time.

5.   Relevance to seasonal prediction of ISM: TIO surface and subsurface temperature biases

It is known that the subsurface temperature of TIO plays a major role in modulating the air-sea interaction processes over the Indo-Pacific domain (e.g., Xie *et al.*, 2002; Luo *et al.*, 2012). Large upper ocean bias in coupled models over the equatorial region influences the predictability of rainfall both locally and remotely (e.g., Kirtman and Vecchi, 2011; Luo *et al.*, 2005). Subsurface ocean temperature biases could alter the sea level changes, the ocean circulation (e.g., Brown *et al.*, 2013) and the Bjerknes feedback (e.g., Keenlyside and Latif, 2007) in coupled models. Srinivas *et al.* (2018a) examined the impact of strong subsurface temperature bias of east equatorial Indian Ocean on regional precipitation in the Climate Forecast System (CFSv2) hindcast for summer season. They noted that zonal distribution of precipitation anomalies around the equator

is opposite in the model during strong bias years as compared to the observations. Differences in rainfall anomaly pattern are influenced by surface wind bias with convergence (90° E - 100° E and 10° S to equator) over the EEIO region, which in turn is favourable for surface and subsurface temperature bias over this region. They suggested that large scale circulation pattern associated with La Niña like events generally influences the EEIO subsurface temperature and this bias in temperature altered the rainfall patterns at 1-month lead prediction (Srinivas *et al.*, 2018a). Koul *et al.* (2018) and Kakatkar *et al.* (2018) carried out hindcast experiments using CFSv2 for summer monsoons of 2012-2014 in which two different ocean initial conditions are utilized. Using improved ocean initial conditions, we could reduce about 10% dry bias over the Indian land region during ISM season. This further suggests the importance of improved subsurface representation for coupled models in predicting the ISMR. Kakatkar *et al.* (2018) also noted that IITM-GODAS with only ARGO data assimilation could capture the ocean state and help to predict ISM rainfall in 2014 and 2015, highlighting the importance of improved ocean initial conditions for monsoon forecast.

Importance of Indian Ocean SST variability in predicting ISM has been discussed by several studies (e.g., Yoo *et al.*, 2006). Basin-wide warming over TIO is well predicted in many coupled models (e.g., Sayantani *et al.*, 2016; Chowdary *et al.*, 2010) and impact of this warming on ISMR is also well seen in 1-month lead prediction [Figs. 8(c&d)]. Some models however have difficulty in predicting the correct decay of El Niño and the associated TIO warming and hence the related impacts (Chowdary *et al.*, 2016a; Srinivas *et al.*, 2019). Li and Yang (2017) pointed out that the warming of TIO and southern Indian Ocean is important for monsoon variation and prediction prior to the full development of the monsoon. Bandgar *et al.*, (2014) suggested that accurate prediction of WNP circulation is useful to improve the ISM prediction. Prodhomme *et al.* (2014) highlighted the importance of TIO SST bias on Indian monsoon and showed that warm bias in western Indian Ocean results to decrease of rainfall over the globe and especially over the monsoon region.

Lee *et al.* (2010) demonstrated that many coupled models display significant biases in representing the seasonal cycle in Indian Ocean SST and those models have difficulty in capturing the second annual mode in precipitation. Thus accurate representation of tropical SST incoupled models is essential for monsoon prediction (e.g., Chowdary *et al.*, 2016a). Chowdary *et al.* (2015b) analyzed evolution of TIO SST annual cycle in CFSv1 and CFSv2. We noted that negative SST tendency over the Arabian Sea is prolonged till April in CFSv1 unlike in

observations and CFSv2. This has delayed the positive precipitation tendency in CFSv1 by a month over the ISM region. Further, we reported that rate of change in SST over the southern TIO is in phase with strong negative precipitation tendency in CFSv2. Analysis of these models suggests that the representation of SST seasonal cycle and its tendency over the TIO are very important for any dynamical operational forecasting system in order to obtain improved rainfall prediction. They concluded that though CFSv2 displays better skills in representing the annual cycle of different ocean- atmospheric components, there exists strong bias especially in radiative and momentum flux components. Sayantani *et al.* (2016) also noted that even many CMIP5 models displayed poor skills in representing TIO SST annual cycle, especially during spring to summer transition period. Parekh *et al.* (2016) on the other hand concluded that improvements of model physics with better ocean model, better run off information, improved data assimilation technique and higher resolution models could contribute significantly towards improved salt distribution in the Indian Ocean. Studies also demonstrated that it is essential to properly represent freshwater flux, current systems and vertical processes (e.g., Benshila *et al.*, 2014; Akhil *et al.*, 2014; Wilson and Riser, 2016; Parekh *et al.*, 2016; Behara and Vinayachandran, 2016) within GCMs in order to simulate realistic surface and subsurface salinity structure in the different parts of the Indian Ocean [Chowdary *et al.*, 2016(b,c)].

6.   Discussions

Changes in magnitude and spatial distribution of subsurface temperature shows detectable difference from that of the surface in TIO region (Hastenrath and Greischar, 1989; Xie *et al.*, 2002). For example, the Arabian Sea and eastern TIO characterized by a warm and deep thermocline is superimposed with cold and warm SST, respectively, in some seasons (e.g., Chowdary *et al.*, 2016b). Over the southwest TIO (thermocline ridge region of Indian Ocean) subsurface temperatures are cooler than the rest of region. Surface and subsurface temperature variations or modes in the TIO display strong impact on Asia rainfall and the Tropospheric Biennial Oscillation (e.g., Ashok *et al.*, 2001; Loschnigg *et al.*, 2003; Wang *et al.*, 2008; Schott *et al.*, 2009). Large biases in ocean and atmospheric fields limits the predictability of rainfall over land regions (e.g., Wang *et al.*, 2008; Yang *et al.*, 2008). Studies have indicated that cold SST biases over NIO during spring and summer are found to affect the mean state of the ISM by weakening the moisture fluxes in many Coupled Model Intercomparison Project (CMIP3 and CMIP5) models (e.g., Turner *et al.*, 2012; Levine *et al.*, 2013). Anomalous warm SST bias over the southwestern TIO weakens the

Findlater jet (Findlater *et al.*, 1969) and modulates the ISM rainfall (Izumo *et al.*, 2008; Marathayil *et al.*, 2013). Therefore, it is essential to understand the mechanisms associated with surface and subsurface temperature modes in TIO and to have a realistic representation of subsurface temperature in coupled models for a skilful prediction of tropical climate, from seasonal to decadal time scales (e.g., Dunstone and Smith, 2010).

Indian Ocean warming signals either on interannual or long times scales generally effects precipitation elsewhere (Yang *et al.*, 2007, Roxy *et al.*, 2015b). On the interannual time scale TIO SST is significantly affected by El Niño during both developing and decay phases (Klein *et al.*, 1999; Alexander *et al.*, 2002; Xie *et al.*, 2009; Park *et al.*, 2010; Chowdary *et al.*, 2012). During the developing phase of El Niño in some occasions, the TIO experiences east-west gradient in SST anomaly referred and is referred to as IOD (Saji *et al.*, 1999; Webster *et al.*, 1999). The IOD plays an important role as a modulator of the ISM rainfall and its relation with ENSO (Ashok *et al.*, 2001; Ajayamohan *et al.*, 2008). North Indian Ocean in particular plays a significant role on ISM especially in the recent years (Chakravorty *et al.* 2016). Atmospheric teleconnections associated with ENSO modulate the surface flux and ocean dynamics in the TIO (e.g., Klein *et al.*, 1999; Alexander *et al.*, 2002; Chowdary *et al.*, 2007), thereby forcing basin-wide SST anomalies. Evaluation of this TIO basin-wide warming and its impacts are therefore important to understand the local air-sea interactions. Though there is a lot of work already done by various researchers to understand the relationship between Pacific climate and Indian Ocean climate and association with high frequency oscillations such as ISO and MJOs etc., a clear understanding is still lacking. This is one of the major problems that is limiting the predictability of seasonal ISM rainfall. Further, a clear vision to develop a decadal forecast system particularly focusing on ISM is yet be developed. Further, how to improve ENSO and non-ENSO teleconnections to ISM rainfall in coupled models is still a question mark. With advancements in computational power, monsoon modelling and observed aspects of monsoon, our group will be focusing on answering the above posing questions.

7.   Summary

The work we have carried for the past two decades is mainly focused on Indian Ocean Climate variability (both Ocean and Atmosphere), Indian Monsoon teleconnections and their association with Pacific modes. We have briefly presented and discussed the review of work done by us in the above mentioned areas in this article. Note that IOD is the second leading mode of TIO SST variability (on annual and in some seasons) time scale and most of the earlier studies highlighted the importance of IOD and associated impacts on ISM rainfall. However, the dynamical impacts of first model of variability called the basin-wide TIO warming, which explains majority of the TIO SST variability, has not been given priority before, but is highly an important issue. Throughout the manuscript, we emphasize to demonstrate this aspect of climate variability. For the last two decades we have made notable progress and pawed the way for future research in this direction. Following are some of the important finding highlighted in this paper.

(*i*)   For the first time north-south dipole mode in TIO subsurface temperature is reported. This subsurface dipole is forced by wind stress curl anomalies, driven mainly by meridional shear in the zonal wind anomalies. A new subsurface dipole index (SDI) has been defined in this study to quantify the intensity of the north south dipole mode. The nature of the north-south dipole in TIO subsurface temperature (mode) is examined in CFSv2. The observations however indicate that this subsurface mode, in general, persists for the next two seasons with stronger signals during December-February, whereas such tenacity is not seen in the model, instead rapid decay of the mode is seen in the model.

(*ii*)   The double Walker cell circulation over the equatorial Indian Ocean region during strong IOD years is reported for the first time. A new index is defined to study the thermocline-SST coupling associated with IOD. Thermocline-SST coupling is robust in both EIO and WIO during strong IOD years, which is primarily responsible for the enhanced SST gradient, strong enough to establish anomalous Walker circulation within the Indian Ocean. The strong convection over the WIO associated with the Indian Ocean Walker cell triggers a secondary cell with subsidence over the African landmass.

(*iii*) Upward and Westward propagation of subsurface temperature anomalies along the thermocline slope is reported for the first time using ARGO observations over the southern TIO region during IOD and El Niño co-occurrence years. This propagation is resulting from a downwelling Rossby wave excited by equatorial zonal wind anomalies. Westward propagation of Barrier Layer thickness embedded with Rossby waves is a new aspect reported.

(*iv*) Studied the interannual sea level variability in the Indian Ocean and explored the role of Indonesian through Flow transport and its interannual and decadal variability on the Indian Ocean sea level variations through OGCM sensitivity experiments.

(*v*) A previously unexplored link between mean and interannual subsurface temperature bias over the equatorial Indian Ocean (EIO) is investigated during boreal summer (June through September; JJAS) in CFSv2. Biases in both horizontal and vertical currents over the EIO region support subsurface warm bias. The evolution of systematic subsurface warm bias in the model shows strong interannual variability. This maximum subsurface warming episodes over the EEIO are mainly associated with La Niña like forcing in the model.

(*vi*) Causes for subsurface temperature biases in the tropical Indian Ocean in the coupled model CFSv2 are examined. In the model, maximum warm bias is reported between 150-200 m depth. Detailed analysis reveals that the enhanced vertical mixing by strong vertical shear of horizontal currents is primarily responsible for TIO subsurface warming.

(*vii*) Examined the SST bias during spring to summer transition months May and June over the Arabian Sea region in the historical simulations of 14 CMIP5, CFSv1 and CFSv2 models. SST annual mean in most of the coupled models show systematic negative bias in the AS region.

(*viii*) A previously unexplored link between spring Wyrtki jet variability and monsoon circulation and rainfall over the adjoining region has been addressed. It is found that anomalous eastward jets accumulate warm water in EIO, leading to anomalous positive upper ocean heat content and supporting more local convection in the east and influences monsoon.

(*ix*) Changes in the low-level summer monsoon circulation over the Arabian Sea and their impact on the ocean dynamics is examined. It is noted that increase in the anticyclonic wind stress curl associated with the change in the monsoon circulation induces downwelling over the central Arabian Sea, favouring upper ocean warming.

(*x*) Observational and model results show that spring asymmetric wind and precipitation pattern over the TIO are well developed when El Niño co-occurred with IOD, which is mainly due to the meridional SST and SLP gradients and stronger northwest Pacific anticyclonic circulation.

(*xi*) While many studies have focused on El Niño teleconnections to ISM rainfall during the developing phase of El Niño, there are limited studies on the relationships with the decay phase of El Niño. Mechanisms that link the decaying El Niño phase to ISM rainfall variations has been brought out in detail both in observations and models.

(*xii*) One of the most recurrent teleconnection patterns in the Western North Pacific (WNP) is the Pacific-Japan (PJ) pattern - For the first time, impact of PJ on ISM variability is explored and coupled and uncoupled pathways that links PJ and ISM are discussed.

(*xiii*) Impact of the Indo-Western Pacific capacitor (IPOC) effect on ISM rainfall is investigated and found that the IPOC mode induces a tripole like rainfall anomaly pattern over the Indian subcontinent and highlighted the importance this mode on interannual variability of ISM rainfall.

(*xiv*) Identified new pathway through the Asian Jet that would explain the ISM rainfall variability associated with Atlantic Niño based on the analysis of the observations and model experiments.

(*xv*) Impact of multi-year La Niña events on south Asian summer monsoon rainfall is examined in observations and CMIP5 models. Analysis is carried out for the successive two summers following La Niña winter peaks and the associated mechanisms are discussed.

(*xvi*) Based on coupled model sensitivity experiments it is revealed that the TIO air-sea interaction trims down suppressed rainfall locally over the ISM region by opposing the influence of Tropical Pacific Ocean during El Niño developing summers. Besides, El Niño induced TIO basin-wide warming supports positive rainfall anomalies over the ISM region by maintaining local convection. TIO local air-sea interaction opposes the Pacific impact even in the absence of Indian Ocean Dipole.

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