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Indian Ocean Dipole : Assessing its impacts on the Indian Summer Monsoon Rainfall (ISMR) across North East India

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सार – हिंद महासागर द्विध्रुवीय (IOD), एक जलवायु विसंगति है, जिसके परिणामस्वरूप उष्णकटिबंधीय पश्चिमी और पूर्वी हिंद महासागर के तापमान के बीच निरंतर समुद्री सतह के तापमान (SST) में बदलाव होता है। इस अध्ययन में, हमने आईएसएमआर के तीनों चरणों के लिए 1960-2020 की अवधि के लिए देश भर में आईओडी और भारतीय ग्रीष्मकालीन मानसून वर्षा (आईएसएमआर) वितरण के बीच टेलीकनेक्शन को विकसित करने के लिए विविधताओं का अध्ययन किया। हमने उपर्युक्त समय क्षितिज के लिए वर्षा, एसएसटी और निम्न-स्तरीय पवन परिसंचरण विसंगतियों का विश्लेषण किया। सकारात्मक आईओडी घटनाओं के परिणामस्वरूप देश भर में क्रमशः ग्रीष्मकालीन मानसून वर्षा वितरण में वृद्धि हुई, जबकि इसके नकारात्मक समकक्ष के कारण आईएसएमआर के प्रारंभिक चरण को छोड़कर वर्षा में कमी आई। हिंद महासागर में एसएसटी, पवन परिसंचरण और नमी संचलन प्रक्रियाओं में भिन्नता आईओडी के सकारात्मक और नकारात्मक चरणों के दौरान विशेष रूप से हाल के दशकों (1991-2020) के दौरान वर्षा में महत्वपूर्ण परिवर्तनों की विशेषता है। पिछले दशकों (1960-1990) की तुलना में सकारात्मक आईओडी घटनाओं के दौरान हाल के समय के क्षितिज में भूमध्यरेखीय हिंद महासागर और अरब सागर में निम्न-स्तरीय भूमध्यरेखीय जेट (एलईजे) भी देखे गए हैं। नमी अभिसरण क्षेत्र के प्रभाव का भी विश्लेषण किया जाता है। जिसके परिणामस्वरूप पूर्वोत्तर और मध्य भारत में उपरोक्त वर्षा की स्थिति होती है। इसके विपरीत, नकारात्मक आईओडी घटनाओं को ऐसे किसी भी नमी आंदोलन तंत्र को वश में करने के लिए पाया गया था। इसके अलावा, पूर्वोत्तर भारत में मानसून के पीछे हटने/वापसी करने पर आईओडी के प्रभाव का विश्लेषण करने के लिए अतिरिक्त जांच की गई है और यह देखा गया है कि एक मजबूत सकारात्मक आईओडी हानिकारक है। उत्तर पूर्व भारत में मौसमी वर्षा (मई-सितंबर) तक (-0.7 एक महीने का अंतराल सहसंबंध)। इसके अलावा, अप्रैल-मई के डीएमआई सूचकांक ने ग्रीष्मकालीन मानसून की वापसी या पीछे हटने के चरण के दौरान, यानी सितंबर के दौरान क्षेत्र में मानसून गतिविधि का एक स्पष्ट संकेत प्रस्तुत किया।

ABSTRACT. The Indian Ocean Dipole (IOD), a climatic anomaly, results in sustained sea surface temperature (SST) variations between tropical western and eastern Indian Ocean temperatures. In this study, we studied the variations to inculcate the teleconnections between IOD and Indian summer monsoon rainfall (ISMR) distribution across the country for the period 1960-2020 for all the three phases of ISMR. We analyzed rainfall, SST and low-level wind circulation anomalies for the above mentioned time horizon. Positive IOD events noticeably resulted in increase in summer monsoon rainfall distribution across the country respectively while its negative counterpart led to decrease in rainfall except for the commencement phase of ISMR. The variations in SST, wind circulation and moisture movement processes across the Indian Ocean characterize significant changes in rainfall during the positive and negative phases of IOD especially during the recent decades (1991-2020). The recent time horizon also witnesses enhanced low-level equatorial jets (LEJ) across the equatorial Indian Ocean and the Arabian Sea during the positive IOD events as compared to the prior decades (1960-1990). The effect of moisture convergence zone is also analyzed which results in above rainfall conditions across northeastern and central India. Conversely, negative IOD events were found to subdue any such moisture movement mechanisms. Furthermore, and additional investigation to analyze the effect of IOD on the retreating/withdrawal monsoon across northeast India has been done and it has been observed that a stronger positive IOD is detrimental to the seasonal rainfall (May- September) over North East India (-0.7 one month lag correlation). Furthermore, the DMI index of April-May presented a clear indication of monsoon activity over the area during the withdrawal or retreating phase of the summer monsoon, *i.e.*, during September.

Key words – Dipole mode index, Indian ocean dipole, Indian summer monsoon rainfall, Sea surface temperatures, Northeast India.

1. Introduction

The meteorological conditions over the North Indian Ocean and surrounding landmass are predominantly influenced by monsoons. It is due to the monsoons that the sea surface temperatures (SSTs) on eastern side of the Indian Ocean become warmer as compared to its western counterpart. The North East part of India is responsible for greater fresh water input into the eastern part of the Ocean in the form of precipitation, surface run off and numerous river systems. This also results in lower basin salinity on the eastern end. The thermocline, which acts as a boundary between warm water of the oceanic mixed layer and the cold water underneath, is much deeper on the eastern side of the Indian Ocean. The unevenness in the SST leads to increased convection in the east than in the west.

In the equatourial region of the Indian Ocean, the wind flow behavior is different than the flow in the Bay of Bengal and the Arabian Sea. The winds across the equatorial Indian Ocean is weaker during the monsoons but relatively strong westerly winds develop during the spring (April-May) and during the fall (October-November) (Wyrtki, 1973). These strong winds force eastward currents along the equatorial region. The warmer layers of the ocean are therefore transported towards the east and as a result the thermocline is deeper in the east than in the west as it accumulates near the boundaries. The thermocline develops and becomes steeper during the spring and the fall. Therefore, these strong winds play an important role in defining the thermocline level in the equatorial Indian Ocean. This validates the strong convection process in the east. The anomaly in the above-described neutral phase during certain years represented by opposite signs of SST aberrations in the east and west, is known as the Indian Ocean Dipole (IOD).

IOD has 2 phases, namely positive IOD and negative IOD. In the former phase, which generally occurs during September- October, eastern Indian Ocean across the equator becomes unusually cold and the western Indian Ocean becomes unusually warm. The colder SSTs results in reduction of atmospheric convection in the east and warmer SST enhance convection in the west. The equatorial jets become weaker which in turn results in lesser movement of warm water creating a shallower thermocline. The overall sea level drops in the eastern part and rises in the centre. The thermocline comparatively becomes much deeper in the centre and in the west. The complete reverse of this is the negative phase of IOD. Negative IOD can be regarded as a further developed phase of the neural or normal condition. This study mostly focuses on the positive phase of IOD and understanding its teleconnections with the Indian summer monsoon rainfall (ISMR).

IOD events are identified using Dipole Model index (DMI) which can be defined as the difference between western and eastern SST anomalies along the equatorial Indian Ocean (Saji *et al*., 1999; Murtugudde *et al*., 2000). Mean anomalies are obtained for the spatial grid 50 °E-70 °E and 10 °S - 10 °N in the west and 10 °S - Equator and 90 °E - 110 °E in the East. For a positive IOD the standard deviation is expected to be higher than 1 for a running period of 3-4 months for the west minus east anomalies (positive) and *vice versa*. It has been observed that the initiation of IOD is heavily linked to the seasonal cycle due to the thermodynamics of air-sea interaction between an atmospheric anticyclone located to the east of the island of Sumatra and the Ocean below which is dependent on the seasonal wind cycle (Annamalai *et al*., 2003; Li *et al*., 2003). A lot of research work has been done to establish the influence of IOD with the ISMR both with and without taking in account the effect of ENSO (Ashok *et al*., 2001, 2004; Izumo *et al*., 2010; Wang and Wang, 2014) but studies focusing on the changes in the interrelationship between ISMR and IOD are sporadic and few. The studies pertaining to the variation in the Indian Ocean dipole-Indian summer monsoon association during the commencement, peak and retreating phases of monsoon are also limited and scarce. The commencement, peak and retreating phases of ISMR have different characteristics and therefore to understand their relationship with IOD, the regional and temporal variability has to be analyzed separately for each phase. In this work attempt has been made to study these changes for the past period (1960-1990) and the recent period (1990-2019) for all the three above-mentioned phases of ISMR and to elucidate the mechanisms responsible for these variations. It is also important to note that Pacific and Indian Ocean uncertainties are intertwined, therefore we have taken in account of all Dipole years in spite of the fact that it is was true positive/negative IOD or an event that coexisted with El Nino/ La Nina events. The objective of the present work is to understand the relationship between IOD and ISMR and assessing its impacts on the summer monsoon rainfall distribution across North East India. Influence of IOD on the rainfall distribution during the withdrawal phase of the monsoon is also investigated. The next section highlights the IOD association with ISMR. Section 3 presents an overview of the climate and weather conditions across North East India. Section 4 utilizes the DMI and ISMR data sets to broadly depict the teleconnections, which is followed by the results (section 5). The last section presents the concluding remarks.

2. IOD and Indian summer monsoon rainfall

During the early 1980s, the discovery of a strong El Nino Southern oscillation (ENSO) event (Bjerkenes, 1969) sparked a major interest among the researchers in understanding the seasonal variability of Indian summer monsoon rainfall (ISMR) related to such anomalous climatic conditions. Pant and Parthasarthy (1981); Rasmusson and Carpenter (1986); Singh & Pai (1999) and Singh *et al*. (2000) owed this to the interannual variation

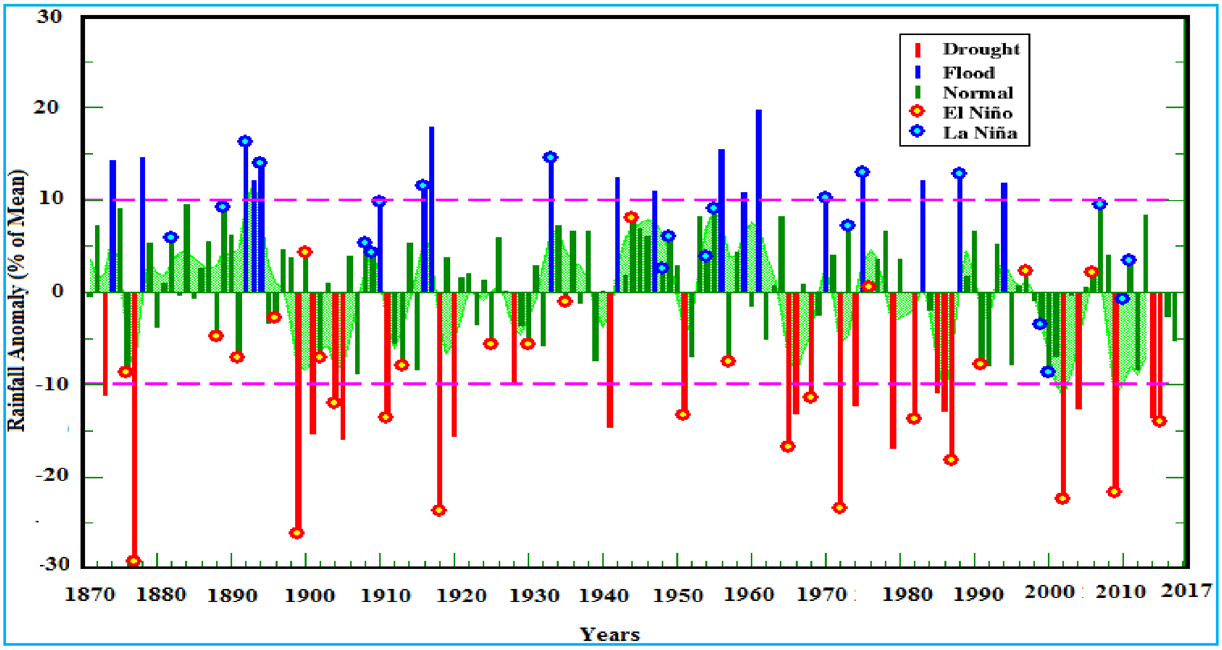


Fig. 1. Time series evolution of ISMR anomalies as percentage of mean across India for the period 1870-2017

of the coupled ocean-atmosphere system across the Pacific. Rasmusson and Carpenter (1986) observed a marked correlation between monsoon rainfall and ENSO events. For the period 1875-1979, the El Nino events resulted in lesser rainfall in 21 out of 25 such cases. Nine out of eleven such seasons produced significant aberrations (Kumar *et al*., 1999. The drought years in the country mostly coincided with the El Nino (warm) events. However, the droughts of 1974 and 1985 coincided with La Nina (cold) events. The excess rainfall seasons were observed to be influenced by La Nina events with exception like in 1997, which was a strong El Nino year. The Fig. 1 below shows the time series Indian summer monsoon rainfall anomalies expressed as percentage departures from its long term mean for the period 1870-2017. The Fig. 1 shows the droughts, floods, El Nino, La Nina events.

The relationship between DMI and ISMR is considerably weaker. For strong positive IOD events (greater than 1 standard deviation), it was observed to have associated with positive aberrations of ISMR. For the period of 1958-1997, eight such positive IOD events (1961, 1963, 1967, 1977, 1983, 1994, 1993 and 1997) coincided with positive ISMR anomalies (Ashok *et al.*, 2001). During the same period two negative IOD events coincided with negative ISMR anomalies. It was also observed that the correlation behavior of ISMR-ENSO and ISMR-IOD is different from each other, *i.e.*, when ISMR-ENSO correlation is strong (negative) ISMR-IOD (positive) correlation is weak and *vice versa*. The DMI

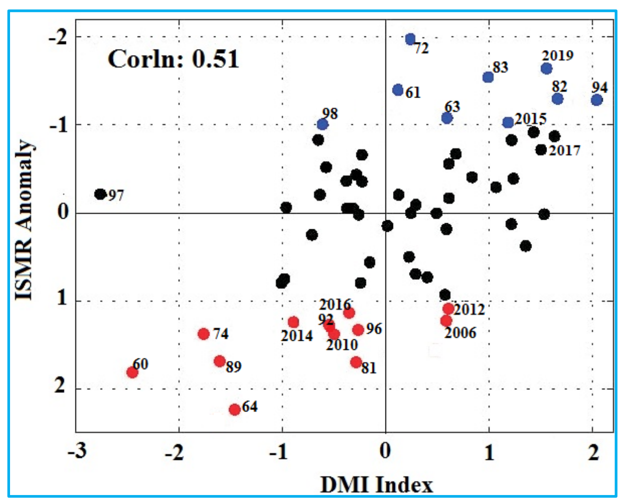


Fig. 2. Scatter diagram depicting normalized ISMR anomalies *vs.* DMI anomalies for the period 1960-2019 (ISMR data *Source* : http://tropmet.res.in and DMI *Source* : http://psl.noaa.gov)

correlation with ISMR anomalies for the period 1960-2016 is depicted in Fig. 2 below. Both the DMI and ISMR anomalies are normalized by their respective standard deviations. These climatic anomalies (ENSO and IOD) certainly influence ISMR but we cannot draw a direct relationship between them as they cannot explain all the droughts and excess monsoon seasons. Coupled climate models such as AGMCs and OAGMCs have also suggested that positive IODs enhance ISMR (Ashok *et al*., 2004; Guan and Yamagata, 2003).

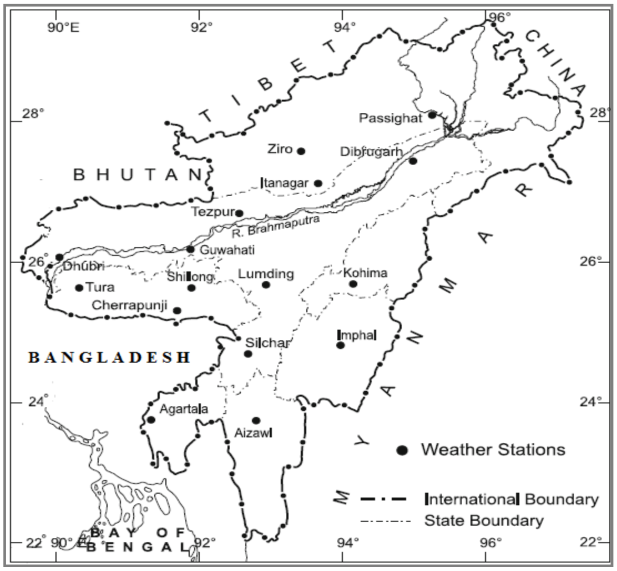


Fig. 3. Map showing the locations of a handful of weather stations across North East India

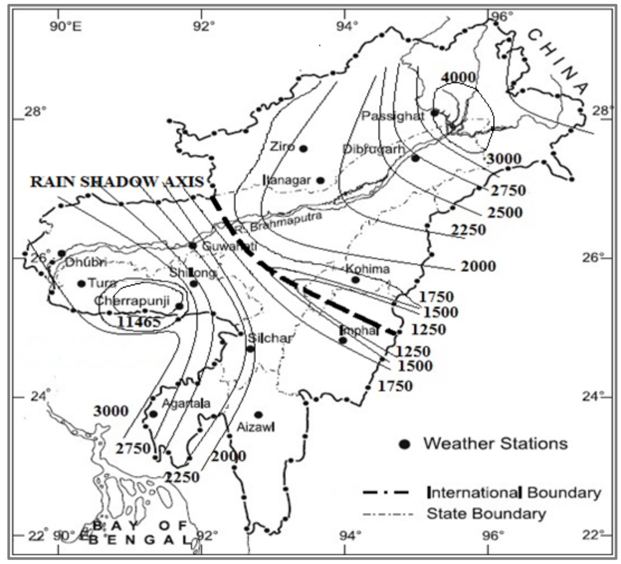


Fig. 4. Isohyets map showing the variations in annual rainfall (Isohyets in mm) in North-East India

3. Climate and weather across North East India

North East (NE) India (located between 22° N - 29° N) comprising of 6 states namely, Assam, Arunachal Pradesh, Manipur, Mizoram, Nagaland and Tripura, has a sub-tropical climate and receives the highest average rainfall as compared to other regions of the country. Northeast part of India along with the western part of Western Ghats are the only regions that receive very heavy rainfall during the retreating monsoon. During the retreating monsoon, in the months of October and November, the southwest monsoon winds become weaker and start to withdraw from the North-Indian region. In our present study,emphasis is on the entire NE region due to its uniqueness of topography and for the fact that this region is the only region across the whole country that receives very heavy rainfall after the withdrawal of southwest monsoon. The NE region along with some important weather stations covering the area is shown in Fig. 3. It is the rainiest region and Cherrapunji, a place in Meghalaya receives an average annual rainfall of 11,420 mm, which is the highest in the world. Barring a few places, most of the region receives an average rainfall of around 2000 mm yearly. The number of rainy days in this part of the country is comparatively much higher, varying from 90-120 days. There are two main river systems in this region, Brahmaputra and Barak. The monsoons occur in the summer, which coincides with the rainy season starting from mid-April until mid-October. The rainiest months are June and July.

Most of the region receives 90% of its rainfall during the summer months from the southeast monsoon. The monsoon burst for the regions downstream of Brahmaputra isin the month of June. Moving eastwards and upstream of Brahmaputra the burst shifts to July. Unopposed southwest monsoon jets incepting from the Bay of Bengal move swiftly towards north of Bangladesh and enters the country in Meghalaya which are then obstructed by the plateau in that region and divides it into two section of wind jets. It is very interesting to note that Cherrapunji and Shillong, 50 kms apart from each other, have drastic difference in average annual rainfall. Cherrapunji receives 11,420 mm mean annual rainfall while Shillong receives only 2,420 mm average annual rainfall. The rain shadow effect due to the plateau of that region plays a very important role. It also restricts rainfall in Guwahati region and has the lowest amount of rainfall (1,717 mm) in the Brahmaputra valley. The rainfall declines as one move towards the east along the Brahmaputra valley. The central region receives the lowest rainfall, which again rises in the North East ward direction and reaches a maximum at Passighat in Arunachal Pradesh. At Passighat the Brahmaputra emerges from the terrains and moves into the plains in Assam. Fig. 4 shows the isohyets (in mm) in the region. The effect of rain shadow axis on the rainfall in the region can be visualized through Fig. 4. The variations in rainfall are considerable as we move towards the central region from either West or East.

This region has a prolonged winter lasting from early November until mid-march. The temperatures in this region are also very contrasting in nature. North-East India has many mountainous ranges and valleys. The temperatures in the Brahmaputra and Barak valley are some what similar with average temperatures around 28° C to 31 °C during the summer months while

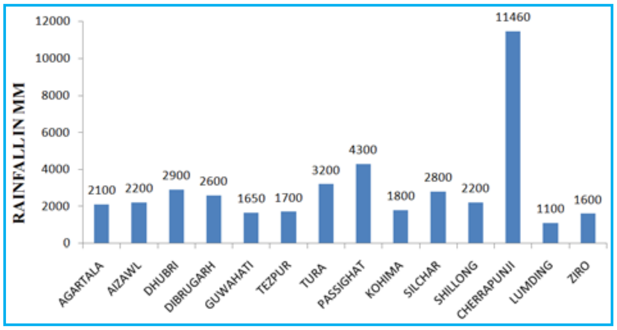


Fig. 5. Average rainfall (mm) for some weather stations for the monsoon period 1960-2019 from Agartala to Ziro

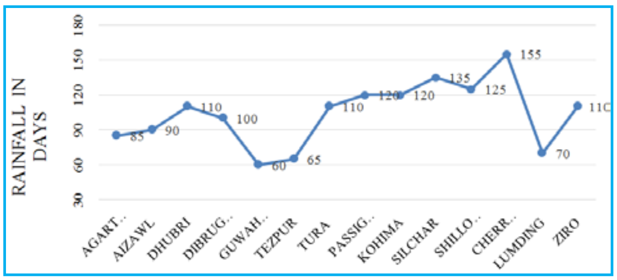


Fig. 6. Average number of rainfall days for the weather stations for the monsoon period during 1960-2019 from Agartala to Ziro

the mean temperatures in winter are around 16 °C - 17 °C. Hilly regions of similar altitudes however show divergent temperatures like Ziro in Arunachal and Shillong in Meghalaya. Ziro has a height of 1595 m ASL and Shillong is at 1476 m ASL. Shillong has 14.7 °C and 5.7 °C as the average Max. and Min. temperatures in the month of January and Ziro has 12.9 °C and -0.2 °C in the month of January. Shillong is nearly 50 kms from Bangladesh and Ziro is in the hilly terrains deep in Arunachal Pradesh. The hilly regions of Meghalaya as mentioned before are influenced by sea and sea winds filled with humidity.

There are three distinct rainfall zones in the Brahmaputra valley with the variation in rainfall as we move from east to west. A rainfall zone located to the west of Guwahati receiving over 2000 mm of rainfall with exception of Dhubri, which receives nearly 2900 mm rainfall annually. A lesser rainfall zone of the central region as we move from Tezpur and Nagaon regions to Lumding. Lumding region receives the least rainfall of 1200 mm annually. The last zone located to the east of Jorhat up to Passighat in the state of Aruncahal Pradesh. There is a steep rise in rainfall in this zone, 2000 mm west of Jorhat to nearly 2600 mm at Dibrugarh annually, and over 4000 mm eastwards of Passighat. The average rainfall and number of rainfall days of few weather stations across the Northeast region during the monsoon period1960-2019 in shown in Figs. 5 and 6 respectively.

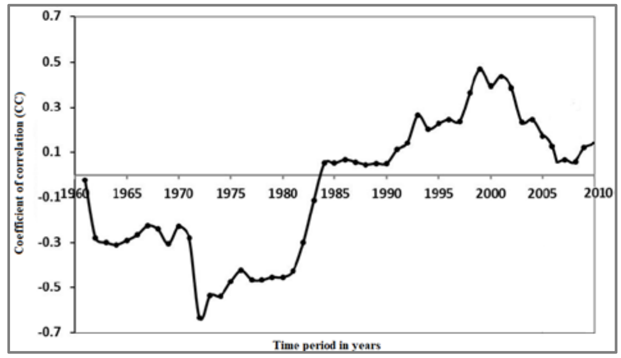
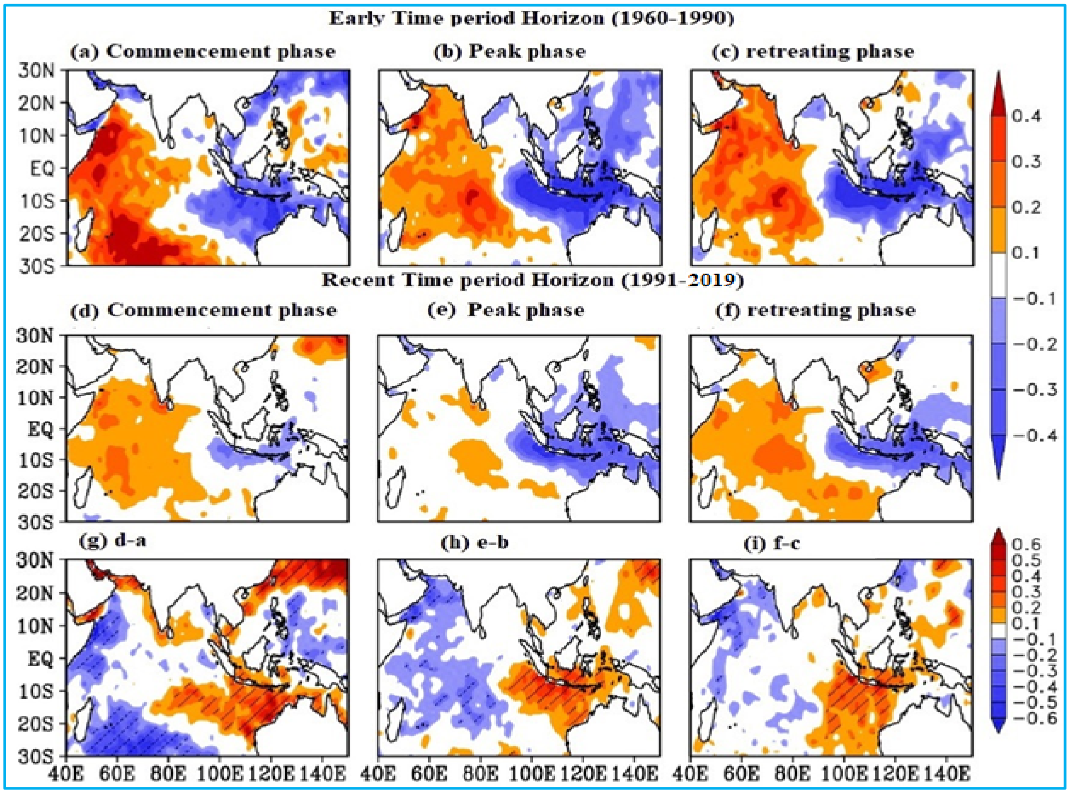


Fig. 7. 20 year sliding coefficient of correlation for the time horizon 1960-2010

4. Data and methodology

The summer monsoon rainfall data for the North East region for the period 1960-2019 has been utilized from the Indian institute of Tropical Meteorology (www.tropmet.res.in). The DMI index for the same period is employed from the data archival section of National Oceanic and Atmospheric Administration (NOAA). Climate variables such as U-wind and V-component along and sea surface temperatures have also been utilized in our study for the same time period. These above-mentioned climate variables are gridded at 2.5° × 2.5° (wind components) and 1° × 1° (SST) spatial resolution respectively. The wind component data sets were acquired from the data archival section of National Centre for Environmental Prediction (NCEP) while the SST data sets were made available in the data section of Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) version 1.1.

For investigating the variations in the association of IOD and ISMR, the total time period was split into two parts, the early decades (1960-1990) and the recent decades (1991-2019), having three decades in each segment. The time period split was conscripted by employed a 20-year sliding correlation coefficient (CC) between IOD and ISMR as shown in figure below. From Fig. 7 we can observe that the CC is negative for the early decades and the shift from negative to positive occurs during the period 1980-1986 and thereafter remains positive throughout (till present). The period from 1980-86 can be coined as the evolution period. Therefore, in our study we have excluded these evolving years. A two-year period, *i.e.*, 1976-77 in the early decades exhibited a climate change in the Pacific region as elucidated by Miller *et al.*, 1994. The commencement and departure dates of ISMR was greatly affected by this change in climate (Sahana *et al.*, 2015). However, from Fig. 7 it is clearly evident that during the climate change a notable negative CC was observed between IOD and ISMR and so



Figs. 8(a-i). Sea surface temperature aberrations characterizing positive Indian Ocean dipole events during the different stages of summer monsoon along with their deficit from prior to recent time scale

it can be consummated that the climate change renders no effect on IOD-ISMR association, further justifying our approach of employing the sliding CC and carrying out the current study.

The DMI index is maximum during the months of October and November (during spring). The amplitude of DMI index is minimum during March-April, which increases from the month of May, and peaks during the autumn. Future time leads correlation between DMI index & western and eastern poles' SST with monthly and seasonal monsoon rainfall for the North East region have been computed. To define the teleconnections between DMI & onset of monsoon over North East India the two future lead time ahead correlations related to April and May rainfall have been computed. Similarly, correlations between the SSTs in western pole during April-May and onset date of monsoon over North East India have also been enumerated.

In this work, Pearson, Kendall and Spearman's rank correlation approaches are employed to study the strength of association between the above-mentioned variables.

Pearson correlation (μ) deliberates the strength of linear association between the variables (*i.e.*, the DMI index and the ISMR anomalies) and is calculated as shown below:

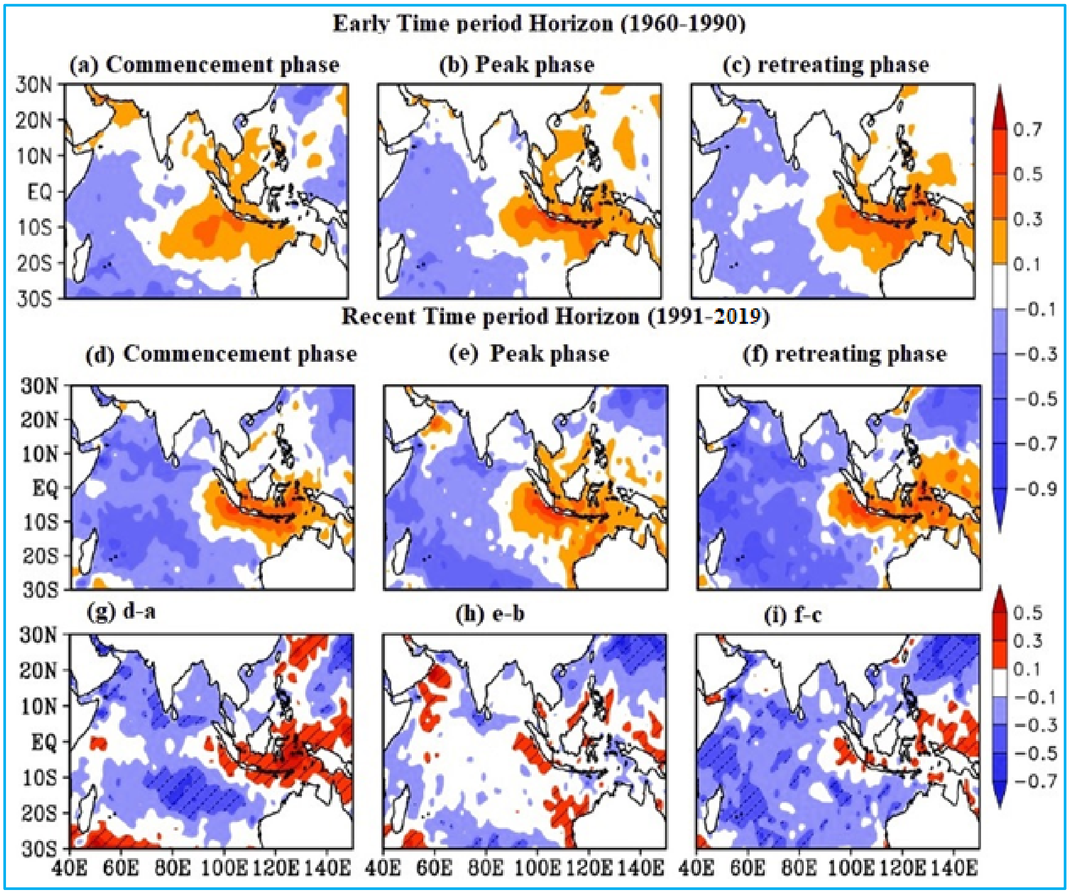
$$\mu = \frac{\sum\left(V2\frac{y}{m} - \overline{V2}_m\right)}{\sqrt{\frac{N}{y=1}\left(V1\frac{y}{m} - \overline{V1}_m\right)^2 \frac{N}{y=1}\left(V2\frac{y}{m} - \overline{V2}_m\right)^2}} \qquad (i)$$

where, $V1\frac{y}{m}, V2\frac{y}{m}$ are variables which denote DMI and the ISMR anomalies for 'm' month of 'y'$^{\text{th}}$ year. $\overline{V1}_m$, $\overline{V2}_m$ are the monthly average of the variables and N denotes the total number of years.

Kendall correlation (τ) investigates the dependencies of the involved variables based on the feature ranking and is calibrated as shown below:

$$\tau = \frac{N_{\text{corvergaent}} - N_{\text{divergent}}}{\frac{1}{2}n(n-1)} \qquad (ii)$$

where, N is the total number of variable sets. For both the variable sets $V1$ and $V2$ a sample pair of DMI and



Figs. 9(a-i). Sea surface temperature aberrations characterizing negative Indian Ocean dipole events during the different stages of summer monsoon along with their deficit from prior to recent time scale

ISMR anomalies may be called as convergent if the ranks of both the elements in *V*1 and *V*2 are same and can be termed as divergent if the ranks differ.

Spearman's correlation is a non-parametric analysis that does not carry any assumptions about the underlying distribution and can be considered a better judge of identifying monotonic behaviour between the variables. It is an appropriate correlation analysis considering the variables in our study are on a least ordinal scale. The data sets in our consideration were first ranked before proceeding with the Spearman's correlation evaluation. The ranking of the variables helps to compare whether on increasing one variable the other follows a monotonic relation with respect to it or not. The correlation can be better understood using the following equation given below:

$$\rho = 1 - \frac{6\sum d^2 i}{n\left(n^2 - 1\right)} \qquad (iii)$$

where,

ρ = Spearman's correlation,

$d^2 i$ = The difference between the ranks of corresponding variables and

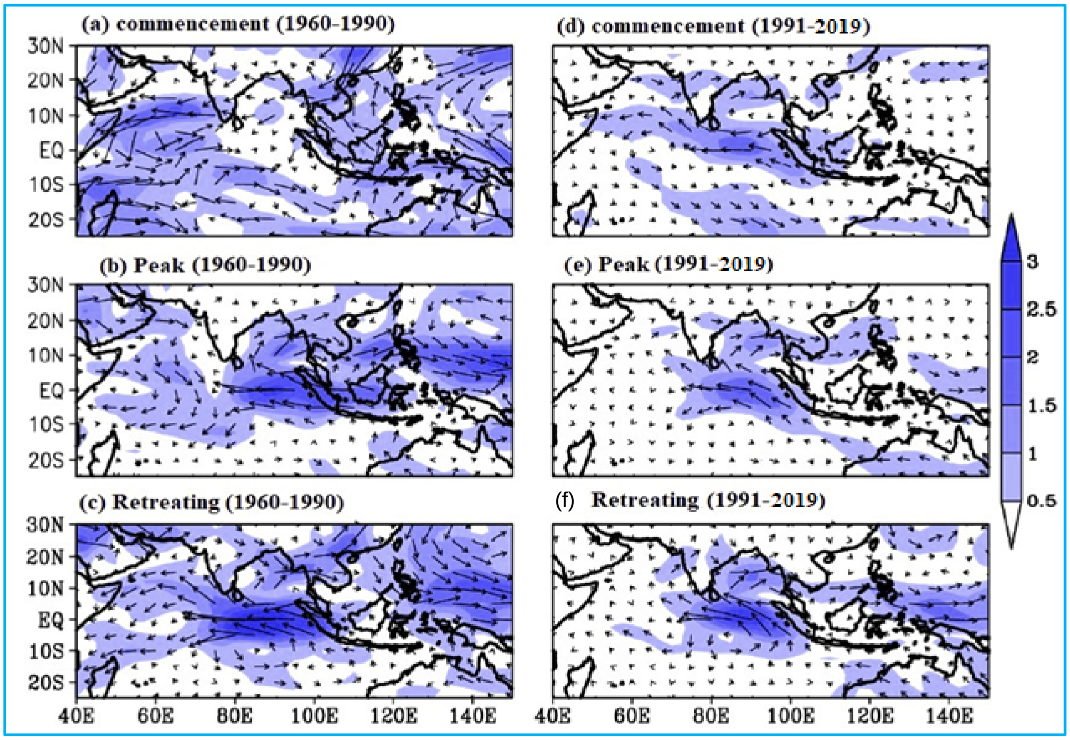
n = Number of observations.

1st of June has been considered as the normal date of onset of monsoon in the region, say for example, if onset date is 27th May the onset anomaly date is considered as -5 and if the onset date is 6th June it is considered as 5.

5. Results and discussion

5.1. *SST anomalies in context to positive and negative IOD phases*

SST aberrations over the equatorial Indian Ocean region is shown in Figs. 8 and 9 respectively taking in



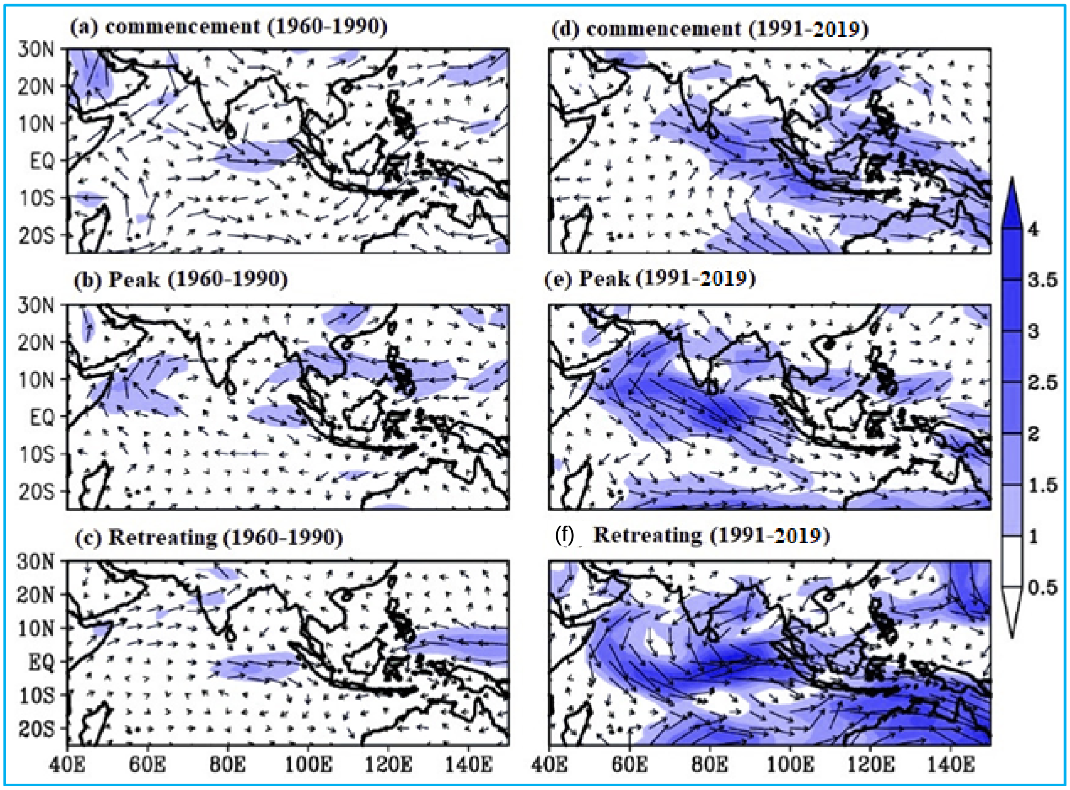
Figs. 10(a-f). 850 hPa Wind circulation aberrations characterizing positive Indian Ocean dipole for different stages of Indian summer monsoon

account of both the negative and positive phases of IOD during the commencement, peak and retreating phases of Indian monsoon. The positive phase of IOD is characterized by rise (drop) in SSTs in western (eastern) Indian Ocean (Murtugudde *et al*., 2000). This behavior is well accounted for all the three phases of ISMR [Figs. 8 (a-c)]. The transmission suits the ISMR across the western part more as compared to its eastern counterpart (Gadgil *et al*., 2004). However, the CCs for SSTs are greatly associated with ISMR over the eastern equatorial Indian Ocean (Vinayachandran *et al*., 2002). For the time period horizon between 1960-1990 warmer SSTs were observed across the western and central Indian Ocean regions during the commencement of monsoon phase [Fig. 8(a)] which falls during the productive monsoon phase [Fig. 8(b)] and then again rises during the retreating phase of ISMR [Fig. 8(c)]. Noticeably, for the recent period 1991-2019, a declining trend in SSTs were observed for all the three phases of monsoon across the central and western regions with a marked decline during the peak monsoon phase [Figs. 8(d-i)].

The negative phase of IOD is characterized by drop (rise) in SSTs in the western (eastern) Indian Ocean for all the three phases of ISMR, observed consistently over the period between 1960-1990. The drop in SSTs were observed to be greater during the commencement and peak phases while the retreating phase showcased a drop [Figs. 9 (a-c)]. For the period 1991-2019, significant drop takes place during commencement [Figs. 9(d&g)] and retreating phases [Figs. 9(f&i)] of monsoon but remains totally unaffected during the peak phase [Figs. 9(e&h)]. On the flip side, there has been an evident rise in SSTs in the eastern equatorial Indian Ocean during the recent years which is consistent for all the phases of ISMR. This warming across the eastern Indian Ocean can be correlated to diminishing monsoonal zonal winds across the entire region regulating the monsoon precipitation (Swapna *et al*., 2014; Roxy *et al*., 2015).

5.2. *Wind circulation lineaments during the positive and negative years of IOD*

The wind circulation aberrations at 850 hPa across the entire Asian sub-continent regions is shown in Figs. 10 and 11 for the positive and negative IOD years respectively. Positive IOD events are characterized by strengthening the convection over the western Indian Ocean and curbing the convection over the eastern Indian Ocean. This cycle of events are correlated to the imposition of easterlies across the equatorial Indian Ocean region (Gadgil *et al*., 2007). Negative IOD events trigger the opposite condition. The period 1960-1990, exhibit a decrease in the strength of low level cross equatorial jets



Figs. 11(a-f). 850 hPa Wind circulation aberrations characterizing negative Indian Ocean dipole for different stages of Indian summer monsoon

(LEJ) over the Indian Ocean region during all the phases of ISMR, superseded by dissimilar pattern of wind circulation at lower levels [Figs. 10(a-c)]. This decrease in strength can be linked to the drop in precipitation across the country during the early time period horizon (1960-1990). However, in the recent time horizon (1991-2019) LEJ grows in strength, evident in all the three phases of ISMR [Figs. 10(d-f)]. The above-mentioned gain in strength in comparison to the period 1960-1990 results in a confluence zone across the northeastern part of the country culminating in excess rainfall during the off-season monsoon period. Noticeably, LEJ circulation aberrations are weak in the southern regions and hence does not account for any changes in rainfall. The commencement phase of monsoon marks gain in strengthening of LEJ across the Arabian Sea [Fig. 10(d)]. This enhanced strengthening across the Arabian Sea results in the fall of SSTs across the western equatorial Indian Ocean [Fig. 8(d)] intensifying moisture movement process around Indian Subcontinent (Murukami *et al.*, 1984). This intensified transport mechanism ensued excess rainfall across the northeastern, central and monsoon deficit regions in India during the recent years. The intensified LEJ is noticeable during the peak and retreating phases across the central and eastern Indian Ocean region [Figs. 10(e&f)]. Therefore, it contributes to the monsoon supply process especially in monsoon deficit regions by generating anomalous westerlies across the Bay of Bengal resulting in excess precipitation. This observation is validated by several previous studies (Ashok *et al.*, 2001; Ajayamohan and Rao, 2008)

In terms of negative phase of IOD, the intensification of westerlies [Figs. 11(d-f)] is perceived for the different phases of ISMR during the recent period (1991-2019). This trend is significant during peak and retreating phase. However, the enhanced LEJ is superseded by a diverging circulation which results in decline of the low level equatorial jets for the same time scale horizon (Anees *et al.*, 2016). It is observed that during the peak and retreating phases of ISMR, the enhanced westerlies are prominent over the western and central Indian Ocean [Figs. 8(e-f)]. One explanation could be the intensified cooling of the same areas [Figs. 9(e&f)]. The intensified cooling interrupts the moisture movement mechanism towards the Indian subcontinent, which leads to lesser precipitation across the country during the period 1991-2019 [Figs. 10(e&f)]. The diverging zone formed over northeast India during the peak and retreating stage of monsoons results in lesser rainfall over the central and sub Himalayan regions. The westerlies are considerably depleted across the southern coastal regions and central

TABLE1

One, two and three month lag-lead CCs for the different regions in NE India

States	One month lag CC	Two month lag CC	Three month lag CC	One month lead CC	Two month lead CC	Three month lead CC
Eastern Assam	-0.75	-0.70	-0.61	-0.38	-0.27	-0.12
Central Assam	-0.72	-0.68	-0.62	-0.35	-0.25	-0.12
Western Assam	-0.65	-0.61	-0.58	-0.34	-0.23	-0.09
Eastern Arunachal Pradesh	-0.58	-0.52	-0.46	-0.28	-0.19	-0.07
Western Arunachal Pradesh	-0.61	-0.56	-0.47	-0.32	-0.21	-0.09
Meghalaya	-0.78	-0.71	-0.67	-0.41	-0.31	-0.19
Manipur	-0.59	-0.52	-0.47	-0.32	-0.26	-0.07
Mizoram	-0.56	-0.50	-0.45	-0.30	-0.23	-0.08
Nagaland	-0.58	-0.51	-0.43	-0.28	-0.19	-0.08
Tripura	-0.61	-0.55	-0.48	-0.31	-0.21	-0.10

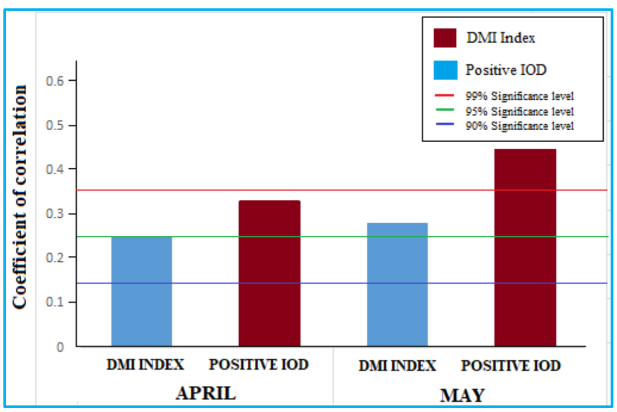


Fig. 12. Figure showing the correlations between DMI index and western pole SST anomaly (pIOD) for the months April and May for the monsoon onset over northeast India

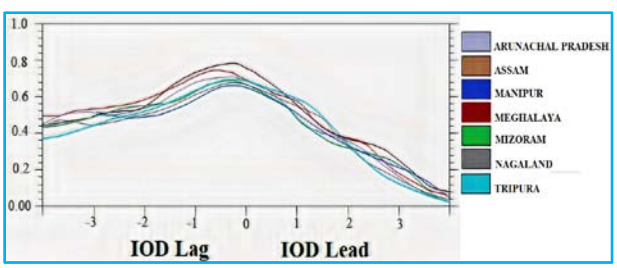


Fig. 13. Lag-lead DMI-ISMR correlations for the different states across North East India

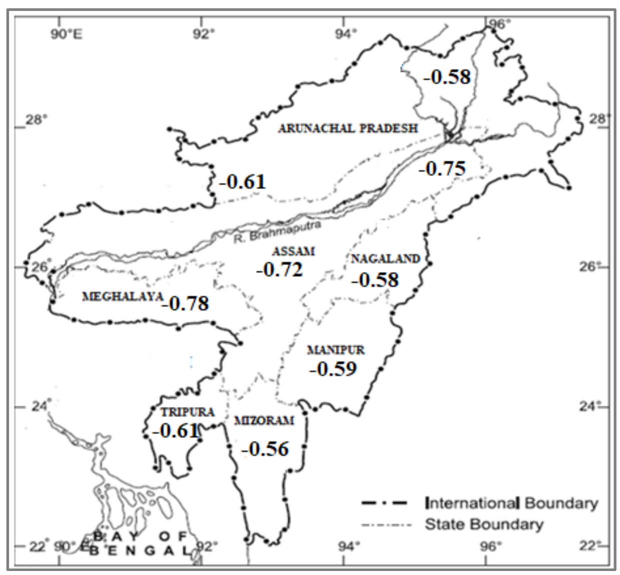


Fig. 14. Lag correlations between western pole (positive IOD) and seasonal rainfall for the six different states in North East India

equatorial Indian Ocean during the commencement phase of ISMR [Fig. 11(d)]. This behaviour is in accordance with the rise in precipitation across the Indian monsoon core regions.

5.3. *Correlation between DMI Index and summer monsoon onset over North East India*

The correlations of summer monsoon onset date across the North East region with DMI and western pole SST anomalies were observed as negative, which indicates that positive IOD during April-May could play a hand in delaying monsoon over the region. The same is supported by the observational correlations with SST anomalies in the western pole. Therefore, warmer SST

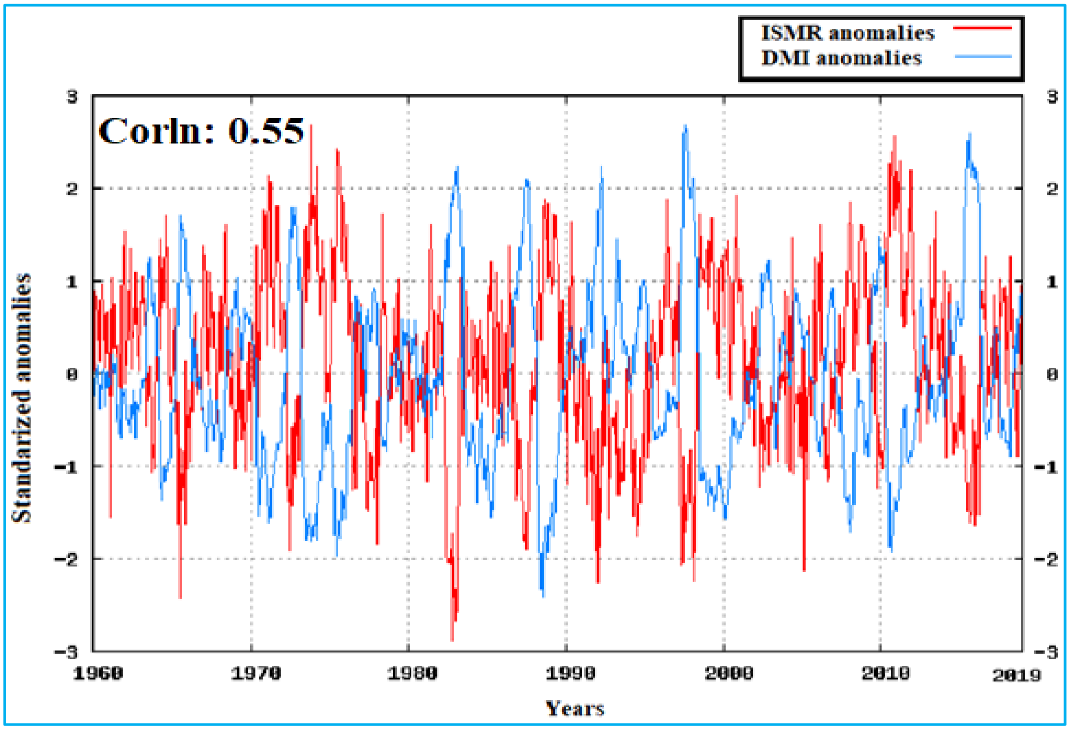


Fig. 15. Correlations between standardized ISMR anomalies and DMI anomalies for the months June-August during the period 1960-2019

anomalies in the West were found to restrict the onset of summer monsoon. SSTs in the month of May significantly correlated with the onset of monsoon with the coefficient of correlation of +0.45, significant at the 99% level as shown in Fig. 12. From the figure it can be observed that correlations between the DMI index and western pole SST anomalies (positive phase of IOD) are at 95% and 99% significant levels for the month of April and May respectively. With modest increase in DMI index for the month of May, SST anomalies for the month of May increased significantly. It was also observed that for 70% such scenarios SST anomalies in the western pole intensified during May.

5.2. *Seasonal rainfall correlations*

Observations from Fig. 14 show that the SST anomalies in the western pole are negatively correlated to ISMR over North East India. Most of the lead-time correlations are generally negative and correlations observed are considerably low as compared to the lag-time correlations. This behavior of positive phase of IOD is similar across the entire region. Most of North East India is land locked except for parts of Tripura and Meghalaya, which are more influenced by sea winds and therefore are more negatively correlated. The correlations between western pole of IOD and monsoon rainfall are significant at the 95% level for 70% of the North East India. The best obtained one, two and three month lag-lead correlations between DMI index and seasonal rainfall for the six different states is shown in Table 1. -0.7 coefficient of correlation (CC) for Meghalaya and central Assam is significant at the 99% level for one-month lag achieved using the non-linear Spearman's rank correlation. The CCs for the same regions are -0.6 for two and three months significant at the 99% level.

Fig. 13 shows the lag lead correlations between DMI and summer monsoon rainfall for various states across NE India. From the figure below, we can observe that the lag CCs are considerably higher than the lead CCs. A possible explanation for this occurrence can be the drop in SSTs observed during the withdrawal phases of summer monsoon (Figs. 8&9) during the recent time period horizon (1991-2019) for both positive and negative IOD events. Therefore, we can assert that the DMI index of preceding one/two/three months, *i.e.*, June, July and August can provide a good indication of precipitation activity across the entire NE region.

5.3. *Monthly rainfall correlations*

Monthly correlations between western pole of IOD and DMI index for the months, June - August are shown in Fig. 15 for the period 1960-2019. The coefficient of correlation was observed to be negatively correlated with

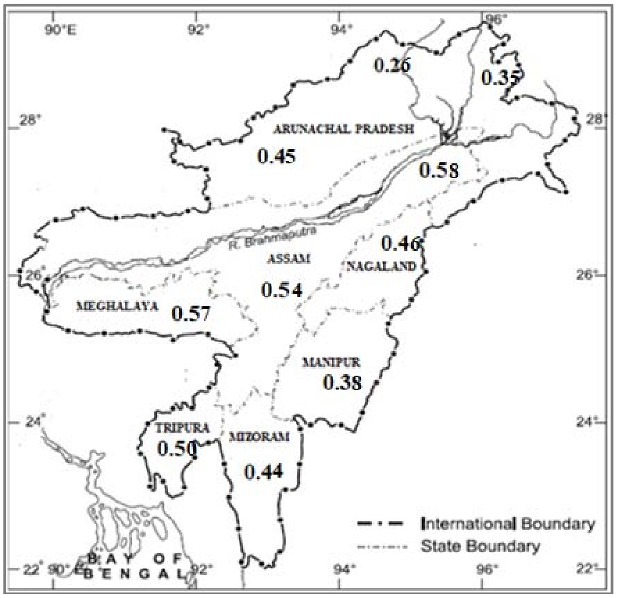


Fig. 16. Lag correlations between eastern pole (negative IOD) and monthly rainfall (June-August) for the six different states in North East India

during the positive phase of IOD events for June-August rainfall months. All the three lead-time (June-August) correlations are consistent for the region. Two months lag correlations are more prominent for august rainfall. SSTs in the eastern pole also yields a similar pattern of relationship with rainfall over eastern and central part of Assam, Meghalaya, Tripura and eastern Mizoram. From Fig. 16, it can be observed that SSTs in the eastern pole is positively correlated to seasonal rainfall over North East region with observed low correlations for certain regions in Arunachal Pradesh and Nagaland. However, the observed correlation of negative IOD phase and June-August monthly rainfall was found to be much weaker than its positive IOD counterpart. For strong phases of p IOD events, the onset date of monsoon over the region is observed to be delayed. Cyclones originating in the Bay of Bengal region also plays an important role in this regard.

6. Conclusions

Research in the last decade exhibits IOD as an important factor that affects the inter annual and seasonal climate across the Indian sub-continent (Ashok *et al.*, 2019; Sartimbul *et al.*, 2018). IOD plays significant role in the onset as well as in the variation of magnitude of ISMR. IOD relationship with ENSO affecting the ISMR is debatable as IOD anomaly events are generated by the India Ocean without being externally forced by coupled Ocean Atmospheric processes in the Pacific (Abram *et al.*, 2008; Horii *et al.*, 2008; Hrudya *et al.*, 2020; Behera *et al.*, 2018). Research has shown that IOD can be generated either by ENSO or by sea-air interaction processes in the Indian Ocean. However, the mechanisms that generate IOD without the presence of ENSO events in still unclear. Our study distinctly shows diminishing association of IOD-ISMR during the commencement phase of monsoon and an enhanced association during the retreating phase. However, during the peak, the association changed from out of state to in state for most of the regions across the country, *i.e.*, negative correlation to positive correlation. During the positive and negative phases of IOD, significant changes in SST anomalies evident during 1991-2019 and these variations can be very much associated with the corresponding precipitation attributes. LEJ was found substantially weak over the southern coastal regions resulting in no variations in precipitation for these areas.

Wind circulation and moisture movement processes were further studied across the equatorial Indian Ocean and Indian subcontinent region. Forceful LEJ were noted across the equatorial Indian Ocean and Arabia Sea for all the monsoon stages during the 1991-2019 period. The rise in strength of these jets results in a convergence section over the northeastern regions of the country. This facilitates more rainfall across these regions due to greater moisture movement. Negative IOD years are characterized by enhanced westerlies that are over shadowed during the peak and retreating phases of monsoon. Weakened LEJ curb the moisture movement process leads to fall in rainfall across the country. This diverging section results in significant reduced precipitation conditions across the sub Himalayan and central eastern regions. However, weaker westerlies across the southern coastal regions and central equatorial Indian Ocean during the commencement phases of monsoon instigate intensified rainfall conditions across majority regions in the country. The sections of convergence and divergence induce rise or fall in rainfall over majority regions in the country with significant changes in wind circulation characteristics and SST variations are witnessed. Although, these variations are consistent for all the stages of ISMR in the country, most apparent variations are noted during the peak and retreating stages. The teleconnections between IOD and ISMR across the North Eastern region of India established using a correlational approach brought out the following results:

(*i*) Positive / negative phase of Indian Ocean Dipole and warmer / colder SSTs in the western pole during April-May caused delayed/early onset of monsoon over North East India.

(*ii*) The IOD climatic anomaly seems to influence the summer monsoon activity over the central and western

Assam, Meghalaya & Mizoram more than over other parts of the region. Positive IOD during April-May, *i.e*., stronger western pole is associated with decline in rainfall over North East India. The correlations are significant at the 99% level for more than 50% of the region. Influence of western pole is greater on the summer monsoon rainfall in this region.

(*iii*) This study also becomes significant as IOD events will certainly affect the retreating monsoon which commences with the beginning of the withdrawal of the south-west monsoon [mid-September-November] and lasts until early January. It is a 3-month long process where it starts from the peninsula in October and from the extreme southeastern tip by December. Retreating monsoons are different from the usual summer monsoons and results in heavy rainfall in the western part of Western Ghats and specially North East India. Hence, one of the key findings of this work, *i.e*., The DMI index of preceding one/two/three months, *i.e*., June, July and August can provide a good indication of summer rainfall activity over the entire region during the withdrawal of monsoon, *i.e*., in the month of September becomes even more significant.

(*iv*) The SSTs of the western pole during March-April are associated with the detrimental monsoon rainfall over North East India during the onset of monsoon, *i.e*., in the month of June. The SST correlations are significant at the 99% level for western & central Assam, Meghalaya and Mizoram and at the 95% level for the other states in the region.

Declarations

Funding : Not Applicable

Conflicts of interest/Competing interests: The authors hereby declare no conflicts of interest or competing interests.

Availability of data and material : (*i*) The summer monsoon rainfall data for the North East region for the period 1960-2019 has been utilized from the Indian institute of Tropical Meteorology (www.tropmet.res.in). (*ii*) The DMI index for the same period is employed from the data archival section of National Oceanic and Atmospheric Administration (NOAA).

Code availability : Not applicable

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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