

Analysing the Changing Variations of Indian Ocean Dipole (IOD)—Indian Summer Monsoon Rainfall (ISMR) Relationship Across Northeast India



Partha Pratim Sarkar, Prashanth Janardhan, and Parthajit Roy

1 Introduction

The meteorological conditions over the North Indian Ocean and surrounding land-mass 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 Northeast part of India is responsible for greater freshwater 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 equatorial region of the Indian Ocean, the wind flow behaviour is different than the flow in the Bay of Bengal and the Arabian Sea. The winds across the equatorial Indian Ocean are weaker during the monsoons but relatively strong westerly winds develop during the spring (April-May) and during the fall (October-November) [1]. 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

P. P. Sarkar (✉) · P. Janardhan · P. Roy
Department of Civil Engineering, National Institute of Technology Silchar, Silchar,
Assam 788010, India
e-mail: Parthasarkar.nits@gmail.com

P. Janardhan
e-mail: prashanth@civil.nits.ac.in

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 result 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 [2, 3]. 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 [4, 5]. 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 Northeast 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 Northeast India. Section 4 utilizes the DMI and ISMR data sets to broadly depict the teleconnections, which is followed by the results (Sect. 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 [6] 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 [7]; Rasmusson and Carpenter [8]; Singh and Pai [9] and Singh et al. [10] owed this to the inter-annual variation of the coupled ocean- atmosphere system across the Pacific. Rasmusson and Carpenter [8] 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 [11].

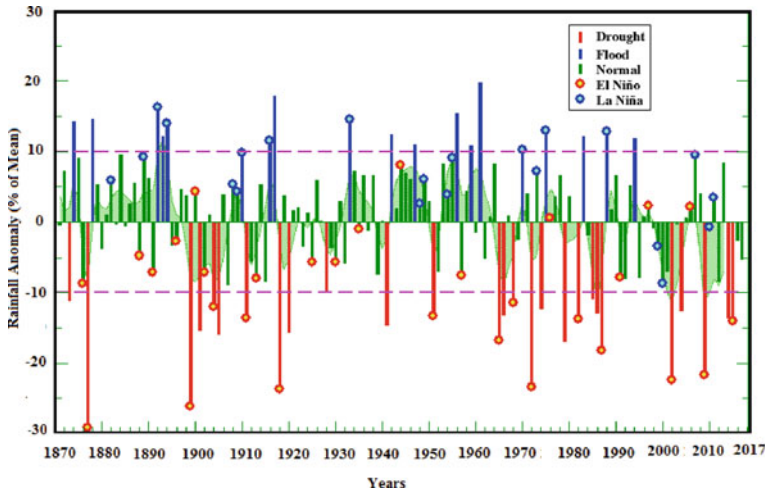
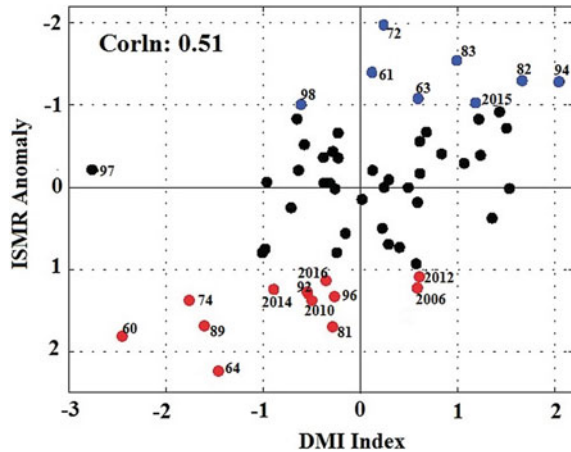


Fig. 1 Time series evolution of ISMR anomalies as percentage of mean across India for the period 1870–2017

The drought years in the country mostly coincided with the El Niño (warm) events. However, the droughts of 1974 and 1985 coincided with La Niña (cold) events. The excess rainfall seasons were observed to be influenced by La Niña events with exception like in 1997, which was a strong El Niño year. Figure 1 shows the time series Indian summer monsoon rainfall anomalies expressed as percentage departures from its long-term mean for the period 1870–2017. Figure shows the droughts, floods, El Niño and La Niña 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 [12]. During the same period, two negative IOD events coincided with negative ISMR anomalies. It was also observed that the correlation behaviour 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 correlation with ISMR anomalies for the period 1960–2016 is depicted in Fig. 2. 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 [13, 14].

Fig. 2 Scatter diagram depicting normalized ISMR anomalies versus DMI anomalies for the period 1960–2016 (ISMR data source <http://tropmet.res.in> and DMI source <http://psl.noaa.gov>)



3 Climate and Weather Across Northeast India

Northeast (NE) India (located between 22° N and 29° N) comprising 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 to 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 is in 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 km apart from

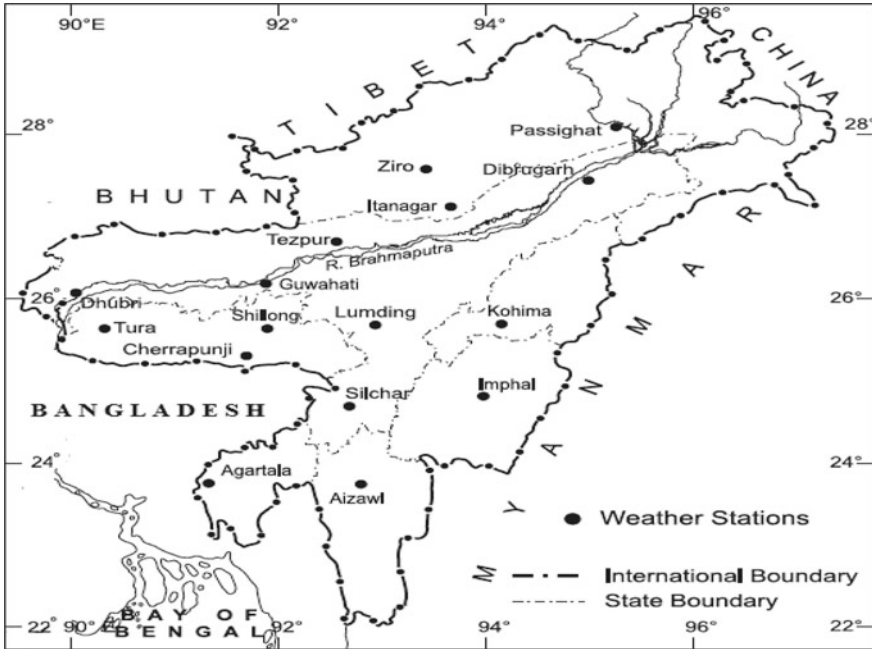


Fig. 3 Map showing the locations of a handful of weather stations across Northeast India

each other, have drastic difference in average annual rainfall. Cherrapunji receives 11,420 mm mean annual rainfall while Shillong receives only 2420 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 (1717 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 Northeast 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. Figure 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. Northeast India has many mountainous ranges and valleys. The temperatures in the Brahmaputra and Barak valley are somewhat similar with average temperatures around 28–31 °C during the summer months while the mean temperatures in winter are around 16–17 °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 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

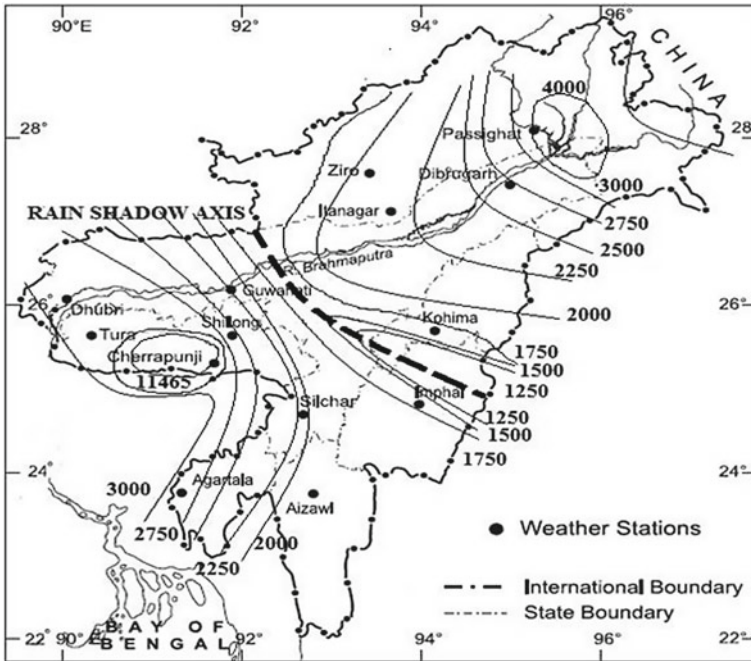


Fig. 4 Isohyets map showing the variations in annual rainfall (Isohyets in mm) in Northeast India

month of January. Shillong is nearly 50 km 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 Arunachal 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 period 1960–2019 is shown in Figs. 5 and 6, respectively.

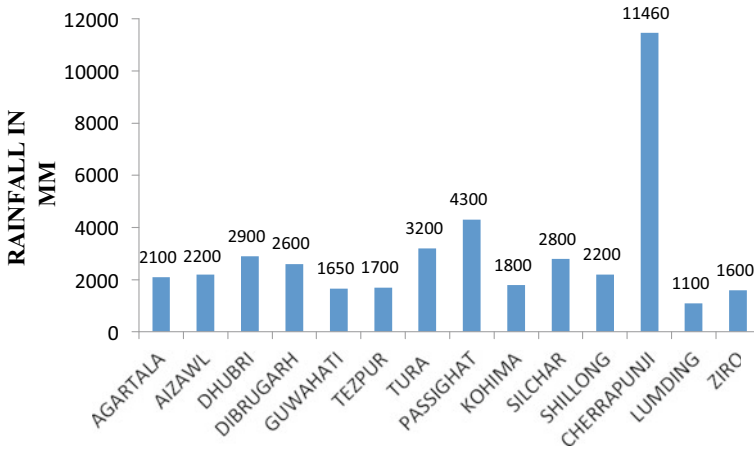


Fig. 5 Average rainfall (in mm) for some weather stations for the monsoon period 1960–2019 from Agartala to Ziro

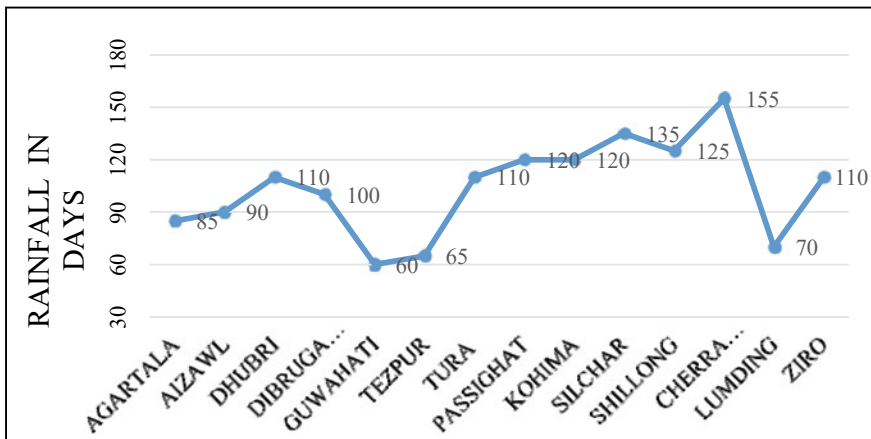


Fig. 6 Average number of rainfall days for the weather stations for the monsoon period during 1960–2019 from Agartala to Ziro

4 Data and Methodology

The summer monsoon rainfall data for the Northeast 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).

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 and western and eastern poles' SST with monthly and seasonal monsoon rainfall for the Northeast region have been computed. To define the teleconnections between DMI and onset of monsoon over Northeast 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 Northeast 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:

$$\mu = \frac{\sum (V1_m^y - \bar{V}1_m)(V2_m^y - \bar{V}2_m)}{\sqrt{(\sum (V1_m^y - \bar{V}1_m)^2) (\sum (V2_m^y - \bar{V}2_m)^2)}} \tag{1}$$

where $V1_m^y, V2_m^y$ are variables which denote DMI and the ISMR anomalies for 'm' month of 'y'th year $\bar{V}1_m, \bar{V}2_m$ are monthly average of the variables, and N denotes the total number of years.

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

$$r = \frac{N_{\text{convergent}} - N_{\text{divergent}}}{\frac{1}{2}n(n - 1)} \tag{2}$$

where N is the total number of variable sets. For both the variable sets $V1$ and $V2$, a sample pair of DMI and ISMR anomalies may be called as convergent if the ranks of both the elements in $V1$ and $V2$ are same and can be termed as divergent if the ranks differ.

Spearman's correlation is a nonparametric 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:

$$\rho = 1 - \frac{6 \sum d^2 i}{n(n^2 - 1)} \tag{3}$$

where

ρ = Spearman's correlation,

d^2_i = The difference between the ranks of corresponding variables,

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, then onset anomaly date is considered as -5 and if the onset date is 6th June, then it is considered as 5 .

5 Results

5.1 *Correlation Between DMI Index and Summer Monsoon Onset Over Northeast India*

The correlations of summer monsoon onset date across the Northeast 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 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. 7. 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. 8 show that the SST anomalies in the western pole are negatively correlated to ISMR over Northeast India. Most of the lead-time correlations are generally negative. This behaviour of positive phase of IOD is similar across the entire region. Most of Northeast 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 Northeast India. The best obtained one, two and three month lag-lead correlations between DMI index and seasonal rainfall for the six different states are given in Table 1. -0.7 coefficient of

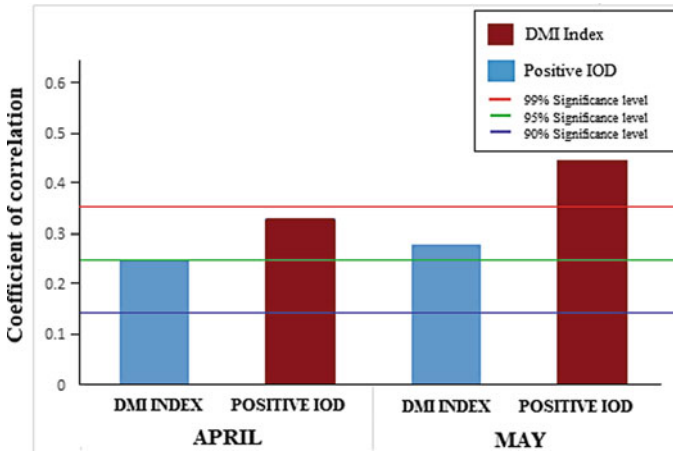


Fig. 7 Correlations between DMI index and western pole SST anomaly (p IOD) for the months April and May for the monsoon onset over Northeast India

correlation (CC) for Meghalaya and central Assam is significant at the 99% level for one month lag achieved using the nonlinear Spearman’s rank correlation. The CCs for the same regions are -0.6 for two and three months significant at the 99% level. From the table 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 during the recent time period horizon (1991–2019) for both positive and negative IOD events.

Table 1 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

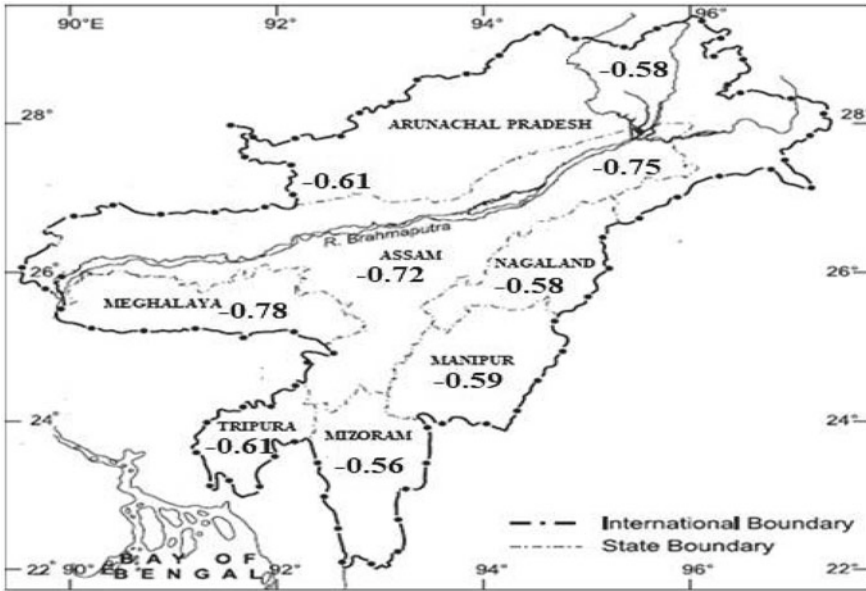


Fig. 8 Lag correlations between western pole (positive IOD) and seasonal rainfall for the six different states in Northeast India

5.3 Monthly Rainfall Correlations

Monthly correlations between western pole of IOD and DMI index for the months June–August are shown in Fig. 9 for the period 1960–2019. The coefficient of correlation was observed to be negatively correlated with 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 yield a similar pattern of relationship with rainfall over eastern and central part of Assam, Meghalaya, Tripura and eastern Mizoram. From Fig. 10, it can be observed that SSTs in the eastern pole are positively correlated to seasonal rainfall over Northeast 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 play an important role in this regard.

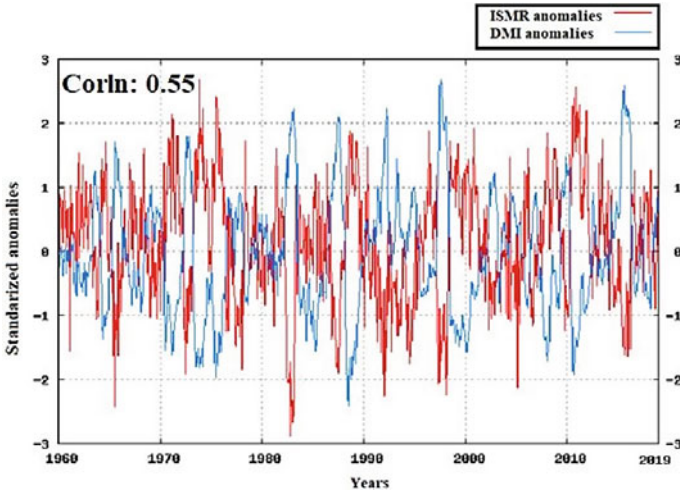


Fig. 9 Correlations between standardized ISMR anomalies and DMI anomalies for the months June-August during the period 1960–2019

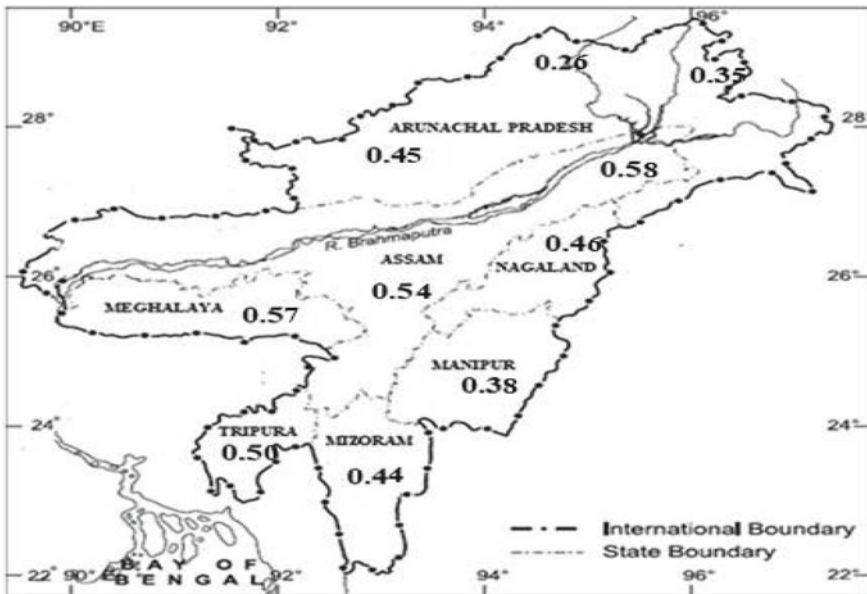


Fig. 10 Lag correlations between eastern pole (negative IOD) and monthly rainfall (June-August) for the six different states in Northeast India

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 [15]. 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 [16–19]. 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 is still unclear. In this work, the teleconnections between IOD and ISMR across the Northeastern region of India has been established using a correlational approach. The study has brought out the following results:

- (1) 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 Northeast India.
- (2) The IOD climatic anomaly seems to influence the summer monsoon activity over the central and western Assam, Meghalaya and 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 Northeast 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.
- (3) This study also becomes significant as IOD events will certainly affect the retreating monsoon which commences with the beginning of the withdrawal of the southwest 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 Northeast 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, it becomes even more significant.
- (4) The SSTs of the western pole during March-April are associated with the detrimental monsoon rainfall over Northeast India during the onset of monsoon, i.e. in the month of June. The SST correlations are significant at the 99% level for western and central Assam, Meghalaya and Mizoram and at the 95% level for the other states in the region.

References

1. Wyrтки K (1973) An equatorial jet in the Indian Ocean. *Science* 181:262–264
2. Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. *Nature* 401:360–363
3. Murtugudde R, McCreary JP, Busalacchi AJ (2000) Oceanic processes associated with anomalous events in Indian Ocean with relevance to 1997–98. *J Geophys Res* 105:3295–3306
4. Annamalai H, Murtugudde R, Potemra J, Xie SP, Liu P, Wang B (2003) Coupled dynamics over the Indian Ocean: spring initiation of the zonal mode. *Deep Sea Res Part II*(50):2305–2330
5. Li T, Wang B, Chang CP, Zhang Y (2003) A theory for the Indian Ocean dipole-zonal mode. *J Atmos Sci* 60:2119–2135
6. Bjerknes J (1969) Atmospheric teleconnections from the equatorial Pacific. *Mon Wea Rev* 97:163–172
7. Pant GB, Parthasarathy B (1981) Some aspects of an association between the southern oscillation and Indian summer monsoon. *Arch Meteorol Geophys Biokl* 29:245–251
8. Rasmusson EM, Carpenter TH (1983) The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon Weather Rev* 111:517–528
9. Singh OP, Pai DS (1996) An oceanic model for the prediction of SW monsoon rainfall over India. *Mausam* 47:91–98
10. Singh OP, Ali Khan TM, Rahman S (2000) Changes in the frequency of tropical cyclones over north Indian Ocean. *Meteorol Atmos Phys* 75:11–20
11. Kumar KK, Rajagopalan B, Cane MA (1999) On the weakening relationship between the Indian monsoon and ENSO. *Science* 284:2156–2159
12. Ashok K, Gaun Z, Yamagata T (2001) Impact of the Indian ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys Res Lett* 28:4459–4502
13. Guan Z, Yamagata T (2003) The unusual summer of 1994 in east Asia: IOD teleconnections. *Geophys Res Lett* 30:L01540
14. Ashok K, Guan Z, Saji NH, Yamagata T (2004) Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon. *J Climate* 17:3141–3155
15. Sartimbul A, Erfan R, Ali MF, Khaidar Z (2018) Anomaly technique for expression the Indian Ocean Dipole in South Java Sea. *Int J Eng Technol* (7):28–30
16. Abram NJ, Gagan MK, Cole JE, Hantoro WS, Mudelsee M (2008) Recent intensification of tropical climate variability in the Indian Ocean. *Nat Geosci* 1:849–853
17. Horii T, Hase H, Ueki I, Masumoto Y (2008) Oceanic precondition and evolution of the 2006 Indian Ocean dipole. *Geophys Res Lett* 35:L03607
18. Hrudya PH, Varikoden H, Vishnu R (2020) A review on the Indian summer monsoon rainfall, variability and its association with ENSO and IOD. *Meteorol Atmos Phys*
19. Behera SK, Ratnam JV (2008) Quasi-asymmetric response of the Indian summer monsoon rainfall to opposite phases of the IOD. *Sci Rep* 8:1–8