

Tropical cyclones over north Indian Ocean during El-Niño Modoki years

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Received: 10 February 2012 / Accepted: 1 April 2013 / Published online: 10 April 2013
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Abstract Tropical cyclones are the most hazardous weather systems, which form over warm ocean waters. The frequencies of tropical cyclones show variabilities over all the oceanic basins, during the El-Niño and El-Niño Modoki years. Recent studies have shown significant impact of air–sea interaction processes like El-Niño and El-Niño Modoki on the cyclone activity over different ocean basins. The results suggest in most cases, El-Niño events suppress the formation of cyclones over various basins. A recent study indicated that concurrent occurrence of El-Niño Modoki and positive Indian Ocean dipole (IOD) events can generate more cyclones over north-west Pacific. We propose to study the impact of El-Niño Modoki events on the formation of tropical cyclones over north Indian Ocean (NIO). Our present study suggests that the cyclogenesis over the NIO is a complex phenomenon, as it is influenced by several coupled ocean atmospheric phenomena such as El-Niño, El-Niño Modoki, IOD and Madden–Julian oscillation.

Keywords Indian Ocean · Tropical cyclones · Cyclogenesis parameter · El-Niño and El-Niño Modoki

1 Introduction

Tropical cyclones form over warm ocean surfaces, having high sea surface temperature (SST) more than 26 °C, low magnitudes of vertical wind shear (VWS) and large magnitudes of low-level relative vorticity (LLRV), coriolis force and middle tropospheric relative humidity. The north Indian Ocean (NIO) accounts for 7 % of global tropical cyclones; furthermore, a great number of cyclones form in the Bay of Bengal than in the Arabian Sea about four times higher (Dube et al. 1997). On an average about 5–6 tropical cyclones form over this basin every year (Singh et al. 2001) in two cyclone seasons, such as pre-monsoon season (March–May) and post-monsoon season (October–December). Studies show that there is an increasing trend in the frequency of intense tropical cyclones over NIO

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(Singh et al. 2000, 2001; Singh 2007; Srivastav et al. 2000). Mooley (1980, 1981) studied the frequency of severe cyclonic storms during the period of 1877–1977 and found that the percentage of storms intensifying into severe cyclonic storms are high during the period of 1965–1977.

There is a significant decreasing trend in the frequency of cyclonic storms over NIO (Srivastav et al. 2000) during the period of 1891–1997; this study further suggests that the weakening of Hadley circulation may be one of the causes of decreased cyclonic activity. Ramesh Kumar and Sankar (2010) studied the impact of global warming on the cyclonic storms over NIO; it states that the frequency of storms and severe storms does not show a dramatic rise despite increase over the SST in the Bay of Bengal from 1951 to 2007 compared to the 1901–1951; this study further states that there is large decrease in the mid-tropospheric humidity over the Bay of Bengal during the period 1951–2007 and the atmospheric parameters such as low-level vorticity, mid-tropospheric humidity and VWS, all play an important role in the genesis and intensification of storms over this basin.

Air–sea interaction processes like El-Niño and La-Niña have significant impact on the cyclone activity over different ocean basins. The results suggest in most cases, El-Niño (La-Niña) events suppress (enhance) the formation of cyclones over various basins. The ENSO events have significant impacts on the hurricane intensity (Landsea et al. 1999) and genesis locations (Elsner and Kara 1999) of the tropical cyclones. There is a tendency toward less (more) tropical cyclones over the Atlantic basin during the El-Niño (La-Niña) years (Gray 1975, 1984). In the western North Pacific, there is a south-eastward (north-eastward) shift of tropical cyclone activity in El-Niño (La-Niña) years (Chan 1985; Dong 1988; Chia and Ropelewski 2002; Wang and Chan 2002). The impacts of El-Niño Modoki events on tropical cyclones are less studied.

El-Niño and El-Niño Modoki events are those air–sea interaction processes of anomalous warming and cooling of SSTs in the tropical eastern and central Pacific Ocean, respectively. The El-Niño event is defined by warmer than normal SSTs in the eastern tropical Pacific Ocean (Philander 1983). The El-Niño Modoki event is defined by the anomalous warming over the central Pacific Ocean and cooler SST anomalies in both west and east along the equator (Ashok et al. 2007; Ashok and Yamagata 2009). These zonal SST gradients result in anomalous two-cell walker circulation over the tropical Pacific with rainfall anomalies in the central Pacific. The El-Niño Modoki and its climate impacts are different from those of El-Niño. The El-Niño Modoki event has significant impacts on the temperature and precipitation over many parts of the globe (Ashok et al. 2007). Pradhan et al. (2011) calculated the El-Niño and El-Niño Modoki years during the period 1979–2004. There were four El-Niño years and seven El-Niño Modoki years during this period; these years are given in Table 1. It is observed that there exist significant differences in the cyclone frequencies over all the cyclone-prone basins, during the El-Niño and El-Niño Modoki years (Table 2).

Pradhan et al. (2011) reported that the co-occurrence of El-Niño Modoki and positive Indian Ocean dipole (IOD) events can produce more cyclones over north-west Pacific. IOD (Saji et al. 1999; Webster et al. 1999) event is characterised by the anomalous warming and cooling of SSTs over the western and eastern equatorial Indian Ocean, respectively; this is a coupled ocean atmospheric process over tropical Indian Ocean and independent of the ENSO in the Pacific Ocean. A positive IOD event is characterised as the warmer than usual SSTs occurred over large parts of the western basin, while SSTs off Sumatra were cooler than usual. For the present study the positive IOD years have been extracted from Saji et al. (1999) and Kripalani and Kumar (2004).

Table 1 Number of cyclones formed over Arabian Sea and Bay of Bengal during El-Niño, El-Niño Modoki and positive IOD years

El-Niño			El-Niño Modoki			Positive IOD		
Years	AS	BB	Years	AS	BB	Years	AS	BB
1982	1	4	1986	0	1	1982	1	4
1983	0	2	1990	0	2	1994	2	2
1987	0	5	1991	0	3	1997	0	3
1997	0	3	1992	2	4			
			1994	2	2			
			2002	1	3			
			2004	3	1			

Table 2 Number of cyclones formed over all the basins during El-Niño and El-Niño Modoki years

Basins	El-Niño	El-Niño Modoki
Atlantic	23	67
East Pacific	83	26
West Pacific	98	208
South Indian	121	194
North Indian	20	32

The El-Niño and positive IOD occurred simultaneously in 1982 and 1997, and El-Niño Modoki and positive IOD occurred simultaneously in 1994. Table 3 presents the variations in the frequencies of cyclones in various basins during these periods. In the west Pacific the frequency is more during the concurrent occurrence of El-Niño Modoki and positive IOD events, and over other basins it is more during the concurrent occurrence of El-Niño and positive IOD events. From the Fig. 1a, b it is observed that there is a tendency to form more (less) cyclones over Bay of Bengal (Arabian Sea) during the co-occurrence of El-Niño and positive IOD events, and a tendency to form more (less) cyclones over Arabian Sea (Bay of Bengal) during the co-occurrence of El-Niño Modoki and positive IOD events (Fig. 1c). Four severe cyclones formed over NIO, during the co-occurrence of El-Niño Modoki and positive IOD events in 1994: two formed in Arabian Sea and two formed in

Table 3 Number of cyclones formed over all the basins during the concurrent occurrence of El-Niño and El-Niño Modoki with positive IOD events

Basins	Concurrent occurrence of (El-Niño and positive IOD)		(El-Niño Modoki and positive IOD)
	1982	1997	1994
Atlantic	05	07	07
East Pacific	23	19	20
West Pacific	26	31	34
South Indian	28	41	30
North Indian	05	03	04

Bay of Bengal. This proves that the co-occurrence of El-Niño Modoki and positive IOD events is conducive for the formation of tropical cyclones over NIO.

2 Data and methodology

The process of initiation of a cyclone is called cyclogenesis. Many authors have tried to quantify this cyclogenesis over various basins. Gray (1975) introduced six primary genesis parameters for tropical cyclone, known as seasonal genesis parameter (SGP), which is the product of three dynamic parameters as well as three thermodynamic parameters, such as (1) LLRV, (2) coriolis parameter, (3) inverse of the vertical shear of the horizontal wind between lower and upper troposphere, (4) ocean thermal energy or SST above 26 °C to a depth of 60 m, (5) vertical gradient of equivalent potential temperature between surface and 500 mb and (6) middle tropospheric relative humidity. Followed by McBride (1981), McBride and Zehr (1981) proposed a daily genesis parameter (DGP) to differentiate the developing and non-developing systems. Royer et al. (1998) developed a yearly genesis parameter (YGP) to study the future changes of tropical cyclogenesis frequency. DeMaria et al. (2001) developed a genesis parameter to evaluate the potential of tropical cyclone formation in the North Atlantic between Africa and Caribbean Islands. Camargo et al. (2007) used a genesis parameter developed by Emanuel and Nolan (2004) known as the genesis potential index (GPI) to diagnose the ENSO effects on tropical cyclone genesis for global ocean basins. This index successfully reproduces the ENSO signals in the best-observed basins such as suppression of genesis in the Atlantic and the eastward shift in mean genesis location in the western North Pacific during El-Niño.

Zehr (1992) proposed a parameter known as genesis parameter (GP), which is the product of three dynamical parameters such as LLRV at 850 hPa, negative of low-level divergence at 850 hPa [for low-level convergence (LLC)] and VWS coefficient. GP is expressed in units of 10^{-12} s^{-2} . His study showed that this GP was useful in differentiating between the non-developing and developing systems in the western North Pacific. Roy Bhowmik (2003) used this GP to study the developing and non-developing systems over NIO and observed GP values around $20 \times 10^{-12} \text{ s}^{-2}$ against T-No:1.5, which has the potential to develop into a severe cyclonic storm. Kotal et al. (2009) introduced a GP and termed it as the genesis potential parameter (GPP) for the Indian seas. The parameter is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability and the inverse of VWS. The result shows that there is a distinction between GPP values for non-developing and developing systems in more than 85 % of cases. The composite GPP value is found to be around three to five times greater for developing systems than for non-developing systems. In this study we are using the Zehr's GP and two thermodynamic parameters defined by Kotal et al. (2009) to discuss the dynamic as well as thermodynamic features of the cyclones over NIO.

$$GP = (A) \times (B) \times (S)$$

where A = low-level relative vorticity at 850 hPa, B = low-level convergence at 850 hPa (negative of low-level divergence at 850 hPa) and S = shear coefficient = $\frac{[25.0\text{ms}^{-1} - (200-850 \text{ SHEAR})]}{20\text{ms}^{-1}}$

Kotal et al. (2009) defined the thermodynamic variables as mid-tropospheric relative humidity (MTRH) variable (M) and the mid-tropospheric instability (MTI) parameter (I), where

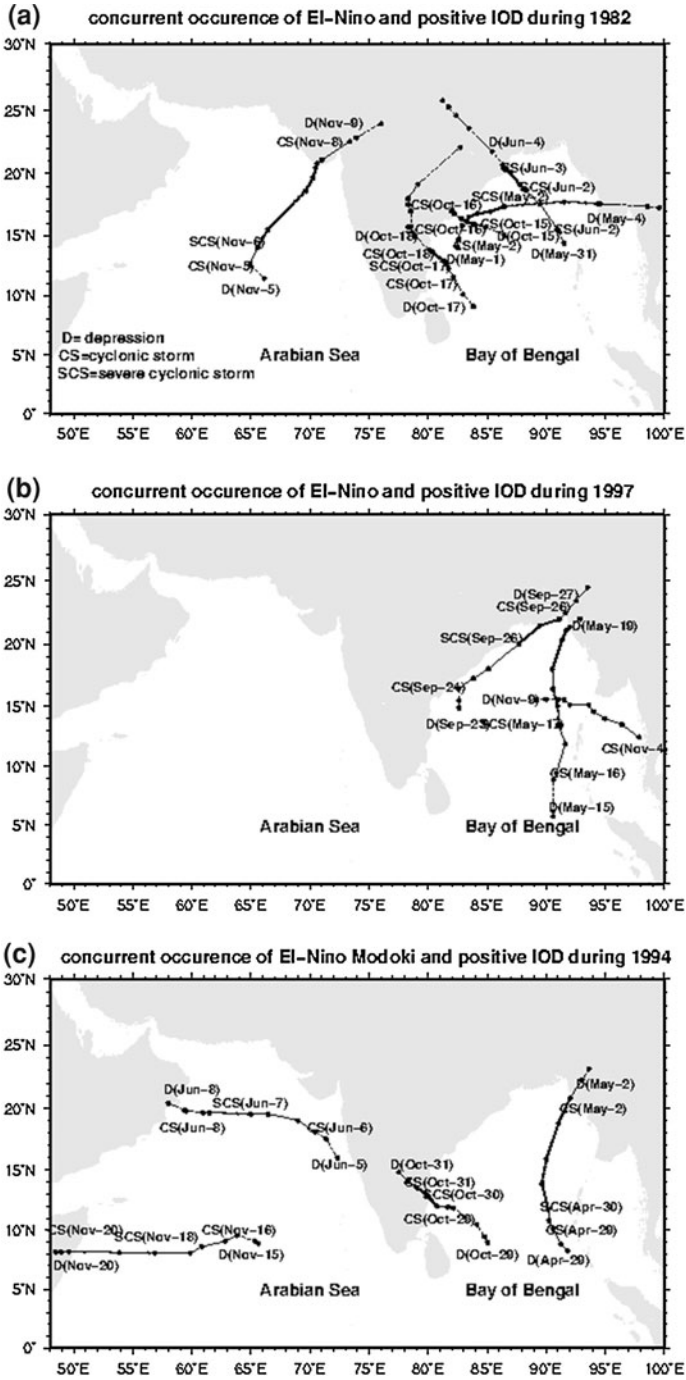


Fig. 1 Cyclones formed over NIO during the concurrent occurrence of El-Niño and positive IOD and El-Niño Modoki with positive IOD

Table 4 Number of cyclones formed over NIO during El-Niño and El-Niño Modoki years

	El-Niño		El-Niño Modoki	
	Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Arabian Sea	0 (0)	1 (0.25)	2 (0.28)	3 (0.42)
Bay of Bengal	3 (0.75)	9 (2.25)	5 (0.71)	10 (1.42)

$$M = \frac{[\text{RH} - 40]}{30}$$

(where RH is the mean relative humidity between 700 and 500 hPa) and the middle tropospheric instability is the temperature difference between 850 and 500 hPa.

$$I = T_{850} - T_{500}.$$

We have prepared the composite anomalies of all the variables namely LLRV at 850 hPa, LLC at 850 hPa, VWS, MTRH and the MTI, using NCEP/NCAR re-analysis-II daily data. All the parameters are averaged with the cyclone days, and the variations in these parameters for the cyclones during the pre-monsoon and post-monsoon seasons of El-Niño and El-Niño Modoki years are studied. The Modoki years we have used in the present study are same as those used by Ashok et al. (2007). We have obtained the cyclone frequencies for various basins from the Unisys Weather (<http://weather.unisys.com/hurricane/>). The genesis locations of the cyclones are obtained from the cyclone e-Atlas prepared by India Meteorological Department (IMD). All the parameters are averaged to the region [50°E–78°E, 0°N–30°N] for Arabian Sea and [78°E–100°E, 0°N–30°N] for Bay of Bengal.

3 Tropical cyclones over NIO during El-Niño and El-Niño Modoki years

Table 4 presents the frequencies of tropical cyclone formed over NIO during El-Niño and El-Niño Modoki years. There were no cyclones over Arabian Sea during the pre-monsoon seasons of El-Niño years, which means the El-Niño years suppress the formation over Arabian Sea during pre-monsoon seasons. And only one cyclone formed during the post-monsoon seasons of El-Niño years. During El-Niño Modoki years the number of tropical cyclones increased over Arabian Sea, than El-Niño years. Out of the four El-Niño years, only one cyclone has formed over Arabian Sea during the post-monsoon season, and this cyclone intensified into a severe cyclone. Twelve cyclones formed over Bay of Bengal in which three have formed during the pre-monsoon seasons and nine have formed during the post-monsoon season. Out of the seven El-Niño Modoki years, five cyclones formed over the Arabian Sea, in which two cyclones formed during the pre-monsoon season and three in post-monsoon season. Fifteen cyclones have formed over Bay of Bengal in which five cyclones formed in pre-monsoon and ten cyclones in the post-monsoon seasons. We could see an enhancement in the formation of cyclones over Arabian Sea during pre-monsoon seasons of El-Niño Modoki years compared to the El-Niño years. Significant differences in the ratios (for the number of cyclones per year) are seen in both basins. There are higher values during El-Niño Modoki (El-Niño) years over Arabian Sea (Bay of Bengal). This indicates that El-Niño Modoki (El-Niño) events are conducive for the formation of tropical cyclones over Arabian Sea (Bay of Bengal).

The ratios of number of cyclones for El-Niño and El-Niño Modoki years are given in brackets in Table 4. From the ratios it can be clearly seen that the number of convective systems is more during the El-Niño years over Bay of Bengal than during the El-Niño Modoki years. In case of Arabian Sea the ratios clearly show that more number of convective systems form over Arabian Sea during El-Niño Modoki years.

The splitting and modification of walker circulation cells have significant impact on the tropical cyclone frequencies over the NIO. During the El-Niño Modoki years the walker circulation cell split over the central Pacific Ocean. The ascending limb of the cell will be over the central Pacific, and the two descending limbs will be over east Pacific and west Pacific Ocean. The descending limb over the western Pacific is close to the Bay of Bengal area. This suppresses the formation of tropical cyclones over the Bay of Bengal during El-Niño Modoki years. But this will not affect the genesis of tropical cyclones over Arabian Sea. During El-Niño years the ascending limb of the walker circulation will be there over east Pacific Ocean and the descending limb will be over/near to the central and west Pacific regions, so the magnitude of the divergence over western Pacific and Bay of Bengal region will be small; this gives a favourable condition for the formation of tropical cyclones over Bay of Bengal.

Pradhan et al. (2011) have shown that the SST anomalies during the boreal summer (June to August) are significantly warmer over the Arabian Sea during El Nino Modoki composites, while they are cooler during the El-Niño events. The entire tropical region is in general warmer during El-Niño winters (Pan and Oort 1983), except the west tropical Pacific Ocean. Yamagata et al. (2004) have shown that it is particularly pronounced in the tropical Indian Ocean through changes of walker circulation.

4 Results and discussion

There were no cyclones over Arabian Sea during pre-monsoon season of El-Niño years. Only one cyclone (black dots represent the genesis locations) formed over Arabian Sea during the post-monsoon season of El-Niño years. From Fig. 2a–c, a large magnitude of LLRV (1.0 to 4.0) $\times 10^{-5} \text{ s}^{-1}$, LLC (-0.4 to 0.4) $\times 10^{-5} \text{ s}^{-1}$ and a small magnitude of VWS (2.0 to 2.5) ms^{-1} were observed over Arabian Sea for the genesis of this cyclone, and from Fig. 3a, b, a small magnitude of MTRH (-0.6 to 0.4) % and a large magnitude of MTI (23 to 24) $^{\circ}\text{C}$ were also observed over this region for the formation of this cyclone. It is noticed that the parameters such as large magnitudes of LLRV and LLC (MTRH) are important (not important) for the genesis of cyclone during this period.

During the pre-monsoon season of El-Niño Modoki years, two cyclones formed over Arabian Sea, and it is noticed that from Fig. 4a–c, a large magnitude of LLRV (0.5 to 1.5) $\times 10^{-5} \text{ s}^{-1}$, LLC (-0.2 to 0.4) $\times 10^{-5} \text{ s}^{-1}$ and a small magnitude of VWS (2.0 to 2.5) ms^{-1} are observed over central Arabian Sea (where the cyclones formed); the magnitude of LLRV was not so large during these periods over this region, and a high magnitude of LLRV (1.5) $\times 10^{-5} \text{ s}^{-1}$ is observed over south-east Arabian Sea. From Fig. 5a, b, a small magnitude of MTRH (-0.54 to 0.2) % and a large magnitude of MTI (24 to 28) $^{\circ}\text{C}$ are also observed. The parameters such as large magnitudes of LLRV, LLC and MTI (MTRH) are important (not important) for the formation of the cyclones during this period. During the post-monsoon seasons of El-Niño Modoki years, three cyclones formed over the same basin. From Fig. 4d–f a small magnitude of LLRV (-0.5 to 0.5) $\times 10^{-5} \text{ s}^{-1}$, LLC (-0.4 to 0.2) $\times 10^{-5} \text{ s}^{-1}$ and VWS (0.8 to 1.4) ms^{-1} is observed over Arabian Sea. From Fig. 5c, d, a large magnitude of MTRH (-0.6 to 0.6) % and MTI

Fig. 2 Variations in dynamic parameters during El-Niño years over Arabian Sea

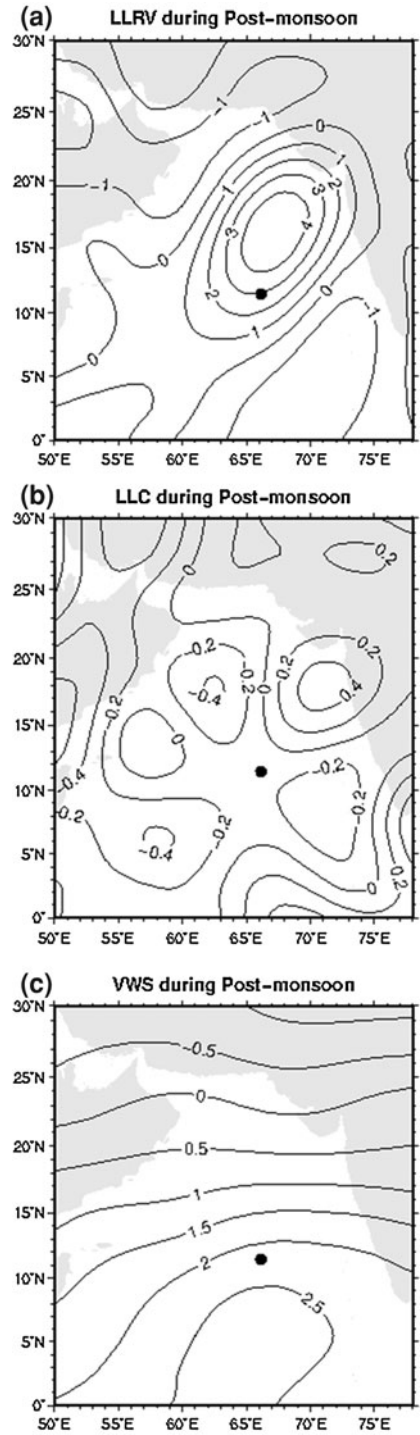
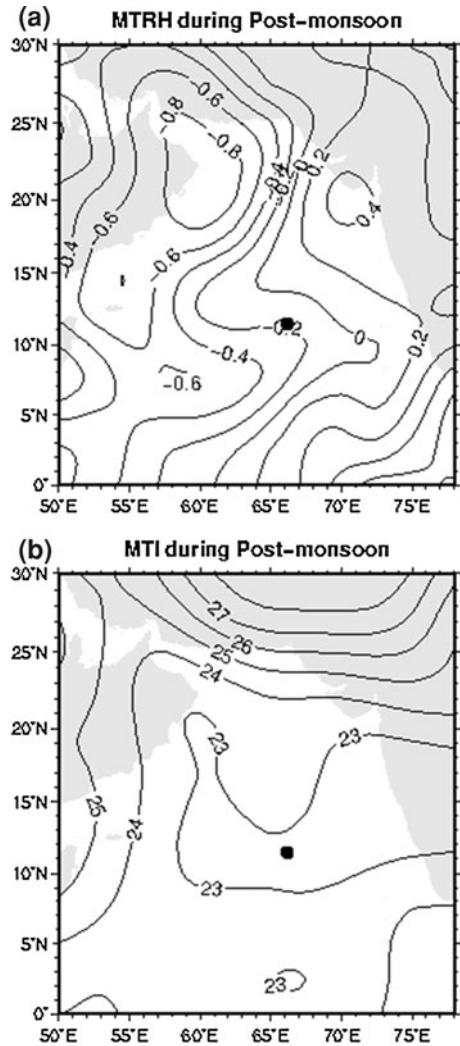


Fig. 3 Variations in thermodynamic parameters during El-Niño years over Arabian Sea



(22 to 25) °C is also observed over this region. The parameters such as small magnitudes of VWS, large magnitudes of MTRH and MTI (LLRV and LLC) are important (not important) for the formation of the cyclones during this period.

There were three cyclones over Bay of Bengal during the pre-monsoon season of El-Niño years. From Fig. 6a–c, a small magnitude of LLRV (-0.5 to 1.0) $\times 10^{-5} \text{ s}^{-1}$, VWS (-25 to -5) ms^{-1} and a large magnitude of LLC (-0.2 to 0.6) $\times 10^{-5} \text{ s}^{-1}$ are observed over central Bay of Bengal around the genesis of cyclones. From Fig. 7a, b, a large magnitude of MTRH (-0.2 to 0.8) % and MTI (23 to 27) °C is also observed over the central Bay of Bengal around the genesis of these cyclones during the pre-monsoon seasons of El-Niño years. The parameters such as large magnitudes of LLC, MTRH, MTI and small magnitude of VWS (LLRV) are important (not important) for the formation of cyclones over this region during this period. From Fig. 6d–f, during the post-monsoon seasons of El-Niño years, nine cyclones formed over Bay of Bengal. A large magnitude of

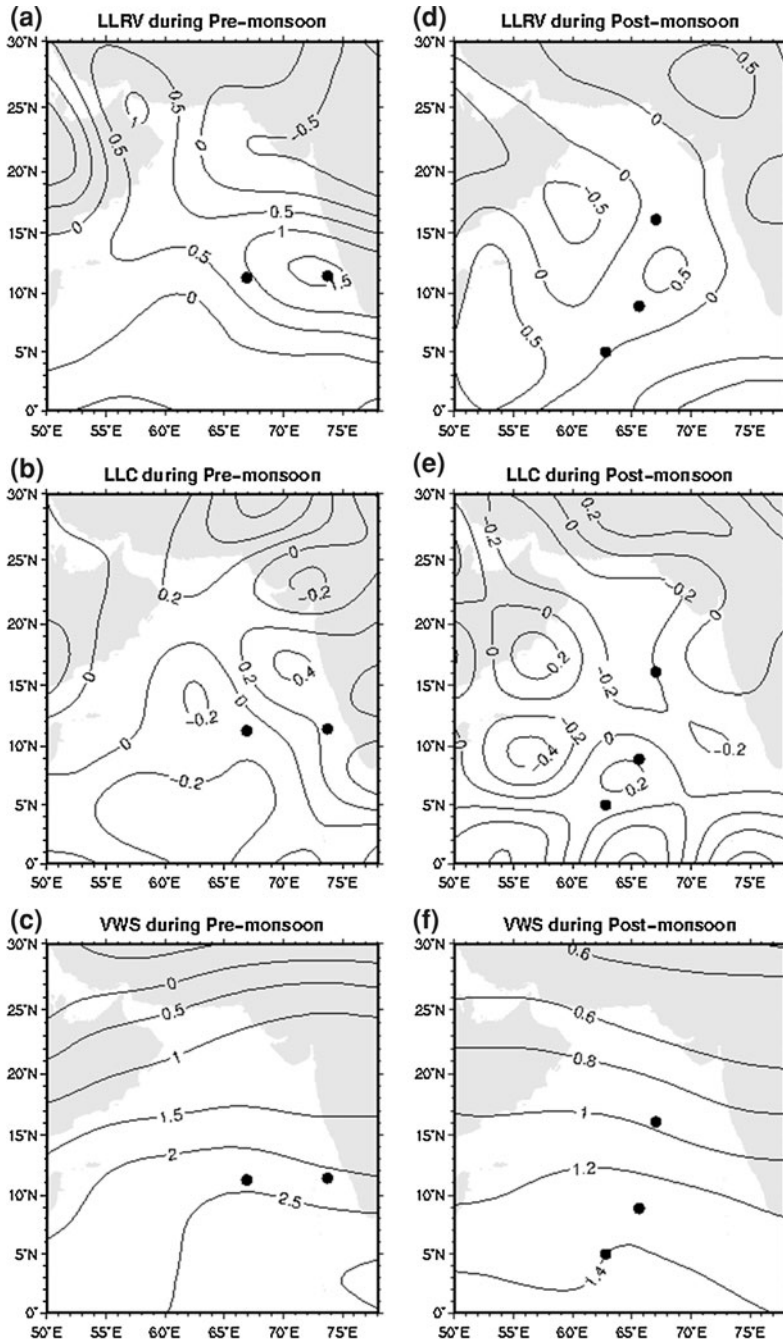


Fig. 4 Variations in dynamic parameters during El-Niño Modoki years over Arabian Sea

LLRV (0.0 to 2.0) $\times 10^{-5} \text{ s}^{-1}$ and a small magnitude of LLC (0.0 to 0.2) $\times 10^{-5} \text{ s}^{-1}$ and VWS (-20 to 10) ms^{-1} are observed over the central Bay of Bengal. From Fig. 7c, d, a large magnitude of MTRH (0.2 to 0.6) % and MTI (22.5 to 23.5) $^{\circ}\text{C}$ is also observed over

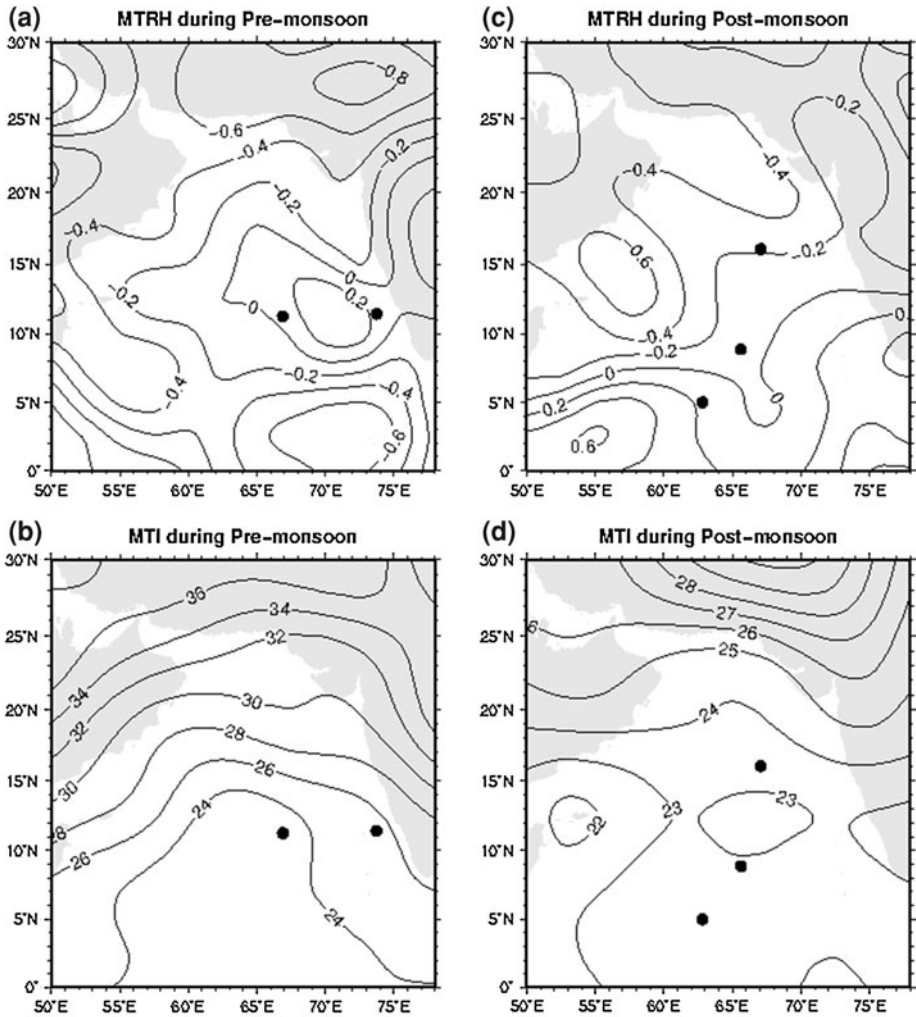


Fig. 5 Variations in thermodynamic parameters during El-Niño Modoki years over Arabian Sea

central Bay of Bengal around the genesis of the cyclones. The parameters such as large magnitude of LLRV, MTRH, MTI and small magnitude of VWS (LLC) are important (not important) for the formation of cyclones over this region during this period.

Five cyclones formed during the pre-monsoon season and ten cyclones during the post-monsoon season over Bay of Bengal for the El-Niño Modoki years. From Fig. 8a–c, a large magnitude of LLRV $(0.0 \text{ to } 1.2) \times 10^{-5} \text{ s}^{-1}$ and small magnitudes of LLC $(-0.2 \text{ to } 0.2) \times 10^{-5} \text{ s}^{-1}$ and VWS $(-15 \text{ to } 0.0) \text{ ms}^{-1}$ are observed over the Bay of Bengal around the formation of the cyclones. From Fig. 9a, b, a large magnitude of MTRH $(-0.2 \text{ to } 0.8) \%$ and MTI $(24 \text{ to } 25) \text{ }^\circ\text{C}$ is also observed over the central Bay of Bengal. These parameters such as large magnitudes of LLRV, MTRH, MTI and small magnitude of VWS (LLC) are important (not important) for the formation of cyclones over this region during this period. During the post-monsoon seasons from Fig. 8d–f, it is noticed a large

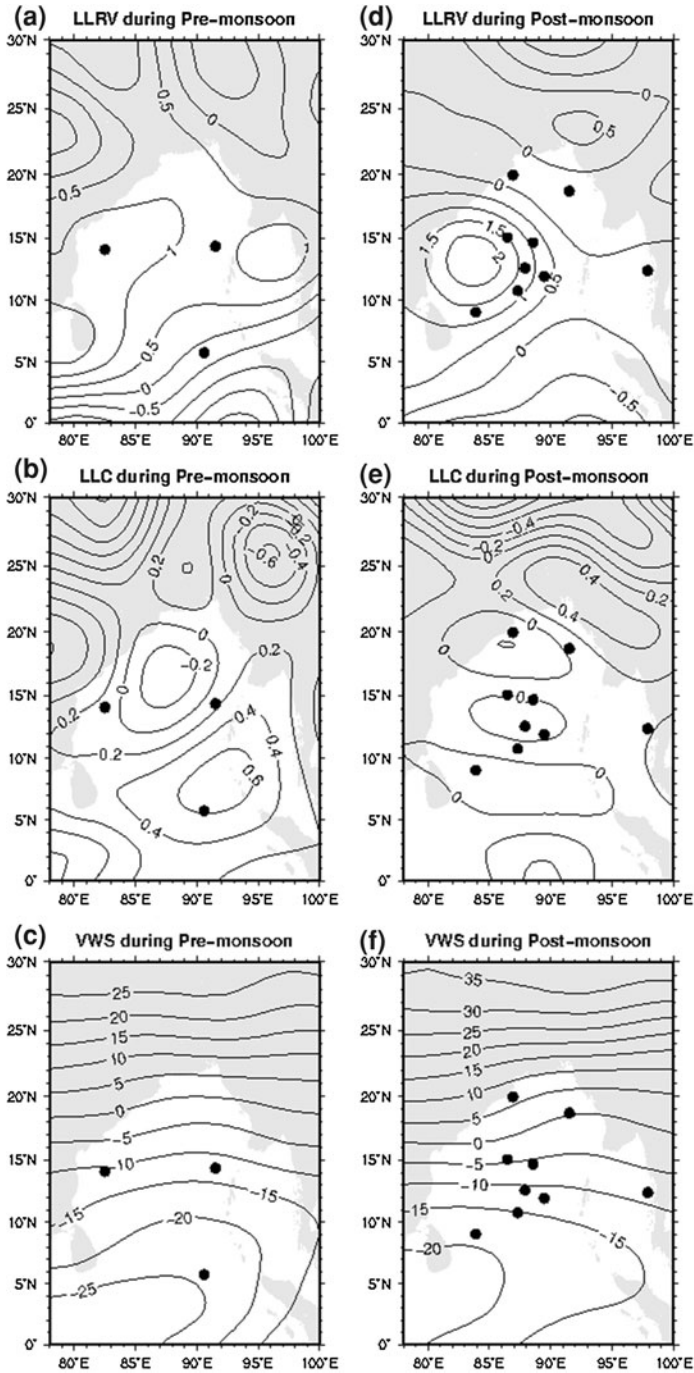


Fig. 6 Variations in dynamic parameters during El-Niño years over Bay of Bengal

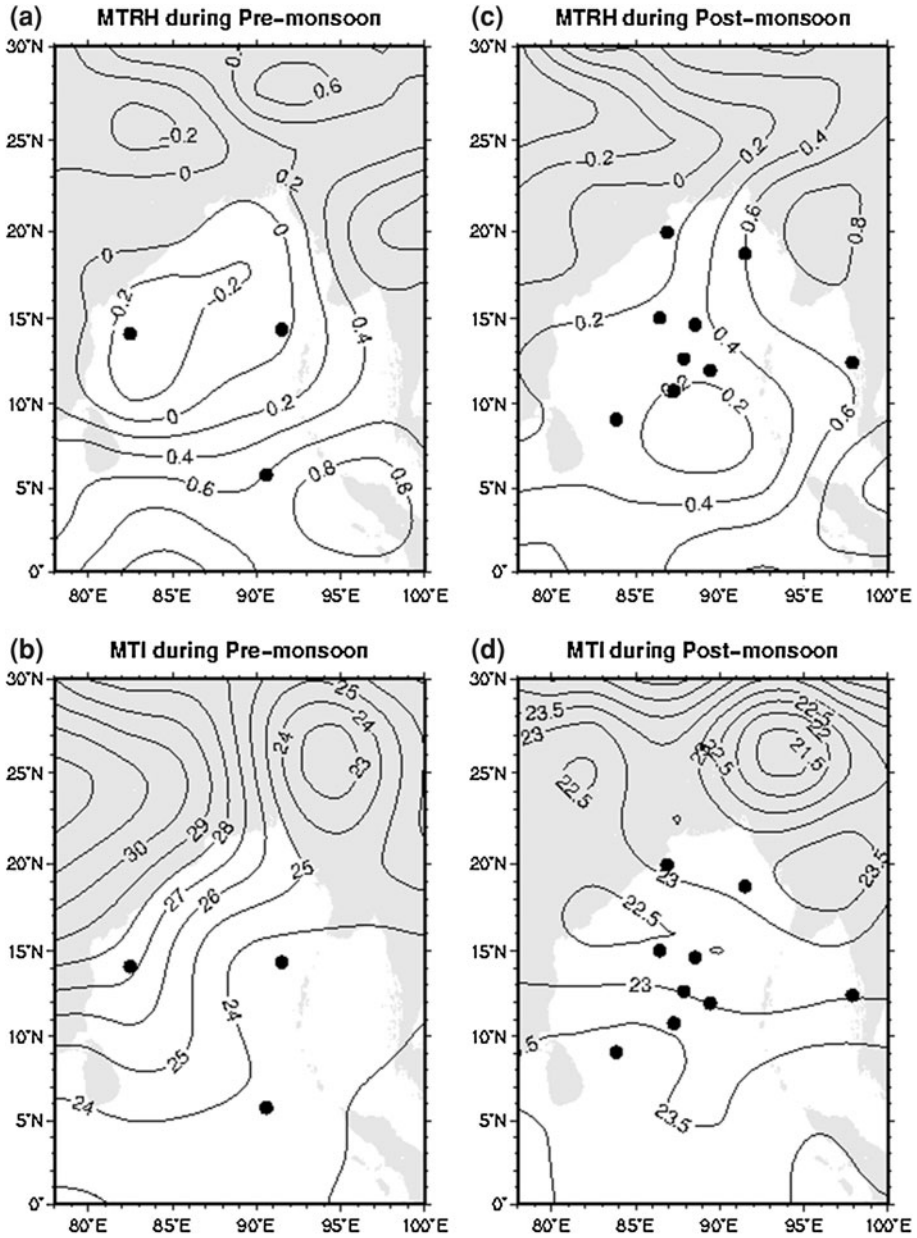


Fig. 7 Variations in thermodynamic parameters during El-Niño years over Bay of Bengal

magnitude of LLRV $(-0.8 \text{ to } 1.2) \times 10^{-5} \text{ s}^{-1}$, LLC $(-0.4 \text{ to } 0.6) \times 10^{-5} \text{ s}^{-1}$ and a small magnitude of VWS $(-4.0 \text{ to } 0.0) \text{ ms}^{-1}$ are also observed over Bay of Bengal. And from Fig. 9c, d, a large magnitude of MTRH (0.2 to 1.0) % and a small magnitude of MTI (22.0 to 23.5) °C are observed over this region around the genesis of cyclones. The parameters such as large magnitudes of LLRV, LLC, MTRH and smaller magnitudes of VWS (MTI)

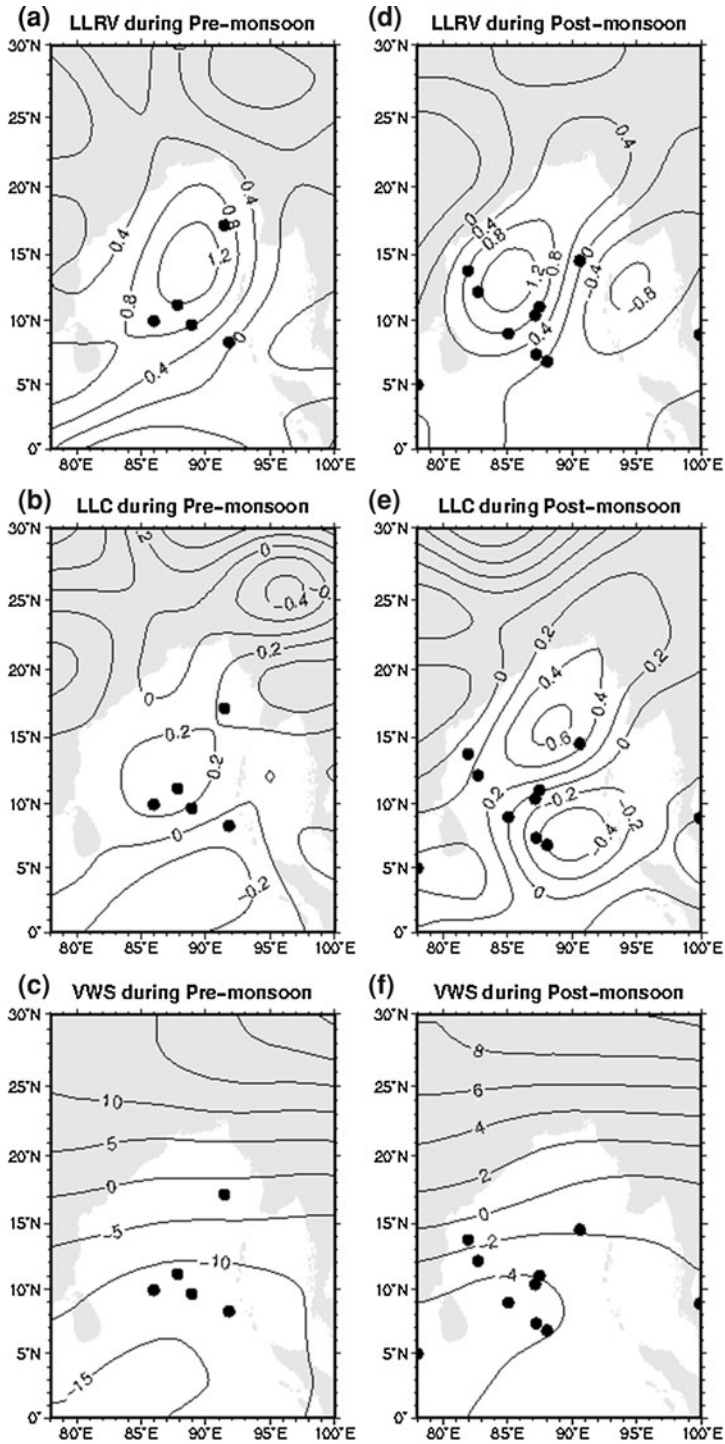


Fig. 8 Variations in dynamic parameters during El-Niño Modoki years over Bay of Bengal

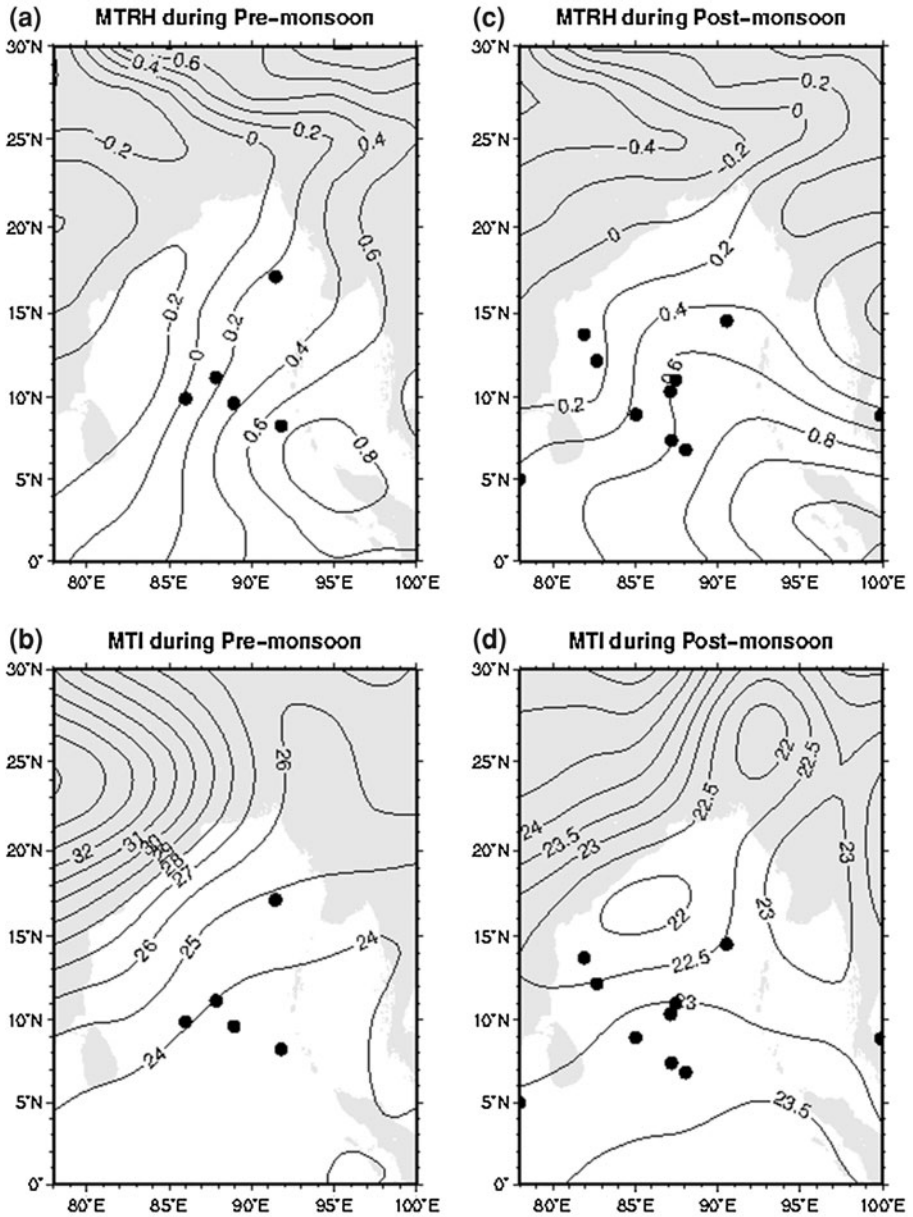


Fig. 9 Variations in thermodynamic parameters during El-Niño Modoki years over Bay of Bengal

are important (not important) for the formation of cyclones over this region during this period.

Guan and Yamagata (2003) and Mujumdar et al. (2007) using AGCM results have found that the PIODs can influence El-Niño and El-Niño Modoki induced circulation and

related cyclogenesis activities. We feel that the concurrent occurrence of El Niño Modoki and PIOD (years 1994, 2002 and 2004) could have thus generated cyclones over the Arabian Sea, whereas pure El-Niño Modoki events (years 1986, 1990 and 1991) could not create atmospheric conditions conducive for cyclogenesis over the Arabian Sea.

Another phenomenon which influences the cyclonic activity over the NIO is the Madden-Julian oscillation (MJO). Krishnamohan et al. (2012) found that about 82 % of the cyclones formed over NIO during the convective phase of MJO. Their study showed that when enhanced convection takes place over the maritime continent and eastern Indian Ocean, it creates favourable environment for cyclogenesis in the Bay of Bengal, which is caused by the strong westerlies at 850 hPa in the equatorial region south of Bay of Bengal which in turn causes strong cyclonic vorticity in the lower troposphere and minimum VWS. This MJO phenomena. One major problem is that the MJO activity can selectively interact with the El-Niño and El-Niño Modoki events.

5 Summary

The air–sea interaction processes such as El-Niño and El-Niño Modoki events have significant impacts on the tropical cyclones over NIO. We have observed that the frequency of tropical cyclones is more (less) over Arabian Sea (Bay of Bengal) during the El-Niño Modoki years compared to the El-Niño years. Our present study suggests that concurrent occurrence PIOD and El-Niño events can significantly alter cyclogenesis parameters over the Arabian Sea as compared to a pure El-Niño Modoki year. The convective phase of the MJO also plays a significant role in the cyclogenesis over the NIO. Our present study suggests that the cyclogenesis formation over the NIO is a complex phenomenon, as it is influenced by several coupled ocean atmospheric phenomena such as El-Niño, El-Niño Modoki, IOD and MJO.

Acknowledgments The authors are grateful to the Director of National Institute of Oceanography for providing all the facilities to carry out this research work and IMD, New Delhi, for providing the cyclone e-Atlas and Unisys Weather. The authors acknowledge the use of NCEP/NACR re-analysis-II daily data and freewares such as FERRET and GMT used in this research work. The authors are grateful to two anonymous reviewers for their useful suggestions and comments in vastly improving an earlier version of the manuscript. The author K. G. Sumesh is very much grateful to University Grants Commission (UGC), New Delhi, for funding this research work. NIO contribution number is 5363.

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