

Tropical cyclones over NIO during La-Niña Modoki years

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Tropical cyclones over NIO (North Indian Ocean) are highly influenced by the El-Niño and La-Niña activities over the Pacific Ocean. Influences of air-sea interaction processes like El-Niño Modoki and La-Niña Modoki on tropical cyclones are less studied. During La-Niña Modoki years the splitting of Walker circulation results in two ascending limbs over the west and east Pacific Ocean, and one descending limb over the Central Pacific, this makes large magnitude for Low Level Convergence over the West Pacific and Bay of Bengal region, which is favorable for the formation of tropical cyclones over Bay of Bengal. Other air-sea interaction parameters such as Low Level Relative Vorticity, Vertical Wind Shear are also found favorable for the cyclones over Bay of Bengal. This study states that the magnitude of Low Level Convergence over Bay of Bengal during La-Niña Modoki years is low compared to that of canonical La-Niña years hence the intensification of cyclones is decreased over this basin during this period. It also results that there are no cyclones over Arabian Sea during La-Niña Modoki years.

[**Key words:** Tropical cyclones, Indian Ocean, La-Niña, La-Niña Modoki, Cyclogenesis parameters.]

Introduction

Arabian Sea (AS) and Bay of Bengal (BB) together named as the North Indian Ocean (NIO), which accounts for 7% of global tropical cyclones, furthermore, a great number of cyclones form in the BB than AS about four times higher¹. Cyclones are forming over these basins in two cyclone seasons, such as Pre-monsoon season (March-May) and Post-monsoon season (October- December). 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 do not show a dramatic rise despite increase over the Sea Surface Temperature (SST) in BB from 1951-2007 compared to the 1901-1951, this study further states that there is large decrease in the mid-tropospheric humidity over BB during the period 1951-2007 and the atmospheric parameters such as low-level vorticity, mid-tropospheric humidity and vertical wind shear, all play an important role on the genesis and intensification of storms over this basin.

Air-sea interaction processes like - , - and IOD (Indian Ocean Dipole) have significant impact on the cyclone activity over different ocean basins. The results suggest in most cases, - (enhances) the formation of cyclones over various basins. The ENSO events have significant impacts on the hurricane intensity³ and genesis locations⁴ of the tropical cyclones. There is a tendency toward less (more) tropical cyclones over the Atlantic basin during the - () years⁵. In the western north Pacific, there is a southeastward

(northeastward) shift of tropical cyclone activity - () years^{6, 7, 8, 9}.

There have been studies by various authors about - , La-Niña and - Modoki and their impacts on the formation and intensification of cyclones in various basins. Pradhan et.al (2011) showed co-occurrence of Positive IOD with - Modoki events can produce more cyclones over North West Pacific. Sumesh and Ramesh kumar (2013) showed that the frequency of tropical cyclones over AS is more during the co-occurrence of Positive IOD with - Modoki events than the co-occurrence of Positive IOD with - events. Scott et.al (2007) studied the weakening of walker circulation in the changing ENSO scenario. During - Modoki events the zonal SST gradients result in anomalous two-cell Walker Circulation over the tropical Pacific with high convective zones associated with high rainfall anomalies in the central Pacific during the - Modoki events. But just opposite situation prevails during La- Modoki events. The impact of - Modoki events on tropical cyclones is less studied.

- and - Modoki events are those air-sea interaction processes of anomalous warming and cooling of SSTs in different parts of tropical Pacific Ocean. The - event is defined by warmer than normal SSTs in the western tropical Pacific Ocean and cooler than normal SSTs in the eastern tropical Pacific Ocean¹³. And the - Modoki event is defined by the cooling over the central Pacific Ocean and flanked by warmer SST anomalies in both west and east along the equator^{14, 15}. During -

Modoki events, the two cell walker circulation results in two convective zones and associated high rainfall anomalies over the east and west tropical Pacific Ocean. The - Modoki and its climate impacts are different from those of - . The - Modoki event has significant impacts on the temperature and precipitation over many parts of the globe¹⁴. Cai and Cowan (2009) showed that - Modoki events can shift the convection zones towards west of the tropical Pacific Ocean, and it results in heavy rainfall over northwestern Australia, rather than over the east as in a conventional - a. This study further states that during an - Modoki event the tendency for lower Australian rainfall is far weaker.

Toshiaki Shinoda et.al (2011) have found two recent - Modoki events, by using an Index EMI2, it is defined as $EMI2 = [SST]A - 0.5[SST]C$, where [SST]A and [SST]C are the average SST anomalies over regions A (165°E-140°W, 10°S-10°N) and C (125°E-145°E, 10°S-20°N) respectively. He also used an Empirical Orthogonal Function (EOF) analysis of surface currents for the period 1993-2009 to find them. The results indicate that strong cyclonic (anticyclonic) circulation anomalies occur in the tropical western Pacific around 5°N-15°N during the 2004 (2000 and 2008) El Nino (La Nina) Modoki events and during the strong traditional El Nino (La Nina) events of 1997 (1998). The frequencies of tropical cyclones over various basins during - and - Modoki events are presented in the Tables 1 and 2 respectively.

| Years | West Pacific | East Pacific | Atlantic | South Indian |
|------------------|--------------|--------------|------------|--------------|
| 1981 | 29 | 15 | 22 | 29 |
| 1984 | 30 | 21 | 20 | 32 |
| 1988 | 26 | 15 | 12 | 21 |
| 1998 | 27 | 16 | 14 | 37 |
| 1999 | 33 | 14 | 16 | 33 |
| 2005 | 25 | 17 | 15 | 26 |
| Total (per year) | 170 (28.33) | 98 (16.33) | 99 (16.50) | 178 (29.66) |

Table. 1-Cyclones formed over various basins during La-Niña years

| Years | West Pacific | East Pacific | Atlantic | South Indian |
|------------------|--------------|--------------|-----------|--------------|
| 2000 | 37 | 21 | 18 | 19 |
| 2008 | 27 | 20 | 17 | 22 |
| Total (per year) | 64 (32.0) | 41 (20.5) | 35 (17.5) | 41 (20.5) |

Table. 2- Cyclones formed over various basins during La-Niña Modoki years

Materials and Methods

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) this is the product of three dynamic parameters as well as three thermodynamic parameters, such as 1. *Low level relative vorticity*, 2. *Coriolis parameter*, 3. *Inverse of the vertical shear of the horizontal wind between lower and upper troposphere*, 4. *Ocean thermal energy or sea surface temperature above 26°C to a depth of 60m*, 5. *Vertical gradient of equivalent potential temperature between surface and 500mb*. 6. *Middle tropospheric relative humidity*. McBride (1981) and 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 formations 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-N .

Zehr (1992) proposed a parameter known as Genesis Parameter (GP), which is the product of three dynamical parameters such as low level relative vorticity at 850 hPa, negative of low level divergence at 850 hPa (for low level convergence) and vertical wind shear co-efficient. GP is expressed in units of $10^{-12}S^{-2}$. His study showed that this genesis parameter was useful in differentiating between the non-developing and developing systems in the western North Pacific. This study²⁵, also found the threshold values for these parameters which are favorable for the formation of a cyclone, such as Low Level Relative Vorticity at 850 hPa is $(1.05)10^{-5}S^{-1}$, Low Level Convergence at 850 hPa is $(0.33)10^{-5}S^{-1}$ and Vertical Wind Shear Co-efficient is $(10.3)ms^{-1}$. In this present paper we are using these threshold values of dynamic parameters for the cyclones over north Indian Ocean.

Roy Bhowmic (2003) used this genesis parameter to study the developing and non-developing systems over NIO, and observed GP values around $(20.0)10^{-12} S^{-2}$ against T-No: 1.5 has the potential to develop into a severe cyclonic storm. Kotal et al. (2009) introduced a genesis parameter 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 vertical wind shear. Result shows that there is a distinction between GPP values for nondeveloping and developing systems in more than 85% cases. Composite GPP value is found to be around three to five times greater than for developing systems than for nondeveloping systems. In this study we are using the Zehr's genesis parameter (GP) and the Thermo-dynamic parameters defined by Gray (1975) and George (1960) to discuss the dynamic as well as Thermo-dynamic features of the cyclones over NIO. According to Gray (1975) the thresholds for Mid Tropospheric Relative Humidity variable (M) is 40%, and if the magnitude of Mid Tropospheric Instability Parameter (I) is greater than 23°C there are more chances for the intensification of cyclones. We keep these values as thresholds for the thermo-dynamic parameters.

The cyclogenesis parameters are

LLRV = low level relative vorticity at 850 hPa

LLC = low level convergence at 850 hPa

(Negative of low level divergence at 850hPa)

(VWSC) Vertical Wind Shear Coefficient = $\{[25.0 - VWS]/20\}$

MTRH = Mid Tropospheric Relative Humidity (M) = $\frac{[RH-40]}{30}$

$$30$$

(Where RH is the mean Relative Humidity between 700 and 500 hPa)

MTI= Middle Tropospheric Instability (the temperature difference between 850 and 500 hPa)

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

We have prepared the composite anomalies of all the variables namely Low Level Relative Vorticity (LLRV) at 850hPa, Low Level Convergence (LLC) at 850hPa, Vertical Wind Shear Coefficient (VWSC), Mid Tropospheric Relative Humidity (MTRH) and the Mid Tropospheric Instability (MTI), using NCEP/NCAR Re-Analysis -II daily data. All the

parameters are averaged with the cyclone days, and studied the variations of these parameters for the cyclones during the pre-monsoon and post-monsoon seasons of - and - modoki years. We have obtained the cyclone frequencies for various basins from the Unisys Weather (<http://weather.unisys.com/hurricane/>). The genesis locations of all the cyclones (black dots) during 1979 to 2010 are obtained from the cyclone e-Atlas prepared by India Meteorological Department (IMD).

Results

There were 6 - and 2 - Modoki years during the study period (1979-2010). We have compared the frequencies of tropical cyclones formed over various basins, namely West Pacific, East pacific, Atlantic and South Indian

- and - Modoki years. Frequencies and per year values for each basin are listed in Tables (1&2). The frequencies and per year values of tropical cyclones formed over NIO during these periods are also presented in Table (3&4). From Table (1&2) it is clear that the frequency of the tropical cyclones are more in the Pacific Ocean during - Modoki years compared to the canonical - years. But it is more in Atlantic and South Indian basin during the La- years compared to the La- Modoki years. In NIO the frequencies of cyclonic storms and severe cyclonic storms show significant variations during these periods. Over BB the number of cyclonic storms is more (less) during La- Modoki (canonical La-) years. And the number of severe cyclonic storms is more (less) during canonical La- (La- Modoki) years. There were very fewer cyclones formed over the AS during the canonical - years and no cyclones formed over AS during - Modoki years. Our present study with a limited period data (1979 - 2010) suggests that the - Modoki events are not favourable for the formation of tropical cyclones over AS.

| Years | Arabian Sea | | Bay of Bengal | |
|------------------|-------------|-----------------|---------------|-----------------|
| | Cyclones | Severe cyclones | Cyclones | Severe cyclones |
| 1981 | 0 | 1 | 3 | 2 |
| 1984 | 0 | 0 | 0 | 3 |
| 1988 | 0 | 0 | 1 | 2 |
| 1998 | 1 | 2 | 0 | 3 |
| 1999 | 0 | 1 | 1 | 2 |
| 2005 | 0 | 0 | 4 | 0 |
| Total (per year) | 1 (0.16) | 4 (0.66) | 9 (1.5) | 12 (2.0) |

Table. 3-Cyclones formed over NIO during La-Niña years

| Years | Arabian Sea | | Bay of Bengal | |
|------------------|-------------|-----------------|---------------|-----------------|
| | Cyclones | Severe cyclones | Cyclones | Severe cyclones |
| 2000 | 0 | 0 | 2 | 2 |
| 2008 | 0 | 0 | 2 | 1 |
| Total (per year) | 0 | 0 | 4 (2.0) | 3 (1.5) |

Table. 4-Cyclones formed over NIO during La-Niña Modoki years

There have been 6 La-Niña and two La-Niña Modoki years during the study period. We have taken the frequencies of all the cyclonic storms and severe cyclonic storms over NIO during these periods. Figure 1: shows that the frequencies of cyclonic storms and severe cyclonic storms over NIO during the La-Niña Modoki years. There were no cyclones over AS during this period. This means that the formation of cyclones and severe cyclones are suppressed over AS during the La-Niña Modoki years. But there were a good number of cyclones and severe cyclones over BB. Furthermore the number of cyclones is reduced over BB during La-Niña Modoki years than the La-Niña years. During the La-Niña years, the warm surface water spreads from west to east; hence the region of atmospheric convection can also shift from west to east. This creates low magnitude of LLC over the West Pacific and BB Region, hence the frequency of tropical cyclones are reduced over BB during the La-Niña years. During the La-Niña Modoki years convection remains in the western pacific region since it is blocked by the cool SST over the central Pacific Ocean, so the magnitude of convection will be more over western Pacific Ocean and BB. Hence the frequencies of tropical cyclones over BB are found to be high during the La-Niña Modoki years. Results show that the magnitude of LLC is found to be low during La-Niña Modoki years than canonical La-Niña years; this is not a favorable condition for the intensification of cyclones. It results that the frequency of severe cyclones is less in BB during La-Niña Modoki years.

Discussion

The number of cyclonic storms that formed over AS is very less compared to that of Severe Cyclonic Storms (Table.3). There have been 1 cyclonic storm and 4 severe cyclonic storms out of 6 La-Niña years. While over BB there have been 9 cyclonic storms and 12 severe cyclonic storms during the La-Niña years. The ratios represent the frequency of tropical cyclones per year. From the ratios it is clear that there are more severe cyclones than cyclones over both basins. During La-Niña years there is large scale extended zonal

convergence over the western Pacific Ocean, which is very close to BB basin, and there is a high probability for the intensification of cyclone to severe cyclone over BB during La-Niña years.

There are no cyclonic storms and severe cyclonic storms formed over AS during the La-Niña Modoki years (Table.4). From this table it is clear that the La-Niña Modoki events are not conducive for the formation of Cyclonic storms and Severe Cyclonic Storms over AS. And it is also states that there are more cyclonic storms than severe cyclonic storms over BB during this period. But the intensification of tropical cyclones has decreased during this period. During La-Niña Modoki years the walker circulation is splitting in to two. The large scale zonal convergence gets blocked by the divergent anomalies over the central Pacific Ocean. During this period the zonal convergence are concentrating in a limited area. Because of this divergence the magnitude of ascending limbs are not that high. Over NIO these convection anomalies are concentrating over BB. The magnitudes of MTI, MTRH and LLRV are also found to be very low during this period that is why there are no cyclones over AS over La-Niña Modoki years.

Combined Figures 2&3, shows the variations of parameters over AS and BB during La-Niña years. There have been 5 cyclones during this period. From (Fig. 2a) it is observed that 4 cyclones out of 5 have crossed the threshold for MTI (23°C), this means MTI is a conducive parameter for the formation of cyclones over AS during this period. From (Fig. 2b) it is observed that no cyclones have crossed threshold for MTRH (40%, or $M=0$). All the cyclones have formed against small magnitudes of MTRH; this means that MTRH is not conducive for the formation of cyclones over AS during this period. From (Fig. 2c) it is observed that 3 cyclones out of 5 have crossed the threshold for LLRV and other two cyclones are formed against LLRV around $(0.5)10^{-5}\text{S}^{-1}$, this means that LLRV is conducive for the formation of cyclones over AS during this period. From (Fig. 2d) it is observed that only two cyclones have crossed the threshold for LLC, all the other cyclones have formed against small magnitudes of LLC, this means LLC is not conducive for the formation of cyclones over AS during this period. From (Fig. 2e) it is observed that all the cyclones have formed against small magnitudes of VWSC, so it is clear that VWSC is a conducive parameter for the formation and intensification of cyclones over AS during the La-Niña years.

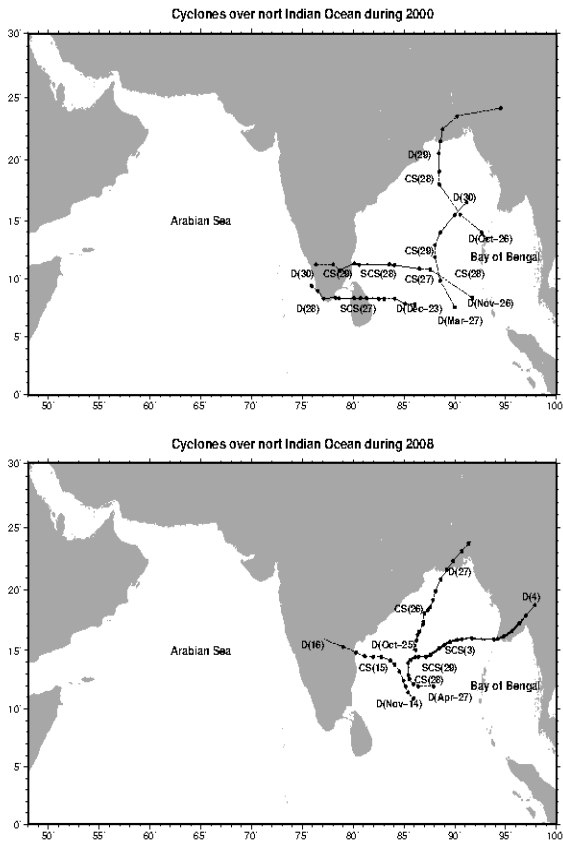


Figure 1-Tropical cyclones formed over NIO during La-Niña Modoki years

From (Fig. 3a), it is observed that all the cyclones have crossed the threshold for MTI and this means that MTI is a conducive parameter for the formation of cyclones over BB during this period. From (Fig. 3b) it is observed that, except two all the cyclones have crossed the threshold for MTRH and they have formed against large magnitudes of MTRH, so it is clear that MTRH is a conducive parameter for the formation and intensification of cyclones over BB during this period. From (Fig. 3c) it is observed that only 5 cyclones have crossed the threshold for LLRV, 3 cyclones have formed against LLRV below $(0.0)10^{-5}S^{-1}$, and all the other cyclones have formed LLRV between $(0.0 - 0.5)10^{-5}S^{-1}$. This means that LLRV is not a conducive parameter for cyclones over BB during this period. From (Fig. 3d) it is observed that no cyclones have crossed the threshold for LLC. This means LLC is not a conducive parameter for the cyclones over BB during this period. From (Fig. 3e) it is observed that all the cyclones have formed against small magnitudes of VWSC, and it is clear that VWSC is a conducive parameter for the formation and intensification of cyclones over BB during the La-Niña years.

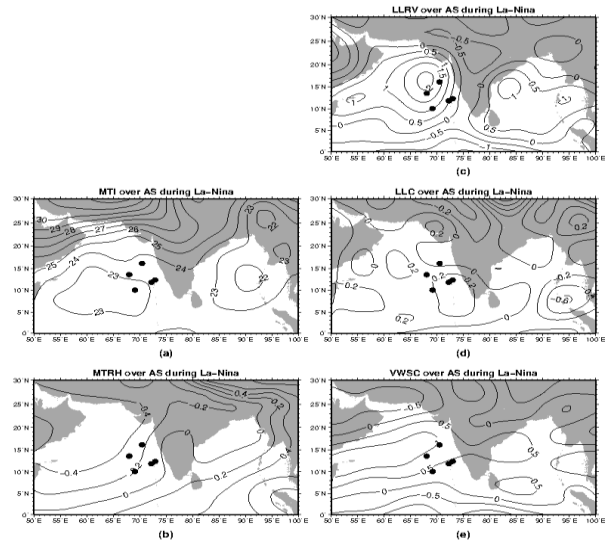


Figure 2-Variations of parameters over Arabian Sea during La-Niña years

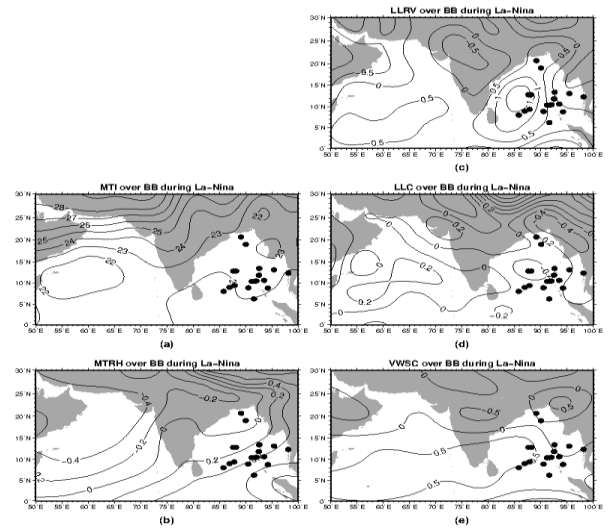


Figure 3-Variations of parameters over Bay of Bengal during La-Niña years

Figure 4, shows the variations of parameters over BB during La-Niña Modoki years. From (Fig. 4a), it is observed that all the cyclones have formed above the threshold for MTI and this means that MTI is a conducive parameter for the cyclones over BB during this period. And from (Fig. 4b), it is observed that except one cyclone all the cyclones have crossed the threshold for MTRH, MTRH is found to be conducive for the formation of cyclonic storms over BB during La-Niña Modoki years. From (Fig. 4c), it is found that, out of 7 cyclones 2 cyclones have crossed the threshold for LLRV, 3 cyclones formed at an LLRV between $(0.0 \text{ to } 0.5)10^{-5}S^{-1}$, and only one cyclone formed at LLRV below $(0.0)10^{-5}S^{-1}$. The magnitudes of LLRV are found to be very low during La-Niña Modoki years compared to La-Niña years. From (Fig. 4d), it is found that, two cyclones have crossed the threshold for LLC. Out of 7 cyclones 2 cyclones have formed at LLC between $(-0.2 \text{ to } -$

$0.4)10^{-5}S^{-1}$, 2 cyclones have formed between $(-0.2$ to $0.0)10^{-5}S^{-1}$, and 3 cyclones have formed above LLC $(0.0)10^{-5}S^{-1}$. The magnitude of LLC over BB is found to be very low during La-Niña Modoki years, this results that the convergence over BB during La-Niña Modoki years is less than that of canonical La-Niña years. That is why the number of cyclones over BB during La-Niña Modoki years is less compared to the number of cyclones over BB during the canonical La-Niña years. From (Fig. 4e), it is found that the magnitude of VWSC is very low during La-Niña Modoki years, all the cyclones have formed at VWS between $(0.0$ to $0.5)m s^{-1}$.

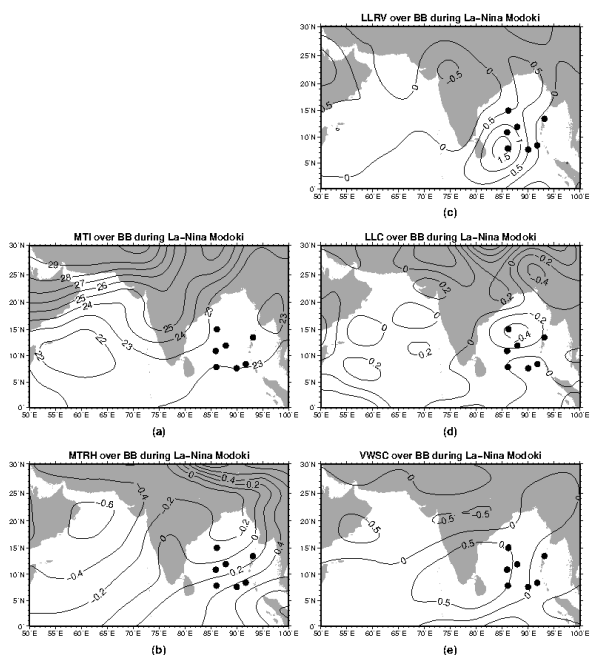


Figure. 4-Variations of parameters over Bay of Bengal during La-Niña Modoki years

Conclusion

The Air-Sea interaction processes such as La- and - modoki events have significant impacts on the tropical cyclones over NIO. The present study results that, in BB the frequencies

And the frequencies of severe cyclonic storms are more during canonical - Modoki years. It also results that, the - modoki events are not conducive for the formation of cyclones over AS. Results show that, over BB there is a reduction in the magnitude of LLC, during La-Niña Modoki years compared to the canonical La-Niña years; this suppresses the formation of severe cyclonic storms. And over AS low magnitudes of MTI, MTRH and LLRV suppresses the formation of cyclonic storms during La-Niña Modoki years. Results of our study are for

a limited period only (1979 – 2010) and cannot be generalized.

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