Chapter 4

Interannual Variations of Tropical Cyclone Activity over the North Indian Ocean

4.1 Introduction

For the Indian Ocean basin, inter-annual climate variability is highly influenced by ENSO. Variability of Indian summer monsoon rainfall (ISMR) in interannual timescales is modulated by ENSO (Sikka, 1980; Pant, 1981; Ashok et al, 2001) although the relationship varies between decades (Kumar et al, 1999). Indian Ocean Dipole (IOD) (Saji et al, 1999), which is another mode of interannual variability in Indian Ocean, characterized by east-west SST anomaly over Indian ocean is highly related with ENSO. A large percentage of positive IOD (negative IOD) years are El Nino (La Nina) years (see table 4.1). Available literature on ENSO-tropical cyclone interaction over North Indian Ocean is mainly concentrated on the Bay of Bengal cyclones during the post-monsoon (October-December) season (Gupta and Muthuchami, 1991; Ng and Chan, 2011; Girishkumar and Ravichandran, 2012). Gupta and Muthuchami (1991) observed that during El Nino years tropical cyclones formed over Bay of Bengal landfalls south of 17°N and the numbers of these storms are highly correlated with the southern oscillation indices. Singh et al (2000) found that the frequency of tropical cyclones in North Indian Ocean during May and November reduces during warm phases of ENSO. Ng and

Chan (2011) showed that apart from the local SST, moist static energy and atmospheric flow patterns forced by ENSO modulates the interannual variability of tropical cyclones over Bay of Bengal during the post-monsoon season. Using 30 years of IBtRACS cyclone data, interannual variations in genesis region, direction of movement and intensity of post monsoon (October-December) tropical cyclones over north Indian Ocean basin associated with ENSO is analysed.

4.2 Methodology

Interannual variation in these cyclones have been studied with respect to, El Nino and La Nina of the years 1979 to 2008. The monthly Nino 3.4 SST indices obtained from the NOAA Climate Prediction Center (CPC) website are used for defining the El Nino and La Nina years, and are listed in table 4.1. The positive/negative IOD years obtained from JAMSTEC website are also listed in 4.1. El Nino (La Nina) years are defined such that the October-December averaged SST anomaly of the region is above (below) a value of 0.5. Thus the years 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004 and 2006 are considered as El Nino-0 years and 1983, 1984, 1988, 1995, 1998, 1999, 2000, 2005 and 2007 years are considered as La Nina years. Thus we have 9 years each of El Nino and La Nina in the 30 years 1979 to 2008. El Nino spans two consecutive years, the first year of which (warming phase) is called El Nino-0 year.

The tropical cyclone Genesis Potential Index (GPI) developed by Emmanuel and Nolan (2004) is used in the study. Camargo et al (2007) subsequently used this index to analyse the effects of ENSO on GPI over the global ocean basins. The GPI is given by

$$GPI = \left|10^5\eta\right|^{3/2} \left(\frac{H}{50}\right)^3 \left(\frac{V_{max}}{50}\right)^3 (1 + V_{shear})^{-2} \tag{4.1}$$

where η is the absolute vorticity at 850 hPa , H is the relative humidity at 600 hPa in percent, V_{max} is the potential intensity Emanuel (1995), and V_{shear} is the magnitude of the VWS between 850 hPa and 200 hPa. The value of V_{max} is calculated as

Table 4.1: List of years when El Nino or La Nina and/or negative or positive IOD occured.

Year	El Nino/La Nina	PIOD/NIOD
1979	-	-
1980	-	NIOD
1981	-	-
1982	El Nino	PIOD
1983	La Nina	-
1984	La Nina	NIOD
1985	-	-
1986	El Nino	-
1987	El Nino	PIOD
1988	La Nina	-
1989	-	-
1990	-	-
1991	El Nino	PIOD
1992	-	NIOD
1993	-	-
1994	El Nino	PIOD
1995	La Nina	-
1996	-	NIOD
1997	El Nino	PIOD
1998	La Nina	NIOD
1999	La Nina	-
2000	La Nina	-
2001	-	-
2002	El Nino	PIOD
2003	-	PIOD
2004	El Nino	-
2005	La Nina	NIOD
2006	El Nino	PIOD
2007	La Nina	-
2008	-	-

$$V_{max} = \sqrt{\frac{T_S}{T_0} - \frac{C_K}{C_D}\left(CAPE^* - CAPE\right)_m} \tag{4.2}$$

where T_S is the SST, T_0 is the mean outflow temperature (temperature at the level of neutral buoyancy), C_K is the exchange coefficient for enthalpy, C_D is a drag coefficient, CAPE* is the convective available potential energy of air lifted from saturation at sea level in reference to the environmental sounding, and CAPE is that of boundary layer air.

For analyzing the parameters related to the tropical cyclones, several parameters such as 850 hPa wind, 850 hPa vorticity, 200 hPa wind, 200 hPa divergence, SST and GPI are composited and analysed. Anomalies of these parameters are computed with respect to a climatological field, which is an averaged field of the season (October-December) from 1979 to 2008.

4.3 Results and discussion

4.3.1 Changes in lower tropospheric circulation

The ENSO is characterized by easterly-westerly fluctuations in the lower troposphere wind over the equatorial Pacific. During a La Nina year or a normal year, large area of warm water over the Western Pacific causes the wind to converge over this region, which becomes the upward limb for Indian Ocean and Pacific Walker cell. During this time, lower tropospheric winds are westerly over the Indian Ocean and easterly over the equatorial Pacific. As the westerly wind flow is established in equatorial Indian Ocean, it enhances cyclonic vorticity north and south of this flow. This will create an increase in cyclonic vorticity over the cyclogenesis region over North Indian Ocean since it is in the wind shear region of these winds. In order to analyse the lower tropospheric circulation patterns, 850 hPa wind and vorticity are composited for El Nino-0, El Nino-1, El Nino+1 and La Nina years.

The changes in lower tropospheric Indian Ocean Walker circulation patterns and their anomalies associated with ENSO are depicted in figure 4.1. During El

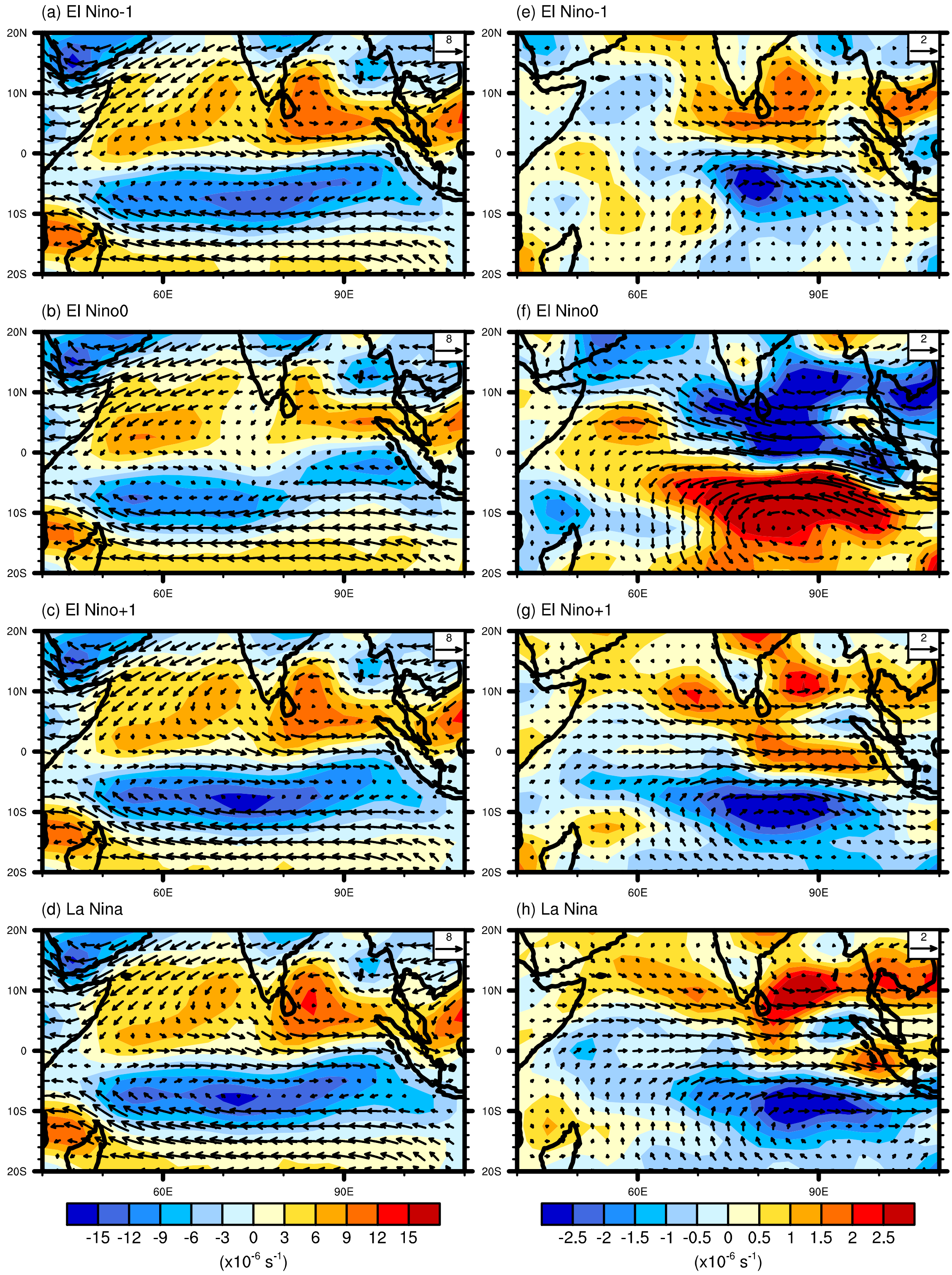

Figure 4.1: Composites of circulation and vorticity patterns and their anomalies associated with different phases of ENSO a) El Nino-1 b) El Nino-0 c) El Nino+1 and d) La Nina years.

Nino-1, El Nino+1 and La Nina years there is strong westerly wind flow over the equatorial Indian Ocean as can be seen from figure 4.1a, 4.1c, 4.1d. There is strong cyclonic vorticity over the North Indian Ocean especially in Bay of Bengal. The anomalous wind and vorticity field also shows the same features. There is strong westerly anomaly and associated increase of the cyclonic vorticity over Bay of Bengal during the non El Nino years. During the El Nino-0 years the convection is shifted to the central Pacific Ocean changing the normal circulation patterns in the whole Indo-Pacific region. Along with this shift, the upward limb of the Walker circulation over the north Indian Ocean shifts to the central Indian Ocean. These changes are depicted in figure 4.1b,4.1f where the reduction in the westerly wind and associated decrease in cyclonic vorticity over the Indian ocean are shown. The anomalies of wind and vorticity also shows the same signal in which a large negative vorticity anomaly region in over the Bay of Bengal. Thus the decrease in the available vorticity for the cyclogenesis is reduced considerably during the El Nino-0 years which lead to the reduced cyclogenesis over the region. Most of the El Nino-0 years are positive IOD years which further reduces the magnitude of the lower tropospheric westerlies over the region.

4.3.2 Changes associated with cyclogenesis

In order to differentiate the general characters of tropical cyclones between El Nino and non El Nino years, composites of tracks are made and analysed.The tropical cyclone tracks composited shows large differences in basic characteristics such as genesis, tracks and intensity of a tropical cyclone during the El Nino and non El Nino years. Figure 4.2 gives the composite of genesis points and tracks of tropical cyclones during October to December for El Nino-1, El Nino-0, El Nino+1 and La Nina years. The first reported point of the cyclone is given as black dot and the colour of the track represents maximum intensity reached by a cyclone. Cyclones are grouped into four categories; Cyclonic storms (CS) (34 to 47 knots), severe cyclonic storms (SCS) (48 to 64 knots), very severe cyclonic storms (VSCS) (64 to 119 knots) and super cyclonic storm (SUCS) (above 119 knots) based on the maximum intensity following IMD classification for Indian Ocean.

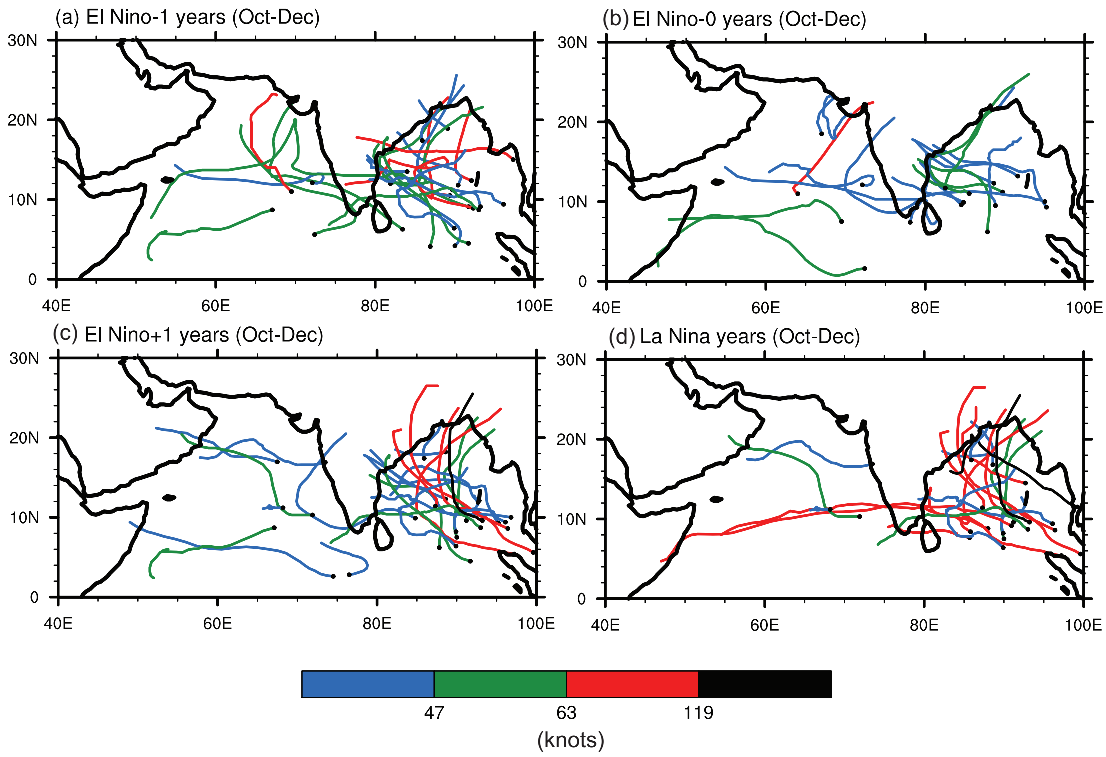

Figure 4.2: Cyclogenesis points and tracks associated with a) El Nino-1 years b) El Nino-0 c) El Nino+1 and La Nina years. The different colours in tracks represent the different intensity categories of the storm.

From figure 4.2, it can be seen that the tropical cyclone activity over the North Indian Ocean basin in comparatively low during the El Nino-0 years. Also the genesis region shifts westward during the El Nino-0 years which is consistent with the result from Girishkumar and Ravichandran (2012). During El Nino-1 and El Nino+1 and La Nina years, cyclone genesis is distributed over the entire Bay of Bengal region. But during El Nino-0 years, cyclogenesis are more constrained in the southern Bay of Bengal as seen from figure 4.2c. Camargo et al (2007) observed that there is a shifting of GPI from northern Bay of Bengal to southern Bay of Bengal during El Nino-0 years. They attributed these changes to the variations in wind shear. The genesis character over the Arabian Sea does not show much change over the years. The variations in GPI associated with ENSO will be discussed in detail on later sections.

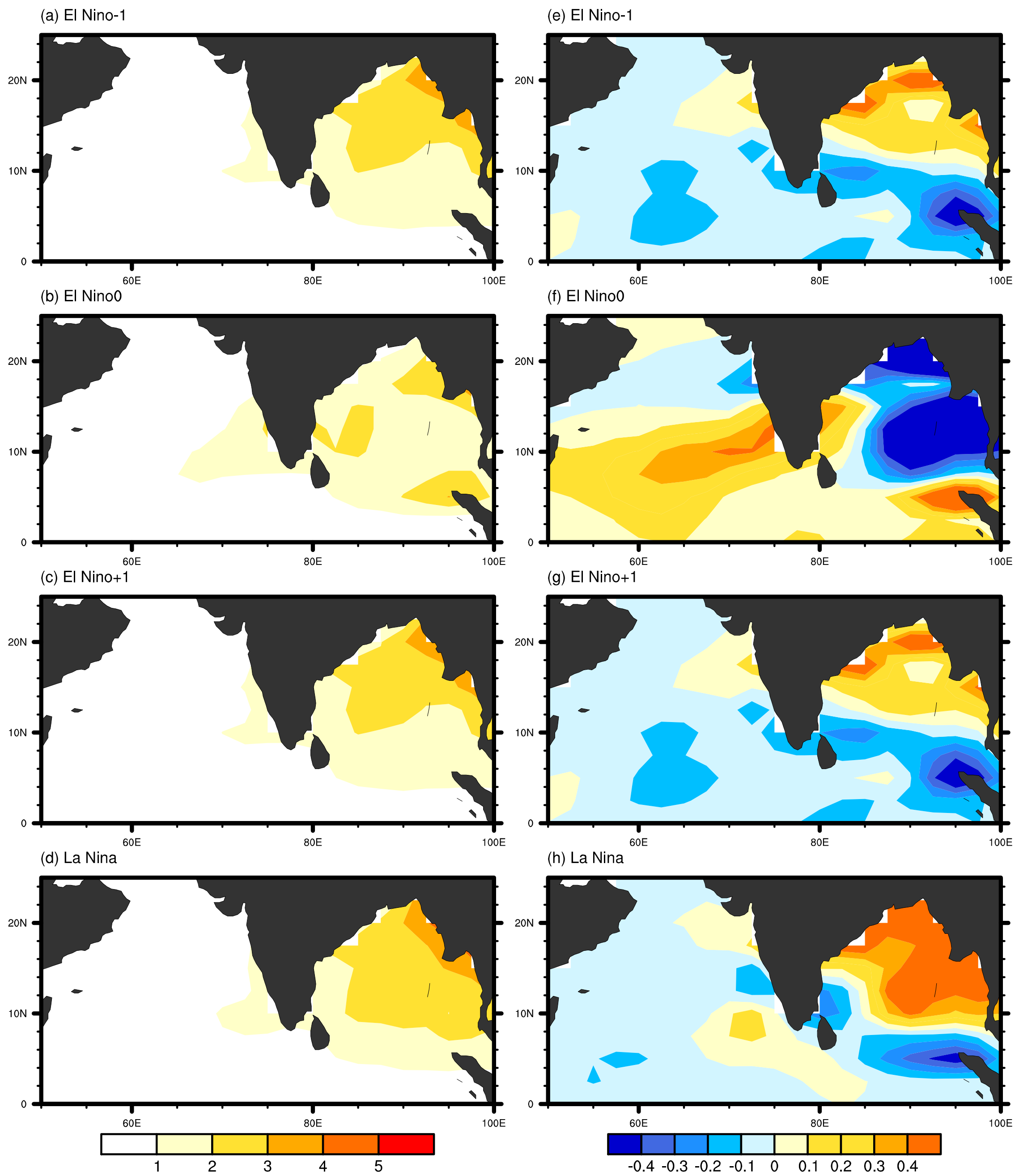

Figure 4.3: Composite GPI patterns and their anomalies associated with different phases of ENSO a) El Nino-1 b) El Nino-0 c) El Nino+1 and d) La Nina years.

4.3.3 Changes in genesis potential index

The variation in the mean genesis regions are analysed using a genesis potential index calculated from the environmental parameters. Camarago et al (2007) used this index to study the ENSO related variations in tropical cyclone genesis around the globe. Menkes et al (2012) evaluated the performance of four cyclogenesis indices in different ocean basins and found that genesis potential calculated by Emmanuel and Nolan (2004) and Tippett et al (2011) are best adjusted indices for North Indian Ocean.

The October-December GPI is composited for different phases of ENSO. Figure 4.3 depict the changes in the genesis potential index and its anomaly associated with the El Nino-1, El Nino-0, El Nino+1 and La Nina years. During El Nino+1 and La Nina years, high values of GPI are available over the North Indian Ocean especially over the Bay of Bengal region. Although there are positive GPI values over Bay of Bengal during El Nino-0 years, the values are much less compared with the La Nina years especially over the northern Bay of Bengal. The composite anomalies of GPI are given in figure 4.3e to 4.3f. During El Nino-0 years large area of negative GPI anomaly is over the Bay of Bengal. Thus the reduced cyclogenesis potential during El Nino-0 is causing the reduction in tropical cyclone activity. For La Nina years the entire pattern is opposite and there is a high value of positive GPI anomaly over Bay of Bengal. From both El Nino-0 and La Nina events it can be seen that the area of activity is enhanced over the western Bay of Bengal which explains the shift in the cyclogenesis area.

The reasons for the reduction in GPI during El Nino-0 years is examined by considering the individual parameters used for calculating the GPI. Relative contributions of each of the 4 parameters used in GPI are examined by the method given in Camarago et al (2007). For each variable, the relative contribution is analysed by recalculating GPI, taking actual varying values of one variable and for other 3 variables, long-term unvarying monthly climatological fields are used. The procedure is then repeated for all the variables. The relative contributions of the four variables are composited for El Nino-0 and non El Nino years. For all the parameters the composite anomaly for El Nino-0 and La Nina years are depicted in figure 4.4. Of the thermodynamic parameters, 600 hPa relative humidity shows a maximum (minimum) over the eastern Bay of Bengal during the La Nina (El Nino-0) years. Maximum potential intensity parameter has not much variability between the periods. The relative contribution of vorticity at 850 hPa is showing a positive (negative) anomaly in Bay of Bengal during La Nina (El Nino-0) years. This is due to the reduced 850 hPa vorticity over Bay of Bengal during the El Nino years. During El Nino-0 years, the relative contribution from VWS shows large positive values over the southern Bay of Bengal and Arabian Sea. This favorable condition during El Nino-0 years is due to the decrease in VWS since both the lower and upper tropospheric wind over Bay of Bengal weakens during the El Nino-0 years. Thus it is inferred that the large contribution from relative humidity and 850 hPa vorticity in the eastern Indian Ocean causes the shifting of genesis region during the El Nino-0 years. Also the southward shifting of VWS component during El Nino-0 years enhances the cyclogenesis over the southern Bay of Bengal which was also observed by Camarago et al (2007).

4.3.4 Changes in intensity

There is strong interannual variation in the intensity of North Indian Ocean cyclones as observed from figure 4.2. Intensity of tropical cyclones are reduced considerably during an El Nino-0 year compared with non El Nino years. The number of tropical cyclone in each intensity category which are formed in different phases of ENSO is given in table 4.2. The total number of tropical cyclones formed during El Nino-0 years are almost equal to the La Nina years with a difference of 4 tropical cyclones. The major difference is in the intensity during the El Nino-0 years since there is a significant decrease in the tropical cyclones with intensity above VSC category. During the El Nino-0 years 95% of cyclones (18 out of 19) formed are under the VSC category but during La Nina years it is only 52% (12 out of 23) and remaining 48% (11 out of 23) are above the VSC.

The maximum potential intensity estimated by Emmanuel (1994) does not consider dynamic influences like VWS which restricts the development of the storm. From the composites of MPI (not shown) it is observed that there are not much differences between the values during El Nino-0 and La Nina years. Also during the El Nino-0 years, VWS is favourable for cyclogenesis in North

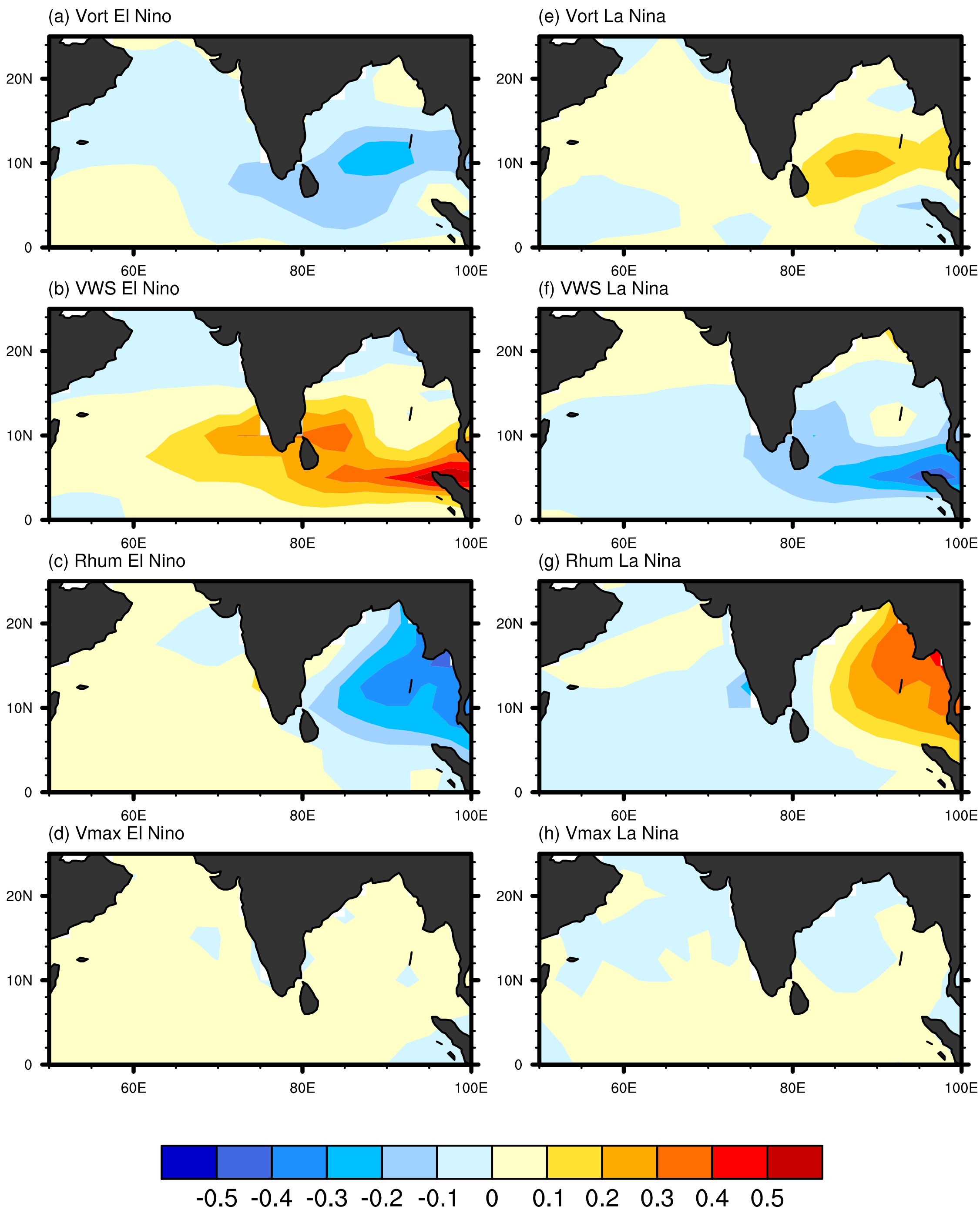

Figure 4.4: Anomalies in genesis potential index owing to the four parameters a) vorticity b) VWS c) relative humidity and d) potential intensity during El Nino-0 (left panel) and La Nina (right panel).

Table 4.2: The distribution of tropical cyclone intensity categories in the different phases of ENSO

Category	Total	CS	SCS	VSC	SUCS
El Nino-1	23	9	9	5	0
El Nino 0	19	12	6	1	0
El Nino+1	27	15	7	4	1
La Nina	23	8	4	9	2

Indian Ocean. Although VWS and thermodynamic MPI are favourable, there is a decrease in the intensity of tropical cyclones during El Nino-0 years. Since North Indian Ocean is bounded by land to the north, the change in the direction of tracks affects the intensity. This is more evident in Bay of Bengal since westward moving storms makes landfall faster than the northward moving storms. The genesis region during El Nino-0 years shifts to the eastern Bay of Bengal and the direction of movement is westward comparing with the northward moving tropical cyclones in non El Nino years. If we set 17°N as a threshold point for land fall, it is seen that most of the tropical cyclones make land fall below this in El Nino-0 years which is consistent with the observation of Gupta and Muthuchami (1991).

Tropical cyclones formed during La Nina years moves northward and makes landfall over north Bay of Bengal. As the tropical cyclones remains over the ocean for a long duration before the landfall, the intensity of the cyclones are increased. A similar type of intensification mechanism was observed in Western North Pacific by Emmanuel (2000) and Camarago et al (2007). Camarago et al (2007) found that although the potential intensity (Emmanuel, 1986) is less over the Western North Pacific, the increase in intensity of tropical cyclones during El Nino-0 years is due to the longer lifetimes that occur as a result of the eastward displacement in mean genesis location. Girishkumar and Ravichandran (2012) reported a similar intensification mechanism for Bay of Bengal cyclones. The shifting of genesis region is found to be caused by variations in vorticity, VWS and relative humidity.

4.4 Conclusion

The interannual variations in the genesis, intensity and tracks of the post-monsoon (October-December) north Indian Ocean tropical cyclones with respect to the ENSO are analysed using data of 30 years. It is observed that there is a reduction in the intensity and frequency of tropical cyclones formed over the north Indian Ocean during the El Nino-0 years compared with the non El Nino years. Due to the changes in circulation patterns associated with El Nino-0, the 850 hPa equatorial westerlies over the north Indian Ocean reduces considerably which in turn reduces the vorticity over the tropical cyclone genesis region. A southward shifting of the genesis region is observed during the El Nino-0 years along with a zonal shift towards east.

Analysis using a genesis potential index (GPI) shows that anomalous negative values of GPI exists over the northern Bay of Bengal during the El Nino-0 years which inhibit cyclogenesis over the region. The relative contribution of individual parameters are examined and it is found that low values of VWS over southern Bay of Bengal during El Nino-0 years favours the southward shift of genesis region. Vorticity and relative humidity parameters are found to be favourable for La Nina years and higher contributions of these parameters are responsible for the westward shift of mean genesis region over the Bay of Bengal. The tropical cyclone tracks are west bound during the El Nino-0 years compared with the northward moving tropical cyclones during La Nina, which is caused by the changes in upper tropospheric circulation patterns. Although the VWS is less favourable compared with El Nino-0 years, tropical cyclones during La Nina intensifies more since the duration of northward moving tropical cyclones over the oceanic region is more due to their northward motion.