ENSO influence on Bay of Bengal cyclogenesis confined to low latitudes

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1 ENSO influence on Bay of Bengal cyclogenesis 2 confined to low latitudes

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14 **Abstract.** The low-latitudinal cyclones (LLCs, originating between 5°N-10°N)
15 constitute $\approx 40\%$ of tropical cyclones (TCs) formed in the Bay of Bengal (BoB). We
16 investigate the interannual variability of post-monsoonal (October to December) BoB
17 LLCs and their teleconnection with El Niño Southern Oscillation (ENSO) and Indian
18 Ocean Dipole (IOD). It is found that the years with the fewer number of BoB LLCs
19 are associated with anomalous equatorial easterlies that are largely connected with
20 the El Niño and positive IOD. Likewise, equatorial westerly phases, often associated
21 with the La Niña and negative IOD years, favour the LLC formation by providing
22 the initial spin-up required for cyclogenesis. This teleconnection between ENSO and
23 BoB TC frequency is confined in the low-latitudinal region with little influence for
24 cyclogenesis north of 10°N during ENSO and IOD except during negative IOD. These
25 results may help extend the lead time and improve the seasonal prediction of BoB
26 TCs.

27 **Keywords:** Low Latitudinal Cyclones, Bay of Bengal, ENSO, IOD

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1. Introduction

Tropical cyclones (TCs) that occur in the Bay of Bengal (BoB) can cause substantial socio-economic damage and loss of life on densely populated coastal areas of the Indian subcontinent, resulting from strong winds, storm surge, and heavy rainfall (O'Hare, 2001, De et al., 2005, Hoarau et al., 2012, Needham et al., 2015). The increasing coastal population has led to a significant increase in cyclone-related losses (Emanuel, 2005). The major environmental factors that influence the genesis of TCs are the Coriolis parameter, relative vorticity, vertical wind shear, atmospheric stability, mid-tropospheric relative humidity, sea surface temperature (SST), and oceanic heat content (Palmen, 1948, Fisher, 1958, Gray, 1968, 1998). These environmental factors are favourable for TC genesis in the BoB during two seasons, viz., pre-monsoon (March-May) and post-monsoon (October-December) (Niyas et al., 2009). Depressions are active during the monsoon season (June-September), but TCs do not form easily in a sheared-environment (Krishnamurthy and Ajayamohan, 2010). The post-monsoon land falling cyclones are devastating to the coastal states of India and Bangladesh (Alam et al., 2003).

In the BoB, the TCs are categorized based on the maximum sustained wind (MSW; Mohapatra et al., 2012) as the following: depression (17-27 knots), deep depression (28-33 knots), cyclonic storm (CS, 34-47 knots), severe cyclonic storm (SCS, 48-63 knots), very severe cyclonic storm (VSCS, 64-89 knots), extremely severe cyclonic storms (ESCS, 90-119 knots), and super cyclonic storm (SuCS, ≥ 120 knots). The maximum number of SCSs and higher categories occur during the post-monsoon season (Mohapatra et al., 2012, table 1).

Despite the basin-wide warming over the north Indian Ocean during the recent decades (Webster et al., 2005, Rao et al., 2012, Kumar et al., 2016, Roxy et al., 2014), the frequency of BoB cyclones has not increased significantly (Bhardwaj and Singh, 2021, Deshpande et al., 2021). The future projections consistently indicate that global warming will increase the intensity of TCs around the globe (Knutson et al., 2010), including the BoB (Mittal et al., 2019). Observations indicate an increase in the frequency of VSCS in the BoB in recent years (Balaguru et al., 2014, Balaji et al., 2018, Deshpande et al., 2021). The amount of energy disbursed by the BoB cyclones has also increased in recent decades (Sahoo and Bhaskaran, 2016).

Apart from these long-term and seasonal changes in the BoB TC frequency, they also exhibit pronounced interannual variability related to natural climate modes. The SST anomalies in the equatorial Pacific during El Niño Southern Oscillation (ENSO) (Pan and Oort, 1983, Trenberth, 1997, McPhaden, 2002) events can remotely influence other oceans through Walker Circulation (Walker and Bliss, 1937). Similarly, the tropical Indian Ocean has a basin-wide variability termed the Indian Ocean Dipole (IOD; Saji et al., 1999). These two leading modes (ENSO and IOD) influence the interannual variability of BoB TCs (Camargo et al., 2007, Hoarau et al., 2012, Girishkumar and Ravichandran, 2012, Felton et al., 2013, Yuan and Cao, 2013, Mahala et al., 2015). La

Niña and negative IOD events are favourable for the severe cyclone activities in the BoB during the post-monsoon season (Girishkumar and Ravichandran, 2012).

The leading climate modes like ENSO and IOD modulate the ocean-atmosphere conditions in different latitudes of the BoB contrarily. This in turn, influences the TC genesis differently at different latitudes. Hence, the primary goal of this study is to understand the interannual variability in BoB-TCs at low (5° - 10° N) and high ($>10^{\circ}$ N) latitudes that are modulated by ENSO and IOD. Past studies on ENSO/IOD teleconnection with the BoB TCs (Girishkumar and Ravichandran, 2012, Felton et al., 2013) considered the TC variability in the entire BoB and may have missed the disparate changes in TC frequency with latitudes. In this study, we show that ENSO/IOD-modulated variability is confined to the frequency of low-latitude cyclones (LLCs, formed between 5° - 10° N) only, with no significant changes in the frequency of high latitude cyclones (HLCs, formed north of 10° N) during contrasting phases of ENSO/IOD.

The rest of the paper is organized as follows: Section 2 details the data and methods adopted for the analyses. The BoB-LLC and its association with two prominent interannual modes of climate variabilities in the Indo-Pacific Ocean (ENSO and IOD) are discussed in section 3. Major environmental factors driving the interannual variability of BoB-LLC are described in section 4. The dependence of BoB-LLC on the equatorial lower-tropospheric westerlies in the Indian Ocean is presented in section 5. Finally, we summarize the results in section 6.

2. Data and methods

The cyclone data from the Regional Specialized Meteorological Centre (RSMC, 2018) is used to determine genesis, location and frequency of cyclones in the BoB during 1979-2020 (Cyclone-eAtlas, 2011). The critical environmental parameters controlling cyclogenesis are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF)'s fifth-generation reanalysis dataset (ERA5, Hersbach et al. 2020). To identify positive and negative phases of ENSO (El Niño /La Niña), we used the Oceanic Niño Index (Trenberth, 1997). The Oceanic Niño Index (ONI) is calculated as the three-month running mean of SST anomalies in the Niño 3.4 region and is obtained from the Climate Prediction Center, National Oceanic and Atmospheric Administration (NOAA, <http://www.cpc.ncep.noaa.gov>). We selected the El Niño (La Niña) years in which the index is greater than (less than) or equal to 0.5°C (-0.5°C) for a minimum of four consecutive overlapping seasons. Dipole Mode Index (DMI) is used to identify the positive and negative phases of IOD (Saji et al., 1999). DMI is defined as the difference in the SST anomalies between the western Indian Ocean (50° - 70° E, 10° S- 10° N) and the southeastern Indian Ocean (90° - 110° E, 10° S- 0°). The DMI index is taken from the NOAA's Physical Sciences Laboratory https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/.

3. Results

3.1. Interannual variability of the Bay of Bengal LLCs and HLCs

During 1979-2020, out of 167 TCs formed in the north Indian Ocean, 48 formed in the Arabian Sea, and 119 formed in the BoB (table 1). The BoB is conducive for TC formation during the pre- and post-monsoon seasons and accounts for 71% of the north Indian Ocean cyclones (table 1). Out of all post-monsoon cyclones in the BoB, 33 (43%) of them were formed over the low latitudinal region (5° - 10° N), and 44 (57%) formed over the north of 10° N (figure 1). Out of the 33 LLCs, 24 (73%) further intensified into SCSs, likely due to their longer travel time over water, whereas, out of 44 HLCs, only 24 (55%) intensified into SCSs (figure 1).

The statistics of LLC and HLC frequency and its teleconnection with ENSO/IOD modes are summarized in table 2. Based on the oceanic Niño index (Trenberth, 1997), there were 12 El Niño and 11 La Niña years during 1979-2020. During El Niño years, the average number of HLCs is the same as its climatological mean (≈ 1 TC per year). In contrast, the average LLC number during El Niño years is reduced by 58% (0.33) from its climatological mean (0.79, table 2). In comparison, the LLC frequency is increased by 38% during the La Niña years. On average, the frequency of LLCs and HLCs is the same during the La Niña years (table 2). Although a 27% decrease in TC frequency during El Niño years and a 19% increase during La Niña years are visible in the total TCs formed over the BoB, the corresponding percentage departures are more in the LLCs (-58% and +38%, table 2).

Similarly, based on the dipole mode index (DMI) during the IOD peak season (September-November), there were 11 positive and 9 negative IOD years during the analysis period. The average frequency of LLC dropped by 42% during positive IOD years and increased by 41% during negative IOD years. The interannual variability in the frequency of LLCs is much more visible and significant than the frequency of the total TCs and HLCs developed over the BoB. The frequency of LLCs during El Niño and positive IOD are fewer than the climatological mean. On the contrary, the frequency of BoB LLCs is more than the climatological mean during La Niña and negative IOD years. The average number of HLCs during all categories of ENSO and IOD does not vary much (close to climatological mean) except for negative IOD. During Negative IOD years, the frequency of HLCs has increased by 38% from its climatological mean (table 2).

Although the frequency of LLCs shows association with ENSO and IOD variability, the intensity of LLCs does not show significant teleconnection. Around 70-83% of LLCs have intensified into SCSs and higher categories (figure 2). However, only 50-67% HLCs have intensified into SCSs and higher categories (figure 2). Overall, this analysis clearly shows that in the BoB, the reduction in TC frequency during El Niño and increase in TC frequency during La Niña is almost entirely due to changes in LLC frequency. The HLC frequency in different phases of ENSO remains nearly constant. For different phases of IOD, there is a change in HLC frequency as well, but the change in LLC

frequency is more prominent (figure 2 and table 2). This observation motivates us to find the underlying causes behind such latitudinal contrasts.

3.2. Environmental conditions responsible for interannual variability of LLCs

To explore the interannual variability in TC frequency in BoB, we analyse the critical environmental parameters that influence cyclogenesis during contrasting ENSO (figure 3) and IOD (figure 4) years. The anomalous SST does not show any significant difference during El Niño (figure 3(a)) or La Niña (figure 3(b)) years over the LLC genesis region (black rectangular box in figure 3). The SST over the LLC genesis region is $28.5^{\circ}\text{--}29^{\circ}\text{C}$ (figure 5(a)) which is much larger than the critical SST (26°C) needed for supporting TC genesis (Gray, 1968). The decline in the LLC frequency during El Niño (table. 2) cannot be attributed to an increase in SST. A mid-tropospheric relative humidity of 50-60% is often needed for the formation of cyclones by keeping an air parcel saturated during ascent (Gray, 1968, Thomas et al., 2014). The mid-tropospheric (700 hPa) relative humidity also increases over the genesis region of LLC during El Niño years (figure 3(c)), which cannot support a reduction in the LLC frequency. The vertical wind shear (between 200 and 850 hPa) in the low latitudinal region is significantly weak during El Niño years (figure 3(e)). This reduced wind shear ($\approx 6 \text{ ms}^{-1}$) is favourable for TC genesis since a critical wind shear of $\approx 10 \text{ ms}^{-1}$ is often considered supportive for TC development (Paterson et al., 2005). Therefore, low vertical wind shear during El Niño years may not limit LLC development.

The other critical factor for cyclogenesis at the low latitudes is relative vorticity (Roose et al., 2021). The ambient rotation (i.e., small Coriolis) is insignificant at the low latitudes. Once a storm forms in the low latitudes under a quieter planetary vorticity environment, it can spin-up faster and develop rapidly into cyclonic intensity than in higher latitudes with a higher Coriolis parameter environment (Bister, 2001, Li et al., 2012). This is because the air in the boundary layer can penetrate closer to the storm center over a weak planetary vorticity environment (DeMaria and Pickle, 1988). The El Niño composites show weakened relative vorticity anomalies compared to the climatological mean (figure 3(g)), supporting a reduction in LLCs frequency (table 2 and figure 2).

During the La Niña years, no significant change in the SST (figure 3(b)) and mid-tropospheric relative humidity (figure 3(d)) anomalies were observed over the low latitudinal region of the BoB. Both SST and mid-tropospheric relative humidity during La Niña years are smaller than El Niño years (figure 5(a,b)). There is an anomalous increase in vertical wind shear over low latitudes (figure 3(f)) and much larger than during El Niño years (figure 5(c)), which is also unfavourable for LLC formation. Contrary to El Niño composites, the anomalous relative vorticity increased significantly over the low latitudes during the La Niña years (figure 3(h), figure 5(d)). The increase in relative vorticity enhances the initial spin-up for the formation of LLCs in a weak planetary vorticity environment.

Similar conditions of El Niño and La Niña years occur during positive and negative IOD years. There is a significant increase in SST and mid-tropospheric relative humidity in the genesis location of LLCs during positive IOD years (figure 4(a, c)). The average values of SST ($\approx 28.5^\circ\text{C}$, figure 5a) and the relative humidity (65%, figure 5(b)) are clearly greater than their critical values for the formation of TCs, while the LLCs are noticeably fewer. As in the case of El Niño, the vertical wind shear in the low latitudes of BoB is reduced (figure 4(e)) during positive IOD years. The vertical wind shear of less than 10 ms^{-1} facilitates intensification of TCs, and values between 2 and 4 ms^{-1} favour significant intensification (Paterson et al., 2005). Therefore, the average vertical wind shear value of $\approx 6 \text{ ms}^{-1}$ over the genesis region of BoB LLC (figure 5(c)) during positive IOD years does not inhibit TC intensification. In a weak planetary vorticity environment, relative vorticity is the major factor for cyclogenesis. The weak lower tropospheric relative vorticity in the LLC genesis location during positive IOD (see figure 4(g) and figure 5(d)) reduces the LLC genesis (table 2).

During the negative IOD years, the SST and mid-tropospheric relative humidity were decreased over the low latitudinal region of the Bay of Bengal (figure 4(b,d)). However, the average values of the SST and mid-tropospheric relative humidity ($\approx 28.5^\circ\text{C}$ and 65%, figure 5(a,b)) are greater than their critical values for the formation of TCs. The vertical wind shear values greater than 11 ms^{-1} favour significant weakening of TC (Paterson et al., 2005). Even though the average vertical wind shear during negative IOD composite is $\approx 12 \text{ ms}^{-1}$ (figure 5(c)), the number of LLCs is more than the climatological mean (table 2 and figure 2). The increased LLCs during negative IOD years can be attributed to the increased absolute vorticity (figure 4(h), figure 5(d)). It is, therefore, evident that the relative vorticity plays a significant role compared to the other parameters responsible for TC genesis in the low latitudinal BoB region.

The distinct behavior of the factors responsible for cyclogenesis in the LLC and HLC region during the contrasting phases of ENSO and IOD are explored further. For example, the composite analysis reveals that the signs of mid-tropospheric relative humidity and vertical wind shear anomalies flip over the Bay of Bengal during positive/negative phases of ENSO and IOD (see figure 3(c,d,e,f) and figure 4(c,d,e,f)). The mean SST over LLC and HLC region during positive/negative phases of ENSO and IOD events are larger ($\approx 28.5^\circ\text{C}$) and sufficient for TC genesis (figure 5(a)). Compared to the HLC region, a large mid-tropospheric relative humidity is present in the LLC region (figure 5(b)); it could be a supporting factor for the intensification of LLCs (figure 2, 3). The average mid-tropospheric relative humidity over the LLC region is above 65% (figure 5(b)). The HLC region has a weak mid-tropospheric relative humidity of about 48% (figure 5(b)). Although the vertical wind shear over the LLC region shows a significant difference between positive and negative phases of ENSO/IOD, the vertical wind shear over the HLC region is close to its climatological mean ($\approx 9 \text{ ms}^{-1}$, figure 5(c)). Even though the relative vorticity significantly reduces over the LLC and HLC region (figure 3(h), 4(h)) during El Niño and positive IOD years, the reduction in the TC frequency is confined only to the LLC frequency (table 2) due to the weak Coriolis force

in low latitudes (figure 5(d)). This indicates the quintessential role of relative vorticity compared to the other three parameters during the contrasting phases of ENSO and IOD, especially over the genesis location of LLC (boxed region in figure 3(e,h), 4(e,h)). Next, we investigate the causes behind this change in relative vorticity.

3.3. Dependence of LLCs on equatorial winds

To understand the formation of unfavourable vorticity pattern for LLC genesis during El Niño and favourable pattern during La Niña years, we show the climatological mean winds (figure 6) that splashes a cyclonic gyre over the low-latitudinal region (5°-10°N) of the BoB during the post-monsoon season. We investigate how the contrasting ENSO/IOD phases modulate this cyclonic gyre since such a gyre can provide an initial spin-up for LLCs to form.

The equatorial winds (over the blue rectangular box in figure. 6(a)) at 850 hPa strongly correlate with the absolute vorticity ($r=0.91$) in the LLC region (black rectangular box in figure 6(a)) of BoB during the post-monsoon season (figure 7(a)). While most of the El Niño events fall in quadrant-III, most La Niña events fall in quadrant-I in figure 7(a) (also seen in figure 3(g,h)). It turns out that 92% of El Niño events are associated with the easterly phase of equatorial winds (figure 7(a)), and the rest are associated with very weak westerly winds. On the other hand, 80% of La Niña events are associated with the westerly phase of equatorial winds (figure 7(a)). In addition, 91% of the positive IOD years are associated with easterly phases of equatorial winds (figure 7(a)). In contrast, all negative IOD years in the analysis period are associated with the westerly phases. In a nutshell, fewer LLCs are associated with the easterly phases of equatorial winds during El Niño and positive IOD. In contrast, a higher number of LLCs are associated with the westerly phases during La Niña and negative IOD events (figure 7(b)).

The climatological westerly winds (figure 6(a)) in the equatorial Indian Ocean weaken during the El Niño and positive IOD years (figure 8(a,c)). This weakened westerly winds (figure 8(a,c)) during El Niño and positive IOD events reduce the absolute vorticity (figure 3(g), 4(g), 7(a)), which in turn affects the LLC genesis in the BoB. During the post-monsoon seasons of La Niña and negative IOD years, the anomalous equatorial westerly winds (figure 8(b,d)) increase the absolute vorticity over the low latitudes of the BoB (figure 3(f), 4(f), 7(a)). This increase in the absolute vorticity associated with stronger equatorial westerlies (figure 7(a)) enhances the formation of LLCs (figure 7(b)).

Even though the relative vorticity plays a decisive role in LLC formation, the vertical wind shear in the low latitudinal region also varies with the contrasting phases of ENSO and IOD. We further explored the reason behind changes in vertical wind shear over the low latitudinal region during opposite phases of ENSO/IOD. Climatologically, equatorial westerlies prevail in the lower troposphere, and easterlies stay in the upper troposphere during post-monsoon months (figure 6). Both the lower-level (850 hPa)

westerlies and upper-level (200 hPa) easterlies weaken during El Niño and positive IOD years (figure 9), resulting in the weakening of the vertical wind shear. Similarly, the enhanced vertical wind shear is caused by the strengthening of anomalous lower-level and upper-level equatorial westerlies during La Niña and negative IOD years (figure 9). Similarly, the enhanced vertical wind shear is caused by enhanced anomalous lower-level and upper-level equatorial westerlies during La Niña and negative IOD years (figure 9).

4. Summary and conclusion

We investigate the interannual variability of post-monsoonal cyclones, focusing on those formed in the low latitudes of the Bay of Bengal (BoB) during 1979-2020 and their teleconnection with El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The main conclusions of this study are:

- (i) Post-monsoon LLC frequency in the BoB significantly decreases during El Niño and positive IOD years. In contrast, the La Niña and negative IOD years are associated with increased post-monsoon LLC frequency (figure 7(b), table 2). In ENSO years, the modulation in TC frequency is confined to the low latitudes only, with no change in HLC frequency. During IOD years, there are changes in HLC frequency, but changes in LLC frequency still dominates.
- (ii) The modulation in relative vorticity was found to be the vital parameter responsible for the interannual variability in BoB LLCs (figure 3(g,h), figure 4(g,h)). The lower-tropospheric zonal winds determined this modulation in relative vorticity. The strong equatorial westerly winds in the Indian Ocean during the post-monsoon season create cyclonic circulation in the low latitudes of the BoB (figure 6) and builds up sufficient relative vorticity (figure 7a). During El Niño and positive IOD years, the climatological westerly winds in the equatorial Indian Ocean weaken (figure 7, figure 8), which reduces the relative vorticity in the BoB (figure 3(g), 4(g), 7(a)). On the other hand, the strengthening of equatorial westerlies enhances the relative vorticity in the low latitudinal region of the BoB during La Niña and negative IOD (figure 7(a)) years. The weakening of relative vorticity significantly reduces the genesis of LLC (figure 7(b)). The reduction in the frequency of TCs associated with the decrease in relative vorticity is confined only in the LLC genesis region under a weak planetary vorticity environment. However, the TC frequency over the HLC region was not significantly affected by the relative vorticity reduction under a stronger planetary vorticity environment compared to the LLC genesis region. These results may help extend the lead time and improve the seasonal prediction of BoB TCs.

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Table 1. Seasonal and annual frequency of TCs formed in the Arabian Sea, Bay of Bengal, and the entire north Indian Ocean during 1979-2020. The number of TCs intensified into SCSs, and higher categories are listed in the parentheses.

Season	Arabian Sea	Bay of Bengal	North Indian Ocean
Jan-Feb	0 (0)	4 (1)	4 (1)
Mar-May	9 (5)	27 (19)	36 (24)
Jun-Sep	16 (11)	11(2)	27 (13)
Oct-Dec	23 (15)	77 (48)	100 (63)
Annual	48 (31)	119 (70)	167 (101)

Table 2. The number of TCs in the Bay of Bengal during post-monsoon months (OND) that are formed over the low latitudes (LLC, formed between 5°N-10°N) and high latitudes (HLC, formed north of 10N) during different phases of ENSO and IOD during 1979-2020.

Year	Total BoB TC (per year)	LLC (per year)	HLC (per year)
All Years	1.83 (77TC/42yrs)	0.79 (33TC/42yrs)	1.05 (44TC/42yrs)
El Niño	1.33 (16TC/12yrs) ↓27%	0.33 (04TC/12yrs) ↓58%	1.00 (12TC/12yrs) ↓5%
La Niña	2.18 (24TC/11yrs) ↑19%	1.09 (12TC/11yrs) ↑38%.	1.09 (12TC/11yrs) ↑4%
Neutral ENSO	1.95 (37TC/19yrs) ↑6%.	0.89 (17TC/19yrs) ↑13%	1.05 (20TC/19yrs) ↑0%
PIOD	1.45 (16TC/11yrs) ↓21%	0.45 (05TC/11yrs) ↓42%	1.00 (11TC/11yrs) ↓5%
NIOD	2.55 (23TC/09yrs) ↑40%	1.11 (10TC/09yrs) ↑41%	1.44 (13TC/09yrs) ↑38%
Neutral IOD	1.72 (38TC/22yrs) ↓6%	0.82 (18TC/22yrs) ↑4%	0.91 (20TC/22yrs) ↓13%
Normal Years	1.73 (19TC/11yrs) ↓6%	0.82 (09TC/11yrs) ↑4%	0.91 (10TC/11yrs) ↓13%
(The “Normal Years” doesn’t include +ve/-ve IOD/ENSO.)

Figure 1. Number of cyclonic (CS) and severe cyclonic (SCS) storms formed over the low latitudes (LLC, originating between 5°N and 10°N) and high latitudes (HLC, originating north of 10°N) in the Bay of Bengal during the post-monsoon season (1979-2020).

Figure 2. Number of cyclonic storms (CS) and severe cyclonic storms (SCS) formed over the low latitudes (LLC, originated between 5°N-10°N) and high latitudes (HLC, originated in a latitude >10°N) of Bay of Bengal during post-monsoon seasons of El Niño, La Niña, positive IOD (PIOD) and negative IOD (NIOD) years during 1979-2020.

Figure 3. El Niño and La Niña composites of anomalous (a,b) sea surface temperature ($^{\circ}\text{C}$) (c,d) mid-tropospheric (700 hPa) relative humidity (%), (e,f) vertical wind shear between 850 and 200 hPa (ms^{-1}), and (g,h) low-level (850 hPa) relative vorticity ($\times 10^{-5} \text{s}^{-1}$) during post-monsoon season. Stippled areas represent regions where anomalies are significant at the 95% confidence level. The black rectangular area ($83^{\circ}\text{-}95^{\circ}\text{E}$, $5^{\circ}\text{-}10^{\circ}\text{N}$) denotes the genesis location of LLCs.

Figure 4. Positive and Negative IOD composites of anomalous (a,b) sea surface temperature (°C) (c,d) mid-tropospheric (700 hPa) relative humidity (%), (e,f) vertical wind shear between 850 and 200 hPa (ms⁻¹), and (g,h) low-level (850 hPa) relative vorticity (x10⁻⁵s⁻¹) during post-monsoon season. Stippled areas represent regions where anomalies are significant at the 95% confidence level. The black rectangular area (83°-95°E, 5°-10°N) denotes the genesis location of LLCs.

Figure 5. Post-monsoon season (a) sea surface temperature ($^{\circ}\text{C}$), (b) mid-tropospheric (700 hPa) relative humidity (%), (c) vertical wind shear between 850 and 200 hPa (ms^{-1}), and (d) low-level (850 hPa) absolute vorticity ($\times 10^{-5} \text{s}^{-1}$) averaged over the low latitudinal genesis region ($5^{\circ}\text{-}10^{\circ}\text{N}$, $83^{\circ}\text{-}95^{\circ}\text{E}$, under red shades), and high latitudinal genesis region ($10^{\circ}\text{-}20^{\circ}\text{N}$, $83^{\circ}\text{-}95^{\circ}\text{E}$, under green shades) during the contrasting phases of ENSO and IOD. The horizontal dashed lines indicate the mean values of four supportive parameters of TCs in LLC and HLC genesis regions.

Figure 6. Post-monsoon seasonal mean winds (ms^{-1}) at (a) 850 hPa, and (b) 200 hPa in the tropical Indian Ocean. The colour bars represent the magnitude of wind. The black rectangular area (83° - 95° E, 5° - 10° N) denotes the genesis location of BoB LLCs, and the blue rectangle (83° - 95° E 2.5° S- 2° 5N,) denotes the area over which equatorial winds are considered.

Figure 7. The relationship between equatorial wind anomalies and (a) low-level absolute vorticity, and (b) BoB LLC frequency. Both equatorial wind anomaly (2.5°S - 2.5°N , 83°E - 95°E) and absolute vorticity anomaly averaged over 5°S - 10°N , 83°E - 95°E are normalized by its own standard deviation. The El Niño, La Niña and neutral ENSO years are marked in red, blue and grey colours respectively. Years are labelled using arrows to the points. The linear trend is shown as the orange line, and the grey shading indicate 95% confidence level in panel (a).

Figure 8. Composite of 850hPa wind anomalies (ms⁻¹) that are statistically significant at 95% confidence level during the post-monsoon season of (a) El Niño, (b) La Niña, (c) positive IOD, and (d) negative IOD years during 1979-2020.

Figure 9. The relationship between vertical wind shear (850-200hPa) averaged over 5°S-10°N, 83°E-95°E, and (a) upper and (b) lower-level equatorial wind (2.5°S-2.5°N, 83°E-95°E). All variables are normalized by its own standard deviation. The El Niño, La Niña and neutral ENSO years are marked in red, blue and grey colours respectively. Years are labelled using arrows to the points. The linear trend is shown as the orange line, and the grey shading indicate 95% confidence level.