ENSO influence on Bay of Bengal cyclogenesis confined to low latitudes

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

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INTRODUCTION
Tropical cyclones (TCs) 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 surges, and heavy rainfall. The increasing coastal population has led to a significant increase in cyclone-related losses. 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. These environmental factors are favourable for TC genesis in the BoB during two seasons, viz., pre-monsoon (March-May) and post-monsoon (October-December). Depressions are active during the monsoon season (June-September), but TCs do not form quickly in a sheared-environment. The post-monsoon land-falling cyclones are devastating to the coastal areas of India and Bangladesh.

In the BoB, the TCs are categorised based on the maximum sustained wind (MSW) 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 (Table 1).

Despite the basin-wide warming over the northern Indian Ocean during the recent decades, the frequency of BoB cyclones has not increased significantly. The future projections consistently indicate that global warming will increase the intensity of TCs around the globe, including the BoB. The intensity of SCS in the BoB during the post-monsoon season has increased from 1981 to 2010. A notable increase in frequency and duration of VSCS in the northern Indian Ocean is reported during 1981 to 2014. In addition, the genesis locations of VSCSs in the BoB have shifted eastward by around 2°, suggesting an increase in storm duration in recent years. A significant growing trend in the annual frequency of VSCS in the Arabian Sea is documented during 1982 to 2019, although no significant trend in the BoB was detected. The amount of energy dispersed by the BoB cyclones has also increased in recent decades.

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) events can remotely influence other oceans through Walker Circulation. Similarly, the tropical Indian Ocean has a basin-wide variability termed the Indian Ocean Dipole (IOD). These two leading modes (ENSO and IOD) influence the interannual variability of BoB TCs. La Niña and negative IOD events are favourable for the severe cyclone activities in the BoB during the post-monsoon season.

The leading climate modes like ENSO and IOD modulate the ocean-atmosphere conditions in different latitudes of the BoB. 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°N) latitudes that are modulated by ENSO and IOD. Past studies on ENSO/IOD teleconnection with the BoB TCs considered the TC variability in the entire BoB. As a result, they may have missed the disparate changes in TC frequency with latitudes. In this study, we show that ENSO/IOD influence is confined to changes in 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 and IOD except during negative IOD.

RESULTS AND DISCUSSION
Interannual variability of the Bay of Bengal LLCs and HLCs
During 1979–2020, out of 167 TCs formed in the northern Indian Ocean, 48 formed in the Arabian Sea, and 119 formed in the BoB.
During El Niño years, the average number of HLCs is less than the climatological mean (Table 1). The BoB is conducive for TC formation during the pre-monsoon season (between 5°N and 10°N) and high latitudes (HLC, originating north of 10°N). The number of TCs intensifies into Severe Cyclonic Storms (SCS), and higher categories are listed in 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)         |

The statistics of LLC and HLC frequency and its teleconnection. Around 70-83% LLCs have intensified into SCSs and higher categories considering all phases of ENSO and IOD (Fig. 2). However, only 50–67% HLCs have intensified into SCSs and higher categories (Fig. 2). Consistent with previous studies, the frequency of TCs in the BoB is higher during La Niña years and fewer during El Niño years (Fig. 2 and Table 2). However, the HLC frequency barely changed during the contrasting phases of the ENSO. For example, the average number of HLCs remains the same (~1 TC per year) for La Niña and El Niño (Table 2). On the other hand, the frequency of LLCs of ~1 TC (per year) during La Niña has declined to ~0.3 TC (per year) during El Niño (Table 2). A similar relationship is found for severe cyclonic storms (SCS), where the changes in TC frequency are dominant in the low latitudes (Fig. 2). Hence, the change in TC frequency in the BoB during different phases of El Niño is dominated by the change in the low latitudinal regions. Overall, this analysis clearly shows that 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. For different phases of IOD, there is a change in HLC frequency as well, but the change in LLC frequency is more prominent (Fig. 2 and Table 2). This observation motivates us to find the underlying causes behind such latitudinal contrasts.

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 (Fig. 3) and IOD (Fig. 4) years. The anomalous SST does not show any significant difference during El Niño (Fig. 3a) or La Niña (Fig. 3b) years over the LLC genesis region (black rectangular box in Fig. 3). The SST over the LLC genesis region is 28.5–29°C (Fig. 5a), which is warmer than the critical SST (26°C) needed for supporting TC genesis. The decline in the LLC frequency during El Niño (Table 2) cannot be attributed to an increase in SST. The tropical cyclone heat potential (TCHP), is another ocean parameter important for the cyclone genesis and intensification, which has been increasing along the Indian coastline over BoB (Fig. 3). During the El Niño years, the mean TC genesis position in the BoB shifts westward, whereas eastern BoB experiences more TCs during the La Niña years, attributed to the ENSO-related changes in TCHP. The change in TCHP over the LLC region is not significant during the contrasting phases of ENSO (Fig. 3c, d). A mid-tropospheric relative humidity of 50–60% is often needed for the formation of cyclones to keep an air parcel saturated during ascent. The mid-tropospheric (700 hPa) relative humidity also increases over the genesis region of LLC during El Niño years (Fig. 3e), 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 (Fig. 3g). This reduced wind shear (<10 ms$^{-1}$) is favourable for TC genesis since a wind shear of <10 ms$^{-1}$ is often considered supportive for TC development. 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. The ambient rotation (i.e., small Coriolis) is insignificant at the low latitudes. Once a storm forms in the low latitudes under a lower planetary vorticity environment, it can spin-up faster and develop rapidly into cyclonic intensity than in higher latitudes with a higher Coriolis parameter environment. The El Niño composites show weakened relative vorticity anomalies compared to the climatological mean (Fig. 3i), supporting a reduction in LLC frequency (Table 2). The vertical wind shear in the low latitudes of BoB is reduced (Fig. 3g) during positive IOD years. The vertical wind shear of <10 ms$^{-1}$ facilitates intensification of TCs, and values between 2 and 4 ms$^{-1}$ favour significant intensification. Therefore, the average vertical wind shear value of 6 ms$^{-1}$ over the genesis region of BoB LLC (Fig. 5c) 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 vorticity in the LLC genesis location during positive IOD (see Fig. 4i and Fig. 5d) reduces the LLC frequency (Table 2). The distinct behaviour of the factors responsible for cyclogenesis of LLCs and HLCs during the contrasting phases of ENSO and IOD is explored further. For example, the composite analysis reveals that the signs of mid-tropospheric relative humidity and vertical wind shear anomalies flip during positive/negative phases of ENSO and IOD (see Fig. 3e–h) and Fig. 4e–h). The mean SSTs over LLC and HLC formation region during positive/negative phases of ENSO/IOD events are high (28.5°C) and sufficient for TC genesis (Fig. 5a). Compared to the HLC genesis region, higher mid-tropospheric relative humidity in the LLC genesis region (Fig. 5b) can support significantly over the low latitudes during the La Niña years (Fig. 3i, j). The increase in relative vorticity enhances the initial spin-up for the formation of LLCs in a weak planetary vorticity environment during La Niña years.

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 (Fig. 4a, e). The average values of SST (>28.75°C, Fig. 5a) and the relative humidity (65%, Fig. 5b) are greater than their critical values for the formation of TCs, while the LLCs are noticeably fewer. As in the case of El Niño, TCHP increases over a small portion of the western half of the LLC genesis region during positive IOD years (Fig. 4c). The vertical wind shear in the low latitudes of BoB is reduced (Fig. 4g) during positive IOD years. The vertical wind shear of <10 ms$^{-1}$ facilitates intensification of TCs, and values between 2 and 4 ms$^{-1}$ favour significant intensification. Therefore, the average vertical wind shear value of 6 ms$^{-1}$ over the genesis region of BoB LLC (Fig. 5c) 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 vorticity in the LLC genesis location during positive IOD (see Fig. 4i and Fig. 5d) reduces the LLC frequency (Table 2).

During negative IOD years, the vertical wind shear decreases over the low latitudinal region of the Bay of Bengal (Fig. 4b, f). However, the average values of the SST and mid-tropospheric relative humidity (28.5°C and 65%, Fig. 5a, b) are greater than their critical values for the formation of TCs. The TCHP significantly increases over only a small portion of the eastern half of the domain (Fig. 4d). The vertical wind shear values >11 ms$^{-1}$ favour significant weakening of TCs. Even though the average vertical wind shear during negative IOD composite is 12 ms$^{-1}$ (Fig. 5c), the number of LLCs is more than the climatological mean (Table 2 and Fig. 2). The increased LLCs during negative IOD years can be attributed to the increased vorticity (Figs. 4i and 5d). 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.

The distinct behaviour of the factors responsible for cyclogenesis of LLCs and HLCs during the contrasting phases of ENSO and IOD is explored further. For example, the composite analysis reveals that the signs of mid-tropospheric relative humidity and vertical wind shear anomalies flip during positive/negative phases of ENSO and IOD (see Fig. 3e–h) and Fig. 4e–h). The mean SSTs over LLC and HLC formation region during positive/negative phases of ENSO/IOD events are high (28.5°C) and sufficient for TC genesis (Fig. 5a). Compared to the HLC genesis region, higher mid-tropospheric relative humidity in the LLC genesis region (Fig. 5b) can support significantly over the low latitudes during the La Niña years (Fig. 3i, j). The increase in relative vorticity enhances the initial spin-up for the formation of LLCs in a weak planetary vorticity environment during La Niña years.

## Table 2. Statistics of post-monsoon season (OND) Bay of Bengal cyclones during contrasting phases of ENSO and IOD during 1979–2020.

| Category          | 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)      | 0.33 (04TC/12yrs) | 1.00 (12TC/12yrs) |
| La Niña           | 2.12 (247TC/11yrs)     | 1.09 (12TC/11yrs) | 1.09 (12TC/11yrs) |
| Neutral ENSO      | 1.95 (37TC/19yrs)      | 0.89 (17TC/19yrs) | 1.05 (20TC/19yrs) |
| PIOD              | 1.45 (16TC/1yrs)       | 0.45 (05TC/11yrs) | 1.00 (11TC/1yrs) |
| NIOD              | 2.55 (23TC/09yrs)      | 1.11 (10TC/09yrs) | 1.44 (13TC/09yrs) |
| Neutral IOD       | 1.72 (38TC/22yrs)      | 0.82 (18TC/22yrs) | 0.91 (20TC/22yrs) |
| Normal Years      | 1.73 (9TC/11yrs)       | 0.82 (09TC/11yrs) | 0.91 (10TC/11yrs) |

The number of TCs that are formed over the low latitudes (LLC, formed between 5°N–10°N) and high latitudes (HLC, formed north of 10°N) are explicitly listed. The up and down arrows indicate the increase and decrease (%) in cyclone frequency from their climatological mean listed in the first row. The “Normal Years” do not include +ve/−ve IOD/ENSO years.
Fig. 3  **El Niño and La Niña composites of critical environmental parameters that influence cyclogenesis.** El Niño and La Niña composites of anomalous a, b sea surface temperature (°C), c, d tropical cyclone heat potential (TCHP, KJ cm⁻²), e, f mid-tropospheric (700 hPa) relative humidity (%), g, h vertical wind shear between 850 and 200 hPa (ms⁻¹), and i, j low-level (850 hPa) relative vorticity (×10⁻⁶s⁻¹). Stippled areas represent regions where anomalies are significant at the 95% confidence level. The genesis location of BoB LLCs is indicated by the black rectangular area (83°–95°E, 5°–10°N).
Fig. 4  Positive IOD and negative IOD composites of anomalous.  

(a) Sea surface temperature (Positive IOD)  

(b) Sea surface temperature (Negative IOD)  

(c) TCHP (Positive IOD)  

(d) TCHP (Negative IOD)  

(e) Relative humidity (Positive IOD)  

(f) Relative humidity (Negative IOD)  

(g) Vertical wind shear (Positive IOD)  

(h) Vertical wind shear (Negative IOD)  

(i) Relative vorticity (Positive IOD)  

(j) Relative vorticity (Negative IOD)  

Fig. 4  Positive IOD and negative IOD composites of anomalous.  

(a, b) Sea surface temperature (°C),  
(c, d) tropical cyclone heat potential (TCHP, KJ cm⁻²),  
(e, f) midtropospheric (700 hPa) relative humidity (%),  
(g, h) vertical wind shear between 850 and 200 hPa (ms⁻¹),  
and  
(i, j) low-level (850 hPa) relative vorticity (x 10⁻⁶ s⁻¹).  

Stippled areas represent regions where anomalies are significant at the 95% confidence level.  
The genesis location of BoB LLCs is indicated by the black rectangular area (83°–95°E, 5°–10°N).  

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intensification of LLCs (Fig. 2). The average mid-tropospheric relative humidity over the LLC region is above 65% (Fig. 5b, red shading). The HLC region has a weak mid-tropospheric relative humidity of about 48% (Fig. 5b, green shading). 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 remains close to its climatological mean (≈ 9 m s$^{-1}$, Fig. 5c).

Even though relative vorticity reduces significantly over the LLC and HLC regions during El Niño (Fig. 3i) and positive IOD years (Fig. 4i), the decline in TC frequency is confined only in the low-latitudinal region (Table 2) due to the weak Coriolis force (Fig. 5d). This indicates the quintessential role of relative vorticity compared to the other parameters during the contrasting phases of ENSO and IOD.

To confirm that the decrease in relative vorticity during El Niño/positive IOD years and its increase during La Niña/negative IOD years was not due to the TC-related circulation anomalies, we removed TC-related anomalies from the basic flow. The results still show reduced relative vorticity during El Niño/positive IOD and enhanced relative vorticity during La Niña/negative IOD over the LLC region (Supplementary Figs. 1 and 2).

**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 examined the seasonal mean low-level winds.
The climatological mean winds (Fig. 6) splash 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 Fig. 6a) at 850 hPa strongly correlate with the absolute vorticity ($r = 0.91$) in the LLC region (black rectangular box in Fig. 6a) of BoB during the post-monsoon season. Both equatorial wind anomalies (averaged over 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 normalised by their 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 indicates 95% confidence level in panel a. During El Niño and positive IOD years, equatorial westerlies weaken leading to reduced absolute vorticity and fewer number of LLCs. The reverse occurs during La Niña and negative IOD years.

The relationship between equatorial wind anomalies, low-level absolute vorticity, and BoB LLC frequency during contrasting phases of ENSO. a Equatorial wind anomalies versus 850hPa absolute vorticity, and b Equatorial wind anomalies versus BoB LLC frequency. Both equatorial wind anomalies (averaged over 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 normalised 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 indicates 95% confidence level in panel a. During El Niño and positive IOD years, equatorial westerlies weaken leading to reduced absolute vorticity and fewer number of LLCs. The reverse occurs during La Niña and negative IOD years.

Fig. 7 The relationship between equatorial wind anomalies, low-level absolute vorticity, and BoB LLC frequency during contrasting phases of ENSO. a Equatorial wind anomalies versus 850hPa absolute vorticity, and b Equatorial wind anomalies versus BoB LLC frequency. Both equatorial wind anomalies (averaged over 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 normalised 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 indicates 95% confidence level in panel a. During El Niño and positive IOD years, equatorial westerlies weaken leading to reduced absolute vorticity and fewer number of LLCs. The reverse occurs during La Niña and negative IOD years.

Fig. 8 Composite of 850hPa wind anomalies (ms$^{-1}$). a El Niño, b La Niña, c positive IOD, and d negative IOD years. Only statistically significant (95% confidence level) anomalies are shown.

The climatological mean winds (Fig. 6) splash 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 Fig. 6a) at 850 hPa strongly correlate with the absolute vorticity ($r = 0.91$) in the LLC region (black rectangular box in Fig. 6a) of BoB during the post-monsoon season (Fig. 7a). Most of the El Niño events fall in quadrant-III, while most La Niña events fall in quadrant-I in...
Fig. 7a. It turns out that 83% of El Niño events are associated with the easterly phase of equatorial winds (Fig. 7a), and the rest are associated with very weak westerly winds. On the other hand, 82% of La Niña events are associated with the westerly phase of equatorial winds (Fig. 7a). In addition, 82% of the positive IOD years are associated with easterly phases of equatorial winds (Fig. 7a). 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 (Fig. 7b).

The climatological westerly winds (Fig. 6a) in the equatorial Indian Ocean weaken during the El Niño and positive IOD years (Fig. 8a, c). This weakened westerly winds (Fig. 8a, c) during El Niño and positive IOD events reduce the absolute vorticity (Figs. 3i, 4i and 7a), 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 (Fig. 8b, d) increase the absolute vorticity over the low latitudes of the BoB (Figs. 3j, 4j and 7a). This increase in the absolute vorticity associated with stronger equatorial westerlies (Fig. 7a) enhances the formation of LLCs (Fig. 7b). The role of equatorial winds in generating relative vorticity is summarised in a schematic (Fig. 9).

Even though the relative vorticity plays a decisive role in LLC formation, the vertical wind shear 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 (Fig. 6). Both the lower-level (850 hPa) westerlies and upper-level (200 hPa) easterlies weaken during El Niño and positive IOD years (Fig. 10), resulting in the weakening of the vertical wind shear. Similarly, the enhanced vertical wind shear is caused by the strengthening of anomalous lower-level westerlies and upper-level easterlies during La Niña and negative IOD years (Fig. 10).

We investigated the interannual variability of post-monsoonal cyclones, focusing on those formed in the low latitudes of the Bay of Bengal (BoB) and their teleconnection with El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). The main conclusions of this study are:
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 (Table 2, Figs. 2 and 7b). In ENSO years, the modulation in TC frequency is confined to the low latitudes only, with no change in HLC frequency. There are changes in HLC frequency during IOD years, but changes in LLC frequency still dominate.

The vital parameter responsible for the interannual variability in BoB LLCs was shown to be relative vorticity (Figs. 3j, 4j, and 7a). 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 (Fig. 6) and build up sufficient absolute vorticity (Fig. 7a). During El Niño and positive IOD years, the climatological westerly winds in the equatorial Indian Ocean weaken (Figs. 7 and 8), which reduces the vorticity in the BoB (Figs. 3i, 4i, and 7a). On the other hand, the strengthening of equatorial westerlies enhances the vorticity in the low latitudinal region of the BoB during La Niña and negative IOD (Figs. 3j, 4j, and 7a) years. The weakening of relative vorticity significantly reduces the genesis of LLC (Fig. 7b). The relative vorticity-induced TC frequency reduction is confined to the LLC genesis region under a weak planetary vorticity environment. However, the TC frequency over the HCL genesis region was not significantly affected by the relative vorticity reduction under a stronger planetary vorticity environment. These results may help extend the lead time and improve the seasonal prediction of BoB TCs.

METHODS
The cyclone data from the Regional Specialized Meteorological Centre43 is used to determine the genesis location and frequency of cyclones in the BoB during 1979–2020. The critical environmental parameters controlling cyclogenesis are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF)'s fifth-generation reanalysis dataset ERA545. To identify positive and negative phases of ENSO (El Niño/La Niña), we used the Oceanic Niño Index (ONI)46. The Oceanic Niño Index (ONI) is calculated as the three-month running mean of SST anomalies in the El Niño 3.4 region. It 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. The Dipole Mode Index (DMI) is used to identify the positive and negative phases of IOD.38 The DMI is defined as the difference in the SST anomalies between the western Indian Ocean (50°–70°E, 10°F–10°N) and the southeastern Indian Ocean (90°–110°E, 10°F–5°S). The DMI index is taken from the NOAA’s Physical Sciences Laboratory https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/. The tropical cyclone heat potential (TCHP) estimation is based on the ocean temperature data (EN447) obtained from the Met Office Hadley Centre. We used monthly data of different environmental parameters influencing TC formation for the composites of El Niño, La Niña, and IOD years based on October–December seasonal mean during 1979–2020.

DATA AVAILABILITY
All data used in this study are publicly available. The ERA5 reanalysis data are available to download from the https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5/. The tracks and frequency of the north Indian Ocean cyclones used in this study are available on the archives of the India Meteorological Department (https://rsmcweddelhi.imd.gov.in).

CODE AVAILABILITY
The codes for analysis, statistical computing, and graphics are based on freeware environments, R version 4.0.5, https://www.R-project.org/), NCAR Command Language (Version 6.6.2; https://doi.org/10.5065/D6WD3XHS). Ferret (version 7.5, http://ferret.pmel.noaa.gov/Ferret/) and CDO (version 1.9.2, https://doi.org/10.5281/zenodo.3539275). All codes developed to analyze the data are available at https://github.com/Shintoroose/NIO_LLC_interannual.

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AUTHOR CONTRIBUTIONS

S.R, R.S.A., and P.R conceived the idea and proposed this study. All the authors discussed the concepts and the methodology. The manuscript was drafted by S.R. and edited by all authors.

COMPETING INTERESTS

The authors declare no competing interests.

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