Environmental Conditions Modulating Tropical Cyclone Formation over the Bay of Bengal during the Pre-Monsoon Transition Period

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ABSTRACT

Globally, the highest formation rate of super tropical cyclones (TCs) occurs over the Bay of Bengal (BoB) during the premonsoon transition period (PMT), but TC genesis has a low frequency here. TCs have occurred over the BoB in only 20 of the past 36 years of PMTs (1981–2016). This study investigates which environmental conditions modulate TC formation during the PMT over the BoB by conducting a quantitative analysis based on the genesis potential parameter, vorticity tendency equation, and specific humidity budget equation. The results show that there is a cyclonic anomaly in the TC genesis group compared to the non-TC genesis group, which is mainly due to the divergence term. A significant difference in vorticity contributes to TC formation over the BoB during the PMT. Furthermore, anomalous cyclonic flow enhances ascending motion, transporting moisture to the midlevel atmosphere. A change in specific humidity (SH) causes an increase in relative humidity, which contributes positively to TC formation. The vertical wind shear also makes a small positive contribution. In contrast to the previous three terms, the contribution from the instability term associated with 500- and 850-hPa air temperatures is negative and almost negligible. In addition, the synoptic-scale disturbance energy is more powerful in the TC genesis group than in the non-TC genesis group, which is favorable for TC breeding. Together, these conditions determine whether TCs are generated over the BoB during the PMT.

1. Introduction

Tropical cyclones (TCs) are one of the most frequent severe weather systems and among the most destructive natural weather phenomena over tropical oceans, causing serious ecological and economic damage and even imposing a substantial threat to human lives. The

north Indian Ocean (NIO) is one of the main ocean basins for TC genesis. Moreover, most NIO TCs generally take place over the Bay of Bengal (BoB) in the NIO. Particularly over the BoB, TCs threaten about one billion people each year in India, Myanmar, Bangladesh, and the wider Southeast Asian region (SEAR) (Webster 2008; Lin et al. 2013).

Although TC frequency is lower over the BoB relative to the western North Pacific (WNP), eastern North Pacific (ENP), northern Atlantic (NATL), southern Indian Ocean (SIO), and western South Pacific (WSP), the formation rate of super TCs (STCs; category 4 or

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TABLE 1. STC formation rate during the TC season for each ocean basin.

Basin	BoB	BoB	WNP	ENP	NATL	SIO	WSP
Months	4–5	10–11	7–10	7–10	7–10	1–4	1–4
STC rate (%)	36.8	10.4	24.5	16.2	12.1	16.1	17.7

above) is much higher over the BoB during the premonsoon transition period (PMT), which is a BoB TC hot season, than over other tropical ocean basins during their TC seasons. Specifically, the STC formation rate reaches approximately 40% over the BoB during the PMT (Table 1). This rate is the highest in the global tropical oceans and even up to approximately 4 times greater than in the North Atlantic (Li et al. 2019). In other words, one of every three TCs that occurs in the BoB during the PMT will develop into a super TC. However, TCs are unable to generate during the PMT of every year. TC genesis has occurred in only 20 of the past 36 years (from 1981 to 2016), in 1982, 1985, 1989, 1990, 1991, 1992, 1994, 1996, 1997, 1998, 2002, 2003, 2004, 2006, 2007, 2008, 2009, 2010, 2013, and 2016 (Table 2).

The understanding of the genesis of TCs during the PMT over the BOB remains very limited. Some studies found that sea surface temperature (SST), low-level relative vorticity, the Coriolis force, vertical wind shear (VWS), conditional instability, and relative humidity (RH) in the lower and middle troposphere were important factors impacting TC formation and development (Palmén 1948; Gray 1968; DeMaria et al. 2001). Among these factors, high SST, high midtropospheric moisture, and cyclonic vorticity are favorable for TC genesis and intensification, while strong VWS is unfavorable for TC formation and tends to weaken the intensity of storms.

Based on previous studies, Gray (1979) proposed a combined index to describe TC genesis. Emanuel and Nolan (2004) further refined Gray's index and proposed a TC genesis potential index (GPI) by fitting large-scale climatological conditions for all ocean basins. While the GPI may adequately capture climatological

TC characteristics across the global oceans, it fails to accurately reproduce interannual, intraseasonal, or even short-period variability in particular basins, such as the WNP (Fu et al. 2012). Specifically, the index cannot clearly describe TC characteristics in the BoB during the PMT because of the relatively low TC frequency. Given the lack of consensus surrounding the TC genesis features in the BoB, Kotal et al. (2009a,b) proposed a genesis potential parameter (GPP), which includes both dynamic and thermodynamic variables, for differentiating between developing and nondeveloping TC systems over the northern Indian Ocean.

Nath et al. (2013) used the GPP to analyze the precyclone status of approximately 30 tropical disturbances over the BoB from 2001 to 2010, enabling them to provide a possible 2-day lead prediction for depression systems in the region. The study examined precyclone genesis conditions during the pre- and postmonsoon transition periods and determined the applicability of the GPP in the BoB basin. However, the TC genesis features and conditions are different during the two periods; for instance, there is greater moisture during the postmonsoon transition period than during the PMT; the differences give rise to variations in TC frequency during the PMT versus the postmonsoon transition period (Li et al. 2013). The current studies do not accurately describe TC genesis features during the PMT. Therefore, this study aimed to use the GPP to investigate the major physical processes that control whether TCs are generated during the PMT over the BoB. The data and methodology are described in section 2, and the results are presented in section 3. Finally, we summarize and discuss the results in section 4.

TABLE 2. BoB TC genesis information during the PMTs from 1981 to 2016. TC yrs are TC genesis years; TC GD denotes the TC genesis date; TC ED denotes the TC ending date.

TC yrs	1982	1985	1989	1990	1991	1992	1994	1996	1997	1998	2002
TC GD	4.30	5.22	5.23	5.03	4.22	5.15	4.26	5.01	5.13	5.13	5.09
TC ED	5.05	5.25	5.27	5.11	4.30	5.20	5.03	5.08	5.20	5.20	5.12
TC yrs	2003	2004	2006	2007	2008	2009	2009	2010	2013	2016	
TC GD	5.08	5.14	4.24	5.13	4.25	4.14	5.22	5.16	5.10	5.18	
TC ED	5.19	5.19	4.29	5.15	5.04	4.18	5.26	5.21	5.16	5.21	

2. Data and methodology

The primary data utilized in the study include 1) TC best-track data from the Joint Typhoon Warning Center (JTWC) and 2) the observed daily air temperature (AT), wind, relative humidity, and specific humidity (SH) data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis. All datasets have a horizontal resolution of 2.5° latitude $\times$ 2.5° longitude.

Based on previous versions of the GPI (Gray 1979; Emanuel and Nolan 2004), Kotal et al. (2009a,b) proposed a GPP appropriate for NIO TC genesis. In this study, we use the GPP as our main diagnostic equation to determine the environmental factors that result in TC genesis over the BoB during some PMTs from 1981 to 2016 but not others. The equation for the GPP is as follows:

GPP

$$= \begin{cases} \zeta_{850} \times M \times I \times S, & \text{if } \zeta_{850} > 0, M > 0, \text{ and } I > 0, \\ 0, & \text{if } \zeta_{850} \leq 0, M \leq 0, \text{ or } I \leq 0, \end{cases}$$

where ζ_{850} = low-level relative vorticity (at 850 hPa); $S = \text{VWS}^{-1}$, where VWS is the vertical wind shear between 200 and 850 hPa (m s^{-1}); $I = T_{850} - T_{500}$ = middle tropospheric instability (the temperature difference between 850 and 500 hPa); and

$$M = (\text{RH} - 40)/30.$$

In this case, M is the middle troposphere relative humidity, and RH is the mean relative humidity between 700 and 500 hPa.

According to Peng et al. (2012) and Fu et al. (2012), the box difference index (BDI) can quantitatively discriminate significant differences between TC and non-TC genesis groups. Therefore, we use the BDI to clearly define the differences between the GPP in the two groups. The BDI is defined as follows:

$$\text{BDI} = \frac{\text{mean}_{\text{TC}} - \text{mean}_{\text{NTC}}}{\sigma_{\text{TC}} + \sigma_{\text{NTC}}}.$$

Mean denotes the mean of all samples for one particular variable, and σ denotes standard deviation. The subscripts “TC” and “NTC” represent the TC and non-TC genesis groups, respectively.

In addition, we use the vorticity tendency formula, the relative humidity function on specific humidity and air temperature, and the specific humidity budget formula to further diagnose the physical processes that determine whether TC activity will occur during a given

PMT. The analysis is described in detail in the following section.

3. Environmental conditions for TC formation

There are two peak TC seasons over the BoB: the PMT (April–May) and the postmonsoon transition period (October–November) (Gray 1968; Yanase et al. 2012; Li et al. 2013). The STC rate is far higher in April–May than in October–November, and it is also the highest rate among all tropical ocean basins during their TC seasons (Table 1). Although the STC formation rate reached approximately 40%, TCs took place over the BoB in only 20 of the past 36 years (1981–2016).

Almost all the TCs took place before or close to the date of the summer monsoon onset because after the summer monsoon breaks out over the BoB, the summer monsoon circulation enhances the vertical wind shear, which effectively inhibits TC genesis. Hence, this paper focuses on TC genesis conditions during the PMT before the summer monsoon onset, which mainly control whether TC genesis occurs over the BoB.

BoB TC activity is a synoptic-scale process and generally occurs only once during a given PMT, if at all. Hence, it is difficult to distinguish significant differences in the signals between the TC and non-TC genesis groups based on the April–May monthly mean datasets. Ge et al. (2013) found that it took no more than 7 days for TC genesis to occur under different convection conditions. In addition, Fu et al. (2007) and Peng et al. (2012) noted some synoptic-scale (less than 8 days) environmental factors that are significantly different between developing and nondeveloping TC groups. We selected 7 days as the hatching period for TC activity because the GPPs from 7 days prior to TC genesis are remarkably different from the GPPs in any other 7-day period from 1 April to the monsoon onset date in non-TC genesis cases. This 7-day hatching period for TC activity is also consistent with the results of previous studies.

Figure 1 shows positive BDIs of the GPP over most areas of the BoB, indicating that the composite GPP in TC genesis cases is greater than in non-TC genesis cases. Meanwhile, the areas with positive GPP anomalies between the TC genesis and non-TC genesis groups are significantly different at or above the 95% level. It is clear that most TC activity occurs in areas with positive GPP anomalies. Therefore, we selected a box (87.5° – 97.5°E , 7.5° – 15°N) as a reference area for further quantitative analysis.

To quantitatively assess the relative contribution of each term, Li et al. (2013, 2015a,b) developed an analysis strategy that involves taking the natural logarithm of

FIG. 1. BDI of GPP between the TC and non-TC genesis groups. The areas with plus signs indicate that the difference in GPP is significant at a level greater than 95%.

both sides of the GPI formula and then applying a total differential to both sides. The algorithm is used here; the change in GPP can be separated into four terms, as follows:

$$\begin{aligned}\delta GPP &= \alpha_1 \delta \zeta_{850} + \alpha_2 \delta M + \alpha_3 \delta I + \alpha_4 \delta S, \\ \alpha_1 &= \overline{M \times I \times S}, \alpha_2 = \overline{\zeta_{850} \times I \times S}, \\ \alpha_3 &= \overline{\zeta_{850} \times M \times S}, \quad \text{and} \\ \alpha_4 &= \overline{\zeta_{850} \times M \times I}.\end{aligned}$$

The calculation results (Fig. 2) indicate that TC genesis during the PMT can primarily be attributed to the relative humidity term. The vorticity term provides a secondary positive contribution. The vertical wind shear term has a very weak positive contribution. The instability term, which is determined by the air temperature difference between the 850- and 500-hPa levels, makes a small negative contribution. Compared to the other terms, the effects of the vertical wind shear and instability terms are almost negligible. These factors together determine TC genesis over the BoB during the PMT. The difference between δGPP and the SUM term (the sum of the four terms) may be attributed to the nonlinear system (Fig. 2).

Composition analysis shows notable cyclonic winds in the TC genesis group but anticyclonic winds in the non-TC genesis group over the BoB. Furthermore, the difference in the circulation field between the TC genesis and non-TC genesis groups shows a cyclonic anomaly with a significance level for the difference greater than 95% (Fig. 3), which may be mainly caused by the SST

FIG. 2. Contributions of the vorticity, relative humidity, air instability, and vertical wind shear to the GPP difference between the TC and non-TC genesis groups. The sum of the four terms is approximately equal to the difference in GPP.

anomaly between the two types of groups (result not shown). Next, we examine what processes cause the positive vorticity difference using the vorticity tendency diagnostic equation, as follows:

$$\begin{aligned}\frac{\partial \zeta}{\partial t} &= \text{term 1} + \text{term 2} + \text{term 3}, \\ \text{term 1} &= -\left(u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} + \omega \frac{\partial \zeta}{\partial p}\right) - v \frac{\partial f}{\partial y}, \\ \text{term 2} &= \frac{\partial \omega}{\partial y} \frac{\partial u}{\partial p} - \frac{\partial v}{\partial p} \frac{\partial \omega}{\partial x}, \quad \text{and} \\ \text{term 3} &= -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)(\zeta + f),\end{aligned}$$

where t is time; p is the pressure surface; u and v are the zonal and meridional wind, respectively; ω is the vertical p velocity; f is the Coriolis parameter; and ζ is vorticity. The vorticity tendency is determined by three major terms, including the 3D vorticity advection term (term 1), the tilting term (term 2), and the divergence term (term 3). Here, the friction term in the free atmosphere is neglected.

Figure 4 shows that the vorticity difference can primarily be attributed to the divergence term, while both the 3D vorticity advection and the tilting term make negative contributions. The sum of the three terms is approximately equal to the vorticity difference tendency, demonstrating that the result is robust.

As a key factor closely associated with TC formation, relative humidity makes the largest contribution to the difference in GPP between the TC genesis and non-TC

FIG. 3. The 850-hPa vorticity anomaly (shading) and wind difference (vector) between the TC genesis and non-TC genesis groups.

genesis groups. In other words, 500–700-hPa relative humidity variations largely control whether TCs are generated over the BoB during the PMT. Given that relative humidity is a function of specific humidity and air temperature, we examined the relative contributions of the two factors and found that the differences in 500–700-hPa relative humidity between the TC genesis and non-TC genesis groups can mainly be attributed to changes in specific humidity, not air temperature (results not shown).

Next, we conducted a moisture budget analysis to examine the specific processes that give rise to specific humidity anomalies q' in the TC genesis and non-TC genesis groups. Following Yanai et al. (1973), Hsu and Li (2012), and Li et al. (2015a,b), the tendency equation for specific humidity anomalies can be written as follows:

$$\frac{\partial q'}{\partial t} = -(\mathbf{V} \cdot \nabla q)' - \left(\omega \frac{\partial q}{\partial p} \right)' - (Q_2/L)',$$

where $\mathbf{V}$ is the horizontal velocity, ω is the p -vertical velocity, Q_2 is the apparent moisture sink, and L is the latent heat constant. In the equation above, $-(\mathbf{V} \cdot \nabla q)'$ denotes anomalous horizontal moisture advection, $-\left[\omega \left(\frac{\partial q}{\partial p}\right)'\right]$ denotes anomalous vertical moisture advection, and $-(Q_2/L)'$ denotes anomalous moisture sources or sinks (Q_2 is primarily determined by surface evaporation and atmospheric condensation).

Figure 5 shows the results of the analysis of the specific humidity anomaly budget. The differences in specific

FIG. 4. Composite 850-hPa vorticity anomaly tendency terms. Terms 1, 2, and 3 are the contributions of the 3D vorticity advection, tilting, and divergence terms, respectively, to the vorticity difference tendency. The sum term is the sum of terms 1, 2, and 3 and is approximately equal to the vorticity difference tendency.

humidity between the TC genesis and non-TC genesis groups may primarily be attributed to vertical advection. Meanwhile, the apparent moisture sink and horizontal advection terms have a small positive and a small negative contribution, respectively (Fig. 5a). Furthermore, we find that vertical advection is mainly controlled by differences in vertical motion and the average specific humidity in the non-TC genesis group (Fig. 5b). The physical interpretation is discussed below. We note that the atmospheric boundary layer vorticity in the PMT during the 7 days prior to TC genesis in the TC genesis group is stronger than any 7-day-averaged vorticity before the monsoon onset date in the non-TC genesis group. Cyclonic flow at the top of the atmospheric boundary layer induces anomalous ascending motion through the Ekman pumping effect (Fig. 6). Considering that water vapor is concentrated in the low-level atmosphere, this anomalous ascending motion can efficiently transport sufficient water vapor to the middle-level atmosphere, increasing the specific humidity and relative humidity differential and eventually determining whether TCs are generated over the BoB during the PMT.

FIG. 5. (a) Composite middle-level specific humidity anomaly tendency terms. (b) Separation of vertical advection of (a) into the product of the non-TC-group averaged ω and specific humidity ($\omega_m SH_m$), the product of the ω difference between the TC and non-TC groups and the non-TC-group averaged specific humidity ($\omega_d SH_m$), the product of the non-TC-group averaged ω and the specific humidity difference between both groups ($\omega_m SH_d$), and the product of the difference in ω and specific humidity between both groups ($\omega_d SH_d$).

The vertical wind shear makes a small positive contribution to the difference in the GPP between the TC genesis and non-TC genesis groups, while the instability term makes a very small negative contribution, which can be neglected (Fig. 7). Although the vertical wind shear is relatively weak in the TC genesis group (Fig. 8), the difference between the two groups is not notable because of the weak winds during the PMT.

Together, these factors result in the difference in GPP between the TC genesis and non-TC genesis groups. These results can help understand why TCs form over the BoB during the PMT in some years but not others. From a synoptic-scale disturbance energy point of view, we can also understand the reasons for TC genesis during some of the PMTs from 1981 to 2016. By using high pass filtering (less than 7 days), the synoptic-scale wind data could be extracted. After that, the disturbance energy in the TC genesis group is much larger during the PMT (April–May) than that in the non-TC genesis group (Fig. 9). The more powerful disturbance may also promote TC genesis during the PMT of some years.

4. Conclusions and discussion

By quantitatively evaluating the various environmental parameters associated with the GPP, we found that the most important parameters in determining TC genesis over the BoB during the PMT are midtropospheric relative humidity and 850-hPa vorticity. Because of the weak winds during the PMT over the BoB, the vertical wind shear makes a small positive contribution, and the effect of the instability term associated with air temperature is negative and almost negligible.

Given the critical role of midtropospheric water vapor and low-level vorticity, vorticity and moisture budget analyses were carried out to further identify the elements that were most crucial to TC formation. The results showed that anomalous vertical advection is the major process affecting moisture change; this vertical advection is primarily caused by vertical motion anomalies and the specific humidity in the non-TC genesis group. Moreover, vertical motion variation can be attributed to the positive vorticity difference, which occurs because of the divergence term.

Based on the results above, we propose the following model of the environmental parameters that modulate TC genesis over the BoB during the PMT.

- 1) The comparison of the TC genesis and non-TC genesis groups shows a significant cyclonic flow anomaly at the 850-hPa level, which is closely related with the SST anomaly between the both groups. Our vorticity budget analysis confirms that the anomalous vorticity is primarily related to the divergence term, while 3D advection and the tilting term cause the opposite effect. However, the divergence term overwhelms the other two terms, leading to the positive vorticity difference between the TC genesis and non-TC genesis groups.
- 2) Cyclonic flow at the top of the boundary layer induces anomalous ascending motion, which transports moisture upward and increases humidity in the lower troposphere. Our moisture budget analysis indicates that anomalous vertical advection is the most important factor for increasing middle-level specific humidity. Changes in specific humidity then control relative

FIG. 6. Composite of ω in the TC genesis group (solid line) and non-TC genesis group (dashed line) and the difference between TC genesis and non-TC genesis groups (dotted line).

humidity, which account for the greatest difference in the GPP between the two groups.

- 3) The vertical wind shear makes a small positive contribution to the difference in GPP. This result occurs because winds are weak during the PMT. Thus, the vertical wind shear is small and does not contribute much to the difference in GPP.
- 4) Finally, the instability term associated with 500- and 850-hPa air temperature is weaker in the TC genesis group than in the non-TC genesis group. This term also makes a small negative contribution to TC genesis, which is essentially negligible.

In summary, these environmental factors combine to determine TC occurrence over the BoB during the PMT in some years and not in others. The synoptic-scale disturbance energy during the PMT is larger in the TC genesis group than in the non-TC genesis group. This condition may make TC genesis more likely during the PMT of some years. Moreover, some questions—for instance, “What is responsible for a cyclonic anomaly in the TC genesis group and where does the synoptic-scale disturbance energy come from during the PMT?”—should

FIG. 7. Composite of the difference in the instability term between the TC genesis and non-TC genesis groups.

be further studied in the future to pave the way for development and improvements to BoB TC forecasting, especially for STC forecasting.

Finally, the higher STC formation rate in April–May than in October–November is a very interesting question. This difference may be mainly attributed to the shift in the ISO propagation path during the pre- and

FIG. 8. Composite of the vertical wind shear difference between the TC genesis and non-TC genesis groups.

FIG. 9. The difference in synoptic-scale disturbance energy during the PMT between the TC genesis and non-TC genesis groups.

postmonsoon transition periods. However, the issue still needs to be investigated in detail.

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