Large-scale atmospheric features favoring the tropical cyclone activity affecting the Guangdong–Hong Kong–Macao Greater Bay Area of China

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1. Introduction

Tropical cyclones (TCs) are rapidly-rotating storm systems generated over tropical oceans, accompanied by violent winds and torrential rains. They often cause significant hazards and damages to human beings’ lives and properties in the coastal areas (Mendelsohn et al 2012, Peduzzi et al 2012, Woodruff et al 2013, Li et al 2017, Tu et al 2018, Zhao et al 2018). Specifically, the coastal areas of southern China frequently face significant threats from the effects of TCs during summer especially those move westward/northwestward from the western North Pacific (WNP; Zhang et al 2019, Zhou and Lu 2019) and northward from the South China Sea (Yang et al 2015, Cao et al 2020). From the annual-mean perspective, the significant poleward and landward migration of TC activity in the past 40 years have been reported, increasing the coastal TC risk of China (Kossin et al 2014, Wu et al 2015, Sharmila and Walsh 2018, Wang and Toumi 2021). In particular, the annual frequency and intensity of the TCs making landfall in southern China exhibit an upward trend during the last decades (Liu and Chan 2018, 2020, Shan and Yu 2021, Yao et al 2021). Thus, an improved understanding of the variability of TC activity over southern China is both scientifically and socially important.

It is worth noting that the Guangdong–Hong Kong–Macao Greater Bay Area (GBA), which is comprised of 11 cities including Hong Kong, Macao,
Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing in southern China (shown as the blue areas in figure 1(a)), is a highly populated area and makes up a significant part of the economic output of China. TCs-induced disasters create a crucial challenge in economic and social development in the GBA (Li et al. 2021). Recently, super typhoons Hato (2017) and Mangkhut (2018) directly attacked the GBA, causing intense floods and severe damages along the coast and seriously threatening the safety of citizens (Yang et al. 2019). Hence, a comprehensive understanding of the characteristics of the TCs that affect the GBA (referred to GBA TCs in this paper for convenience) and the responsible mechanisms is required for decision making and management of disaster prevention and mitigation.

Both the monsoon trough (MT) and the WNP subtropical high (WNPSH) have been recognized as two atmospheric circulation systems that could affect the variability of TC activity over the WNP (Harr and Elsberry 1991, Chen et al. 2009, Huang et al. 2018, Wang and Wang 2019, Feng and Wu 2022). Along the convergence zone between the southwest monsoonal wind and the trade wind, above 70% of the WNP TCs is generated within the MT (Molinari and Vollar 2013). The MT could increase lower-level vorticity and convergence, and mid-level moisture, providing a favorable environment for the development of synoptic-scale disturbances, which may further evolve into TC embryos (Chen et al. 2004, Cao et al. 2014). Several studies have indicated that the longitudinal extension of the MT could determine the mean tropical cyclogenesis locations (Wu et al. 2012, Hu et al. 2018). Additionally, the MT exhibits a coherent migration with the WNPSH, which greatly influences the TC tracks across the WNP region. The intensification (weakening) of the WNPSH accompanied by a weaker (stronger) MT could lead to more westward (recurred) TC movement (Chen et al. 2009). Zhang et al. (2019) have suggested that the easterly steering flow at the mid-troposphere significantly modulates the landfall frequency of TCs in southern China, closely linked to the WNPSH activity. Accordingly, whether the above atmospheric circulation systems present different or special characteristics for the GBA TC activity remains unclear and deserves thorough investigations, which is of great concern in the current study.

Moreover, the variability of sea surface temperature (SST) plays a critical role in regulating global atmospheric circulation, since it not only can modulate air-sea interaction locally, but also exerts remote effects via an atmospheric bridge process (i.e. Walker circulation) within the tropics (Klein et al. 1999, Alexander et al. 2002, Lau and Nath 2003, Song et al. 2020) and a planetary-scale wave response connecting the extratropics (Hoskins and Karoly 1981, Simmons et al. 1983, Sardeshmukh and Hoskins 1988, Jin and Hoskins 1995). Notably, Zhou and Lu (2019) have observed that the TC landfall in the southern coastal East Asia is closely related to El Niño–Southern Oscillation, which affects the upper- and lower-tropospheric circulation over the WNP and East Asia and induces changes in the steering flow. Tu and Chen (2019) have suggested that the local convection over the tropical western Pacific could provoke a Matsuno–Gill-type pattern (Matsuno 1966, Gill 1980) or meridional wave train pattern (Nitta 1987, Huang and Sun 1992) to affect the overlying atmospheric circulation and guide the TC tracks toward Taiwan. Hence, this study will clarify whether and how tropical convection affects the large-scale circulation around the GBA and modulates the regional TC activity.

The remainder of this paper is organized as follows. Section 2 provides a description of the data and methods applied. Section 3 briefly introduces the climatological characteristics of the GBA TCs and identifies the large-scale circulation anomalies corresponding to the interannual variations of GBA TC frequency. Section 4 discusses the impact of atmospheric heating on atmospheric circulation anomalies and GBA TC activity. Finally, section 5 summarizes the main features of the results obtained.

2. Data and methodology

The monthly atmospheric variables with a $2.5° \times 2.5°$ resolution analyzed in this study came from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis product (Kalnay et al. 1996). Monthly interpolated outgoing longwave radiation (OLR) data with a $2.5° \times 2.5°$ resolution (Liebmann and Smith 1996) were obtained from the National Oceanic and Atmospheric Administration (NOAA). Monthly SST data with a $2° \times 2°$ resolution were obtained from the NOAA Extended Reconstructed SST version 5 (Huang et al. 2017). Daily observed precipitation data from 27 meteorological stations in the GBA were acquired from the National Meteorological Information Center, China Meteorological Administration.

The TC best-track data were attained from the Shanghai Typhoon Institute of the China Meteorological Administration, including the location and intensity of TCs at a 6 h interval (Ying et al. 2014, Lu et al. 2021). Only the TCs with at least the tropical storm intensity (maximum sustained wind speed exceeding 17.2 m s$^{-1}$) were counted. In this analysis, a TC genesis was defined as the TC first attains the tropical storm intensity. The genesis and track density were the accumulated counts of TC appearances in every $5° \times 5°$ box calculated from the TC location data and spatially smoothed using the following method: $T(x,y) = 1/4(T_{x,y}) + 1/8(T_{x+1,y} + T_{x+1,y} + T_{x-1,y} + T_{x-1,y}) + 1/16 (T_{x-1,y-1} + T_{x-1,y+1} + T_{x+1,y-1} + T_{x+1,y+1})$. 

2.1 TC activity

The TC activity is measured by the number of TCs per season in a region. The TC season is defined as the period from May to October each year. The TC activity index is calculated as the number of TCs per season divided by the area of the region. The TC activity index is also normalized by the average number of TCs in each region to obtain a normalized TC activity index. The average number of TCs in each region is calculated as the average of the normalized TC activity index over the period of 1980-2020. The normalized TC activity index is calculated as

$$\text{Normalized TC activity index} = \frac{\text{Number of TCs per season}}{\text{Average number of TCs in each region}}$$

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Figure 1. (a) Locations of meteorological stations (red dots) in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA, blue area). (b) Monthly mean of the GBA TC frequency. The annual mean value is revealed in the upper left corner.

where the subscripts \(x\) and \(y\) denote the zonal and meridional coordinates, respectively.

To assess the impact of TCs, we defined their activity affecting the GBA when the following criteria were simultaneously conformed: (a) the minimum distance between the TC center and any meteorological station in the GBA was less than 500 km, and (b) any meteorological station in the GBA received a rainfall amount above 50 mm \(d^{-1}\), as shown in figure 1(a). In this study, we only applied the data over the satellite era from 1980 to 2019 when TC data were relatively reliable. Moreover, we focused on the TC activity during peak summer (July–September, JAS) over the WNP (100\(^\circ\)E–180\(^\circ\), north of the equator), because it is the active TC season for southern China (Zhang et al 2019, Yao et al 2021). To reduce the effect of global warming, we removed the long-term linear trend of the monthly reanalysis data. The significance of the composite anomalies and linear correlations was examined using the two-tailed student’s \(t\)-test.

The genesis potential index (GPI; Emanuel and Nolan 2004, Murakami and Wang 2010) is usually applied to assess the large-scale environment of TC genesis, since it can capture the TC genesis variations in different ocean basins (Camargo et al 2007, Bruyère et al 2012, Yu et al 2016, Yuan et al 2019). A new dynamic GPI (DGPI) was recently developed by Wang and Murakami (2020), which improves the skills in representing the interannual variations of TC genesis frequency in the WNP. The improved GPI was calculated as follows in this study:

\[
\text{DGPI} = (2 + 0.1V_s)^{-1.7} \left( 5.5 - \frac{\partial u}{\partial y} 10^5 \right)^{2.3} \\
\times (5 - 20\omega)^{3.3} (5.5 + |10^5\eta|)^{2.4} e^{-11.8} - 1
\]

(1)

where \(V_s\) is the magnitude of the vertical wind shear between 850 hPa and 200 hPa, \(\frac{\partial u}{\partial y}\) is the meridional gradient of zonal wind at 500 hPa, \(\omega\) is vertical \(p\)-velocity at 500 hPa, \(\eta\) is the absolute vorticity at 850 hPa, and \(e\) is the natural logarithm.

To illustrate the propagation characteristics of the stationary Rossby wave trains, we calculated the horizontal component of the wave activity flux (WAF) in the spherical coordinates following Takaya and Nakamura (2001),

\[
WAF_H = \frac{p\cos\phi}{2|U|} \left\{ \frac{U}{\sin\phi} \left( \frac{\partial \Psi'}{\partial x} \right)^2 - \Psi' \frac{\partial^2 \Psi'}{\partial \lambda^2} + \frac{V}{\sin\phi} \left( \frac{\partial \Psi'}{\partial \lambda} \frac{\partial \Psi'}{\partial x} \right) + \frac{V}{\sin\phi} \left( \frac{\partial \Psi'}{\partial \lambda} \frac{\partial \Psi'}{\partial y} \right) + \frac{\partial \Psi'}{\partial \phi} \left( \frac{\partial \Psi'}{\partial \phi} \right)^2 - \Psi' \frac{\partial^2 \Psi'}{\partial \lambda \partial \phi} \right\}
\]

(2)

where \(p\) is the pressure; \(a\) is the earth radius; \(\phi\) and \(\lambda\) are the latitude and longitude, respectively; \(U\) and \(V\) are the climatology of the zonal and meridional wind, respectively; \(|U|\) is the magnitude of \((U, V)\); and \(\Psi'\) is the perturbation streamfunction relative to climatology.

Additionally, numerical experiments were performed using the Community Atmosphere Model version 4 (CAM4; Neale et al 2013). The CAM4 is the
atmospheric component of the NCAR Community Earth System Model version 1.2.2, with a horizontal resolution of 1.9° × 2.5° and 26 hybrid sigma levels.

3. Large-scale circulation anomalies related to the frequency of the GBA TCs

About three TCs affect the GBA in each peak summer during 1980–2019, accounting for 75% of the annual total amounts (figure 1(b)). Most of them are generated over the South China Sea and the Philippine Sea before moving northwestward toward southeastern China (figure 2(a)). The tracks of these TCs are substantially along with the southwestern boundary of the WNPSH.

Previous studies have indicated that the frequency of the TCs invading southeastern China is related to the meridional variation of the western edge of the WNPSH (Tu and Chen 2019) and the zonal shift of the MT (Wu et al 2012, Hu et al 2018). Analogously, the frequency of the GBA TCs is significantly correlated with the positive geopotential height anomalies at 500 hPa to the northeast of the GBA, whereas a negative center is located to the southwest (figure 2(b), shadings). Similar results could be observed at 850 hPa (figure not shown). It seems that a planetary-scale wave train from Southeast Asia extends to Northeast Asia with an anomalous cyclonic circulation over Southeast Asia and Northeast Asia, and an anticyclonic circulation over East Asia (also see Zhou and Lu 2019), which mesh a southeasterly wind anomalies toward the GBA (figure 2(b), vector), favoring the impact of TCs on the area.

To clarify the relationship between large-scale circulation anomalies and the frequency of the GBA TCs, a meridional pressure gradient index (MPGI) is defined as the difference in normalized area-averaged geopotential height anomalies at 500 hPa between a northeastern box (100° E–135° E, 25° N–35° N) and a southwestern box (75° E–120° E, 15° N–25° N), as shown in figure 2(b). It is worth noting that the frequency of the GBA TCs is directly related to the MPGI with a correlation coefficient up to 0.54 (figure 2(c)), exceeding the 99.9% confidence level. Six active GBA TC years (1984, 1985, 1995, 2003, 2006, and 2013) and six inactive GBA TC years (1987, 1988, 1997, 1998, 2014, and 2015) are identified (figure 2(d)), referred to active years and inactive years respectively in this paper for convenience. (A criterion of 0.65 standard deviations of the MPGI and the frequency of the GBA TCs happens to yield the same samples of 6 years for both active and inactive groups.)

Table 1 presents the average frequency of the GBA TCs and all WNP TCs during the JAS of two
Table 1. Average frequency of the GBA TCs, all WNP TCs, and their ratio during the JAS of 1980–2019 in climatology, active years, inactive years, and their difference. Bold values indicate the significant values above the 99% confidence level.

|            | Climatology | Active years | Inactive years | Difference |
|------------|-------------|--------------|----------------|------------|
| GBA TC     | 2.95        | 4.50         | 1.17           | 3.33       |
| WNP TC     | 14.05       | 12.83        | 11.50          | 1.33       |
| Ratio      | 21.00%      | 35.06%       | 10.14%         | 24.92%     |

Figure 3. (a) Composite patterns of geopotential height at 500 hPa (red contour, gpm) and 850 hPa (shading, gpm) during the active years. Olive curve denotes the zero line of zonal wind at 850 hPa (i.e. MT). (c) Moving tracks and genesis locations of the TCs during the active years. Blue dots and green lines represent the GBA TCs. Gray dots and lines represent the WNP TCs. (b) and (d) are the same as (a) and (c), but for inactive years. Composite differences in (e) TC track density (shading) and steering flow (vector, m s\(^{-1}\)), and (f) genesis density between the active and inactive years. Pink vectors and white dots denote the significant values above the 90% confidence level.

The effects of the different configurations of MT and WNPSH are examined for the two categories. As shown in figures 3(a) and (b), to the southwest of the WNPSH (i.e. 5865, 5873, and 5880 gpm contours at 500 hPa; red curves), the transition between westerly and easterly winds along the 850 hPa geopotential height contours comprises the MT, an elongated region of relatively low atmospheric pressure, whose central position can be depicted by the zero line of the zonal wind speed (olive curve). In the active years, the MT intensifies and extends eastward from the northern South China Sea to the west of 150\(^\circ\) E, and the composite WNPSH ridge is located in the north of the GBA at approximately 27\(^\circ\) N (figure 3(a)). Along the geopotential height contours, southeasterly wind lies around the Luzon Strait and causes more WNP TCs to make landfall in southeastern China.
Figure 4. Composite differences in (a) dynamic genesis potential index, (b) vertical wind shear (m s$^{-1}$), (c) 500 hPa meridional gradient of zonal wind (10$^{-3}$ s$^{-1}$), (d) 500 hPa vertical velocity (10$^{-2}$ Pa s$^{-1}$), and (e) 850 hPa absolute vorticity (10$^{-6}$ s$^{-1}$) between the active and inactive years. White dots denote the significant values above the 90% confidence level.

In the inactive years, however, the MT exhibits an eastwards shift extending from the east of the Taiwan island to the east of 150° E, and the WNPSH ridge shifts southward to the south of the GBA (figure 3(c)), providing northerly steering flow in the region of the Luzon Strait. The WNP TCs form outside the South China Sea are more likely to recurve northward (figure 3(d)), so that the number of invading TCs for GBA is decreased. To investigate the influences of large-scale flows on TC tracks, figure 3(e) shows the composite differences in the steering flow, defined as the pressure-weighted wind averaged from 850 hPa to 300 hPa, and the TC track density between the active and inactive years. With the corresponding circulation changes, significant anticyclonic steering flow anomalies are observed over the East Asia coast, resulting in a significant positive track density anomaly in southeastern China. This feature means that the TCs generated in the WNP are probably guided by anomalous easterly steering flow to move toward southeastern China, instead of moving northward, consequently increasing the TC activity affecting the GBA.

Additionally, the above spatial patterns of atmospheric circulation may affect the genesis of the WNP TCs. Compared with the inactive years, the WNP TCs are more likely to form near the mainland during the active years, corresponding to a significantly positive (negative) genesis density anomaly in the west (east) of 140° E over the WNP (figure 3(f)). As in previous studies (Gray 1968, Wu and Wang 2004, Gao et al 2020, Zhao et al 2021), large-scale environmental conditions related to TC genesis are further examined. Figure 4(a) shows the composite differences in DGPI between the active and inactive years. A distinct east-west dipole pattern is observed in the north of 10° N over the WNP, which is in good agreement with the spatial distribution of the TC genesis density anomaly, indicating that the DGPI is suitable for diagnosing TC genesis in this study. Four components of the DGPI, 850–200 hPa vertical wind shear, 500 hPa meridional gradient of zonal wind, 500 hPa vertical p-velocity, and 850 hPa absolute vorticity, are further examined. Compared with the inactive years, significantly larger meridional shear vorticity of the zonal winds (figure 4(c)) and ascending motions (figure 4(d)) at the mid-level, and positive vorticity (figure 4(e)) at the lower-level are responsible for the more TC genesis during the active years. This result demonstrates that the WNPSH retreats from the South China Sea and shrinks northeastwards, and the MT moves into the South China Sea and covers the west of 150° E, which provide favorable cyclonic convergent conditions for the formations of TCs in the western WNP. Therefore, it is suggested that the tacit-and-mutual configurations of the MT and the WNPSH not only provide a favorable dynamic environment for the higher genesis frequency of the WNP TCs near the mainland, but also guide the TCs to move toward the GBA along the southeasterly steering flow during the active years.
Figure 5. (a) Climatology of 850 hPa horizontal wind (vector, m s$^{-1}$). Composite differences in (a) sea surface temperature (shading, °C), (b) outgoing longwave radiation (shading, W m$^{-2}$), (c) vertical circulation (vector; black vectors denote the significant values above the 90% confidence level) and vertical velocity (shading, −10$^{-2}$ Pa s$^{-1}$) averaged between 10° S and 10° N, and (d) 500 hPa stream function (contour, 10$^6$ m$^2$ s$^{-1}$) and T-N wave activity flux (vector, m$^2$ s$^{-2}$; values less than 0.4 are omitted) between the active and inactive years. Plus signs denote the significant values above the 90% confidence level. Blue box (120° E–150° E, 5° S–10° N) in (b) indicates the key region of convective heating.

4. Convective heating modulating the shifts of the MT and the WNPSH

The SST anomalies in tropical oceans could affect the overlying atmospheric circulation via the interactions between the atmospheric and oceanic processes. Thus, to investigate the possible mechanisms for the shifts of the MT and the WNPSH, we examine the potential tropical forcing in the Indo-Pacific Oceans.

Figures 5(a) and (b) show the composite differences in SST and OLR between the active and inactive years. A La Niña pattern accompanied by a cold anomaly in the equatorial central-eastern Pacific and a warm anomaly in the western Pacific is observed during the active years. With the lower-level background southeasterly wind, the underlying warm (cold) SST anomaly yields stronger (weaker) convection to the northwest. Notably, an enhanced Walker circulation is characterized by a strong ascending anomaly over the western Pacific warm pool and a descending anomaly over the equatorial central Pacific (figure 5(c)). Subsequently, a pair of cyclonic circulation anomalies straddling the equator to the west of the convective heating over the western Pacific warm pool, and a pair of anticyclonic circulation anomalies to the east, appear in the composite difference in streamfunction at 500 hPa (figure 5(d)), featuring a typical Matsuno–Gill response to tropical heating source (Matsuno 1966, Gill 1980). The lower-level cyclonic circulation anomalies to the northwest of the convective heating facilitate a strengthening of the southwesterly monsoon circulation, which reduces the SST from the western Indian Ocean to the South China Sea through the wind–evaporation–SST feedback (Wang et al 2000). Thus, the negative SST anomalies over the Indian Ocean are mainly
a result of atmospheric influence, indicating that the Indian Ocean SST anomalies play a weaker role in inducing atmospheric anomaly compared with the Pacific SST. Meanwhile the easterly wind anomalies of the southern flank of the anticyclonic circulation anomalies with the Matsuno–Gill response reinforce the background easterly and divergent outflow from the Walker circulation (figure 5(c)). Therefore, the La Niña-type Walker circulation over the Pacific and the monsoon-enhanced Walker circulation over the Indian Ocean persistently maintain the ascending anomaly over the western Pacific warm pool.

Furthermore, a meridional wave train exists in the Southeast and Northeast Asian regions (figure 5(d)). A cyclonic circulation anomaly is located in the region of 75°–115° E/5°–25° N, and an anticyclonic one in the northeast with a center over the Korean Peninsula. This wave-like spatial pattern is similar to that in figure 2(b). Analysis of the horizontal WAF reveals a wave train propagation from Southeast Asia to Northeast Asia through a mechanism as for the formation of the Pacific–Japan or East Asia–Pacific teleconnection pattern in summer (Nitta 1987, Huang and Sun 1992). Specifically, the divergence aloft excited by tropical heating can generate a Rossby waves with the background vorticity gradient, and further produce a wave train propagating poleward as energy dispersion along a great circle path in the subtropical jet stream (Hoskins and Karoly 1981, Simmons et al 1983, Sardeshmukh and Hoskins 1988, Jin and Hoskins 1995). Hence, considering the variation of this Rossby wave train pattern, we suggest that the tropical convection anomaly would modulate the shifts of the MT and the WNPSH, consequently favoring the TC activity affecting the GBA.

The causal link between the topical convective anomaly and the wave train teleconnection is further investigated by conducting experiments with the CAM climate model. Here, the control experiment (CTL) was forced by monthly SST with the climatological annual cycle of 1982–2001 (Hurrell et al 2008). The sensitive experiment (SEN) was the same as the CTL except for intensifying the convective heating over the western Pacific (120° E–150° E, 5° S–10° N; box in figure 5(b)) by imposing an amplification factor of 1.2. The heating profile was calculated as the area average of the heating over the western Pacific (figure 6(a)). Both experiments were integrated for 15 years, and the outputs of the last 10 years were analyzed. The differences between the SEN and the CTL represent the effect of the convective heating over the western Pacific. The simulated circulation anomalies with the zonal mean removed (figure 6(b)) present a stationary eddy wave-like spatial pattern at 500 hPa, with negative geopotential height anomalies over South and Northeast Asia, and positive anomalies over East Asia. Correspondingly, significant southeasterly wind anomalies are found over the Philippine Sea, similar to the observed results discussed above (figure 2(b)). Hence, the impact of the convection anomaly over the western Pacific warm pool on the atmospheric circulation observed can be well simulated in the CAM climate model.

5. Concluding remarks

This study reveals the characteristics of the GBA TC activity and their associated large-scale circulation features during the peak TC season (July–September) of 1980–2019. According to the criteria based on the affected areas and intensity of TCs, approximately three TCs affect the GBA during the peak TC season every year. Notably, the different configurations of the MT and the WNPSH exert significant impacts on the interannually varying frequency of the GBA TCs, as implied by the coefficient (0.54) of correlation between the circulation index and the GBA.
TCs, which exceeds the 99.9% confidence level. Such a strong link is mainly due to the favorable steering flow and large-scale dynamic conditions. On the one hand, intensified and westward-shifted MT and northeastward-shrunk WNPSH are associated with the southeasterly wind anomalies over the southeast coast of China, causing more TCs to move northwestward toward the GBA. On the other hand, the cyclonic convergent conditions related to the tacit-and-mutual configurations of the MT and the WNPSH lead to significantly larger meridional shear vorticity of the zonal winds and ascending motions at the mid-level and positive vorticity at the lower-level that favor more TC genesis in the west of 140°E over the WNP. By contrast, the steering wind anomalies and dynamic conditions for TC genesis are opposite in the inactive TC years.

Further statistical and numerical analyses indicate that the shifts of the MT and the WNPSH could be related to the anomalous tropical convective activity over the western Pacific warm pool, which is associated with the ascending branches of the La Niña-type Walker circulation over the Pacific and the monsoon-enhanced Walker circulation over the Indian Ocean. Particularly, the above-normal convective activity over the western Pacific warm pool could trigger a lower-level cyclonic circulation anomalously to the southwest of the GBA as a Matsuno–Gill response. Meanwhile, a mid-tropospheric wave train from Southeast Asia to Northeast Asia is excited, which in turn affects the shifts of the MT and the WNPSH.

Our result provides a valuable insight onto the study of regional TCs and climate. It is interesting to find that the GBA TC activity is very sensitive to the variations of large-scale atmospheric circulation, and to identify a key tropical region as the source of the anomalous atmospheric circulation verified by both statistical analyses and numerical experiments. Thus, recent prediction and efficient monitoring measurements of the variations of large-scale circulation and its related cause are critical for foreseeing the regional TC activity, which deserves further investigations.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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10