Characteristics and Diagnosis of the Landfalling Tropical Cyclones in the Guangdong-Hong Kong-Macao Greater Bay Area of China During 1981–2018

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Abstract: This paper applies statistical and synthetic analysis methods to study the characteristics of the three types of tropical cyclone (TC) that landed in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) from 1981 to 2018 and the reasons for the differences of TC-induced wind and precipitation. The results show that there are interdecadal changes in the frequency and intensity of the landfalling TCs in the GBA, with decreased frequency but increased intensity in the 2010s. The TCs that landed in the west of the Pearl River Estuary (PRE) have the highest frequency and the strongest intensity during landing, which bring the strongest winds; the TCs that landed in the PRE have the lowest frequency and the shortest duration after landing, which cause the strongest precipitation; the TCs that landed in the east of the PRE have the longest duration on the land. This study shows that near the center of the TCs that landed in the PRE, there is a weak anomalous cyclonic shear compared with the ones that landed in the west of the PRE. It is a confluence area of anomalous north wind and anomalous southwest wind, with better water vapor convergence and dynamic rising conditions, which is conducive to the formation of heavy precipitation. Compared with the TCs that landed in the PRE and in its east, there is a closed positive anomalous center of pressure gradient in the northwest center of the TCs that landed in its west, resulting in higher wind speeds in the west of the PRE. The characteristics of the three types of TCs in the GBA are highly related to TC-induced damage. In the future, the GBA needs to focus on preparing for TCs landing in its west. Zuhai, Jiangmen and Huizhou are key cities to guard against TCs. The results of this study provide foundations for effective management and reduction of TC disaster risks in the future development of the GBA.

Key words: landfalling TCs; characteristics; diagnosis; Guangdong-Hong Kong-Macao Greater Bay Area

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1 INTRODUCTION

Affected by global warming, severe tropical cyclones (TCs) in the northwest Pacific have increased significantly in recent decades, with greater destructive power (Emanuel [1]; Webster et al. [2]; Li and Zhou [3]; Knutson et al. [4]). China is one of the countries with the worst TC disaster in the world. According to statistics, an average of 7.2 TCs made their landfall in China each year from 1949 to 2015. From 1990 to 2015, there were an average of 359 deaths and a direct economic loss of RMB 39.87 billion Yuan per year caused by TCs (Jiao et al. [5]). With population growth and rapid urbanization, the economic and social losses caused by TCs have increased significantly (Qin et al. [6]). In particular, the coastal river deltas are the areas with higher risk of TC disasters (Yin et al. [7]), among which, Guangdong Province has the highest frequency of disastrous landfalling TCs (Zhang et al. [8]; Chen et al. [9]; Wen et al. [10]).

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is located on the coast of central Guangdong Province. It is one of the three mega-city clusters in China, the GDP of which accounts for 12% of the country. It consists of Guangzhou, Foshan, Zhaqing, Shenzhen, Dongguan, Huizhou, Zuhai, Zhongshan, Jiangmen, and two special administrative regions of Hong Kong and Macao. Over the past decade, the number of TC that landed in the GBA with extreme intensity has increased significantly (Luo et al. [11]). Against the background of climate change and rising sea levels, cities such as Guangzhou, Dongguan, Shenzhen, Zhongshan, and Zuhai in the GBA are facing high

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disaster risks of TCs (Yin et al.\textsuperscript{[11]}). For example, strong Typhoon Hato landed in Zhuhai, causing 24 deaths and a direct economic loss of RMB 28.9 billion Yuan in the Chinese mainland; strong Typhoon Mangkhut landed in Taishan City, causing a direct economic loss of RMB 14.4 billion Yuan in Guangdong Province (NCC\textsuperscript{[12]}). Therefore, TC disaster is one of the climate issues that the GBA has to face in the process of economic development. Analyzing the climatic characteristics and causes of TCs landing in the GBA is very important for the region to adapt to climate change and reduce disaster-induced losses.

In recent years, the climatic characteristics and impact of TCs landing in China have attracted the attention of many scholars. Studies have shown that the number of strong typhoons landing in China had increased (Wu et al.\textsuperscript{[13]}, Wang et al.\textsuperscript{[14]}, Xiao et al.\textsuperscript{[15]}, Yin et al.\textsuperscript{[16]}, Li and Zhou\textsuperscript{[17]}), resulting in the increase of the annual average intensity of extreme gales (Lu et al.\textsuperscript{[18]}) and the precipitation of a single TC (Ying et al.\textsuperscript{[19]}). The intensity and the potential destructive power of the TCs that landed in southern China have also increased (Yin et al.\textsuperscript{[20]}, Liu et al.\textsuperscript{[21]}). There are many studies on the formation mechanism of TC precipitation and wind field from the perspective of large-scale environmental field (Chen et al.\textsuperscript{[22]}, Li et al.\textsuperscript{[23]}, Tan et al.\textsuperscript{[24]}, Liu et al.\textsuperscript{[25]}). The different TC landfall locations would result in different impact (Yin et al.\textsuperscript{[26]}, Kim et al.\textsuperscript{[27]}, Ye et al.\textsuperscript{[28]}). Previous studies have mostly analyzed the climatic characteristics of landfalling TCs on a large spatial scale, and performed numerical simulation and diagnosis of particular TC cases (Ren et al.\textsuperscript{[29]}). For the specific area of the GBA, there are few studies on the characteristics and synthetic diagnostic analysis of landfalling TCs (Zhang et al.\textsuperscript{[30]}).

In view of this, based on TC frequency, intensity, track, duration, high winds, heavy precipitation and other factors, this paper studied the climate characteristics of landfalling TCs in the GBA from 1981 to 2018 in three different landing locations, and made preliminary diagnosis of the difference in TC-induced wind and precipitation. It is aimed to provide scientific support for the decision-making and management of TC disaster risks reduction in the GBA.

2 DATA AND METHOD

2.1 Data

The daily (Chinese Standard Time from previous 20h to current 20h) precipitation and maximum wind speed (10-minute average) data of 29 meteorological observatories in the GBA used in this paper (Fig. 1) were from the Daily Meteorological Dataset of Basic Meteorological Elements of China National Surface Weather Station issued by the National Meteorological Information Center of China Meteorological Administration (Ren et al.\textsuperscript{[11]}). The best track data compiled by the Shanghai Typhoon Institute of China Meteorological Administration were used in this paper, containing the latitude, longitude, and wind speed intensity of the TC center every 6 hours (Ying et al.\textsuperscript{[32]}, Lu et al.\textsuperscript{[33]}). Considering the large uncertainty of the TC track data before the 1980s and the lack of observational data of strong winds, this paper selected the period between 1981 and 2018 for analysis.

![Figure 1. Schematic diagram of the location and meteorological observation stations in the GBA.](image-url)
The TC disaster data during 1991–2018 were from the National Climate Center, excluding the data of the Hong Kong Special Administrative Region and Macao Special Administrative Region. Among them, the direct economic loss was revised to the 2010 price level using the price index. According to the national standard of TC classification (CMA\textsuperscript{[14]}), TCs are classified as tropical depression (TD, 10.8–17.1 m s\(^{-1}\)), tropical storm (TS, 17.2–24.4 m s\(^{-1}\)), strong tropical storm (STS, 24.5–32.6 m s\(^{-1}\)), typhoon (TY, 32.7–41.4 m s\(^{-1}\)), strong typhoon (STY, 41.5–50.9 m s\(^{-1}\)) and super typhoon (super TY, \(\geq 51.0\) m s\(^{-1}\)).

The data used in the diagnostic analysis were the ERA-5 atmospheric reanalysis data (Hersbach et al.\textsuperscript{[15]}), including parameters such as 850 hPa meridional wind, zonal wind and specific humidity, sea level air pressure, and multi-layer vertical velocity. The data resolutions of time and space are hour by hour and 30 km respectively.

2.2 Method

In the statistics of TC-induced wind and precipitation, the number of heavy rainfall days (HRD) referred to the number of days with daily precipitation \(\geq 100\)mm, and the number of high wind days (HWD) referred to the number of days with maximum daily wind speed \(\geq 17.2\) m s\(^{-1}\). Mean process precipitation (MPP) and mean process wind speed (MPW) respectively referred to the average of TC-induced process precipitation and process maximum of the daily wind speed at each station. The maximum daily precipitation (MDP) and maximum daily wind speed (MDW) respectively referred to the maximum daily precipitation and wind speed among the stations for each TC. Then, the MMDP and MMDW are respectively short for the average of MDP and MDW for many TCs.

In this paper, for a more detailed analysis of the characteristics of landfalling TCs in GBA, landfalling TCs were divided into three categories according to landing locations, namely, landing in the west of Pearl River Estuary (PRE), landing in the PRE, and landing in the east of the PRE. At the same time, the differences of atmospheric circulation factors of the three types of landfalling TCs were diagnosed and analyzed by using the synthesis method. The synthesis analysis steps were as follows:

1. Determine the latitude and longitude of the TC’s landing location, and use the ERA-5 data cell (0.25\degree \times 0.25\degree) as the background to find the cell of the landing location;

2. Center on the cell of the landing location, expand at equal intervals in four directions of east, south, west and north, and form a study area consisting of 80 \times 80 grid points to meet the upper limit about 1100 km of the TC outer radius;

3. According to the study area where each TC was formed, extract the hourly atmospheric circulation variable values on 80 \times 80 grid points. The period was from 6 hours before the TC landfall to 6 hours after the landfall, including the 13 time periods. The values of each variable at 13 times were averaged to get the average volume field for each TC;

4. The average volume field for each TC were further synthesized and averaged to obtain the average volume field for the three categories of landfalling TC, respectively;

5. Perform comparative diagnostic analysis based on the average volume field of various types of TCs.

3 RESULTS

3.1 Overview of the landfalling TCs

From 1981 to 2018, a total of 32 numbered TCs (landfall intensity of 17.2 m s\(^{-1}\) and above) landed in the GBA, with an average landfall intensity of 30.9 m s\(^{-1}\); there were 12 TCs with the intensity of typhoon and above, including 2 strong typhoons, namely Hato and Mangkhut, with landfall intensity of 48 m s\(^{-1}\) and 42 m s\(^{-1}\) respectively. In terms of interdecadal variation (Table 1), the number of landfalling TCs was the highest (11) in the 2000s; although the landing frequency was the least in the 2010s among the recent three decades, the average landfall intensity was the highest, reaching 34.7 m s\(^{-1}\). More than half of the TCs reached the intensity of typhoon and above, and the two strong typhoons landing in the GBA both occurred in the 2010s. This was in line with previous studies which argued that global warming might lead to an increase in the proportion of strong typhoons (Wang et al.\textsuperscript{[14]}; Lee et al.\textsuperscript{[15]}), as well as with the fact that the intensity of typhoons landing in southern China in the past some 10 years has significantly increased (Luo et al.\textsuperscript{[11]}).

From the monthly frequency and average intensity of landfalling TCs of the GBA in the past some 40 years (Fig. 2), it can be seen that the period between July and September was active with 81.3% of the total landfalling TCs in the GBA (26 TCs). Moreover, TCs classified as typhoon and stronger TCs all occurred during that period. The average landing intensity in September was the strongest, reaching 34.4 m s\(^{-1}\).

From the perspective of the spatial distribution of landing locations (Fig. 3), the number of TCs landing in Jiangmen, Huizhou, Zuhai, Shenzhen, Hong Kong, and Zhongshan was 10, 6, 6, 5, 4, and 1 respectively, and the average intensity was 30.5 m s\(^{-1}\), 29.7 m s\(^{-1}\), 33.0 m s\(^{-1}\), 29.8 m s\(^{-1}\), 25.8 m s\(^{-1}\) and 30.0 m s\(^{-1}\) respectively.

According to disasters statistics of landfalling TCs in the GBA during 1991–2018, it can be found that, on average, TCs that landed in the GBA caused 5.6 deaths and a direct economic losses of RMB 1.74 billion Yuan annually. It is an area that is heavily affected by TC disasters in China (Jiao et al.\textsuperscript{[17]}). In the past some 30 years, the direct economic losses caused by TCs in the GBA have increased significantly (Table 1). The average annual direct economic losses in the 2010s reached RMB 5.93 billion Yuan, which was 4.6 times of that in the 1990s (RMB 1.28 billion Yuan). On the one hand, it
was because of the higher intensity of the TCs that landed in the 2010s, the rapid economic and social development of the GBA in the past some 10 years, and the increase in population and economic exposure. This was an important reason why TCs have increased their economic and social impact in recent years (Zhang et al. [37]). On the other hand, it was also related to the rapid development of the GBA urbanization since the 2010s (Qin et al. [6]).

3.2 Three types of landfalling TCs

Landfalling TCs in the GBA can be divided into three categories according to the distance from the landing position to the trumpet-shaped topography of the PRE, namely, landing in the west (the west of the PRE), landing in the PRE, and landing in the east (the east of the PRE). The number of TCs that landed in the above mentioned three areas was 14, 7 and 11 respectively, with an average landfall intensity of 33.4 m s⁻¹, 28.6 m s⁻¹, and 29.1 m s⁻¹. Among them, 7 typhoons and above landed in the west, 4 landed in the east, and 1 landed in the PRE. Strong typhoon Hato and Mangkhut made their landfall in the west. It can be seen that the TCs that landed in the west had the highest frequency and the strongest intensity. Moreover, there were interdecadal

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Table 1. The decadal frequency, intensity and economic loss of landfalling TCs in the GBA.

| Decade | Frequency | Landfall frequency of typhoon and above | Average landfall intensity (m s⁻¹) | Economic loss (RMB 1 billion RMB) | Death toll |
|--------|-----------|----------------------------------------|----------------------------------|---------------------------------|------------|
| 1980s  | 5         | 1                                      | 32.0                             |                                 |            |
| 1990s  | 9         | 4                                      | 30.6                             | 1.28                            | 15         |
| 2000s  | 11        | 3                                      | 27.9                             | 1.78                            | 25         |
| 2010s  | 7         | 4                                      | 34.7                             | 5.93                            | 8          |

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Figure 2. Monthly frequency (a) and average intensity (b) of landfalling TCs in the GBA during 1981–2018.

Figure 3. Landing positions of landfalling TCs in the GBA during 1981–2018 (The red box: landfalling TCs in the PRE).
changes in the landing locations. The TCs that landed in the GBA in the 1980s were all in the western track and TCs mainly landed in the PRE in the 1990s, while TCs mostly landed in the eastern track in the 2000s (7 TCs) and in the western track in the 2010s (5 TCs).

3.2.1 TRACKS OF TCs

Figure 4 illustrates the tracks of the three types of landfalling TCs in the GBA. Most of the TCs that landed in the GBA were generated in the ocean at 135°–140°E east of the Philippines. Only Mangkhut and Ellen were generated near 165°E. Due to the long duration, Mangkhut and Ellen had enough time to develop and strengthen, and eventually became super typhoons. Mangkhut made landfall in the west with an intensity of 42 m s\(^{-1}\) (strong typhoon level), and Ellen made landfall in the PRE with an intensity of 40 m s\(^{-1}\) (typhoon level).

As for the three types of TC tracks, it can be found that the TCs that landed in the west were mainly westbound, and most of them entered Guangxi Province (Fig. 4a). After landing, their duration was longer with an average duration of 19.6 h on the land (the central wind speed was 10.8 m s\(^{-1}\) and above; the same below). Most of the TCs that landed in the PRE moved towards the north-central part of Guangdong Province after landing, and would soon disintegrate or die out, with an average duration of 16.7 h on the land (Fig. 4b). Some of the TCs that landed in the east moved westward towards Guangxi Province after landing (Fig. 4c), and some of them moved towards Jiangxi Province, with the longest on-land duration up to 20.6 h (Fig. 4d).

Figure 4 further shows the average position of the Northwest Pacific Subtropical High (NPSH). It can be found that the NPSH corresponding to westbound TCs was relatively westward (Fig. 4a and Fig. 4c). The

![Figure 4. Track diagram of three types of landfalling TCs (a: landfall in the west; b: landfall in the PRE; c: landfall in the east. The colors of the track line represent different TC levels, among which gray means below the intensity of tropical depression, green means tropical depression, blue means tropical storm, cyan means severe tropical storm, yellow means typhoon, orange means strong typhoon and red means super typhoon. Numbers near the birth point of typhoon indicate the TC number ID. The shaded area represents the average position of the NPSH).](image-url)
NPSH ridge in Fig. 4c was more westward and northward, which leads to TCs mostly crossing the Bashi Channel. However, in Fig. 4a, TCs mostly made landfall over Luzon Island. The NPSH corresponding to northbound TCs was relatively eastward (Fig. 4b and 4d). The NPSH ridge in Fig. 4d was more eastward and southward, which made the genesis position of TCs in Fig. 4d more southward. The TCs in Fig. 4d mostly moved through the central Philippines, while TCs in Fig. 4b mostly made landfall over Luzon Island. Above all, the NPSH plays a key role in the development of TC tracks landing in the GBA.

3.2.2 TC-INDUCED WIND AND PRECIPITATION

The precipitation information of each meteorological station caused by the three types of TCs was calculated to obtain the MPP. It can be seen that the TCs that landed in the PRE caused a total of 13 stations’ MPP to exceed 100 mm, and that in the two sides of the PRE reached 150 mm and above (Fig. 51b). Among them, the MPP in Shenzhen (198.7 mm) and Doumen (196.8 mm) exceeded 190 mm, becoming the largest and second largest value of the MPP among the three types of TCs. The TCs that landed in the east caused more precipitation to the west of the PRE. 10 stations’ MPP exceeded 100 mm (Fig. 51a). Among them, the MPP of Shangchuan Island and Shenzhen was 186.3 mm and 161.8 mm respectively, the largest and second largest value of the MPP caused by the TCs that landed in the west. The TCs that made landfall in the east caused the MPP to exceed 100 mm only in five stations (Fig. 51c), the largest of which occurred on Shangchuan Island (132.8 mm).

The statistics of the MPW caused by the three types of TCs indicated that the TCs that landed in the west could cause greater wind speeds in the west of the PRE, with the MPW exceeding 15 m s\(^{-1}\) in 5 stations (Fig. 5IIa). Among them, the MPW of Shangchuan Island (27.1 m s\(^{-1}\)) and Zhuhai (23.3 m s\(^{-1}\)) exceeded 20 m s\(^{-1}\), becoming the largest and second largest of the three types of TCs. The TCs that landed in the PRE caused the MPW in 3 stations to exceed 15 m s\(^{-1}\), of which Shangchuan Island (18.6 m s\(^{-1}\)) was the largest (Fig. 5IIb). The MPW of most of the TCs that landed in the east was 9 m s\(^{-1}\) and below, and only the MPW of Huidong exceeded 15 m s\(^{-1}\) (16.2 m s\(^{-1}\)) (Fig. 5IIc). It can be seen that compared with the other two types of landfalling

Figure 5. The MPP and the MPW of the three types of landfalling TCs (a: landing in the west, b: landing in the PRE, c: landing in the east; I refers to precipitation, units: mm; II refers to wind speed, units: m s\(^{-1}\)).
TCs, the TCs that landed in the east had a relatively small impact range.

Regional average statistics show (Table 2) that the strong winds caused by TCs that landed in the west were relatively strong, with the MMDW reaching 28.6 m s⁻¹ and an average HWD of 4.7, which were much larger than those landed in the PRE and in the east. The precipitation caused by the TCs that landed in the PRE were relatively strong; the MPP, MMDP, and average HRD of which were 99.9 mm, 220.0 mm, and 8.1, respectively. In particular, the MMDP was 58.7 mm and 43.0 mm more than that of the other two types, indicating that the TCs that landed in the PRE were easier to bring heavy rainfall.

Table 2. The characteristics of the three types of landfalling TCs in the GBA.

|                      | Landing in the west | Landing in the PRE | Landing in the east |
|----------------------|---------------------|--------------------|---------------------|
| Total frequency      | 14                  | 7                  | 11                  |
| MPP (mm)             | 93.4                | 99.9               | 73.3                |
| MMDP (mm)            | 161.3               | 220.0              | 177.0               |
| MMDW (m s⁻¹)         | 28.6                | 20.8               | 17.6                |
| HRD (station/day)    | 7.4                 | 8.1                | 6.1                 |
| HWD (station/day)    | 4.7                 | 2.7                | 0.6                 |

3.2.3 TC-INDUCED DAMAGE

Studies have shown that the landing location and movement path are the key factors to the impact of TC disasters (Jie et al. [8]; Li et al. [3]). Table 3 shows losses caused by landing TCs since 1991 in the GBA and Table 4 shows the statistical results of the three types of landfalling TCs. The results showed that the cumulative death toll caused by TCs that landed in the west and east was 77 and 72 respectively, while the number caused by TCs that landed in the PRE was 13. The direct economic loss caused by the TCs that landed in the PRE was RMB 2.61 billion Yuan, accounting for 5.2% of the total loss, that caused by the TCs that landed in the east was RMB 6.35 billion Yuan, accounting for 12.6% of the total loss, and that caused by the TCs that landed in the west was the highest, reaching RMB 41.52 billion Yuan, 82.2% of the total loss, far more than those of the other two types of landfalling TCs.

We further analyze the spatial distribution of disaster-induced losses. Due to limited samples, if the average value is used in spatial analysis, on the one hand, the corresponding average value of the cities with fewer samples may not have climatological significance; on the other hand, the local extreme large value may also enlarge the average value as a whole, resulting in defects in horizontal comparison. Therefore, cumulative analysis is adopted in this paper.

Table 3. Losses caused by landing TCs since 1991 in the GBA.

| TC number ID | Deaths (persons) | Economic loss (RMB 100 million Yuan) | Category | TC number ID | Deaths (persons) | Economic loss (RMB 100 million Yuan) | Category |
|--------------|------------------|--------------------------------------|----------|--------------|------------------|--------------------------------------|----------|
| 9108         | 1                | 3.1                                  | I        | 0707         | 0                | 0.1                                  | II       |
| 9316         | 31               | 23.6                                 | I        | 0812         | 0                | 0.9                                  | II       |
| 9318         | 18               | 47.6                                 | I        | 9505         | 6                | 14.1                                 | III      |
| 0907         | 1                | 4.2                                  | I        | 9509         | 3                | 10.1                                 | III      |
| 0915         | 1                | 9.3                                  | I        | 0013         | 0                | 2.9                                  | III      |
| 1208         | 8                | 11.5                                 | I        | 0104         | 0                | 1.8                                  | III      |
| 1713         | 13               | 239.8                                | I        | 0313         | 56               | 22.1                                 | III      |
| 1714         | 0                | 3.2                                  | I        | 0409         | 0                | 0.0                                  | III      |
| 1822         | 4                | 72.8                                 | I        | 0806         | 7                | 6.7                                  | III      |
| 9206         | 1                | 0.7                                  | II       | 0904         | 0                | 0.0                                  | III      |
| 9710         | 0                | 6.2                                  | II       | 0906         | 0                | 3.1                                  | III      |
| 9908         | 12               | 8.7                                  | II       | 1604         | 0                | 1.4                                  | III      |
| 9910         | 0                | 9.6                                  | II       | 1702         | 0                | 1.3                                  | III      |

*I refers to TCs landing in the west, II refers to TCs landing in the PRE, and III refers to TCs landing in the east.
In terms of the spatial distribution (Fig. 6), among the cities in the GBA, the largest cumulative direct economic losses caused by TCs were in Zhuhai (RMB 21.03 billion Yuan), followed by Jiangmen (RMB 10.51 billion Yuan) and Huizhou (RMB 5.75 billion Yuan). The TCs that landed in the west caused 99% and 97% of their own total losses in Zhuhai and Jiangmen respectively; the largest direct economic losses caused by TCs that landed in the east occurred in Huizhou, accounting for 64% of the total losses in Huizhou. By contrast, the figure for the TCs that landed in the west was 22%. The cumulative direct economic losses caused by TCs that landed in the PRE were relatively small.

### Table 4. Cumulative losses caused by three types of landfalling TCs in the GBA.

|                         | Landing in the west | Landing in the PRE | Landing in the east |
|-------------------------|---------------------|--------------------|--------------------|
| The number of deaths (persons) | 77                  | 13                 | 72                 |
| Direct economic loss (RMB 100 million Yuan) | 415.2               | 26.1               | 63.5               |
| Proportion of deaths (%) | 47.5                | 8.0                | 44.5               |
| Proportion of direct economic loss (%) | 82.2                | 5.2                | 12.6               |

**Figure 6.** The cumulative death toll and direct economic losses caused by three types of landfalling TCs during 1991–2018 (a: landfall in the west, b: landfall in the PRE, and c: landfall in the east; I refers to the death toll, units: person; II refers to the direct economic loss, units: RMB 100 million Yuan).

### 3.3 Diagnosis of Atmospheric Circulation Field

This paper applied the synthetic analysis method mentioned in Section 2.2 to diagnose the basic atmospheric circulation field before and after the TCs made their landfall, in order to further analyze the reasons of differences in the wind and precipitation characteristics among the three types of landfalling TCs.
in the GBA. Circulation fields related to precipitation included 850 hPa wind field, 850 hPa water vapor flux divergence field, 850 hPa vorticity field, and vertical velocity profile, and the circulation fields related to wind speed were mainly horizontal pressure gradients.

Figure 7 shows the differences of the 850 hPa synthetic wind field between the TCs that landed in the PRE and the ones in the west and east. It can be seen that, compared with the TCs that landed in the west (Fig. 7a), the one that landed in the PRE had a southwest-northeast anomalous wind speed zone, and a weak abnormal cyclonic shear from the center of the TC to the point (40, 50) on its north side. Compared with the TC that landed in the east (Fig. 7b), there was no abnormal wind speed zone in Fig. 7a, but an obvious anomalous confluence area near the center, where northerly and southwesterly wind anomalies met, forming a weak cyclone circulation in the northeast. The weak anomalous shear and the anomalous convergence of the north and south air flow were conducive to the convergence of water vapor around the center of the TC. As shown in Fig. 8, compared with the TCs that landed in the west (Fig. 8a) and the east (Fig. 8b), the ones that landed in the PRE had an obvious water vapor anomalous convergence center, which was conducive to the formation of precipitation system and heavy precipitation of the TCs that landed in the PRE.

Figure 9 shows the distribution of the relative vorticity difference at 850hPa. Near the TC center, there was an abnormally closed area of positive vorticity with a radius of about 100–200 km in Fig. 9a and 9b, indicating that near the center of the TC that landed in the PRE, the cyclonic circulation was more intense. The diagnostic analysis of the vertical velocity longitude-altitude profile (Fig. 10) showed that roughly within the longitude range corresponding to the grid points No. 37–45, there were obvious abnormal ascending motions in Fig. 10a and 10b, which could extend to the upper troposphere. Abnormal ascending movement was conducive to transporting water vapor upwards and promoting the development of precipitation.

In summary, the diagnosis of some factors related to precipitation near the TC center shows that the TCs landing in the PRE were more likely to bring heavy precipitation.
rainfall, making the MPP, MMDP and the number of heavy rainstorm days larger than that of the TCs landing in the west and east.

The uneven distribution of the horizontal air pressure leads to pressure gradient, which makes the air flow from the high-pressure area to the low-pressure area, the main factor in the formation of wind. Under normal circumstances, areas with dense isobars (high pressure gradients) tend to have higher wind speeds, while the wind speeds in areas with sparse isobars are relatively low. Of course, the surface wind speed has a lot to do with the roughness of the local underground surface and topography. For the convenience of calculation, by taking the TC center point as the basic point and the average pressure of the four grid points in the cell where the TC center was located as the basic value, this paper calculated the difference between the pressure of each grid point and the basic point, which is divided by the distance of the two grid points. The obtained value represents the pressure gradient between two points. Fig. 11 shows the difference of the composite pressure gradient between the TCs landing in the west, in the PRE and in the east. It can be seen that in the two figures, there was a closed center of the

![Image](image_url)

**Figure 9.** Same as Fig. 7, but for the relative vorticity (units: 10^-5 s^-1).

![Image](image_url)

**Figure 10.** Same as Fig. 7, but for the vertical velocity longitude-height profile difference averaged along the 35-50 grid point latitude (y-axis units: hPa, vertical speed: 10^-1 Pa s^-1).

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positive anomaly in the range of 40–45 in the northwest of the TC center, indicating that the TC that landed in the west has a larger pressure gradient in these areas, which led to a relatively high wind speed to a certain extent. This corresponded to the larger wind speed area in the west of the PRE in Fig. 5IIa. On the contrary, the negative value areas in the northeast of the TC center showed that the wind speed in the area east of the PRE caused by the TC that landed in the west was relatively low.

![Figure 11](image)

**Figure 11.** The difference of the composite pressure gradient between the TCs that landed in the west and the ones that landed in the PRE (a) and in the east (b) (units: hPa/0.25°; 0.25° is the grid resolution).

4 CONCLUSION AND DISCUSSION

This paper studies the characteristics of landfalling TCs in the GBA during 1981–2018, focusing on the frequency, intensity, track, duration, high wind, and heavy precipitation of TCs in three different landing locations. The reasons for the difference in TC-induced wind and precipitation at the landing position were diagnosed and analyzed to obtain the following conclusions:

1. A total of 32 TCs landed in the GBA from 1981 to 2018. Among them, Jiangmen had the largest number of landfalling TCs and Zhuhai had the strongest landfalling TCs. The frequency and intensity of landfalling TCs in the GBA had interdecadal changes. The landfall frequency decreased in the 2010s, but the intensity increased. July to September was the active period of landfalling TCs in the GBA, with the strongest average landfall intensity in September. Landfalling TCs had a serious economic and social impact on the GBA. During 1991–2018, landfalling TCs caused an average of 5.6 deaths per year, with a direct economic loss of RMB 1.74 billion Yuan, and the economic losses were on the rise. The average annual direct economic loss in the 2010s was 4.6 times that of the 1990s. Among the cities, Zhuhai had the largest cumulative direct economic loss, followed by Jiangmen and Huizhou.

2. Landfalling TCs in the GBA can be divided into three types: landing in the west, in the PRE, and in the east according to their landing locations. The TCs that landed in the west had the highest frequency and the strongest intensity. Among them, the intensity of 58.3% of the TCs that landed in the GBA reached the level of typhoon and above. The strong winds caused by TCs that landed in the west were relatively strong. MMDW and HWD were much larger than those landing in the PRE and in the east; the number of TCs that landed in the PRE was the least, causing MPP and MMDP to be the largest among the three types of TCs. The frequency and intensity of TCs that landed in the east were between that of the other two types.

3. The synthetic diagnosis of atmospheric circulation before and after the TCs made landfall shows that, compared with the TCs that landed in the west and east, there was an obvious water vapor anomalous convergence center around the center of the TC that landed in the PRE and a closed center of positive vorticity anomaly, which was accompanied by abnormal ascending movements, all conducive to the strong precipitation brought by the TCs that landed in the PRE. Compared with the TC that landed in PRE and in the east, there was a closed positive anomaly center of pressure gradient in the northwest of the TC center that landed in the east, which to a certain extent led to higher wind speeds in the west of the PRE. In areas with negative values in the northeast, the wind speed in the east of the PRE was relatively low to a certain extent.

The landing location has interdecadal changes, and the majorities landed in the west in the 2010s. Zhuhai, Jiangmen, and Huizhou were the three cities with the largest economic losses caused by the TCs that landed in the GBA. Especially in the 2010s, TC disasters were very severe, and 99% of the losses in Zhuhai and 97% of the losses in Jiangmen were caused by TCs that landed in the west.

TC disasters were the result of the superposition of hazard factors such as strong winds, rainstorms, storm surges and the exposure and vulnerability of disaster-
bearing bodies caused by TCs (Li et al. [3]). Therefore, in the process of the GBA construction, it is necessary to improve urban resilience and pay special attention to prevent TCs landing in the west.

The work of this paper is still preliminary. In the next step, we will do more detailed evaluation work by using the numerical model to analyze the distance and azimuth between the TC center and the area where heavy precipitation or strong wind occurs. The underlying surface and disaster information will also be considered to discuss the disaster mechanism of wind and precipitation caused by TCs.

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