Statistical Features of Tropical Cyclones Affecting China and Its Key Economic Zones

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ABSTRACT

Recent trends and variability in tropical cyclone (TC) frequency and intensity are examined for TCs that affected China, with particular focus on those TCs that affected China's key economic zones (e.g., the Yangtze River Delta, the Pearl River Delta, and the Beijing-Tianjin area). The results show that the frequency of TCs affecting China weakly declined during the 1980s and 2000s, followed by a slight increase. The time series of TC frequency shows insignificant variations at periods of 2–6 yr during the past 60 years; these variations are significantly correlated with ENSO activity. The frequency of TCs affecting the Pearl River Delta area is strongly correlated with the ENSO cycle while the frequency of TCs affecting the Yangtze River Delta is not. The TC frequency varies differently for TCs of different intensities. Tropical storms (TSs) affecting China were small in total number, but have clearly increased in frequency. The frequencies of severe tropical storm (STS), typhoon (TY), severe typhoon (STY), and super typhoon (super TY) affecting China declined significantly during the 1970s and 1980s, but the numbers of STY and super TY have increased over the 2000s.

The typical intensity of TCs affecting China declined over the 60-yr timeframe, but increased over the most recent 10 years (2000–2010). This increase in the intensity of TCs has particularly impacted the Yangtze River Delta area, which has experienced increased numbers of STYs and super TYs. These tendencies are observed in changes of the maximum intensity of TCs affecting both China in general and the Yangtze River Delta in particular during both the full 60-yr analysis period and the latest 10-yr period; however, these tendencies are not observed in changes of the average intensity of TCs. By contrast, both the extreme intensity and the average intensity of TCs affecting the Pearl River Delta have decreased throughout the analysis period, including the most recent decade.

Key words: tropical cyclones, features, economic zones

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1. Introduction

The severity of disasters caused by tropical cyclones (TCs) has motivated growing scientific attention to trend analysis of global TC impacts since the beginning of this century. In addition, the increasing concern regarding global warming has stimulated focused interest in how TC activities may change in the future. Emanuel (2005) noted that the Index of Potential Destructiveness (PDI) of TCs has increased significantly, while Landsea (2005) argued that this increase was at least in part because of underestimation of PDI for TCs that occurred before the 1960s. Changes in the frequency of typhoons in some areas might suggest a change in TC behavior, but no significant change has been identified in this connection on global scales (Landsea et al., 1998; Landsea et al., 2006; Chan and Shi, 1996; Chan, 2005, 2006; Henderson-Seller et al., 2006; Klotzbach, 2006). The contradictory nature of these results has aroused the interest of Chinese scientists, and has motivated an increase in the number of related studies.

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Most studies show that the frequency of TCs making landfall in China has declined in recent years. Yang et al. (2009) used data from the Tropical Best Track Database to analyze the frequency and intensity of TCs that made landfall in China during the period 1949–2006, along with changes in the associated probability distributions. They noted that the annual frequency of landfall TCs in China has declined over the past 58 years, while the average intensity has increased. Wang Ling et al. (2006) also reported a decline in the number of TCs over the northwestern Pacific and a weak decline in the number of TCs that made landfall in China over the past 35 years (1971–2005). Wang and Ren (2007) analyzed the occurrence of three types of severe tropical cyclones (STC) at typhoon (TY) intensity during the period 1957–2004. They suggested that the frequency of TCs had decreased significantly and this trend was inversely proportional to the trend in TC intensity. They also showed a linear decline in maximum TC intensity. Cao et al. (2006) and Wang Xiaoling et al. (2006) found a weak increase in the frequency of TCs affecting China from the 1950s to the early 1970s, which was then followed by a significant decline. The frequency of TCs that affected China peaked in the 1960s. Hu et al. (2008) suggested that TC landfall locations and areas changed significantly in the mid 1990s (around 1995). Ren et al. (2007) studied the geographical distribution, seasonal changes, and interdecadal changes of the first and last TCs making landfall in China in each season. They reported substantial interdecadal changes in first-landfall TCs superposed onto a long-term trend toward later dates, but identified no long-term trend in the timing of last-landfall TCs. These studies differed in the temporal coverage of the data used, and may therefore only partially explain differences in the evolution of TC characteristics. Furthermore, few detailed analyses of changes in TCs have focused on how those changes affect different regions in China. Further study is still needed.

Tian (2003) explored the causes and mechanisms of interannual and interdecadal variations in landfalling TCs by analyzing relationships between global surface temperature and TCs in the northwestern Pacific from 1949 to 1998. He pointed out that global warming was associated with a reduced frequency and weakened intensity of TCs over the northwestern Pacific. This relationship was particularly notable during the 1990s, when warming was particularly rapid. Ye and Dong (2002) noted that the frequency of landfalling TCs was negatively correlated with equatorial eastern Pacific sea surface temperature (SST) and positively correlated with the East Asian trough index. Wu et al. (2003) analyzed the impact of sub-surface water temperature in the western Pacific warm pool and South China Sea on TCs during 1949–1999 and found that the number of TCs that occurred over the northwestern Pacific was larger when the equatorial western Pacific warm pool sub-surface water temperature anomaly was positive during the summer half year, and vice versa. He et al. (1999) used synthetic statistical correlation and typical year composite analysis methods to analyze relationships between El Niño (EN) and anti-El Niño (AE) or La Niña events and TC activity in the northwestern Pacific during the period 1884–1996. They noticed that TC activity in the northwestern Pacific decreased during EN years but increased during AE years. TC activity was also affected by the strength of the EN or AE event, the timing of the onset and demise of EN or AE, and the TC formation area. Lin and Zhang (2004) found that the annual number of TCs affecting China is positively correlated with temperature in the northwestern Pacific warm pool (10°–20°N, 120°–150°E) and negatively correlated with temperature in the equatorial central and eastern Pacific (10°S–5°N, 180°–90°W). TCs affecting China are smaller in number but stronger in intensity during EN years, but larger in number and weaker in intensity during La Niña years. The data used in these studies were mainly collected until the 1990s, and the conclusions should continue to be validated in the context of new data.

Previous studies have mainly focused on the impact of TCs, particularly landfalling TCs, upon China as a whole. Comparatively, few studies have examined changes in the frequency or intensity of TCs affecting China. China has a vast territory with a coastline of more than 18000 km. TCs making landfall affect a variety of locations and areas within China; the distribution of these locations and areas changes with the changing climate. The economic development of China is geographically unbalanced. Three economic zones (the Yangtze River Delta, the Pearl River Delta, and the Beijing-Tianjin area) account for 6.3% of the total area of the country, 26% of the total population, and 41% of the national GDP. The GDP percentage has continued to increase in recent years. The Yangtze River Delta and Pearl River Delta economic zones, which are both located in coastal Southeast China, often suffer heavy economic losses from TCs. Studies of changes in the frequency and intensity of TCs affecting the three economic zones are therefore essential in addressing the impact of climate change in China, especially in the context of global warming. This initiative has substantial social and economic significance.

2. Data and methods

The data used in this study are from the China Meteorological Administration (CMA) Tropical Cyclone Best Track Database, covering the period 1951–2010. The data contain the TC central location (latitude and longitude), minimum central pressure (hPa), maximum central wind speed, duration of impact upon China, number of rain days, number of heavy rain days, maximum hourly precipitation, maximum wind speed time, maximum wind speed, extremely strong wind speed, and number of gale-force wind days. The data are strictly quality controlled and are the most authoritative data on TCs in China.

The database considers a TC to have impacted China if at least one of 358 selected stations across the country meets one or more of the following conditions:

(1) Event rainfall $\geqslant$ 50 mm;

(2) Average wind speed $\geqslant 13.9$ m s^{-1} or gust wind speed $\geqslant 17.2$ m s^{-1}; or

(3) Event rainfall $\geqslant$ 30 mm and average wind speed $\geqslant 10.8$ m s^{-1} or gust wind speed $\geqslant 13.9$ m s^{-1}. Tropical depressions are excluded from this study.

An area within which are stations that meet at least one of the above conditions is defined as a TC-affected area. The key economic zones studied here, i.e., the Pearl River Delta, the Yangtze River Delta, and the Beijing-Tianjin area are economically well-developed. TCs are considered to have affected the Yangtze River Delta when observations of 32 stations satisfy the criteria. These 32 stations are located in Zhejiang and Jiangsu provinces and in Shanghai municipality, an area that covers the administrative jurisdictions and cities of Shanghai, Nanjing, Suzhou, Yangzhou, Zhenjiang, Taizhou, Wuxi, Changzhou, Nantong, Hangzhou, Ningbo, Huzhou, Jiaxing, Zhoushan, Shaoxing, and Taizhou. TCs are considered to have impacted the Pearl River Delta when observations at eight specifically selected stations satisfy the criteria. This region covers the administrative jurisdictions and cities of Guangzhou, Shenzhen, Zhuhai, Zhongshan, Dongguan, Huizhou, Zhaoqing, and Jiangmen. TCs are considered to have affected Beijing-Tianjin if observations at three specifically selected stations in Beijing, Tianjin, and Tanggu satisfy the relevant criteria.

The TC best track data are used with the above definition of impact criteria to analyze the annual frequencies of TCs that affected China as a whole and the three key economic zones of Beijing-Tianjin, Yangtze River Delta, and Pearl River Delta in particular.

3. Changing frequency of TCs affecting China's key economic zones

3.1 Frequency of TCs that made landfall in or affected China

Figure 1 shows the evolution of the frequency of TCs that made landfall in or affected China. The number of TCs affecting China ranged from 6 to 24 per year, with an average of approximately 12 and a periodic annual fluctuation (solid line in Fig. 1a); however, the amplitude of the annual fluctuation has been significantly reduced since 1999. The overall change in annual frequency suggests a weak decline (Fig. 1a). Figure 1b shows that the interdecadal frequency was the highest in the 1970s (140) and the lowest in the 1950s and 1990s (~110). The frequency of TCs affecting China slowly increased from the 1950s to 1970s,

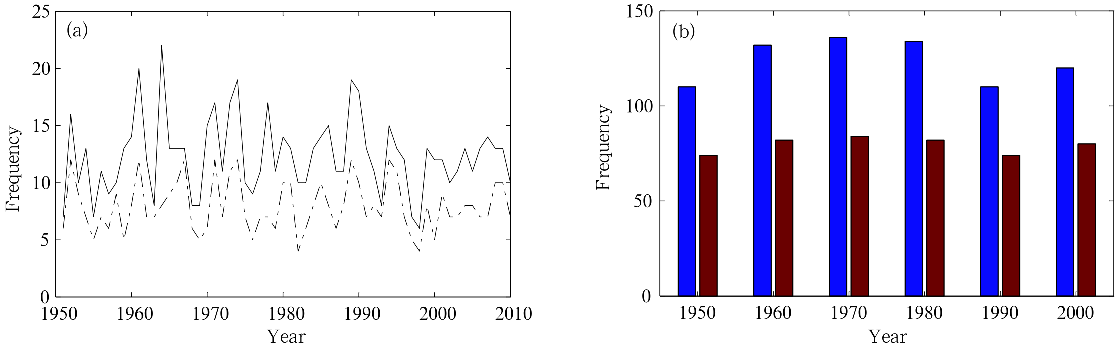

Fig. 1. (a) Annual frequency of TCs that made landfall in (dotted line) or affected (solid line) China and (b) decadal frequency of TCs that made landfall in (red bars) or affected (blue bars) China during the period 1951–2010.

began to decline in the 1970s, and then declined rapidly from the 1980s to 1990s. These trends are consistent with the majority of previous studies (e.g., Wang Xiaoling et al., 2006; Yang et al., 2009). The frequency of TCs over the past decade was significantly higher than the frequency in the 1990s (Fig. 1b). This phenomenon was not revealed by previous studies due to the limited length of the available data.

The annual number of landfalling TCs over China between 1951 and 2010 ranged from 4 to 12, with an average of 8 and a cyclical annual variation (dotted line in Fig. 1a). The number of TCs making landfall over China fluctuated dramatically from year to year before 2000, with a range of 4 to 12. This number varied much less after 2000, with 7–10 landfalling TCs per year. These features agree well with the annual variations in the frequency of TCs affecting China (solid line in Fig. 1a). The annual frequency of landfalling TCs appears to have weakly declined over the analysis period.

Further comparison indicates a relationship between the number of landfalling TCs and the number of affecting TCs on both annual and interdecadal time scales. The correlation coefficient between the two annual frequencies is 0.676. Both decadal frequencies rose from the 1950s to 1970s, after which both declined in the 1990s. After 2000, the frequency of landfalling TCs rebounded significantly. The maximum number of landfalling TCs (84) was recorded in the 1970s, while the minima were recorded in the 1950s and 1990s (74). Affecting TCs significantly outnumbered landfalling TCs each year, indicating that a large number of affecting TCs do not make landfall. It is therefore not enough to consider only the effect of landfalling TCs when studying the effects of TCs on China.

The annual differences between landfalling and affecting TCs fluctuate dramatically without obvious regularity, from a minimum of 0 to a maximum of 15 with an average of 4. The difference has become more stable since 1998, with values of 3 to 5. The difference between the decadal frequencies of affecting and landfalling TCs increased in the 1950s, peaked in the 1970s and 1980s, decreased rapidly in the 1990s, and became insignificant after 2000.

3.2 Frequency of TCs affecting the key economic zones

Beijing-Tianjin area: Due to its relatively high latitude, there are few TCs on record that affected this region. A total of 14 TCs affected this region between 1951 and 2010, with no more than one per year (Fig. 2a). The interdecadal frequency of affecting TCs was the highest in the 1950s (5), followed by the 1990s (3). The variations show little regularity (Fig. 2b).

Yangtze River Delta: The annual frequency of TCs affecting this region peaked at 11 in 1990, with a minimum of 0 in 1993 (Fig. 2c). The frequency of TCs affecting the Yangtze River Delta fluctuated dramatically in the 1990s (e.g., 0, 9, and 2 in 1993, 1994, and 1995). Hu et al. (2008) also identified a significant change or mutation in the frequency and spatial distribution of landfalling TCs in the mid 1990s. The interdecadal frequency of TCs affecting the Yangtze

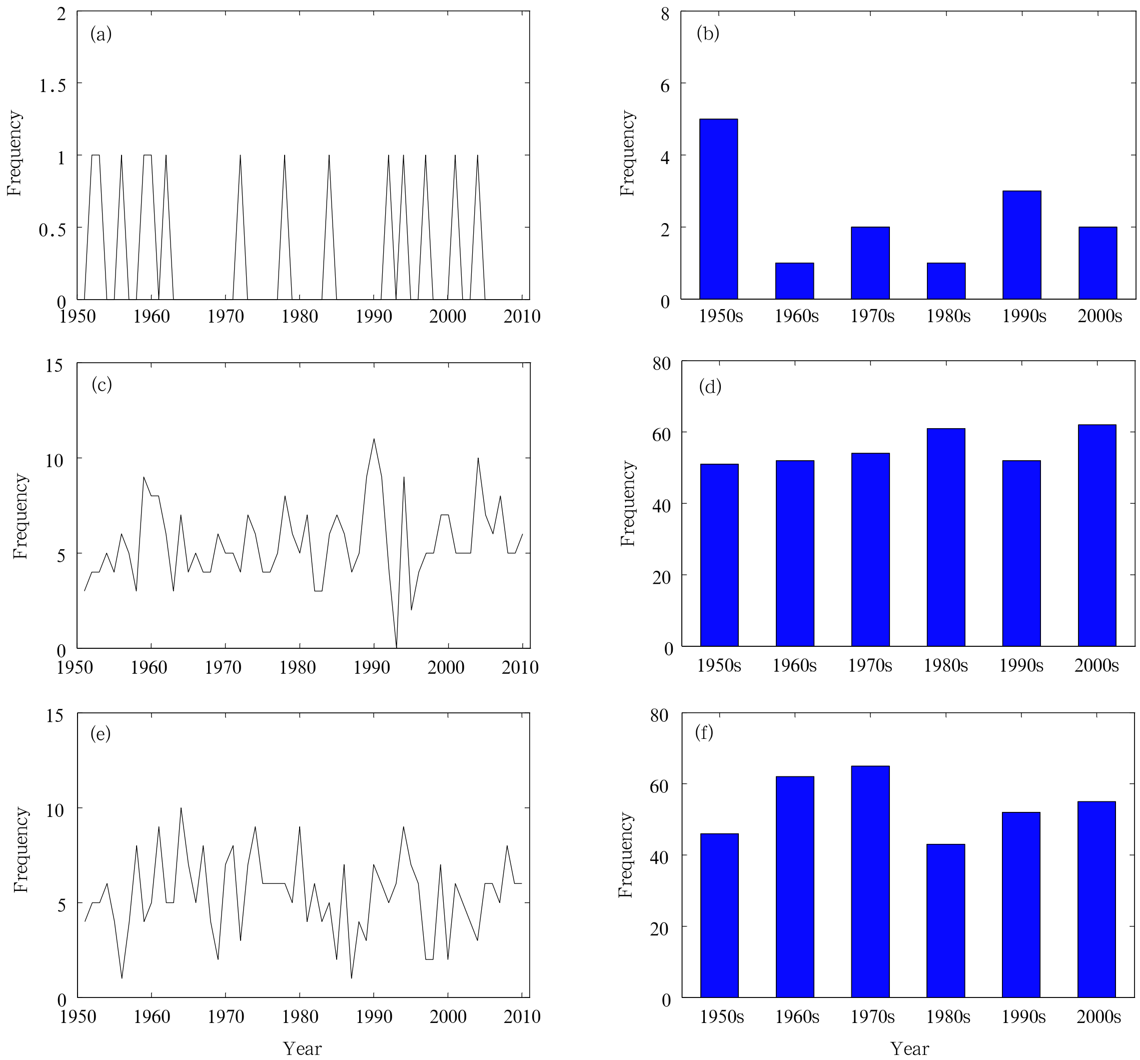

Fig. 2. Frequency of TCs affecting China's key economic zones during 1951–2010. (a, b) The Beijing-Tianjin economic zone; (c, d) the Yangtze River Delta economic zone; and (e, f) the Pearl River Delta economic zone. Curves represent annual variations and bars represent decadal variations.

River Delta rose slightly from 52 in the 1990s to 62 in the 2000s (Fig. 2d).

Pearl River Delta: The average annual frequency of TCs affecting this region is 5.3, slightly lower than that in the Yangtze River Delta. This frequency peaked at 10 in 1964, with a minimum of 1 occurring in both 1965 and 1987 (Fig. 2e). The annual variation contains a clear periodicity. For example, the frequency of affecting TCs increased during the periods 1951–1965, 1969–1975, 1987–1994, and 2000–2008, while it decreased during the periods 1965–1969, 1980–1987, and 1995–1998. The interdecadal frequencies increased from the 1950s to 1970s and from the 1980s to 2000s. The highest decadal frequency (65) occurred in the 1970s, while the lowest (42) occurred during the 1950s. The frequency dropped sharply between the 1970s and 1980s, with only 43 affecting TCs recorded during the 1980s (Fig. 2f).

The annual frequencies of TCs that affected the Yangtze River Delta and Pearl River Delta key economic zones are divided by the annual frequency of TCs affecting China to obtain the year-by-year proportions of TCs that affected the two regions (Fig. 3). The annual proportion of TCs affecting the Yangze

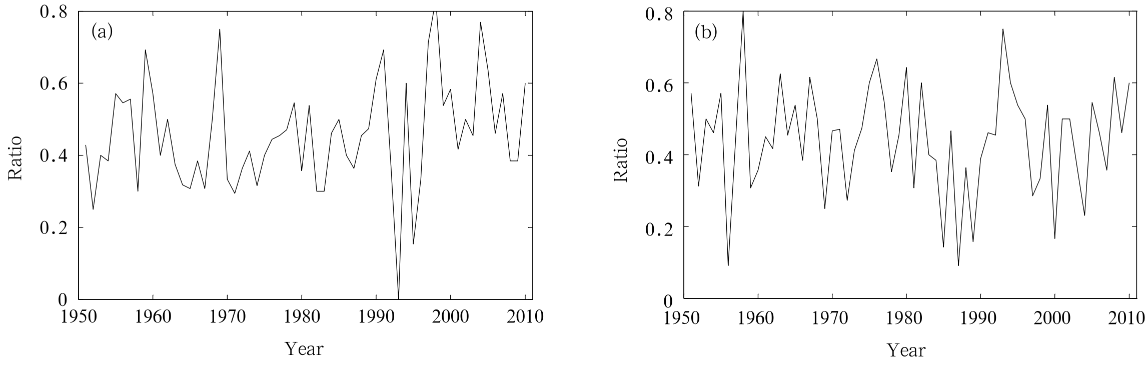

Fig. 3. Time series of the ratio of the number of TCs affecting (a) the Yangtze River Delta key economic zone and (b) the Pearl River Delta key economic zone, relative to the number of all the TCs affecting China.

River Delta ranged from 0 to 0.83, with an average of 0.47. This quantity fluctuated dramatically during the period 1990–1995. The analogous decadal proportion dropped from 0.49 to 0.40 during the 1950s–1970s and then rose after the 1980s, reaching a maximum of 0.53 during 2000–2010. This value means that more than half of TCs that affected China affect the Yangtze River Delta after 2000. The proportion of TCs affecting the Pearl River Delta ranges from 0.1 to 0.8, with an average of 0.43. The interannual variations are similar to the variations in frequency. The proportion of TCs affecting the Pearl River Delta rose from 0.38 in the 1950s to 0.48 in the 1970s, dropped sharply to 0.32 in the 1980s, increased dramatically to 0.47 in the 1990s, and then decreased slightly to 0.46 in the 2000s. The long-term trends in the proportion of affecting TCs suggest an increase over the Yangtze River Delta since the 1980s and a slight decline over the Pearl River Delta during the recent decade.

3.3 Time series analysis of TCs affecting China and its key economic zones

We apply Morlet wavelet transformations to the time series of the numbers of landfalling and affecting TCs over the Yangtze River Delta and Pearl River Delta. This approach allows us to identify and test the significance of cycles in the time series.

Figure 4 shows that both landfalling and affecting TCs varied in cycles over the period 1951–2010. The frequency of landfalling TCs in China varied at a significant cycle of 2–6 yr, with peak power at 4 yr. This cycle changed over the time period 1951–2010, as evidenced by the significance of a 4–6-yr cycle during the 1950s and 1960s, cycles of 3–4 and 6–8 yr in the 1970s, and an approximately 4-yr cycle during the 1980s and early 1990s. The cyclical variation in the 21st century is not statistically significant. The frequency of TCs making landfall over China also appears to vary on a

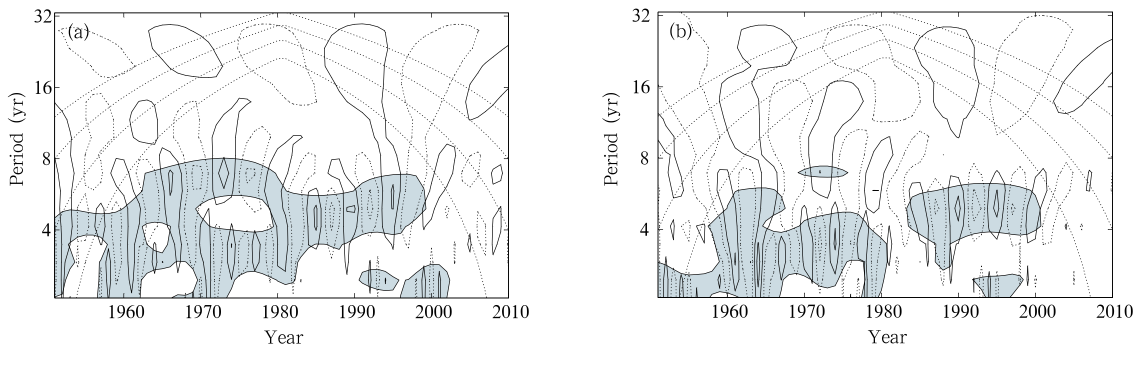

Fig. 4. Wavelet analysis of the frequency of (a) TCs that made landfall over China and (b) TCs that affected China between 1951 and 2010. Shading indicates statistical significance at the 95% confidence level.

20-yr interdecadal cycle; however, this cycle does not pass the significance test.

The numbers of affecting and landfalling TCs in China are strongly correlated, with a correlation coefficient of 0.69, indicating that the frequencies of landfalling and affecting TCs varied in similar ways. Like landfalling TCs, the frequency of affecting TCs varied cyclically with a period of 2–6 yr. Also like landfalling TCs, the significant cycle of affecting TCs varied on a period of 4–6 yr from the 1980s to 2000s, while no significant cycle can be identified during the 21st century. However, the two time series differed somewhat before the 1980s, when the cyclical variation of affecting TCs was more concentrated on a 2–4-yr period than that of landfalling TCs. This 2–4-yr cycle prior to the 1980s is statistically significant. Interdecadal variations in the number of affecting TCs also mirror those in the number of landfalling TCs, with an evident 20-yr cycle. This interdecadal cycle is not statistically significant, probably because of the short length of the available time series.

Additional wavelet analysis shows that the variations in the frequencies of TCs that affected the Pearl River Delta and Yangtze River Delta do not follow the variations in the frequency of TCs that affected China (Fig. 5). No significant cycle can be identified in the frequency of TCs that affected the Yangtze River Delta between 1951 and 1980, but the frequency of these TCs varied on a significant 6-yr cycle between 1980 and 2000. The frequency changed dramatically in the early 1990s, due to the significant annual variation mentioned above. These significant year-to-year fluctuations result in the identification of a significant 1-yr cycle during that period; however, this annual oscillation did not last. The frequency of TCs that affected the Pearl River Delta was significantly cyclical throughout the analysis period. This cycle was approximately 3 yr prior to the 1970s, followed by a diversification and acceleration of the cycle after 1975. This accelerated cycle persisted until 2005. Interdecadal variations also appeared to be cyclical, but were not statistically significant over this period.

In short, the variations in the frequencies of TCs affecting the Pearl River Delta and Yangtze River Delta key economic zones differed significantly from each other. Furthermore, these frequencies behaved differently from the frequency of TCs affecting China as a whole. These inconsistencies may be related to climatic differences in different regions of China, and should be the subject of further research.

3.4 Relationships between ENSO and TCs affecting China and its key economic zones

The time series analysis in the previous section shows that the numbers of TCs affecting and landfalling in China vary at different cycles. The period of these cyclical variations is similar to the typical period of ENSO variations. It is therefore logical to further analyze the connections between ENSO activity and the number of TCs affecting or making landfall in China. In fact, a number of previous studies have focused on these connections. In this paper, we study the relationship between ENSO and the number of TCs that specifically affect China and its key economic zones. This analysis enables us to further understand how these frequencies change over time. We use the

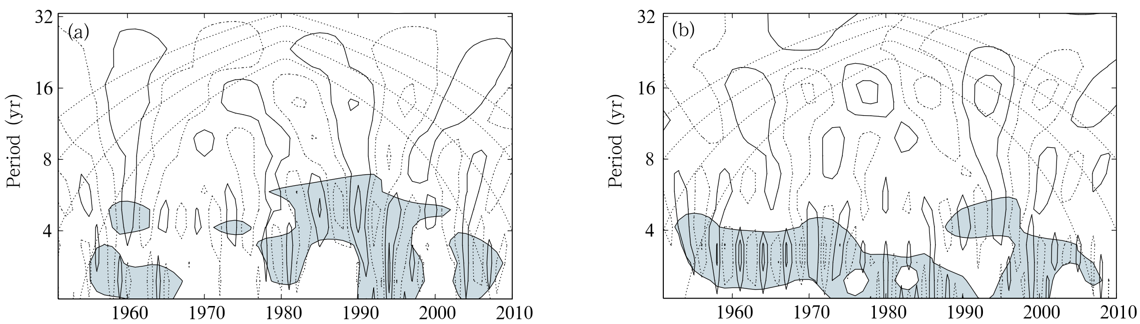

Fig. 5. Wavelet analysis of the frequency of TCs affecting the (a) Yangtze River Delta and (b) Pearl River Delta. Shading indicates statistical significance at the 95% confidence level.

NINO3 index as an indicator of ENSO activity. The NINO3 index is an average of sea surface temperatures in the region 5°N–5°S, 150°–90°W. We analyze the correlation coefficient between the NINO3 index and frequency of landfalling and affecting TCs during the period 1951–2010 (Table 1).

The relationship between the NINO3 index and the frequencies of landfalling and affecting TCs in China is strong, with correlation coefficients of –0.35 for landfalling TCs and –0.44 for affecting TCs. Both correlations are significant at the 95% confidence level. These results indicate that the frequencies of landfalling and affecting TCs are both reduced when the NINO3 index is high; conversely, the frequencies are relatively high when the NINO3 index is low, indicating a negative relationship. Specifically, TCs are less likely to make landfall in or affect China during EN years, and more likely to make landfall in or affect China during AE years. This result is consistent with the findings of He et al. (1999), and indicates that the frequency of landfalling and affecting TCs in China is closely related to ENSO. Zhang et al. (1996) and Zhang et al. (1999) showed that an anomalous anticyclone appears over the northwestern Pacific during EN years, and reported that this anticyclonic anomaly is unfavorable for TC generation. This may account for the reduced occurrence of TCs in China during EN episodes.

The correlation between the NINO3 index and the number of TCs that affect the key economic zones is significantly weaker than that between NINO3 and the number of TCs that affect China as a whole. The frequency of TCs affecting the Yangtze River Delta is not significantly correlated with the NINO3 index (Table 1). The frequency of TCs affecting the Pearl River Delta region is significantly correlated with the NINO3 index, but its correlation coefficient is lower than that of TCs affecting China as a whole. The underlying mechanisms that describe the relationship between NINO3 index and TC activity in these two regions remain to be investigated. The difference between the regional correlations and the countrywide correlation suggests that the impact of ENSO on TC activity in China is large scale rather than regional. The frequency of TCs affecting different regions differs significantly under the same ENSO conditions; accordingly, the fact that the frequency of affecting and landfalling TCs in China is well correlated with the NINO3 index does not mean that a similar relationship exists for other regions or sub-regions. Studies of changes in regional TC frequencies should be carried out on regional scales.

We also calculate correlation coefficients between the annual frequencies of landfalling and affecting TCs in China and the seasonal mean NINO3 index for each calendar season (i.e., spring (MAM), summer (JJA), autumn (SON), and winter (DJF)). The results are shown in Table 2. The NINO3 index is significantly correlated with the frequencies of landfalling and affecting TCs in China for all seasons but winter. There is no significant correlation between the NINO3 index and the frequency of TCs affecting the Yangtze River Delta region, while the correlation between the NINO3 index and the frequency of TCs affecting the Pearl River Delta is only significant during spring. This suggests that no general relationship exists between

Table 1. Correlations between annual mean ENSO index and the frequency of TCs making landfall in or affecting China and its key economic zones

Correlation	Landing in China	Affecting China	Affecting Yangtze River Delta	Affecting Pearl River Delta
NINO3 index	**–0.34973**	**–0.44095**	–0.24519	**–0.27992**

Note: Bold font indicates correlations that are significant at the 95% confidence level.

Table 2. Correlations between the seasonal mean NINO3 index and the frequency of TCs making landfall in or affecting China and its key economic zones affecting TC

Correlation	Landing in China	Affecting China	Affecting Yangtze River Delta	Affecting Pearl River Delta
Spring (MAM)	**–0.29704**	**–0.4334**	–0.24734	**–0.28464**
Summer (JJA)	**–0.28592**	**–0.43816**	–0.26701	–0.24741
Autumn (SON)	**–0.30169**	**–0.3313**	–0.16599	–0.22917
Winter (DJF)	–0.25406	–0.26789	–0.12609	–0.21496

Note: Bold font indicates correlations that are significant at the 95% confidence level.

ENSO activity and TCs affecting the Yangtze River Delta or Pearl River Delta in all seasons but the spring. The key factors determining the frequency of TCs affecting these regions are more complicated, and require further research.

The results in Table 2 also indicate that the frequency of TCs affecting China is most closely related to the NINO3 index during spring and summer. The SST anomaly usually occurs slightly before the summer (JJA) season, when TCs are most frequent. This result is therefore useful for predictions of the frequency of TCs affecting China.

4. Changing intensity of TCs affecting China and its key economic zones

In addition to changes in the frequency of TCs that make landfall in or otherwise affect China and its key economic zones, many scientists are concerned about changes in TC intensity. In this study, we classify TCs based on their intensity as tropical storms (TSs), severe tropical storms (STSs), typhoons (TYs), severe typhoons (STYs), and super typhoons (super TYs), in accordance with the National Standard on TC intensity (GB/T 19201–2003). We count the frequency of each class of TCs separately and analyze the following two aspects of affecting TCs: the variation of intensity over the life cycle of each TC, and the variation of the average and maximum intensity of each TC during the period in which it affects China and its key economic zones. These two variations are often associated with each other; however, they can differ in features and significance. The latter variation reflects the direct impact of a TC upon our focus regions better than the former.

4.1 Intensity variations of TCs landfalling in or affecting China during their life cycles

Variations in the intensity of TCs affecting China: Figure 6 shows decadal variations in the frequencies of affecting TCs at different levels of intensity. These decadal variations differ substantially for different classes of TCs. The frequency of affecting TSs declined during the 1950s (see Fig. 6a), reaching a minimum in the 1970s. The frequency then increased, reaching a maximum in the 2000s. The maximum observed in the early 2000s was three times as large as the minimum observed in the 1970s. The numbers of STS-, TY-, STY-, and super TY-level TCs that affected China consistently declined from the 1970s or 1980s to 1990s. The decreases in the numbers of STS- and TY-level TCs even continued into the 2000s. The most significant reduction in terms of magnitude was in the frequency of STS-level TCs, which dropped sharply from 42 in the 1980s to 18 in the 2000s. Similarly, the frequency of super TY-level TCs dropped from 38 in the 1960s to 16 in the 1990s. The frequency of STY-level TCs declined monotonically throughout the analysis period, but at a smaller magnitude than the frequencies of STS- and super TY-level TCs. The numbers of STY- and super TY-level TCs observed during the 2000s outnumbered those observed during the 1990s by 10 and 6, respectively.

The significant increase in the intensity of affecting TCs during the 2000s has drawn considerable attention from the national and international academic communities. Based on an analysis of optimized 1970–2004 typhoon location data, Webster et al. (2005) suggested that the number of super TYs (hurricanes of category 4 or 5) had increased significantly worldwide. They reported that super TYs accounted for 35% of the total number of TCs observed during the 1990s but only 20% of the TCs observed during the 1970s. These changes in intensity were largest in the North Pacific, Indian Ocean, and southwest Indian Ocean basins, with smaller changes observed in the North Atlantic. Based on this result, it is often assumed that global warming will lead to increases in the typical intensities of TCs or hurricanes; however, not all researchers share this view. Knaff and Sampson (2006) reanalyzed the maximum intensity of typhoons in the Northwest Pacific during 1966–1987, and argued that the annual increase in the frequency of super TYs was significantly smaller than that obtained using the original optimized location data. We have shown that the numbers of STYs and super TYs affecting China did increase in number during the 2000s; however, these numbers declined in previous decades. It is therefore still difficult to project whether the increase in the in-

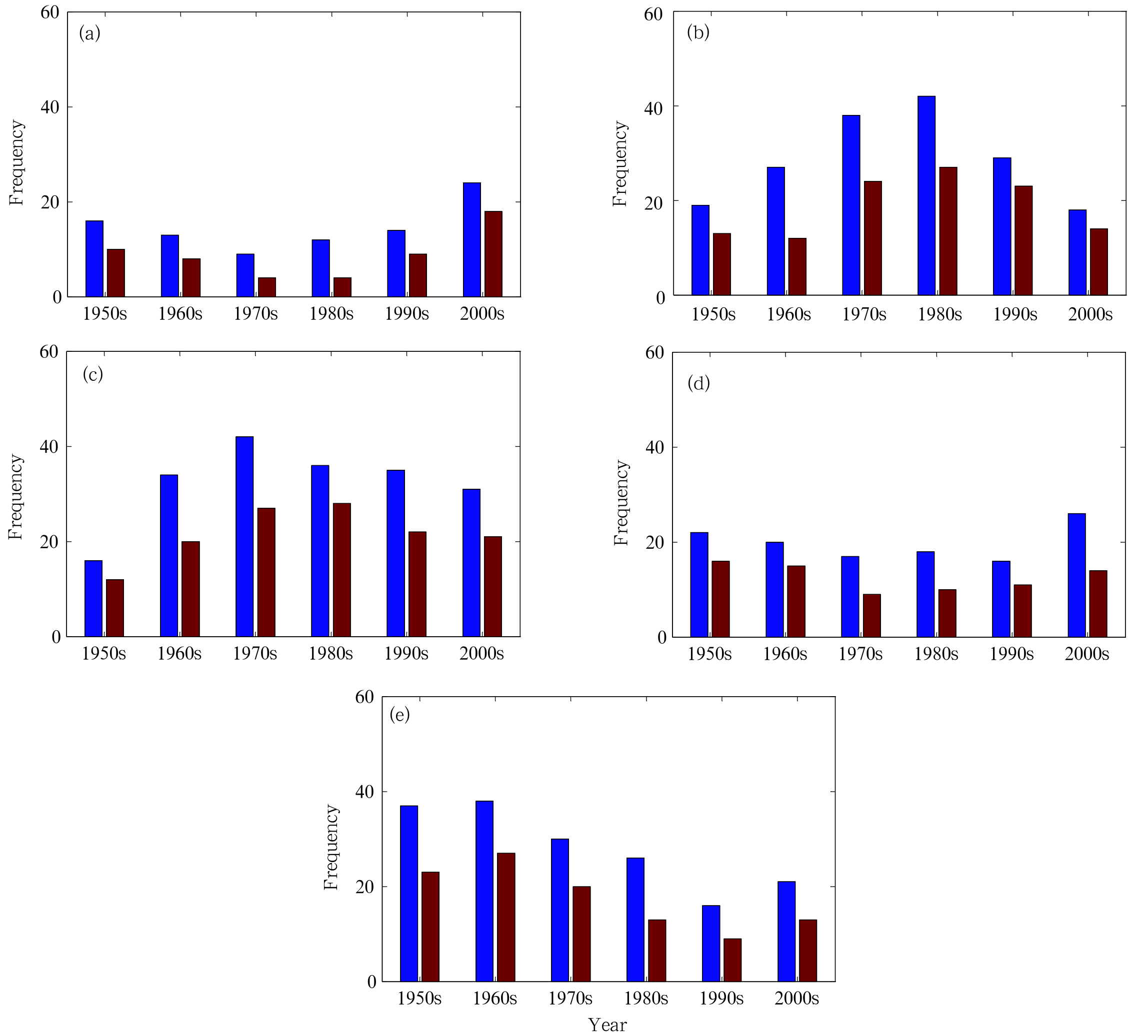

Fig. 6. Decadal variations in the frequency of landfalling and affecting TCs in China at (a) TS, (b) STS, (c) TY, (d) STY, and (e) super TY intensity levels. Blue bars represent landfalling TCs and red bars represent affecting TCs.

tensity of TCs affecting China will continue into the future based on the data available, let alone the question on whether the observed increase is directly linked to global warming. These questions should continue to be addressed in future investigations that can make use of longer-term data.

Variations in the intensity of TCs making landfall in China: Figure 6 also shows the decadal variations in the frequency of different classes of TCs making landfall in China. STSs, TYs, and super TYs represent the majority of landfalling TCs in China, while the proportion of TSs is the smallest. Variations in the frequencies of different categories of landfalling TCs in China are quite similar to those of affecting TCs. The main difference is in changes in the frequencies of STYs and super TYs making landfall in China, which, in contrast to the frequencies of affecting STYs and super TYs, did not increase substantially during the 2000s relative to the preceding decade. While the intensity of TCs affecting China has significantly increased in this century, the intensity of TCs making landfall in China has not.

4.2 Intensity variations of TCs affecting China's key economic zones

We analyze variations in the intensity of TCs affecting each of China's key economic zones, with particular focus on the maximum observed intensity.

Beijing-Tianjin area: The number of TCs affecting this region was small, with a total of only 14 on record (figure omitted). These TCs were typically strong in average intensity; the majority was TYs or super TYs. Seven of the 14 TCs affecting this region were super TYs. This is typical of TCs affecting high latitude regions, because only particularly intense TCs can last long enough and move far enough northward to affect Beijing and Tianjin, which are located in northern China. No significant decadal changes can be identified due to the limited number of samples, but the overall frequency appears to decrease over the analysis period, especially after 2000.

Yangtze River Delta: Figure 7 shows changes in the decadal frequencies of different categories of TCs that affected the Yangtze River Delta and Pearl River Delta between 1951 and 2010. Changes in the frequency of different category TCs affecting the Yangtze River Delta are similar to changes in the frequency of different category TCs affecting China (see Fig. 6). The number of TSs affecting the Yangtze River Delta has increased since the 1970s, while the number of STSs has decreased over the same period. The frequency of TYs also decreased, but not significantly. The frequency of STYs affecting the Yangtze River Delta generally rose over the analysis period, but not

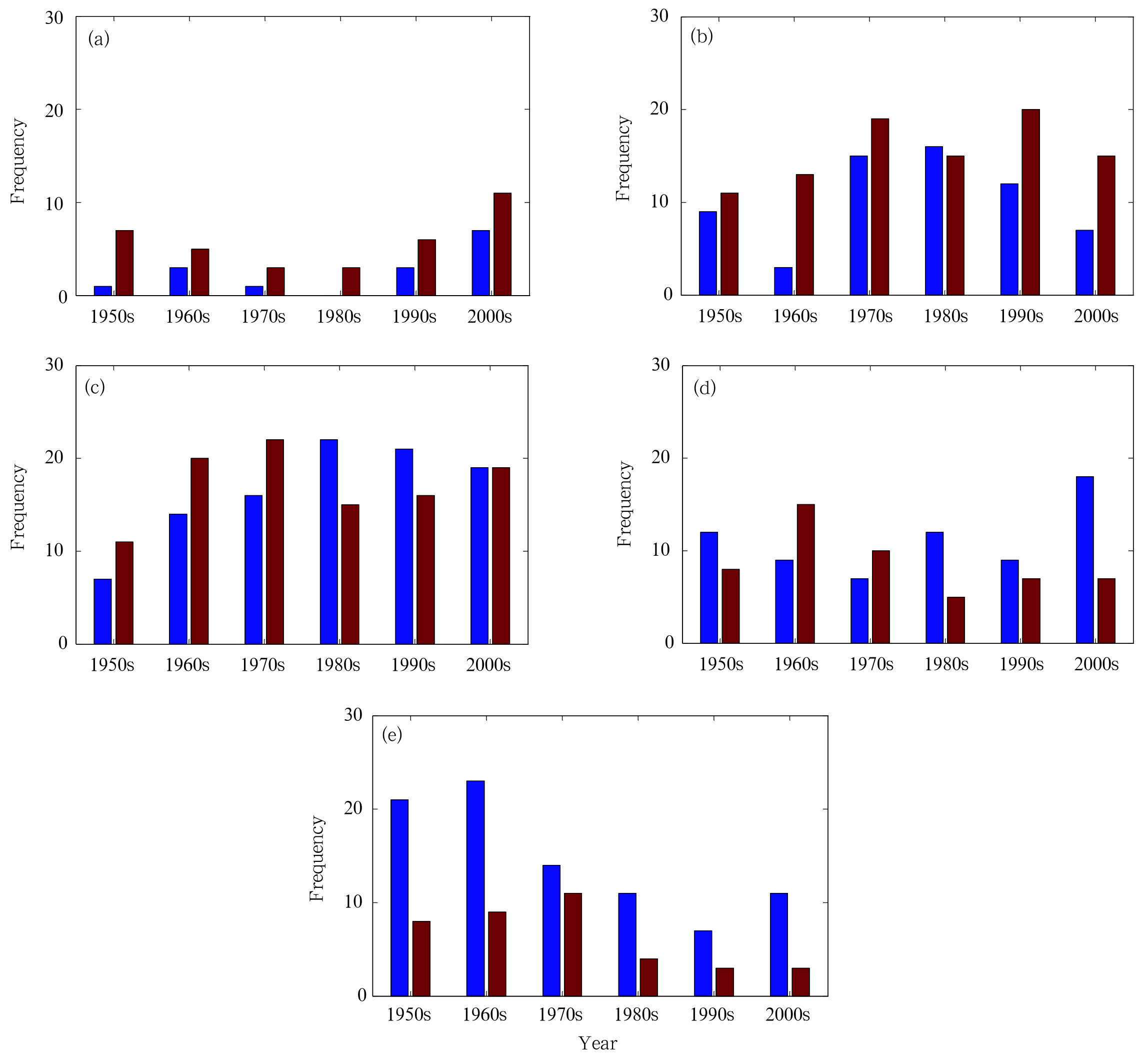

Fig. 7. Decadal variations in the frequency of TCs affecting the Yangtze River Delta and Pearl River Delta at (a) TS, (b) STS, (c) TY, (d) STY, and (e) super TY intensity levels. Blue bars represent TCs affecting the Yangtze River Delta and red bars represent TCs affecting the Pearl River Delta.

monotonically, reaching a maximum of 18 in the 2000s. The frequency of super TYs declined from the 1960s to 1990s, reaching a minimum of 7 in the 1990s, then increased again to 11 in the 2000s. The frequencies of both STYs and super TYs affecting the Yangtze River Delta were significantly larger over the 2000s than over the 1990s.

Pearl River Delta: Figure 7 shows that changes in the decadal frequencies of various category TCs that affected this region have certain unique features relative to those in the other regions. The frequency of TSs affecting the Pearl River Delta (Fig. 7a) increased significantly, similar to the changes in TSs affecting China (Fig. 6) and the Yangtze River Delta. Changes in STSs and TYs (Figs. 7b and 7c) have been cyclical since the 1960s with no significant long-term increase or decrease. STYs and super TYs have significantly decreased since the 1970s: the number of STYs dropped from 10 to 6 while the number of super TYs dropped even more dramatically, from 9 to 3. These results indicate that the frequencies of STYs and super TYs that affected the Pearl River Delta were significantly less than those affecting the Yangtze River Delta. By contrast, TSs and STSs affecting the Pearl River Delta significantly outnumbered those affecting the Yangtze River Delta. TCs affecting the Pearl River Delta came mostly from the South China Sea, so the time between storm generation and making landfall over or otherwise affecting the Pearl River Delta was typically relatively short. The geographical location and boundaries of the South China Sea pose such a limitation that TCs often do not have enough time to become very strong. STYs and super TYs located over the South China Sea and affecting the Pearl River Delta may also come from the east of the Philippines. Most TCs affecting the Yangtze River Delta originally formed over the Northwest Pacific and then moved northwestward. Before these storms make landfall over coastal eastern China or affect the Yangtze River Delta after turning northward, they have traveled across a vast area of ocean and have often attained maximum development. In addition, many TCs that affect the Yangtze River Delta have passed over the Kuroshio. Heating associated with the Kuroshio could intensify these storms, so they are often quite strong.

4.3 Changes in annual maximum and average TC intensity during the impact period

The previous section provides an analysis of changes in the frequency of different category TCs that affected China's key economic zones, with focus on changes in the intensity of TCs over their entire life cycle. By contrast, this section focuses on changes in the intensity of TCs during the affecting period. The analysis comprises two parts: changes in the maximum intensity during the affecting period, and changes in the average intensity during the affecting period.

Changes in maximum intensity during the affecting period: We analyze the TCs that affected entire China, the Yangtze River Delta, and the Pearl River Delta. The maximum intensity during the affecting period is measured as the maximum observed wind speed during the affecting period. Table 3 shows the decadal mean maximum intensities of TCs affecting China and its key economic zones, as observed during the affecting period. The mean maximum intensity of TCs affecting China has declined significantly since the 1950s. The mean annual maximum wind speed during the affecting period dropped from 79.5 m s^{-1} in the 1950s to 51 m s^{-1} in the 1990s, before recovering slightly during the 2000s. This recent recovery is consistent with the previously mentioned changes in maximum intensity over the full life cycle of the storms (Section 4.1).

Changes in the intensity of TCs affecting the Pearl River Delta over the analysis period are much weaker

Table 3. Decadal averages of annual maximum affecting-period intensity (m s^{-1}) of TCs that affected China and its key economic zones

	1950s	1960s	1970s	1980s	1990s	2000s
China	79.5	69.0	65.0	57.0	51.0	56.2
Yangtze River Delta	76.5	68.0	60.5	55.0	43.5	55.2
Pearl River Delta	59.0	61.5	56.0	47.5	45.8	44.5

than changes in the intensity of TCs affecting the Yangtze River Delta (Table 3). The affecting-period intensity of TCs affecting the Pearl River Delta was strongest during the 1960s, whereas the affecting-period intensity of TCs affecting the Yangtze River Delta was strongest during the 1950s. The maximum affecting-period intensity of TCs affecting the Pearl River Delta has continued to decrease even into the 2000s.

Changes in average intensity during the affecting period: Table 4 shows decadal variations in the average affecting-period intensity of TCs affecting China and its key economic zones. The decadal mean affecting-period intensity of TCs affecting China did not vary significantly during the analysis period, with an average of about 26 m s^{-1} and typical fluctuations of about 2 m s^{-1}.

The annual mean affecting-period intensity of TCs affecting the Yangtze River Delta peaked twice (figure omitted), one in the late 1950s and the other in the early 1990s, with values of annual mean affecting-period intensity of approximately 40 m s^{-1}. With the exception of these peaks, the average affecting-period intensity fluctuated around 30 m s^{-1} throughout the analysis period. The decadal means also fluctuated around 30 m s^{-1}, with a minimum of 29 m s^{-1} in the 1970s. The decadal mean intensity increased to 31 m s^{-1} in the 1980s, and has remained at approximately 30 m s^{-1} over the last 20 years. The average affecting-period intensity of TCs affecting the Pearl River Delta was approximately 26 m s^{-1} prior to the 1990s, but has been steady at a lower value of 23 m s^{-1} over the past 20 years. This result indicates that the average affecting-period intensity of TCs affecting the Pearl River Delta has weakened over the analysis period. The average affecting-period intensity of TCs affecting the Yangtze River Delta is significantly higher than that of TCs affecting the Pearl River Delta.

Table 4. Decadal averages of affecting-period intensity (m s^{-1}) of TCs affecting China and its key economic zones

	1950s	1960s	1970s	1980s	1990s	2000s
China	28.8	27.1	26.7	27.5	25.4	27.0
Yangtze River Delta	32.5	32.3	28.8	31.6	30.3	30.1
Pearl River Delta	26.0	26.0	26.1	26.1	22.7	23.3

5. Conclusions and discussion

In this paper, we have analyzed TCs that affected China and its key economic zones (the Yangtze River Delta, the Pearl River Delta, and the Beijing-Tianjin area) over the period 1951–2010. We produced time series of the frequency, intensity classification, maximum intensity, and average intensity of these TCs. We examined interannual and interdecadal variations in the number and intensity of TCs that affected China and its key economic zones. The frequency of affecting and landfalling TCs in China is significantly correlated with the NINO3 index. The frequencies of TCs that affected the Pearl River Delta and the Yangtze River Delta also varied cyclically, with periods ranging from 2 to 6 yr. The frequency of TCs affecting the Pearl River Delta was significantly correlated with ENSO, while that of TCs affecting the Yangtze River Delta was not. The frequencies of TCs affecting China and its key economic zones vary significantly by region. These inconsistencies maybe resulted from climatic features of southern China and should be studied further.

The intensity of TCs affecting China declined over most of the analysis period before increasing in the 2000s. The intensity of TCs affecting the Yangtze River Delta also increased significantly from the 1990s to the 2000s, as did the frequencies of STY and super TY. The maximum affecting-period intensity of TCs affecting both China in general and the Yangtze River Delta in particular declined from the 1950s to the 1990s, but increased significantly in the 2000s. By contrast, the maximum affecting-period intensity of TCs affecting the Pearl River Delta continued to decrease even into the 2000s. The average affecting-period intensity of TCs affecting the Pearl River Delta weakened during the analysis period, whereas the average affecting-period intensity of TCs affecting entire

China and the Yangtze River Delta in particular did not change significantly.

This study was based on the TC Annual Report edited by the CMA. The optimized TC data produced by the Japan Tokyo Typhoon Centre (RSMC Tokyo) are known to differ operationally from the CMA data, so are the data produced by the US Joint Typhoon Warning Centre (JTWC). Such differences could influence the results and conclusions of our analysis; however, this study has focused specifically on TCs that affected China and its key economic zones. We therefore consider the data based on China's meteorological observations to be most reliable. The use of data from multiple centers could help to clarify differences in statistical results, and enable a better understanding of how the character of TCs that affected China may change under climate change. We have also limited our analysis to the frequency and intensity of the TCs that affected China. Future studies should also emphasize regional changes in wind and rain associated with these TCs.

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