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VARIATION CHARACTERISTICS OF TROPICAL CYCLONES MAKING LANDFALL IN CHINA AT DIFFERENT INTENSITIES

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Abstract: According to the national standard (2006) on tropical cyclone (TC) intensity, TCs are categorized into six intensity types, namely, tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), severe typhoon (STY), and super severe typhoon (SSTY). Fifty-eight years (1949–2006) of the datasets from the *Yearbook of Typhoons* and *Yearbook of Tropical Cyclones* were used to study the variation characteristics of TCs making landfalls in mainland China, Hainan and Taiwan islands. The main results are as follows. First, interannual or interdecadal variations in the number of landfalling TCs at different intensities exist. As far as long-term trends are concerned, the TD and TS frequencies show a significant linearly decreasing trend while those of STY show a significant linearly increasing trend. Second, a significant period of 6–8 years exist in the variations of annual landfalling TD, TS, and STS frequencies while quasi-16-year periods are found in the annual TY frequency. Third, TD and TS are generated mostly over the South China Sea, while TY, STY, and SSTY mostly over the waters southeast of the Bashi Channel and the ocean to the east of the Philippines. Fourth, as far as interdecadal trends are concerned, the frequencies of landfalling TD and TS generated over the South China Sea show significant linearly decreasing trends. However, TY and STY show significant linearly increasing trends.

Key words: statistical characteristics; tropical cyclones; landfall; variation trends

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1 INTRODUCTION

With global warming as well as increased frequency of extreme weather, the issue of variation tendencies of tropical cyclones (TCs) and associated landfall over the western North Pacific has become a research focus in recent years[1–6]. Studies suggested that the total number of TCs making landfalls in China shows a decreasing trend during the last 60 years[7–9]. However, periods of longer low-frequency oscillations may exist on centennial or longer time scales[9]. In the 14th session of the National Tropical Cyclone Science Seminar (Shanghai, 2007), Lei et al.[9] summarized the most recent advances in studies on the effects of global warming on TC activities, and argued that professional and research communities (the International Workshop on Tropical Cyclones-VI and Intergovernmental Panel on Climate Change) have not reached a global common ground on the future variation trends of TC activities. The two main limitations in the research results of Lei et al. are (1) the homogeneity and unreliability of data and (2) the uncertainty in climate model output. The data quality problem has aroused concern among domestic and overseas scholars. Comparing 16-year long datasets from three major meteorological forecasting centers, namely, the China Meteorological Administration (CMA), Regional Specialized Meteorological Center (RSMC) Tokyo, and Joint Typhoon Warning Center (JTWC), Yu et al.[10] found significant differences in TC intensity. For example, the maximum wind speeds for the same TC determined by the three centers differ by 30 m/s and above. Analyses by Lei et al.[9] showed that the location error of TCs is up to 54.4 km and the intensity error of TCs reaching the typhoon (TY) category is smaller than that of the other categories. The CMA has collected 60 years of TC data for the western North Pacific since 1949. These data are recorded in the *Yearbook of Typhoons* and *Yearbook of Tropical Cyclones*. Ren et al.[11] discussed some of

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the limitations of this dataset, noting the lack of quantitative description of TC landing sites—the historical records of TC landing sites were marked by place names, without longitude or latitude coordinates. In response to this problem, they formulated a set of processing methods that specifies, by linear interpolation, the maximum wind speed near the eye as well as the longitude and latitude coordinates of the sites where the TC landed. Their studies represent important contributions to the quantification of TC landfall location. However, records of TC landing intensity prior to 1973 suffer from insufficient information. For example, data on TC landing intensity includes minimum pressure only. Without data on central maximum wind speed, such records will bring inconvenience to related research on the climatology of TCs at different intensities because the existing TC intensity categories are determined based on maximum wind speed. In recent years, TC activity trends at different intensities and their interrelationships have been separated from the overall situation of typhoon research. Yuan et al.[12] investigated the temporal and spatial variations of TCs at different intensities using the best-track data provided by the JTWC on TCs over the western North Pacific from 1945–2005. They argued that as far as the long-term trend is concerned, the frequencies and observation times of tropical storms show significant linearly increasing trends, while the mean intensity of TCs and numbers of the TCs of other intensity categories do not exhibit any significant linearly increasing or decreasing tendencies. Each category has a different correlation with the ENSO index. Yan et al.[13] found a similar trend based on the recent TC data on the western North Pacific over the last 58 years. Although the studies above have revealed some variation characteristics of TC activities at different intensities, we still have little understanding of the characteristics in connection with landfalling TCs at different intensity categories for the aforementioned data limitations. In this paper, we divided TC intensity according to the air pressure equivalent of maximum wind speed using the barometric wind reduction law, and focused on examining the variation trends of landfalling TCs at different intensity categories based on previous research findings. Through this approach, we can better understand the climatological variation characteristics of TCs making landfalls in China in the past decades and provide further reference to reveal relevant mechanisms.

2 DATA AND METHODS

The data used in this study were taken from the *Yearbook of Typhoons* (1949–1990)[14] and *Yearbook of Tropical Cyclones* (1991–2006)[15] available from the CMA. As mentioned above, the records of TC landing intensity prior to 1973 merely provide the lowest pressure while the national standard (2006) on TC intensity is based on maximum wind speed. In this paper, we redefined TC intensity categories based on barometric pressure to make data comparable. According to the barometric wind reduction law, each wind speed range of the six TC intensity categories was translated to its equivalent value associated with barometric pressure. More specifically, individual categories were measured as follows: for tropical depression (TD), minimum central pressure (P_{min}) $\geqslant$ 998 hPa; for tropical storm (TS), 998 hPa $>$ P_{min} $\geqslant$ 988 hPa; for severe tropical storm (STS), 988 hPa $>$ $P_{min} \geqslant 977$ hPa; for TY, 977 hPa $>$ $P_{min} \geqslant 961$ hPa; for severe typhoon (STY), 961 hPa $>$ P_{min} $\geqslant$ 941 hPa; and for super severe typhoon (SSTY), P_{min} $<$ 941 hPa. Furthermore, for a TC making two or more landfalls, only the data from the first landfall was used in the calculation. Climatological trend coefficients and the Morlet wavelet transform were employed to analyze the long-term trend of TC landfall frequency.

3 TEMPORAL VARIATION CHARACTERISTICS OF LANDFALLING TCS AT DIFFERENT INTENSITIES

Between 1949 and 2006, a total of 1972 TCs (including TDs) were generated in the western North Pacific with a long-term average of 34 per year and 526 of them (or an average of nine per year) made landfall in China (Table 1). TY comprises the highest proportion of the total number of landfalling TCs, accounting for 23.6%; the sum of TS, STS, and TY accounts for 70%.

3.1 *Experiment design*

The interannual variations of landfalling TCs with six intensity categories (Fig. 1) and a list of associated parameters of climatological trends (Table 2), developed based on data between 1949 and 2006, show that the frequencies and observation numbers of TD and TS exhibit a significant linearly decreasing trend in the 58 years, and the climatological trend coefficients are both -0.36 at the 0.01 significance level. However, the numbers of TCs in other intensity categories do not exhibit any significant linearly increasing or decreasing tendency. As to the interdecadal variations, three variation patterns exist as follows.

Table 1. Summary of landfalling TCs in China in 1949–2006.

TC category	Landfalls	Proportion in total landfalls (%)	Annual mean landfalls
TD	92	17.5	1.58
TS	122	23.2	2.10
STS	121	23.0	2.09
TY	124	23.6	2.14
STY	51	9.7	0.88
SSTY	16	3.0	0.27
Total TCs	526	100	9.069

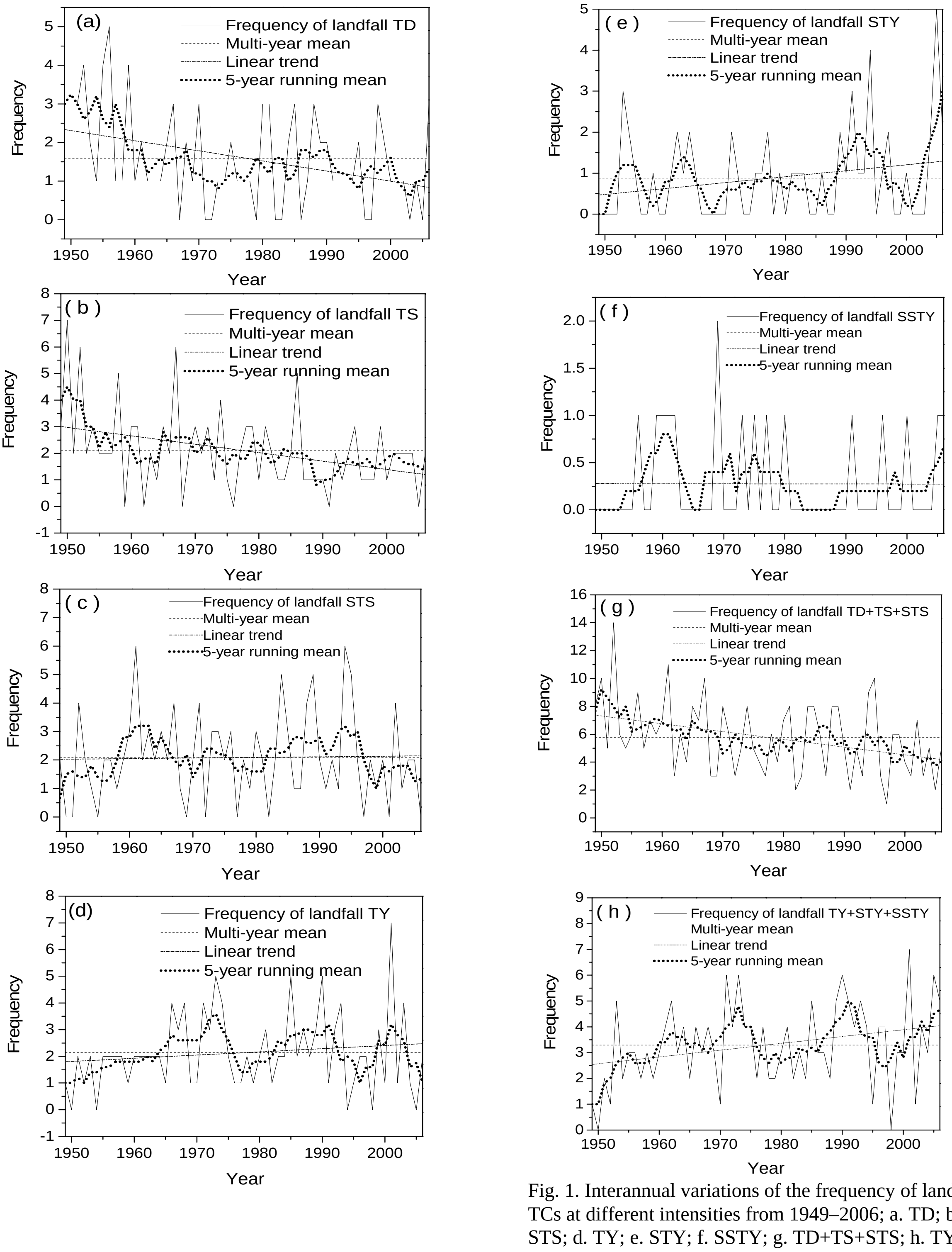


Fig. 1. Interannual variations of the frequency of landfalling TCs at different intensities from 1949–2006; a. TD; b. TS; c. STS; d. TY; e. STY; f. SSTY; g. TD+TS+STS; h. TY+ STY +SSTY.

Table 2. Climatological tendency coefficients, linear regression coefficients, oscillatory periods and correlation coefficients between the landfall frequency and cyclogenesis frequency for the same category of intensity. Unit of periods: year

Parameters	Climat. trend coeff.	Lin. reg. coeff.	Oscill. per.	Corr. coeff.
TD	-0.36	-0.026	6, 36	0.61
TS	-0.36	-0.032	8, 40	0.67
STS	0.023	0.002	6, 36	0.42
TY	0.14	0.012	16, 40	0.39
STY	0.22	0.015	12, 36	0.03
SSTY	-0.002	0.015	16, 40	0.12
TD+TS+STS	-0.36	-6E-05	6–8, 36	0.84
TY+STY+SSTY	0.29	0.264	16, 40	0.37

(1) Linearly decreasing for TD and TS (Figs. 1a and 1b). From the 1950s to the early 1960s, the 5-year running mean of the TD or TS number was above the average; from the mid-1960s to the late 1980s, it fluctuated around the mean; from the 1990s up to now, it reduced to a level below the average.

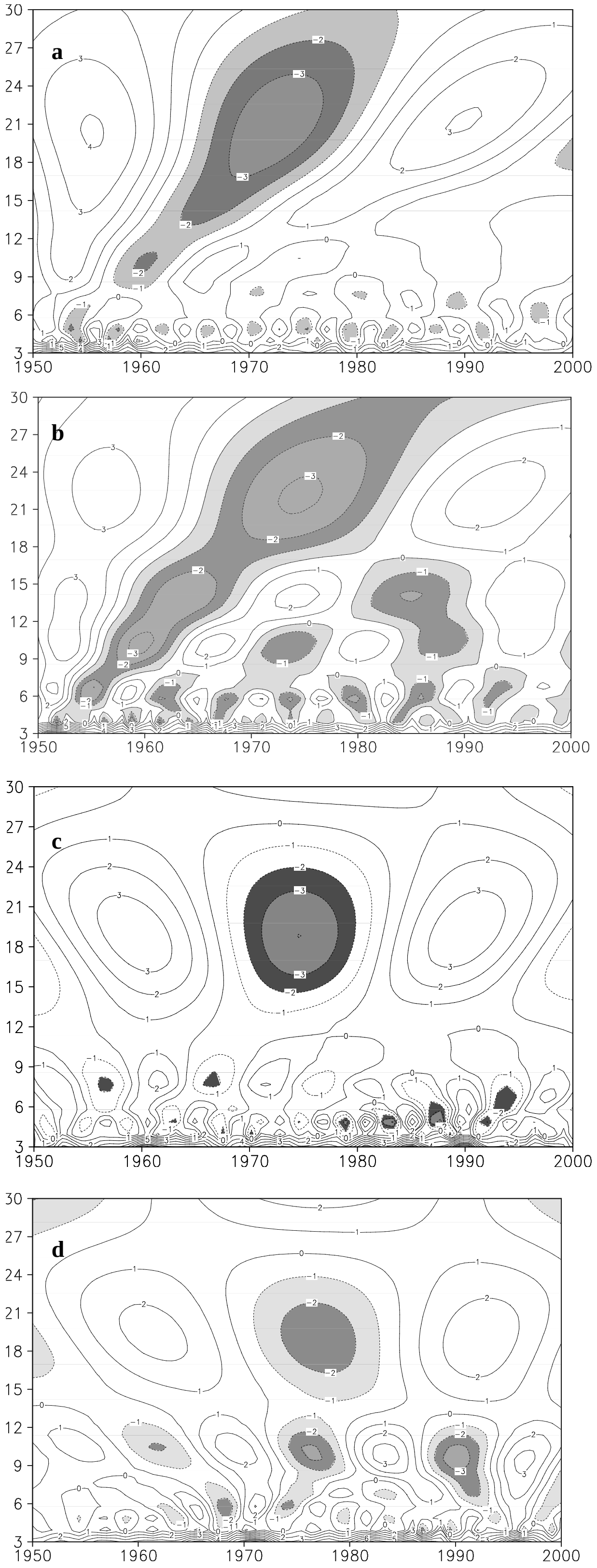
(2) Fluctuations for STS and TY. As to STS, landfalls were more active from the mid-1950s to the mid-1960s and from the early 1980s to the late 1990s than those from the late 1960s to the 1970s and the early years of the 21st century. As to TY, the number of landfall increased in the periods of 1963–1976 and 1982–1992 but decreased in other periods.

(3) Reverse change patterns for STY and SSTY. As to STY, the number of landfalling STY was relatively small from the 1950s to the 1980s and became large in the 1990s and beyond. In contrast, the number of landfalling SSTY was relatively large in the 1950s to the 1970s but relatively small in the 1980s and afterwards.

The correlation between the total number of the generated TCs and that of the landfalling TCs in the same categories of intensity during the same period shows that the value of correlation reduces as the intensity increases. TDs and TSs have correlations of up to 0.61 and 0.67, while STYs and SSTYs have correlations of merely 0.03 and 0.12. In other words, weak TCs have greater probability of making landfalls than strong ones.

3.2 *Oscillation period*

Figure 4 shows the oscillation period of the landfalling TCs at the six intensity categories calculated by wavelet transform analysis. Interannual periods of 6–8 years are observed for TD, TS, and STS and a significant interdecadal period of quasi-16 years for TY. Furthermore, 36–40-year periods may exist in the interdecadal variations for all TC intensities. In view of the 58-year duration of the data, caution must be exercised in using interdecadal periods to predict future landfalling TC activities. Longer time series data are required to examine the rationality of these conclusions.



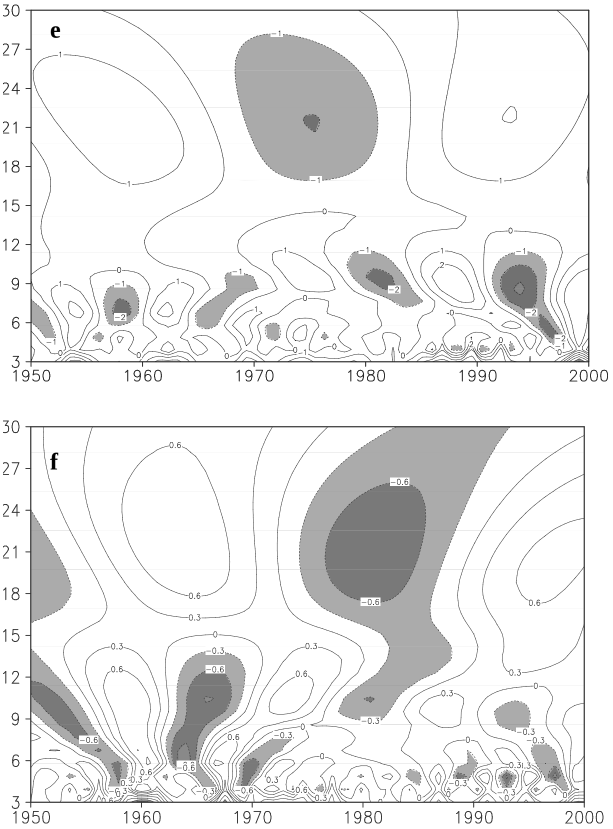


Fig. 2. Oscillation period of the landfalling TCs at the six intensity categories determined by wavelet analysis. The ordinate is for the half-period (unit: year) and the abscissa denotes the year. a. TD; b. TS; c. STS; d. TY; e. STY; f. SSTY.

3.3 *Intensity change*

TC intensity could be quantified by the central minimum air pressure and maximum wind speed, which consists of the extreme intensity value and mean intensity value. In this paper, the extreme value in one particular year is referred to as the extremum in that year. The mean value is referred to as the arithmetic mean of its values over the year. Between 1949 and 2006, the extreme minimum air pressure of TC in the landfall stage ranged from 920–990 hPa, and did not exhibit any significant linearly increasing or decreasing tendency on a yearly basis (Fig. 3). However, the mean minimum air pressure shows a slight linearly decreasing trend at a rate of 1.6 hPa per 10 years. The interannual variation of maximum wind speed looks very similar to that of extreme minimum air pressure. Therefore, in 58 years, the annual extreme intensity of TC at landing time has little variation tendency, while the annual mean intensity exhibits a slight linearly increasing trend.

3.4 *Monthly and diurnal variation*

Figure 4 shows that very few TCs make landfall in China from January to March. The peak landfall months in a year are July to September. The stronger a TC is, the shorter the time interval between two landfalls. For example, TD could make landfall from April to December while SSTY could make landfall only from July to October. The distribution of the monthly variation of landfalling TDs and STYs is bimodal; the first peak time of landfall is September and the second is June and July. The monthly variation of landfalling TSs, STSs, TYs, and SSTYs show single-peak distribution, in which the peak for STS is in July while that of the other three categories is in August. In the 58 years, the frequency of landfall increased in July and August but decreased in the other months. TCs making landfalls in September were the strongest, followed by those in July, August, October, June, November, May, December, and April.

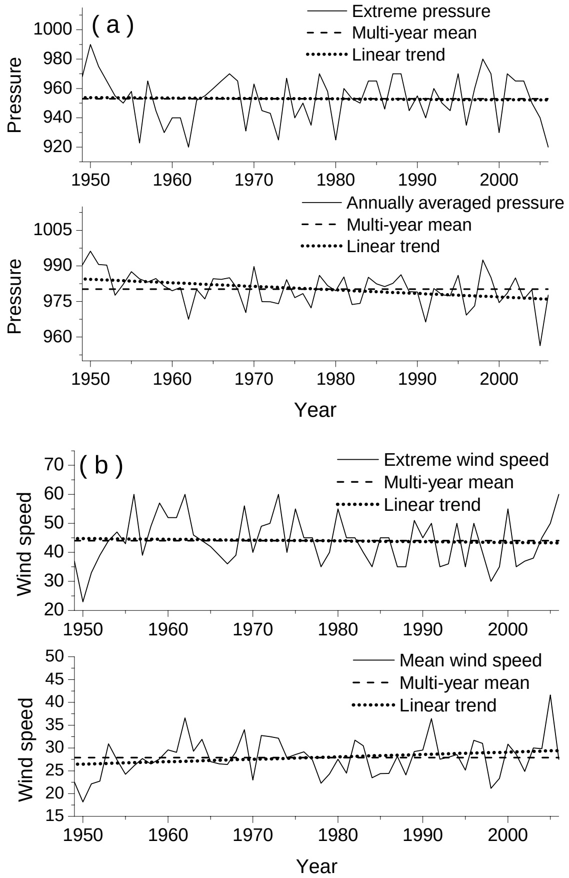


Fig. 3. Intensity chage of landfalling TCs from 1949–2006 a. air pressure (hPa); b. wind speed (m/s)

As shown in the statistical analysis of the diurnal variation of landfall time, a TC is likely to make landfall at midday, morning, and evening. The peak landfall times are at 1100–1200 (Beijing Standard Time, the same hereafter) for TD, STY, and SSTY; 0300–0400 for TS and STS; and 1900–2000 and 2300–2400 for TY.

4 SPATIAL VARIATIONS OF LANDFALLING TCS AT DIFFERENT

INTENSITIES

4.1 *Cyclogenesis area*

Based on the method of Yu and Yao[2], the region of the Northwest Pacific between 0–40° N and 100–80° E was divided into 5° × 5° squares, forming 128 squares in all. Then, each of the squares in which a TC had been generated was tabulated. A summation of these squares yielded a relative likelihood of eventual landfall in China.

The most notable pattern in Fig. 5 is that the TCs making landfalls in China were generated in the (1) northeastern South China Sea (18–22° N, 115–120° E); (2) Bashi Channel (13–17° N, 130–135° E); and (3) ocean surface east to the Philippines (10–15° N, 140–145° E). Figs. 4a and 4b show that the northeastern South China Sea is more likely to give rise to a landfalling TD or TS. Figs 4c and 4d show that both the northeastern South China Sea and Bashi Channel are favorable in contributing to a landfalling STS or TY. Figs. 4e and 4f show that the ocean east off the Philippines is likely to contribute to a landfalling STY or SSTY. The coefficient between the longitude of cyclogenesis and the minimum air pressure of a landfalling TC is up to -0.44, showing that the more eastward TCs are generated, the stronger they are when making landfalls. Similarly, the coefficient between the latitude of cyclogenesis and minimum air pressure is 0.21, which means that the more southward the TCs are generated, the stronger they are when making landfalls.

Table 3 presents the proportion of the number of landfalling TCs generated in the South China Sea in the total TC number. 56.5% of the TDs and only 3.9% of the STYs are generated over the South China Sea, and of the 16 SSTYs that made landfalls in China, all were generated in the western North Pacific. When interdecadal variations of landfalling TCs generated in the South China Sea are taken into account, a decreasing trend for TD and TS and increasing trend for STS, TY, and STY are identified. In contrast to the situation in the 1950s to the 1980s, two STYs were generated in the South China Sea and eventually made landfalls in China in the recent two decades. Therefore, the mechanism of rapid intensification for TCs generated in the South China Sea deserves more attention.

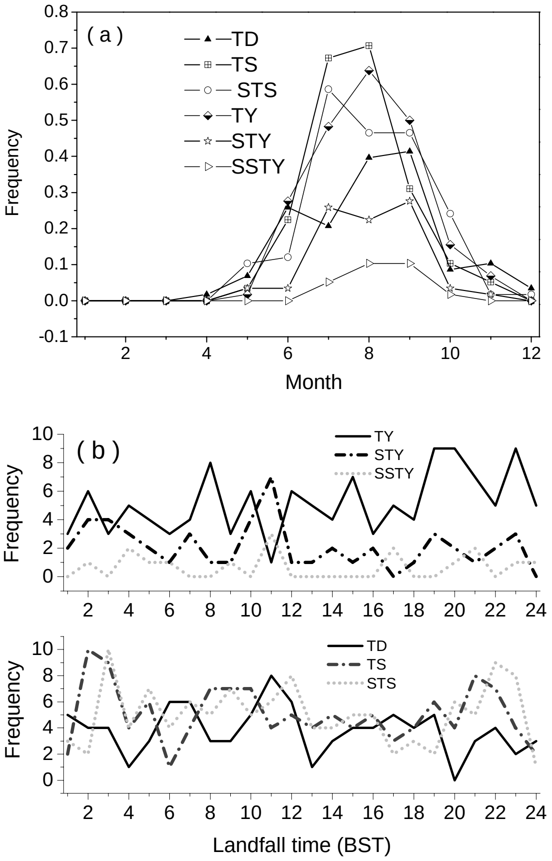


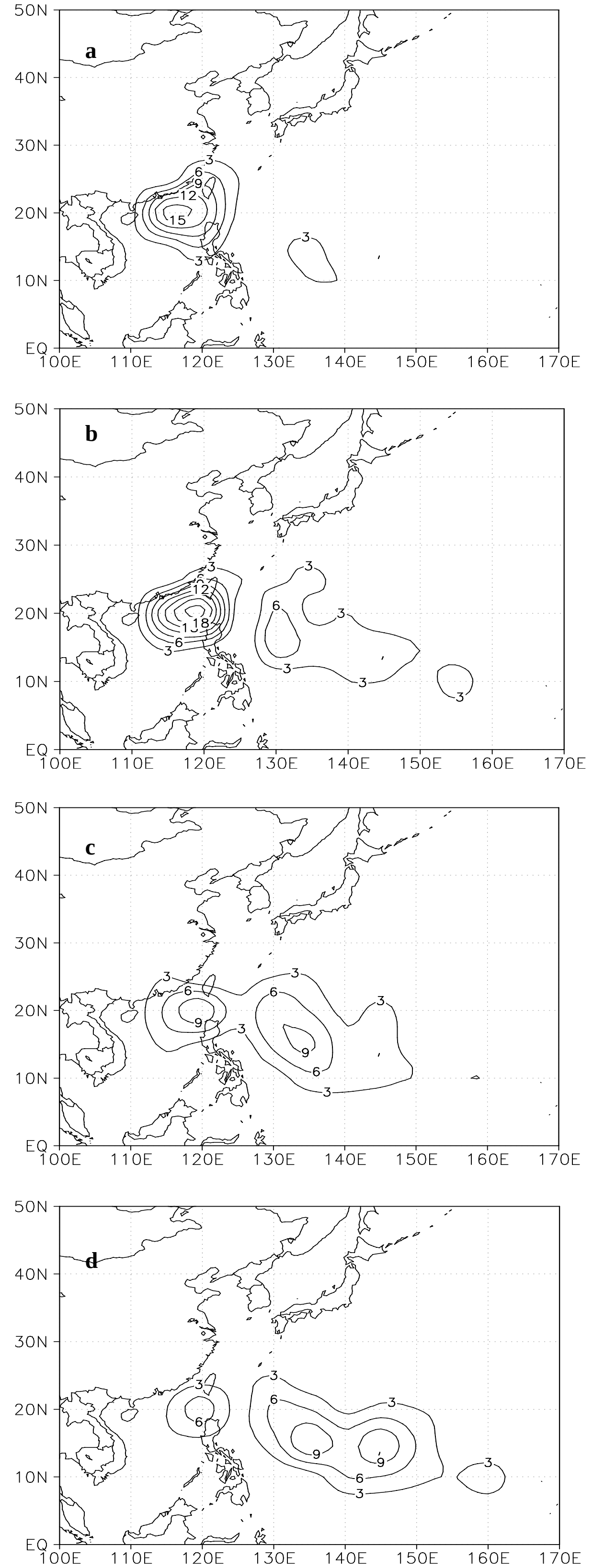
Fig. 4. Monthly (a) and diurnal (b) variations of TCs making landfalls in China from 1949–2006 at different intensities.

Table 3. Proportion of the number of landfalling TCs generated in the South China Sea in the total TC number of TCs at different intensities (unit of proportion: %).

period	TD	TS	STS	TY	STY	SSTY
Total TCs	56.5	44.3	24.0	12.1	3.9	0.0
1950s	61.3	51.6	21.4	7.1	0.0	0.0
1960s	71.4	40.9	15.4	21.1	0.0	0.0
1970s	60.0	38.1	20.0	14.1	0.0	0.0
1980s	41.2	50.0	25.9	8.0	0.0	0.0
1990s	61.5	40.0	22.7	23.8	7.7	0.0
2000-2006	42.9	45.5	50.0	6.3	10.0	0.0

4.2 *Landfall sites*

Figure 6 shows the variation trend of the 5-year mean longitude and latitude of TCs making landfalls in China. The number of SSTYs is too small to be meaningful and therefore is not calculated here. The landfall locations of TD and STY vary more widely than the others and have an out-of-phase relationship (Fig. 6). For example, while the TD made landfall more northward, the STY landed more southward. Comparatively, the mean locations of TS, STS, and TY varied little. On average, the stronger the TC is, the more eastward its landfall location. TD, TS, and STS are likely to make landfalls in areas east to the estuary of the Pearl River, Guangdong. TY, STY, and STY are more likely to make landfalls in Fujian.



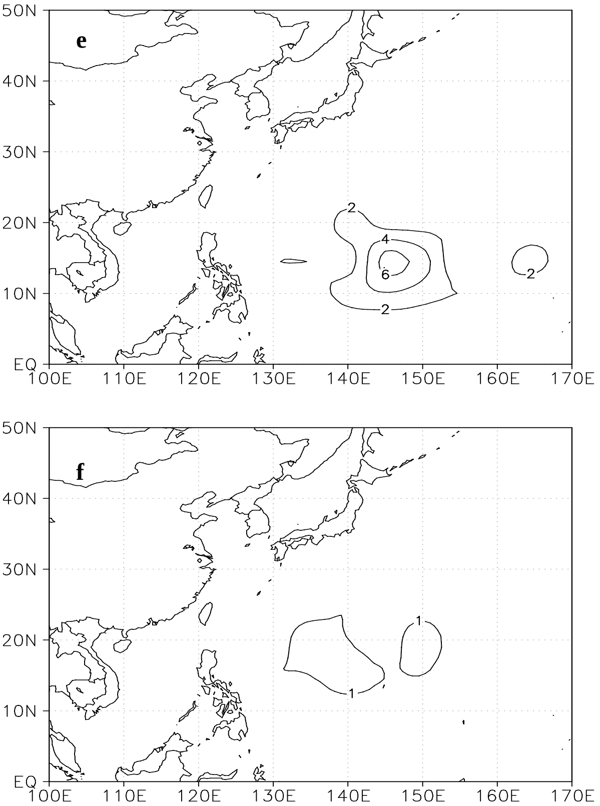


Fig. 5. Source locations of landfall TCs at different intensities from 1949–2006. a. TD; b. TS; c. STS; d. TY; e. STY; f. SSTY

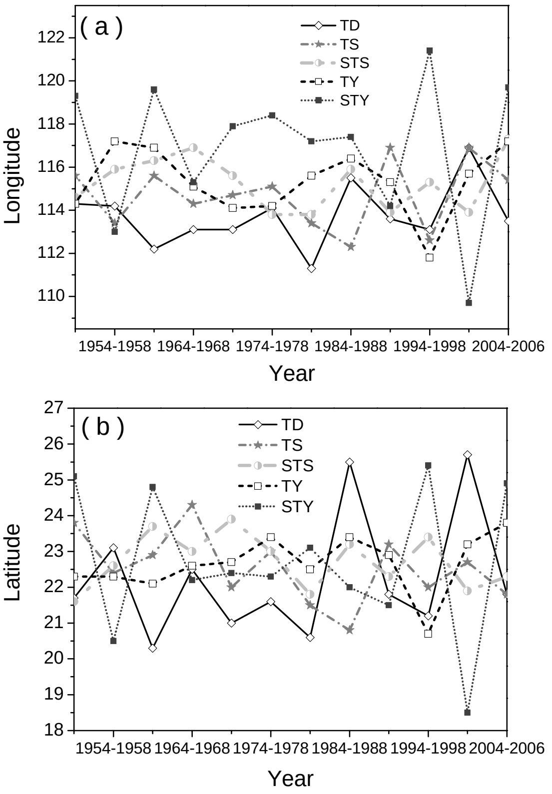


Fig. 6 Mean longitude (a) and latitude (b) of the landfall sites for TCs at different intensities from 1949–2006.

5 CONCLUSIONS

The 58-year datasets from 1949–2006 were used to study the characteristics of temporal and spatial variations of TCs in six intensity categories (TD, TS, STS, TY, STY, and SSTY) making landfalls in China’s mainland, Hainan and Taiwan islands. The main results are as follows.

(1) Over the past 58 years, interannual and interdecadal variations of the number of landfalling TCs in six difference intensity categories exist. As far as long-term trends are concerned, the frequencies of TD and TS show a significant linearly decreasing trend, while the frequencies of STY show a significant linearly increasing trend. In the variations of annual TD, TS, and STS frequencies, significant periods of 6–8 years exist, and the annual TY frequency shows a period of quasi-16 years.

(2) TCs at different intensities making landfalls in China concentrate in July through September. The stronger a TC is, the shorter the time interval between two landfalls in the course of a year. A TD makes landfall from April to December, while SSTY does only from July to October. The daily peak times of landfall is at 1100–1200 for TD, STY, and SSTY; 0300–0400 for TS and STS; and 1900–2000 and 2300–2400 for TY.

(3) TCs making landfalls in China were generated in the (1) northeastern South China Sea (18–22° N, 115–120° E); Bashi Channel (13–17° N, 130–135° E); and (3) ocean surface east to the Philippines (10–15° N, 140–145° E). The northeastern South China Sea is more likely to contribute to landfalling TDs and TSs. The Bashi Channel is likely to contribute to landfalling STSs and TYs. The ocean east to the Philippines is likely to contribute to landfalling STYs or SSTYs.

(4) In terms of the interdecadal variations of landfalling TCs generated in the South China Sea, a decreasing trend for TD and TS exists, but an increasing trend is observed for STS, TY, and STY.

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