Spatial and Temporal Variations of Tropical Cyclones at Different Intensity Scales over the Western North Pacific from 1945 to 2005*

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ABSTRACT

The tropical cyclone (TC) track data provided by the Joint Typhoon Warning Center (JTWC) of the U.S. Navy over the western North Pacific (including the South China Sea) from 1945 to 2005 are employed to analyze the temporal and spatial variations of TCs of different intensity classifications. Most of the TCs occurred between 15° and 25°N, from the northern part of the South China Sea to the eastern part of the Bashi Channel until near 140°E. Most of the severe and super typhoons occurred over waters from the eastern part of the Bashi Channel to about 140°E. The TCs in a weakening or steady state take up a weak majority in the area west of 123°E and north of 20°N; those in an intensifying or steady state are mostly found in the area east of 123°E and south of 20°N. For severe tropical storms, typhoons, severe typhoons, and super typhoons, their average decaying rates are all greater than the respective average growing rates; for tropical storms, however, the average decaying rate is smaller than the average growing rate. Generally speaking, the stronger the TC, is the faster the intensification (weakening) is. The percentage of weak TCs is higher in June to August while that of strong TCs is higher in September to November, than in other months. There are annual, interannual, and interdecadal variations in the observed number (every 6 h) and frequency of TCs at different intensity scales. As far as the long-term trend is concerned, the frequency and observed number of tropical storms have a significant linear increase, but the averaged intensity and number of TCs of other intensity categories do not exhibit such a significant linear trend. In El Niño years, the number and percentage of super typhoons are significantly higher, while the total number of tropical storms, severe tropical storms, typhoons, and severe typhoons is significantly lower, and the mean intensity of TCs is prominently stronger; in La Niña years, however, the opposite is true.

Key words: Tropical Cyclone, intensity, frequency, temporal and spatial variations, western North Pacific

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1. Introduction

The western North Pacific is where the tropical cyclone (referred to as TC hereafter) is mostly generated. There are more than 20 TCs per year over this region, taking up about 1/3 of the global total. Meanwhile, this part of the ocean is also the only place where the TC can be observed in every month of the year. Standing next to the western North Pacific, China is one of the few countries subject to serious TCs in the world. The strong winds, torrential rains, and storm surges accompanying the arrival of TCs often cause serious damage to national economy and people's livelihood and property in coastal areas.

Over the past few years, much work has been done on the TCs and their patterns of activities and climatological characteristics (Chen and Huang, 2006). The TC is marked by annual, interannual, and interdecadal variations, as shown in some studies (Liebmann et al., 1994; Chan and Shi, 1996; Ho et al., 2004; Huang and Chen, 2007), and changes have taken place in the generation, track and intensity of tropical storms against the background of global climate warming, as shown in others (Knutson et al., 1998; Chan and Liu, 2004; Wu and Wang, 2004; Emanuel, 2005; Webster et al., 2005). The past decade has witnessed a large amount of work by Chinese researchers on the interactions of the TC with other systems as well as its migratory track, intensity change, structural characteristics and landfall (Chen and Meng, 2001; Lei and Chen, 2001;

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Chen., 2004a, b; Wang and Qian, 2005). Interdecadal, interannual, monthly, and daily variations of TC intensity and basic characteristics of its regional distributions were studied using 35-yr TC data (Yu and Duan, 2002). The TC tended to weaken in the 1970s and 1990s while showing tendencies of gradually intensifying in the 1980s. On average, the TC is a little stronger in the El Niño years but a bit weaker in the La Ni?a years, as shown in a study of TC intensity based on the data over the western North Pacific for 1970–2004 (Li et al., 2006). The northern part of the South China Sea (SCS) and waters east of the Philippines are two areas with high frequency of intensifying TCs, as reported in a statistical study on the variation of TC intensity over the western North Pacific from 1949 to 2003 (Yu and Yao, 2006). Up to the present, some advances have been achieved in the studies of the TC intensity but they remain relatively lagged behind the progress in other research topics of TCs (Duan et al., 2005; Chen and Qiu, 2005). While previous works put much emphasis on the abrupt change of TC intensity and mechanisms responsible for it, no detailed study has been carried out to reveal the variation patterns of TCs with varying intensity.

With a 1945–2005 TC dataset for the western North Pacific, this work intensively studies the spatial distribution and temporal variation of TCs with varying intensity.

2. Data and methods

The data used in this study are from the Joint Typhoon Warning Center (JTWC) of the U.S. Navy, namely, the best track of TCs over the western North Pacific (https://metoc.npmoc.navy.mil/jtwc/best-tracks). They cover a time period from 1945 to 2005 and an area of the entire western North Pacific and the SCS (no special description will be given if the same area is referred to again in the remaining text of this paper). The best TC track dataset includes latitudes and longitudes of the TC and maximum wind speed near the TC center observed every 6 h. According to the latest standard of TC intensity adopted in June 2006 in China, the TC is classified into six categories based on the maximum wind speed (see Table 1), namely, tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), severe typhoon (STY), and super typhoon (SuperTY). Included in the dataset of TC best track are all TCs that have at least reached the intensity level of TS so discussion therein does not include the TD, which is never complete as a group and always falls short of the TS intensity. There are a total of 1555 samples of TCs in the dataset, among which the data measured since the 1970s are more accurate and thus more representative than those before, because satellite observations have been incorporated thereafter. Even with satellite data, discrepancies are bound to occur between different sources of TC data (Yu et al., 2006), but the issue of accuracy and representation will not be dealt with in this study. For the ENSO index, the data provided by the Japan Meteorological Agency (JMA) are utilized (http://www.coaps.fsu.edu/products/jma-index.php).

Table 1. Classification of TCs based on their intensity levels

Intensity levels	Wind speed (m s^{-1})
TD (Tropical Depression)	10.8–17.1
TS (Tropical Storm)	17.2–24.4
STS (Severe Tropical Storm)	24.5–32.6
TY (Typhoon)	32.7–41.4
STY (Severe Typhoon)	41.5–50.9
SuperTY (Super Typhoon)	$\geqslant$ 51.0

In this study, wavelet analysis is used to probe into the local features of the data time series. To study the relationship between two variables, the Pearson correlation coefficient is used.

3. Spatial distribution of TCs at different intensity levels

Figure 1 gives the number of times for which TS, STS, TY, STY, and SuperTY have been observed during the 61 years (1945–2005) in the 5°×5° longitude-latitude grid meshes. It shows that the region with the largest occurrences of TS and STS is located over the northern SCS, where both the storms locally developed and those migrated from the western North Pacific meet each other; the region with the most appearances of TY is from the northern SCS to waters in eastern Bashi Channel; the region with the most appearances of STY and SuperTY is from waters east of the Bashi Channel to the ocean near 140°E, where warm sea surface temperature (SST) and weak vertical wind shear provide favorable environmental conditions for the development and intensification of the TC, making it a contrast to either the low latitudes where the TC forms but develops insufficiently, or the high latitudes where SST is relatively low and vertical wind shear is relatively strong, unfavorable for the TC development and intensification (Yuan et al., 2007).

Figure 2 gives the meridional and zonal distributions of the number of observed TCs of different intensity for the period of 1945–2005. The peak value of the meridional variation is between 125°E and 130°E for TS, TY, STY, and SuperTY while it is between 130° and 135°E for STS, of which the longitudes between

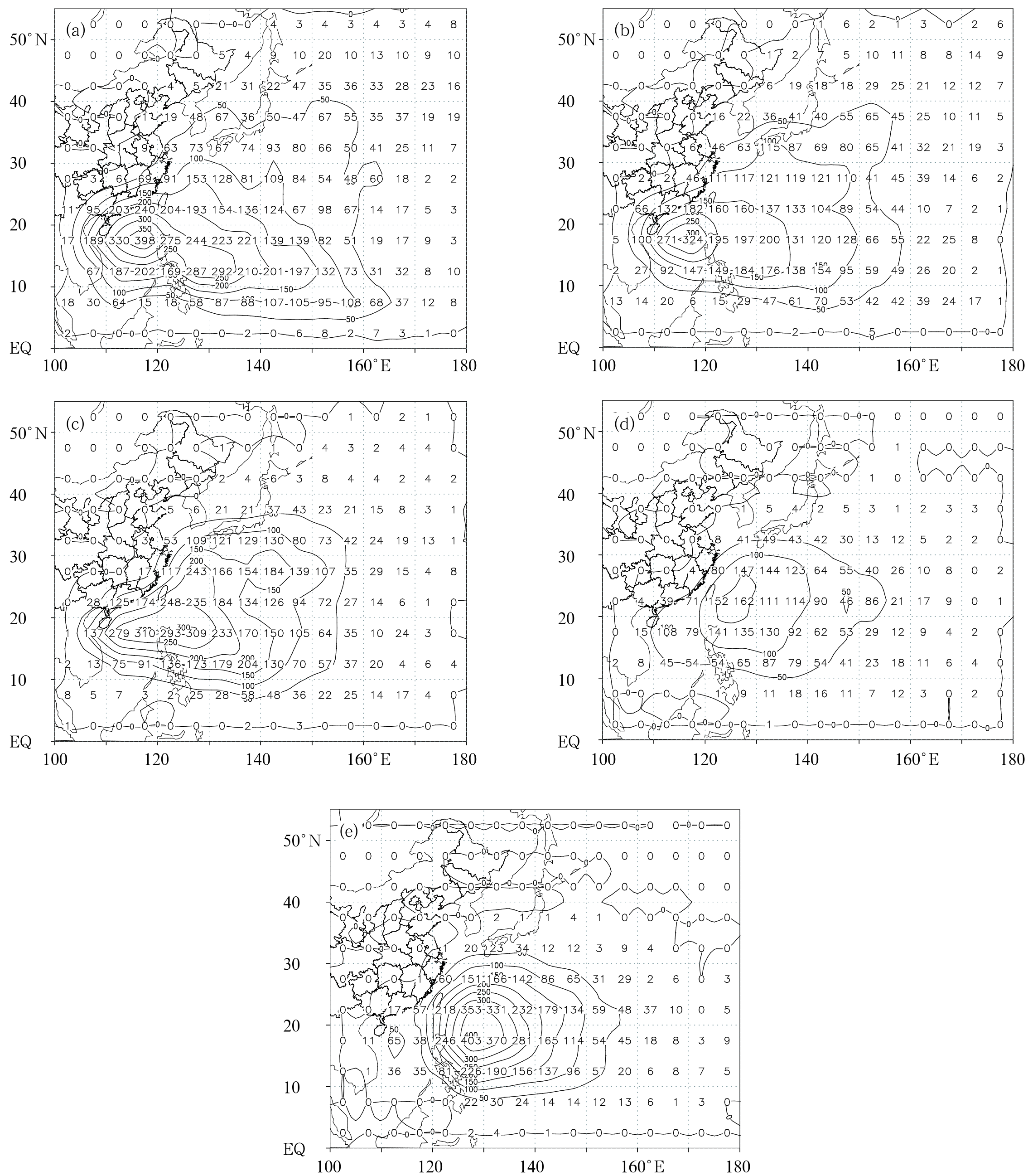

Fig. 1. Number of observations of TCs with different intensity levels in the 5°×5° longitude and latitude bins during the 1945–2005 period. (a) TS, (b) STS, (c) TY, (d) STY, and (e) SuperTY. The isoline is at an interval of 50.

125° and 135°E is the section where TCs of different intensity are observed with the largest number, flanked by two regions of decreasing number of observations both to the east and west (Fig. 2a). The peak value of the zonal variation is between 15° and 20°N for TS, STS, TY, and SuperTY while being between 20° and 25°N for STY, of which the latitudes between 15° and 25°N is the section where TCs of different intensity are observed with the largest number, flanked by two regions of decreasing number of observations both to the north and south (Fig. 2b). The aforementioned meridional and zonal distributions of the number of observed TCs are related to a number of factors such as the land-sea contrast of the western North Pacific, the distribution of SST, the location over which the TC forms and moves, and the distribution of the subtropical high and atmospheric vertical wind shear. Besides, the number of observed TSs is generally greater than that of STSs while the number of observed STSs is basically larger than that of STYs.

To study the variation trend or variability in TC intensity, the following approach is adopted in which the maximum TC wind speed for the next successive moment is subtracted from that of the current moment (with a 6-h interval) before being divided by 6 to indicate the TC variation trend or variability. The negative, zero, and positive values indicate weakening, steady, and intensifying TCs, respectively negative, zero and positive values indicate weakening, a ges steady, intensifying TCs, respectively. Figure 3 gives the percentage distributions with the latitude and longitude of weakening, steady and intensifying TCs, It is shown that most of the TCs are weakening or steady when they are west of 123°E but intensifying or steady east of it (Fig. 3a); more TCs are weakening or steady than those intensifying west of 123°E due to landfall or land effects while TCs tend to intensify and sustain over extensive waters east of 123°E. Another finding is that TC is mostly weakening or steady north of 20°N but mostly intensifying or steady south of it (Fig. 3b); the TC tends to sustain or intensify due to the presence of warm ocean surface and weak vertical wind shear south of 20°N in the western North Pacific, but it is not likely for the TC to intensify north of 20°N, because the SST is gradually decreasing and the vertical wind shear is intensifying over these waters.

Figure 4 gives the percentages of observations of weakening, steady, or intensifying TCs with varying intensity. For TS and STS in any of the three states, the percentages are all decreasing, but they are increasing for STY and SuperTY, of which STY has the minimum percentage among TCs at all levels of intensity. In the weakening state, the percentage does not differ much between TS, STS, TY, and SuperTY; in the steady state, it is the largest for TS but relatively small for STY and SuperTY; in the intensifying state, it is gradually decreasing from TS to STY while being a little larger for SuperTY than for STY.

Figure 5 gives the percentages of TC observations with varying intensity at the weakening, steady and

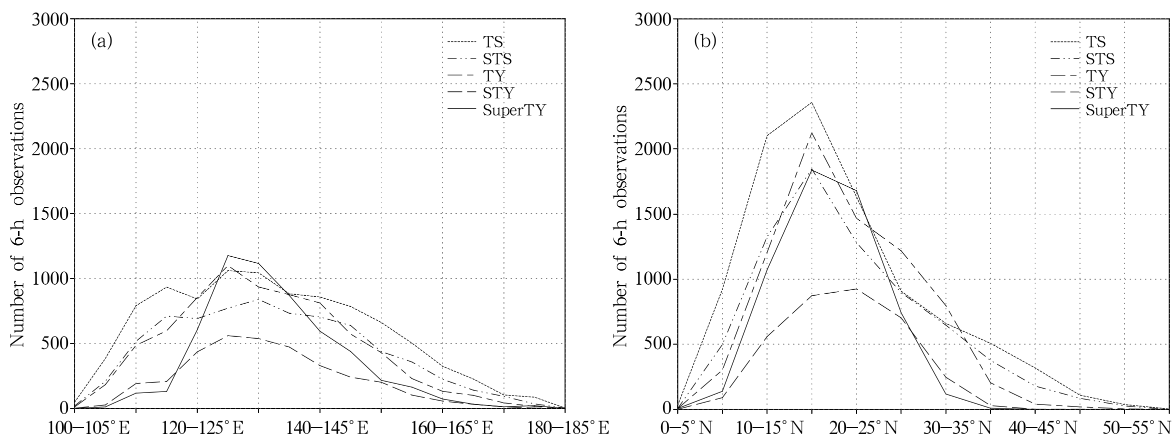

Fig. 2. Number of observations of TS, STS, TY, STY, and SuperTY along every 5° longitude bins (a) and 5° latitude bins (b) during the 1945–2005 period.

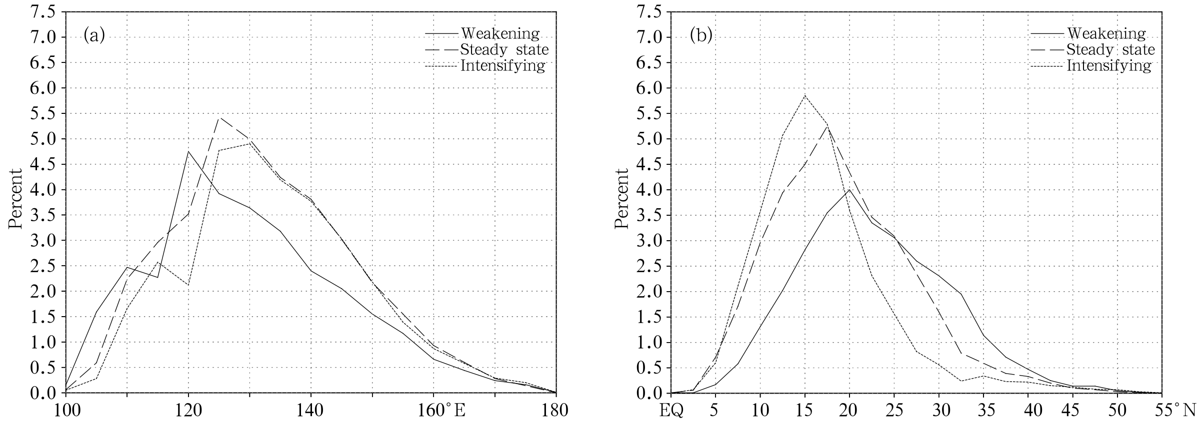

Fig. 3. Percentage distributions of all observations of TCs with different intensification tendency as a function of (a) latitude and (b) longitude during the 1945–2005 period.

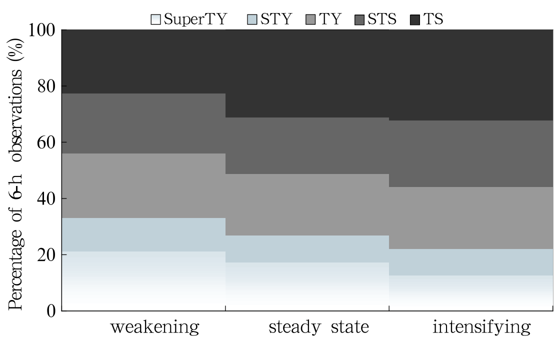

Fig. 4. Percentages of TCs with different levels of intensity from TS (black) to SuperTY (light gray) that are weakening, stabilizing, or intensifying during the 1945–2005 period.

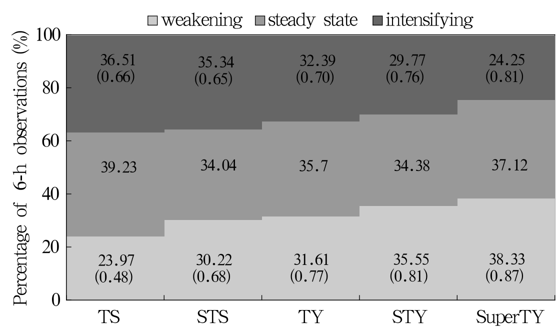

Fig. 5. Percentages of weakening (light gray), steady (gray), or intensifying TCs at different intensity scales in 1945–2005. Mean intensifying or weakening rates are shown in parentheses.

intensifying states in 1945–2005. It can be seen that for both TS and TY the percentages are the largest at the steady state but the smallest at the weakening state; for STS the percentage is the highest at the intensifying state but lowest at the weakening state while things are just the opposite in the case of STY and SuperTY, suggesting that STS has a larger ratio of intensification while STY and SuperTY have a larger ratio of weakening. Except for the case in which the intensifying rate is a little smaller for STS than for TS, TCs with other levels of intensity tend to grow with the increase of intensity, showing that the stronger the TC, the faster it intensifies except for STS. Additionally, the weakening rate also increases with the growth of TC intensity, i.e., the stronger the TC, the faster it weakens as well. It can then be known from the above analysis that the stronger the TC, the faster it intensifies/weakens; STS, TY, and SuperTY weaken faster than they intensify while TS intensifies faster than it weakens.

4. Temporal variation of frequency of TCs with varying intensity

Figure 6 shows variations of the multi-year (1945–2005) and daily accumulated number of 6-h observations of TCs at different intensity scales from April 1 to December 31. A 5-day running average is applied to obtain the results. It can be seen that TC is the most active from July to October; the largest number of 6-h observations of TSs appears from early August to mid-September; the largest numbers of 6-h observations of STSs and TYs are found from mid-August to mid-September; the largest number of 6-h observations of STY is seen in September;

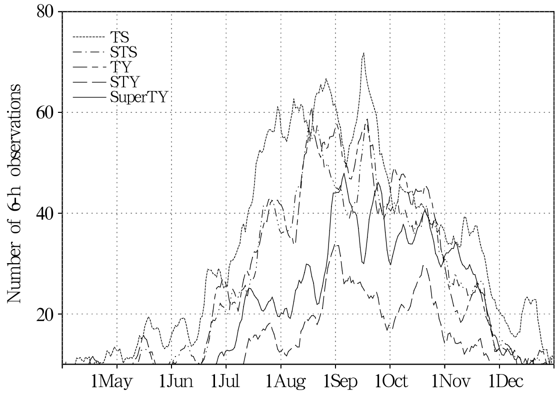

Fig. 6. Variations of the multi-year (1945–2005) and daily accumulated number of 6-h observations of TCs in different intensity categories.

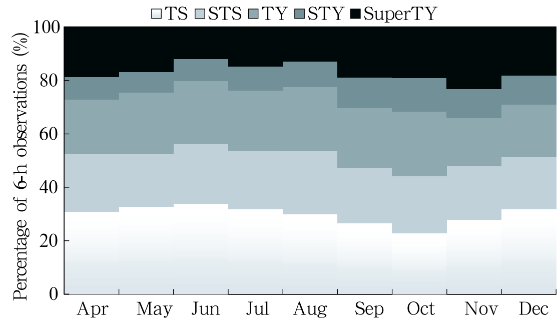

Fig. 7. Percentages of TCs with different intensity from April to December.

a peak of the number of observations of SuperTYs occurs from the end of August to early September while another peak shows up in mid-October. For TCs with different intensity, the number of 6-h observations generally increases spirally before the peak but decreases spirally afterward.

Figure 7 gives the percentages of TCs with different intensity in April-December of 1945–2005. It shows that the percentage differs across the months: TS and STS take up about 50% in each of the months, and so do TY, STY, and SuperTY; in September to November, particularly, the numbers of observations of TS and STS are a bit smaller than 50% while being just more than 50% in other months; although having the highest percentage of observation (56.3%) in June, TS and STS have the lowest percentage in October (44.4%). Relatively speaking, TS and STS have larger percentages in June–August than in other months while TY, STY, and SuperTY have larger percentages in September-November. For TCs with all different levels of intensity, TS has the largest percentage while STY has the smallest. There is not much difference between STS and TY in individual monthly ratios; STY has the highest ratio in October (12.5%) and the lowest in May (7.6%); SuperTY has the highest ratio in November (25.1%) and the lowest in June (11.9%).

Figure 8 gives the annual variations of the number of 6-h observations of TCs with different intensity in 1945–2005. It is noted that the number of 6-h observations of TSs (counted 1 once a TS appears in the 6-h observational data, and counted 2 if it appears again in the next 6-h data record, while in fact the latter is the same TS as before) shows a significant linear increase from 1945 to 1995 but decreases remarkably after 1995, which is mainly due to the shortened life cycle of TSs after that point. Over the course of the 61 years, the number of 6-h observations is generally in a significant linear increase, with the coefficient being 0.29 for the correlation between the annual number of 6-h observations of TSs and the overall tendency, and the significance level being 5% (p-value being 0.02). The time from 1945 to 2005 witnesses no significant linear rise or fall in the annual number of 6-h observations of STSs, TYs, STYs, and SuperTYs. More 6-h observations of STSs are found during the mid-1960s to mid-1990s than other time periods. More 6-h observations of SuperTYs are seen from the 1950s to the 1960s than from the 1970s to the 1980s.

Annual, interannual or interdecadal variations exist in the number of 6-h observations of TCs with various levels of intensity. Annual variation is the common characteristic for all TCs. Apart from that, TS is also featured with an interdecadal variation with a 18-yr period, STS with an interdecadal variation with a 50-yr period, TY with an interannual variation with 2-3-yr period and interdecadal variation with a 30-yr period, STY with an interannual variation with a 2-6-yr period and intedecadal variation with a 18-yr period, and SuperTY with an interdecadal variation with a 38-yr period (Fig. 9).

On average, 4.3 TSs form each year. The number of formed TSs (counted only one time from formation to extinction of a TS) for 1945–2005 tends to have a significant yearly linear increase, which correlates with the trend by a 0.36 coefficient and at a 5% significance level (with a 0.004 p-value). The average numbers of STS, TY, STY, and SuperTY generated per year are 4.3, 5.0, 3.0, and 9.0, respectively, with an increasing trend for STY but a decreasing one for SuperTY, which are insignificantly linear in both cases (Fig. 10). Meanwhile, the number of formed TCs with different intensity also shows annual, interannual, and

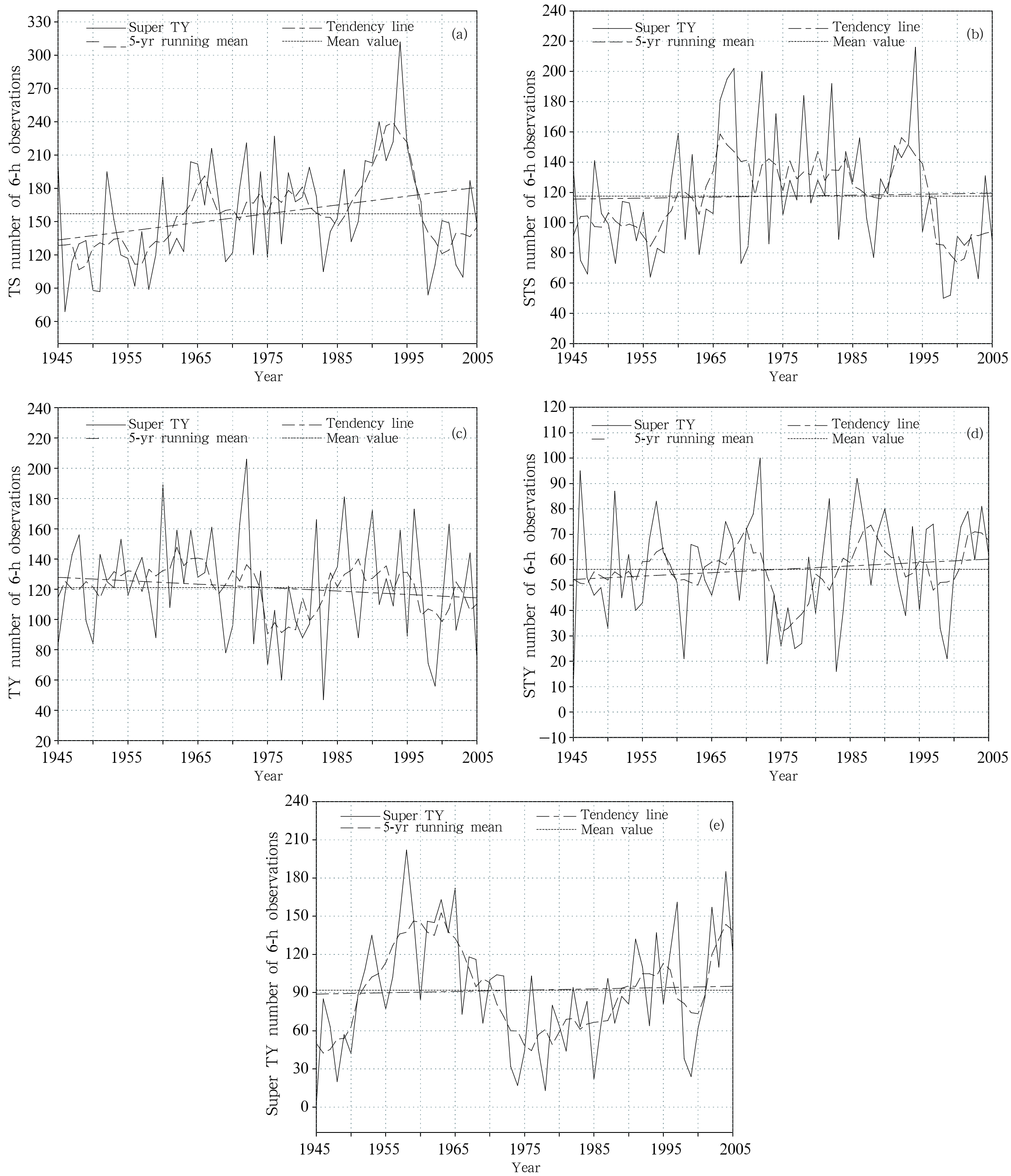

Fig. 8. Annual variations of the number of 6-h observations of TCs with different intensity from 1945 to 2005. (a) TS, (b) STS, (c) TY, (d) STY, and (e) SuperTY. The long-short dashed is line the trend, the dotted line is the mean, and the long dashed curve is the 5-yr running mean.

interdecadal variations similar to the number of 6-h observations of TCs (figure omitted).

The annual mean of maximum TC wind speed can be known based on relevant values observed every 6 h. As indicated by the data analysis, the maximum annual mean TC wind speed for 1945–2005 varies significantly on interannual and interdecadal scales. The multi-year mean of maximum TC wind speed is about 35.0 m s^{-1}; it is relatively large from the early 1950s to the early 1970s but becomes smaller from the early

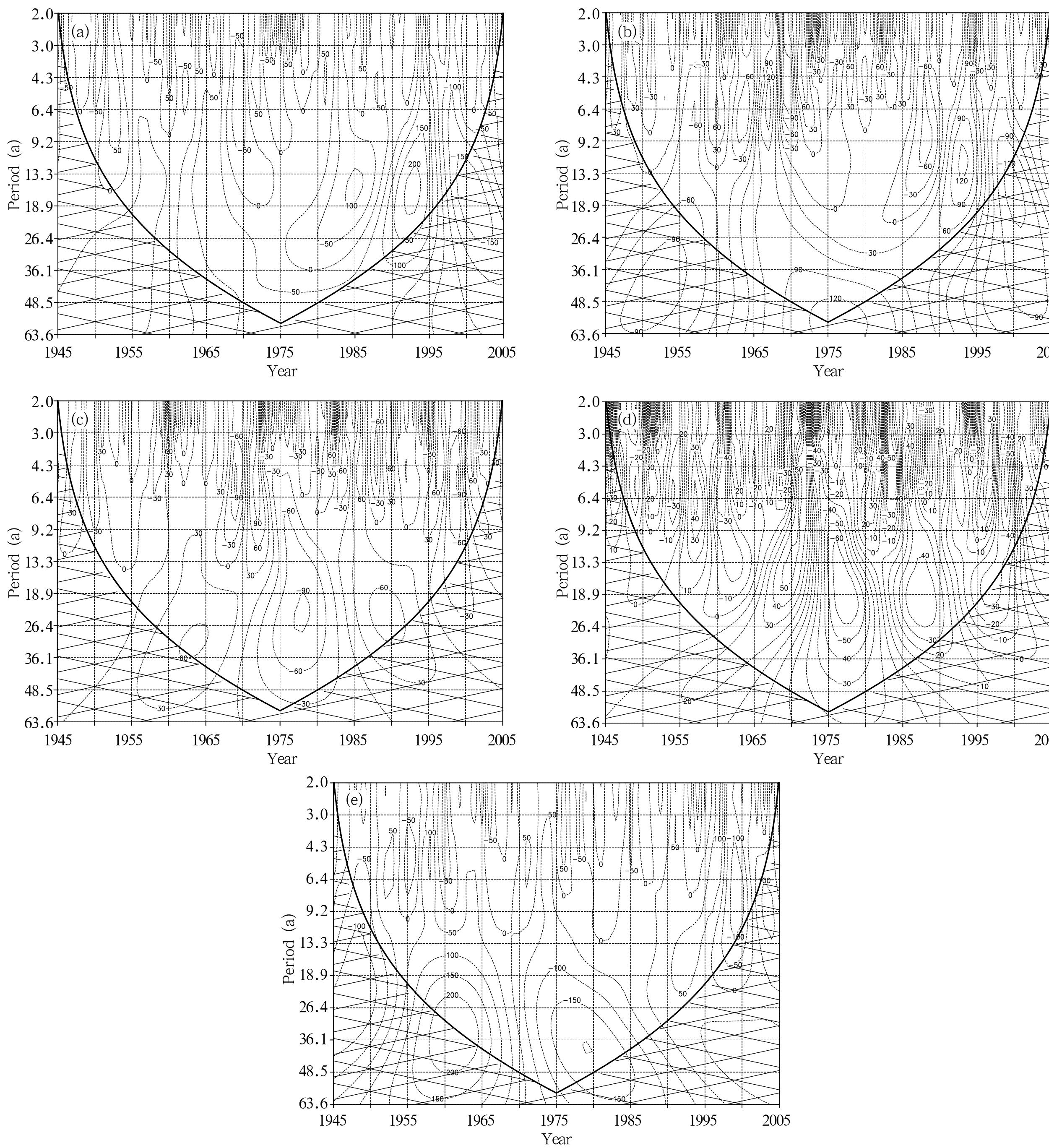

Fig. 9. The Mexican hat wavelet analysis of the number of 6-h observations of TCs with different intensity during the 1945-2005 period. (a) TS, (b) STS, (c) TY, (d) STY, and (e) SuperTY. The region below the bold solid line indicates the “cone of influence.”

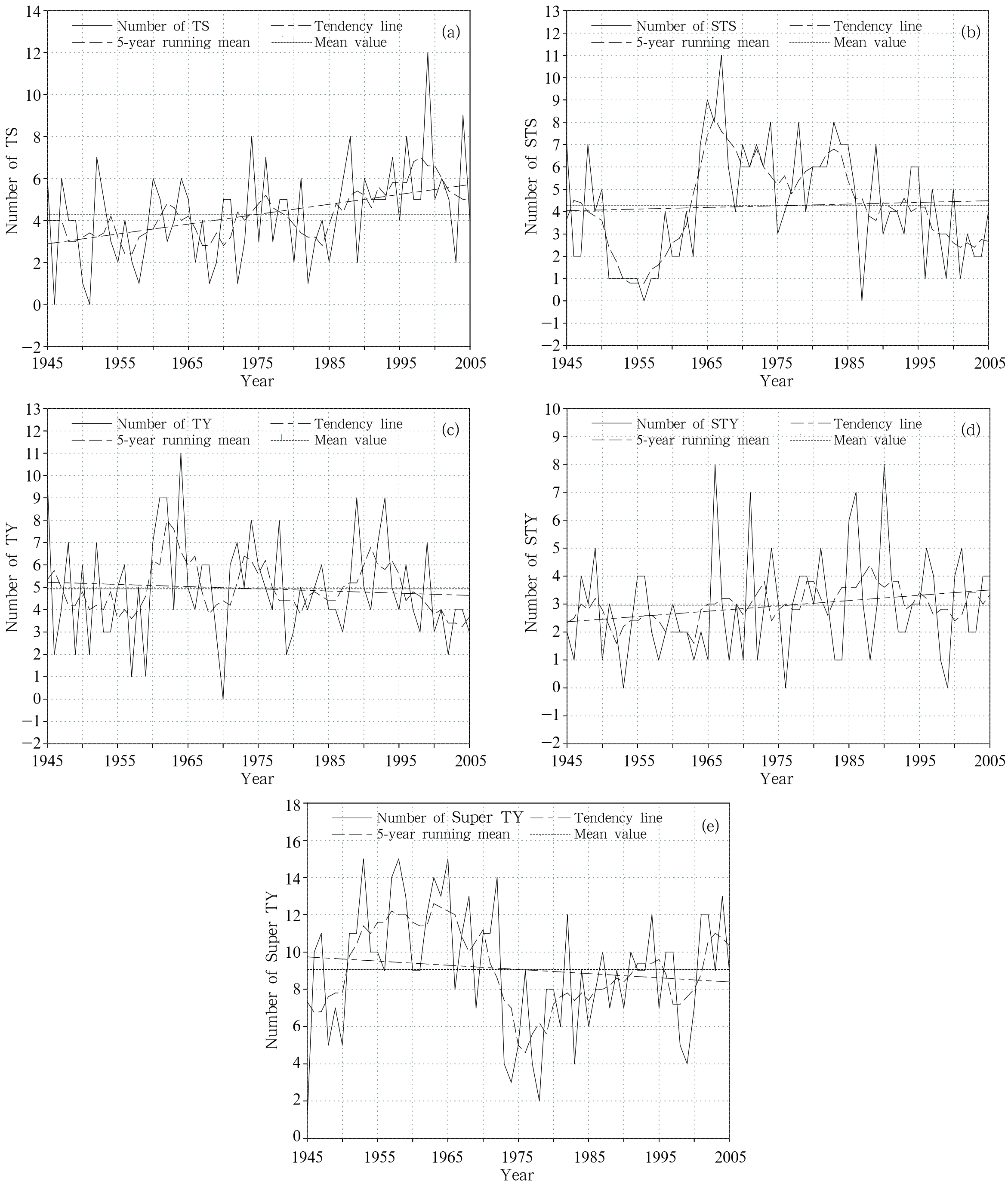

Fig. 10. As in Fig. 8, but for the number of formed TCs instead of the number of 6-h observations of TCs.

1970s to the mid-1980s (figure omitted). Over the years (1945–2005), it has a significant positive correlation with the ENSO index with the correlation coefficient being 0.274 and at the 5% significance level (with a 0.033 p-value). It is shown that TCs are much stronger in El Niño years than in La Niña years. Besides, weak, linearly weakening trends are found in both the average maximum wind speed and the number of formed SuperTYs (Fig. 10e). This indicates that the mean intensity of TCs and the number of SuperTYs do not show significant linear increases with the warming of the global climate.

The annual number of cyclogenesis over the western North Pacific is correlated to some degree with the ENSO index (Table 2). The total annual number of cyclogenesis for TS, STS, TY, and STY is negatively correlated

Table 2. Pearson's correlation of annual TC number from 1945 to 2005

Variables	Pearson correlation coefficient	*p*-value
ENSO index and total number of TS, STS, TY, STY	−0.265	0.039
ENSO index and number of SuperTY	0.388	0.002
ENSO index and ratio of SuperTY number to total TC number	0.397	0.002
ENSO index and total number of TCs	−0.004	0.975
Total number of TS, STS, TY, STY versus number of SuperTY	−0.375	0.003

with the ENSO index with a correlation coefficient (CC) of −0.265 and with a 0.039 *p*-value. The number of SuperTYs is positively correlated (CC: 0.388) with the ENSO index with a 0.002 *p*-value. The ratio of SuperTY, or its percentage with regard to the total number of TCs, is positively correlated (CC: 0.397) with the ENSO index with a 0.002 p- value. However, the total number of TCs in the western North Pacific is not appreciably correlated with the ENSO index. Additionally, the total number of TSs, STSs, TYs, and STYs is highly negatively correlated (CC: −0.375) with the number of SuperTYs with a 0.003 *p*-value. All the above correlations are at the 5% significance level.

Figure 11 gives the annual variations of the standard deviation of the ENSO index, total number of TS, STS, TY, and STY, number of SuperTY and ratio of SuperTY to total TC. It can be seen that the years with large ENSO indexes are usually associated with higher number of SuperTY but lower total number of TS, STS, TY, and STY; otherwise is generally true in the years of small ENSO indexes. As Wang and Zhang (2002) stated, the anomalies of equatorial westerlies at the lower levels over the western North Pacific during the El Niño years can cause positive shear vorticity, which is favorable for the development of TCs and otherwise is true in the case of the La

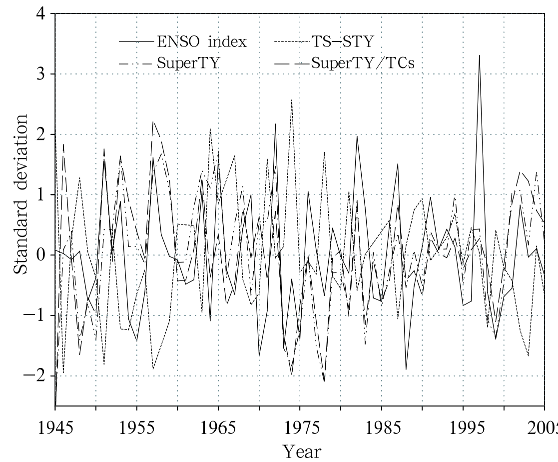

Fig. 11. Annual variations of the standard deviations of the ENSO index, total number of TS, STS, TY, and STY, number of SuperTY, and ratio of SuperTY number to total TC number during the period 1945–2005.

Niña years. During the El Niño years, environmental conditions are favorable for TCs to develop and intensify in the western North Pacific, making it more likely for them to strengthen into SuperTYs; otherwise is true in the case of the La Niña years. It well accounts for the phenomenon that the ENSO index is highly positively correlated with the number of SuperTYs and the ratio of SuperTY number to the total TC number but negatively correlated with the total number of TS, STS, TY, and STY.

5. Conclusions and discussion

The following main conclusions have been drawn after the above analyses of the variations of TCs in different intensity classes over the western North Pacific in 1945–2005.

(1) Areas with the most observations of TS, STS, and TY cover the northern SCS to the eastern Bashi Channel while those of most STYs and SuperTYs lie from waters east of Bashi Channel to around 140°E. The meridional section between 125° and 130°E and the zonal section between 15° and 25°N are where peak observations of TCs with all levels of intensity are located.

(2) In the western North Pacific, slightly more TCs are weakening or steady when they are west of 123°E; most of the TCs are intensifying or steady

east of 123°E or south of 20°N while they are mostly weakening or steady north of it. The percentages of STY observations are the smallest whether STYs are in the weakening, steady, or strengthening state; in the strengthening state,the percentages of observations gradually decrease from TS to STY, being a little larger for SuperTY than for STY. For the largest percentage of observations, STS is at the strengthening state, TS and TY are at the steady state, and STY and SuperTY at the weakening state. Generally speaking, the stronger the TC, the faster it intensifies or weakens; STS, TY, STY, and SuperTY weaken faster than they intensify.

(3) The TC is the most active from July to October. Peak daily numbers of 6-h observations of TS, STS, TY, and STY occur in August and September. There are two peaks of daily numbers of 6-h observations of SuperTY: one appears from the end of August to early September and the other in the mid-October. Relatively weak TCs (TS and STS) take up higher percentages in June, July, and August than in other months while relatively strong TCs (TY, STY, and SuperTY) take up larger percentages in September, October and November than in other months.

(4) For both the number of observations every 6 h and the number of formations, western North Pacific TCs are all characterized by annual, interannual or interdecadal variations regardless how intense they are. On the long-term trend of the observation and formation numbers, TSs tend to have significant linear increases while STS, TY, STY, and SuperTY show no signs of linear increase or decrease in a significant way.

(5) In the western North Pacific, the mean intensity of TCs and the number of SuperTYs do not show significant linear increases under the global climate warming. The ENSO index is highly positively correlated with the number of SuperTY and the ratio of SuperTY to total TC while it is significantly negatively correlated with the total number of TS, STS, TY, and STY. At the same time, the number of SuperTY is also strongly negatively correlated with the total number of TS, STS, TY, and STY. El Niño years witness a much larger number and ratio of SuperTY number to total TC number and much higher mean TC intensity while La Niño years come the opposite.

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