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Non-Stationary Variation of Tropical Cyclones Activities in the Northwest Pacific*

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ABSTRACT

Based on the analysis of tropical cyclone (TC) database in the Northwest Pacific (NWP) from 1945 to 2008, we not only extract the temporal variation of TC intensity and frequency, but also give their spatial distribution both in the NWP and in the South China Sea (SCS). The results show that there is an observational increase of TC activities, which manifests as the enhancement of the power dissipation index (PDI) and the growth of TC frequency, especially for typhoons and strong typhoons. The inhomogeneous spatial distributions of TC frequency and intensity are also provided both in the NWP and in the SCS. For example, the region of Zhongsha Islands and Dongsha Islands in the SCS (15°~22°N, 115°~120°E), west to the Philippine Islands is the place with frequent occurrence of strong typhoons, among which the wind speed of 7 TCs in 64 years exceeds 60 m/s.

Key words: *the Northwest Pacific*; *the South China Sea*; *tropical cyclone*; *non-stationary*; *intensity*; *frequency*

1. Introduction

The Northwest Pacific (NWP) is the place where the most frequent and intense tropical cyclones (TCs) occur among the global sea areas. The flooding on Chinese Mainland and wave climate in the sea areas of China are heavily dependent on TCs activities along with accompanied strong winds, torrential rain and huge waves, causing great losses in economic and social property. In recent years, the extreme marine events evidently occur more often than ever. For example, when the hurricanes of Katrina and Rita were haunting about the Gulf of Mexico in 2005, the 167 offshore platforms and 183 oil pipelines were damaged, resulting in 40 percent oil production of Gulf of Mexico interruption. In the South China Sea (SCS), a great many offshore structures were also threatened by super strong typhoons such as Typhoon Pearl in 2006. Very probably the accidents can be attributed to the underestimation of marine environment parameters, for instance, wind speeds with different return periods in the engineering design. Naturally, the task of predicting the trends of TC intensity and annual frequency become a challenging issue we have to confront. In the estimation of extreme wind speed with different return periods, we need to take the influence of non-stationary stochastic process into consideration, hoping to

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provide more reasonable basis for offshore engineering standard or criterion revision in the near future.

Many studies have been conducted to explore whether the TC activities is strengthened or not. Based on a Carnot cycle theoretical model, Emanuel (1987, 1991) predicted that increased atmospheric CO_2 content yields an increase in TC wind speed. Integrating Coupled Model Inter-comparison Project (CMIP21) climate models with a nested regional model, Knutson (1999, 2001, 2004, 2007) found the average results of 6% increase in TCs maximum surface wind speed under the assumption of 80-year linear growth trends of +1% annually in CO_2 content. Analysis of observational database (Emanuel, 2005; Chen, 2009) also demonstrates that the tendency of TC intensity, measured by power dissipation index (PDI) and averaged accumulated cyclone energy (ACE), does well agree with that of sea surface temperature (SST) increase in the NWP.

Based on the raw TC data analysis from 1957 to 2004, however, Tian and Weng (2006) gave the conclusion that both TC frequency and intensity in the NWP showed significant decreasing trends, where the results much depended on the reliability of the raw data used. Using atmosphere-ocean coupled general circulation models, Yokoi and Takayabu (2009) revealed that the frequency variations in the different NWP areas exhibited increasing trend in the eastern part of NWP and decreasing trend in the west part of NWP including the SCS. However, the authors assume that the decrease seems to heavily rely on the weakening pre-set activity of tropical depression-type disturbance.

The objective of the present study is to analyze the trends of TCs activities according to the TC database released by China Meteorological Administration (CMA). The temporal variation of intensity in terms of wind speed/PDI and frequency both in the NWP and in the SCS during 1945 ~ 2008 is provided. In addition, the analysis of TCs spatial distribution in the NWP and the SCS is also carried out so that we are able to identify the marine area of strong TC occurrence. Very likely, the TC activities are steadily growing in spite of slight depression at the beginning of the 21st century.

2. TC Database and Pre-Processing

2.1 TC Database

The time series of TC database in the NWP have been collected continuously during 1945 ~ 2008 from the software—the Retrieval System of TC in the NWP, which is released by CMA (http://www.typhoon.gov.cn). The database contains each TC′s location, central atmospheric pressure, maximum wind speed and moving speed recorded every six hours or even in shorter interval as well as the distribution of strong wind and heavy rainfall induced by TCs and the source areas of TCs generation.

2.2 Pre-Processing of TC Database

Because of the changing observation methods and estimation techniques in history, which may render the recorded history data deviate from the real TC information in the NWP (Emanuel, 2005b, 2008; Kossin, 2007; Landsea, 2007), necessary adjustments were made in the recorded raw TC intensity data according to the Dvorak methods introduced by Emanuel. We use Eq. (1) to revise the recorded TC wind speed.

$$V_{max}' = \omega V_{max} + 0.228(1-\omega) V_{max}^{1.288}, \quad (1)$$

where V_{max} is the recorded raw maximum wind speed, V_{max}' is the revised maximum wind speed, and ω is the weight factor. We select $\omega = 0.3$ for the period of 1945 ~ 1966, $\omega = 0.8$ for 1967 ~ 1972 and $\omega = 1$ since 1973. In the following analysis of TC intensity and frequency variation, the revised maximum wind speed V_{max}' is used in the present study.

3. Inter-Annual Variation of TC Intensity

3.1 Characteristics and Trends of TC Wind Speed Inter-Annual Variation

Six grades of TCs intensity are classified according to the lifetime-maximum wind speed. Usually, we define the annual average wind speed as the average of lifetime-maximum wind speed of all TCs in a certain year and the annual maximum wind speed as the lifetime-maximal wind speed of the strongest TC in a certain year. So based on the analysis of the TC database in the NWP from 1945 to 2008, we have obtained inter-annual variation and characteristics of the annual average wind speed and the maximum wind speed in the NWP and SCS, respectively.

From Fig. 1a we can see that the annual average wind speed in the NWP mainly ranges from 35 m/s to 45 m/s and the annual maximum wind speed in 64 years reaches as high as 84 m/s. Meanwhile, there are five in 64 years that have at least one TC with lifetime-maximum wind speed exceeding 80 m/s. Mostly it happened after 1973. From Fig. 1b we can see that the annual average wind speed in the SCS mainly ranges from 30 m/s to 40 m/s and the annual maximum wind speed in 64 years reaches as high as 69 m/s. The number of year with the annual maximum wind speed exceeding 60 m/s is five in 64 years, which mostly happened after 1970s.

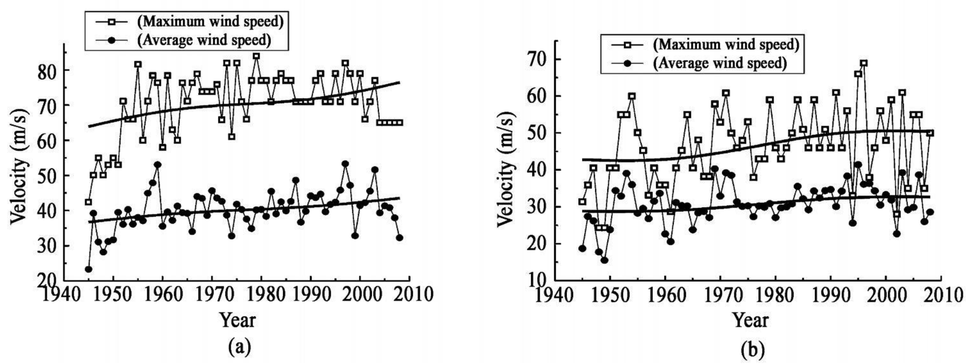

Fig. 1. Trends of the TC wind speed inter-annual variation: (a) in the NWP; (b) in the SCS. The square frams and dots denote the annual maximum and average wind speed respectively during period of 1945 ~ 2008 and they all show increasing trends. The thick solid lines are long-term trends extracted by FFT filter.

In order to obtain the trends of inter-annual wind speed variation in the NWP, we averagely divide the 64 years into four intervals and calculate the mean of annual maximum wind speed and the mean of annual average wind speed in 16-year intervals. As shown in Table 1, the mean of annual average wind speed ranges from 37.1 m/s in the first interval (1945 ~ 1960) to 42.2 m/s in the last interval (1993 ~ 2008). The mean of annual maximum wind speed seems to increase at first and finally decrease a little in the last interval (1993 ~ 2008). In the 90s of the 20th century and the first several years of the 21st century, the El-Nino Events happened frequently. Feng (2001) and Zhao (2006) assumed that the more intense the TCs are, the smaller chance for them to happen in the El-Nino year. Very probably, the decreasing trend in the last interval can be attributed to the El-Nino Events′ influence on the TCs activities. Likewise, if we also divide the 64 years into 4 intervals as we did in the NWP, we can find that the mean of annual average wind speed and the mean of annual maximum wind speed in the SCS all display increasing trends, ranging from 27.8 m/s to 32.6 m/s and 40.5 m/s to 49.4 m/s, respectively.

Table 1 The mean of annual maximum wind speed (AMWS) and the annual average wind speed (AAWS) of 16-year interval in both the NWP and the SCS

	1945 ~ 1960	1961 ~ 1976	1977 ~ 1992	1993 ~ 2008
The mean of AMWS (SCS) (m/s)	40.5	46.3	49.7	49.4
The mean of AMWS (NWP) (m/s)	61.7	72.7	75.1	71.4
The mean of AAWS (SCS) (m/s)	27.8	30.6	31.6	32.6
The mean of AAWS (NWP) (m/s)	37.1	40.1	41.1	42.2

We know that the TC activities are influenced by many factors, such as El-Nino Events, SST, solar activities, and so on. From Fig. 1 we can see that the annual maximum wind speed and annual average wind speed both show increasing trends with strong short period fluctuation. So, in order to extract the long-term trends and inter-decadal variability of the TC wind speed, we use the Fast Fourier Transformation (FFT) Filter to remove the high frequency components of the wind speed data series. We set the cutoff frequency to be $1/16\ s^{-1}$, which means that only the components of the period is larger than 16 years, the trend term is reserved. As shown in Fig. 1a and Fig. 1b, the thick solid lines present long-range variation trends of the annual maximum and the annual average wind speed respectively. From the four lines we can see that long-term increasing trends both in the NWP and the SCS are evident.

3.2 Characteristics and Trends of the TC PDI Inter-Annual Variation

The TC lifetime defined as the time interval from its occurrence to disappearance is the embodiment of the TC energy. Nevertheless, only one factor among lifetime and maximum wind speed is not sufficient to characterize the intensity of a TC. Based on the statistics (Emanuel, 2005a), the actual monetary loss caused by TCs rises roughly as the cubes of the wind speed. So Emanuel (2005a) defined the power dissipation index (PDI) as a major parameter,

$$PDI = \int_0^{\tau} {V'_{\max}}^3 \mathrm{d}t, \tag{2}$$

where $V'_{\max}$ is the revised maximum wind speed, and τ is the life time of the TCs. The PDI of each TC is calculated by summing up cubes of the maximum wind speed reported every six hours over the lifetime τ. We integrated over an entire year as the characterization of the TC intensity in one year in the NWP (Fig. 2a) and the SCS (Fig. 2b), respectively. As shown in Fig. 2, the growth of the PDI in the NWP has increased significantly since 1970s, and by the end of the 20th century, the PDI even reached 2 times that in 1970s. The PDI in the SCS shows strong fluctuation with slow increase, reaching 1.3 times by the end of the 20th century since 1970s.

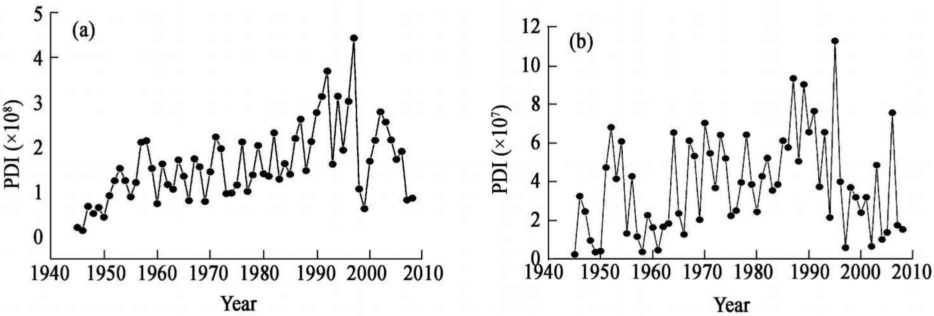

Fig. 2. Trends of the TCs PDI inter-annual variation: (a) in the NWP; (b) in the SCS. The dots denote the PDI during the period of 1945 ~ 2008.

4. Characteristics and Trends of the TC Annual Frequency Variation

Annual frequency which is defined as TCs' number occurring in a certain year is another important factor to characterize TCs activities. When the lifetime-maximum wind speed reaches 32.7 m/s and 41.5 m/s, we call the TC as typhoon and strong typhoon, respectively. By analyzing the 64-year TC database, we obtained the annual frequency variation of the TC, typhoon and strong typhoon in the NWP and the SCS.

As shown in Fig. 3, the annual frequency both in the NWP and the SCS increases slowly except at several extreme years in the 1960s and 1970s in the SCS. The annual frequency of the typhoon ($V'_{max} > 32.7$ m/s) and strong typhoon ($V'_{max} > 41.5$ m/s) are also calculated. As shown in Fig. 4, the frequencies of typhoon and strong typhoon present steadily increasing trends in the NWP and show slow increase with strong fluctuation in the SCS.

In order to further analyze the temporal variation of annual frequencies of the TC, typhoon and strong typhoon, we divide the 64 years data into two interval groups: 1945 ~ 1977 and 1978 ~ 2008 and calculate the average annual number of TCs in the two time intervals. Table 2 shows that there are averagely 22.5 and 8.7 TCs occurring in the NWP and the SCS per year, with an increase of 15% and 9%, respectively. In the NWP, the average annual number of typhoons rises from 11.6 to 15.6 and strong typhoons from 7.3 to 10.9, resulting in 35% and 50% increase, respectively. Regarding the region of the SCS, the average annual number of typhoons rises from 3.1 to 4.2 and strong typhoons from 1.1 to 1.9, with an apparent growth rate of 35% and 72%. Based on the above analysis, we can conclude that the increasing annual frequencies of TCs are mainly manifested as the increasing numbers of typhoons and strong typhoons.

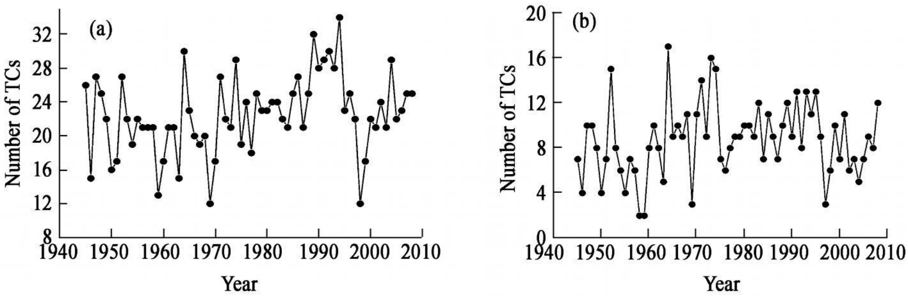

Fig. 3. Inter-annual variation of TC number: (a) in the NWP; (b) in the SCS. The dots denote the annual number of TC occurrence from 1945 to 2008 and the frequency of TC shows slow increase with strong fluctuation.

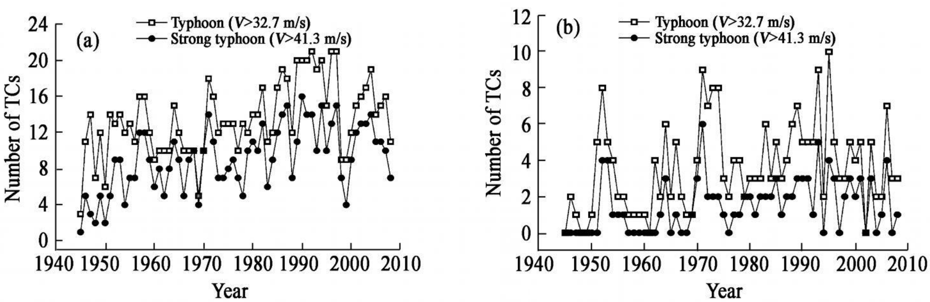

Fig. 4. Inter-annual variation of typhoons′ and strong typhoons′ number: (a) in the SCS; (b) in the SCS. The square frames and dots denote the frequency of the typhoons and strong typhoons from 1945 to 2008 respectively and they all show an obvious increase.

Table 2 Annual frequency variation of TCs in the NWP and SCS

	1945～2008	1945～1976	1977～2008	Rate of increase
TC (NWP)	22.5	21.1	24.1	15%
TC (SCS)	8.7	8.4	9.1	9%
Typhoon (NWP)	13.6	11.6	15.6	35%
Typhoon (SCS)	3.7	3.1	4.2	35%
Strong typhoon (NWP)	9.1	7.3	10.9	50%
Strong typhoon (SCS)	1.5	1.1	1.9	72%

5. Spatial Variation Characteristics of TC Frequency

In the vast area of the NWP, the analysis of TCs spatial distribution is also carried out so that we are able to identify the marine area of strong TC occurrence. By processing the TC location and wind speed database recorded every six hours, we divided the vast NWP area (0°～60°N, 80°～180°E) into 240 subareas ($5^\circ \times 5^\circ$) and counted the numbers of the TCs and the maximum wind speed occurring in 64 years in each $5^\circ \times 5^\circ$ subarea. The number of TCs occurring in respective subareas is defined as the TCs whose recorded path, i.e. the area swept by maximum wind speed radius region falling within the range of minimum longitude/latitude and maximum longitude/latitude values of the selected subareas. Usually, a TC may stay longer than 6 hours in a definite subarea, which would be recorded twice or more. In this situation, we only count once.

In addition, TC′s influence exerted on the nearby subareas is considered as follows:

$$V(r) = \begin{cases} V_0 \dfrac{r}{r_0} & r \leqslant r_0 \\ V_0 \left(\dfrac{r_0}{r} \right) & r_0 < r < R \end{cases} \tag{3}$$

where r is the minimum distance between the center of a TC (location recorded) and the nearby subareas, V_0 is the maximum wind speed recorded every six hours, r_0 is the radius of the maximum wind speed empirically set as $r_0 = 40$ km, R is the periphery radius of TCs set as $R = 1000$ km. If $V(r)$ is larger than 10.8 m/s (the lowest wind speed for a TC) in the nearby subareas, we can say that the TC passes through the nearby subareas.

From Fig. 5 we can see that the most frequent occurrence of TCs happen in the region which lies to the east of Philippine Islands. In particular, the subarea of $15^\circ \sim 20^\circ$ N, $125^\circ \sim 130^\circ$ E is the place where TC happens most frequently, i.e. totally we have 374 TCs in 64 years resulting in 6 TCs per year on average. From Fig. 6 we can see that the maximum wind speed in 64 years reaches 85 m/s in the subarea ($10^\circ \sim 15^\circ$ N, $135^\circ \sim 140^\circ$ E). And there are 10 subareas with the maximum wind speed in 64 years exceeding 82 m/s, which are mostly located to the northeast of Philippine Islands.

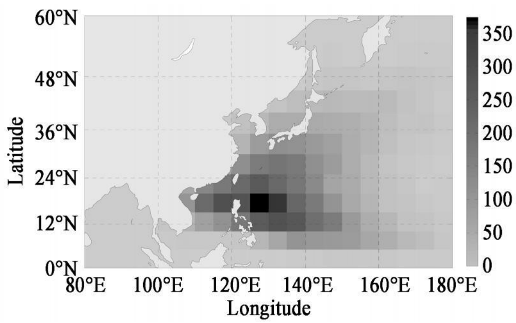

Fig. 5. Numbers of TCs occurrence in the $5^\circ \times 5^\circ$ subareas of the NWP in 64 years. The grayscale bar of the right displays the calibration of the numbers of TCs occurrence.

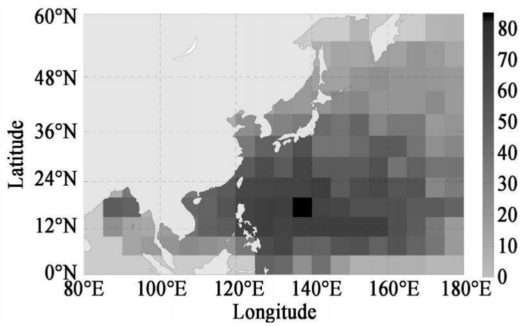

Fig. 6. Maximum wind speeds of TC occurrence in the $5^\circ \times 5^\circ$ subareas of the NWP in 64 years. The grayscale bar of the right displays the calibration of maximum wind speed of TC.

Likewise, we divided the SCS ($0^\circ \sim 25^\circ$ N, $105^\circ \sim 120^\circ$ E) into 375 subareas ($1^\circ \times 1^\circ$) and counted the number of TCs and the maximum wind speed in 64 years in each subarea. From Fig. 7 we know that in different subareas, the frequency and intensity of TCs varied largely. The place of most frequent occurrence of TCs is centered in the region of 15°～22°N, 110°～120°E, where the Dongsha Island, Zhongsha Island are located in. As shown in Fig. 8, the maximum wind speed in 64 years to the east of Nansha Island (5°～10°N, 115°～120°E) is only 28.5 m/s, while super strong typhoons happen frequently with 7 TCs′ maximum wind speed in 64 years exceeding 60 m/s to the west of the Philippines (15°～22°N, 115°～120°E) in SCS region. So in the ocean engineering construction in the areas with frequent and intense TCs occurrence, it is indispensable to take the TC′s influence under the background of climate change into consideration.

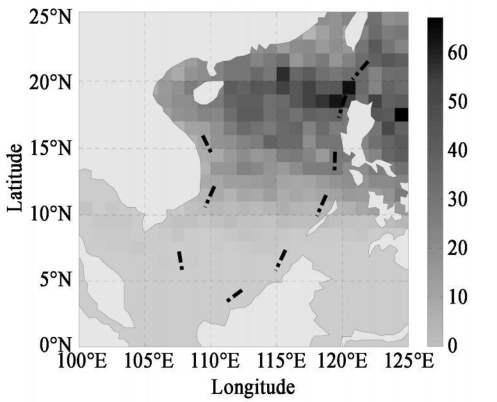

Fig. 7. Numbers of TCs occurrence in the 1°× 1° subareas of the SCS in 64 year. The grayscale bar of the right displays the calibration of the numbers of TCs occurrence.

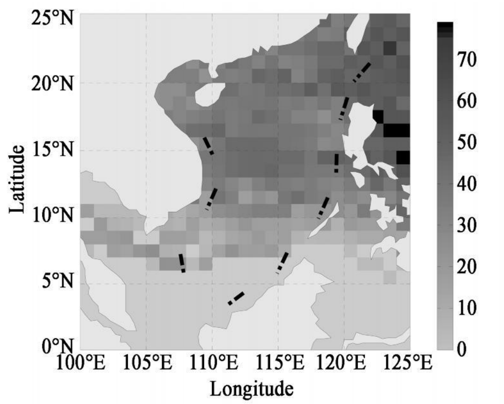

Fig. 8. Maximum wind speeds of TCs occurrence in the 1°× 1° subareas of the SCS in 64 years. The grayscale bar of the right displays the calibration of maximum wind speed of TCs.

6. Conclusions

Based on the analysis of the TC database in the NWP from 1945 to 2008 released by CMA, the characteristics and trends of the TC wind speed, PDI, annual frequency and spatial variation both in the NWP and the SCS are systematically summarized. The results show that very probably the TC activities are gradually strengthened. The manifestations are presented below: (1) the annual average and maximal wind speed are all growing steadily with time; (2) the TC intensity displays significant increase in terms of PDI since 1950s; (3) the annual frequency increase mainly manifests the increase in the number of typhoon and strong typhoon; (4) the spatial frequency distribution of the TC is inhomogeneous. For example, the area of Zhongsha and Dongsha Islands in the SCS, west of Philippine Islands, is the place where strong typhoons happen frequently.

In a word, the variation of intensity and frequency of TCs turns out a non-stationary process. Obviously, their effects on the design of ocean engineering now have become an issue of great concern in estimating extreme wind speed and wave climate parameters, which is of great significance in the revision of offshore engineering standard or criterion to avoid accidents in operation.

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