Variation Characteristics of Tropical Cyclones Making Landfall over China between 1951 and 2015 and Their Relationship with ENSO

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Abstract. Based on tropical cyclone (TC) data provided by the America Joint Typhoon Warning Center, this paper analyzes the variation characteristics of tropical cyclones making landfall over China during the 65-year period of 1951–2015 and their statistical relationship with the El Niño–Southern Oscillation (ENSO). The conclusions are as follows. (1) The landfall frequency during the period of 1951–2015 has strong inter-annual and inter-decadal variability characteristics, and an abrupt change in the landfall frequency occurred in 1988. However, from the long-term variation frequency trend, the landfall frequency decreased slowly from the late 1980s to 2015. (2) The landfall intensity increased rapidly from the late 1950s to the early 1960s, with an abrupt change occurring in 1996. In addition, there is a significant decreasing trend and then an increasing trend from the late 1960s to 2015. (3) There are significant negative correlations between the landfall frequency and the sea surface temperature (SST) in the ENSO-3.4 region. All the sliding correlation coefficients are negative from 1961 to 2002. A strong abrupt change in their correlation occurred in 1970, changing from a weak negative to a strong negative correlation. (4) There are no significant negative correlations between the landfall intensity and the SST in the ENSO-3.4 region, and their sliding correlation coefficient of inter-annual variability shows that there is an alternating appearance of positive and negative correlations. A strong abrupt change occurs in 1999, changing from a weak positive correlation to a strong negative correlation. The significant negative correlation occurred in the 2005. (5) The TC genesis locations move to the southeast in El Niño years and shift to the northeast in La Niña years. (6) TC frequency that influences the Chinese continental coast line in El Niño years is less than that which influences Japan. Meanwhile, in La Niña years, the TC frequency that influences Japan and its surrounding waters, the China Sea, the Bohai Sea, and the South China Sea, increases, while it decreases in the Taiwan Province.

1. Introduction
Tropical cyclones (TCs), called typhoons in Southeast Asia, are a type of extreme weather event that has the potential to cause tremendous losses of human lives and property due to excessive and torrential rainfall, storm tides, landslides, debris flows, flash floods, and strong winds. For example, in 2004, ten TCs caused widespread damage in Japan[1]. Between 1995 and 1999, damages in the...
Economic and Social Commission for Asia and the Pacific/World Meteorological Organization (ESCAP/WMO) Typhoon Committee member areas in the western North Pacific were estimated to be approximately $3620 million (U.S. dollars) with average annual human casualties exceeding a thousand (ESCAP/WMO 2001). Therefore, the changing properties of TC events such as their intensity, frequency, duration, tracks, the effects of global warming on tropical cyclone intensity, and their linkages with large-scale circulation variability are attracting increasing attention from meteorologists, hydrologists, and governments across the globe[2-7].

Many scholars have attempted to test the relationships between TC activity and climatic signals such as the El Niño–Southern Oscillation (ENSO)[8-11]. In addition, some scholars have researched how ENSO, the quasi-biennial oscillation, and the Madden–Julian oscillation affect western North Pacific TC activity. For example, Pudov and Petrichenko[12, 13] found an increase in the intensity of TCs during El Niño years. Since then, many authors have examined the relationship between ENSO and the number of western North Pacific TCs. The results have not been consistent in all cases, presumably due to differences in both the data and the techniques used[14,15]. Li and Wang[16] argue that ENSO affects the large-scale atmospheric circulation, therefore further affecting the activity of TCs in the western North Pacific.

Even though there is no significant linear relationship between the number of TCs and ENSO, a nonlinear relationship between ENSO and the number of TCs has been found in several studies; this is especially evident when the ENSO forcing is strong[17]. Chia and Ropelewski[18] argue that the western North Pacific has a larger number of generated strong tropical storms during El Niño years. However, there are also scholars who think that this trend is not correlated to ENSO.

Currently, most studies have focused on the relationship between TC activity in the western North Pacific and ENSO. Very few studies have tried to examine the relationship between the landfalling TCs’ frequencies, intensities, genesis locations, tracks, and observed intensities and ENSO, for which there exist differences.

Based on the TC data provided by the America Joint Typhoon Warning Center, this paper studies the inter-annual and inter-decadal variability trends of TCs making landfall over China during the period of 1951–2015, which shows the statistical relationship between the landfall frequency, the landfall intensity, and ENSO, and further discusses the characteristics of the TC genesis locations, tracks, observed intensities, and space variations. These results could provide a scientific basis for short-term climatic predictions of TCs making landfall over China.

2. Data and Methodology

We used the Joint Typhoon Warning Center TC best-track data covering the period of 1951–2015. These datasets commonly include the locations of the TC centers, the maximum sustained wind speeds at 6-h intervals, the center of the wind speed, and the maximum wind (the 1-min observed center). Wu and Zhao[19] have noted that the Joint Typhoon Warning Center TC best-track data over the western North Pacific is more reliable than other data; and Chan[20] has argued that the Joint Typhoon Warning Center TC intensity data is more reliable. This paper uses TCs that reached at least tropical storm intensity (maximum sustained winds >17.2 m s⁻¹ based on the Japan Meteorological Agency/JMA rating) or higher. The main typhoon season in China is from May to November (Fig. 1); therefore, the TC index in this paper is also from May to November.

The SST data are from HadISST, a dataset provided by the Hadley Center of the UK Met Office (the link for the data is http://hadobs.metoffice.com/hadisst/data/download.html), which contains a unique combination of monthly globally complete fields of SST and sea ice concentration on a 1° latitude–longitude grid from 1870 to the present.

The SST anomaly (SSTA) over the Niño-3.4 region(5°N–5°S, 170–120°W) appears to be a meaningful indicator for ENSO events because the equatorial east–west SST gradient in this area is the largest. In addition, it has been found that the Niño-3.4 SSTA is better correlated with the overall TS activity over the western North Pacific. To further study the relationship between TC activity and the sea surface temperature (SST) during the period of 1951–2015, this paper uses the sea surface temperature variation over the Niño-3.4 region to represent the ENSO variation.

This ensures that the ENSO signal is evident during the peak May–November TC landing season in the western North Pacific. The Niño-3.4 SSTA is therefore used as the reference for classifying the
ENSO events. A year is classified as El Niño (La Niña) if the mean May–December Niño-3.4 SSTA is >0.5°C (<−0.5°C)[14]. The SSTA data were obtained from the National Centers for Environmental Prediction Climate Prediction Center from the reconstruction of sea surface temperature data in the ERSSTv4 extension[21, 22].

This process yields 16 El Niño years (1951, 1953, 1957, 1958, 1963, 1965, 1969, 1972, 1982, 1987, 1991, 1997, 2002, 2004, 2009, and 2015), 15 La Niña years (1954, 1955, 1964, 1970, 1971, 1973, 1974, 1975, 1988, 1999, 2000, 2007, 2010, and 2011), and 34 ENSO neutral years (1952, 1956, 1959, 1960, 1961, 1962, 1966, 1967, 1976, 1977, 1978, 1979, 1980, 1981, 1983, 1984, 1985, 1986, 1989, 1990, 1992, 1993, 1994, 1995,1996, 2001, 2003, 2005, 2006, 2008, 2012, 2013, and 2014) (Fig. 2).

The defined El Niño and La Niña years in this study are basically the same as those obtained using Zhao’s et al.[23] method of defining El Niño years as the former 25% Niño-3.4 SSTA and La Niña years as the latter 25% Niño-3.4 SSTA. However, other traditional definitions are slightly different.

**Figure 1.** The climatological monthly variation of the frequency of landfalling TCs in China for the period of 1951–2015.

**Figure 2.** The time series of the ENSO-3.4 SSTA index (°C) for the May–November season in the period of 1951–2015. The horizontal lines show the ENSO-3.4 SSTA index value equal to ±0.5.

### 3. Annual Variation Characteristics of Landfall Frequency and Landfall Intensity

#### 3.1. Annual Variation Characteristics of Landfall Frequency

Of the TCs (except the tropical depressions) generated over the western North Pacific (including the South China Sea), 498 TCs made landfall over China from 1951 to 2015. Including the islands of Taiwan and Hainan (a TC is only counted once when it makes landfall directly or brushes past the island), the annual landfall rate is 7.7 and the lowest rate was 2, which occurred in 1958, while the highest rate was 17, which occurred in 1974.

Fig. 3a shows that the landfall frequency during the period of 1951–2015 has strong inter-annual and inter-decadal variability characteristics. The period from the early 1950s to the late 1960s was a decreasing period, while those from the mid 1960s to the early 1980s and from the late 1980s to 2015 were increasing periods. This paper uses the general moving t-test to analyze the time series of the landfall frequency. Fig. 3b shows that the statistical value of t is over the significant level test of 0.05 (T0.05=2.101), which indicates that an abrupt change in the landfall frequency occurred in 1988 and then there was an increasing period. However, as a long-term variational trend, the landfall frequency decreased slowly in the inter-annual oscillation from the late 1980s to 2015. Wavelet analysis was carried out on the landing frequency (Fig. 3c and d), landing frequency cycle oscillation for 6 years.
Figure 3. (a) the time series of the landfall frequency (the trend line failure to pass 95% confidence tests), (b) the moving t-test of the time series in Figure 3a. (c) wavelet power spectrum, (d) global wavelet spectrum. In panels (b), the black dotted line indicates the critical 0.05 significance level line. In panels (c), the black dotted line indicates boundary effect line. In panels (c) and (d), the black line indicates the critical 0.05 significance level line.

3.2. Annual Variation Characteristics of Landfall Intensity

The landfall intensity of the TCs in a given year is defined as the mean of the intensities at the time when the TC center was closest to the coastal areas on a 6-h basis [24]. From 1951 to 2015, the landfall intensity reached a maximum value of 67.76 m/s in 1958, with a minimum value of 24.11 m/s in 1978 and an average value of 33.07 m/s. Fig. 4a shows that the period from the late 1950s to the early 1960s was a rapidly increasing period, and there is an obviously decreasing and then increasing trend from the late 1960s to 2015. Using the moving t-test to analyze the time series of the landfall intensity, Fig. 4b shows that the statistic value of t is over the significant level test of 0.01 (T0.01=2.878), which indicates that an abrupt change in the landfall intensity occurred near 1966 and 1987.

Figure 4. (a) the time series of the landfall intensity (the trend line failure to pass 95% confidence tests), (b) the moving t-test of the time series in Figure 3a. In panels (b), the black dotted line indicates the critical 0.05 significance level line.

4. The Relationship between TC Activity and ENSO

4.1. The Statistical Relationship between the Landfall Frequency, Intensity, and ENSO

Fig. 5a shows the distribution of the correlation coefficient between the landfall frequency and the SST for the Pacific region (January–December). The TC frequency has a negative relationship with the SSTA over the ENSO-3.4 region (green rectangular area), and the correlation coefficient reaches a maximum value of −0.3 (red shading), which indicates that there are less TCs making landfall in El Niño years while the contrary occurs in La Niña years. The result is in agreement with other studies.
This paper uses the sliding correlation method to analyze the long-term variation characteristics of the relationship between the landfall frequency and the SST. Fig. 5b shows the inter-annual variability of the correlation coefficient. All the sliding correlation coefficients are negative from 1961 to 2002. The significant negative correlation occurred in the late 1970s. A moving t-test is made on the sliding correlation coefficient. Fig. 5c shows that the t value surpasses the significant level of 0.05 (T0.05=2.101) in 1970, 1987, and 2000, which means that abrupt changes occurred around 1970, 1987, and 2000. There is a strong abrupt change in 1970, before which the negative correlation was weak and after which there is a strong negative correlation. However, weak positive and negative correlations alternatively occurred in the 2000s.

Fig. 5d shows the distribution of the correlation coefficients between the landfall intensity and the SST for the Pacific (January–December), and there is no significant correlation over the ENSO-3.4 region. When we further study the inter-annual variability of the sliding correlation coefficient of the landfall intensity and the SSTA over the ENSO-3.4 region (Fig. 5e), we see that positive and negative correlations alternatively occur and that periodic characteristics are very obvious. A moving t-test was made on the sliding correlation coefficient. Fig. 5f shows that the t value surpasses the significant level of 0.05 (T0.05=2.101) in 1999, which means that abrupt changes occurred around 1999. A strong abrupt change occurs in 1999, changing from a weak positive correlation to a strong negative correlation. The significant negative correlation occurred in the 2005.

![Figure 5. Spatial patterns of the correlation relations between SST and (a) the landfall frequency and (d) the landfall intensity. The time series of sliding correlation coefficients between SSTA in the ENSO-3.4 region and (b) the landfall intensity and (e) the landfall intensity. The moving t-test of the 11 years for the time series (c) in Figure 4b and (f) in Figure 4e. In panels (a) and (d), the light and dark red shading shows differences significant at the 90% and 95% confidence levels, respectively. In panels (a) and (d), the green rectangular box indicates the ENSO-3.4 region. In panels (c) and (f), the black dotted line indicates the critical 0.05 significance level line.](image)

4.2. *The Relationship between ENSO and the TC tracks*
The TC tracks can be described by the TC passage frequencies. The TC passage frequencies are the number of TCs passing through each 5° × 5° grid area at 6-h intervals, where a TC is only counted once even if it enters the same grid box several times, which could reflect the chances of being influenced by TCs in a certain region.

One major track in Fig. 6a moves from the tropical Pacific to the Philippine Sea and the South China Sea, and another one moves from the tropical Pacific northwestward to Korea and Japan influencing the region around the East Asia coast. The maximum value of the TC frequency occurred over the central region of 118°E 18°N. Fig. 6b of the El Niño versus the neutral years shows that the contour lines are mostly negative over all of the Chinese mainland, which means that the TC frequency is less during El Niño years. This indicates that TCs making landfall over China decrease during El Niño years. Meanwhile, the contour lines are mostly positive in Japan, indicating that TCs making landfall over Japan increase during El Niño years. Fig. 6c contrasts La Niña years with neutral years, and the positive contour lines are located in the area around the Japan Sea, China Sea, Bohai Sea, and South China Sea, which indicates that the TC frequency increases around the Bohai Sea, Jiao Zhou Peninsula, and southern China coastal areas. The contour lines values are negative over the regions of Taiwan and its surrounding areas and the southeastern Chinese coastal area, which indicates that the TC frequency decreases around these regions. Fig. 6d contrasts La Niña years with El Niño years; the distribution shows a pattern decreasing southward and northward and increasing in the middle. The positive values are mostly located over two regions, over the China Sea and the Bohai Sea and over the South China Sea and the Philippines and its surrounding areas, which indicates that the TC frequency increases in the Shan Dong and Jiang Su Provinces of China, while the TC frequency decreases in the southern part of China and over the region of 150°E 7.5°N.

Figure 6. Geographical distribution of the TC passage frequencies (number per year) in each 5°×5° grid area in (a) neutral years, (b) El Niño years minus neutral years, (c) La Niña years minus neutral years, and (d) La Niña years minus El Niño years. The light and dark blue shading indicates areas where the t-test is significant at the 90% and 95% levels, respectively.

5. Conclusions

Based on the TC data provided by the America Joint Typhoon Warning Center, this paper analyzes the trends of the TC frequency, intensity, and inter-annual and inter-decadal variability during the 65-year period of 1951–2015 and then discusses the variation characteristics of the TCs’ genesis locations, tracks, and observed intensity and spatial variations. The conclusions are as follows.
(1) The landfall frequency during the period of 1951–2015 has strong inter-annual and inter-decadal variability characteristics, and an abrupt change in the landfall frequency occurred in 1988. However, from the long-term variation frequency trend, the landfall frequency decreased slowly from the late 1980s to 2015.

(2) The landfall intensity increased rapidly from the late 1950s to the early 1960s, with an abrupt change occurring in 1996. In addition, there is a significant decreasing trend and then an increasing trend from the late 1960s to 2015.

(3) There are significant negative correlations between the landfall frequency and the sea surface temperature (SST) in the ENSO-3.4 region. All the sliding correlation coefficients are negative from 1961 to 2002. A strong abrupt change in their correlation occurred in 1970, changing from a weak negative to a strong negative correlation.

(4) There are no significant negative correlations between the landfall intensity and the SST in the ENSO-3.4 region, and their sliding correlation coefficient of inter-annual variability shows that there is an alternating appearance of positive and negative correlations. A strong abrupt change occurs in 1999, changing from a weak positive correlation to a strong negative correlation. The significant negative correlation occurred in the 2005.

(5) TC frequency that influences the Chinese continental coast line in El Niño years is less than that which influences Japan. Meanwhile, in La Niña years, the TC frequency that influences Japan and its surrounding waters, the China Sea, the Bohai Sea, and the South China Sea, increases, while it decreases in the Taiwan Province.

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