Autumn Tropical Cyclones over the western North Pacific during 1949–2016: A Statistical Study

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ABSTRACT

We used tropical cyclone (TC) best track data for 1949–2016, provided by the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI), and a TC size dataset (1980–2016) derived from geostationary satellite infrared images to analyze the statistical characteristics of autumn TCs over the western North Pacific (WNP). We investigated TC genesis frequency, location, track density, intensity, outer size, and landfalling features, as well as their temporal and spatial evolution characteristics. On average, the number of autumn TCs accounted for 42.1% of the annual total, slightly less than that of summer TCs (42.7%). However, TCs classified as strong typhoons or super typhoons were more frequent in autumn than in summer. In most years of the 68-yr study period, there was an inverse relationship between the number of autumn TCs and that of summer TCs. The genesis of autumn TCs was concentrated at three centers over the WNP: the first is located near (14°N, 115°E) over the northeastern South China Sea and the other two are located in the vast oceanic area east of the Philippines around (14°N, 135°E) and (14°N, 145°E), respectively. In terms of intensity, the eight strongest TCs during the study period all occurred in autumn. It is revealed that autumn TCs were featured with strong typhoons and super typhoons, with the latter accounting for 28.1% of the total number of autumn TCs. Statistically, the average 34-knot radius (R34) of autumn TCs increased with TC intensity. From 1949 to 2016, 164 autumn TCs made landfall in China, with an average annual number of 2.4. Autumn TCs were most likely to make landfall in Guangdong Province, followed by Hainan Province and Taiwan Island.

Key words: western North Pacific, autumn tropical cyclone, statistical characteristics

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1. Introduction

Despite no evidence of a clear long-term trend in global tropical cyclone (TC) occurrence frequency, it is known that there exists natural variation in TC activity in individual regions (Emanuel, 2018). The western North Pacific (WNP) is the most active region for TC activity among all of the ocean basins (Chen et al., 2012); the average number of TCs occurring in this region each year is about 30, taking over 30% of the global total of 80 (Chan, 2005) and approximately 40% of the global accumulated cyclone energy (Maue, 2011). Severe TCs are often accompanied by destructive wind, high storm surge, torrential rain, and severe flood, resulting in serious property damage and loss of life (Wang and Wu, 2004). Hence, many studies have focused on understanding the long-term trend of TC activity and its drivers.

Our understanding of TC climatology has greatly advanced over recent years. Results show that the El Niño–Southern Oscillation (ENSO) (Wang and Chan, 2002; Ho et al., 2004; Camargo and Sobel, 2005), intraseasonal oscillation (ISO) (Liebmann et al., 1994; Li and Zhou, 2013), Pacific decadal oscillation (PDO) (Goh and Chan, 2010; Liu and Chan, 2013), quasi-biennial oscillation (QBO) and the Madden-Julian Oscillation (MJO) have significantly influenced tropical cyclone activity in the WNP. In addition, it is also found that TCs in the WNP are affected by the Intertropical Convergence Zone (ITCZ) (Li and Zhou, 2013; Chen et al., 2012), seasonal changes (Zhao and Li, 2011), and ENSO events (Miyake and Chan, 2004; Li and Zhou, 2013).

Despite the efforts in understanding the factors responsible for TC changes, the mechanisms involved remain uncertain. For instance, the variation of TC activity in the WNP is limited to a few years with a large number of TCs occurring at a particular time. This phenomenon is more obvious during the late summer and early autumn (Wang and Wu, 2004; Ho et al., 2004; Camargo and Sobel, 2005; Chen et al., 2012). Therefore, a detailed understanding of the factors involved is imperative to improve our ability to predict TC activity and their impacts in the WNP.

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cillation (QBO), and sea surface temperature (SST) and its zonal gradient (Wang et al., 2013; Li and Zhou, 2014) may affect TC activity over the WNP and the South China Sea. Variations in TCs in the WNP are actually controlled by a combination of climatic phenomena active at different timescales (Li and Zhou, 2018). Previous studies have provided a valuable basis for further studies of climatological characteristics of TCs. In terms of TC seasonal variations, it is found that a higher percentage of late season (October–December) TCs develop into typhoons than do the TCs during the peak season (July–September), and about 67% (59%) of TCs intensify into typhoons during the late (peak) season in the WNP (Hsu et al., 2014).

Late season TC frequency in the WNP changed abruptly in 1998, with more activity before 1998 and less activity after 1998 (Hsu et al., 2017). The intensity variation during the TC lifetime also shows seasonal phase locking. The frequencies of four types of TC, including those with rapid intensification, slow intensification, slow weakening, and rapid weakening, all reach a maximum in September (Yu and Yao, 2007). The variation of autumn TCs is related to ENSO and the Indian Ocean dipole (IOD). When El Niño Modoki and IOD occur simultaneously, the genesis area of autumn TCs is more eastern than that of pure El Niño Modoki (Zhu and Meng, 2015). Zhao and Wang (2016) identified that the interdecadal modulation of the PDO can change the relationship between ENSO and TC activity during the late season in the WNP. Takahashi et al. (2011) showed that cold surges can restrict convection over the South China Sea, thus decreasing the TC genesis frequency during the late season (especially in October and November). Analyzing the extremely low TC activity over the WNP and the South China Sea during the late season (October–December) in 2010 and 1998, Zhao et al. (2014) demonstrated that it mainly resulted from the sea surface temperature anomaly in the WNP basin. Fan et al. (2019) compared the phase differences of the interdecadal variability of TC activity in the peak and late seasons over the WNP and demonstrated that late season TC activity is related to the east–west sea surface temperature gradient across the equatorial Pacific.

Generally, the economic losses caused by summer TCs are higher than those caused by autumn TCs. However, in recent years this trend has reversed, with landfall TCs in autumn often exceeding the strong typhoon intensity threshold when making landfall. Fourteen typhoons occurred in the WNP during autumn 2016, which was a typical TC active year compared with the past several years (11 TCs on average). The direct economic losses caused by Meranti (2016), Megi (2016), Sarika (2016), and Haima (2016) totaled 49.18 billion RMB, accounting for 68% of the whole-year loss (Gao et al., 2018). Strong wind and rain brought by autumn TCs can cause frequent occurrence of urban waterlogging, debris flow, landslides, and other disasters, resulting in crop damage, infrastructure damage, and traffic disruption (Chen and Ding, 1979).

There have been numerous recent studies on WNP TCs making landfall in China. Autumn TCs are distinctive and particularly difficult to forecast. For example, the strongest and largest TC in the WNP was Typhoon Tip (1979), which formed near Hiroshima on 5 October 1979. Typhoon Tip had a minimum central pressure of 870 hPa at 0200 Beijing Time (BJT) 5 October, which is the lowest sea level pressure ever recorded in history. Another TC with extreme winds was Typhoon Ida (1958), which formed on 20 September 1958, and had a central maximum wind speed reaching 110 m s\(^{-1}\) at 0800 BJT 24 September. Though both of the above historical TCs occur in autumn, little is known about the spatial and temporal distributions of autumn TCs and their evolution characteristics, as few studies have used objective quantitative statistics based on long historical time series.

In this work, a climatological statistical analysis of autumn TCs in the WNP for a 68-yr period (1949–2016) is carried out to improve the understanding of autumn TCs and to further reveal their genesis and evolution features. The remainder of this paper is organized as follows. Section 2 presents the data and methods. The statistical characteristics of autumn TCs over the WNP are detailed in Section 3, and the characteristics of autumn TCs making landfall in China are detailed in Section 4. Finally, conclusions and discussion are presented in Section 5.

2. Data and methods

Among different data sources, uncertainties exist in estimates of the long-term trend in strong TC activity (Ren et al., 2011a). In the analysis of TC intensity, a more significant strengthening trend after 1977 is apparent in data from the Joint Typhoon Warning Center (JTWC) in Guam, USA, compared with data from the Japan Meteorological Agency (JMA) and the Hong Kong Observatory (HKO) of China (Wu et al., 2005). A comparison of datasets from the China Meteorological Administration (CMA) and the JTWC shows differences in the frequency of strong TCs since the end of the 1980s. However, the CMA dataset includes more TC data made after landfall and thus is more suitable for the analysis of
TCs affecting China (Ren et al., 2011b).

Three datasets from the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI) were employed in this study. First, we obtained the TC best track dataset (1949–2016), which consists of the name, latitude, longitude, central minimum pressure, and central maximum sustained wind speed of TCs observed at 6-h intervals (Ying et al., 2014). Second, we used a TC size dataset derived from geostationary satellite (GOES, Meteosat, GMS, MTSAT, and FY2) infrared images for 1980–2016 (Lu et al., 2017). Third, we used the landfalling TC dataset (1949–2016), which has a complete record of landfalling TC category. In addition, we used the NCEP/NCAR reanalysis monthly mean dataset at 2.5° × 2.5° horizontal resolution. The large-scale steering flow is defined as the pressure-weighted mean flow from 850 to 300 hPa (Wu et al., 2005). According to the Chinese national standard (GB/T 19201–2006), TCs are classified into six categories based on 2-min mean wind speed: tropical depression (TD; 10.8–17.1 m s⁻¹), tropical storm (TS; 17.2–24.2 m s⁻¹), strong tropical storm (STS; 24.5–32.6 m s⁻¹), typhoon (TY; 32.7–41.1 m s⁻¹), strong typhoon (STY; 41.5–50.9 m s⁻¹), and super typhoon (SupTY; > 51 m s⁻¹). In addition, we also used the Yearbook of Typhoons for 1949–1990 (CMA, 1950–1991) and the Yearbook of Tropical Cyclones for 1991–2016 (CMA, 1992–2017), which provide statistics for landfalling TCs.

In this work, the WNP refers to the region of the Pacific Ocean north of the equator and west of 180°, including the South China Sea. Autumn TCs are defined as the TCs with intensity reaching or exceeding TS strength from 0000 BJT 1 September to 2300 BJT 30 November in a given year. The TC occurrence time is defined as the time at which the TC intensity reaches the TS intensity. The intensity category is determined by the maximum intensity during the lifetime of the TC; for example, if a TC developed into a TY during its lifetime, the intensity category would be “TY,” consistent with operational forecasting conventions. The TC genesis location refers to the location where the cyclone first reaches the TS intensity. The number of landfalling TCs does not take into account multiple landfall events or sub-centers; however, the number of landfalling TCs in a given province takes multiple landfalling events into account.

3. Characteristics of autumn TCs over the WNP

3.1 Frequency

Time series of the genesis frequency of autumn TCs and all TCs over the WNP are shown in Fig. 1. In the 68 years, 11.3 TCs per year occurred in autumn over the WNP, with a maximum autumn frequency of 18 TCs in 1964 and a minimum of 6 TCs in 2010. The number of TCs in autumn has a weak decreasing trend over the period, but this trend is not as prominent as that for annual TC frequency, consistent with the findings of Hsu et al. (2014). There are clear wavelike characteristics in the time series at the interdecadal scale. TC frequency is generally below the climatic average before the 1960s, above the climatic average in the 1960s, below the climatic average from the 1970s to 1985, above the climate average from 1985 to 1995, and below the average after 1995 (Fig. 1). This variation pattern might be associated with the abrupt decrease in TC frequency in autumn over the WNP since 1998 (Hsu et al., 2017) and the decrease in overall TC activity since the mid-1990s (Choi et al., 2015; Lin and Chan, 2015). In 2013 and 2016, there are 15 and 14 autumn TCs, respectively, which are above the
climatic average. These two positive autumn anomalies may be related to the atmospheric thermal and dynamic circulation anomalies caused by the autumn SST anomalies in the equatorial central Pacific (Liu and Chan, 2013; Fan et al., 2019).

Table 1 shows the seasonal variation of TC genesis frequency over the WNP during 1949–2016. TCs mainly occurred in summer and autumn. Annual average numbers of summer and autumn TCs over the period are 11.5 and 11.3, which equate to 42.7% and 42.1% of the total number of TCs in an average year, respectively. Combined summer and autumn TCs make up 84.8% of the total number of TCs.

Time series of the frequency of summer and autumn TCs as a percentage of the annual total during the period 1949–2016 (Fig. 2) show that in more than 70% (49 of 68) of years, the proportion of autumn TCs was inversely related to that of summer TCs. The annual proportion of autumn TCs reached its peak (64.3%) in 1998, when the annual proportion of summer TCs was only 28.6%. Thus, the proportion of autumn TCs in 1998 was 21.6% higher than the average of the period, while that of summer TCs was 14.6% lower than the time series average. A similar inverse pattern occurred in 1954 and 2007, when the anomaly proportions for autumn (summer) TCs were 17.8% (−10.8%) and 14.3% (−12.4%), respectively.

Table 1. Seasonal variation of TC genesis frequency over the WNP during 1949–2016

| Season                  | Total TC number | Annual average TC number | Percentage (%) |
|-------------------------|-----------------|--------------------------|----------------|
| Summer (June–August)    | 781             | 11.5                     | 42.7           |
| Autumn (September–November) | 770           | 11.3                     | 42.1           |
| Winter (December–February) | 130            | 1.9                      | 7.1            |
| Spring (March–May)      | 146             | 2.1                      | 8.0            |
| Total                   | 1827            | 26.9                     | 100.0          |

3.2 Track

In order to understand the characteristics of autumn TC tracks, especially their similarities and differences with those of summer TCs, the track density in each season, along with the difference field, is shown in Fig. 3. The variability in TC track density reflects both the variation in the location of TC genesis and that in TC tracks (Mei et al., 2015). Figure 3 clearly shows that autumn TCs are more active at lower latitudes, and that the region to the west of 140°E, the South China Sea, and the region east of the Philippines have the highest frequency of autumn TCs. Contrasting with summer TCs, fewer autumn TCs affect Taiwan, Hainan, and the coastal areas of mainland China. Furthermore, the area affected by autumn landfalling TCs is not as large as that affected by summer landfalling TCs. Contrasting with the summer landfalling TCs, autumn landfalling TCs mainly affect the Southeast and South China coastal areas, and rarely affect areas of the China mainland north of 30°N (Figs. 3a, b). The difference in the climatological spatial distribution between summer and autumn TC track density (Fig. 3c) reveals that the tracks of autumn landfalling TCs are farther south than those of summer landfalling TCs, indicating that autumn landfalling TCs on average have more westward tracks and less northward tracks than summer landfalling TCs. These trends are closely related to differences in atmospheric circulation between summer and autumn TCs.
the two seasons, especially the direction and intensity of the large-scale steering flows.

Figure 4 shows the mean large-scale steering flow and subtropical high at 500 hPa for summer and autumn during 1949–2016. In autumn, the mean subtropical high moves southward and westward compared with its location in summer, and strong easterly steering flows are noted in the tropical area over 0°–20°N, 90°E–180°. In summer, the easterly steering flows gradually weaken as they approach the Philippines and turn into a more northerly direction in the WNP. Steering flows in the South China Sea show significant differences to those in the same area in autumn. Consequently, the prevailing tracks of autumn landfalling TCs are more westward, and the prevailing tracks of summer landfalling TCs are more northward.

Fig. 3. Spatial distributions of the climatological TC track density over the WNP during 1949–2016, calculated at each 1° × 1° grid cell in (a) summer (June–August), (b) autumn (September–November), and (c) the difference (autumn minus summer) field. Black crosses in (c) indicate the areas where the track density difference is statistically significant at the 95% confidence level based on the Student’s t-test.
3.3 Intensity

Table 2 shows the frequency distribution of TCs with different intensities occurring in summer, autumn, and the full year over the WNP from 1949 to 2016. On average, there are 4.1 TS, 6.3 STS, 5.8 TY, 4.6 STY, and 6.0 SupTY each year. The most common intensity category is STS, making up 23.5% of annual TCs, with SupTY and TY ranking second (22.4%) and third (21.6%), respectively. TS is the least frequent category, accounting for only 15.3% of annual TCs. The frequency distribution of TCs at different intensities in summer is basically the same as the annual results. The proportion of STS is the highest (26.1%), followed by TY (24.3%), and the proportion of SupTY is only 18.3%. In autumn, the highest number and proportion (28.1%) is for SupTY. Although TC genesis frequency in summer is higher than that in autumn, the number and proportion of STY and SupTY events are higher in autumn. Autumn SupTY accounts for almost half of the annual number. The reason is that the cold airflows in the Northern Hemisphere be-

| Intensity scale | Average | Percentage (%) | Average | Percentage (%) | Average | Percentage (%) |
|-----------------|---------|----------------|---------|----------------|---------|----------------|
|                 | Annual  | Summer         | Autumn  |               |         |               |
| TS              | 4.1     | 15.3           | 1.9     | 16.5           | 1.5     | 13.2           |
| STS             | 6.3     | 23.5           | 3.0     | 26.1           | 2.3     | 20.1           |
| TY              | 5.8     | 21.6           | 2.8     | 24.3           | 2.3     | 20.2           |
| STY             | 4.6     | 17.2           | 1.7     | 14.8           | 2.1     | 18.4           |
| SupTY           | 6.0     | 22.4           | 2.1     | 18.3           | 3.2     | 28.1           |

Fig. 4. Mean 500-hPa geopotential height (contours; dagpm) and large-scale deep layer mean steering flows (shading; m s$^{-1}$) from 850 to 300 hPa in (a) summer (June–August) and (b) autumn (September–November) during 1949–2016.
come stronger in autumn and can reach tropical regions, which is conducive to the development and intensification of TCs. This phenomenon has been shown in case studies (Dong et al., 2013; Wang et al., 2018) and was reviewed by Yu (2012).

The annual number of autumn TCs of different intensities during 1949–2016 is shown in Fig. 5. Despite the overall decreasing trend of autumn TCs over the period, the annual average genesis frequency of autumn SupTY increased after 2011 compared with the previous 40 years.

Fourteen of the top 20 TCs with the lowest central pressure during 1949–2016 are autumn TCs. Only two of the top 10 TCs with the lowest central pressure occurred in summer, and the rest are all autumn TCs (Table 3). The strongest TC in the WNP is Typhoon Tip (1979), which has the lowest sea level pressure on record. The TC with the strongest wind speed is Typhoon Ida (1958), which formed on 20 September 1958, and the central maximum wind speed reached 110 m s\(^{-1}\) at 0800 BJT 24 September.

### 3.4 Size

Based on the CMA-STI TC size dataset for 1980–2016, the statistical characteristics of the 34-knot radius (R34) for each category of summer and autumn TCs are shown in Fig. 6. The average R34 is 146 km for TS, 171 km for STS, 185 km for TY, 226 km for STY, and 255 km for SupTY for autumn TCs. The corresponding values for summer TCs are 157 km for TS, 177 km for STS, 205 km for TY, 226 km for STY, and 257 km for SupTY. The results show that R34 increases with TC intensity for both summer and autumn TCs. The SupTY category has the smallest variation of R34 of all the TC intensity categories, indicating that the strongest TCs

![Fig. 5. Annual frequencies of autumn TCs with different intensities over the WNP during 1949–2016.](image)

### Table 3. Top 20 TCs with the lowest central minimum pressure in the WNP during 1949–2016

| History ranking | Year | Month | Day | Time (BJT) | Minimum pressure (hPa) | TC name (ID) |
|-----------------|------|-------|-----|------------|------------------------|-------------|
| 1               | 1979 | 10    | 05  | 0200       | 870                    | Tip (1979)  |
| 2               | 1973 | 10    | 02  | 0800       | 875                    | Nora (1973) |
| 3               | 1975 | 11    | 16  | 0800       | 875                    | June (1975) |
| 4               | 1983 | 9     | 20  | 0200       | 876                    | Forrest (1983) |
| 5               | 1958 | 9     | 20  | 2000       | 878                    | Ida (1958)  |
| 6               | 1978 | 10    | 17  | 1400       | 878                    | Rita (1978) |
| 7               | 1984 | 10    | 22  | 2000       | 879                    | Vanessa (1984) |
| 8               | 1971 | 11    | 08  | 0800       | 884                    | Irma (1971) |
| 9               | 1959 | 8     | 25  | 0200       | 885                    | Joan (1959) |
| 10              | 1951 | 8     | 10  | 2000       | 886                    | Marge (1951) |
| 11              | 1966 | 6     | 20  | 1400       | 886                    | Kit (1966)  |
| 12              | 1961 | 9     | 08  | 0200       | 888                    | Nancy (1961) |
| 13              | 1969 | 9     | 19  | 0200       | 888                    | Elsie (1969) |
| 14              | 1983 | 8     | 04  | 1400       | 888                    | Abby (1983) |
| 15              | 2014 | 7     | 10  | 0800       | 888                    | Rammamasun (2014) |
| 16              | 1954 | 8     | 24  | 0800       | 890                    | Ida (1954)  |
| 17              | 1962 | 10    | 01  | 2000       | 890                    | Emma (1962) |
| 18              | 1980 | 10    | 03  | 0200       | 890                    | Wynne (1980) |
| 19              | 2013 | 11    | 03  | 1400       | 890                    | Haiyan (2013) |
| 20              | 2016 | 9     | 09  | 0800       | 890                    | Meranti (2016) |
have a consistent outer size.

3.5 Spatial distribution

In order to analyze the regional characteristics of autumn TC genesis in the WNP, the WNP region was divided into $5^\circ \times 5^\circ$ boxes and the genesis frequency was calculated in each box. The spatial distribution of autumn TC genesis frequency is shown in Fig. 7.

We find from Fig. 7 that there are three high value centers of autumn TC genesis; the first is located near (14°N, 115°E) over the northeastern South China Sea, and the other two are located in the vast oceanic area east of the Philippines around (14°N, 135°E) and (14°N, 145°E), respectively. SupTYs hardly occurred over the South China Sea, and SupTYs that formed in October and November are mostly located south of 15°N. From September to November, there is generally an equatorward shift of the genesis location of autumn TCs. In contrast, there is no obvious trend in meridional shift from September to November, for the average longitude during the period is 146.6°E, 144.8°E, and 149.1°E in September, October, and November, respectively.

![Fig. 6. Boxplots of the 34-knot radius (R34; km) for each category of (a) summer and (b) autumn TCs in the WNP during 1980–2016. For each box, the dot represents the median, the middle line represents the average, the upper (lower) end of the box represents the average plus (minus) the variance, and the whiskers represent the extreme values.](image)

![Fig. 7. Spatial distribution of autumn TC genesis frequency (shading) and the genesis location of SupTYs in the WNP from 1949 to 2016. Black circles denote SupTYs that formed in September; green crosses denote SupTYs that formed in October; and red boxes denote SupTYs that formed in November. The black, green, and red solid lines indicate the average latitude and longitude of the SupTY genesis locations.](image)
4. Characteristics of autumn landfalling TCs in China

4.1 Frequency

From 1949 to 2016, 529 TCs made landfall in China, with an average of 7.8 each year. The maximum number of landfalling TCs in a given year was 12 (1952, 1961, 1971, 1989, and 1994), and the minimum number was 4 (1982). The frequency decreased on average by 0.5 every 10 yr, though this trend is not significant. Before the late 1990s, the annual landfalling TC frequency and its climatic anomaly were relatively large. However, after the late 1990s, the annual landfalling TC frequency and its climatic anomaly were relatively small. For instance, the mean annual number of landfalling TCs was 7.1 from 1996 to 2016, which is 0.7 less than the average from 1949 to 2016. In total, 164 TCs made landfall in China in autumn, with an average of 2.4 per year and a maximum of 5 (1952 and 1974). However, in the autumns of 1959, 1984, 1997, 2006, and 2012, no TC made landfall in China (Fig. 8).

In terms of seasonal variations over the period (Table 4), TCs mainly made landfall in China in summer and autumn, but never in winter. Summer landfalling TCs, with an average number of 5.1 per year, account for the largest proportion (65.8%) of landfalling TCs in a given year, followed by autumn landfalling TCs, which account for more than 30%. The frequency of autumn landfalling TCs does not show a significant long-term trend. There has been a slight decrease in landfalling TCs since the late 1990s, with an average annual landfalling frequency of 2.1 in the recent 20 years. About 28.9% of the total TCs during the study period made landfall in China, including 44.6% in summer and 21.3% in autumn.

The variation in the proportion of landfalling TCs in autumn is consistent with that for the year as a whole. The proportion of annual landfalling TCs increased by around 0.8 per decade over the period. However, the increasing trend in autumn is not as significant as that for the year as a whole, with an average increase in the landfalling frequency of about 0.3 per decade. The landfalling TC ratio in the autumns of 1973, 2010, 1999, 2008, and 1985 reached 50.0%, 50.0%, 44.4%, 44.4%, and 40.0%, respectively, which are the top five highest values during 1949–2016 (Fig. 9).

4.2 Intensity

Table 5 presents the frequency distribution of landfalling TCs at different intensities in summer and autumn over the WNP during 1949–2016. The annual frequency of autumn landfalling TCs is 0.2 for TS, 0.4 for STS, 0.6 for TY, 0.4 for STY, and 0.7 for SupTY. By comparing with the summer landfalling TC frequencies, we find that although the frequency of every TC intensity category in summer is higher than that in autumn, the landfalling ratios for SupTY and STY in autumn are higher than those in summer.

The annual number of autumn landfalling TCs in each

| Season (June–August) | Total number | Annual average landfalling TC number | Season ratio (%) | Landfalling ratio (%) |
|----------------------|--------------|--------------------------------------|-----------------|-----------------------|
| Summer (June–August) | 348          | 5.1                                  | 65.8            | 44.6                  |
| Autumn (September–November) | 164       | 2.4                                  | 31.0            | 21.3                  |
| Winter (December–February) | 0         | 0.0                                  | 0.0             | 0.0                   |
| Spring (March–May)     | 17           | 0.3                                  | 3.2             | 11.6                  |
| Total                  | 529          | 7.8                                  | 100.0           | 28.9                  |
intensity category during 1949–2016 is shown in Fig. 10. On average, autumn landfalling TCs with the largest numbers are SupTYs (29.9%), followed by TYs (24.4%). Since the early 2000s, the number of autumn landfalling SupTYs has increased significantly. For example, there were four autumn landfalling SupTYs in 2016 and two autumn landfalling SupTYs in 2015, exceeding the climatological average (0.7). Overall, there is no significant annual linear trend of autumn landfalling TCs with different intensities over the 68-yr period (figure omitted).

4.3 Spatial distribution

Figure 11 shows the frequency distribution of the genesis location of autumn TCs making landfall in China during 1949–2016. Most of the autumn TCs that made landfall in China were generated over the ocean west of 150°E, with high value centers over the eastern South China Sea and at around 130°E. Compared with the genesis distribution of all autumn TCs (Fig. 7), the genesis locations of landfalling autumn TCs are farther westward, with autumn TCs formed over the ocean close to 170°E rarely making landfall in China. The genesis char-

Table 5. Frequency distribution of landfalling TCs at different intensities in summer and autumn over the WNP during 1949–2016

| Intensity scale | Total number | Summer Annual average number | Percentage (%) | Autumn Annual average number | Percentage (%) |
|----------------|--------------|-----------------------------|----------------|-------------------------------|----------------|
| TS             | 46           | 0.7                         | 13.2           | 15                           | 0.2            | 9.1            |
| STS            | 92           | 1.4                         | 26.4           | 30                           | 0.4            | 18.3           |
| TY             | 90           | 1.3                         | 25.9           | 40                           | 0.6            | 24.4           |
| STY            | 51           | 0.8                         | 14.7           | 30                           | 0.4            | 18.3           |
| SupTY          | 69           | 1.0                         | 19.8           | 49                           | 0.7            | 29.9           |
acteristics of SupTYs making landfall in autumn are similar to those of lower intensity landfalling TCs. SupTY genesis hardly ever occurred in the South China Sea, and most of the SupTYs formed in October and November were generated south of 15°N.

In autumn, as the subtropical high retreats eastward and southward, the genesis locations and tracks of TCs are farther southward than in any other seasons. The southward moving cold air in autumn is more active, which prevents the subtropical high from moving northward and further makes it harder for the autumn TCs to move northward (Fig. 4). Therefore, the TCs mostly make landfall in the southern coastlands of China (Fig. 12). Autumn TCs made landfall in Guangdong Province most frequently; from 1949 to 2016, there were 68 autumn TCs in total making landfalling in Guangdong, equating to an average of 1.0 landfalling autumn TC per year and accounting for almost 1/3 of all landfalling TCs.

Fig. 11. Spatial distribution of autumn landfalling TC genesis frequency (shading) and the genesis locations of SupTYs making landfall in China during 1949–2016 (markers). Black circles denote the SupTYs in September; blue crosses denote those in October; and red squares denote those in November.

Fig. 12. Frequency distribution of autumn TCs making landfall in different provinces of China during 1949–2016. Note that the number of landfalling TCs in a given province takes multiple landfalling events into account.
The second most frequent landfalling location was Hainan Province with 51 autumn TCs making landfall over the period, giving a frequency of 0.8 per year and accounting for almost 1/4 of all landfalling TCs. Taiwan ranks the third, with an average of 0.6 autumn landfalling TCs per year. Fujian Province, which is affected by Taiwan, ranks the fourth with an average of 0.4 autumn landfalling TCs per year. During 1949–2016, the total number of autumn landfalling TCs in Zhejiang, Guangxi, Shanghai, and Hong Kong was 10 or less in each province, while other northern coastal provinces saw no autumn landfalling TCs.

In this study, the climatological characteristics of autumn TCs are investigated and several distinct features have been quantified. Our results provide an important basis for further studies of the mechanisms behind autumn TCs in the WNP. In particular, understanding of the characteristics of autumn TCs making landfall in different provinces will be important for civil disaster prevention. Despite the fundamental objective findings of this paper, there remain a number of open questions regarding autumn TCs. Aspects of autumn TCs that require further exploration include their precipitation characteristics, their long-term trends, and the exact loss to China as a result of their occurrence.

5. Conclusions and discussion

Based on the CMA-STI data, NCEP/NCAR reanalysis data, and the CMA TC yearbooks, for a 68-yr period (1949–2016), we have analyzed the spatial and temporal characteristics and variability of autumn TCs over the WNP (including the South China Sea) in terms of their genesis and landfalling locations, genesis frequency, track density, and intensity.

In the WNP, TCs occurred mainly in summer (42.7%) and autumn (42.1%), which, in combination, account for 84.8% of the total annual TCs. The number of TCs in autumn in the WNP showed a slight decreasing trend over the past 68 years. In most years, an increase in the number of autumn TCs was associated with fewer summer TCs.

In autumn of 1949–2016, there were three high value centers of TC genesis frequency in the WNP, the first is located near (14°N, 115°E) over the northeastern South China Sea, and the other two are located in the vast oceanic area east of the Philippines around (14°N, 135°E) and (14°N, 145°E), respectively. TCs in the SupTY category rarely formed in the South China Sea.

During 1949–2016, the top eight TCs with the lowest minimum central pressure all occurred in autumn. For autumn TCs, the proportion of SupTY was the highest (28.1%). Although the total number of TCs in autumn was less than that in summer, the number of STYs and SupTYs in autumn was more and the proportion was higher. The average R34 of summer and autumn TCs increased with the TC intensity scale.

During 1949–2016, 164 autumn TCs made landfall in China, with an average of 2.4 each year. Autumn TCs most frequently made landfall in Guangdong Province, followed by Hainan and Taiwan. From 1949 to 2016, the total number of autumn landfalling TCs in Zhejiang, Guangxi, Shanghai, and Hong Kong was 10 or less in each province, while other northern coastal provinces saw no autumn landfalling TCs.

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