

# Distribution Characteristics of the Intensity and Extreme Intensity of Tropical Cyclones Influencing China

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## ABSTRACT

To address the deficiency of climatological research on tropical cyclones (TCs) influencing China, we analyze the distributions of TCs with different intensities in the region, based on the best-track TC data for 1949–2011 provided by the Shanghai Typhoon Institute. We also present the distributions of 50- and 100-yr return-period TCs with different intensities using the Gumbel probability distribution. The results show that TCs with different intensities exert distinctive effects on various regions of China and its surrounding waters. The extreme intensity distributions of TCs over these different regions also differ. Super and severe typhoons mainly influence Taiwan Island and coastal areas of Fujian and Zhejiang provinces, while typhoons and TCs with lower intensities influence South China most frequently. The probable maximum TC intensity (PMTI) with 50- and 100-yr return periods influencing Taiwan Island is below 890 hPa; the PMTI with a 50-yr return period influencing the coastal areas of Fujian and Zhejiang provinces is less than 910 hPa, and that with a 100-yr return period is less than 900 hPa; the PMTI with a 50-yr return period influencing the coastal areas of Hainan, Guangdong, and the northern part of the South China Sea is lower than 930 hPa, and that with a 100-yr return period is less than 920 hPa. The results provide a useful reference for the estimation of extreme TC intensities over different regions of China.

**Key words:** tropical cyclone, intensity, extreme, Gumbel distribution

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## 1. Introduction

Extreme weather and climate events receive much attention. For example, the Super Typhoon Haiyan (the strongest tropical cyclone ever recorded in the world) in November 2013, the extreme heavy rainfall in Beijing on 21 July 2012, and Hurricane Sandy in November 2012 in the U.S., all resulted in great losses of human life and severe property damage. The intensity of extreme tropical cyclones (TCs) is also of great concern. Emanuel (1987) used a Carnot cycle model to estimate the maximum possible intensity of TCs over water due to climate warming. Many studies (e.g., Emanuel, 2005, 2008; Webster et al., 2005; Klotzbach, 2006; Elsner et al., 2008) have reported that the maximum TC intensity has increased since the 1970s or

1980s. However, the relationship between TC intensity and climate change/global warming remains an open question (Landsea, 2005; Pielke et al., 2005). Using the best-track data from the Joint Typhoon Warning Center (JTWC), Chan (2006) found that the quantity of intense TCs over the western North Pacific (WNP) did not increase significantly from 1960 to 2004. However, an increasing trend in the peak intensity and frequency of intense typhoons has been found in the WNP basin from 1975 to 2007, based on the TC track data from the JTWC, the Regional Specialized Meteorological Center (RSMC) of Tokyo, and the Shanghai Typhoon Institute (STI) of the China Meteorological Administration (Wu and Zhao, 2012).

In tropical waters, where TCs are active, due to the lack of direct observations of pressure and winds,

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estimation of the maximum potential intensity of TCs is an important aspect of TC research. Miller (1958) presented an estimation method for the lowest pressure of hurricanes based on SST and radiosonde data. Three decades later, Emanuel (1988) developed a model for computing the maximum intensity of hurricanes based on Carnot's principle. Holland (1997) improved the estimation method of Miller (1958); the new method is more dependent on the convective available potential energy (CAPE) of the environmental atmosphere. However, Camp and Montgomery (2001) suggested that the model developed by Emanuel (1988) is more effective than that by Holland (1997). Yu et al. (2010) presented estimates and changes in the TC potential intensity over various TC basins using 70-yr forecasts of thermal and dynamical factors produced by a global ocean-atmosphere coupled model.

Extreme-value statistical methods based on historical TC intensity data are also an important approach for estimating the maximum intensity of TCs, wherein the Gumbel probability distribution is one of the most important methods, being recommended by the International Atomic Energy Agency (IAEA) (Gumbel, 1958; IAEA, 1981; Emanuel and Jagger, 2010).

TCs that influence China originate mainly from the WNP and the South China Sea (SCS). Thus, there have been a number of studies on the climatological distribution of TCs over these waters (e.g., Chen and Ding, 1979; Wang, 1991; Chen et al., 1999; Wang and Qu, 2007; Yuan et al., 2009; Chao and Chao, 2012). Chen et al. (1999) presented histograms showing the average and maximum intensity of TCs landing in China. Yu and Duan (2002) used 35-yr data to analyze the statistical characteristics of TC intensity changes in the WNP. Li et al. (2004) analyzed the characteristics including the frequency and location of TCs landing in China. Wang and Ren (2008) and Wang et al. (2008) presented the overall characteristics of climate change with respect to the frequency and intensity of TCs landing in and influencing China.

However, there is a lack of studies concerning the intensity and extreme intensity of TCs influencing China. Thus, this paper aims to describe TC inten-

sity characteristics based on the best-track TC data by use of the Gumbel probability distribution, and to analyze the intensity of TCs with 50- and 100-yr return periods, and finally to provide a reference for the estimation of extreme TC intensity.

## 2. Data and methods

The data in this paper are the TC best-track data (including minimum central pressure and maximum wind speed) recorded every 6 h over the WNP (including the SCS and the waters north of the equator and west of longitude 180°) during the period 1949–2011, released by the STI, CMA. Previous studies (Ren et al., 2011; Wu and Zhao, 2012) have compared the differences among best-track datasets issued by the STI, RSMC, and JTWC. Wu and Zhao (2012) showed that the TC intensity dataset of the JTWC is relatively more reliable than the other two datasets, but Ren et al. (2011) suggested that each dataset has certain advantages and it is difficult to draw a conclusion as to which dataset is the best. The main objective of this paper is not to compare the three datasets. Given that the STI dataset provides TC minimum central pressure and maximum wind speed every 6 h and has the longer sequence, we therefore use this dataset in the present study.

Ren et al. (2007) defined TCs that influence China as those causing precipitation over mainland China and Taiwan Island or Hainan Island. Their purpose was to study the precipitation distribution produced by these TCs. In this paper, TCs influencing China are defined as any TC whose center enters any location within a radius of 300 km of China and its surrounding waters. The reason for selecting a radius of 300 km is that the TC radius of surface wind of Beaufort force 6 usually exceeds this range (Chen and Ding, 1979), and it is also roughly equal to the 2.5° grid distance used in this paper. In addition, the IAEA recommends this radius value to assess the impact of TCs on nuclear power plants (IAEA, 1981). A general purpose of this paper is to study the different-intensity TCs influencing China, hence the definition of such TCs is altered from that proposed by Ren et al. (2007).

TCs originating from the WNP basin mainly influence central and eastern China and its surrounding waters. Therefore, our study area is chosen as ( $10^{\circ}$ – $55^{\circ}$ N,  $100^{\circ}$ – $130^{\circ}$ E), and is divided into  $2.5^{\circ} \times 2.5^{\circ}$  latitude-longitude grids. Moreover, the waters within the study area are referred to as the surrounding waters of China.

Based on the 6-h best-track data, statistics related to the number and minimum central pressure of TCs whose centers enter any grid point within a radius of 300 km are determined, and then the minimum central pressures of the TCs are sorted in descending order; thus, the lowest and the 95th percentile of the lowest central pressures of the TCs are obtained for the period 1949–2011.

In order to analyze the distribution of extreme TC intensity, based on the sequence of the yearly lowest minimum central pressure of TCs at each grid point, the minimum central pressure of TCs having different mean recurrence intervals can be obtained by using the Gumbel distribution (Gumbel, 1958; IAEA, 1981). The minimum central pressure distributions of TCs with 50- and 100-yr return periods are thus given in this paper.

The cumulative probability density function of the Gumbel distribution is as follows:

$$P(x) = \exp\{-\exp[-(x - a)/b]\},$$

where  $P(x)$  is the probability that  $x$  is not exceeded, and  $a$  and  $b$  are the location and scale parameters, respectively.

Different methods can be used to estimate  $a$  and  $b$ , and this paper uses the Lieblein technique (Gumbel, 1958; IAEA, 1981), as recommended by the IAEA. The Lieblein technique is widely used for estimating the probable maximum intensity of TCs influencing nuclear power plants.

The detailed steps involved in estimating the parameters  $a$  and  $b$  for each grid point are as follows. First, during 1949–2011, the TCs whose centers enter this grid point within a radius of 300 km are selected. Next, the yearly lowest minimum central pressure is determined among those TCs. Note that the yearly lowest minimum central pressure is not necessarily the lowest minimum central pressure of a TC during its

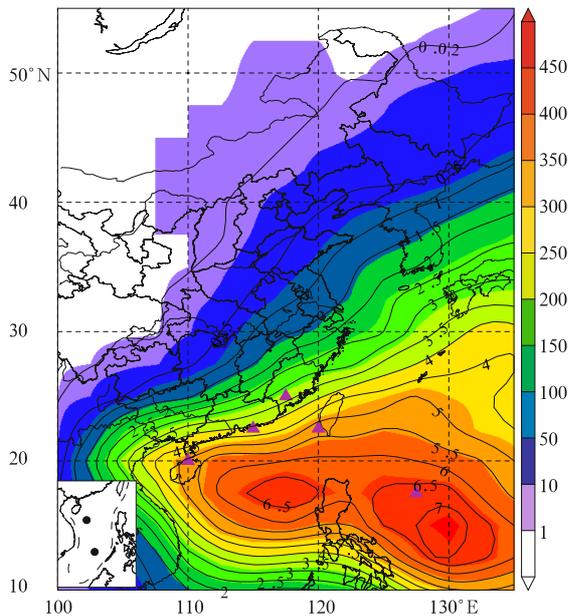
life cycle. Also, if there is no TC influencing a certain grid point in 1 yr, we use 1010 hPa to represent the yearly lowest minimum central pressure. Thus, the 63-yr sample sequence used to estimate the extreme central pressure of TCs is established. Finally, the Lieblein technique is used to estimate the parameters  $a$  and  $b$  in the Gumbel distribution.

Accordingly, the probability distribution curve and the standard deviation of the TC central pressure are calculated at each grid point, and then the extreme intensities of the TCs with 50- and 100-yr return periods at each grid point are obtained.

### 3. Frequencies of TCs with different intensities

Distributions of the total and annual average number of TCs influencing China and its surrounding waters during 1949–2011 are given in Fig. 1. To facilitate the description, distribution of the total TC number is mainly described in the text. It should be noted that, as described in Section 2, the total number of TCs influencing China and its surrounding waters is generally different from the literature, e.g., the number of TCs through the same resolution grid box in the present study differs from that given by Chen and Ding (1979).

Figure 1 shows that the WNP east of the Philippines and the northern part of the SCS are the two areas yielding the most number of TCs in China and its surrounding waters during 1949–2011. The maximum number in the SCS is more than 400, while that in the WNP is more than 450, so the maximum annual average number is greater than 6. Over mainland China, the total number of TCs decreases from southeast to northwest, and the number in coastal areas is larger than that in inland areas, while that in the south is more than in the north. The areas farthest west influenced by TCs include western Yunnan Province and the Hetao area (Yellow River Bend) of central Inner Mongolia, while the most northerly area is Heilongjiang Province. The total number of TCs influencing Hainan and Taiwan islands is the most (more than 300) for land areas of China; the total number of TCs influencing the coastal areas of Guangdong



**Fig. 1.** Total (shaded) and annual average (black solid lines) number of TCs influencing China and its surrounding waters during 1949–2011. Triangles indicate the grid points of the typical sites where extreme TC intensity analyses are performed in detail.

Province is the second most (more than 250); while the total number of TCs influencing the coastal areas of Guangxi Region and Fujian Province is the third (more than 200).

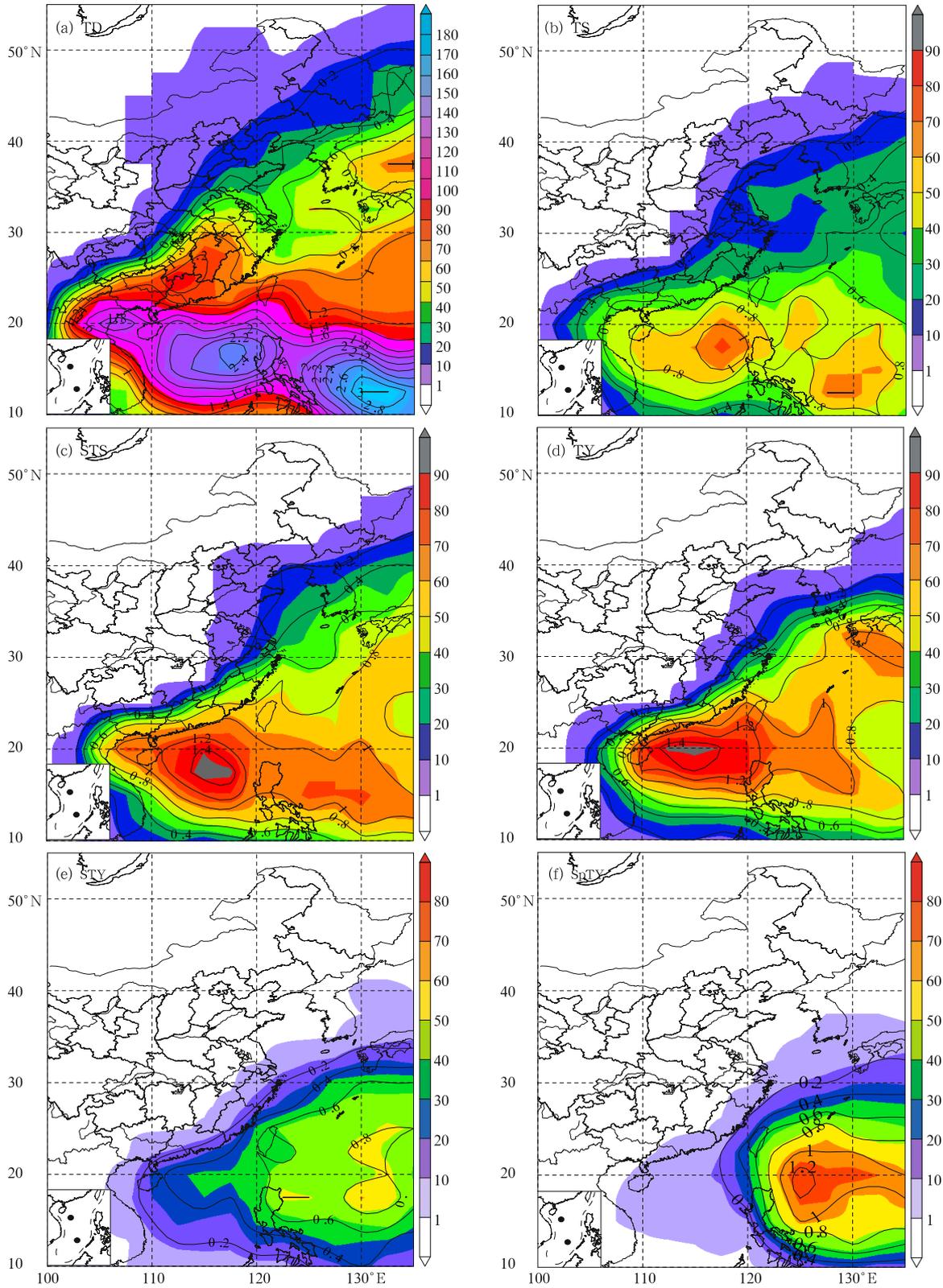
Overall, the areas influenced by TCs in mainland China mainly include the “first-ladder” terrain area (three ladders of terrain exist in mainland China) and the Yunnan-Guizhou Plateau. The total number of TCs influencing the “second-ladder” terrain area (excluding the Yunnan-Guizhou Plateau) is generally less than 10 during 1949–2011. The areas to the west of central and western Sichuan, Gansu, and Qinghai provinces have never been directly influenced by TCs from the NWP in this 63-yr period.

According to the Grade of TCs developed by the China Meteorological Administration (National Standards Committee of China, 2006), the total and annual average numbers of TCs with different intensities, i.e., tropical depression (TD), tropical storm (TS), severe tropical storm (STS), typhoon (TY), severe typhoon (STY), and super typhoon (SuperTY), are given in Fig. 2, based on the maximum wind speed of TCs in

the best-track data. Figure 2 shows that the distributions of the number of TCs with different intensities are significantly different.

The area influenced by TDs is wider than that influenced by TCs with other intensities, and the number of TDs is the largest among the different TC intensity types. The frequency distribution of TDs presents several high-frequency centers, the two most significant ones of which are the WNP east of the Philippines and the northern part of the SCS, where the numbers of TDs are more than 150, and the total numbers of TCs are also the largest. In the Beibu Gulf and its surrounding area, northern Guangdong Province and southern Hunan Province, the northeastern part of the East China Sea, and the Japan Sea, the numbers of TDs are also high. Guangxi Region, Guangdong Province, southern Hunan Province, and Jiangxi Province are the areas most frequently influenced by TDs in mainland China, where the numbers of TDs are higher than those in Fujian and Zhejiang provinces. These areas also appear as a high-frequency tongue extending northeasterly from Guangxi Region and Guangdong Province to Jiangxi Province and southern Anhui Province, and this may be one of the reasons for the higher occurrence frequency of heavy rainfall and short-duration heavy rainfall over these areas (Zhang and Lin, 1985; Chen et al., 2013). Comparing Fig. 1 with Fig. 2a shows that the TCs influencing the “second-ladder” terrain area of China mainly belong to the TD category, which is consistent with the fact that, after landfall, TCs weaken rapidly due to the impact of the underlying surface.

TSs and the TC types with intensities above TS level influence only the “first-ladder” terrain area of China, the surrounding waters, and the northeastern Yunnan-Guizhou Plateau; it is difficult for them to affect the “second-ladder” terrain, with the exception of the southeastern Yunnan-Guizhou Plateau. The frequencies of TSs are significantly lower than those of TDs, so are the frequencies of TCs with intensities above the TS level. There are three high-frequency centers of TSs in China and its surrounding waters, of which the northern SCS is the most significant, followed by two others in the WNP east of the Philip-



**Fig. 2.** Total (shaded) and annual average (black solid lines) numbers of TCs with different intensities during 1949–2011. (a) TD, (b) TS, (c) STS, (d) TY, (e) STY, and (f) Super TY.

piners. The largest numbers of TSs occur in Guangdong Province and Guangxi Region of mainland China—larger than those in Fujian and Zhejiang provinces. The most northerly area influenced by TSs is Heilongjiang Province; however, the numbers of TSs in eastern North China, western and northern Northeast China, are only 1–5 (the annual average number is about 0.1), and the most northerly areas influenced by greater than 5 TSs are eastern Liaoning Province and eastern Jilin Province.

The STS frequency distribution is very similar to that of TSs. The STSs in the northern SCS have the highest frequencies, followed by those in the WNP east of the Philippines; moreover, the numbers of STSs in these two areas are more than those of TSs. The STSs influence Guangdong Province and Guangxi Region the most frequently in mainland China—more frequently than TSs do, and more frequently than in Fujian and Zhejiang provinces. The most northerly area influenced by STSs is eastern Heilongjiang Province; however, the numbers of STSs in eastern North China, southern and eastern Northeast China are only 1–5, and the most northerly areas influenced by greater than 5 STSs are eastern Liaoning Province and southeastern Jilin Province.

The areas influenced by TYs lie significantly farther south and farther east than those influenced by TDs, TSs, and STSs. The most northerly areas influenced by TYs are Shandong Peninsula, southern Liaodong Peninsula, the eastern Bohai Sea, and the northern Yellow Sea. The northern SCS is a center of the highest frequencies of TYs. TYs influence Guangdong Province and Guangxi Region the most frequently in mainland China—more frequently than Fujian and Zhejiang provinces. The numbers of TYs influencing Guangdong Province and Guangxi Region are higher than those of TSs, and almost the same as those of STSs.

The areas influenced by STYs and SuperTYs are situated significantly farther south and farther east than those influenced by TYs. The most northerly areas influenced by STYs and SuperTYs reach only as far as the mouth of the Yangtze River, the southern Yellow Sea, the southern Korean Peninsula, and the southern Japan Sea. The highest frequency cen-

ter of STYs and SuperTYs is mainly located in the WNP east of Taiwan Island and the Philippines. The northern SCS is influenced by a certain frequency of STYs, but a very low frequency of SuperTYs. Taiwan Island is the area influenced by STYs with the highest frequency out of the land areas of China, followed by Hainan Island, and then Guangdong, Fujian, and Zhejiang provinces. Eastern Guangxi, eastern Jiangxi, southern Jiangsu, and southern Anhui provinces are also influenced by a certain frequency of STYs. Taiwan Island is also the area influenced by SuperTYs with the highest frequency out of the land areas of China, followed by Fujian and Zhejiang provinces; southern Guangdong Province and Hainan Island are also influenced by a certain frequency of SuperTYs.

Accordingly, in the surrounding waters of China, the area influenced by TDs with the highest frequency is the WNP east of the Philippines, followed by the northern SCS; the area influenced by TSs, STSs and TYs with the highest frequency is the northern SCS; and the area influenced by STYs and SuperTYs with the highest frequency is the WNP east of the Philippines. This result is consistent with the conclusion of Chen et al. (1999) who indicated that most of the stronger TCs originated over the ocean east of 125°E.

Out of the land areas of China, Hainan Island especially, and also the coastal areas of Guangdong Province and Guangxi Region, experience the highest frequencies of TDs, TSs, STSs, and TYs. The area influenced by STYs with the highest frequency out of the land areas of China is Taiwan Island, followed by Hainan Island, and then the coastal areas of Guangdong, Fujian, and Zhejiang provinces. The area influenced by SuperTYs with the highest frequency out of the land areas of China is also Taiwan Island, followed by the coastal areas of Fujian and Zhejiang provinces.

Based on the distributions of TCs with different intensities, we can conclude the following. The intensities of TCs influencing Inner Mongolia, North China, Northeast China, and Central China do not exceed the TS grade. Those TCs influencing Shandong and northern Jiangsu provinces do not exceed the TY grade. Meanwhile, the areas influenced significantly by SuperTYs are Taiwan Island, Fujian and Zhejiang

provinces, which is consistent with the conclusion obtained by Chen et al. (1999), who showed that land-falling typhoons in Fujian and Zhejiang provinces have stronger intensities.

The minimum central pressure of TCs is more reliable and more representative than the maximum wind speed to characterize TC intensity (Holliday and Thompson, 1979). Therefore, in the following, we use the distribution of the minimum central pressure of TCs to analyze the distribution of extreme intensity of TCs that influence China and its surrounding waters.

#### 4. Extreme intensity of TCs

##### 4.1 Historical extreme intensity distribution

The lowest and the 95th percentile (sorted in descending order) of the lowest minimum central pressures of TCs are used to characterize the extreme intensity of historical TCs at each grid point in China and its surrounding waters during 1949–2011 (distributions are shown in Fig. 3). Figure 3 reveals that the extreme intensities of TCs decrease from the southeast to northwest over mainland China, that TCs over coastal areas are generally stronger than those over inland areas, and that those over the south are stronger than over the north. Yet, the extreme intensities of TCs over the coastal areas of Fujian and Zhejiang provinces are stronger than those over Hainan Island and the coastal areas of Guangdong Province and Guangxi Region, because Fujian and Zhejiang provinces are prone to STYs and SuperTYs.

Both Figs. 3a and 3b show that the extreme intensities of TCs over the WNP east of the Philippines and Taiwan Island are stronger than those over the SCS. The distribution shows that the lowest minimum central pressures of TCs over the WNP east of the Philippines are less than 880 hPa, and those over the northern SCS are only less than 930 hPa; thus, there is a difference of about 50 hPa. The 95th percentile of the lowest minimum central pressures of TCs over the WNP east of the Philippines is less than 920 hPa, while that over the northern SCS is less than 960 hPa; this means there is a difference of about 40 hPa, and

the difference is slightly lower than that of the lowest minimum central pressures of TCs between these two areas. This indicates that the difference in the extreme intensities between these two areas is about 50 hPa.

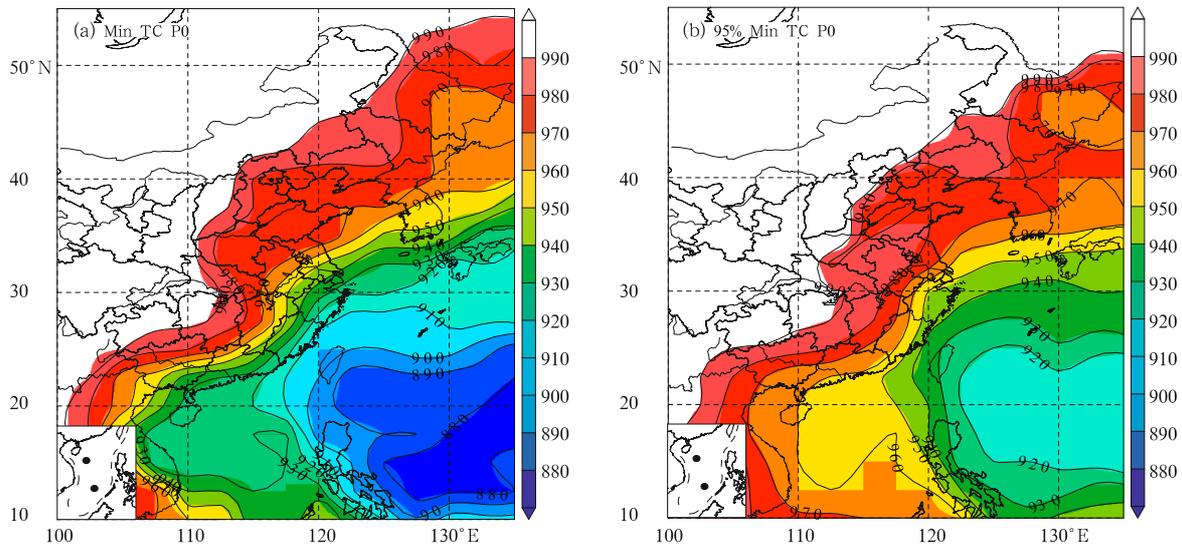
The extreme intensities of TCs over Taiwan Island are significantly stronger than those over Hainan Island. The lowest minimum central pressures of TCs over Taiwan Island are less than 900 hPa, and those over Hainan Island are only less than 930 hPa; thus, there is a difference of about 30 hPa. The 95th percentile of the lowest minimum central pressures of TCs over Taiwan Island is less than 930 hPa, while that over Hainan Island is less than 960 hPa, meaning that there is also a difference of about 30 hPa. This suggests that the difference in the extreme intensities between these two areas is about 30 hPa.

The lowest minimum central pressures of TCs over the coastal areas of Guangdong Province and Guangxi Region are about 930 hPa, and the 95th percentile of the lowest is about 960–970 hPa. Meanwhile, the lowest central pressures of TCs over the coastal areas of Fujian and Zhejiang provinces are about 910 hPa, and the 95th percentile is about 940–950 hPa. This reveals that the difference in the extreme intensities between these two areas is about 20 hPa.

The lowest minimum central pressures of TCs are about 930–950 hPa over central Guangxi Region, northern Guangdong Province, eastern Jiangxi Province, northern Zhejiang Province, southern Jiangsu Province and Shanghai, and the 95th percentile is about 950–970 hPa. This is because the TCs influencing these regions are mainly TYs and TCs with intensities below the TY level.

The lowest minimum central pressures of TCs are about 960–970 hPa over northern Guangxi Province, western Jiangxi Province, central and northern Jiangsu Province and Shandong Peninsula, and the 95th percentile is about 960–980 hPa, because the TCs influencing these regions are mainly STSs, TSs, and TDs.

The lowest and the 95th percentile of the lowest minimum central pressures of TCs are about 970–980 hPa over western Shandong Province, North China and Northeast China, because the TCs influencing th-



**Fig. 3.** (a) The lowest and (b) the 95th percentile of the lowest minimum central pressures of TCs during 1949–2011.

ese regions are mainly TSs and TDs. However, the lowest and the 95th percentile of the lowest minimum central pressures of TCs are below 970 hPa over eastern Heilongjiang Province, which may be associated with the fact that this region is a plain and adjacent to the Japan Sea, meaning that TCs passing over the area are able to easily gain in strength. However, TCs with this intensity are even weaker than extreme extratropical cyclones, because the extreme intensity of extratropical cyclones has been recorded at 926 hPa (Wallace and Hobbs, 2006).

Based on the best-track dataset of TCs during 1949–2011, the above analyses demonstrate that the extreme intensities of TCs over the WNP east of the Philippines can be less than 880 hPa; those over Taiwan Island are less than 900 hPa; those over the coastal areas of Zhejiang and Fujian provinces are less than 920 hPa; those over Hainan Island and the coastal areas of Guangdong Province are less than 930 hPa; those over the inland areas of Zhejiang, Fujian, Guangdong, and Guangxi are less than 960 hPa; and those over the coastal areas north of Jiangsu Province and the inland areas of China are generally higher than 960 hPa.

#### 4.2 Extreme intensity estimate

The Gumbel distribution is the probabilistic method that the IAEA recommends to estimate the

minimum central pressure of probable maximum TCs. In this paper, the distributions of TC intensities with 50- and 100-yr return periods estimated by using the Gumbel distribution are given in China and its surrounding waters, as shown in Fig. 4. The TCs with intensities of 50- and 100-yr return periods belong to extreme weather and climate events. In China and its surrounding waters, the spatial distributions of TC intensities with 50- and 100-yr return periods are very similar to that of the lowest minimum central pressures of TCs during 1949–2011, albeit with some differences in values. Figure 4 also shows that the contours of the minimum central pressure of TCs in the coastal area are very dense, revealing that TCs weaken rapidly after entering the 500–700-km range of land.

Figure 4a shows that the minimum central pressures of TCs with a 50-yr return period over the WNP east of the Philippines are less than 860 hPa; and in particular, those over part of this area are lower than 840 hPa, which are very strong for TCs. In the next section, we further analyze their possibilities based on the physical causes of TC development. It is known that the lowest minimum central pressure ever observed in a TC was 870 hPa in the center of TC “Tip” in the WNP in 1979 (Wallace and Hobbs, 2006). The minimum central pressures of TCs with a 50-yr return period over Taiwan Island are less than 890 hPa; those over the coastal areas of Zhejiang and Fujian provinces

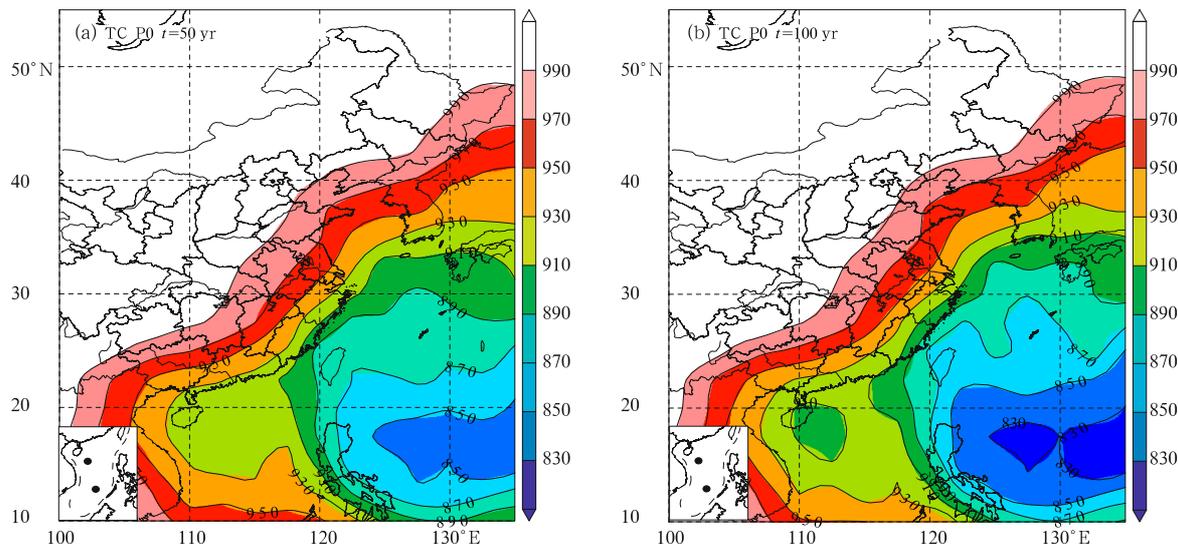


Fig. 4. Minimum central pressures of TCs with (a) 50- and (b) 100-yr return periods.

are less than 910 hPa; those over Hainan Island and the coastal areas of Guangdong Province are less than 930 hPa; those over southern Jiangsu Province, Shanghai, southern and eastern Jiangxi Province, inland Zhejiang Province, inland Fujian Province, inland Guangdong Province, and southern and central Guangxi Region are less than 960 hPa; those over eastern Shandong Peninsula, central Jiangsu Province, southern Anhui Province are less than 970 hPa; but those over other regions of mainland China are generally higher than 970 hPa.

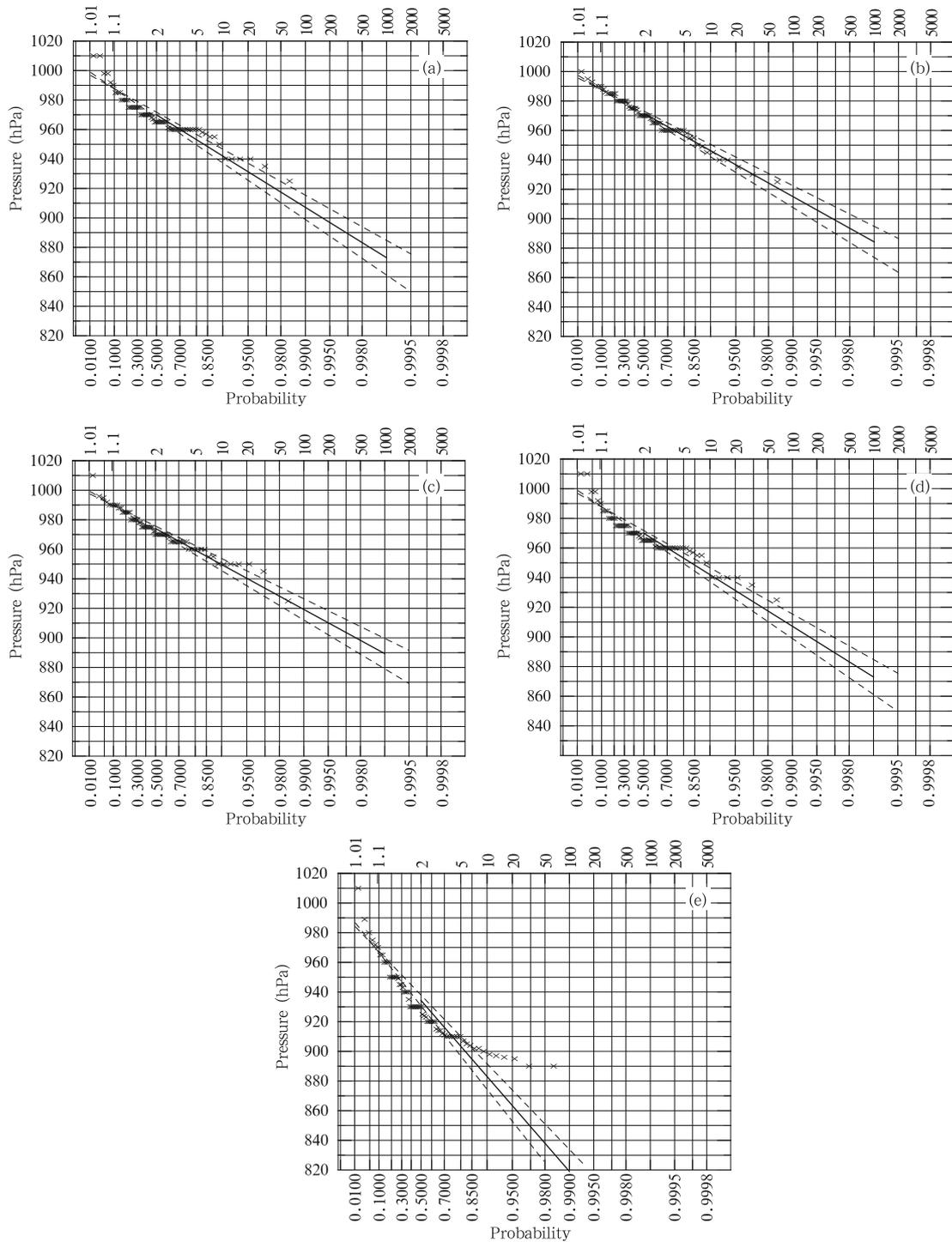
Figure 4b shows that the minimum central pressures of TCs with a 100-yr return period over the WNP east of the Philippines are less than 850 hPa; and in particular, those over some part of this area are lower than 820 hPa, which are stronger than those with a 50-yr return period. Meanwhile, those over Taiwan Island are less than 880 hPa; those over the coastal areas of Zhejiang and Fujian provinces are less than 900 hPa; those over Hainan Island and the coastal areas of Guangdong Province are less than 920 hPa; those over southern Jiangsu Province, Shanghai, southern and eastern Jiangxi Province, inland Zhejiang Province, inland Fujian Province, inland Guangdong Province, and southern and central Guangxi Region are less than 950 hPa; those over eastern Shandong Peninsula, central Jiangsu Province, and southern Anhui Province

are less than 960 hPa; but those over other areas of mainland China are generally higher than 970 hPa. Overall, the minimum central pressures of TCs with a 100-yr return period over the areas of China significantly influenced by TCs, such as Taiwan Island, Hainan Island, Zhejiang Province, Fujian Province, Guangdong Province, and Guangxi Region, are lower by about 10 hPa than those with a 50-yr return period.

#### 4.3 Extreme intensity estimate over typical areas

We choose five typical grid points that are prone to strong TCs: Hainan Island (20°N, 110°E), coastal Guangdong (22.5°N, 115°E), coastal Fujian (25°N, 117.5°E), Taiwan Island (22.5°N, 120°E), and the WNP (17.5°N, 127.5°E) (denoted by the triangles in Fig. 1)—to estimate the reliability of extreme intensities of TCs obtained by means of the Gumbel distribution.

Based on the best-track dataset of TCs during 1949–2011, the fitted Gumbel distributions of minimum central pressures of TCs at the five grid points are given in Fig. 5. The solid line is the fit cumulative probability of the Gumbel distribution for the yearly lowest minimum central pressure of TCs during the 63-yr period, and the dashed lines are the standard deviations of the fit. Figure 5 suggests that the



**Fig. 5.** Fitted Gumbel distributions of minimum central pressures of TCs at five grid points: (a) Hainan Island (20°N, 110°E), (b) Guangdong Province (22.5°N, 115°E), (c) Fujian Province (25°N, 117.5°E), (d) Taiwan Island (22.5°N, 120°E), and (e) the WNP (17.5°N, 127.5°E), during 1949–2011. Vertical axis: pressure (hPa); lower abscissa, cumulative probability; upper abscissa: the average return periods (yr). The solid skew line is the fitted cumulative probability of the Gumbel distribution; dashed lines are the standard deviations of the fit; crosses are the yearly lowest minimum central pressures of TCs.

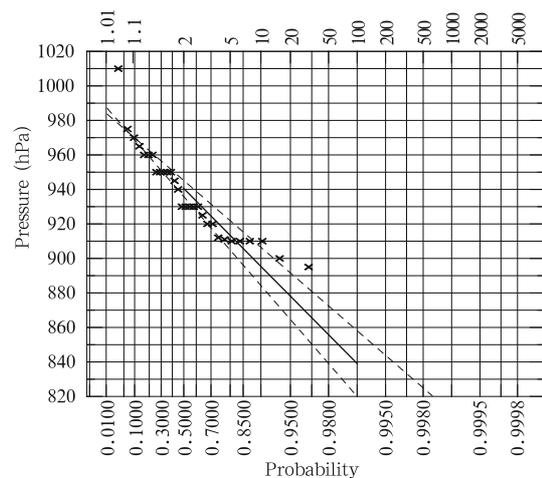
estimated Gumbel distributions using the Lieblein technique better fit the distributions of the yearly lowest minimum central pressure of TCs at Hainan Island, coastal Guangdong, coastal Fujian, and Taiwan Island; but for the WNP, there are larger differences of minimum central pressure of TCs with a 10-yr return period between the fitted and the actual values. Therefore, whether or not the Gumbel distribution is suitable to be used to estimate the extreme intensities of TCs over the WNP east of the Philippines needs to be studied further.

In order to compare the estimates of extreme intensities of TCs using datasets with different time spans, we also obtain the distributions of TC intensities with 50- and 100-yr return periods, estimated by using the Gumbel distribution based on the best-track dataset of TCs during 1981–2011 (figure omitted here). The results are basically consistent with those obtained based on the 1949–2011 data, although there are 10–20-hPa differences between the estimates. This illustrates that, provided the dataset covers a certain time span, the estimates of TC intensities using the Gumbel distribution are stable based on datasets with different time spans.

Based on the best-track dataset of TCs during 1981–2011, the fitted Gumbel distribution of minimum central pressures of TCs at the WNP point (17.5°N, 127.5°E) is shown in Fig. 6, which fits well with the distribution of the yearly lowest minimum central pressure of TCs during 1981–2011. However, there are some differences between Figs. 6 and 5e. This may be related to the different time spans of the datasets used in the different figures. Pielke et al. (2005) and Elsner et al. (2008) pointed out that, before the 1970s, the lack of routine satellite data causes historical TC intensity data to possess a certain degree of inaccuracy; however, Chan (2006) reported that, for the 1960s, given that some aircraft reconnaissance data of TCs over the WNP are available, the reliability is relatively high.

Emanuel (1987) estimated the probable maximum TC intensity (PMTI) over various TC basins using the Carnot cycle. He found that, assuming a sea surface relative humidity of 78%, a thermodynamic ef-

iciency of  $\varepsilon = 0.33$ , and  $SST = 32^\circ\text{C}$ , the PMTI is 849 or 829 hPa when the SST is  $33^\circ\text{C}$ . Furthermore, the PMTIs given by Emanuel (1987) when the SST is 32 or  $33^\circ\text{C}$  are roughly equal to the TC intensities with 50- and 100-yr return periods over the WNP east of the Philippines given in this paper using the Gumbel distribution. In August, the mean climatological SST over the WNP is about  $29^\circ\text{C}$ , and does not exceed  $30^\circ\text{C}$ . The SST over the tropics and subtropics has increased by an average of  $0.2^\circ\text{C}$  over the past 50 years (Pielke et al., 2005). Assuming the current extreme SST over the WNP east of the Philippines is up to  $30^\circ\text{C}$ , and SST increases by  $0.5^\circ\text{C}$  every 50 years, it will therefore take 300 yr for SST to reach  $33^\circ\text{C}$ . According to the estimates given by Emanuel (1987), the PMTI for  $SST = 33^\circ\text{C}$  is roughly equal to the intensity with a 100-yr return period over the WNP east of the Philippines given in this paper by using the Gumbel distribution. Thus, if the estimates given by Emanuel (1987) are more accurate, the TC intensities with 50- and 100-yr return periods over the WNP east of the Philippines are overestimated in this paper, and similar conclusions can also be obtained from the differences between the fitted Gumbel distribution and the actual values in both Figs. 5e and 6. It should be noted that the fitted Gumbel distribution overestimates the extreme TC intensities over the WNP east of the Philippines,



**Fig. 6.** As in Fig. 5e, but for the fitted Gumbel distribution of minimum central pressures of TCs at the WNP point (17.5°N, 127.5°E) during 1981–2011.

but its intensifying trend of the extreme TC intensities with longer return periods agrees with that of the actual TC intensities.

#### 4.4 Classification of areas influenced by TCs

Based on the analyses in Sections 4.1 and 4.2, there are larger differences in extreme intensity of TCs over different areas of China and its surrounding waters, so the areas can be classified according to these differences (Fig. 7).

The extreme-intensity TCs over the WNP east of the Philippines are the strongest in China and its surrounding waters, and the historical lowest minimum central pressure of TCs is below 880 hPa; and those with 50- and 100-yr return periods are also lower than 880 hPa. According to the estimates given by Emanuel (1987), TCs with a minimum central pressure of 880 hPa have maximum wind speeds of up to  $80 \text{ m s}^{-1}$ , approximately.

The extreme-intensity TCs over Taiwan Island are only weaker than those over the WNP east of the Philippines, and the historical lowest minimum central pressure of TCs is below 900 hPa. Those with 50- and 100-yr return periods are lower than 890 hPa, and TCs with a minimum central pressure of 890 hPa have maximum wind speeds of up to  $79 \text{ m s}^{-1}$ , approximat-

ely (Emanuel, 1987).

The historical lowest minimum central pressure of TCs over the coastal areas of Zhejiang and Fujian provinces is below 920 hPa. Those with a 50-yr return period are lower than 910 hPa, and those with a 100-yr return period are lower than 900 hPa. TCs with a minimum central pressure of 900 hPa have maximum wind speeds of up to  $75 \text{ m s}^{-1}$ , approximately (Emanuel, 1987).

The historical lowest minimum central pressure of TCs over Hainan Island, the coastal areas of Guangdong Province, and the northern SCS is below 930 hPa, while those with a 50-yr return period are lower than 930 hPa, and those with a 100-yr return period are lower than 920 hPa.

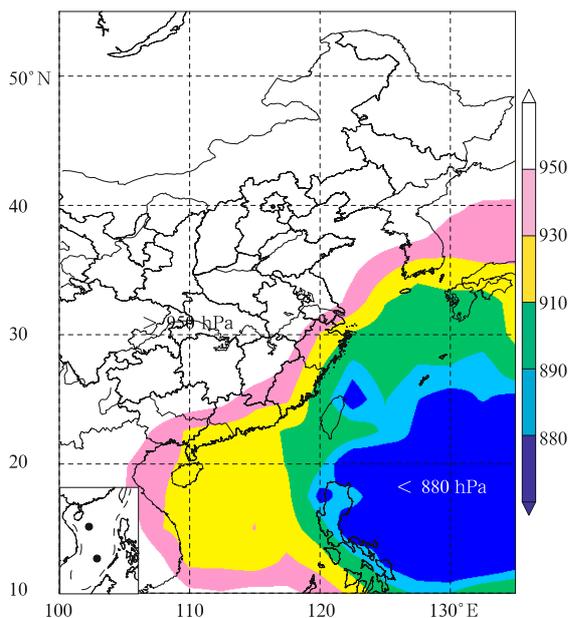
The historical lowest minimum central pressure of TCs is below 960 hPa over southern Jiangsu Province, Shanghai, southern and eastern Jiangxi Province, inland Zhejiang Province, inland Fujian Province, inland Guangdong Province, and inland Guangxi Region, while those with a 50-yr return period are lower than 950 hPa, and those with a 100-yr return period are lower than 950 hPa.

The historical lowest minimum central pressure of TCs is generally higher than 960 hPa over the coastal areas north of central Jiangsu Province and other inland areas of China, while those with a 50-yr return period are higher than 950 hPa, and those with a 100-yr return period are higher than 940 hPa.

Accordingly, the classification of areas is given in Fig. 7, based on the distribution of the minimum central pressure of TCs with a 50-yr return period.

## 5. Conclusions and discussion

Extreme weather and climate events frequently cause serious casualties and adverse social impacts. Based on the best-track TC data over the WNP during 1949–2011, the distributions of different intensities and extreme values of TCs influencing China and its surrounding waters are obtained in this study, by using the Gumbel distribution. By doing so, we have contributed to addressing the lack of research on the climatological distribution of extreme-intensity TCs, and we thus also provided a reference for estimating



**Fig. 7.** Classification of areas based on the minimum central pressures of TCs with a 50-yr return period.

the probable maximum intensities of the TCs affecting China.

We found that different areas of China and its surrounding waters are influenced by the TCs with different intensities. TDs have the highest frequency and influence the widest area. STYs and SuperTYs have the highest frequency in the WNP east of the Philippines. Of the land areas of China, SuperTYs have the highest frequency in Taiwan Island, followed by the coastal areas of Fujian and Zhejiang provinces. Meanwhile, STYs have the highest frequency in Taiwan Island, followed by Hainan Island, and then the coastal areas of Fujian and Zhejiang provinces. TSs, STSs and TYs have their highest frequencies in the northern SCS. TDs, TSs, STSs and TYs have their highest frequencies in South China. It is difficult for TSs and TCs with intensities above the TS level to influence the “second-ladder” terrain area (with the exception of the southeastern Yunnan-Guizhou Plateau) and other inland areas of China.

According to the differences of extreme TC intensities in different areas of China and its surrounding waters, a classification of areas influenced by TCs with different extreme intensities has been presented. Over the WNP east of the Philippines, the TC intensities with 50- and 100-yr return periods are lower than 880 hPa and more than  $80 \text{ m s}^{-1}$  in terms of their maximum wind speed. Over Taiwan Island, the TC intensities with 50- and 100-yr return periods are lower than 890 hPa and have maximum wind speeds of more than  $79 \text{ m s}^{-1}$ . Over the coastal areas of Zhejiang and Fujian provinces, the TC intensity with a 50-yr return period is lower than 910 hPa and is lower than 900 hPa with a 100-yr return period. Over Hainan Island, coastal Guangdong, and the northern SCS, the TC intensity with a 50-yr return period is lower than 930 hPa and is lower than 920 hPa with a 100-yr return period. Over southern Jiangsu Province, Shanghai, southern and eastern Jiangxi Province, inland Zhejiang Province, inland Fujian Province, inland Guangdong Province, and inland Guangxi Region, the TC intensity with a 50-yr return period is lower than 960 hPa and is lower than 950 hPa with a 100-yr return period.

Although the Gumbel distribution has been widely used in extreme estimates, there is a large difference of TC intensity between the fitted Gumbel distribution and the actual one over the WNP east of the Philippines. Therefore, whether or not the Generalized Extreme Value (GEV) distribution, which has been applied more widely, can be used to estimate extreme TC intensities over this region requires further study.

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