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Changes in Regional Heavy Rainfall Events in China during 1961–2012

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ABSTRACT

A new technique for identifying regional climate events, the Objective Identification Technique for Regional Extreme Events (OITREE), was applied to investigate the characteristics of regional heavy rainfall events in China during the period 1961–2012. In total, 373 regional heavy rainfall events (RHREs) were identified during the past 52 years. The East Asian summer monsoon (EASM) had an important influence on the annual variations of China's RHRE activities, with a significant relationship between the intensity of the RHREs and the intensity of the Mei-yu. Although the increase in the frequency of those RHREs was not significant, China experienced more severe and extreme regional rainfall events in the 1990s. The middle and lower reaches of the Yangtze River and the northern part of South China were the regions in the country most susceptible to extreme precipitation events. Some stations showed significant increasing trends in the southern part of the middle and lower reaches of the Yangtze River and the northern part of South China, while parts of North China, regions between Guangxi and Guangdong, and northern Sichuan showed decreasing trends in the accumulated intensity of RHREs. The spatial distribution of the linear trends of events' accumulated intensity displayed a similar so-called "southern flooding and northern drought" pattern over eastern China in recent decades.

Key words: China, regional heavy rainfall events

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1. Introduction

Precipitation extremes have been investigated in many studies, due to their significant influence on human society. One early example is a study by Iwashima and Yamamoto (1993) for extreme precipitation in Japan. Many studies then focused on precipitation extremes and their climate changes (e.g. Karl and Knight, 1998; Suppiah and Hennessy, 1998; Plummer et al., 1999; Easterling et al., 2000; Roy and Balling, 2004; Groisman et al., 2005; Zhai et al., 2005; Alexander et al., 2006; Trenberth et al., 2007; Peterson and Manton, 2008; Zhang et al., 2011, Zwiers et al., 2013). The main conclusion, which was also concluded in IPCC AR4 (Trenberth et al., 2007), was that over the past few decades there has been an increase in the number of heavy precipitation events (e.g. 95th percentile) within many land regions, including China.

A further analysis of the indices applied in the above studies shows that most of them focused on extremes at individual points (stations). But extreme precipitation events, which cause severe floods, such as the 2010 summer flood in Pakistan and the 1998 summer flood in China, are generally regional phenomena, i.e. regional extreme events, meaning that they persist for a long period and cover a large area.

Recently, some studies have paid attention to regional extreme precipitation events. Tang et al. (2006) analyzed the climatology of persistent heavy rainfall events in China during 1951–2004. Using station daily precipitation data and the corresponding 30 km $\times$30 km gridded data, the definition of persistent heavy rainfall (PHR) events was given mainly in three aspects—intensity, extent, and duration—and 197 PHR events were then identified. According to the definition that the HREs (heavy rainfall events) are those rainfall events with daily rain rates exceeding 25 mm d^{-1}, Chen et al. (2012) showed that the HREs have experienced strong decadal variability in eastern China during the past 50 years, and the decadal features varied across regions. Based on individual-station-based extreme event analysis, and then assessing the spatial contiguity of the individual events, Qian (2011) and Chen and Zhai (2013) identified regional persistent extreme precipitation events (PEPEs) in China.

Using cluster analysis and area-averaged rainfall series, Teixeira and Satyamurty (2011) developed an approach to identify heavy and extreme rainfall events in southern and southeastern Brazil during 1960–2004. Ren et al. (2012) de-

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veloped an objective identification technique for regional extreme events (OITREE) using daily observations and showed a simple example of applying it to identify regional heavy precipitation events in China. The OITREE has three advantages: (1) it takes into consideration both the spatial impacted area and the temporal continuity of a regional event; (2) it constructs an index system for regional extreme events, which includes five single indices and an integrated index to estimate the intensity, duration, and impacted areas of extreme events; and (3) it is easy to apply to different extreme events, such as regional high and low temperature extreme events and drought events.

In this study, we used the OITREE method to capture regional extreme precipitation events across mainland China during the period 1961–2012. The temporal and spatial variations of those extreme events were also explored.

2. Data and method

2.1. *Data*

A daily precipitation dataset of 723 stations for the period 1961–2012 from the National Meteorological Information Center of China was used in this work. After 52 stations with less than 40 years of data or more than 10% missing data were eliminated, there were 671 stations left to be studied. These stations were well distributed across most of the country, especially in the central and eastern mainland of China (Fig. 1a). Among these stations, there were still some missing records, which accounted for about 0.5% of the total dataset. The missing records were replaced by zero in this study, so that all daily records were available for the period 1961–2012.

The disaster data of yearly national agricultural areas affected by flood was used in this study in calculating the weighted coefficients of the integrated index. The disaster data were from the website of the Chinese Agriculture Dataset (http://zzys.agri.gov.cn).

2.2. *Method*

The OITREE method (Ren et al., 2012) for identifying regional heavy rainfall events (RHREs) has five steps: (1) select a daily index for each individual point (station) to represent rainfall conditions; (2) separate the daily heavy rainfall belts; (3) distinguish the temporal continuity of rainfall events; (4) construct the index system of RHREs; and (5) estimate their intensity. The following sections give a brief introduction to the procedure and the selection of parameters used in the OITREE method to identify RHREs (Table 1). The details of the method can be found in Ren et al. (2012) and Wang et al. (2013).

2.2.1. *Procedure and selection of parameters*

In this study, daily precipitation for individual stations was used to represent a rainfall event. The threshold for defining daily abnormal heavy rainfall for a station was selected to be the 95th percentile of all daily precipitation, which was equal to or more than 0.1 mm during 1981–2010. If the daily precipitation at a station exceeded the threshold, then this station was considered to be an abnormal heavy rainfall station for the day. The 95th percentile precipitation threshold varied widely across China from less than 10 mm in Northwest China to more than 50 mm along the southern littoral regions (Fig. 1b).

Neighbor stations were defined as being less than 230 km apart; and the threshold for the number of stations in a daily abnormal heavy rainfall belt was five. The neighboring abnormal ratio was 0.2, which meant that an abnormal station could be considered as an abnormal belt center if the ratio was larger than 0.2.

Once the spatial abnormal heavy rainfall belts had been determined, the temporal continuity of a rainfall event needed to be distinguished. In this procedure, no gap was allowed within a heavy rainfall event, and the ratio of spatial overlap for two daily heavy rainfall belts was set to be 0.1.

When all the HREs had been detected, the index system, which included an integrated index (Z) and five single indices—duration (D), the maximum value of extreme daily precipitation (I_1), accumulated precipitation intensity (I_2), accumulated impacted area (A_s), and maximum impacted area (A_m)—was applied to assess their intensities. The integrated index, which was a function of the five single indices, was designed as follows:

$$Z = F(I_1, I_2, A_s, A_m, D) = e_1 I_1 + e_2 I_2 + e_3 A_s + e_4 A_m + e_5 D \,, \quad (1)$$

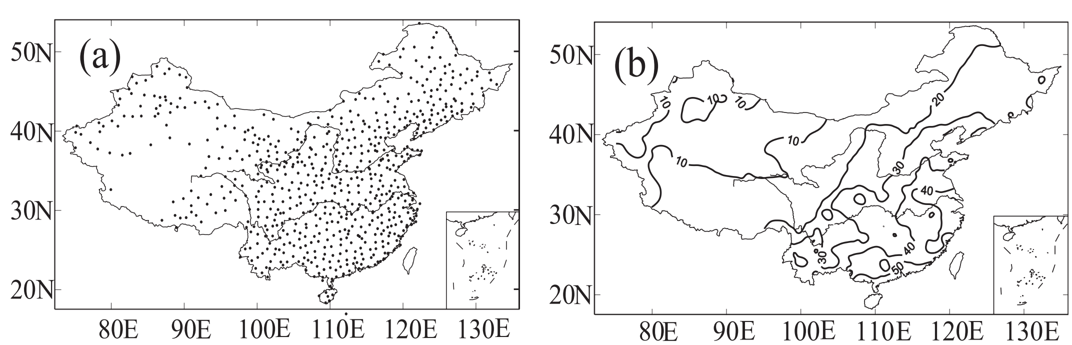

Fig. 1. Spatial distribution of (a) the 671 stations in mainland of China and (b) the 95th percentile threshold value of daily precipitation (units: mm) in China.

Table 1. Values of the main parameters in the OITREE method for China's RHREs.

Parameter name	Code	Meaning	Value
The neighbor stations distance	d_0	The distance to define the neighbor stations	230 km
The neighboring abnormal ratio	R_0	The threshold value of ratio between the numbers of abnormal stations and the neighbor stations	0.2
Minimum number of abnormal stations	M_0	The minimum number of abnormal stations contained in one abnormal belt	5
Extreme threshold value	P_0	Thresholds of abnormal stations	The 95th percentile of daily precipitation
Overlap ratio	C_0	The ratio of spatial overlap between an ongoing heavy rain event and abnormal rain belt, when the ratio is more than C_0, the rain belt belongs to the ongoing event	0.1
Weighted coefficients in the formula of the integrated index	e_1, e_2, e_3, e_4, e_5	The weighted coefficients of the integrated index	0.18, 0.24, 0.21, 0.18, 0.19
Grade threshold values	Z_1, Z_2, Z_3	According to the integrated index Z, RHREs are classified into four grades: extreme, $Z \geqslant Z_1$; severe, $Z_1 > Z \geqslant Z_2$; moderate, $Z_2 > Z \geqslant Z_3$; slight, $Z < Z_3$	2.17, 1.09, 0.50

where the variables I_1, I_2, A_s, A_m, and D were standardized values, respectively, and e_1, e_2, e_3, e_4, and e_5 were their weighted coefficients. The weighted coefficients were defined experientially based on the correlations between the yearly cumulative value of five individual indices and the corresponding yearly national agricultural areas affected by flood from 1971 to 2010. The Pearson correlation coefficient values were 0.45, 0.60, 0.53, 0.45, and 0.47 for I_1, I_2, A_s, A_m, and D, respectively, all of which were statistically significant at the 1% level. The relative percentages of the Pearson correlation coefficients were then calculated to obtain the five weighted coefficients, e_1, e_2, e_3, e_4, and e_5 [Eq. (2); Gong et al., 2012], which had the values 0.18, 0.24, 0.21, 0.18, and 0.19, respectively. The larger the coefficient, the greater its influence on the integrated index (Ren et al., 2012):

$$e_i = \frac{R_i}{\sum\limits_{i=1}^{n} |R_i|} , \qquad (2)$$

where $n = 5$ and the variables R_i are the correlation coefficients between the individual index and the areas affected by flood.

The main advantage was that the integrated index Z, is constructed from the five standardized single indices, so that RHREs in different regions can be compared and assessed.

2.2.2. *Classification of China's RHREs*

Based on the OITREE method, 1394 rainfall events were identified during 1961–2012. The range of values of the integrated index Z was between -0.97 and 7.50, and the number of events with a small value of $Z < 0.25$ was large. Considering the significant influence of strong events and the recommendation of Ren et al. (2012), the threshold of the integrated index Z for defining an RHRE for China was 0.25. There were then 373 RHREs in total. Based on the suggestion for the proportions for classifying RHREs (Ren et al., 2012), there were 37 extreme RHREs (10%), 75 severe RHREs (20%), 149 moderate RHREs (30%), and 112 slight RHREs (40%) over China.

In addition, the non-parametric Kendall's tau test (Kendall and Gibbons, 1981) was used to analyze the linear trends of RHREs, and the statistical significance of a trend was assessed at the 5% level.

3. Effect of the identification

On the basis of the integrated index, the top 10 extreme RHREs during the past 52 years are shown in Fig. 2 and Table 2. Eight of the top 10 events (Nos. 1, 2, 3, 4, 5, 6, 7, and 9) were concentrated in or included the middle and lower reaches of the Yangtze River region, and five of them (Nos. 1, 2, 3, 7, and 9) covered South China. Among the top 10 events, five occurred in the 1990s. When compared with studies such as Ding (2008) and NCC (2010), all the top 10 events had corresponding records and were widespread, persistent rainfall disasters with noticeable impacts (Table 2). The top RHRE occurred during 13–27 June 1998, and covered most of southern China. In 1998, extensive extreme floods devastated the Yangtze River valley in southern China and the Nenjiang–Songhuajiang valley in Northeast China, causing about $36 billion of economic losses and more than 3000 deaths (NCC, 1998).

4. Results and analysis

The frequency distributions of single indices for the 373 China RHREs are shown in Fig. 3. The duration ranged between 2 to 15 days, and the highest frequencies were 146 at 3 days and 111 at 2 days (Fig. 3a). Figure 3b represents the frequency distribution of extreme intensity, which ranged from 50 mm to 620 mm, with two peak frequencies of 50 at around 180 mm and 41 at around 260 mm. The accumulated impacted area varied from 1.0×10^5 km^2 to 4.0×10^6 km^2,

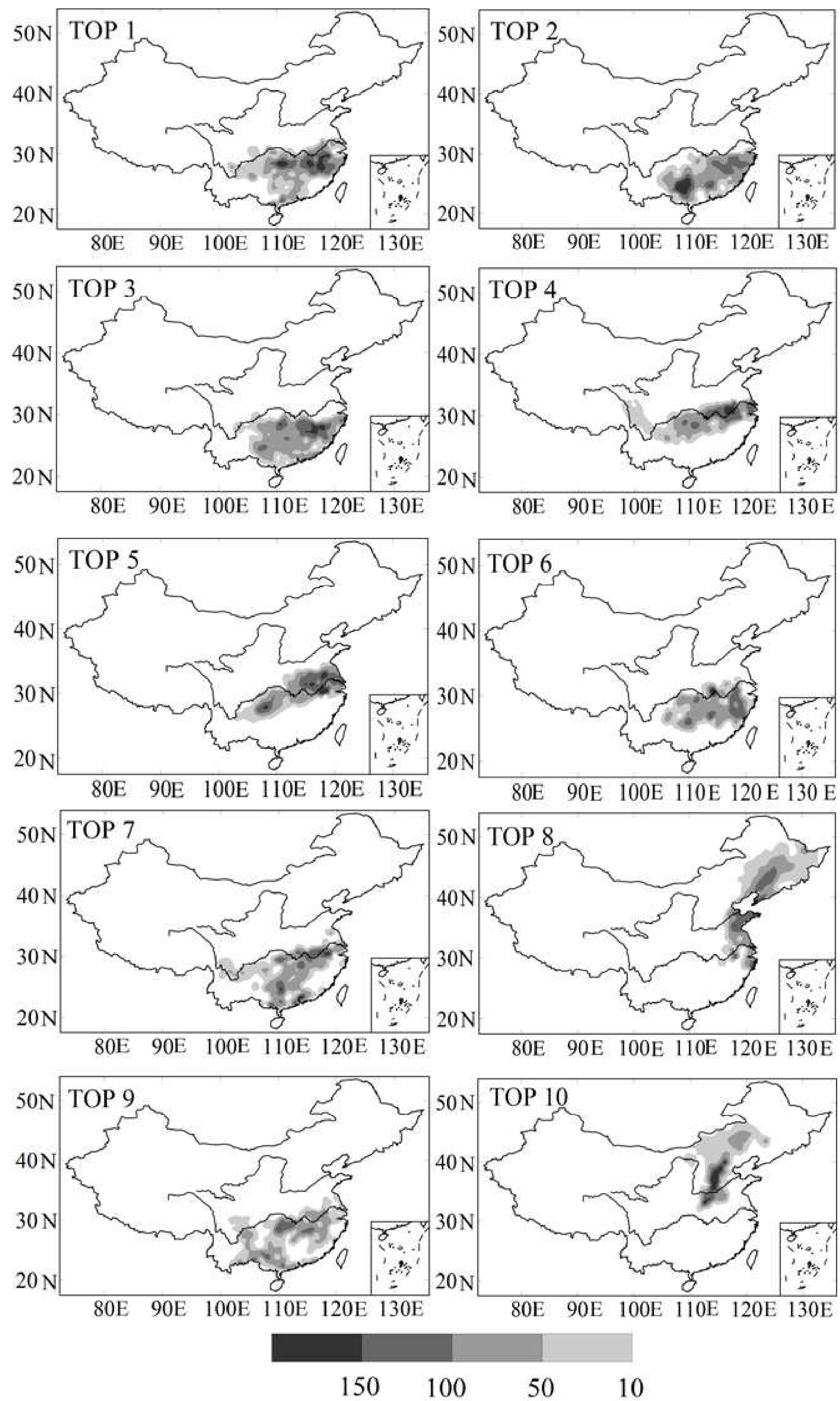

Fig. 2. Distributions of extreme intensity (I_1, units: mm) for the top 10 extreme RHREs for China during 1961–2012.

Table 2. List of the top 10 RHREs over China and their corresponding records in previous studies.

Order	Beginning and end time	Location	Records: Reference #1	Records: Reference #2
1	13–27 June 1998	Southern part of the MLYZ and South China	During summer 1998, the Yangtze River experienced heavy rainstorms and serious flooding.	
2	12–21 June 1994	Southern part of the MLYZ and South China	During the middle of June 1994, the southern part of the MLYZ and South China received 200 to 700 mm of rainfall, and South China experienced a 1-in-50-years flooding.	
3	17–26 June 2010	Southern part of the MLYZ and South China	—	During middle and late June 2010, the southern part of the MLYZ and South China experienced persistent heavy rains, Jiangxi province encountered the strongest rainstorm on record, casualties and losses were serious.
4	24 June to 1 July 1999	Areas along the Yangtze River	In late June and early July 1999, the Yangtze River experienced heavy rains, with precipitation of 150 to 700 mm and a 1-in-50-years flooding occurring in the Taihu Lake basin.	
5	1–7 July 1991	Areas along the MLYZ	In early July 1991, the Jiang-Huai area experienced prolonged and severe rainfall.	
6	13–21 June 1982	The MLYZ	During the middle of June 1982, the southern part of the MLYZ encountered a continuous heavy rainfall event.	
7	26 June to 1 July 1981	The MLYZ and South China	During late June and early July 1981, Hubei, Hunan, Guangxi etc. were hit by heavy rainstorms and serious floods.	
8	18–22 August 1997	Eastern part of coastal China and eastern Northeast China	In middle and late August 1997, large coastal areas of eastern China were hit by Typhoon Winnie, with strong wind and torrential rains which resulted in serious casualties and losses.	
9	27 June to 4 July 1966	Southern part of the MLYZ, southeastern part of Southwest China and western South China	During late June and early July 1966, South China and the southern part of the MLYZ suffered from heavy rainfall, resulting in serious casualties and losses.	
10	2–9 August 1963	North China and western Northeast China	During early August 1963, the Haihe River basin and North China, especially Hebei province, experienced severe rainstorm and floods due to persistent heavy rains lasting one week, which was named the “63·8 rainstorm”.	

MLYZ: middle and lower reaches of the Yangtze River.
Reference #1: *China Meteorological Disasters Book* (consolidated volume) (Ding, 2008).
Reference #2: *National Climate Impact Assessment* (NCC, 2010).

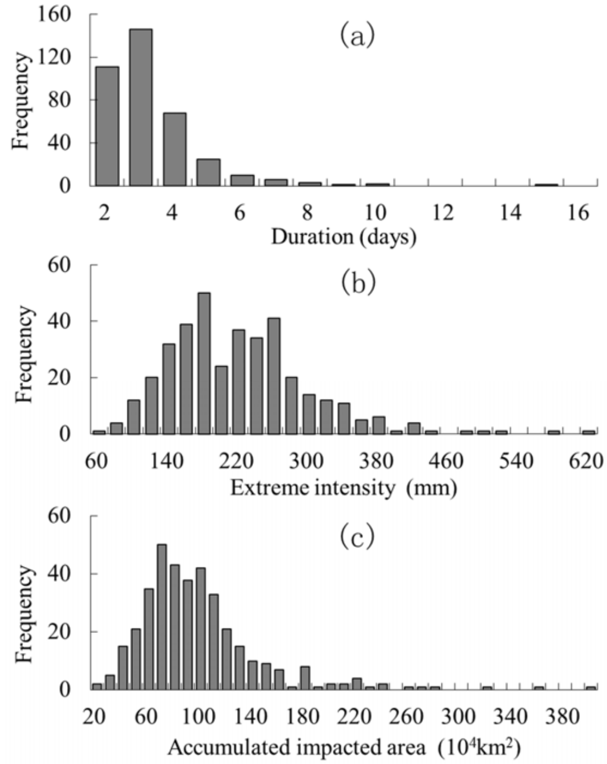

Fig. 3. Distributions of the frequency of single indices for the 373 RHREs over China: (a) duration; (b) extreme intensity; (c) accumulated impacted area.

with peak frequencies of 40 to 50 at about 7.0×10^5 km^2 to 10.0×10^5 km^2 (Fig. 3c).

4.1. *Temporal variations*

Figure 4 shows variations of China's RHREs frequency during 1961–2012. Frequent events occurred in the 1960s, the early 1980s, the middle and late 1990s, and several recent years; low frequencies occurred in the 1970s, and the middle and late 1980s. The three highest annual frequencies were 14 in 2008, 13 in 1964, and 12 in 1995 and 2010. There were only three events in 1987 and 1978 (Fig. 4). There were 181 RHREs in China during the period from 1991 to 2012, accounting for about 49% of the total events. Frequent extreme and severe RHREs could also be found in the middle and late 1990s and the early 2000s (Fig. 4). Frequencies of total events and extreme and severe events both showed obvious but not significant increasing trends, especially since the 1990s (Fig. 4).

Figure 5 shows variations of the annual accumulated integrated index Z, and single indices for Chinese RHREs during 1961–2012. The annual accumulated index Z, displayed an obvious but not significant increasing trend of 5.4% (10 yr)$^{-1}$ (Table 3, Fig. 5). Large interannual and decadal-scale variability was notable for the time series of Z, which was similar to that for frequency (Fig. 4). High values appeared in the early 1980s, the middle and late 1990s and in several recent years. The top three years were 1998, 1994, and 1995,

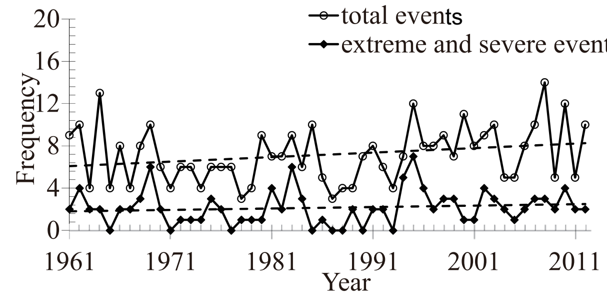

Fig. 4. Temporal variation of the annual frequencies for the total RHREs over China and the extreme and severe events during 1961–2012. Dashed lines are their linear trends.

while low values occurred in the 1970s and the middle and late 1980s.

All single indices of RHREs represented obvious increasing trends with values between 5.9% and 8.7% (10 yr)$^{-1}$ during the past 52 years, but only the trend of extreme intensity, I_1, was statistically significant at the 5% confidence level (Table 3). The interdecadal variations for the single indices were similar to those of the frequency and accumulated integrated index Z. They had high values during the middle and late 1990s and several recent years, such as 2008 and 2010 (Fig. 5).

To understand the reasons for the annual variations of China's RHREs, the relationships between China's RHREs, the activity of Northwest Pacific tropical cyclones (TCs), and the activity of the East Asian summer monsoon (EASM) were analyzed. The frequency of TCs affecting China (Ren et al., 2011) represents the activity of Northwest Pacific typhoons; while the Mei-yu, which generally occurs from mid-June to mid-July and is the main stage of the EASM with abundant rainfall mainly appearing over the middle and lower reaches of the Yangtze River valley and nearby regions, represents the EASM's activity. Table 4 presents their correlation coefficients. China's RHREs show positive correlation relationships with the Mei-yu and negative correlation relationships with the frequency of TCs affecting China, but only the correlation relationships of the accumulated precipitation intensity (I_2) of China's RHREs with the Mei-yu precipitation amounts and the Mei-yu precipitation intensity (Zhao, 1999) were significant, with the correlation coefficients being 0.42 and 0.39, respectively. The above results mean that the

Table 3. Linear trend of different indices for RHREs over China during 1961–2012 [units: % (10 yr)$^{-1}$]. Values in bold are statistically significant at the 5% confidence level.

Index name	Linear trend
Integrated index (Z)	5.4
Extreme intensity (I_1)	**8.2**
Accumulated intensity (I_2)	8.7
Maximum impacted area (A_m)	6.9
Accumulated impacted area (A_s)	5.9
Duration (D)	6.5

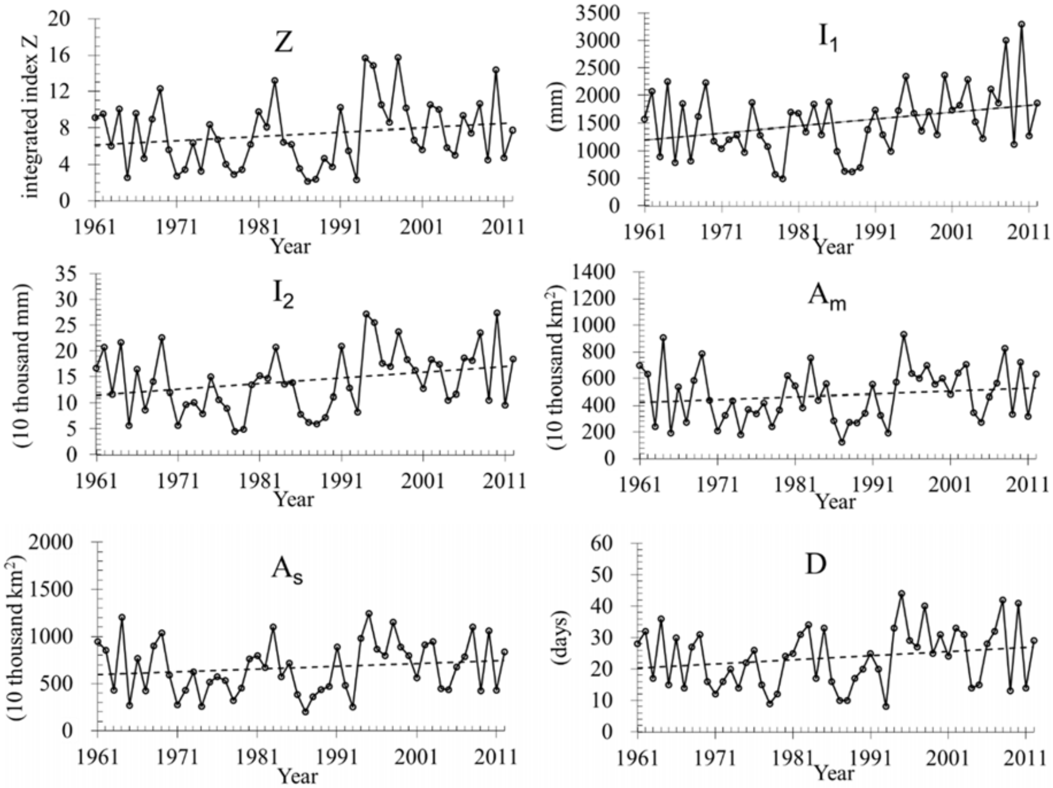

Fig. 5. Temporal variation of the accumulated integrated index *Z* and five single indices for the RHREs over China during 1961–2012, with dashed lines representing their linear trends.

Table 4. Correlation coefficients between RHREs over China, the Mei-yu, and TCs affecting China during 1961–2012. Values in bold are statistically significant at the 5% confidence level.

	Mei-yu					TCs
	Onset date	Retreat date	Duration	Precipitation amount	Precipitation intensity	Frequency of affecting TCs
Frequency of RHREs	0.05	0.10	0.15	0.28	0.26	−0.13
Accumulated intensity of RHREs	0.06	0.15	0.17	**0.42**	**0.39**	−0.20

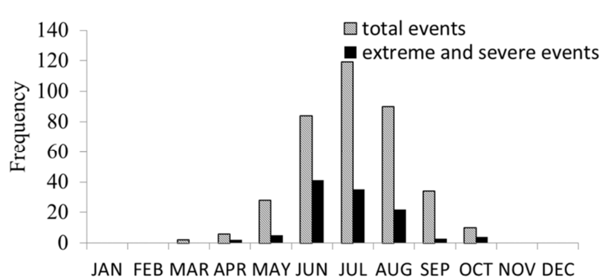

Fig. 6. Monthly frequencies of total events and extreme and severe events for the RHREs over China during 1961–2012.

activity of China's RHREs was mainly affected by the EASM activities. Meanwhile, considering the low contribution (about 6% for mainland China) of TC precipitation to total precipitation, the obvious differences between the TC precipitation pattern (Ren et al., 2011), in which the central values were found on the southern and southeastern coasts, and the pattern of frequency for China's RHREs (Fig. 7), as well as the negative correlation relationships between the Mei-yu

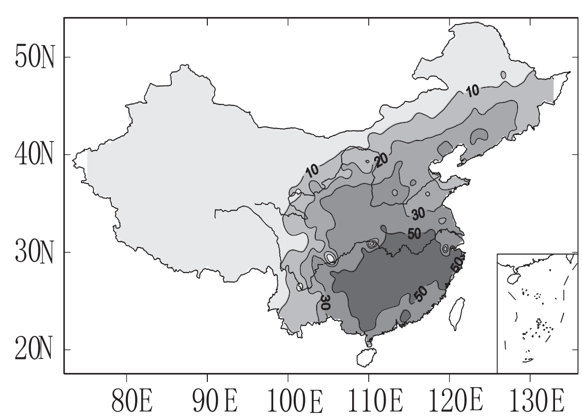

Fig. 7. Spatial distribution of the frequency of RHREs over China during 1961–2012.

activity and TC activity found by Liu et al. (2011), it is easy to understand that TCs affecting China played a weak role in China's RHREs.

According to the monthly variations of the frequencies of China's RHREs and extreme and severe events during the past 52 years, China's RHREs occurred from March to October, while extreme and severe events occurred from April to October. Furthermore, both of them showed that RHREs occurred most frequently in summer (June, July, and August), accounting for 79% and 88% of their annual rates, respectively, with the peak frequency in July for total events and in June for extreme and severe events (Fig. 6). The distinct seasonal variation of the frequency of China's RHREs (Fig. 6) and the distribution of their geometrical centers (Fig. 8, discussed in detail later) showed pronounced characteristics in the onset, advance, and retreat of the EASM.

4.2. *Spatial variation*

Based on the statistics of individual stations, the spatial distribution of the frequency of RHREs could be analyzed (Fig. 7). Most of central and eastern China experienced more than 10 RHREs during the past 52 years, with 50–80 events occurring in the middle and lower reaches of the Yangtze River and northern areas of South China. The middle and lower reaches of the Yangtze River and northern South China were the areas of the country most vulnerable to RHREs.

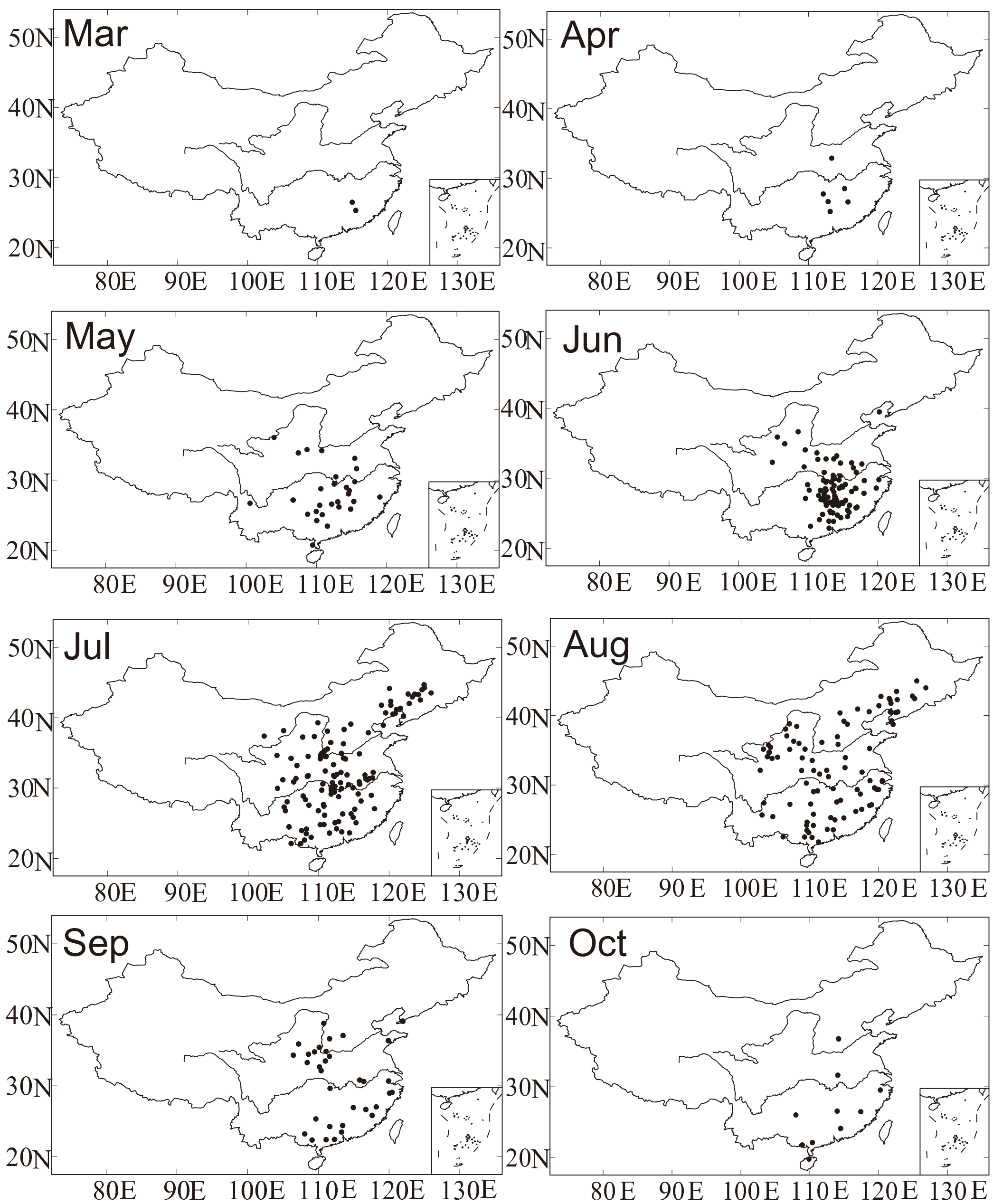

Fig. 8. Monthly distributions of the geometrical centers of the RHREs over China from March to October.

Chen and Zhai (2013) showed that regional PEPEs occurred mostly in the southern part of China (south of 34°N), particularly in the Yangtze–Huai River valley, the regions south of the Yangtze River (26°–34°N), and South China (south of 26°N), which was similar to the areas of frequent RHREs.

Figure 8 shows the monthly distributions of the geometrical centers of China's RHREs from March to October. The geometrical center was calculated as the geometric center of the event's maximum impacted area. The maximum impacted area was regarded as a rectangle, created by selecting the most northeast and southwest points. During March to April, only a few events occurred in South China and parts of the middle reaches of the Yangtze River. During May, alongside the onset of the EASM, 28 RHRE events occurred in South China and the southern part of the middle and lower reaches of the Yangtze River. During the process of the EASM in summer, the area covered by the RHREs expanded northward significantly. The RHRE frequency increased rapidly in June (84 events), with more events hitting the middle and lower reaches of the Yangtze River compared with May. In July, the location of the geometrical centers of the RHREs expanded northward, reaching North China and Northeast China, and the frequency reached 119, which accounted for about 32% of the total events. In August, although the number of events (90) was less than in July, the location of these events was similar to in July. In September, along with the retreat of the EASM, the area covered by the RHREs shrank southward and the event frequency decreased quickly compared with August. There were only 10 events in October, which were mainly due to TCs, located primarily in the coastal regions of South China and Southeast China.

The spatial linear trends of the frequency and accumulated intensity of RHREs are shown in Fig. 9. The frequencies generally showed slightly increasing trends across the whole country, except for several locations in North China and Southeast China, with obvious increasing trends [values of above 0.06 (10 yr)$^{-1}$] in parts of the middle and lower reaches of the Yangtze River and eastern Southwest China (Fig. 9a). For accumulated intensity (Fig. 9b), slightly decreasing trends mainly appeared in parts of North China, northern Sichuan province, and regions between Guangxi and Guangdong provinces, while increasing trends covered most of the remainder of China, with obvious significant increasing trends [values of above 10 mm (10 yr)$^{-1}$] in most of southern China, especially in Southeast China and Hunan province. Based on the main spatial distribution characteristics of accumulated intensity trends, five stations—Beijing, Wuzhou, Jinhua, Zhijiang, and Ziyang—were selected to represent North China, regions between Guangxi and Guangdong, Southeast China, Hunan, and northern Sichuan, respectively (Fig. 9b). Figure 10 shows the temporal variation of accumulated intensity for the five representative stations. Beijing, Wuzhou and Ziyang showed obvious but not significant decreasing trends (Fig. 10a), while Jinhua and Zhijiang showed evident increasing trends, with a significant trend in Zhijiang (Fig. 10b).

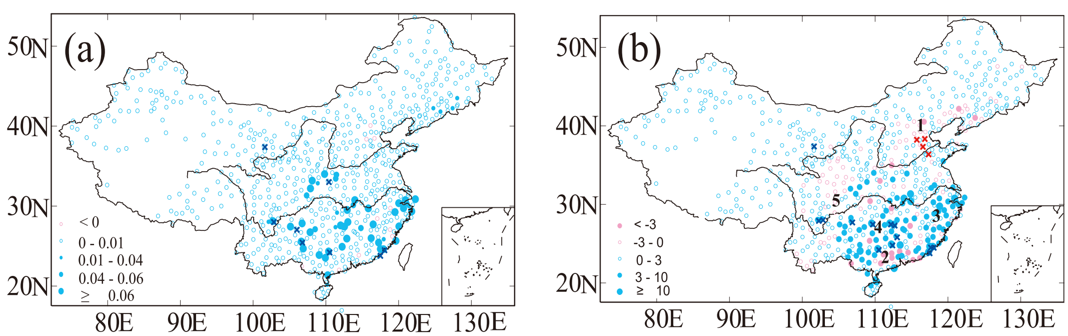

Fig. 9. Spatial linear trends of the (a) frequency of annual events [(10 yr)$^{-1}$] and (b) accumulated intensity [mm (10 yr)$^{-1}$] of RHREs in China. Crosses indicate that trends are significant at the 5% level and number symbols represent the five representative stations: (1) Beijing; (2) Wuzhou; (3) Jinhua; (4) Zhijiang; (5) Ziyang.

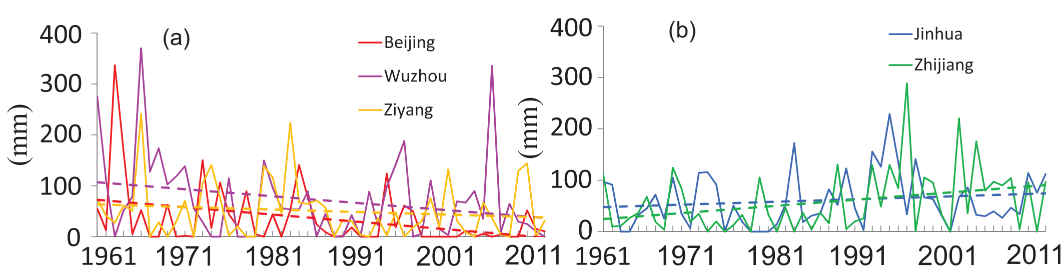

Fig. 10. Temporal variation of the annual accumulated intensity of RHREs for (a) Beijing, Wuzhou and Ziyang, and (b) Jinhua and Zhijiang stations during 1961–2012, with dashed lines representing their linear trends.

5. Conclusion

In this study, the OITREE was applied to identify RHREs in China during the period 1961–2012. The results showed that all the top 10 RHREs had corresponding records in existing studies, suggesting that the OITREE method performed well in identifying the RHREs. There were 373 RHREs over China, including 37 extreme events, 75 severe events, 149 moderate events, and 112 slight events.

The duration of the RHREs varied from 2 to 15 days; the highest frequencies were 146 with a duration of 3 days and 111 with a duration of 2 days. In terms of the seasonal variation, the RHREs occurred from March to October, while extreme and severe events occurred from April to October, both showing that events were most frequent in the summer (June, July, and August), accounting for 79% and 88% of the annual rates, respectively, with the peak frequency in July for total events and in June for extreme and severe events. The distinct seasonal variation of the frequency of China's RHREs (Fig. 6) and the distribution of their geometrical centers (Fig. 8) showed pronounced characteristics in the onset, advance, and retreat of the EASM.

With respect to annual variation, the activity of China's RHREs was mainly affected by EASM activity; significant correlation relationships were found between the accumulated precipitation intensity of China's RHREs and Mei-yu precipitation amounts and intensity.

Although no significant trend was detected for most indices of the RHREs in China during 1961–2012, obvious increasing trends could be found in frequency and intensity, which is consistent with previous work (Easterling et al., 2000; Groisman et al., 2005; Alexander et al., 2006; Trenberth et al., 2007). Chen et al. (2012) also found that regional heavy rainfall in China shows strong decadal variability rather than a linear trend. China experienced more frequent and severe RHREs in the middle and late 1990s, and more extreme RHREs were also found in the late 2000s; similar conclusions were drawn by Chen and Zhai (2013) and Qian (2011). The middle and lower reaches of the Yangtze River and the northern part of South China were the areas across the country that were most vulnerable to RHREs, and they experienced 8 of the top 10 most severe RHREs during the past 52 years. The frequency and accumulated intensity of RHREs in these regions has also increased. The spatial distribution of the trends of the RHREs' accumulated intensity exhibited a similar pattern to the so-called "southern flooding and northern drought" pattern over eastern China in the last five decades, consistent with the results of previous studies (Zhai et al., 2005; Wang and Zhou, 2005; Yao et al., 2008). This rainfall pattern is related to the weakening trend in the summer monsoon over central-east China.

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