Duration and Seasonality of Hourly Extreme Rainfall in the Central Eastern China

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ABSTRACT

Compared with daily rainfall amount, hourly rainfall rate represents rainfall intensity and the rainfall process more accurately, and thus is more suitable for studies of extreme rainfall events. The distribution functions of annual maximum hourly rainfall amount at 321 stations in China are quantified by the Generalized Extreme Value (GEV) distribution, and the threshold values of hourly rainfall intensity for 5-yr return period are estimated. The spatial distributions of the threshold exhibit significant regional differences, with low values in northwestern China and high values in northern China, the mid and lower reaches of the Yangtze River valley, the coastal areas of southern China, and the Sichuan basin. The duration and seasonality of the extreme precipitation with 5-yr return periods are further analyzed. The average duration of extreme precipitation events exceeds 12 h in the coastal regions, Yangtze River valley, and eastern slope of the Tibetan Plateau. The duration in northern China is relatively short. The extreme precipitation events develop more rapidly in mountain regions with large elevation differences than those in the plain areas. There are records of extreme precipitation in as early as April in southern China while extreme rainfall in northern China will not occur until late June. At most stations in China, the latest extreme precipitation happens in August–September. The extreme rainfall later than October can be found only at a small portion of stations in the coastal regions, the southern end of the Asian continent, and the southern part of southwestern China.

Key words: extreme precipitation, hourly rainfall, rainfall duration, rainfall seasonality

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1. Introduction

Extreme precipitation usually refers to the rainfall instances that are rare and with rainfall intensity far beyond local climatology. Because of massive rainfall amount produced in a short time, extreme precipitation can lead to severe disasters such as flood, landslide, and debris flow, and usually causes extensive loss of life and property. Therefore, the features and mechanisms of extreme precipitation have received special attention from the fields of meteorology, climatology, and hydrology (Zhai et al., 1999; Easterling et al., 2000; Alexander et al., 2006).

Due to complicated weather conditions and climate backgrounds, and influenced by various factors, extreme precipitation in China exhibits significant regional differences. Zhai et al. (2005) selected the 95th percentile of historical rainfall as the threshold of extreme precipitation, pointing out that extreme precipitation increased in western China and mid-lower reaches of the Yangtze River while decreased in North China and the Sichuan basin. Yu and Li (2012) fitted the amount-intensity curve with exponential distribution and defined the double e-folding decay intensity as the threshold of extreme precipitation, finding that the extreme precipitation in southern China has sig-

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nificantly increased over the past 40 years. Using Generalized Pareto Distribution to fit daily rainfall data, Dong et al. (2011) analyzed the distribution of formal parameter, and evaluated the trend of extreme precipitation over Huang-Huai and Jiang-Huai regions.

By synthesizing the above studies and the research progress in this field (Li et al., 2008; Jiang et al., 2009; Zhang and Wei, 2009), it can be known that there are three key questions in the study of extreme precipitation: the method for threshold determination, the temporal resolution of rainfall data, and the scientific issues about extreme precipitation. The determination of threshold is the most important question, which directly concerns the sample selection and further affects the analysis results. Objectivity, quantification, and comprehensive consideration for local climate background, especially for the feature of the tail of probability distribution, are highly essential in threshold determination.

In the respect of rainfall data, most studies on extreme precipitation in China focused on daily rainfall amount. However, daily data might have biases in describing rainfall intensity, such as overestimates of the intensity of light precipitation with long duration, underestimates of the intensity of heavy precipitation with short duration, and dividing the intensity of one precipitation event longer than 24 h into different days. Since the intensity is a fairly important factor in the selection of extreme events, hourly precipitation data should be used, which could not only present a better reflection of precipitation intensity, but also preserve more details of precipitation process (Trenberth et al., 2003). The importance of hourly data has been gradually recognized. Using hourly precipitation data, Yu et al. (2010) illustrated the variation features of the "southern flood and north drought" (SFND) distribution, finding that the moderate rainfall is the dominant factor in causing SFND. Also based on hourly data, Zhang and Zhai (2011) investigated the applicability of the fixed threshold for extreme hourly precipitation over eastern China, and defined the 95th percentile as the relative threshold for extreme hourly precipitation. Moreover, Zhang and Zhai (2011) analyzed the distribution and variation trend of extreme precipitation during the past 40 years, suggesting that the rainfall amount and rainfall frequency have consistent distribution patterns in variation trend; that is, significant increase in Northeast China and the mid-lower reaches of Yangtze River, and decrease in northern China.

In the respect of scientific issues about extreme precipitation, most studies concentrate on the variation trend of extreme precipitation, while fewer studies have emphasized the characteristics of rainfall event itself. Calculating the crucial parameters of extreme precipitation processes and understanding the generality of extreme precipitations are a foundation not only important to mastering the characteristics of such events, but also key to making better forecasts and predictions in disaster prevention and mitigation.

Aiming at addressing the above questions, this paper fits the long-term hourly rainfall data with the Generalized Extreme Value (GEV) distribution, and analyzes the duration and seasonal characteristics of extreme precipitation over China. The GEV distribution has a solid mathematical foundation, which could objectively extrapolate the extreme values and precisely identify the intensity thresholds for rainfalls with different return periods. Meanwhile, the results provide instructions to the selection of extreme events, and offer valuable references at corresponding level (N-year return period) in hydrological engineering, infrastructure planning, and other relevant fields. Furthermore, long-term hourly precipitation data guarantee the precision of precipitation intensity, as well as provide sufficient samples (50 annual extremes) to the GEV distribution. Based on hourly intensity thresholds and hourly precipitation data series, the characteristics of extreme precipitation events will be analyzed on hourly scale in this paper.

2. Data and methodology

The dataset of hourly raingauge records at 575 stations over mainland China from 1954 to 2010 has been used in this study. This dataset was obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA) and has undergone strict quality control, including consistency test and extreme value test for climate background and single station. Further quality control (Li et al., 2011) has also been applied as follows: daily rainfall amount (Rh) is calculated by the hourly data and is compared with the record of daily rainfall amount (Rd); if |Rh − Rd| > Rd/10, the records of hourly data for this particular day are regarded as missing values; if effective observation is less than 15% of the annual total, the hourly records in this year are marked as missing values. Finally, 321 stations without a missing year during 1961–2010 were chosen to analyze the precipitation characteristics over mainland China. Besides, at each station, a rainfall event starts when measurable precipitation ($\geqslant$ 0.1 mm h^{-1}) occurs after 2 or more dry hours. Following Yu et al. (2007), the duration of a rainfall event is defined as the number of hours from the beginning to the end of the event, during which time there is no intermittence or at most a 1-h intermittence.

The first and foremost question in the study of extreme weather or climate events is the definition and selection of extreme events. This paper adopts GEV distribution (Coles, 2001) to identify the intensity thresholds of precipitation with different return periods. By taking Yueyang station as an example, the methodology is briefly illustrated here. Firstly, we find out the annual maximum of hourly precipitation amount ($R_{\rm AM}$), and depict its empirical distribution function by circles and corresponding lines in Fig. 1a. The minimum, maximum, and mean values of $R_{\rm AM}$ during 1961–2010 are 12.6, 90.0, and 36.11 mm h^{-1}, respectively. According to the classical theory of extreme value, the distribution of $R_{\rm AM}$ is calculated as follows:

$$G(x;\mu,\sigma,\xi) = e^{-(1+\xi\frac{x-\mu}{\sigma})^{-\frac{1}{\xi}}}, \quad (1)$$

where $\sigma > 0$ and G is the distribution of the generalized extreme value. Based on $R_{\rm AM}$ in the 50-yr period of 1961–2010, G can be obtained through maximum likelihood estimation; e.g., at Yueyang station, parameters $\mu = 30.701$, $\sigma = 10.012$, and $\xi = -0.025$. Meanwhile, the classical model of $R_{\rm AM}$ is calculated by using Eq. (1) and shown by the curve in Fig. 1a. Comparion of the statistical distribution and the model result shows that the distribution calculated from Eq. (1) can reasonably reproduce the key features of the empirical distribution, and thus is a reliable estimation of the distribution of $R_{\rm AM}$. Based on this curve,

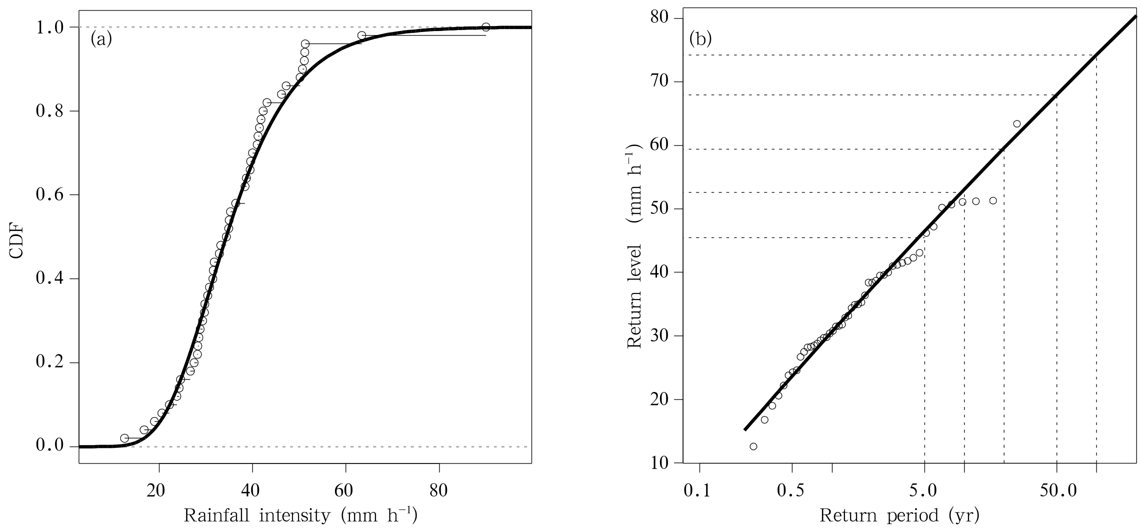

Fig. 1. (a) Cumulative distribution function of hourly precipitation during 1961–2010 at Yueyang station (hollow circles and horizontal lines are observation results; curves are estimation results of cumulative distribution function); (b) rainfall intensities on different return periods at Yueyang station (hollow circles are observation results, solid lines denote estimation results of cumulative distribution function, and dotted lines represent estimation results of 5-, 10-, 20-, 50-, and 100-yr return period from left to right).

it is convenient to identify the cumulative probability (vertical coordinates) corresponding to certain intensity (horizontal coordinates). Conversely, the intensity threshold for a specific probability or certain return period can be calculated from the inverse function of Eq. (1). Therefore, based on the empirical distribution and the GEV distribution, Fig. 1b shows the rainfall intensities on different return periods at Yueyang station, and the return periods of 5, 10, 20, 50, and 100 yr and their corresponding intensities (45.44, 52.62, 59.38, 67.94, and 74.24 mm h^{-1}) are indicated with dotted lines. In this way, the distribution of R_{AM} and the intensity threshold for the crucial return period is respectively estimated at 321 stations over China.

For the 50-yr period, the expected frequencies of rainfall events with return periods of 5, 10, 20, 50, and 100 yr are 10, 5, 2.5, 1, and 0.5, respectively. There might be some biases between expected frequencies and actual frequencies, and whether these biases are in the reasonable scope is an important criterion to test the reasonability of intensity thresholds. Figure 2 shows the statistical distribution of actual frequencies of rainfall events at the 321 stations. Average frequencies for the above return period are 12.59, 5.82, 2.76, 0.99, and 0.38, respectively. This result is close to the expected frequencies. The box at each return period covers at most 3 occurrences of extreme rain hours. The dispersion is relatively high at 5-yr return period; the frequency at one station reaches 22 occurrences there, but it falls back to 8 at 10-yr return period. It is worth noting that the dispersion is very low at 50-yr return period. There are 180 stations (accounting for 56.07% of the total) having 1 extreme rainfall event at 50-yr return period. The good coherence between actual frequency and expected frequency further proves the reasonability of the methodology.

3. Results

3.1 Distribution of thresholds

With the identified threshold, it is possible to select rainfall events at certain levels, and to analyze the various features of rainfall events. Since the rainfall events with 5-yr return period have the scarcity attribute of extreme events and contain more samples than the events with longer return periods, the following analysis on the features of extreme precipitation will focus on rainfall events with 5-yr return period. The thresholds of hourly intensity for 5-yr return

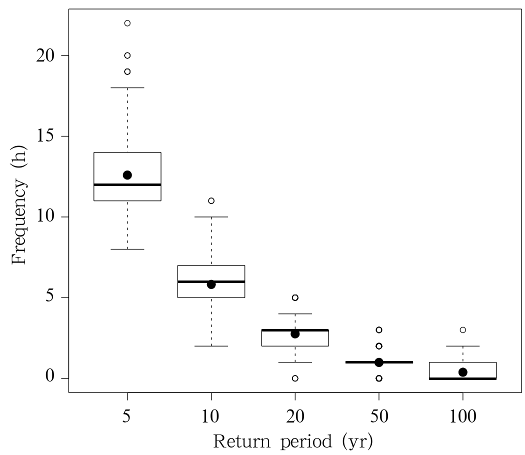

Fig. 2. Distribution of rainfall frequency (rainfalls are classified by threshold values for different return periods, abscissa represents rainfalls with 5-, 10-, 20-, 50-, and 100-yr return period, ordinate indicates statistical results of rainfall frequency (with unit of h as frequency also equals duration for consecutive hourly rainfalls) at 321 stations (h), thick lines are the medians of rainfall frequency at 321 stations, solid circles are mean values, top (bottom) edge of each box is rainfall frequency of the 75th (25th) percentile, hollow circles mark the frequency values 1.5 times higher than the height of each box).

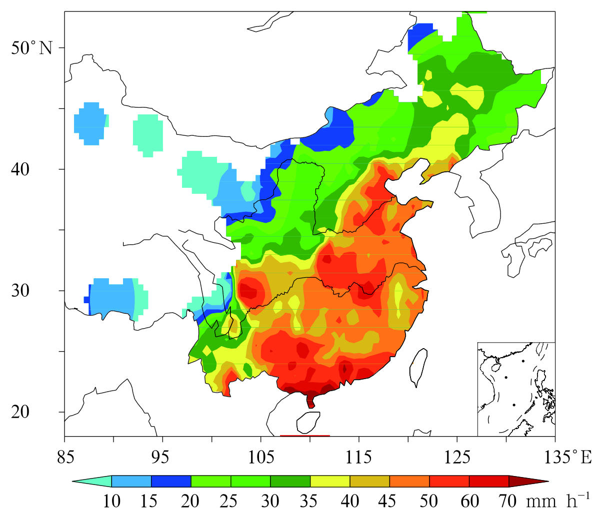

Fig. 3. Distribution of threshold values of hourly rainfall intensity (mm h^{-1}) of 5-yr return period.

period events present an inhomogeneous distribution over China. The maximum threshold among the 321 stations is 84.53 mm h^{-1}, while the minimum is only 4.56 mm h^{-1}. There are 8 (5) stations with threshold higher (lower) than 70 (10) mm h^{-1} and all of them are located in the southern coastal (Northwest) China. Figure 3 shows the distribution of intensity thresholds for extreme precipitation with 5-yr return period. A line from northeast to southwest separates China into a southeastern high-value area and a northwestern low-value area. Four large centers in the high-value area are located over North China, mid and lower reaches of the Yangtze River, southern coastal China, and west of the Sichuan basin. There is a relatively low-value belt in eastern China between 25° and 28°N.

3.2 Characteristics of extreme precipitation processes

Understanding the characteristics of extreme precipitation processes can provide valuable references to

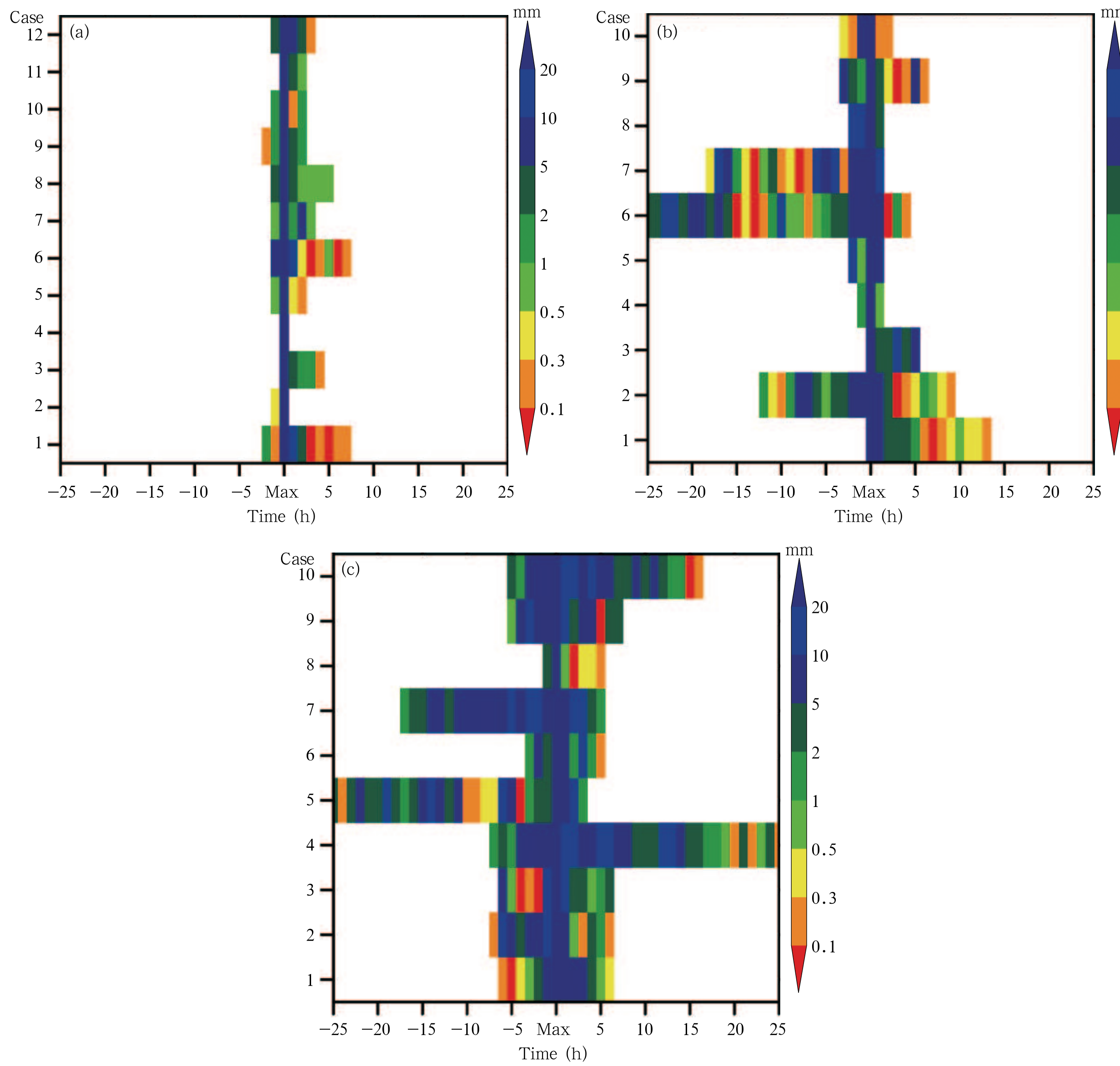

Fig. 4. Evolution of hourly precipitation intensity (mm h^{-1}) of 5-yr return period at (a) Weichang, (b) Yueyang, and (c) Shanwei stations (abscissa is converted to the relative time (h) to precipitation peaks, and ordinate represents different rainfall events).

weather forecast, disaster prevention, and damage alleviation. This section makes a comparison analysis on the characteristics of rainfall process among the three stations located in North China, the mid and lower reaches of Yangtze River, and southern coastal China, respectively. In Fig. 4, different colors are used to present features of the precipitation process with 5-yr return period at Weichang, Yueyang, and Shanwei stations. There are 12, 10, and 10 events reaching the standard of 5-yr return period at the three stations. The most evident differences among the three stations lie in rainfall duration and amount during the precipitation process. With relatively short duration in each event, Weichang station in Northeast China presents an average rainfall duration of 5 h over 12 events, and holds relatively weak intensities (except for the peak hour) with an average process rainfall amount of 44.78 mm only. Accompanied by longer rainfall duration, Yueyang station in central China has a 12-h average duration and a 112.44-mm process rainfall amount. Located in the southern coastal China, Shanwei station experiences rainfalls of more than 6 h in each event, and has average rainfall duration as long as 21.4 h. Moreover, the proportion of intense precipitation in Shanwei station is much larger than the other two stations. Consequently, contributed by both long duration and high intensity, Shanwei station has an average process rainfall amount of 250.04 mm.

The remarkable differences among the three stations suggest that the characteristics of rainfall events are regionally dependent. As an important aspect of the regional climate feature, the rainfall duration has attracted some concerns (Yu et al., 2007; Li et al., 2011). But the duration of extreme precipitation is rarely discussed. As shown in Fig. 5a, there are 66 stations having an average duration shorter than 6 h, which are located in Northeast China, northern and eastern North China, Northwest China, and western Southwest China. Meanwhile, 252 stations have an average duration longer than 6 h, among which 44 stations are longer than 12 h. The high value areas are mainly distributed in coastal regions, the Yangtze River valley, and east of the Tibetan Plateau. The abundant water vapor supply over the coastal regions and the unique altostratus and nimbostratus to the east of the Tibetan Plateau provide favorable background for occurrences of long-duration extreme precipitation (Yu et al., 2004). Another important feature is the duration from precipitation occurrence to precipitation peak (DOP). DOP reflects the speed of precipitation development and is directly connected to the warning and response time of disasters. The geographical distribution of DOP is shown in Fig. 5b. There are 30 stations with a DOP longer than 6 h, and most of these stations are located in coastal regions. Meanwhile, 71 stations present a DOP shorter than

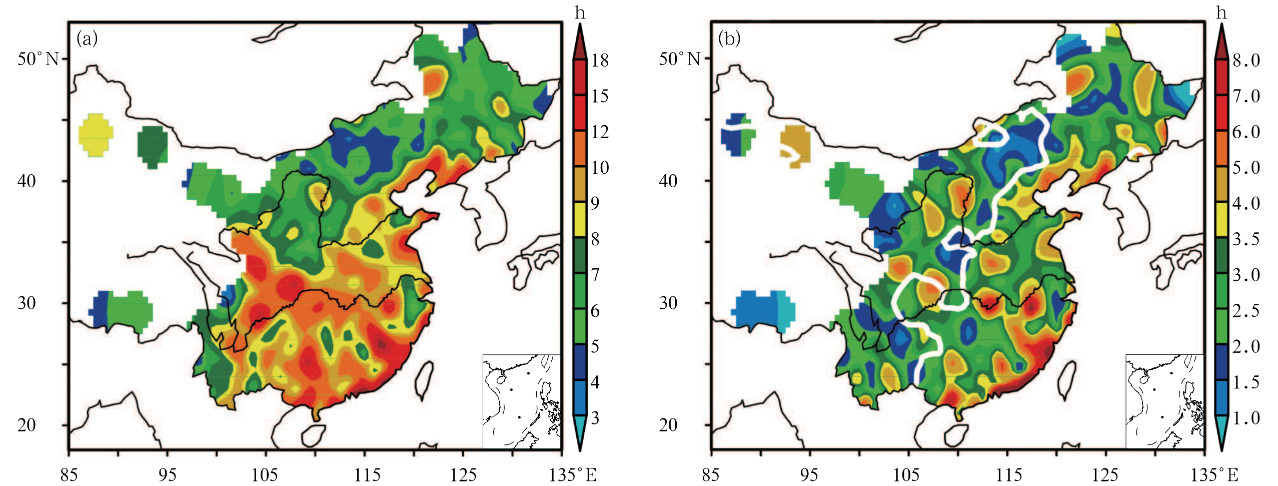

Fig. 5. (a) Distribution of average rainfall duration (h) for precipitation events of 5-yr return period; (b) as in (a), but for duration from precipitation occurrence to precipitation peak (h). White thick curve denotes the topographic height contour of 1200 m.

2 h, and the low value centers can be connected by the topographic height contour of 1200 m (the white thick curve). Spreading along with the Great Khingan Mountains, Taihang Mountains, Wu Mountains, and Xuefeng Mountains, these low value stations are located on the boundary line between the second and the third terrain ladders, and other sporadic low value stations mostly lie to the east of complex terrains. The high value center of average duration in the Sichuan basin in Fig. 5a disappears in Fig. 5b. At Yibin station, which is located on a large terrain gradient, the average duration is as long as 15.4 h, while the DOP is only 1.7 h. These results suggest that the rapid development of extreme precipitation is possibly related to topographic effects. Since geographical regions with complex terrains always have a potential danger of geological disasters, the fast development of extreme precipitation could cause landslides or debris flows in these regions. Therefore, it is necessary to make a further analysis on the processes and mechanisms of precipitation in these regions.

3.3 Seasonal characteristics of extreme precipitation

In most regions of China, precipitation presents remarkable seasonal variations, i.e., the amount and intensity of precipitation are often concentrated in certain period of a year. This notable seasonal change also exists in extreme precipitation, making the occurrence date another important feature of extreme precipitation. In order to represent the seasonal characteristics of extreme precipitation, we identified the occurrence date of precipitation with 5-yr return period, and then found the date of the first and the last occurrence time.

The dashed line in Fig. 6a illustrates the probability density distribution of the first occurrence time of 321 stations over China. Spreading from spring to summer, the dispersion of the first occurrence date among stations is relatively large. At 52 stations, the annual first extreme precipitation occurs in April. It is also found that 84 stations have the first occurrence of extreme precipitation in May. June has the biggest number of stations (130 stations), and the peak of probability density appears in its later period. After July, the probability density curve drops fairly fast. Figure 6b presents the distribution of the first occurrence time of extreme precipitation. Spring dominated stations are located in South China, corresponding to the spring persistent rainfall there with long durations

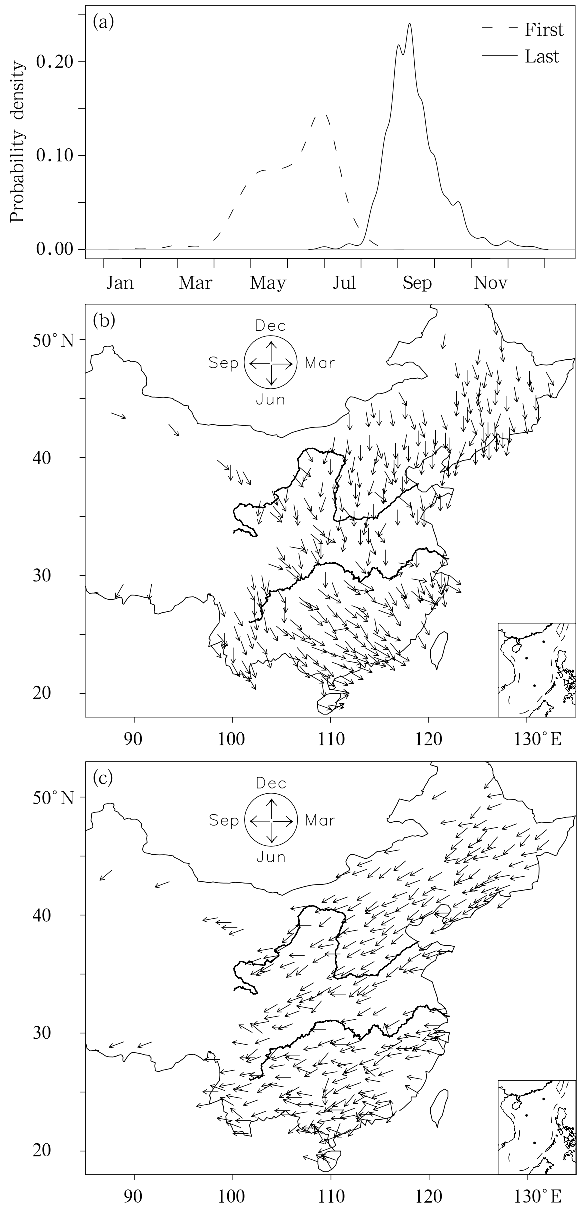

Fig. 6. (a) Probability density distribution of the first occurrence time (dashed line) and the last occurrence time (solid line) of extreme precipitation with 5-yr return period. (b) Distribution of the first occurrence time of precipitation with 5-yr return period (arrows point to the season of rainfall occurrence at 10-day intervals). (c) As in (b), but for the last occurrence time.

(Tian and Yasunari, 1998; Wan and Wu, 2007). Most stations in North China and Northeast China have its first extreme precipitation around the end of June.

Compared to the first occurrence time, the probability density distribution of the last occurrence time has a higher peak and a more concentrated distribution. At 80% stations, the annual last extreme precipitation occurs from mid August to late September. Correspondingly, vector directions of the last occurrence time are highly consistent (Fig. 6c). Only a few stations located in the coastal regions and Southwest China have extreme precipitation until after October. Since understanding of the general range of the occurrence date of extreme precipitation could provide better monitoring and warning of disastrous weather, it is especially necessary to conduct intensive case analyses and diagnoses on extreme precipitation events that happen outside the traditional flood season.

4. Conclusions

Using hourly station raingauge data during the past 50 years, the intensity thresholds of extreme precipitation are identified through Generalized Extreme Value (GEV) distribution, and the characteristics of extreme precipitation events are analyzed in this paper. The major conclusions are summarized as follows.

(1) Using the GEV method, the intensity thresholds of hourly precipitation can be reasonably and objectively identified.

(2) The distribution of thresholds of extreme precipitation with a 5-yr return period is complicated and regionally dependent. Generally, the thresholds in Southeast China are much higher than that in Northwest China.

(3) North China has a short average duration of extreme precipitation, while the southern coastal regions, the Yangtze River valley, and the eastern edge of the Tibetan Plateau present long average durations of above 12 h. In areas with great altitude differences and complex geographic conditions, the extreme precipitation events usually experience a rapid development from its occurrence to peak.

(4) The occurrence of extreme precipitation has significant seasonal variations. Some stations in southern China record extreme precipitation in as early as April, while most parts of northern China have the annual first occurrence of extreme precipitation until the end of June. The annual last extreme precipitation events are concentrated in August and September.

The intensity thresholds of extreme precipitation provide an objective standard and reliable criterion to define hourly extreme precipitation over China. The analyses in this paper are based on station raingauge data, and the understanding of rainfall events can be further enriched with the combination of atmospheric circulation data, radar data, and satellite remote sensing data. Circulation data could supply three-dimensional structure and evolutionary feature of extreme precipitation, and offer information on the large-scale background and influencing system, such as the typhoon in coastal regions, the vortex downstream of the Tibetan Plateau, and the mesoscale advection on the Meiyu front. The remote sensing data can provide information about rainfall structure and cloud microphysics, which makes it possible to investigate the precipitation and cloud features at higher temporal and spatial resolutions. With a full combination of both macroscopic and microscopic information, the cognition of extreme precipitation events would be further enhanced.

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