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Persistent extreme precipitation events in China during 1951–2010

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ABSTRACT: Persistent extreme precipitation events (PEPEs) in China are investigated in the context of a new definition that considers both the persistence and the extremity of daily precipitation at individual stations. An identification method for regional PEPEs is designed based on joint application of this definition and a spatial contiguity criterion. Between 1951 and 2010, individual-station-based PEPEs occurred mainly in Central–Eastern China (26–34° N) and South China (south of 26° N). Relatively few PEPEs were observed in the northern part of China (north of 34° N). Individual-station-based PEPEs in Central–Eastern China and South China were also typically of higher intensity and longer duration than those observed in the northern part of China. Altogether, 74 regional events are identified. The stations involved in these regional events correspond to the centers of intense precipitation associated with the event. These areas are prone to severe flooding. Of the 74 identified PEPEs, 70 occurred in the central and southern parts of eastern China (primarily the Yangtze–Huai River Valley and South China). Only 4 events occurred in the northern part of China. Regional PEPEs occurred more frequently after 1990, with higher mean intensity, longer mean duration, and larger affected areas. The 74 regional PEPEs are classified and analyzed according to occurrence time, geographical location, and the influence of typhoons.

KEY WORDS: Persistent extreme precipitation · Regional event · Disaster · Climate change

1. INTRODUCTION

Many studies of climate extremes (e.g. Karl & Knight 1998, Zhang et al. 2000, Klein Tank & Können 2003, Zhai et al. 2005, Alexander et al. 2006, Klein Tank et al. 2006) are based primarily on analysis of an isolated 1 d event. The Expert Team on Climate Change Detection and Indices (Peterson et al. 2001) has used daily temperature and precipitation data to develop indices that enable monitoring of extreme weather and climate events. These indices are widely used in climate change studies (Easterling et al. 2000); however, they are often designed to identify 'moderate extreme events,' which only represent exceedance of a certain relative threshold (typically defined as a percentile value) but are not necessarily disaster-related. Many weather-related disasters are associated with long-lasting (persistent) extreme events, which can cause (directly or indirectly) substantial socio-economic damage (Easterling et al. 2000). For example, a 12 d extreme precipitation event in 1998 triggered a severe flood in the Yangtze River Valley, resulting in a death toll of more than 3000, and direct economic losses of 250 billion Yuan RMB (US$40 billion; Lu 2000). It is therefore logical to develop new indices that explicitly account for extreme phenomena that occur over longer time scales (Zhang et al. 2011).

Multi-day extreme events have received substantial scientific attention. Some studies have identified multi-day extreme events based on the duration of rainfall events (Karl & Knight 1998, Dairaku et al. 2004, Junker et al. 2008). Others have focused on events for which the total precipitation amount over a time period of N days exceeds a certain percentile, or

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occurs with a certain recurrence interval (Kunkel et al. 1999, Peterson et al. 2001, Kunkel 2003, Schmidli & Frei 2005). N is usually artificially prescribed. These identification methods have then been used to study changes in the frequency, intensity, and duration of multi-day extreme events (e.g. Zolina et al. 2010, Groisman et al. 2012).

Precipitation totals alone are not adequate for depicting a persistent extreme precipitation event (PEPE). Several recent studies have also examined the spatial coherence of extreme precipitation among neighboring stations (Tang et al. 2006, Ren et al. 2012); however, these studies have mainly focused on transient multi-day intense precipitation events, which move from place to place. Such transient events may be less likely to cause disasters than stationary multi-day extreme events.

This study focuses on the disaster-causing capability of PEPEs. A new definition of PEPEs based on precipitation data at individual meteorological stations is given. The frequency, duration, and intensity of these individual-station-based PEPEs are investigated. An identification method for regional PEPEs is then designed on the premise of temporal persistence at a group of nearby stations, followed by a discussion of the distribution and recent climate variability of these regional events. The regional PEPEs are described in detail, providing a base to study the underlying mechanisms of these high-impact precipitation events.

2. DATA AND METHODS

2.1. Data

This study is based on daily precipitation amounts at 756 stations with detailed metadata provided by the Climate Data Center (CDC) of the National Meteorological Information Center, China Meteorological Administration (available online at http://cdc.cma.gov.cn/home.do, in Chinese). The data set provides geographical coverage of China during the period 1951–2010, and was subjected to some rigorous quality control procedures by the CDC during March 2011–June 2012, including completing some missing observations and rectifying suspect/wrong observations. This data set comprises both reference stations and basic stations in China, and is the best currently available for climate studies in China (Zhai et al. 2005). Missing values are set as −999 to ensure that they have no influence on the identification of persistent events.

China is a monsoon-influenced country, with intense precipitation occurring primarily during the warm season (Ding & Chan 2005). This study therefore focuses on the period from April to October (the warm season). In Eastern China (east of 95° E) where warm-season extreme daily precipitation amounts >50 mm have predominantly occurred (Tao 1980), the number of stations increased over time during 1951–1960, reaching 600 in 1961 (and has almost stabilized at this number since then; Fig. 1. These 600 stations are included in the identification of PEPEs.

2.2. Identification of PEPEs

The procedure has 2 stages: (1) identification of individual-station-based PEPEs; (2) identification of regional PEPEs based on the spatial contiguity of individual-station-based events.

2.2.1. Individual-station-based PEPEs

Considering the high potential impact of extreme events, the absolute threshold for extreme precipitation is defined to be 50 mm d^{-1}. This threshold is widely used by operational meteorological services in China to indicate precipitation that is intense enough to greatly influence human activity, or trigger human disasters. A daily precipitation amount of 50 mm exceeds the 95th percentile of precipitation at most (>90% of) stations in China during the warm season. Here, the absolute threshold is used also because of its importance in considering the adaptive capacity of societies toward extreme events (Beniston et al. 2007).

To comprehensively account for both the persistence and accumulated amounts of extreme precipitation, a PEPE is defined as an event that meets the following criteria: (1) the daily precipitation amount

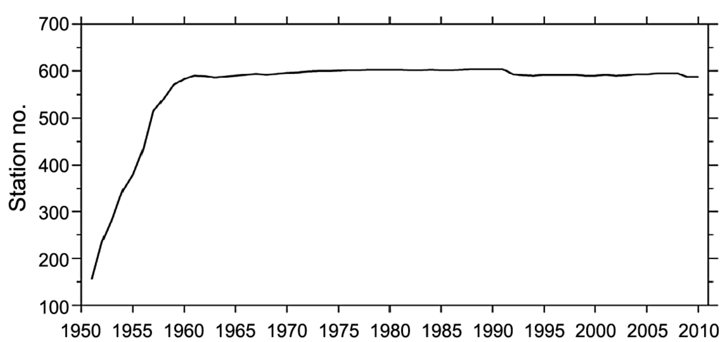

Fig. 1. Number of stations in Eastern China (east of 95° E) during the warm season from 1951–2010

must exceed 50 mm for at least 3 consecutive days. The event comes to an end when the daily precipitation amount is <50 mm for the following 2 consecutive days. The requirement for the initial 3 d (the preliminary period) ensures that all PEPEs must persist for at least that long. (2) The extreme precipitation is then allowed to break for at most 1 d before continuing. This second requirement guarantees that the break is not too long and that the accumulated precipitation amount over the entire event is taken into account. If the extreme precipitation process breaks for 2 or more days, the PEPE is considered concluded.

For example, consider an 8 d precipitation event with daily precipitation amounts of 10, 50, 50, 50, 45, 155, 12, and 15 mm. According to the above definition, the duration of the event is 5 d (from the second through the sixth day), and the accumulated precipitation amount is 350 mm. If the event were not allowed to break, the event would only last for 3 d (from the second to the fourth day), with an accumulated precipitation amount of 150 mm. The fifth and sixth day would then be disregarded, even though they are very important to the disaster potential of the event.

Multi-day extremes are often identified using an N-day sliding window technique (Osborn & Hulme 2002, Kunkel 2003). This type of method only accounts for N-day precipitation totals and does not guarantee the persistence of extreme precipitation throughout the process. For example, a 5 d event with daily precipitation of 0, 0, 200, 0 and 0 mm might be selected as a multi-day extreme even though extreme precipitation only occurred on the third day. Furthermore, if the selected N is too short, a PEPE of long duration would be artificially separated into several episodes. The integrity of PEPEs can therefore not be ensured using this technique. By contrast, the definition used here successfully identifies periods of arbitrary length composed of consecutive high-impact days.

The guarantee of persistence of extreme precipitation makes the definition in this study more rigorous than that formulated by Lu et al. (2011). Likewise, the events identified using this definition are more meaningful in the context of weather-related disasters. The definition provided by Lu et al. (2011) is better suited to the study of droughts (Lu 2009).

PEPEs of at least 3 d duration are usually associated with long-lived (several days) anomalies in the large-scale circulation (Samel & Liang 2003, Hong et al. 2011). These events are capable of inducing severe flooding at regional scales (Galarneau et al. 2012). Although some 1 d extremes may also cause substantial damage, they are usually local phenomena caused by meso-scale convection (Ogden et al. 2000, Zanon et al. 2010). These types of extremes are beyond the scope of this study.

2.2.2. Regional events

Identification of regional PEPEs requires consideration of 2 factors: temporal persistence and spatial contiguity. The method used to identify regional PEPEs is therefore based on the temporal persistence of extreme precipitation at a group of nearby stations. This approach differs from previous studies that focused on spatial extent (Tang et al. 2006, Ren et al. 2012). The method groups all neighboring individual-station-based PEPEs with durations that overlap for at least 1 d into 1 regional-scale event. Every station involved in the regional PEPE must meet the criteria for an individual-station-based PEPE. This requirement guarantees that the identified event was anchored within a relatively concentrated region with multiple affected stations. Grumm & Hart (2001) noted that the extreme weather events with the greatest economic and human impact are typically distinguished by either their intensity or their areal coverage. The method used here aims to account for both of these characteristics.

The method is implemented as follows.

Step 1. Select individual-station-based PEPEs with at least 1 d of temporal overlap. Gather these events into an ensemble based on the initial date.

Step 2. Assess the spatial contiguity of the individual events within the ensemble identified in Step 1. The core region is defined as any group of neighboring stations located less than 200 km from each other.

Step 3. Check again that the individual events retained in Step 2 contain at least 1 d of temporal overlap, since some stations in the ensemble may have been removed.

These 3 steps result in the identification of a regional PEPE if the final core region contains at least 3 stations. The steps are then iterated using the individual-station-based events that are not accounted for by any previously identified regional event until no new regional events can be identified.

Taking a regional event during 7–9 August 1956 as an example (Table 1): 3 individual-station-based events were firstly gathered into an ensemble considering temporal overlaps during their durations. These 3 stations constituted the core region according to the spatial contiguity criteria. Afterwards, the temporal overlap of their durations was checked again. These 3 stations were finally retained and a regional event was identified.

Table 1. Regional persistent extreme precipitation case during 7–9 August 1956

Station	Longitude (°E)	Latitude (°N)	Accumulated precip. (mm)
59644	109.1	21.3	303.6
59632	108.4	21.6	223.3
59626	107.6	21.3	389.4

2.3. Methods for trend estimation

The number of extreme events does not follow a normal distribution (Zhai et al. 2005); linear regression is therefore not very appropriate to estimate trends of PEPEs. Trends of different parameters of regional PEPEs, such as frequency, duration, intensity, and affected area can be estimated using the Kendall's tau-based slope estimator (Sen 1968). This method is non-parametric and does not assume the distributional form for the data under investigation. In addition, it is not sensitive to outliers. The fact that autocorrelation may render the significance test of a trend unreliable is taken into account by performing an iterative procedure introduced by Zhang et al. (2000) and further refined by Wang & Swail (2001). Monte Carlo simulation indicates that this procedure is more appropriate for trend detection (Zhang & Zwiers 2004). The procedure outlined by Wang & Swail (2001; see their Appendix A) is adopted in this study. The statistical significance of the trend is assessed based on Kendall's tau test at the 5% level.

3. CLIMATE FEATURES OF PEPES

3.1. Individual-station-based events

3.1.1. Seasonality

PEPEs occur principally from April through June in South China (south of 26° N), especially in June (figure not shown), corresponding to the pre-flood season of South China. June and July are the prime periods when PEPEs occur in the Yangtze-Huai River Valley and in regions immediately south of the Yangtze River. The occurrence peaks in June, consistent with the 2 mo rainy season during June–July, known as the Mei-Yu period (Ding & Chan 2005). The events in northern China (north of 34° N) occur in July and August. South China experiences another period of frequent PEPE occurrences in the post-flood season, including August, September, and October, during which time typhoons may be a key factor.

3.1.2. Frequency

Individual-station-based PEPEs are rare throughout most of China, with no events detected in many western regions (Fig. 2). In the regions where PEPEs occur, the lowest frequencies are found in the northern part of China and the highest frequencies are found in the southern part of China. Several stations in the northern part of China recorded only 1 PEPE between 1951 and 2010. PEPEs occurred most often in the Yangtze-Huai River Valley, in the regions immediately south of the Yangtze River, and in South China. The eastern part of the Sichuan Basin also experienced PEPEs relatively frequently. The station at Dongxing in Guangxi province experienced the most PEPEs, with a total of 34 events in 60 yr. Only 17 stations experienced >10 PEPEs between 1951 and 2010. Most of these stations are located in South China.

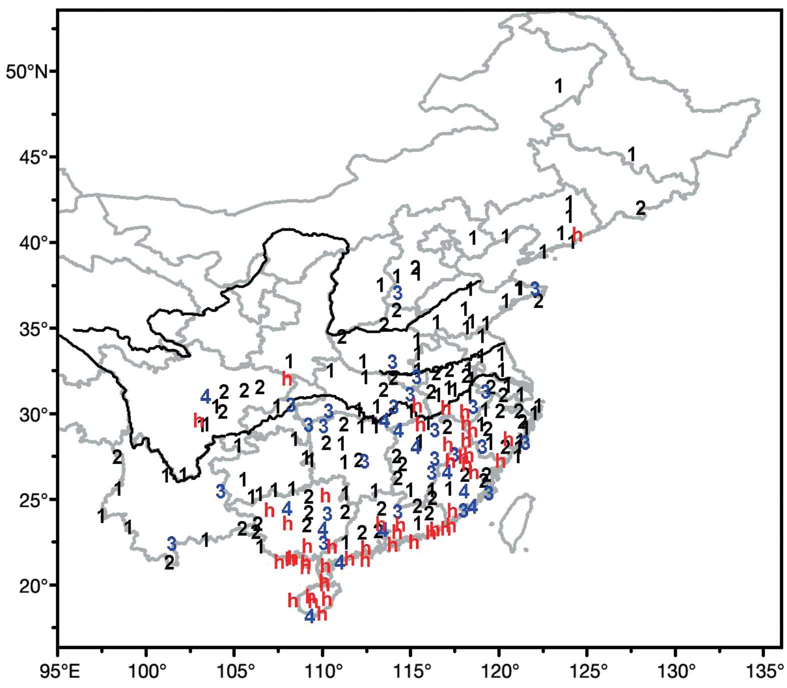

Fig. 2. Frequency of individual-station-based persistent extreme precipitation events. The colors and numbers indicate the number of events identified between 1951 and 2010 (1–2 events in black, 3–4 events in blue, and red 'h' representing high frequencies ≥5). Black lines: major rivers; gray lines: provinces

3.1.3. Duration

Most (79%) of the events lasted for a total of 3 d (Fig. 3a). Longer-duration events are less frequent (11% lasted 4 d and 10% lasted 5 d or longer) and mainly occurred in the southern part of China (Fig. 3b–c). Fig. 3d shows that the events with the longest duration (5 d or longer) primarily occurred either in the middle–lower reaches of the Yangtze River or in South China. The longest-lasting event lasted for 12 d. This event occurred at Wu-Yi Mountain station from 13–24 June 1998, with an accumulated precipitation amount of 1021.2 mm.

3.1.4. Intensity

The intensity of the events is described by calculating the equivalent days of rainstorm as:

$$I = \frac{\text{Total precipitation amount}}{50} \quad (1)$$

The criteria used to identify PEPEs ensure that every event is intense enough to cause flooding; however, the events may still be classified according to their relative intensity. Fig. 4a shows the average intensity of the PEPEs observed at each station. The average intensity in equivalent days is >5 at most stations. A value of 5 indicates that the average event brought approximately 250 mm of precipitation. The average intensity index is 7 or larger at a number of stations in the southern part of North China, in the Yangtze–Huai River Valley, and in some parts of South China. This means that on an average, the events in these regions brought approximately 350 mm of precipitation. Such intense precipitation is very likely to trigger severe flooding. More intense events (Fig. 4c,d) tended to occur in the

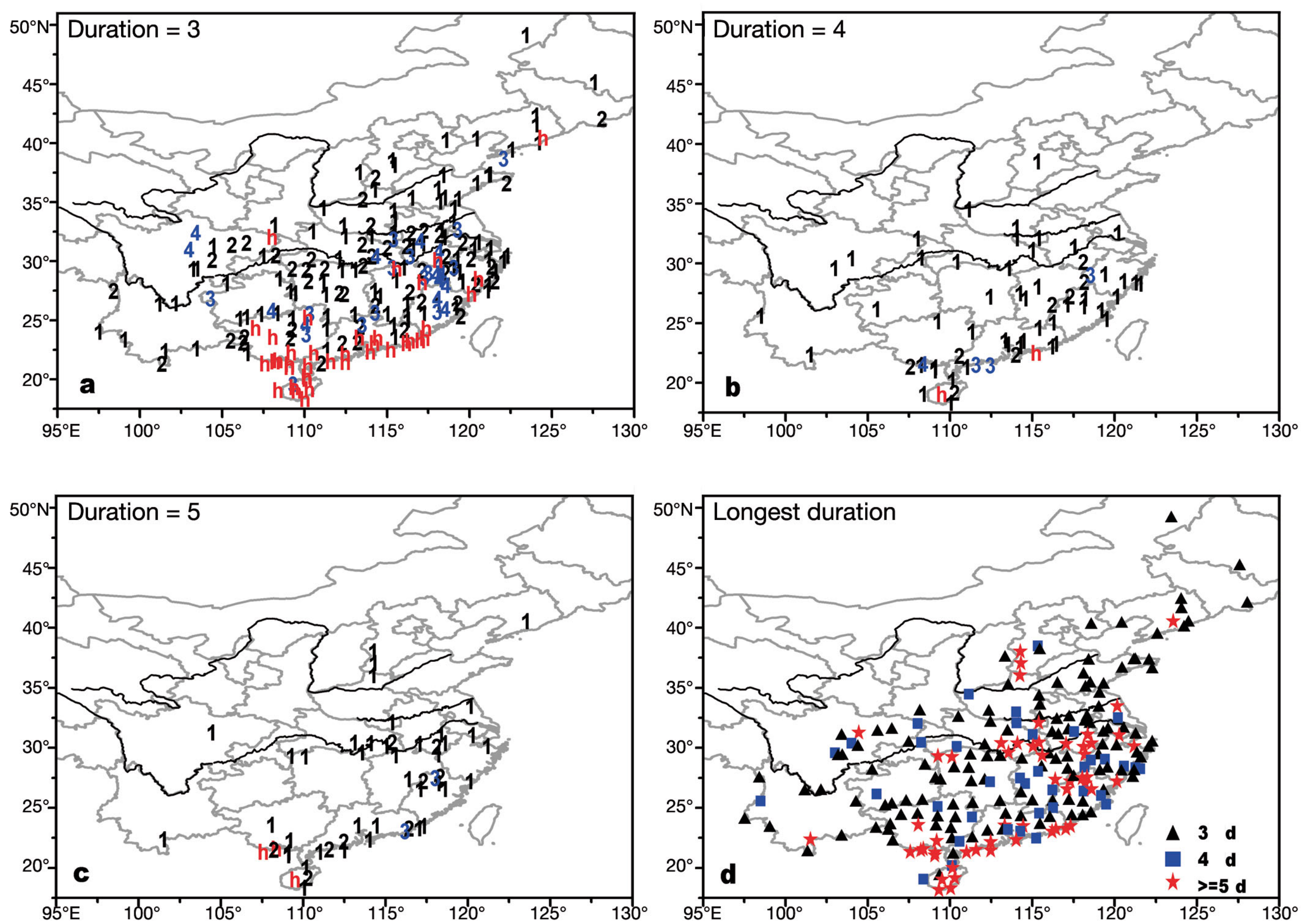

Fig. 3. Duration of individual-station-based events, showing frequencies of events with a total duration of (a) 3 d, (b) 4 d, and (c) ≥5 d. (d) The longest duration observed at each station. The numbers and symbols used in (a–c) are the same as those used in Fig. 2. The triangles, squares, and stars in (d) represent durations of 3 d, 4 d, and ≥5 d, respectively

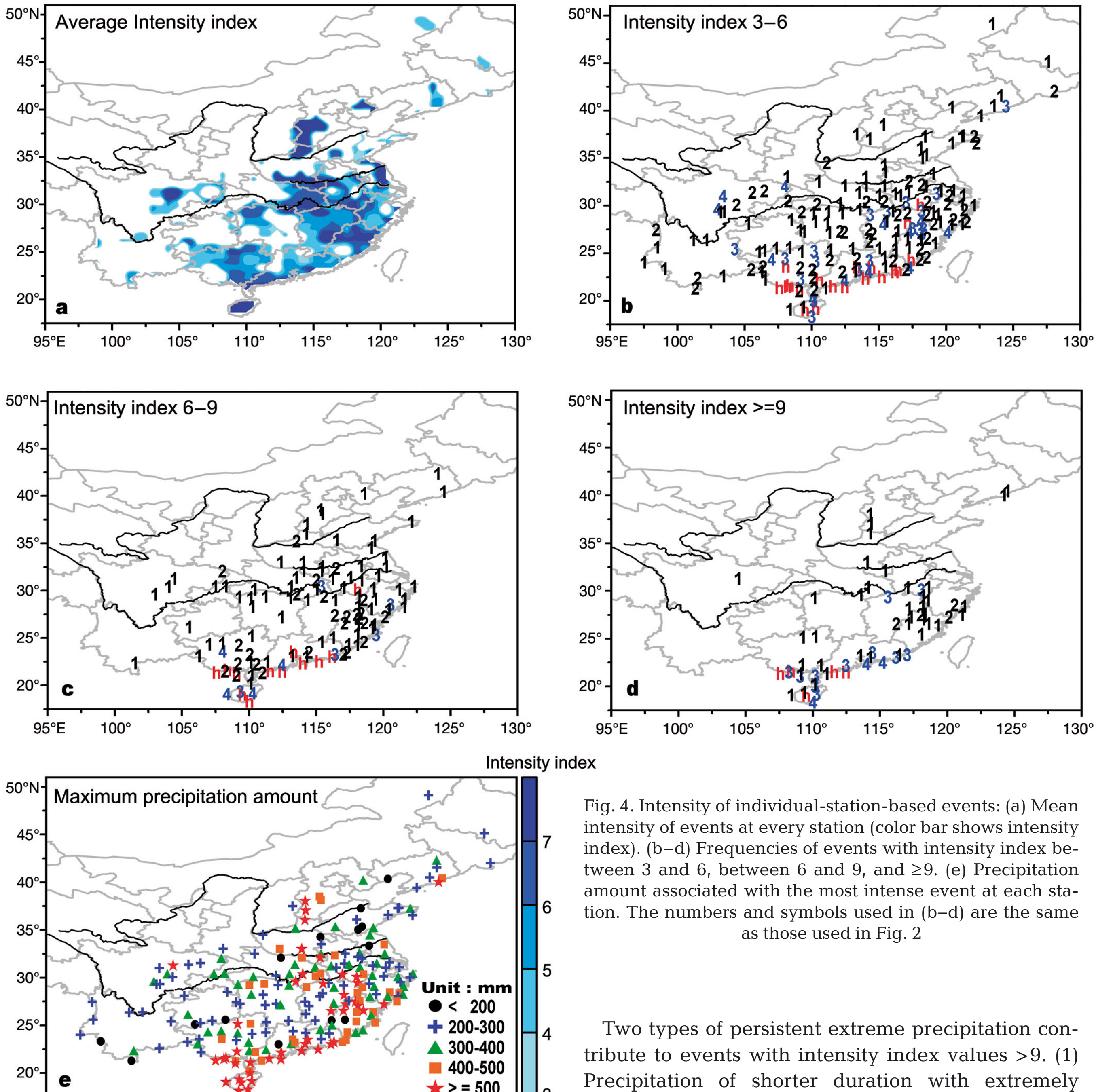

Fig. 4. Intensity of individual-station-based events: (a) Mean intensity of events at every station (color bar shows intensity index). (b–d) Frequencies of events with intensity index between 3 and 6, between 6 and 9, and ≥9. (e) Precipitation amount associated with the most intense event at each station. The numbers and symbols used in (b–d) are the same as those used in Fig. 2

Yangtze–Huai River Valley, the regions immediately south of the Yangtze River, and South China, with the most intense events concentrated in South China and the lower reaches of the Yangtze River (Fig. 4d). A number of the events in South China were caused by typhoons or the remnants of typhoons, which can result in large-scale damage in a relatively short time (Chien & Kuo 2011).

Two types of persistent extreme precipitation contribute to events with intensity index values >9. (1) Precipitation of shorter duration with extremely intense precipitation rates. For example, a 5 d event at Qionghai from 3–7 October 2010 brought 1358.0 mm with successive daily precipitation amounts of 91.9, 228.8, 614.7, 293.7, and 128.9 mm. (2) Precipitation of longer duration. An example of this type is the event during 13–24 June 1998 at Wu-Yi Mountain, during which 1021.2 mm of precipitation fell over 12 d. Fig. 4e shows the amount of precipitation accumulated during the most severe event observed at each station. Events for which accumulated precipitation exceeded 500 mm occurred predominantly in

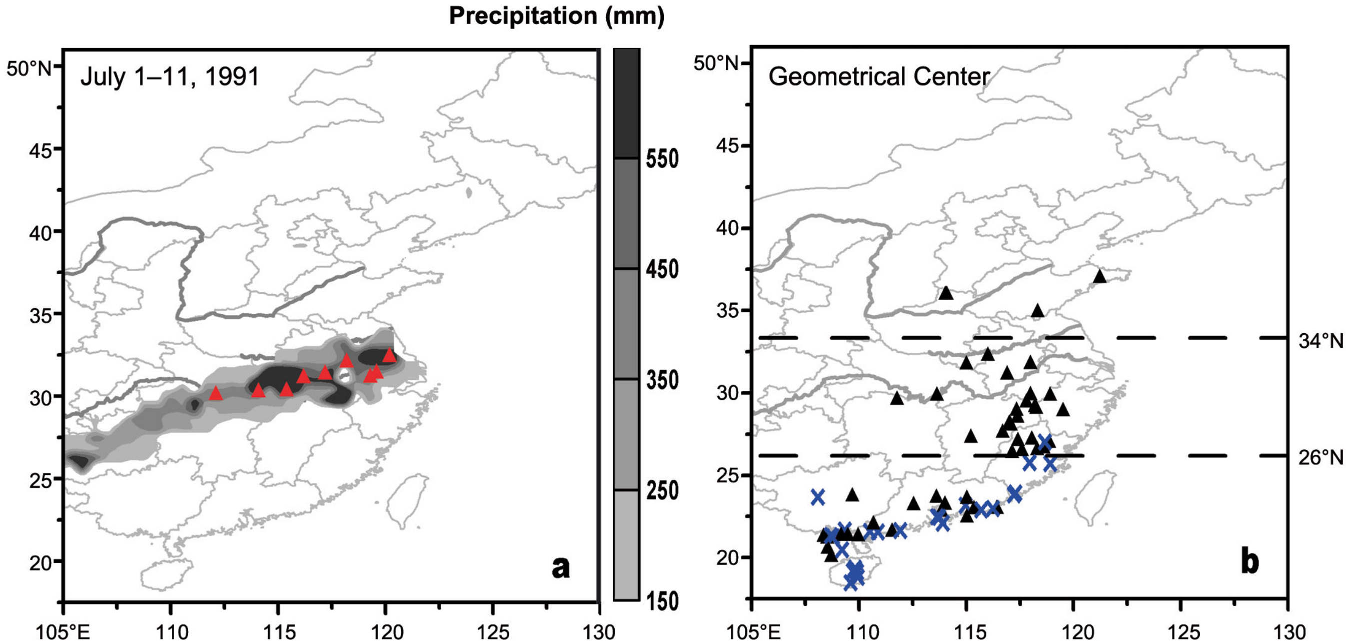

Fig. 5. (a) Example of regional persistent extreme precipitation events (PEPEs), with the involved stations marked by red triangles. Shading indicates regions with accumulated precipitation amount in excess of 150 mm. (b) Mean locations of the geometric centers of the 74 identified regional PEPEs (crosses: events caused by typhoons and/or typhoon remnants; triangles: all other events)

the middle and lower reaches of the Yangtze River, northern Fujian province, and South China. This pattern resembles the distribution of the longest duration observed at each station (Fig. 3d), indicating that the duration of the PEPE was the principal causal factor for high impact events.

The highest intensity index was observed at Qionghai during the event mentioned above (3–7 October 2010), when precipitation equivalent to 27 rainstorms fell over only 5 d.

The average daily precipitation amount during PEPEs exceeds the 99th percentile of daily precipitation amount at each station during the warm season. The identified PEPEs are therefore of very small probability. Even though the seasonality of these events matches the seasonality of monsoonal precipitation, PEPEs represent anomalous extreme precipitation processes rather than common monsoonal precipitation events.

3.2. Regional events

A total of 74 regional PEPEs were observed in China during the period 1951–2010. Fig. 5a presents an example that occurred during 1–11 July 1991. This regional PEPE caused damage to an area of 11 260 000 ha with a death toll of 1800. Approximately 3 million houses were damaged or destroyed, and the economic losses totaled 70 billion Yuan RMB (US$11 billion). All of the stations marked in Fig. 5a experienced ≥3 consecutive days of extreme precipitation, and the duration of the extreme precipitation at neighboring stations overlapped for at least 1 d. The area covered by those stations corresponds well to the locations of the maximum precipitation amounts (over 550 mm).

Examination of the other identified regional events (not shown) indicates similar consistency between the locations of the involved stations and the centers of maximum precipitation amount. This consistency highlights the importance of persistent extreme precipitation in causing floods. These synoptic multi-day precipitation processes also affect other stations (Tang et al. 2006, Ren et al. 2012); however, either the intense precipitation at those stations lasts for only 1 d or the intensity is not high enough to cause disaster. The regions identified by this method are highly concentrated, and the requirement that every involved station observed at least 3 consecutive days of intense rain ensures that these stations represent the core area of the precipitation event (as displayed in Fig. 5a). This core area is most vulnerable to severe flooding.

Fig. 5b shows the mean locations of the geometrical centers of the 74 identified regional PEPEs. Most of these events occurred 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). Many of the events along the southeast coast were associated with typhoons and/or the remnants of typhoons. No regional events occurred in western China (west of 105° E).

3.3. Climate variability of regional PEPEs

The climate variability of various characteristics of regional PEPEs between 1951 and 2010 is shown in Fig. 6. The spatial extent of the affected area is calculated using a 'frozen grid' method (Jones et al. 1986), which is widely used in station data analysis (Zhai et al. 2005). The occurrence frequency of regional PEPEs varied on a decadal timescale, with higher frequencies after 1990 and from the mid-1950s to the mid-1970s. Only 5 regional events occurred between the mid-1970s and the mid-1980s. To eliminate the possible uncertainties caused by the inadequate number of stations during 1951–1960 (Fig. 1), the trend analysis is conducted during the period from 1961 to 2010. Table 2 lists trends for the frequency, intensity, duration, and spatial extent of regional PEPEs. Generally, the annual number of regional PEPEs increased with time between 1961 and 2010. These events also appear to last longer, be stronger, and affect larger areas. The trends of intensity, duration, and spatial extent of regional PEPEs are statistically significant at the 5% level. However, the trends in these parameters between 1961 and 1990 are much smaller (and not statistically significant). The significant positive trends over the study period may therefore be attributed primarily to the variations between 1991 and 2010. As shown in Fig.6, regional PEPEs occurred more frequently after 1990, with higher intensity (larger *y*-axis value), longer duration (red color), and larger affected areas (squares and crosses).

The 70 regional events that occurred in the southern part of China (south of 34° N) are divided into 3 categories based on timing, location, and the influence of typhoons: a Central–Eastern China (26–34° N) category (including the Yangtze–Huai River Valley and the regions immediately south of the Yangtze River), a South China category, and a typhoon-influenced category. Only 4 events are identified in the northern part of China over 60 yr, and their decadal variability is not analyzed here. Table 3 lists the occurrence frequencies of events in these 3 categories for each decade. Events in the Central–Eastern China and South China categories occurred more frequently before 1970 and after 1990. In fact, the total number of such events in the 2 decades after 1990 is more than the total number in the 4 decades before 1990. These events occurred much less frequently between 1971 and 1990, and then experienced the highest decadal frequency between 1991 and 2000. The events influenced by typhoons varied in a different way. The number of these events increased or stayed the same in each successive decade, with the largest occurrence between 2001 and 2010. Like the first 2 categories, the total number of regional PEPEs increased substantially after 1990 with the largest number occur-

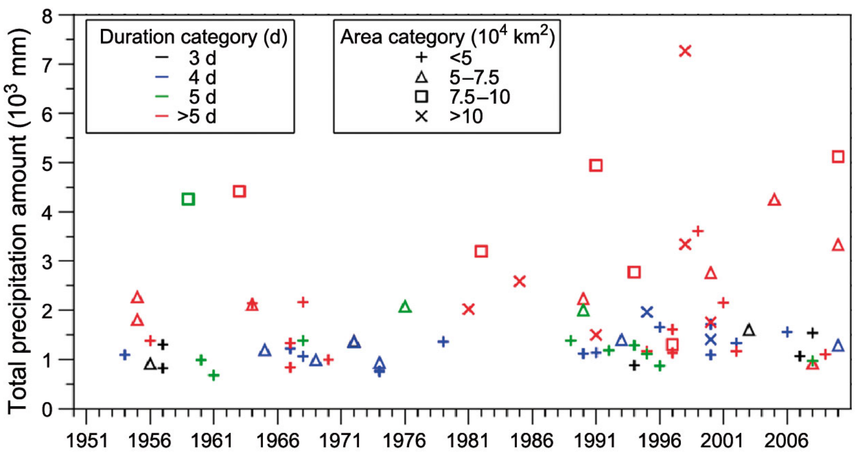

Fig. 6. Temporal variability of regional persistent extreme precipitation events grouped by intensity, which is calculated as the sum of the precipitation amount at every station included in the event divided by 1000. The duration of the event is indicated by the color, and the spatial extent of the affected area is indicated by the symbol

Table 2. Kendall's tau-based linear trends of various regional persistent extreme precipitation event characteristics per 10 yr time period. *Significant at the 5% level

	1961–2010	1961–1990
Frequency of occurrence	0.10	0.00
Duration (d)	0.50*	0.00
Intensity (mm)	246.86*	0.01
Affected areas (10^4 km^2)	1.00*	0.01

Table 3. Decadal occurrence frequency of regional events. C–E China: cases in Central–Eastern China; S China: cases in South China; Typhoon: cases influenced by typhoon and/or typhoon remnants

	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010
C–E China	2	6	1	2	9	5
S China	4	3	1	0	9	1
Typhoon	3	3	4	5	5	7
Total	9	12	6	7	23	13

ring between 1991 and 2000. Regional PEPEs occurred much less frequently between 1971 and 1990 relative to other decades during 1951–2010. Most of the events during this lull period belonged to typhoon-influenced category.

The detailed characteristics of these 70 regional PEPEs are summarized in Tables A1–A3 in the Appendix. These details including the beginning and ending dates of each PEPE, the duration, the number of affected stations and the size of the affected area, the approximate boundaries in latitude and longitude, and the maximum and minimum observed daily precipitation. These cases and categories lay the groundwork for further study into the underlying formative mechanisms.

4. DISCUSSION

Although the number of stations was much smaller during the period 1951–1960 than during other decades, 1951–1960 was not the decade with the lowest number of regional PEPEs. This indicates that there exists a significant decadal or inter-decadal variability in the number of regional PEPEs, with peaks during 1951–1970 and 1991–2010, and a trough during 1971–1990. In the most recent 2 decades, China has witnessed frequent PEPEs.

Precipitation records are missing from up to 40 stations in some years during the period from 1991–2010 (Fig. 1); of these, 30 stations (75%) are located in the west, northwest, and northeast China, where no regional PEPEs were observed according to our definition. The other 10 stations are located in Eastern China. A re-calculation of regional PEPEs was performed with these 40 stations removed to further evaluate the uncertainties in the trend estimation of regional PEPEs caused by the missing value in these stations. The same conclusions were achieved. Accordingly, these 40 stations have no influence on the estimation of the trends of regional PEPEs.

However, if a network with the 200 stations built before 1953 is used, only 6 regional PEPEs can be identified during 1951–2010 based on the adopted spatial contiguity criteria. Using a network of the 400 stations built before 1957, 21 regional PEPEs are identified. It is clear that the increase in the number of regional PEPEs is related to the increase of available stations from 1951–1960. Obviously, the affected area of PEPEs during 1951–1960 is very likely to be underestimated due to the sparse distribution of stations. After 1961, a consistent observation network of 600 stations in Eastern China was established, with more than 5 stations included in the grid of 200 × 200 km. This observation network is dense enough to assess the spatial contiguity based on the criteria adopted in this study, despite the fact that data are missing from some stations in some years. Accordingly, the trend analyses based on these 600 stations have eliminated the uncertainties caused by the inconsistency in station number, and the corresponding conclusions are reliable.

Considering the disaster-causing capability of PEPEs, the threshold and spatial contiguity criteria adopted in this study are mainly designed for Eastern China, where precipitation is abundant and floods occur frequently. Similar to the criteria described by Grumm & Hart (2001), the PEPEs in this region belong to rare meteorological–sociological events, rather than merely rare meteorological events. In western and northwestern parts of China, precipitation of 10 mm d^{-1} is rarely observed. Consequently, for the arid west region of China, the absolute threshold of 50 mm d^{-1} is not appropriate to identify extreme precipitation. Alternatively, a lower absolute threshold or a relative threshold based on a percentile value (for instance, 90th or 95th percentile) can be adopted to define PEPEs. Of particular note is that the PEPEs based on relative thresholds may not be capable of triggering disasters. Further, the spatial contiguity criteria for regional PEPEs in western China would also need to be adjusted based on the sparser spatial distribution of stations.

The conception and identification procedures of persistent extreme precipitation in this study can also be applied in other regions of the world based on their own precipitation thresholds and spatial contiguity criteria, which will be of practical value in understanding multi-day extreme events and related disaster impact assessment.

5. CONCLUSIONS

We created a definition for PEPEs that focuses on the potential for weather-related disaster. This definition requires that extreme precipitation (daily precipitation of ≥50 mm) persist for at least 3 consecutive days at an individual meteorological station. This definition accounts for both the persistence of intense precipitation and the accumulated precipitation amount, and therefore allows the identification of PEPEs with a high potential for causing substantial socio-economic damage. An identification method for regional PEPEs then follows with the added criteria of spatial and temporal coherence in individual-station-based events. The main conclusions are summarized as follows.

1. Individual-station-based PEPEs in China occurred most frequently in the Yangtze–Huai River Valley, the regions immediately to the south of the Yangtze River (26–34° N), and South China (south of 26° N). Relatively few such events are observed in the northern part of China (north of 34° N). The seasonality of these events closely corresponds to the seasonality of monsoonal precipitation. Individual-station-based events in the Yangtze–Huai River Valley, the regions south of the Yangtze River, and South China were typically more intense and lasted longer than those that occurred in the northern part of China.

2. A total of 74 regional PEPEs occurred in Eastern China between 1951 and 2010. Extreme precipitation persisted for at least 3 consecutive days at every station included in the regional events, and the spatial extent of such events is highly concentrated. These requirements for temporal persistence and spatial coherence ensure the identification of relatively stationary regional events, rather than transient events. These events occurred more frequently after 1990, with higher intensity, longer duration, and larger affected areas.

3. The 70 regional PEPEs observed in the southern part of China are divided into 3 categories: a Central–Eastern China category (including events in the Yangtze–Huai River Valley and the regions immediately south of the Yangtze River), a South China category, and a typhoon-influenced category. Events in the Central–Eastern China and South China categories occurred more frequently before 1970 and after 1990, particularly during the decade between 1991 and 2000. The frequency of the typhoon-influenced events increased monotonically during the study period. Overall, regional PEPEs occurred most frequently after 1990, with a peak between 1991 and 2000.

Each regional PEPE is described in detail. These detailed cases provide a basis from which to study the formative mechanisms and predictability of these high-impact precipitation events.

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LITERATURE CITED

Alexander L, Zhang X, Peterson T, Caesar J and others (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109, doi:10.1029/2005JE002462

Beniston M, Stephenson DB, Christensen OB, Ferro CA and others (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Change 81(Suppl):71–95

Chien FC, Kuo HC (2011) On the extreme rainfall of Typhoon Morakot (2009). J Geophys Res 116:D05104, doi:10.1029/2010JD015092

Dairaku K, Emori S, Oki T (2004) Rainfall amount, intensity, duration, and frequency relationships in the Mae Chaem watershed in Southeast Asia. J Hydrometeorol 5:458–470

Ding YH, Chan JC (2005) The East Asian summer monsoon: an overview. Meteorol Atmos Phys 89:117–142

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. Science 289:2068–2074

Galarneau TJ Jr, Hamill TM, Dole RM, Perlwitz J (2012) A multiscale analysis of the extreme weather events over Western Russia and Northern Pakistan during July 2010. Mon Weather Rev 140:1639–1664

Groisman PY, Knight RW, Karl TR (2012) Changes in intense precipitation over the central United States. J Hydrometeorol 13:47–66

Grumm RH, Hart R (2001) Standardized anomalies applied to significant cold season weather events: preliminary findings. Weather Forecast 16:736–754

Hong CC, Hsu HH, Lin NH, Chiu H (2011) Roles of European blocking and tropical-extratropical interaction in the 2010 Pakistan flooding. Geophys Res Lett 38:L13806, doi:10.1029/2011GL047583

Jones P, Raper S, Kelly P, Wigley T, Bradley R (1986) Northern hemisphere surface air temperature variations 1851–1984. J Clim 25:161–179

Junker NW, Grumm RH, Hart R, Bosart LF, Bell KM, Pereira FJ (2008) Use of normalized anomaly fields to anticipate extreme rainfall in the mountains of northern California. Weather Forecast 23:336–356

Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. Bull Am Meteorol Soc 79:231–241

Klein Tank A, Können G (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. J Clim 16:3665–3680

Klein Tank A, Peterson T, Quadir D, Dorji S and others (2006) Changes in daily temperature and precipitation extremes in central and south Asia. J Geophys Res 111: D16105, doi:10.1029/2005JD006316

Kunkel KE (2003) North American trends in extreme precipitation. Nat Hazards 29:291–305

Kunkel KE, Andsager K, Easterling DR (1999) Long-term trends in extreme precipitation events over the conterminous United States and Canada. J Clim 12:2515–2527

Lu E (2009) Determining the start, duration, and strength of flood and drought with daily precipitation: rationale. Geophys Res Lett 36:L12707, doi:10.1029/2009GL038817

Lu E, Higgins W, Mo K, Halpert M (2011) A method for identifying the events that can best become extremes. Proc 36th NOAA Annual Climate Diagnostics and Prediction Workshop, Fort Worth, TX, 3-6 October 2011. National Weather Service (NWS) Southern Region Headquarters and the National Climatic Data Center (NCDC) Climate Services Division, Fort Worth, TX, p 41–47

Lu RY (2000) Anomalies in the tropics associated with the heavy rainfall in East Asia during the summer of 1998. Adv Atmos Sci 17:205–220

Ogden F, Sharif H, Senarath S, Smith J, Baeck M, Richardson J (2000) Hydrologic analysis of the Fort Collins, Colorado, flash flood of 1997. J Hydrol (Amst) 228:82–100

Osborn TJ, Hulme M (2002) Evidence for trends in heavy rainfall events over the UK. Philos Trans R Soc Lond A Math Phys Eng Sci 360:1313–1325

Peterson TV, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N (2001) Report on the activities of the Working Group on climate change detection and related rapporteurs 1998–2001. World Meteorological Organisation Rep WCDMP-47, WMO-D 1071. WMO, Geneva

Ren F, Cui D, Gong Z, Wang Y and others (2012) An objective identification technique for regional extreme events. J Clim 25:7015–7027

Samel AN, Liang XZ (2003) Understanding relationships between the 1998 Yangtze River flood and northeast Eurasian blocking. Clim Res 23:149–158

Schmidli J, Frei C (2005) Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. Int J Climatol 25:753–771

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389

Tang Y, Gan J, Zhao L, Gao K (2006) On the climatology of persistent heavy rainfall events in China. Adv Atmos Sci 23:678–692

Tao SY (1980) The torrential rain in China. Science Press, Beijing

Wang XL, Swail V (2001) Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. J Clim 14:2204–2220

Zanon F, Borga M, Zoccatelli D, Marchi L, Gaume E, Bonnifait L, Delrieu G (2010) Hydrological analysis of a flash flood across a climatic and geologic gradient: the September 18, 2007 event in Western Slovenia. J Hydrol (Amst) 394:182–197

Zhai P, Zhang X, Wan H, Pan X (2005) Trends in total precipitation and frequency of daily precipitation extremes over China. J Clim 18:1096–1108

Zhang X, Zwiers FW (2004) Comment on 'Applicability of prewhitening to eliminate the influence of serial correlation on the Mann–Kendall test' by Sheng Yue and Chun Yuan Wang. Water Resour Res 40:W03805, doi:10.1029/2003WR002073

Zhang X, Vincent LA, Hogg W, Niitsoo A (2000) Temperature and precipitation trends in Canada during the 20th century. Atmos Ocean 38:395–429

Zhang X, Alexander L, Hegerl GC, Jones P and others (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdiscip Rev Clim Change 2:851–870

Zolina O, Simmer C, Gulev SK, Kollet S (2010) Changing structure of European precipitation: longer wet periods leading to more abundant rainfalls. Geophys Res Lett 37:L06704, doi:10.1029/2010GL042468

Appendix

Table A1. Information of regional persistent extreme cases: Central–Eastern China type. Detailed information for each case includes the start and end dates, the duration in days, the number of affected stations, the affected area, the boundaries, and the maximum and minimum precipitation amounts observed at affected stations during the event

Year	Start date (mo)	Start date (d)	End date (mo)	End date (d)	Period (d)	No. stations	Affected area (10^4 km^2)	Boundary °N	Boundary °S	Boundary °W	Boundary °E	Max. precip. (mm)	Min. precip. (mm)
1954	7	4	7	7	4	3	3.23	32.55	32.10	115.37	117.23	430.20	265.40
1955	6	18	6	23	6	6	5.70	29.44	28.41	115.59	119.39	516.80	265.40
1961	6	7	6	11	5	3	2.59	31.26	28.18	117.13	119.29	264.90	172.00
1964	6	24	6	29	6	5	5.29	30.44	29.24	110.10	115.40	574.90	262.20
1967	6	17	6	22	6	3	2.59	29.00	27.03	114.55	118.54	358.90	197.60
1968	6	16	6	19	4	3	1.82	27.03	26.39	118.10	118.59	424.50	303.90
1968	7	13	7	20	8	5	4.84	33.36	30.40	113.10	119.02	565.90	305.50
1970	7	8	7	14	7	4	3.47	30.08	27.55	115.59	118.32	295.60	177.60
1974	7	14	7	17	4	3	2.59	30.08	29.18	117.12	118.17	279.50	238.70
1982	6	13	6	19	7	9	9.16	28.04	27.03	111.28	118.32	551.50	240.80
1989	6	29	7	3	5	4	3.80	29.00	27.48	114.23	118.54	379.30	302.80
1991	6	12	6	15	4	4	3.80	32.33	31.53	115.37	120.53	370.40	231.60
1991	7	1	7	11	11	9	9.05	32.52	30.21	112.09	120.19	742.20	369.90
1992	7	4	7	8	5	4	3.47	28.04	25.31	117.28	119.47	447.90	215.30
1995	6	21	6	26	6	3	2.07	30.08	28.41	118.09	118.54	469.00	286.00
1996	6	29	7	2	4	4	2.77	30.21	29.43	118.09	120.10	619.90	291.20
1997	7	7	7	12	6	5	4.66	30.44	26.51	116.20	122.27	389.10	275.10
1998	6	12	6	27	16	12	10.78	30.37	23.48	113.32	118.59	1053.90	283.60
1999	6	24	7	1	8	7	4.84	31.09	29.37	113.55	120.10	813.50	313.80
2000	6	9	6	12	4	6	4.68	28.04	25.31	118.02	120.12	376.50	204.20
2002	6	14	6	17	4	3	2.54	26.54	26.39	116.20	118.10	551.30	378.80
2003	7	8	7	10	3	5	5.57	31.11	28.50	108.46	115.01	481.70	197.20
2005	6	18	6	24	7	9	7.26	27.55	23.48	114.44	120.12	706.80	295.10
2006	6	4	6	7	4	5	3.47	28.04	26.55	116.39	119.08	421.10	219.00
2010	6	17	6	25	9	6	5.08	27.55	26.54	116.39	118.32	754.40	441.10

Table A2. Information of regional persistent extreme cases: South China type. See Table A1 for details

Year	Start date (mo)	Start date (d)	End date (mo)	End date (d)	Period (d)	No. stations	Affected area (10^4 km^2)	Boundary °N	Boundary °S	Boundary °W	Boundary °E	Max. precip. (mm)	Min. precip. (mm)
1955	7	17	7	25	9	5	6.37	25.48	22.39	110.10	117.30	482.90	310.30
1956	8	7	8	9	3	3	7.26	21.57	21.27	107.58	109.08	389.40	223.30
1957	5	12	5	14	3	3	2.74	23.52	23.05	113.32	114.44	311.30	210.60
1959	6	11	6	15	5	9	9.03	23.48	22.21	110.05	116.41	737.00	298.80
1964	6	9	6	16	8	5	4.89	25.31	21.50	111.58	119.47	662.20	307.00
1968	6	10	6	14	5	3	3.15	23.48	22.48	114.44	116.41	612.40	319.30
1969	4	13	4	16	4	3	6.78	22.21	21.44	110.56	112.46	395.50	293.90
1972	6	15	6	17	3	5	5.81	23.47	22.48	115.22	117.30	341.90	220.80
1991	6	7	6	12	6	3	10.89	21.57	21.32	107.58	112.46	679.30	358.40
1994	6	13	6	17	5	3	3.39	25.13	22.21	109.24	110.56	583.90	306.00
1994	7	14	7	21	8	4	8.47	21.57	21.02	107.58	109.08	1156.60	387.30
1995	6	5	6	8	4	4	11.86	21.50	21.32	107.58	112.46	807.50	251.40
1997	7	2	7	9	8	3	2.98	24.12	22.32	110.31	114.00	434.70	288.60
1997	7	19	7	24	6	4	9.68	21.57	18.30	107.58	110.02	584.50	192.90
1998	7	1	7	9	9	5	10.89	21.57	18.14	107.58	110.02	863.20	263.30
2000	7	17	7	22	6	6	10.08	23.20	21.44	108.21	113.50	435.00	230.80
2000	8	1	8	4	4	4	12.10	21.57	21.32	107.58	112.46	410.40	269.50
2008	7	7	7	12	6	3	7.26	23.24	21.44	112.46	116.41	323.90	288.80

Table A3. Information of regional persistent extreme cases: Typhoon-influenced type. See Table A1 for details

Year	Start date (mo)	Start date (d)	End date (mo)	End date (d)	Period (d)	No. stations	Affected area (10^4 km^2)	Boundary °N	Boundary °S	Boundary °W	Boundary °E	Max. precip. (mm)	Min. precip. (mm)
1956	9	17	9	24	8	3	3.39	27.20	24.54	118.06	120.12	491.30	412.90
1957	10	12	10	14	3	3	4.84	19.31	19.02	109.35	110.28	636.90	178.60
1960	8	24	8	28	5	3	3.15	23.48	23.02	114.25	116.18	390.70	298.10
1965	9	27	9	30	4	3	6.86	23.02	21.44	112.27	116.18	612.30	218.80
1967	8	4	8	7	4	3	3.63	24.42	22.25	107.02	109.18	558.10	331.70
1967	9	13	9	19	7	3	4.60	20.00	18.30	109.50	110.15	494.30	369.30
1972	8	18	8	21	4	5	5.81	23.47	21.50	111.58	117.30	384.30	223.20
1974	10	18	10	21	4	3	6.78	22.48	21.44	112.46	115.22	399.10	244.60
1976	9	19	9	23	5	5	5.08	22.46	21.09	108.37	111.58	482.30	340.40
1979	9	20	9	23	4	3	4.84	19.02	18.14	109.31	110.02	565.10	354.20
1981	9	28	10	4	7	4	11.45	22.15	21.30	107.58	112.47	558.60	403.30
1985	8	26	8	31	6	6	11.05	23.25	21.02	105.50	112.46	612.10	306.30
1990	7	30	8	4	6	5	5.45	26.05	23.02	116.18	119.17	537.50	330.90
1990	8	19	8	23	5	6	5.31	28.49	23.26	117.02	120.55	516.40	225.00
1990	10	3	10	6	4	3	4.60	20.20	18.30	109.50	110.11	452.70	330.60
1993	9	24	9	27	4	3	6.78	22.48	21.44	112.46	115.22	641.90	247.30
1994	8	4	8	6	3	3	3.11	24.30	23.24	116.41	118.04	410.60	193.50
1995	7	31	8	4	5	3	3.39	23.47	22.48	115.22	117.30	390.70	342.70
1996	8	11	8	15	5	3	3.63	21.47	21.02	108.21	109.08	379.50	239.10
2000	10	13	10	19	7	4	5.81	20.00	19.02	109.35	110.28	819.00	596.70
2001	8	29	9	5	8	5	4.76	23.10	21.50	111.58	116.18	671.90	329.50
2002	9	12	9	17	6	3	2.90	22.32	21.09	110.18	114.00	557.90	294.40
2008	7	28	8	1	5	3	2.51	30.08	24.54	118.09	119.31	394.00	252.60
2008	8	7	8	9	3	4	4.84	21.57	21.02	108.21	109.08	484.70	301.10
2009	8	5	8	10	6	3	3.39	21.27	19.06	108.37	110.18	604.20	234.00
2010	10	1	10	9	9	6	9.20	20.20	18.14	109.31	110.28	1488.10	528.80
2010	10	15	10	18	4	3	6.05	19.14	18.30	109.50	110.28	521.50	369.60

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