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Determining starting time and duration of extreme precipitation events based on intensity

Er Lu[1,2,*], Wei Zhao[1], Liqing Gong[1], Hongxing Chen[1,3], Huan Wang[1], Xin Li[1], Jinbo Song[1], Juqing Tu[1], R. Wayne Higgins[2], Mike S. Halpert[2]

[1]Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, PR China

[2]NOAA Climate Prediction Center, College Park, Maryland 20740, USA

[3]Chengdu University of Information Technology, Chengdu, Sichuan, PR China

ABSTRACT: For daily precipitation, previous studies have mainly identified extremes over fixed durations. The goal of our study was to identify over which multiday period a rainfall event can best be described as an extreme. Specifically, we extrapolated the starting time and duration within a rainfall episode to best describe an event with that starting time and duration as an extreme, compared to events with other starting times and durations. The principle is that the precipitation intensity averaged over this period is comparably (relative to duration) the strongest among all the events that have different starting times and durations. For this purpose, the 'extreme' intensity–duration (EID) relation is established through mathematical modeling based upon our understanding of the issue of identifying the extremes. The constraints in the model between 'extreme' intensity and duration require that the single parameter contained in the EID relation be between, but not too close to, 0 and 1. Tests show that extremes can be well identified with the EID approach by simply assigning a moderate value to the parameter, and the identification of extremes is not sensitive to which value is chosen for this parameter. The estimation with multiyear data and a regression indicates that the parameter is truly moderate between 0 and 1, but the value relies on the threshold used for determining the initial extreme intensities. It is therefore suggested that a fixed moderate value be given to the parameter in the operational identification of the extremes. As a real application of the method, we determined the starting time and duration of the extreme in a recent heavy rainfall that occurred over Beijing.

KEY WORDS: Climate extremes · Identifying extremes · Monitoring and detections · EID constraints · Mathematical modeling

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1. INTRODUCTION

With the frequent occurrence of high-impact events in recent decades under global warming, weather and climate extremes have become an important focus in the atmospheric sciences (e.g. Karl & Knight 1997, Easterling et al. 2000, Meehl et al. 2000, Dairaku et al. 2004, Allan & Soden 2008). Several international conferences have been organized in recent years, including a workshop held in Hawaii during 2007 (Garrett & Müller 2008), a workshop sponsored by the World Climate Research Programme in 2010 (Zolina et al. 2010), and NOAA's Climate Diagnostic and Prediction Workshop held in 2011, to review the metrics and methodologies for defining, exploring, understanding, and predicting the extremes on time scales from daily to decadal.

Weather and climate extremes, which may include heavy precipitation, droughts, heat waves, and hurricanes, have become the object of climate monitoring,

*Corresponding author: elu@nuist.edu.cn

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similar to monsoons (e.g. Lu & Chan 1999, Zeng & Lu 2004). Proper monitoring and detection of such extremes are essential for the mitigation of losses they may cause, and are the basis for a better understanding of the mechanisms of their formation. Reasonable determinations of the starting time, duration, and intensity of climate extremes are particularly important for the reliable assessment of changes in the extremes under warming scenarios. Corresponding to the different definitions of weather and climate extremes, various methods have been developed to detect them (e.g. Karl et al. 1996, Mudelsee 2006). Most previous studies have identified extremes of a single climate variable, such as precipitation, although multiple variables have also been used, e.g. in the Climate Extremes Index (Karl et al. 1996), in an attempt to evaluate the overall extremity of the climate.

From daily precipitation data, researchers have mainly reported daily extremes (e.g. Karl & Knight 1998, Klein Tank & Können 2003, Zhai et al. 2005, Wang et al. 2008). However, such studies are not just concerned with extremes over an exact 24 h period; the primary reason they seek to determine daily extremes is that they are using daily data. Extremes over a longer, but fixed, duration, e.g. the 5 d or monthly extreme, have also been identified in some studies by simply averaging the daily data over the chosen period. However, these studies did not sufficiently utilize the value of the daily data. The extremes of a specific duration were generally captured from the data by setting a threshold (e.g. 1‰ or 1%), and extremes of different durations were separately identified with the method. However, as will be pointed out in Section 3, there may be an imbalance among these 'threshold-determined' intensities of different durations.

In the present study, we used daily (and hourly) precipitation to identify the extremes that might be of a multiday (and multi-hour) duration. As will be illustrated from a real example in Section 3.4, such detection of extremes is required in the climate service department. Since the purpose of this article is to propose a novel method, we focus on a precipitation episode, i.e. a rainfall episode of ca. 10 d. Our task is to find the event (a period specified by a starting time and a duration within the episode) that is most extreme, or can best be described as an extreme. More specifically, we aim to identify from which day and over which duration during the examined episode the event (with this starting time and duration) can best be considered an extreme, compared to events with other starting times and/or durations. In other words, the extreme needs to be 'best described' in terms of starting time and duration.

The method for identifying the extreme among a range of durations should be as objective as possible. For this purpose, we propose a mathematical model that includes 2 reasonable constraints, based upon our understanding of the issue. With the model, a baseline relation is established which prescribes the minimum intensity that an event of a specific duration needs to reach in order for the event to be considered an extreme. The actual intensity calculated from the data can then be compared with this prescribed intensity. The method should contain, if needed, only a single parameter, which ideally is between 0 and 1, similar in style to Lu (2009), who proposed a method to monitor drought based on physical considerations and mathematical derivations. With an adjustable decimal fraction number, we may conveniently analyze the behavior of the result under various circumstances, such as when the parameter is given a moderate value (e.g. 0.5) or tends toward the 2 special cases of being 0 and 1, as illustrated by Lu (2009).

Two datasets for rainfall in Beijing are used in this study. One is the daily precipitation recorded over 60 yr from 1951–2010, and the other is hourly precipitation recorded on 21–22 July 2012.

2. ISSUES AND CONSIDERATIONS

2.1. Issues with the generally used methods

Using daily precipitation, most previous studies have sought daily extremes, and extremes of other durations were not considered. In a precipitation process, if there is no daily extreme, it may still contain extremes of other durations. In Fig. 1a, precipitation is strong on Day 6 (15 units). Suppose this intensity just reaches the standard of daily extreme. In Fig. 1b, the intensities on Days 6 and 7 are less than this standard, so the rainfall on each of those days alone is not considered extreme.

However, these intensities are still fairly strong, and what is important is that these 2 precipitation days are consecutively combined. The overall impact of this 2 d event may be equivalent to, or stronger than, that of the 1 d event shown in Fig. 1a. Hence, this 2 d event should also be regarded as an extreme. The question is, with the standard of the 1 d extreme, how can we identify the 2 d extreme? Or, how can we compare extremes of different durations? This is the main task of our study and will be explored further in Section 3.

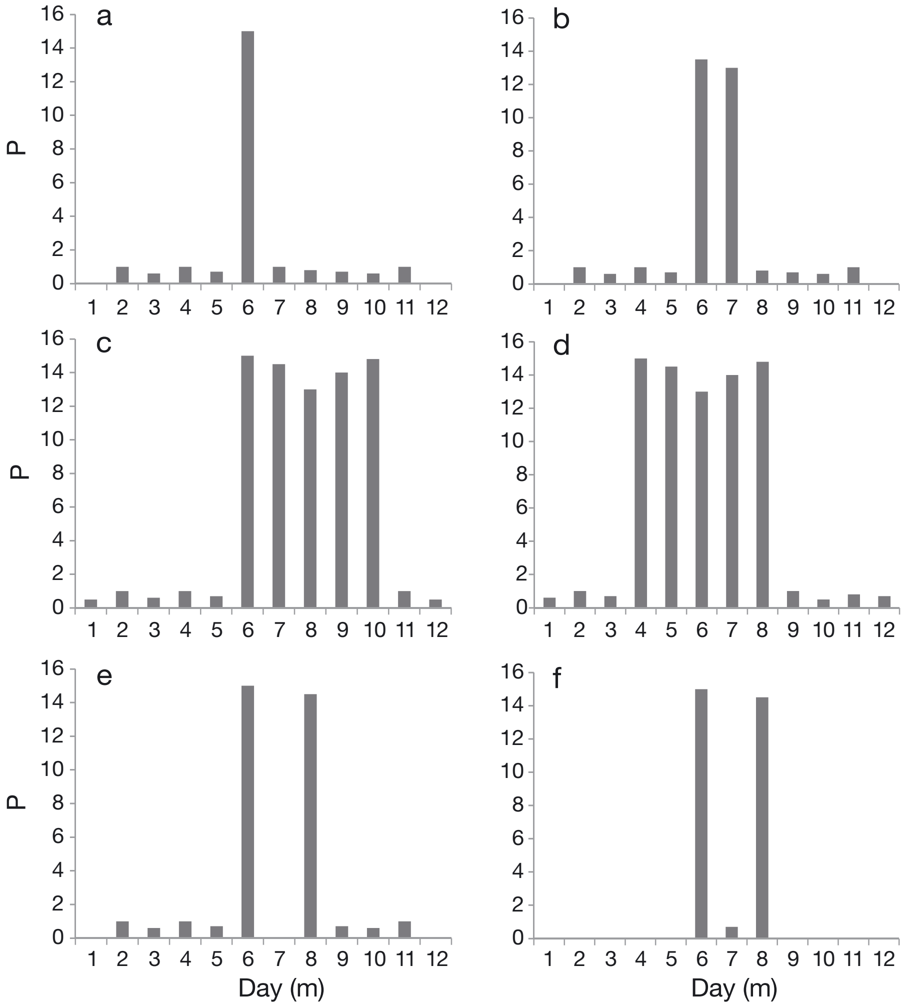

Fig. 1. Conceptual multiday rainfall processes pertaining to identifying the extremes over multiday durations. An appropriate unit can be given to precipitation

In previous studies that examined multiday precipitation extremes, the durations were generally fixed (e.g. Klein Tank & Können 2003, Zhai et al. 2005). The precipitation intensity is calculated as the simple average of the daily precipitation over the period of the fixed duration. The extremes are then sought with the criterion determined by a threshold. To identify the 5 d extreme, for example, precipitation is first averaged over 5 d periods, say, from Day 1 to Day 5, and from Day 6 to Day 10, etc. In Fig. 1c, the 5 days that have strong precipitation happen to be in the same 5 d period used for calculating the average. Thus the averaged precipitation of this period will be strong. Suppose this averaged intensity just reaches the standard of the 5 d precipitation extreme.

In Fig. 1d, although the 5 d precipitation event from Day 4 to Day 8 is exactly the same as the 5 d event in Fig. 1c, the 5 d are split into 2 periods, with 2 days in the period from Day 1 to Day 5 and 3 days in the period from Day 6 to Day 10. Thus, the averages of each of these 2 periods are not very strong. Different from Fig. 1c, extremes may therefore not be identified in Fig. 1d, indicating that when averages are used to identify extremes of a fixed duration, the choice of the starting date may influence the result.

Instead of determining multiday extremes, some previous studies focused directly on persistent rainfalls and analyzed their lifespans (e.g. Karl & Knight 1998, Dairaku et al. 2004, Junker et al. 2008). However, as pointed out by Junker et al. (2008), the starting and ending times of a multiday rainfall episode can be difficult to determine when rainfall comes as a result of several consecutive storms with small breaks in between. In addition to the breaks, the difficulty in determining the span may also be due to light rains that appear in the beginning and ending stages of the rainfall process.

In Fig. 1e, light rains occur from Day 2 to Day 5, followed by a heavy rain on Day 6 and a break with no rain on Day 7. After that, heavy rain occurs on Day 8, again followed by light rains from Day 9 to Day 11. Because of the break, the entire process may not generally be treated as a persistent rainfall process; rather, it contains 2 precipitation episodes, from Day 2 to Day 6 and from Day 8 to Day 11, and extremes are generally found in each of the episodes. Since the precipitation intensities averaged over each of the periods are not very strong, the result might be that no extreme is identified in either of the 2 periods and thus the entire process.

Throughout the duration of a multiday extreme, can a break be included in the middle? Should the light rains be included in the span? What is the criterion for inclusion or exclusion? In fact, there is no need to consider the light rains and breaks when determining the span of the extreme (and even the persistent rainfall process), and we may well make changes to the light rains and breaks. In Fig. 1e, the break on Day 7 can be changed to a light rain, so the original 2 processes, from Day 2 to Day 6 and from Day 8 to Day 11, can be turned into a persistent rain-

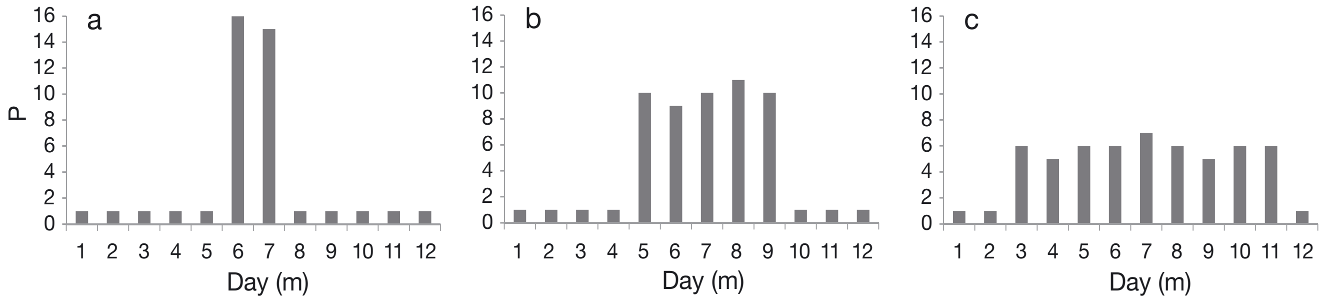

Fig. 2. Conceptual rainfall episodes, in which extremes are relatively easy to identify intuitively. An appropriate unit can be given to precipitation

fall process. We may also change the light rain days, in the beginning stages of the process from Day 2 to Day 5 and in the ending stage from Day 9 to Day 11, to rainless days, so the span of the rainfall process can be shortened.

After these changes, the rainfall process becomes a 3 d event, as shown in Fig. 1f. With the shortening of the span, although there is a decrease in rainfall total, the averaged precipitation intensity has increased, and this makes the event easier to be identified as an extreme. These modifications, which actually induce very little change to the entire process, can improve our understanding on the starting time, duration, and intensity of an extreme event.

2.2. Considerations and the new approach

Because we do not feel comfortable with the issues mentioned above, we developed a new method with the intention to overcome or avoid these issues. The extreme to be identified can be a daily extreme or an extreme of a longer duration. There is no need to average the daily data over a given duration first in order to find the extremes of this duration. Extremes are evaluated by comparisons among all events whose periods have different starting times and durations, and thus the value of the daily data is fully utilized. The duration, or the period of an event, can be a portion of the rainfall process, and it may even contain a break. We can thus eliminate the issue of whether the light rains should or should not be included in the duration.

In order to verify the ability of the proposed approach to find the most possible extreme in a rainfall process among the events that have different starting times and durations, some special rainfall processes are provided in Fig. 2. The daily rainfall data of these processes will be used as the input in the new method. In these rainfall episodes, extremes are relatively easy to identify intuitively, based on our understanding of extremes of multiday durations.

In Fig. 2a, as analyzed above, although the precipitation on each of Days 6 and 7 may not be an extreme, the precipitation of these 2 days combined can best be considered an extreme within the rainfall process. Similarly, for precipitation from Day 5 to Day 9 in Fig. 2b, although the precipitation on each of these days, or every consecutive 2 or 3 d within the process, may not be an extreme, this 5 d precipitation event can best be described as an extreme. For the rainfall process shown in Fig. 2c, the most possible extreme is the 9 d precipitation event from Day 3 to Day 11.

Similar to Lu (2009), our new approach here is intended to be objective, but still leaves space to be flexible. It contains a parameter, a decimal fraction, in the established relation. Perturbations will be given to the parameter, to examine whether the identification of extremes is sensitive to changes in this parameter.

Again, the new approach is currently used to find the most possible extreme event in a single rainfall process, as shown in Fig. 2. When a multiyear dataset is used, this event still needs to be compared to events found from other historical rainfall processes to determine, over the long-term perspective, whether it can really be considered an extreme.

3. METHOD FOR IDENTIFYING EXTREME EVENTS

3.1. Mathematical model and the prescribed 'extreme' intensity

For the new method to be objective, a mathematical model is proposed based upon our understanding to prescribe the 'extreme' intensity, which is the baseline of intensity an event of a specific duration should reach in order for the event of that duration to be considered an extreme. The model contains 2 reasonable constraints.

(1) With an increase in duration, the precipitation intensity of the extreme should decrease. For a specific place, for example, if the daily precipitation extreme has an intensity of 200 mm d^{-1}, the intensity of the weekly extreme may go down to 40 mm d^{-1}, whereas the intensity of monthly extreme might be as weak as 5 mm d^{-1}. The decrease of the 'extreme' intensity (I_e) with duration (T) can be expressed as

$$\frac{dI_e}{dT} < 0 \tag{1}$$

(2) With an increase in duration, although intensity decreases, there should be an increase in the rainfall total of the extreme. For example, it is reasonable to assume that a 5 d precipitation extreme has more rainfall total than a 3 d extreme, since both are extremes and the former lasts for a longer period of time. The increase in the rainfall total (the product of intensity and duration) with duration can be expressed as

$$\frac{d(I_e T)}{dT} > 0 \tag{2}$$

Combining Eqs. (1) and (2) yields

$$0 < a < 1 \tag{3}$$

where

$$a = -\frac{1}{I_e}\frac{dI_e}{d(\ln T)} \tag{4}$$

measures the relative decrease of 'extreme' intensity ($-dI_e/I_e$) with respect to the logarithm of duration ($\ln T$). Since our purpose is to prescribe the I_e, and it is the quantity to be obtained (not the one we already had), we treat the parameter a in Eq. (4) as a constant.

Let $T = n\Delta T$, where ΔT is the increment in duration (e.g. 1 d or 1 h), which depends on the time resolution of the data, and n is the number of the increment, reflecting the length of the duration. A range of durations, e.g. with n varying from 1 to 10, may be considered in order to find the event that can best be considered an extreme.

Rewrite Eq. (4) as $d(\ln I_e) = -a\,d(\ln T)$. Integrating this equation, with T varying from ΔT to $n\Delta T$ and I_e correspondingly from $I_e(1)$ to $I_e(n)$, yields

$$I_e(n) = I_e(1)n^{-a} \tag{5}$$

where $I_e(1)$ is the 'extreme' intensity over the shortest duration ΔT, which is limited by the time resolution of the data.

Again, the 'duration' here for the extreme is not the entire lifespan of a rainfall process, but rather a time period to be determined that best allows a precipitation event of this period to be considered an extreme. The duration can be part of the lifespan of the rainfall, and may even contain a rainfall break.

3.2. Relative intensity and the determination of starting time and duration

As mentioned above, our task here is to find, within a precipitation episode (e.g. a process of ca. 10 d), from which date and over which duration an event (with this given starting time and duration) can best be considered an extreme event, compared to all other events that have other starting times and/or durations within the same episode.

Intensities averaged with daily data over the different durations should not be compared directly, since they are for different durations. The above prescribed 'extreme' intensity, as a standard, can be used to convert intensity to 'relative intensity', which can be expressed as

$$R(n,m) \equiv \frac{I(n,m)}{I_e(n)} \tag{6}$$

Where $I(n,m)$ is the average of daily precipitation over the time period that centers on date m and has a duration n. Substituting Eq. (5) into Eq. (6), we obtain

$$R(n,m) = n^a I(n,m) \tag{7}$$

in which the $I_e(1)$ has been omitted since it is a constant, and the purpose of using the relative intensity in Eq. (7) is to make a comparison among the different durations within the episode. Because of this, what we find is the event (merely based on the data of this episode) that is most likely to be an extreme. To determine whether this event can eventually be an extreme when assessed within a long-term scope with multiyear data, the $I_e(1)$ needs to be given.

The advantage of the relative intensity is that, with factor n^a, the weaker intensity of a longer-duration event calculated from the data can be enlarged, so the strengths of the events that have different durations (and starting times) can be compared.

Through running the date (m) and the comparison among different durations (n), the most possible extreme event, which exhibits the strongest relative intensity $R(n_0,m_0)$ within the rainfall episode examined, can be identified. With the located m_0 and n_0, the starting time and the duration of the most possible extreme event can be determined.

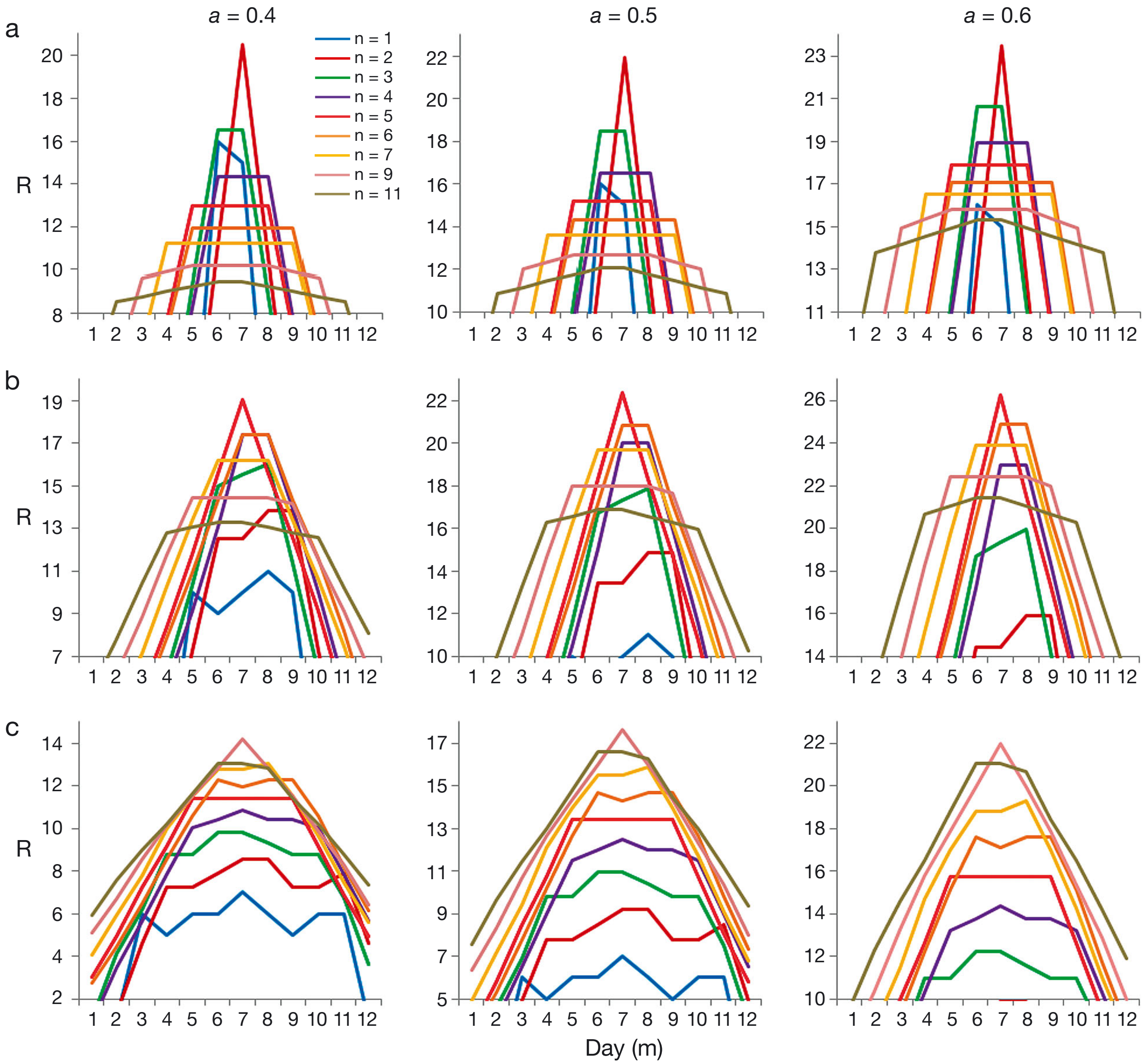

Fig. 3. Relative intensities (R) over 9 durations (1, 2, 3, 4, 5, 6, 7, 9, and 11 d) with input data from Fig. 2 and with parameter *a* (see Eq. [5]) being 0.4, 0.5, and 0.6. For convenience, the curves with even numbers of days have been shifted to the right by a half day

Fig. 3 presents the results of relative intensity with input data from Fig. 2. To focus on the single episodes in Fig. 2, the precipitation before Day 1 and after Day 12 are all taken as 0. In order to better obey the constraints of Eqs. (1) and (2), the parameter *a* should be neither too close to 0 nor too close to 1 in Eq. (3). Here we apply 3 moderate values (0.4, 0.5, and 0.6) to the parameter to examine the differences in the results.

Nine durations (1, 2, 3, 4, 5, 6, 7, 9, and 11 d) are included in the plot for comparing relative intensities. In the plot, for convenience, the relative intensity given to date *m* is calculated with the data from Day $m - (n - 1)/2$ to Day $m + (n - 1)/2$ if duration *n* is an odd number, but from $m - (n - 2)/2$ to $m + n/2$ if it is an even number.

In Fig. 3a, plots with different values of the parameter *a* all indicate that relative intensity is strongest over the 2 d duration, thus this 2 d event can best be considered an extreme. These plots all show that the next possible extreme is the 3 d event. However, whether the 1 d or 4 d event is more likely to be an extreme depends on the value of the parameter. In Fig. 3b, results from different values of the parameter show that the most possible extreme event is over the 5 d duration that centers on Day 7, so the event starts on Day 5 and ends on Day 9. The 6 d event is the next possible extreme, and whether the 4 d or 7 d event is more extreme depends on the value of the parameter. In Fig. 3c, the most possible extreme event is over the 9 d duration centering on Day 7, so the extreme starts on Day 3 and ends on Day 11. Detections with different values of the parameter all indicate that the possibility of being extreme decreases for events of 11 d, 7 d, and other durations, and the 1 d and 2 d events are the least possible extremes.

The above results are consistent with what we have derived intuitively, which demonstrates the robustness of the EID approach. This example is for single rainfall episodes that provide very limited data. This suggests that even without historical multiyear data, the EID method can still identify extreme events of different durations, simply by assigning a moderate value to the parameter, and the extreme identifications are not sensitive to the parameter. In the operational detection with data of a long temporal series, it is possible that a multi-day period is included in 2 or more extreme events that have different starting times and/or durations, as long as they have the same relative intensity.

3.3. Estimating the parameter with multiyear data and a regression

For a given duration, we can first average the daily data from multiple years over that duration, and then use the 1% (or 1‰) threshold to determine the corresponding baseline intensity, as was conventionally done in previous studies. However, the baseline intensities obtained separately for each of the durations may exhibit an imbalance, since the data's spectrum of intensity over that duration might be irregular in structure.

This issue can be illustrated with the simple case in Fig. 4. For a precipitation process that indefinitely repeats the episode shown in this figure, the baseline intensity of daily extreme, based on the 1% threshold, is around 10 units. The baseline intensity of the 2 d extreme goes down sharply to about 5 units. However, for the 3 d extreme, the baseline intensity goes back to approximately 6.7 units. It is not reasonable, according to the above analysis, that the 3 d extreme possesses stronger baseline intensity than the 2 d extreme, which can lead to, from Eq. (5), a negative value for the parameter a.

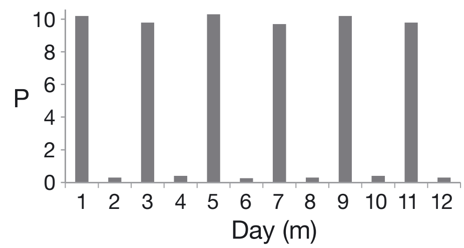

Fig. 4. Conceptual multiday rainfall process whose spectrum of intensity over a given duration might be irregular in structure. An appropriate unit can be given to precipitation

Taking logarithms of Eq. (5), we have $\ln I_e(n) = -a\ln n + I_e(1)$. Based on this relation, a regression equation is proposed as

$$\ln \tilde{I}_e(n) = -a \ln n + c \tag{8}$$

where $\tilde{I}_e(n)$ are the baseline intensities of different durations, but are determined individually for each of the durations with a 1% (or 1‰) threshold. The parameter a, along with constant c, can then be determined by using the regression and the baseline intensities.

Through the regression, the parameter a has been adjusted among different durations, although the baseline intensities that are individually determined with the threshold may have an imbalance among the different durations.

The regression includes a range of durations, depending on the issue studied. Since the $\tilde{I}_e(n)$ in Eq. (8) is regressed with ln n (not n), in order to produce a better regression effect, we let ln n take an approximately equal increment. Considering this, we may take n as 1, 2, 3, 5, 7, 11, 15, 31, 61, 91, in which pentad (5 d), weekly, monthly, and seasonal scales are included.

Data of daily precipitation in Beijing for the 60 yr period from 1951–2010 are utilized to estimate the parameter. Within the 60 yr, the events that have different durations (n) all have a great number of samples, and their sample numbers are almost the same. The baseline intensity required by the regression can be determined through simply omitting a certain number (k) of the samples that are strongest in intensity among the total samples, resulting in a similar effect to applying the thresholds. For a given number of the samples omitted, a value of the parameter a can be obtained with the regression.

Fig. 5 shows how the parameter estimated varies with k, the number of the samples omitted. It is shown that the parameter can reach 0.6 if baseline intensities are defined with an omission of just 1 to 2 samples, which represents the threshold for finding

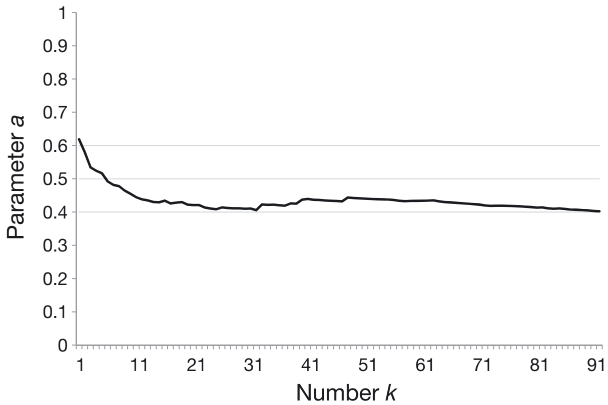

Fig. 5. Plot showing how the parameter *a*, estimated with the regression, varies with the threshold, or the number *k* (i.e. the number of the omitted samples that are strongest in intensity) used to determine the baseline 'extreme' intensity individually for each of the durations. Data of daily precipitation in Beijing for the 60 yr period from 1951–2010 are used. Gray lines indicate levels of parameter *a* as in Fig. 3

the once-in-30-to-60-yr extreme. With the varying of the threshold from 1 to 4‰, the parameter estimated from the regression changes between 0.4 and 0.5.

The above result indicates that when estimating the parameter using the regression, the value of the parameter obtained depends on the threshold we use to obtain the initial baseline intensities, but is truly moderate between 0 and 1. We therefore suggest that, based on the results of this example and the tests in Fig. 3, parameter *a* be taken as 0.5 (or 0.45) for the general identification of extremes in precipitation.

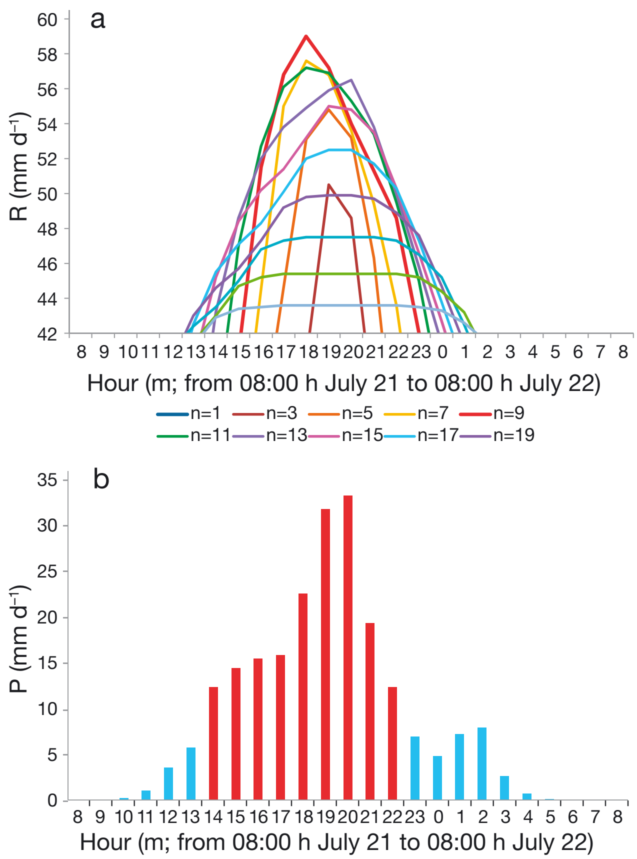

Fig. 6. (a) Relative intensity (R) and (b) hourly precipitation (P, in mm d^{-1}) recorded during a heavy rainfall that occurred from 21–22 July 2012 in Beijing. Relative intensity is strongest for the 9 h period that centers on 18:00 h on 21 July. Thus the extreme event (i.e. the hours in the rainfall process over which the rainfall is most extreme), is identified as starting at 14:00 h on 21 July and lasting for 9 h. The precipitation of these hours is marked red in panel b

3.4. Real example of an application

Although daily precipitation has been used in all the above examples to introduce the EID approach, as mentioned above, the method can be used for all timescales, depending on the resolution (unit) of the precipitation data. Here, we use hourly observed data to present a real example of applying the EID method to identify the period of a precipitation extreme.

The heavy rainfall that occurred in Beijing during 21–22 July 2012 is considered a recent high-impact weather event. In order to answer the question as to how extreme the event is, e.g. whether this is a once-in-a-century event, we need to clarify over which period the rainfall event can best be considered an extreme. Since there are no sufficient historical hourly data, and, as stated above, the data's spectrum of intensity may be irregular in structure, we use the EID method to find the starting time and duration over which the event can best be considered an extreme.

Fig. 6a presents the relative intensities averaged over different durations that center at different hours, calculated from Eq. (7) with parameter *a* being 0.5. It is shown that relative intensity is strongest for the 9 h centered on 18:00 h on 21 July. Thus the extreme event (i.e. the hours in the process over which the rainfall is most extreme), is identified as starting at 14:00 h on 21 July and lasting for 9 h. The precipitation of these hours is marked red in Fig. 6b. This result implies that when these 9 consecutive hours are combined, the rainfall event can best be described as an extreme. If the remaining hours (in blue), or part of them, are included, the event may not be that extreme.

4. SUMMARY, DISCUSSION, AND FURTHER WORK

4.1. Summary

The purpose of this study was to develop a method to find extremes among a range of durations. As an example, we examine a rainfall episode that lasts ca. 10 d. We determine the starting time and the duration over which the event (with this particular starting time and duration) can best be considered an extreme compared to those events that have other starting times and/or durations.

The baseline intensities of different durations, prescribed from a mathematical model, are used to find the extremes (specified by starting time and duration) from the intensities calculated from the data. This approach allows a balance (or match) among the baseline intensities of the different durations. In previous studies, the standards of extreme intensities were determined separately for each fixed duration with a threshold. However, that method may lead to an imbalance among the extreme intensities of different durations.

There is no absolute standard (or truth) for providing the baseline intensity, and what we can do is simply to prescribe this intensity as reasonably as possible. The 2 constraints that constitute the model based upon our understanding require that, with an increase in duration, baseline intensity needs to decrease, while total precipitation needs to increase. To better obey these constraints, the single parameter contained in the baseline relation needs to have a moderate value between 0 and 1.

Tests show that, by simply assigning moderate values to the parameter, extremes of different durations can be well identified with the EID approach, and the identifications are not sensitive to which value is chosen for this parameter. Using multiyear data, we estimate the parameter with a regression, and results show that the parameter is truly moderate between 0 and 1. However, in the estimation, we need to first define the initial extreme intensities with a certain threshold. Results show that the estimated value of the parameter varies with the threshold. Therefore, in the operational detection of extremes, we can simply assign a moderate value to the parameter. A value of 0.5 is thus suggested. As a real application of the EID method, the starting time and duration of the extreme in a recent high-impact heavy rainfall are determined.

4.2. Discussion

The EID method proposed in this study calculates intensities from original data. This is different from conventional statistical methods such as the Extreme Value Theory (e.g. Haan & Ferreira 2006), which models extremes with shape and scale parameters.

Theoretically, the strongest intensity should be found from the instantaneous values of intensity. In practical analysis of data, the strongest intensity can be obtained from the shortest duration given by the time resolution of the data. The intensity of a longer-duration event should be weaker. Thus, the prescribed 'extreme' intensity needs to decrease with duration. This intensity-duration pattern makes the parameter positive in the EID. The duration in the EID is just a portion of the rainfall process; it may not cover the light and small rains at the beginning and ending stages of the process, but may include a break in the middle of the process. The duration can be any period of time as long as the relative intensity can be the strongest.

Differently, in intensity-duration-frequency (IDF) studies (e.g. Hallack-Alegria & Watkins 2007), the duration is the actual lifespan of a rainfall process. In a specific region, strong rainfall may last for a certain period of time, e.g. 30 min (e.g. Hershfield 1972). Rainfall that lasts for a shorter time (e.g. 2 min) or a longer time (e.g. 24 h) is generally weaker in intensity. In IDF, which uses duration to examine the extremes that have long return periods, Sherman's equation (e.g. Moncho et al. 2009) is in a form similar to our Eq. (5). Due to this intensity-duration pattern, the parameter contained in the equation can be negative.

The regression used for estimating the parameter does not have to be statistically significant. As mentioned above, the initial extreme intensities determined separately for each of the durations with a specific threshold may have an imbalance among the different durations. Our purpose is to figure out, through the regression, a value for the parameter to prescribe the extreme intensities. Therefore, for the purpose of having a balance among the initial extreme intensities of different durations, the more insignificant the regression is, the more necessary the regression becomes, in order to obtain a value for the parameter appropriate for different durations.

The definition of weather and climate extremes is still an issue under debate, as indicated from the frequent workshops in recent years. Based on our understanding from this study, a definition can be proposed as follows. To a single climate variable of interest, an extreme is the event (characterized by a given starting time and duration) whose intensity is relatively the strongest (relative to duration), when compared to those events with other starting times and/or durations.

4.3. Further work

The EID approach can be widely applied in operational weather and climate studies, e.g. to improve definitions and refine the grading scales. In the Beijing Climate Center, for example, the definition of the 'flooding' that has been monitored routinely as a service includes a master prescription of rainfall of 10 days, supplemented with a minor one for 20 d. However, there is no prescription for the period lengths in between. The EID relation will be used to grade the range and provide details so that all flooding events over the range will be reasonably captured. In addition, the EID method will be used to better define the concepts such as 'persistent precipitation event' and 'precipitation concentration degree,' which pertain to continuous multiday rainfall. The general considerations of the EID might also be useful in solving issues in many other relevant areas in both natural and social sciences.

In order for a precipitation event to be considered extreme, it should be strong in intensity, affect a wide region, and last for a long period of time. We therefore need to use these 3 elements, i.e. the intensity, the area affected, and the time maintained, to describe an extreme. In previous studies, the extremes found were generally for precipitation measured at a particular station or in a given area, and the duration was also fixed. In the present study, the extremes are still defined for a given station or area, but they are identified from among a range of durations.

In our forthcoming work, we will further identify precipitation extremes from both time and space. Of the 3 elements required for describing an extreme, we hope that the area affected can be very large and the duration can be very long. However, if the area assessed is too large and the time considered is too long, then the precipitation averaged over the area and that time period, which is used to indicate the intensity of the extreme, would be too small. Hence, we must have a balance among the geographic region, the time period, and the intensity.

The principle of the EID, which is currently used for temporal series, will be applied to the spatial distribution of precipitation. We will develop the method by applying the EID to both time and space, to simultaneously identify both the time period and the geographical region over which a precipitation event can best be considered an extreme. This will allow us to determine over which period and over which region the intensity averaged is relatively the strongest, when compared to events that have other starting times and durations and occur over regions of other sizes.

In addition, by using certain thresholds (e.g. 1‰, 1%, or 5%) and the regression, the behavior of the parameter *a*, which is therefore threshold-dependent, can be assessed with data of different quantities, over different regions, and during different seasons. It can be expected that under some circumstances, especially when the intensity spectrum of the data is irregular in structure, the values of the parameter retrieved may be not so moderate.

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