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A Method for Identifying the Events That Can Best Become Extremes

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1. Introduction

Is climate going crazy under global warming? Are climate extremes more frequent in the warmed climate? Climate change and extremes have become one focus of climate research (*e.g.*, Karl and Knight 1997; Meehl *et al*. 2000; Easterling *et al*. 2000a; Dairaku *et al*. 2004; Allan and Soden 2008), and several international conferences have recently been organized to stress these hot topics. The workshop held in 2007 in Hawaii reviewed the understanding and prediction of extreme events and of changes in their frequency and intensity (Garrett and Müller 2008). The workshop on "metrics and methodologies of estimation of extreme climate events" held in 2010 in France sponsored by the World Climate Research Programme (WCRP) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) pointed out that good statistical methods are essential for exploring, defining, and estimating weather and climate extremes (Zolina *et al.* 2010). Climate extremes include heavy precipitation, floods, heat waves, droughts, storm surges, and hurricanes, among many others. The Climate Extremes Index (CEI) proposed by Karl *et al*. (1996) has been used to indicate the overall extreme situations of the climate.

Suitable methods are required to find out the extremes from climate data (*e.g.*, Karl *et al*. 1996; Mudelsee 2006). The detection of extremes for a specific climatic quantity, *e.g.*, precipitation, has been investigated in many studies. One of the focuses is to analyze the extremes in daily precipitation (*e.g.*, Karl and Knight 1998; Klein Tank and Können 2003; Zhai *et al.* 2005; Wang *et al*. 2008). There are two problems with the previous daily precipitation analyses. One is that the extremes detected depend on the choice of the starting time of the day. The other is that the extremes are only for the 1-day (24-hour) duration, not including those over other durations (*e.g.*, the shorter durations of 12 or 6 hours and longer durations of 2 or 4 days). A precipitation event that cannot be an extreme over the 1-day duration may become extremes over other durations. These extremes with different durations can all bring, in one way or the other, serious economic and societal damages.

The extremes in multiday precipitation have been detected generally based on the lifespan of rainfall (Karl and Knight 1998; Dairaku *et al*. 2004; Junker *et al*. 2008). Junker *et al*. (2008) pointed out that the starting and ending times of multiday events can be difficult to determine when precipitation comes as a result of several consecutive storms with small breaks between them. It is possible that the intensity averaged over the entire multiday rainfall period is not sufficiently strong to be an extreme, but the intensity over part of the period is relatively strong enough to become an extreme.

Figure 1 shows conceptually some 12-day precipitation processes. In Figure 1a, although the precipitation in each of day 6 and day 7 may not be an extreme, the precipitation of these two days may possibly be an extreme. For the precipitation from day 5 to day 9 in Figure 1b, though the precipitation in each day (or every consecutive 2 days) of the period may not be an extreme, this 5-day precipitation event may be an extreme. The precipitation process in Figure 1c may be best detected as an extreme over a 9-day duration (it is also acceptable if treated as over an 8-day or 10-day duration), but relatively it should not be regarded as a 1-day or 3-day extreme.

The issue investigated in this study is, for a precipitation process, to identify the starting time and the duration so that the intensity of the event with the starting time and duration (the intensity averaged over the period with the starting time and duration) can best become an extreme, compared with those corresponding

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to other durations and starting times. In other words, extreme events should be "best described", in terms of starting time and duration, which can be determined based on intensity.

Extremes, along with drought and monsoons, are important objects of climate monitoring. Lu and Chan (1999) and Zeng and Lu (2004) proposed methods to determine the strength of monsoon and the onset and retreat dates of monsoon. Lu (2009) developed a methodology to monitor and predict drought. It is based on theoretical considerations and mathematical derivations, and the single parameter contained in the relation can be determined with data. The present study on detecting extremes is similar in style. The key is to establish a relation that prescribes how "extreme" intensity varies with duration.

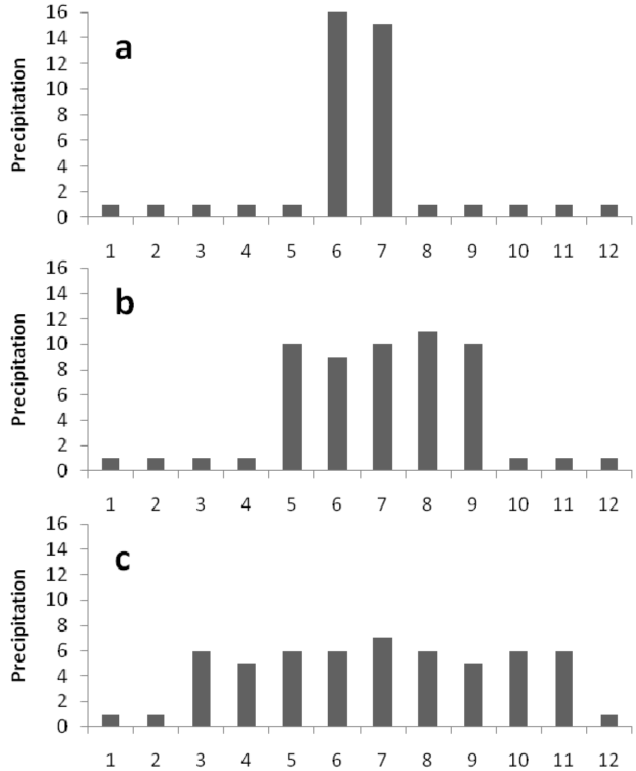

Fig. 1 Conceptual cases that may contain extremes over multi-day durations. An appropriate unit can be given to precipitation.

2. Best describing extremes and capturing them across a range of durations

a. Theoretical relation of "extreme" intensity with duration

Let's first consider the case of setting discount rates in stores for promotion. The general consideration for setting the rates of a product is that for the buyers to buy more, the unit price of the product should decrease with the number of the pieces to be bought in order to save money. However, for the sellers to gain more profit, the total money received from the sales should increase with the number of the pieces to be sold.

The same principle can be applied to establish the relation between "extreme" intensity and duration. The first constraint is that the "extreme" intensity I_e should decrease with the duration T, which can be expressed as

$$\frac{dI_e}{dT} < 0 . \quad (1)$$

The second constraint is that, though with a weaker intensity, the total amount over a longer duration should be larger. Or, the product of the intensity and duration should increase with duration, and this can be expressed as

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

Combining relations (1) and (2) yields

$$0 < a < 1 , \quad (3)$$

where

$$a = -\frac{1}{I_e}\frac{dI_e}{d(lnT)} \quad (4)$$

indicates the relative decrease rate of "extreme" intensity with respect to the logarithm of duration.

Based on the definition and meaning of the parameter a, it is reasonable to assume it as a constant, although the values of the parameter estimated from data over different duration ranges (based on certain definition of the extremes in the data) may change, as will be discussed in section c.

Denote $T = n\,\Delta T$, where ΔT is the increment in duration (*e.g.*, 1 day or 1 hour) based 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 with n from 1 to N (*e.g.*, from 1 to 7) may be considered to capture extremes more completely.

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

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

where $I_e(1)$ is the maximal “extreme” intensity that is over the shortest duration limited by the time resolution of the data.

Note that the duration here is not the lifespan of rainfall, but the time period to be found to make the precipitation intensity averaged over the period become an extreme. The duration can be part of the lifespan of rainfall, and may even contain a rainfall break.

It should also be noted that for the purpose of best describing extremes in this study, the intensity always decreases with duration, and the parameter a is always positive. Differently, in the intensity-duration-frequency (IDF) studies, the duration for examining the extremes (the events with long return periods) is the actual lifespan of the events. The Sherman’s equation on IDF has the same form as equation (5), but the parameter a in the equation may take negative values. The reason is that the precipitation events that may become extremes should normally last for a certain period of time (*e.g.*, 30 minutes), and the events that last for shorter periods are generally weaker in intensity (*e.g.*, Hershfield 1972).

b. Best describing extremes with starting time and duration

Denote the intensity calculated from the data over duration $n\Delta T$ centering at time $m\Delta T$ as $I(n, m)$. The relative intensity of the event is defined as

$$R(n,m) \equiv \frac{I(n,m)}{n^{-a}} = n^a I(n,m)\,. \qquad (6)$$

The purpose of defining the relative intensity is to enlarge the data-calculated intensities of longer durations with the theoretically-derived “extreme” intensity-duration relation so that the intensities of the events over all other durations can be compared with the one over the shortest duration. Through the running of m and the comparison among different values of n, the possible extreme, which has the strongest relative intensity $R(n_0, m_0)$ in a process, can be identified. With the values of n_0 and m_0, the starting time and the duration of the extreme can be determined.

Figure 2 presents the relative intensities with input data from Figure 1. The parameter a takes the moderate values of 0.4, 0.5, and 0.6 to better obey the relations (1) and (2). The data before day 1 and after day 12 are all taken as zero in the calculation. Nine durations (1, 2, 3, 4, 5, 6, 7, 9, and 11 days) are included in the plot for comparing the relative intensities. For the convenience to make the plot, the relative intensity given to day m uses the data from day $m - (n - 1)/2$ to day $m + (n - 1)/2$ if the duration n is an odd number, but from day $m - (n - 2)/2$ to day $m - n/2$ if n is an even number.

Figure 2a shows that the precipitation event can be best described as an extreme (with strongest relative intensity) over the 2-day duration. It is also acceptable if regarded as over the 3-day duration. Both of these can be concluded from the plots with the three values of the parameter a. Whether the extreme can be regarded as over durations of 1-day or 4-days depends on the choice of the parameter. In Figure 2b, results from all the three values of the parameter show that the extreme is over the 5-day duration, and it is still acceptable if regarded as over the 6-day duration. However, whether it can be regarded as over durations of 4 days or 7 days depends on the value of the parameter. In Figure 2c, the different parameter values all indicate an extreme over duration of 9 days. It is acceptable if regarded as over durations of 11 or 7 days, or even 6 or

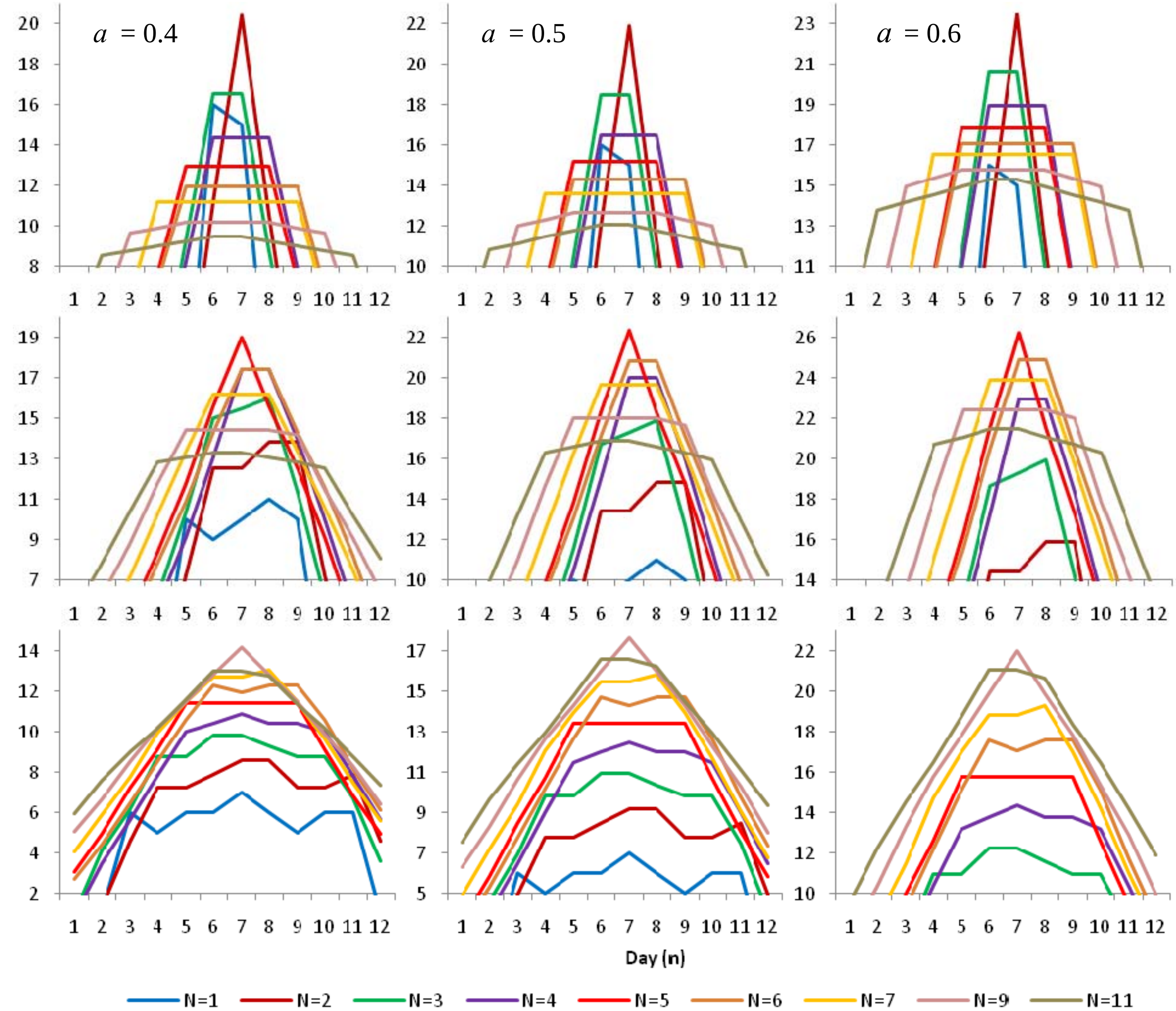

Fig. 2 Relative intensities over 9 durations (1, 2, 3, 4, 5, 6, 7, 9, and 11 days) with input data from Figure 1 and parameter a being 0.4, 0.5, and 0.6, respectively. Note that the curves with even numbers of duration have been made a half-day rightward shift for convenience of making the plots.

5 days, but definitely not 1 or 2 days. Along with the durations, the starting times for the best possible extremes can also be determined based on the maximal relative intensities in the plots and their corresponding values of n and m.

What are shown in Figure 1 are single precipitation processes with limited data. The results suggest that the present method can well detect these typical extremes with different durations through simply giving moderate values to the parameter a, and the detections are not very sensitive to the parameter.

c. Determining the parameter with regression from data

For climatic detection with multi-year data, the value of the parameter a can be determined from the data. Based on equation (5), a regression between the logarithms of duration n and "extreme" intensity $I_e\,(n)$ can be established as

$$\ln I_e\,(n) = -\,a \ln n + c, \qquad (7)$$

where a is the parameter to be determined, and the constant c can also be determined from the data.

For a specific duration n, which varies from 1 to N, the "extreme" intensity $I_e\,(n)$ over the duration can be defined as the intensity that is the strongest 5% of the intensities that are over all the n consecutive days within the multi-year data. With all these values of n and the such-defined $I_e\ (n)$, the values of a and c can be regressed from equation (7). Then, with the parameters a and c determined, the final value of each "extreme" intensity $I_e\ (n)$ can be calculated from the duration n with equation (7).

Note that due to the possible irregular structure in the data's spectrum of intensity over duration, the values of the parameter a determined from equation (5) with the data-defined $I_e(1)$ and $I_e(n)$ may be quite different. The advantage of using the above regression is that the determination of the parameter takes into account comprehensively the overall structure of the intensity spectrum. Also note that the constant c might have large deviation from the data-defined $I_e(1)$, depending on the structure of the intensity spectrum.

d. Capturing extremes across a range of durations

For assessing and understanding the changes in weather and climate extremes, it would be more complete to detect the extremes across a range of durations rather than just over a single (1-day) duration. With the running of the date, if the data-calculated intensity is greater than the "extreme" intensity obtained from regression (7), then an extreme is detected. If precipitation is particularly strong and persistent during a process so that the data-calculated intensities over several different durations are all greater than their corresponding "extreme" intensities, then the process can be detected as extremes over all these durations.

The annual (or seasonal) total of the extremes over each duration can be determined for each year (season), and the change over the multi-years can be analyzed. To be convenient, an alternative way can be used. That is, compare the data-calculated intensity and the regressed "extreme" intensity for each day, and take the number of the days with $I(n, m) > I_e(n)$ in the year (season) to examine the change of the extremes over the duration.

It would be interesting to investigate the relationships between the changes (trends) in the numbers of the extremes over different durations. If daily precipitation extreme has an increasing change, will the extremes over durations of 2 and 4 days have increasing changes either? In some areas, *e.g.*, in Japan, there was no increase in the seasonal total precipitation, but there was an increase in the frequency of the 1-day precipitation extremes (Easterling *et al.* 2000b). The total number of the extremes across a range of durations can also be analyzed to explore more completely the change of precipitation extremes.

In addition to the numbers of the extremes over different durations, the sum of the relative intensities, from equation (6), of all the extremes during the year (season) may also be utilized to assess the changes in the extremes.

3. Summary and discussions

The extremes detected by using daily precipitation data in the previous studies mainly include the following three types: the daily precipitation extremes; the extremes in monthly, seasonal, and annual precipitation totals; and the extremes in the continuous multiday rainfall processes. These studies had not made full use of the daily data. Many researchers examined the extremes in daily precipitation, and what they actually concerned about is not just the extremes that have the exact 24-hour duration; the major reason of finding the daily extremes is that they were using the daily precipitation data. Events with other durations (*e.g.*, 2 or 4 days) may also be important in bringing losses as long as they can be sufficiently strong (relative to their durations), and thus can become extremes.

Therefore, for the purpose of studying the changes of weather and climate extremes, it is far from complete to merely consider a single duration of a day, and it is more suitable to find out all the extremes that are over at least a range of durations (*e.g.*, from 1 to several days). The events that cannot become daily extremes might become extremes over other durations. The goal of this study is, for a precipitation process, to determine the duration and starting time of an event (within the process) that can best become an extreme.

The key of the approach in this study is to prescribe reasonably the intensities of the extremes that are over the different durations. Theoretically, the strongest intensity should be found from the instantaneous values of intensity. In the practical analysis with data, the strongest intensity can be obtained from the shortest duration considered. The value of the intensity averaged over a longer duration should go down. So, the "extreme" intensity always decreases with duration.

The other constraint of the "extreme" intensity-duration relation is that, in spite of the decrease of the intensity with duration, the total accumulation of precipitation should increase with duration. These are reasonable considerations, and might be applied to many other problems, such as determining how the intensity of flood or drought that make human or crops unendurable varies with the lasting time of the flood or drought. These constraints ensure that "extreme" intensity does not decrease linearly with duration.

A theoretical "extreme" intensity-duration relation is thus derived. The relation contains only a single parameter, and it can be treated as a constant. The conceptual examples given in this study are just rainfall episodes, but the extremes over the different durations can be well detected with simply giving moderate values to the parameter, and the detections are not very sensitive to the parameter.

For detecting extremes with multi-year data, the value of the parameter can be determined from the data by using the regression between the logarithms of the duration and the corresponding initial "extreme" intensity defined with the data. The final values of the "extreme" intensities can be computed with the parameter determined from the regression equation. It is noticed that the regression relation obtained from the data may not be statistically significant, but this does not matter, since the purpose here is just to prescribe the "extreme" intensities with considering the overall structure of the intensity spectrum.

Through capturing the extremes over different durations with the method of this study, relationships between daily extremes and the extremes over other durations will be analyzed. The changes of the total extremes across a range of durations will also be investigated. The Climate Extremes Index (CEI) even combines the extremes of different quantities.

Although daily precipitation is used in this study as an example, the method can be applied to detect extremes over durations at hourly scales if hourly data are available. The method can also be used to detect extremes of other climate quantities such as heat waves. All these applications and relationship analyses will be carried out in the next-step work by using real observations and data from climate models.

The definition of weather and climate extremes is still an issue in debate, as indicated from the workshops of the recent years, which aimed to summarize, compare, and assess the various definitions and to develop a common framework. Based on the understanding from this research, a definition can be proposed as follows. To a specific weather and climate quantity of interest, an extreme is the event whose intensity corresponding to its starting time and duration is relatively the strongest compared with those with other durations and starting times.

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