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Advances in Climate Change Research 9 (2018) 161−169

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Review

A research progress review on regional extreme events

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Received 29 November 2017; revised 12 May 2018; accepted 31 August 2018
Available online 6 September 2018

Abstract

An extreme (weather and climate) event does not only mean that an extreme occurs at a location, but more generally it can impact a certain area and last a certain period of time, which is defined as a regional extreme event (REE) with a certain impacted area and duration. The concept of REE has been defined to allow mainly objective assessment of the events without a pre-determined boundary and duration. This paper reviews the studies on REEs published during the past 20 years, especially recent years. Mainly in view of methodology, these studies can be divided into three types: studies focusing on spatial simultaneity, studies focusing on temporal persistence, and studies identifying REEs. The methods identifying REEs include two kinds, e.g., type-I methods stressing REE's temporal persistence within a relatively certain area and type-II methods focusing on catching a complete REE. Identification methods proposed in this paper could provide valuable information for various purposes, such as real-time monitoring, estimating long-term changes, mechanism diagnosis, forecasting study and even attribution analysis. Research on REEs is important for objectively defining extreme weather and climate events, which depends on the spatial and temporal scales of interest. Such an objective definition will support ongoing climate monitoring and improve the assessment of how regional extreme events have changed over time.

Keywords: Extreme (weather and climate) events; Regional extreme events; Research progress; Review

1. Introduction

During the past several decades, climate change and extreme weather and climate events have become a field of increasing concern. Recently, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Extremes (SREX) (IPCC, 2012) assessed the complex relationship between disasters and extreme events, which depends on exposure and vulnerability as well as the severity of the extreme event itself, and provided a comprehensive overview of extreme events including the definitions, classifications, and research results.

Most observational studies of extreme events have been carried out over the last 30 years. Karl et al. (1984), which was one of the earliest studies, conducted a study on extreme temperatures and diurnal temperature range. Precipitation extremes became a focus later; one early example is a study of extreme precipitation in Japan by Iwashima and Yamamoto (1993).

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Peer review under responsibility of National Climate Center (China Meteorological Administration).

https://doi.org/10.1016/j.accre.2018.08.001

Since the early 1990s, international research efforts on extreme events (Karl et al., 1986, 1991; Plantico et al., 1990; Horton, 1995; Easterling et al., 1997; Zhai and Ren, 1997; Collins et al., 2000) were strongly driven by two developments. The first one was the establishment of IPCC in 1988 and its series of assessment reports from 1990 onwards, and the second was the Climate Variability and Predictability (CLIVAR) project launched in 1993. Later, two other developments, the workshop on indices and indicators for climate extremes held in the U.S. in 1997, and the birth of the Expert Team on Climate Change Detection and Indices (ETCCDI), provided a catalyst for the research work in various aspects of extreme weather and climate events.

A number of papers were produced as a result of the 1997 workshop and subsequent regional workshops (Karl and Knight, 1998; Ren and Zhai, 1998; Suppiah and Hennessy, 1998; Groisman et al., 1999; Jones et al., 1999; Plummer et al., 1999; Zhai et al., 1999). More comprehensive global or semi-global studies also emerged, either consolidating the results of regional workshops or carrying out independent analyses (Easterling et al., 2000; Frich et al., 2002; Groisman et al., 2005; Alexander et al., 2006; Zhang et al., 2011).

New analyses at the global, regional, and national scales have continued to be published, covering most parts of the world (Klein-Tank et al., 2006; Barrucand et al., 2008; Kenyon and Hegerl, 2008, 2010; Kunkel et al., 2008; Pavan et al., 2008; Peterson et al., 2008; Rusticucci and Renom, 2008; Scaife et al., 2008; Alexander et al., 2009; Choi et al., 2009; Pryor et al., 2009; Lupikasza, 2010; Toreti et al., 2010; Morak et al., 2011, 2013; Zwiers et al., 2011; Li et al., 2012; Meehl et al., 2012; Weaver, 2012; Skansi et al., 2013; Villarini et al., 2013; Westra et al., 2013). These analyses, and in particular global-scale analyses such as Donat et al. (2013a, b, c), formed the basis for the conclusions on changes in extreme weather and climate events in the IPCC Fifth Assessment Report (AR5) (IPCC, 2013). AR5 showed that it is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale.

Other types of extreme weather and climate events considered in AR5, such as floods, tropical and extratropical storms, and small-scale severe weather events (thunderstorms, hail, and tornadoes), are beyond the scope of this article. However, drought, which can be defined according to special indices like temperature and precipitation extremes, is a special case, as it is already routinely analyzed on a spatial basis.

Drought index studies have a long history, with Penman (1948) developing an aridity index and Palmer (1965) proposing the Palmer Drought Severity Index (PDSI). There has been a marked upsurge in activity in this area over the last 20 years (Karl et al., 1996; Dai et al., 1998; Szinell et al., 1998; Kunkel et al., 1999; Heim, 2002; Zou et al., 2005; Sheffield et al., 2009, 2012; Vidal et al., 2010; Dai, 2011a, 2013; Dorigo et al., 2012; Schrier et al., 2013). As the direct measurements of variables such as soil moisture are so few (Robock et al., 2000), precipitation-based indices (e.g., PDSI, Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index (SPEI)) and hydrological drought indicators (Vidal et al., 2010; Dai, 2011b) are generally applied for assessing drought. The drought index and associated timescale can strongly influence the long-term trends and intensity of the drought events (Sheffield et al., 2009; Vidal et al., 2010).

Indices of extreme temperature and short-period precipitation are a more recent development, with the 1997 workshop on indices and indicators for climate extremes being a major catalyst for their development. The ETCCDI has led the standardization of extreme temperature and precipitation indices, with the development of a standard set of 27 indices (http://etccdi.pacificclimate.org/indices_def.shtml), which have been used in many of the station- and grid-based studies cited in this paper.

These drought, temperature, and precipitation indices are generally designed for use at specific locations (a place or a grid point), although the results from multiple locations/grid points may be aggregated, as in many of the studies cited in this paper. However, the spatial extent and the temporal persistence of an extreme event are two important aspects of its character and defining them is therefore important. In this paper, an extreme event, which has a certain impacted area and duration, is defined as a regional extreme event (REE). Some notable examples of REEs are the 2003 boreal summer heat wave in Europe, the 2009/2010 drought in Southwest China, the 2010 boreal summer Russian heat wave, and so on.

Most of these studies have been focused on specific points (typically, a defined set of stations or grid points). However, some studies, particularly during the last 20 years, pay attention to REEs. The present article intends to review these studies and identify the progress in research of REEs. Mainly in view of methodology, studies of regional extreme events can be divided into three types: those focusing on spatial simultaneity analyses (Section 2), those focusing on temporal persistence (Section 3), and those identifying REEs (Section 4). In Section 5, a summary and discussion will be given. In addition, by taking both the spatial and temporal scales of an extreme (weather and climate) event into consideration, the authors has tried to propose a new definition of extreme weather and climate events at the end of this paper.

2. Spatial simultaneity analyses

Extreme events at individual stations may occur simultaneously or have close relationships. Some studies have focused on spatial characteristics of extremes, defining characteristic modes of spatial variability based on data for individual stations, mainly through statistical methodologies such as correlation analyses, empirical orthogonal function (EOF) analyses and cumulative frequency distribution (CFD).

Mainly by use of correlation analyses, some studies paid attention to spatial simultaneity analyses on drought, precipitation extremes, and temperature extremes. Oladipo (1986) studied the drought patterns in the Interior Plains of North America, and found four patterns of moisture anomaly with distinct differences between the eastern, western, southern, and extreme northern parts of the analyzed region. In general, large-scale droughts do not frequently cover the region as a whole, which means that drought in the Interior Plains of North America generally occurs at sub-regional scales. Min and Qian (2008) analyzed regional characteristics of precipitation extremes in China during 1960−2003. Their results indicated that extreme precipitation events bear a close spatial relationship mainly over southern China. Gong et al. (2009) analyzed regional characteristics of temperature extremes in China using the 1948−2005 NCEP/NCAR reanalysis dataset, and found that eight different zones exist.

Using EOF analysis and the PDSI, Dai et al. (1998) analyzed global variations of droughts and wet spells during 1900−1995 and found that the first leading EOF of the monthly PDSI correlates significantly with ENSO events in time and space. Later, Dai et al. (2004) extended their dataset to perform a more in-depth study, which confirmed their previous findings.

Applying the method of CFD, Huang and Qian (2009) studied the regional characteristics of extreme temperatures during 1961−2002 in China. They presented an example of applying the CFD method at Nanjing station. First, the cumulative frequency distribution was transformed into the probability distribution, and then, the concurrence stations were defined as those which had probability greater than a threshold value (such as 0.2).

Among the methods of EOF, CDF and correlation analysis mentioned above, EOF can reveal directly regional characteristics with similar variations at different stations, while both CDF and correlation analysis present regional characteristics that show simultaneous occurrences with specific stations/grids. Meanwhile, above studies cover drought, precipitation extremes, and maximum and minimum extreme temperatures. Though most of them do not focus on regional extreme events themselves, they reveal characteristics that occur simultaneously at different stations/grids in a same region and are a basical property of a regional extreme event. However, studies in this section almost do not pay attention to another basical property of a regional extreme event—temporal persistence.

3. Studies focusing on temporal persistence

In temporal terms, temporal persistence or the duration is an important character of REEs. Many studies focus on temporal persistence and identify the duration basing on analyzing time series. Generally, methods are of two types: the first involving time series at individual locations or grid points, and the second involving a spatial average over a defined region. These studies mainly focused on heat waves, and some examples are presented below; while several other studies examined the methods to identify episodes in time within a longer time series.

3.1. Different methods for identifying heat wave events

An example of the analysis of location-specific or defined-region-specific time series is the assessment of heat waves. Since IPCC AR4, in addition to the studies cited below, many studies (Fischer and Schar, 2010; Kuglitsch et al., 2010; Perkins et al., 2012; Pezza et al., 2012; Donat et al., 2013a, c; Perkins and Alexander, 2013; Peterson et al., 2013) have studied changes in multi-day temperature extremes and assessed different heat wave indices such as frequency, intensity, duration, and spatial extent.

Site-based studies include those of Della-Marta et al. (2007) and Habeeb et al. (2015). In Della-Marta et al. (2007), when the maximum number of consecutive days of the summer maximum temperature (DSMT) exceeds the 95th daily percentile of DSMT during June−August, a heat wave (HW) is defined, based on which the heat wave duration was assessed across a number of European stations. From the time series of the DSMT measured in Paris in 2003, heat waves with the duration of even 12 days can be identified and traced.

In contrast, Habeeb et al. (2015) used minimum apparent temperature, which is a function of both temperature and humidity, to define heat waves. A heat wave is defined when minimum apparent temperature exceeds the 85th percentile threshold and this occurs for at least two consecutive days. In addition, variations in four heat wave aspects including frequency, duration, intensity, and timing during 1961−2010, in 50 large U.S. cities, were examined in this study.

Using gridded data, Perkins et al. (2012) proposed three definitions of heat wave/warm spell based respectively on maximum temperature, minimum temperature, and the excess heat factor (EHF) (an index combining maximum temperature, minimum temperature, and an "acclimatization factor"), noting that different applications may require different definitions of a "heat wave". For each index, a heatwave/warm spell is defined when the respective threshold is exceeded for at least three consecutive days. Further to the three indices, a multi-aspect framework, where various attributes of heatwave frequency, intensity, and duration are represented, was applied.

Hansen et al. (2012) and Coumou et al. (2013) considered monthly means in gridded datasets of the 131-year (1880−2010) combined land-ocean surface temperature data provided by NASA-GISS (Hansen et al., 2010). They indicated that record-breaking temperatures, or temperatures in the uppermost part of the frequency distribution, substantially exceed what would be expected by chance in recent decades, but caution is required when making inferences between the studies considering only monthly means and those considering shorter periods for multi-day events and/or using more complex definitions for heat wave events.

3.2. Common methods for identifying episodes in time series

A typical case of the methods seeking to identify episodes within a time series is that of Biondi et al. (2002, 2005, 2008). The authors examined time series based on either individual stations or a fixed region, with characteristic parameters gradually becoming more and more comprehensive and rich. For example, in the Biondi et al. (2008) method, the following factors are considered.

(1) Duration. Duration is the length of the time period between the event starting and ending time, i.e., the number of time intervals (e.g., days, months or years) during which the process remains continuously above (or below) the threshold.

(2) Magnitude. Magnitude is the sum of all the process values (the observations minus the threshold) during a given duration, hence it is equivalent to the area under (or above) the reference level. Its formula is as follows:

$$X = \sum_{i-1}^{N} V_i \sum_{i-1}^{N} (W_i - w), \tag{1}$$

where w is the time-invariant reference level (threshold), and V_i is the departure of W_i from w.

(3) Peak value. Peak value is the (absolute) maximum departure reached by the process within a given episode. Its formula is as follows:

$$R = \max_{1 \le i \le N} |V_i| = \max_{1 \le i \le N} |W_i - w|, \tag{2}$$

as can be seen, studies in this section mainly focus on heat waves, and some methods have been developed to identify heat wave events, with differences in indices, thresholds and time scales. Meanwhile, several studies pay attention to develop common methods for identifying episodes in time series. Actually, the methods for identifying heat wave events could be summarized to belong to a certain common method for identifying episodes in time series, with differences in values of the parameters such as index, threshold and time scale. In addition,it needs to be pointed out that, studies in this section almost pay little attention to another basical property of a regional extreme event–the spatial extent or impacted area.

4. Identifying REEs

This section has proposed the concept that a REE possesses both regional and process characteristics, i.e., a certain impacted area and a duration. Several methods have been developed to identify different kinds of REEs. The methods used to identify REEs in these studies can be mainly divided into two types. The two types differ from each other mainly in the viewpoint stressed. Type-I methods stress REE's temporal persistence within a relatively certain area, while type-II methods focus on catching a complete REE. Meanwhile, a method developed by Tang et al. (2006) is much complex and different from above two kinds of methods.

4.1. Type-I methods stressing REE's temporal persistence within a relatively certain area

Several studies (Ding and Qian, 2011; Qian et al., 2011, 2014; Zhang and Qian, 2011; Chen and Zhai, 2013) have developed methods of this type based on station time series, identifying individual-station time series events at first and then considering the spatial consistency of these events to identify REEs. The techniques dealing with regional drought events (Qian et al., 2011), regional high temperature events (Ding and Qian, 2011), and regional low temperature events (Zhang and Qian, 2011) have similar ideas, whilst those dealing with regional extreme precipitation events (Chen and Zhai, 2013) and dealing with cold–wet spells (Qian et al., 2014) are similar in general but different from them in the timing of events.

The concept in the three methods used by Ding and Qian (2011), Qian et al. (2011), and Zhang and Qian (2011) shares the following technical steps (Fig. 1):

- First, choose a suitable technique to identify time series events. For example, the techniques described in Section 3 could be selected to define individual-station-based events.
- Second, define adjacent stations. A distance of 200–550 km (200 km in Chen and Zhai (2013)) was selected as thresholds for defining the two stations i and j as adjacent stations to each other.
- Third, define the regional event. If there are at least five adjacent stations (three in Chen and Zhai (2013)) which have the occurrence of the same type of individual-station-based events (such as drought, heavy precipitation, high temperature or low temperature) over the same time period, it can be defined as a regional event as a whole.
- Fourth, establish an index system for regional events. There are three single indices for a regional event: duration, extent, and intensity. Here duration is the length (in days) of the same time period for all the adjacent stations involved.

Techniques in Chen and Zhai (2013) and Qian et al. (2014) define a specific event starting from the first day of any of the individual station-based events involved to the last day of any station-based event.

The obvious character of these methods is stressing REE's temporal persistence within a relatively certain area. While the methods can effectively identify REEs that have serous impacts on relatively certain areas, the distribution of stations applied may influence directly the results, with a more high-resolution and more evenly-distributed distribution proving more accurate results.

4.2. Type-II methods focusing on catching the complete REE

In this section, the methods directly deal with daily (or monthly) impacted areas of REEs and then consider the

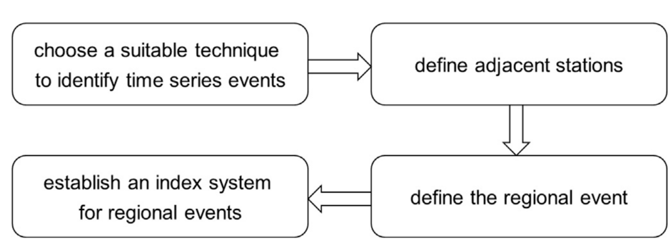

Fig. 1. The general flowchart for the methods stressing REE's temporal persistence within a relatively certain area.

temporal persistence to identify REEs. To identify regional drought events from monthly soil moisture data, Andreadis et al. (2005) developed a technique that can be summarized into three steps:

- Step 1, for each grid point, select the soil moisture percentile value of 20% as the threshold for drought status.
- Step 2, use a simple clustering algorithm to identify drought clusters in the spatial distribution for each month: starting from each grid under drought status, and then in the surrounding 3 × 3 grids, to identify the adjacent drought grids and combine them into a drought cluster. Repeat the procedure at each "adjacent drought grid," then obtain the complete drought clusters (or drought area; the minimum extent of a drought cluster is defined as 10 grid boxes).
- Step 3, determine the drought time continuity between adjacent time steps: during a drought process, some small drought clusters (drought areas) can be merged into a bigger drought cluster, while a bigger drought cluster may also be split into multiple small drought clusters, and ultimately to form a complete drought event that meets the standards of extent and duration.

This method was applied to drought studies in the U.S. (Andreadis et al., 2005) and to global and continental droughts (Sheffield et al., 2009). Sheffield et al. (2009) identified the extreme drought events that occurred globally and for each continent. The drought event with the longest duration of 49 months occurred in Asia during 1984–1988, and the second one was the 1950–1953 North American drought event which lasted 44 months, while the one with the largest impacted area was the African drought in the early 1980s, with its peak extent covering 11 million km^2 in April 1983.

Drought is the kind of regional extreme events which has almost the largest time scale. Considering regional extreme events having the same characteristics of impacted area and duration, is it possible to develop a common technique for identifying regional extreme events? The answer is yes.

By focusing on common regional extreme events, the Chinese Academy of Meteorological Sciences and Beijing Climate Center have launched a series of studies. Ren et al. (2012) developed an objective identification technique for regional extreme events (OITREE), which includes several parameters that permit empirical or subjective values and can deal with any area of concern and any sort of extreme events that can be represented by a daily index at individual point. The method is simple conceptually: a model named "the string of candied fruits" was first proposed, and with the idea of the model, the daily impacted areas can be reasonably strung together to form a complete regional event (Fig. 1 in the reference). In addition, an index system for regional weather and climate events, including five single indices and an integrated index, was specially proposed. Similar to type-I methods, the distribution of stations applied also may influence directly the results. Till now, OITREE has been widely applied in studying different types of regional extreme events in China (An et al., 2014; Li et al., 2014; Wang et al., 2014, 2017; Gong et al., 2012, 2014; Ren et al., 2015; Zou and Ren, 2015).

5. Discussion and summary

This paper reviews the studies on REEs (especially observation studies) and associated methodologies during the last 20 years. Generally, these studies can be divided into three types: the first type is spatial simultaneity analyses, seeking to define characteristic spatial modes of variability of extreme events. Statistical methodologies applied in such studies are mainly empirical orthogonal function (EOF) analyses, cumulative frequency distribution (CFD), and correlation analyses. This type of studies focuses on the impacted area of an extreme event, but pays little attention to the duration. The second type is identifying temporal persistence, of which heat waves are a much studied example. Several studies focused on methods to identify common time series events in either an individual-station time series or a fixed-region time series, on a variety of timescales. This kind of studies, on the other side, pays attention to the duration, and only some of them studying on a fixed-region time series notice the impacted area. The third type is identifying REEs. To identify a REE that has a certain impacted area and duration, from the view of idea, the existing methods can be divided into two kinds, e.g., type-I methods stressing REE's temporal persistence within a relatively certain area and type-II methods focusing on catching a complete REE, have mainly been developed to identify different kinds of regional events. This type of studies pays attention to both the impacted area and the duration of an extreme event.

The studies documented in this paper show that research of regional extreme weather and climate events has been attracting more and more attention. The first type and the second type studies are still worth researching and encouraged to be carried out for different regions and different REEs when necessary. However, some issues about the third type studies need to be especially acknowledged and discussed. Firstly, the events identified by the methods including both type-I methods and type-II methods, which might be directly called REEs, are not actually extreme but generally regional events. Under a new index system for the regional events, only those events, which meet the statistical extreme standards, are actually REEs. Secondly, the regional events identified by type-I methods generally show obvious temporal persistence and easily result in disasters within the impacted areas. Meanwhile, the regional events identified by type-II methods include not only the regional events with obvious temporal persistence but also the regional events showing movements during the courses of the events. Then, it is not difficult to understand that the results of type-II methods contain the results of type-I methods, with a regional event of type-I methods being the same as or a part of a corresponding regional event of type-II methods. Thirdly, for a specific region of concern such as the mainlandor a province of China, results of the methods, including both type-I methods and type-II methods, are comparable and can be used for estimating long-term changes when data are available. Studies (Ding and Qian, 2011; Qian et al., 2011, 2014; Zhang and Qian, 2011; Chen and Zhai, 2013; Ren et al. 2012, 2015; Gong et al., 2012; An et al., 2014; Li et al., 2014; Wang et al., 2014, 2017; Zou and Ren, 2015) mentioned in Section 4.2 all deal with estimating long-term changes of the REEs. Fourthly, the methods are encouraged to be applied in not only new studies on identifying REEs for different regions but also operations on monitoring different REEs. If focusing on regional events with obvious temporal persistence, a type-I method is a good choice, otherwise, a type-II method is a better one. Since 2010, the OITREE has been applied in the operations of Beijing Climate Center (available online at http://cmdp.ncc-cma.net/cn/monitoring.htm), with its products of four different REEs within China being absorbed in China Climate Change Monitoring Bulletin. Finally, based on the results of the methods, researches with different purposes can be carried out. One kind of studies is estimating long-term changes for the REEs mentioned before. In addition, with such a system and related database, users could easily gain access to both historical cases and real-time ones, which have been widely employed in mechanism diagnosis and impact evaluation (Chen and Zhai, 2014a; b; Gong et al., 2014; Ramos et al., 2016). Further, long-lasting extremes tend to be associated with slowing-evolving circulation patterns, which are more predicable with longer lead time (up to two weeks, see Dole et al., 2011; Chen and Zhai, 2014a), and Zhou and Zhai (2016) establish an analog prediction system for forecasting persistent extreme precipitation (PEP) in the Yangtze−Huai River Valley. From the perspective of attribution, Sun et al. (2016), Burke et al. (2016) and Sun et al. (2018) study on the 2015 extreme high temperature events in western China, extreme rainfall in Southeast China during May 2015 and the 2016 super cold surge in eastern China, respectively. It's no doubt that similar studies might also be done for historical REE cases.

In summary, identification methods proposed in this review could provide valuable information for various purposes, such as real-time monitoring, estimating long-term changes, mechanism diagnosis, forecasting study and even attribution analysis. In addition, whilst a standardized set of indices for point-specific temperature and precipitation extremes exists through the work of the ETCCDI, no comparable standardized set of definitions exists for regional-scale events.

Until now, there is no unique definition of what constitutes an extreme weather and climate event in the scientific literature, given variations in regions and sectors affected (Stephenson et al., 2008). A representative one is given in the SREX, and the report defines an "extreme climate or weather event" or "climate extreme" as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (IPCC, 2012).

Considering the progress of regional extreme event research, the Commission for Climatology (CCl) of World Meteorological Organization (WMO) started a Task Team on Definitions of Extreme Weather and Climate Events (TT-DEWCE) in 2010 (Baddour and Bessemoulin, 2009; WMO, 2010). It can be seen from the above review that extreme (weather and climate) events are generally a regional phenomenon, i.e., a regional event with a certain spatial scale and a certain time scale. From above analysis, we can see that the first type and the second type of studies mainly pay attention to either the impacted area or the duration of an extreme event, and the third type of studies pays attention to both the two aspects. In any new definition of an extreme (weather and climate) event, it is very important and necessary not only to keep the core content of existing definitions but also to fully absorb the new understanding, which is that an extreme event has a certain spatial scale (the impacted area) and a certain time scale (the duration), in regional extreme weather and climate event research. In this conceptual framework, an extreme event at individual points (stations) can be treated as a special case of REEs when the spatial scale is a point.

To attempt to do this, the authors would like to tentatively and preliminarily propose a definition of extreme weather and climate events as follows. For a weather and climate phenomenon (event) with a certain spatial scale and time scale, if there is an indicator (variable or index) that can represent the event and when it meets the statistical extreme standards, i.e., the value of the indicator being above (or below) the upper (or lower) threshold in the tail of its probability distribution function, then the event is called an extreme weather and climate event.

Acknowledgments

The authors would like to express their sincere thanks to the two anonymous reviewers and Dr. Yang Chen for helpful suggestions and comments. This research was supported by the National Natural Science Foundation of China (41175075, 41375056, and 91224004), China Meteorological Administration Climate Change Special Fund (CCSF201333), European Union-funded project-Uncertainties in Ensembles of Regional Reanalyses (UERRA, FP7-SPACE-2013-1 607193), and Spanish Ministry of Economy and Competitiveness (MINECO) grant CGL 2014-52901-P.

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