Journal of Hydrology 562 (2018) 305–317

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

On the event-based extreme precipitation across China: Time distribution patterns, trends, and return levels

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ARTICLE INFO

This manuscript was handled by C. Corradini, Editor-in-Chief, with the assistance of Corrado Corradini, Associate Editor

Keywords:
Event-based extreme precipitation
Time distribution pattern
Trend
Return level
China

ABSTRACT

The preceding and succeeding precipitation (P-S-P) of a precipitation extreme often contribute to flooding initiated by the extreme event itself. In this study, the concept of event-based extreme precipitation (EEP), defined as a precipitation event (daily precipitation ≥ 1 mm for successive days) having at least one daily precipitation extreme (daily precipitation ≥ the 99th percentile), is proposed to consider P-S-P of daily extreme precipitation. Further, the time distribution patterns, trends, and return levels of EEPs across China are analyzed based on a 0.5 × 0.5° gridded precipitation dataset covering 1961–2016. The data demonstrate the EEP concept, that multi-day EEP with daily extreme precipitation occurring late in the event is predominant in China except for the Northwest where single-day EEP prevails. Over west China, EEP is increasing and becomes more temporally concentrated. In the lower Lantsang River, along the southeast coastline and on the Hainan Island, the 20- and 50-yr return levels of EEP would exceed 300 and 400 mm, respectively. Moreover, global warming possibly induces more single-day EEPs in the Northwest. The EEP concept may help guide attempts to manage extreme precipitation on event basis, which is particularly useful for regions characterized by long-lasting extreme precipitation.

1. Introduction

The fifth Intergovernmental Panel on Climate Change (IPCC) reported that the atmospheric temperature during the last century has increased by approximately 0.74 °C and is projected to increase another 1.8–4 °C in the coming century (IPCC, 2014). An important consequence of the increase in air temperature is that the atmosphere tends to hold much more water vapors, leading to intensification of extreme precipitation across many regions (IPCC, 2014; Donat et al., 2016; Fischer and Knutti, 2016; Prein et al., 2016; Wang et al., 2017a). Understanding extreme precipitation behaviors is essential and increasingly necessary for flooding prevention, disaster prediction and mitigation (Easterling et al., 2000; Kendon et al., 2014; Capello et al., 2016; Zhang et al., 2017).

A precipitation event is often characterized by three stages, i.e. initiation, development and decay stages which altogether may last a few days (White et al., 2017). Occasionally, extreme precipitation occurs during the development stage where precipitation intensity exceeds a given threshold or a percentile value (Xu et al., 2012; Hitchens et al., 2013). For such a precipitation event containing extreme precipitation, the total precipitation amount is composed of extreme precipitation and the preceding and succeeding precipitation (P-S-P). Most of studies on extreme precipitation characteristics (e.g. frequency, duration and amount) often separate extreme precipitation from P-S-P (Karl and Knight, 1998; Wentz et al., 2007; Min et al., 2011; Vittal et al., 2013; Ma et al., 2015; Xiao et al., 2016). In fact, while extreme precipitation can pose considerable flooding, P-S-P could worsen the situation (Hamidreza et al., 2010). For example, the heavy precipitation event that struck the Yangtze-Huai River basin (around 30–34° N, 112–120° E) from June 8th to 16th in 1991, has brought approximately 200 mm total precipitation. The precipitation amounts on June 8th, 13th and 14th were 40, 50 and 45 mm, respectively (Lu et al., 2017). Suppose the 50 mm precipitation on June 13th just reaches the standard of daily extreme. The precipitation amounts on June 8th and 14th are less than this standard and could not be considered as extreme. Nevertheless, the precipitation amounts on these two days are still fairly heavy and were reported to induce flooding as well (Tao, 1993; Lu and Ding, 1997; Wang et al., 2000). More importantly, these two precipitation amounts occurred closely to that on June 13th and therefore the precipitation amounts on these three days altogether could trigger an extremely

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https://doi.org/10.1016/j.jhydrol.2018.05.028
Received 23 March 2018; Received in revised form 8 May 2018; Accepted 11 May 2018
Available online 12 May 2018
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heavy flooding through cumulative runoff generation (Lu et al., 2015; She et al., 2015). Therefore, the overall impact of the three daily precipitation events might be underestimated if the 50 mm 'extreme' precipitation is solely considered regardless of the 40 mm preceding precipitation and the 45 mm succeeding precipitation. In this regard, extreme precipitation should be better defined with consideration to P-S-P.

Existing observational evidence has characterized daily extreme precipitation in terms of frequency, intensity and amount (Goswami et al., 2006; You et al., 2011; Madsen et al., 2014). However, the time distribution pattern (TDP), also referred to as the temporal profile of extreme precipitation, remains highly uncertain and intractable. For one, natural extreme precipitation processes are rather complex and difficult to characterize (Ghassabi et al., 2016). Second, and equally important, the investigation on such issue often requires high quality data that are not widely available nowadays particularly in underdeveloped and developing countries (Zhao et al., 2005; Huffman et al., 2007). TDP of extreme precipitation plays a critical role in hydraulic structure design, numerical weather prediction, hydrologic forecasting, reservoir operation, and flooding control, since it determines surface runoff and river flow processes (Hamidreza et al., 2010). It has only been discussed in some regions previously, mostly on daily and small spatial scales (Keifer and Chu, 1957; Pilgrim and Cordery, 1975; Yen and Chow, 1980; Huff, 1990; Cen et al., 1998; Bonta, 2004; Hamidreza et al., 2010; Ghassabi et al., 2016). More recently, meso-scale and large-scale TDPs of extreme precipitation have received an increasing attention (Hitchens et al., 2013; Trier et al., 2014; Zuluaga and Houze, 2015). For China, few systematic measurements have been made on TDPs of extreme precipitation, and previous studies mainly focus on daily extreme precipitation (Chen et al., 2015; Hu et al., 2017; Wu et al., 2018). For multi-day extreme precipitation over China, however, the TDPs still remain unknown and require more documentation.

On the other hand, although trends in extreme precipitation across China have been discussed in the last few decades (Wang and Zou, 2005; Gemmer et al., 2011; Yang et al., 2012; Li et al., 2016), the trends documented in published works may not completely agree, partly due to the use of different extreme precipitation definitions, datasets, and study periods (Dash et al., 2009; Ghosh et al., 2009; Wu et al., 2016). In particular, when extreme precipitation is defined in different ways, the characteristics and trends of extreme precipitation may differ substantially from one another (Vittal et al., 2013; She et al., 2015). A further study on trends in extreme precipitation over China can not only enable a comparison between studies but also enrich our knowledge of extreme precipitation changes, which is beneficial for developing appropriate adaptation and mitigation strategies (Guo et al., 2017).

This then is the focus of our paper, where we introduce a new concept of extreme precipitation to consider P-S-P of extreme precipitation, and examine the TDPs and trends of extreme precipitation events in China. Within the concept framework, a precipitation event is defined as daily precipitation no less than 1 mm for successive days (You, et al., 2011; Oueslati et al., 2017), whilst a daily precipitation extreme is defined as daily precipitation exceeding the 99th percentile (Gemmer et al., 2011). The precipitation event having at least one daily extreme is termed as an event-based extreme precipitation (EEP). By definition, an EEP could include daily extreme precipitation and P-S-P. The EEP concept can also identify extreme precipitation of different durations in an objective way, which is an important step towards improving our understanding of extreme precipitation as an event-based phenomenon (Lu et al., 2017; White et al., 2017). In addition to the introduction of the EEP concept, examination of TDPs and trends of EEPs in China, we will estimate EEP return levels and further discuss the relationship between EEP changes and global warming. We hope this study could help decision makers and stakeholders better manage extreme precipitation in a warming world.

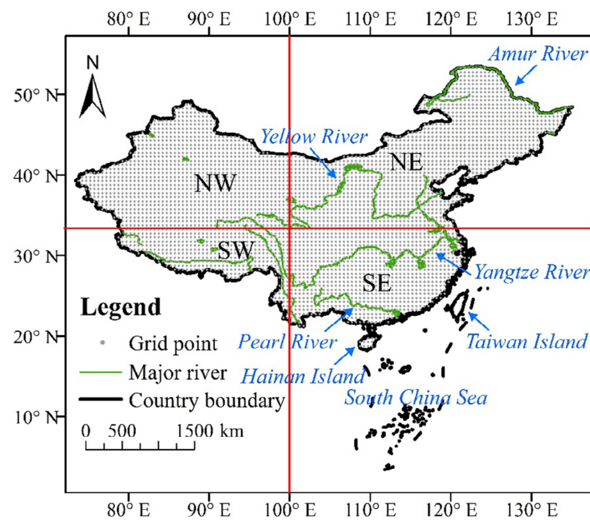

Fig. 1. Locations of the 3825 grid points and four sub-regions in China: Northwest China (NW, 33–50° N, 74–100° E), Northeast China (NE, 33–55° N, 100–134° E), Southeast China (SE, 18–33° N, 100–123° E), and Southwest China (SW, 21–33° N, 78–100° E).

2. Data and methods

2.1. Data source

A high-resolution (0.5 × 0.5°) gridded daily precipitation dataset (V2.0) obtained from Chinese Meteorological Administration (http://www.cma.gov.cn/) is used in the study. The dataset covers the period of 1961–2016, which was generated from 2472 observed rain gauge stations across China by thin plate spline interpolation method and GTOPO30 (Global 30 Arc-Second Elevation) data resampling. The quality of the dataset was strictly controlled by National Meteorological Information Centre (NMIC, 2012). It is considered as the latest gridded precipitation data for China which has not yet been widely used (Wu et al., 2016; Lu et al., 2017). The total 3825 grid points are stippled in Fig. 1.

To explore the relationship between EEP and global warming, the GISTEMP global surface temperature dataset is employed in the study (Hansen et al., 2010). This dataset is available at https://data.giss.nasa.gov/gistemp/, and has been utilized to diagnose the relationship between precipitation change and global mean temperature anomaly in China (Ma et al., 2015).

2.2. Regional division

The precipitation regime over China indicates a substantial spatial variability due to the vast territory and complex terrain features (Yang et al., 2012). Therefore, it is necessary to divide China into sub-regions to capture regional features of changes in extreme precipitation (Guo et al., 2017). Previous studies on extreme precipitation over China have divided the country into several sub-regions with different division standards (Ma et al., 2015; Guo et al., 2017; Wang et al., 2017b). In this study, the China mainland is divided into four sub-regions, i.e. Northwest China (NW, 33–50° N, 74–100° E), Northeast China (NE, 33–55° N, 100–134° E), Southeast China (SE, 18–33° N, 100–123° E) and Southwest China (SW, 21–33° N, 78–100° E). The four sub-regions are shown in Fig. 1.

2.3. Definition of EEP

The first step of identifying EEPs from precipitation time series is to define a threshold that delineates precipitation events. Generally, the threshold of 1 mm is used to classify wet and dry days because very

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