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Drought frequency change: An assessment in northern India plains

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ABSTRACT

Following the debate on whether drought has become more severe under climate change, this paper assesses drought frequency in northern and eastern India using two datasets of Palmer Drought Severity Index (PDSI) (generated by Dai, 2013 and Sheffield et al., 2012). The univariate return period for three drought characteristics (duration, severity and peak intensity) is examined regarding whether drought has occurred with longer duration, higher severity and/or larger peak intensity. The spatial variation of those changes is analyzed through eight areas in the study region. The temporal and spatial comparisons based on the univariate return period show different change patterns of duration, severity and peak intensity in different areas. Generally, in the areas which plant wheat more than rice (areas 1 and 2), drought has been alleviated in duration and intensity after 1955; while in the areas which plant more rice than wheat (areas 3–8), drought have been aggravated in duration, severity and intensity (except for area 8, a coastal area). This spatial change pattern may imply potential crop pattern change, for example, switching from rice to wheat in areas 3–7. Furthermore, the bivariate return period for pairs of drought characteristics based on the copulas and considering correlation between the drought characteristics is examined to understand how bivariate return periods change over time and space. Finally, it is also found that one data set (Sheffield et al.) results in more severe, longer and more intense drought in most of the areas, especially for the drought events with long-return-periods than the other (Dai).

1. Introduction

Drought is a recurrent extreme climate phenomenon. It can last for weeks, months, even years, and the spatial extent of droughts is usually larger than other natural hazards (e.g., floods and hurricanes) (Obasi, 1994), resulting in devastating impacts on agriculture, water resources, environment and human lives (Hao et al., 2014; WMO, 2006). Droughts differ significantly in terms of spatial characteristics from one region to another. In India, drought occurs mostly due to the failure of south-west monsoon (June–September) (Ganguli and Reddy, 2012). About 33% of the arable land in India is considered to be drought-prone and a further 35% can also be affected under extreme climate conditions (Reddy and Ganguli, 2012). Northern and eastern India is a major agriculture area of India, especially for wheat and rice production. Drought frequency analysis in this region is needed to conduct risk evaluation and select drought-relief measures.

Drought identification and quantification are prerequisites to drought frequency analysis. Numerous drought indices are used to quantify drought events, including the widely used PDSI (Palmer Drought Severity Index) and SPI (Standardized Precipitation Index) (Mishra and Singh, 2010), and recent new indices, e.g., SPEI (Standardized Precipitation Evapotranspiration Index) (Masud et al., 2015), and SDI (streamflow drought index) (Madadgar and Moradkhani, 2013; Sadri and Burn, 2014). PDSI is probably the most popular regional drought index to monitor droughts and to assess agricultural impacts (Mishra and Singh, 2010). Recent advances in technologies use improved methods, e.g., using the Penman-Monteith equation instead of Thornthwaite to calculate Potential Evapotranspiration (PET) (Dai, 2011); using self-calculating technologies (Wells et al., 2004), etc.); accounting for snowmelt using degree-day model (van der Schrier et al., 2013); more accurate climate datasets have also been used to improve the quantification of PDSI at the global scale (Sheffield et al., 2012). Those updated PDSI data sets have been used to explore how drought is changing under climate change. However, there have been conflicting results from recent studies (Dai, 2013; Sheffield et al., 2012; Trenberth et al., 2013; van der Schrier et al., 2013) due to different forcing climate

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datasets, methods involved in calculating potential evapotranspiration, self-calculating periods, and other factors.

Drought occurs event by event; different events last a wide range of time periods and some can last over multiple years. Therefore, it is not appropriate to assess drought return periods using the classic procedures applied to intra-year extreme events (e.g., floods, Shiau and Shen, 2001), which only consider annual maximum. The length of a drought event and the cumulative severity can be more important than the maximum intensity of the event for assessing its impact on natural and human systems (e.g., agriculture and water demand). Thus, it has been suggested to use multiple characteristics including expected drought inter-arrival time, severity (S), duration (D), and peak intensity (I) for drought assessment (Shiau, 2006; Shiau and Shen, 2001). Given that the multiple drought characteristics are correlated, recent studies propose to assess drought return periods based on those correlated variables. Copulas (Sklar, 1959) based on joint multivariate probability distributions allow modeling a multivariate distribution by separately dealing with marginal distributions and joint dependences among variables (Madadgar and Moradkhani, 2013; Sadri and Burn, 2014; Wong et al., 2010; Xu et al., 2015). Thus it has been widely used to analyze return periods of the various extreme hydroclimatic variables including precipitation extremes (Liu et al., 2014), peak flow and water volume for rainfall frequency (Zhang and Singh, 2007), flooding events (De Michele et al., 2005) and drought events. Specifically, bivariate copulas has been applied to calculating drought return period based on the combination of two factors among D, S and I using the time series of the various indices, such as SPI (Chen et al., 2013; Lee et al., 2013; Wong et al., 2010), SPEI (Masud et al., 2015), and SDI (Madadgar and Moradkhani, 2013; Sadri and Burn, 2014). Moreover, integrated drought indices based on multivariate copulas are suggested, e.g., probability-based overall water deficit index from multiple drought-related indices (Kao and Govindaraju, 2010), multivariate drought index utilizing information from multiple hydroclimatic variables (Rajsekhar et al., 2015) and integrated multivariate standardized drought index (e.g., standardized Palmer drought index-based joint drought index, SPDI-JDI) (Ma et al., 2014; Ma et al., 2015). Especially, in India, copulas have been applied to deriving drought severity-duration-frequency or intensity-area-frequency curves based on SPI using bivariate copulas in two western states (i.e., Gujarat, western Rajasthan) (Reddy and Ganguli, 2012; Ganguli and Reddy, 2013). Mishra and Singh (2010) reviewed mostly used drought indices and concluded that PDSI based on an inherent time scale is suitable for assessing agricultural impacts (e.g., Quiring and Papakyriakou, 2003; Lee and Nadolnyak, 2012; Yan et al., 2016). Drought characteristics (e.g., frequency and severity) based on monthly PDSI were used to generate a drought risk index to assess the relationship between drought and crop yield reduction (Li et al., 2009). Understanding the change in multiple drought characteristics (D, S and I) is needed to examine both the separate and joint effect of the characteristics on agriculture.

The IPCC AR5 concludes that there is not enough evidence available in favor of or against any global trend in drought with high confidence, and admits that the global increasing trend in drought suggested by the IPCC AR4 was probably overestimated (IPCC, 2013). The same concern presents itself with the various assessments at the regional scale. The purpose of this study is to provide a more comprehensive drought assessment using PDSI at the regional level (i.e., northern and eastern India). Compared to previous studies (Dai, 2013; Sheffield et al., 2012) that focus on trend analysis in time series of a drought index, our study distinguishes the changes in multiple drought characteristics. We use a time series of drought events to examine 1) the characteristics of the time series such as D, S and I of drought events, and 2) the changes associated with both individual and joint drought characteristics. Using the copulas to simulate the joint distribution of multiple drought variables, we will assess both the univariate and multivariate return periods of drought during three historical periods (1900–1954 and 1955–2012 of Dai (2013) and 1948–2008 of Sheffield et al. (2012)). We will conduct the assessment in eight areas in our study region located in northern India plains. Due to data availability and the advantage of PDSI that better help assess agriculture impacts (Mishra and Singh, 2010), we choose PDSI as the drought index for the assessment. Based on the outputs, we attempt to understand the change in bivariate return period of both D and S or both D and I over thresholds. Specifically, we will address the following questions: 1) has severe drought become more frequent, longer-lasting, or more intense over the historical period? 2) How are the two datasets (Dai and Sheffield et al.) distinguished, in severe or mild droughts, or in long or short droughts? 3) Did the multivariate return period change over time and space?

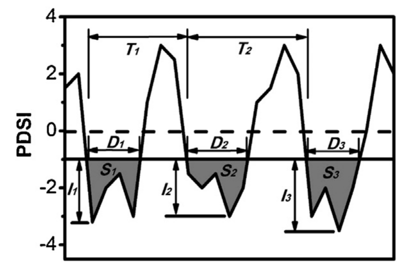

Fig. 1. Definition sketch of drought events; D_i is the duration, S_i is the severity, I_i is the peak intensity and T_i is the inter-arrival time.

The remaining parts of the paper are organized as follows. Section 2 describes the data and the case study. Section 3 presents the methods including the theory of copulas and the return periods of drought. Section 4 presents the results including the univariate and bivariate drought frequency analysis, and calculation of return periods. Section 5 provides the conclusions.

2. Data and study region

2.1. The characteristics of a drought time series

PDSI is a meteorological drought index using precipitation and temperature for estimating moisture supply and demand within a two-layer soil model (Palmer, 1965). The basis of the index is the difference between the amount of precipitation required to retain a normal water-balance level and the amount of actual precipitation (supply-demand concept of water balance). Fig. 1 shows the sketch of a time series of monthly PDSI. A drought event has four major components (Saghafian and Mehdikhani, 2014): a) duration (D) expressed in months, during which drought index is continuously below a prescribed critical level; b) drought inter-arrival time (T) expressed in months, which is the time range between the initiation time of two consequent drought events; c) severity (S) indicating the cumulative deficiency of a drought event below the critical level; and d) peak intensity (I), which indicates the maximum absolute value of a monthly drought index below the critical level.

Eleven states for drought and moist events are identified with PDSI: extremely wet, very wet, moderately wet, slightly wet, incipient wet spell, near normal, incipient drought, mild drought, moderate drought, severe drought and extreme drought (Palmer, 1965). To focus on relatively severe drought events, the truncation level is set to −1 (corresponding to "mild drought") in this study, which means that only the events with PDSI less than −1 are collected to form the time series for the drought assessment in this