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Spatio-temporal variation of drought in China during 1961–2012: A climatic perspective

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SUMMARY

Understanding the spatial and temporal variation of drought is essentially important in drought assessment. In most previous studies, drought event is usually identified in space and time separately, ignoring the nature of the dynamic processes. In order to better understand how drought changes have taken place in China during the past half-century, we carried out a comprehensive analysis of their spatio-temporal variation based on multiple drought indices from a climatic perspective. A 3-dimensional clustering method is developed to identify drought events in China from 1961 to 2012 based on the 0.25° gridded indices of SPI3 (3 months Standardized Precipitation Index), RDI3 (3 months Reconnaissance Drought Index) and SPEI3 (3 months Standardized Precipitation Evapotranspiration Index). Drought events are further characterized by five parameters: duration, affected area, severity, intensity, and centroid. Remotely sensed soil moisture data were used to validate the rationality of identified drought events. The results show that the two most severe drought events in the past half century which occurred in the periods 1962–1963 and 2010–2011 swept more than half of the non-arid regions in China. Large magnitude droughts were usually centered in the region from North China Plain to the downstream of Yangtze River. The western part of North China Plain, Loess Plateau, Sichuan Basin and Yunnan-Guizhou Plateau had a significant drying trend, which is mainly caused by the significant decrease of precipitation. The three drought indices have almost the same performance in the humid regions, while SPI and RDI were found to be more appropriate than SPEI in the arid regions.

1. Introduction

Drought is a natural phenomenon in which the natural water availability for a region is lower than that under normal conditions for a prolonged period. It may last for weeks, months, years or even decades. Drought is one of the costliest and most widespread natural disasters (Wilhite, 2000; Bryant, 2005) that may have devastating impacts on agriculture, water resources, environment and human lives. Droughts occur over most parts of the world, both in wet and humid regions (Dai, 2011). Understanding the spatial and temporal variations of drought is of primary importance for freshwater planning and management (Mishra and Singh, 2010).

Due to the monsoon climate interacted with the complicated geographical landscapes, severe drought of high frequency is one of the most devastating natural disasters in China. According to statistics, the drought affected area and drought damaged area have greatly increased in the past 50 years (Wang et al., 2012). In the 2000s, extreme droughts occurred frequently in China, for example, the winter–spring drought in southwest China during 2009–2010 (Lu et al., 2011; Zhang et al., 2012a; Zhao et al., 2013) and the spring–summer drought over the middle and lower reaches of Yangtze River in 2011 (Lu et al., 2013). They brought significant socio-economic and eco-environment damages. China is facing an increasing drought risk in the 21st century under the changing climate. Better understanding of the drought changes in the past is important for managing the future drought risk.

1.1. Drought index and drought identification

Drought is monitored and quantified by drought indices, and various indices have been developed to depict the drought in different applications (Dracup et al., 1980; Wilhite and Glantz, 1985). Among these indices, the standardized precipitation index (SPI; McKee et al., 1993) is the most popular one. SPI has the advantages of flexible time scale and simple calculation procedure. However, SPI also has disadvantages; it only utilizes precipitation information, without considering other meteorological variables that play

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important roles during the development of a drought event (Taylor et al., 2012; Teuling et al., 2013). Recently, many attempts have been made to improve SPI by incorporating other hydrometeorological variables. Tsakiris et al. (2007) proposed the Reconnaissance Drought Index (RDI) based on the quotient of cumulative precipitation and cumulative potential evapotranspiration following the same methodology as with SPI. Vicente-Serrano et al. (2010) developed the standardized precipitation evapotranspiration index (SPEI), defined as the difference between the cumulative precipitation and the cumulative potential evapotranspiration, and found that it is sensitive to the temperature. In China, China Meteorological Administration (CMA) uses the meteorological composite index (CI) for drought monitoring, which is a combination of one-month SPI, 3 month SPI and monthly relative humidity index (P/E_p) (CMA, 2006). Ma et al. (2013) formulated the standardized Palmer drought index (SPDI) by combining the methodology of PDSI (Palmer Drought Severity Index; Palmer, 1965) and SPI. Kao and Govindaraju (2010) proposed the joint drought index (JDI) based on the joint distribution of accumulated precipitation and streamflow using copulas. Following the framework similar to that of JDI, Hao and AghaKouchak (2013) proposed the multivariate standardized drought index (MSDI) by combining accumulated precipitation and soil moisture. However, there have been only a few studies (Guttman, 1998; Khalili et al., 2011; Vicente-Serrano et al., 2012) carried out for the inter-comparison among the different drought indices.

Drought identification and characterization is a pre-requisite to spatial and temporal variation analysis and drought frequency analysis. In general, drought is often characterized by its duration, severity, intensity and spatial extent. Yevjevich (1967) proposed the one-dimensional truncation method to extract drought duration, severity, and intensity from drought index sequence. Statistical methods, such as wavelet analysis (Min et al., 2003), empirical orthogonal functions (Kim et al., 2011; Song et al., 2013), principal component analysis (PCA) and cluster analysis (Chen and Yang, 2012; Gocic and Trajkovic, 2014), Shannon entropy (She and Xia, 2012) have been widely employed to estimate the spatial pattern of drought. All these methods discard much of the spatio-temporal information by reducing drought events to a lower-order subspace (Lloyd-Hughes, 2012), thereby not enabling to capture the real drought structure in space–time dimensions. Meanwhile, many other studies have been devoted to identification of drought event based on image recognition methods. For example, Andreadis et al. (2005) proposed a clustering algorithm to extract the voxels of drought connected in space and time. Lloyd-Hughes (2012) extended the clustering algorithm to 3-dimensional space (longitude, latitude, and time), fulfilled the complete spatio-temporal representation of the drought event. However, these methods have been barely used in drought assessments due to their complexity.

1.2. Previous studies on China drought

In the context of climate change, the spatial and temporal variation of drought ranging from regional to national scale has become a research hot topic in China. The previous studies of drought during the past decades using SPI showed that the eastern part of China being far more hazardous than the western part (He et al., 2011); north Xinjiang had a decreasing trend of drought severity (Zhang et al., 2012b); severe drought increased gradually over China, while rapidly increased in southwest China (Yang et al., 2013). It was found that positive feedback from low precipitation and high temperature maintained the severe drought during 2009–2010 in southwest China (Lu et al., 2011; Zhang et al., 2012a; Zhao et al., 2013). Therefore, the temperature is also incorporated into the drought assessment. Based on the commonly used drought index CI, Yu et al. (2013) found that the drought frequency was lower in summer and autumn, and higher in winter and spring over southwest China; Song et al. (2013) evaluated the spatial and temporal distribution of drought over the Songnen Plain of northeast China; Qian et al. (2011) ranked regional drought events from 1960 to 2009, and found that droughts frequently occurred in Southwest China and the Yellow River basin. Yu et al. (2014) used the SPEI index and reported that drought was becoming more severe since late 1990s for most parts of China, and the drying area increased by 3.72% per decade. Using the land surface model simulated soil moisture, Wang et al. (2011) quantified drought in China during 1950–2006 and found that central and northeastern China had significant drying trend, whereas Xinjiang and Tibetan Plateau showed significant wetting trend, and the drying area was larger than the wetting area; Wu et al. (2011) found a significant increasing trend of drought occurrence frequency, particularly in north China.

Although such a variety of studies have focused on the spatial and temporal variation of drought in China, yet the methods used for drought identification in previous studies were always simplified to a lower dimension. Consequently drought variations were analyzed in time and space separately, either the time evolution of drought over a fixed area or the drought spatial patterns at a certain time. These simplified methods are inadequate to describe the spatio-temporal structure of drought. Therefore, it is necessary to identify and characterize drought events in a 3-dimensional framework for a better understanding of the spatio-temporal variation. Furthermore, the inter-comparison among the different drought indices was rarely done in previous studies.

1.3. Objectives and structure of this study

The present study focusses on the long-term drought assessment in China using a 3-dimensional identification and characterization approach in a multi-metric framework. It aims to evaluate spatio-temporal variation of drought during the past half century. Firstly, three most widely used meteorological drought indices, namely SPI, RDI, and SPEI were calculated. Then, the 3-D drought identification method was adopted to identify the drought events based on these three indices. Finally, the spatial and temporal variation of drought events in the past 52 years were analyzed.

The remaining parts of this paper are organized as follows. Section 2 describes the data sets and methodology used. Section 3 presents the validation of identified drought events and their spatio-temporal variations. Section 4 discusses drought trend influenced by precipitation and potential evaporation, and the disadvantages of the climatic drought indices. Finally, some conclusions are given in Section 5.

2. Data and methodology

2.1. Data and study area

Daily gridded ($0.25° \times 0.25°$) precipitation data from 1960 to 2012 were acquired from National Meteorological Information Center (NMIC). They are generated from observations of over 2419 national-level gauges, interpolated using the kernel interpolation algorithm controlled by the background climatology fields. Absolute error of 91% of the data set is less than 0.1 mm/day, meaning this data set can capture the rainfall temporal process and spatial distribution accurately (Shen et al., 2010). The gridded precipitation data was integrated into the monthly scale for the drought analysis.

To calculate the potential evaporation (E_p), daily meteorological data set, including air temperature (T), wind speed, relative humidity, sunshine time, and pressure from 743 gauges (see Fig. 1) over