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The propagation from meteorological to hydrological drought and its potential influence factors

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ABSTRACT

It is important to investigate the propagation from meteorological to hydrological drought and its potential influence factors, which helps to reveal drought propagation process, thereby being helpful for drought mitigation. In this study, Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were adopted to characterize meteorological and hydrological droughts, respectively. The propagation time from meteorological to hydrological drought was investigated. The cross wavelet analysis was utilized to examine the correlations between hydrological and meteorological droughts in the Wei River Basin (WRB), a typical arid and semi-arid region in China. Moreover, the potential influence factors on the propagation were explored from the perspectives of large-scale atmospheric circulation anomaly and underlying surface characteristics. Results indicated: (1) the propagation time from meteorological to hydrological drought has noticeably seasonal characteristics, that in spring and summer is short, whilst that in autumn and winter is long; (2) hydrological and meteorological droughts are primarily characterized by statistically positive linkages on both long and short time scales; (3) El Niño Southern Oscillation (ENSO) and Arctic Oscillation (AO) are strongly correlated with actual evaporation, thus strongly impacting the propagation time from meteorological to hydrological drought. Additionally, the propagation time has roughly positive associations with the parameter *w* of the Fu's equation from the Budyko framework.

1. Introduction

Drought is a kind of extreme natural disasters resulting from abnormal decreases in precipitation (Oladipo, 1985; McKee et al., 1993; Wilhite et al. 2000; Huang and Chou, 2008; Wang et al., 2011a; Huang et al., 2014a, 2015a,b), which can give rise to a large number of losses in the fields of economy, ecology, and environment (e.g. crop losses, degradation and desertification, urban water supply shortages, forest fires, etc.) (Flannigan and Harrington, 1988; Nicholson et al., 1998; Austin et al. 1998; De Gaetano, 1999; Evans and Geerken, 2004). Compared to other kinds of natural hazards, the spatial extent of drought is extremely larger and its influencing time is commonly much longer. Thus, the damages caused by drought are expected to be highly larger than other natural hazards (Mishra and Singh, 2010; Xu et al., 2014).

Over the past century, the global climate and environment have witnessed remarkable changes, in which global warming is one of the most striking characteristics, which leads to accelerating the rate of water circulation, thereby resulting in highly frequent extreme events such as droughts and floods at the global scale (Willems, 2000; Kunkel, 2003; Roy and Balling, 2004; Beniston and Stephenson, 2004; Christensen and Christensen, 2004; Leng et al., 2015a,b). The frequency of drought tends to increase under the context of global warming. Hence, many scientists made a lot of attempts to investigate drought, which mainly consist of spatial and temporal differences of drought (Lana et al., 2001), the mitigation of drought effects (Huang and Chou, 2008), the frequency analysis of drought (Huang et al., 2014b; Mondal and Mujumdar, 2015) and drought prediction based on various atmospheric circulation indices (Cordery and McCall, 2000). Amongst these previous studies, more efforts have been focused on developing reliable drought indices, which can be applied for earlier detection of droughts including their intensity and spatial extent. For instance, Standardized Precipitation Index (SPI) is one of the widely used indices to monitor drought as sole parameter (e.g. Hayes et al., 1999) or in combination with other meteorological indices (for Iran, Morid et al., 2006), and to make a spatial and temporal

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analysis of drought (in Greece, Livada and Assimakopoulos, 2007). However, studies focused on studying the propagation from meteorological drought to hydrological drought and their associations were highly rare (Vicente-Serrano and López-Moreno, 2005; Van Loon and Laaha, 2015; Barker et al., 2016), which is of important significance to reveal drought propagation process and mechanism, thus being helpful for establishing drought early warning system. Commonly, meteorological drought develops and ends relatively quickly, whilst hydrological drought is the result of meteorological drought. The two kinds of droughts can reflect the different stages of drought development to a certain degree. In general, the occurrence of hydrological drought is later than meteorological drought, and the corresponding propagation time depends on local landscape condition (Pandey and Ramasastri, 2001). Therefore, investigation of the propagation time from meteorological to hydrological drought and its potential influence factors has important significance for establishing an effective monitoring and warning system of hydrological drought based on meteorological drought. This system is highly helpful for the mitigation of droughts and is expected to largely decrease drought-caused damages. Therefore, investigation of the propagation from meteorological drought to hydrological drought and its potential influence factors has importantly practical meanings.

Although SPI has been widely adopted to investigate drought in various regions, it is broadly accepted that SPI with different time scales can impact the assessment of drought conditions in different regions due to the fact that the response of different usable water sources to precipitation deficit can be extremely different. The fundamental advantage of SPI is that it can be computed for a variety of time scales, which allows SPI to monitor short-term drought such as agricultural drought and long-term drought such as hydrological drought (Mishra and Singh, 2010). For instance, Szalai et al. (2000) stated that agricultural drought was characterized best by SPI at a scale of 2–3 months. Hence, the appropriate time scale of SPI can be used to reflect the propagation time from meteorological to hydrological drought. Recently, the Budyko hypothesis has been widely utilized to investigate basin-scale water and energy balances (Yang et al., 2008; Roderick and Farquhar, 2011; Wang and Hejazi, 2011b; Yang and Yang, 2011; Xu et al., 2014; Yang et al., 2014), and the Fu's equation is one of the formulations of the Budyko curve (Yang et al., 2007; Li et al., 2013). The parameter w of the Fu's equation modifies the partitioning of precipitation between evaporation and runoff. The Budyko hypothesis is an effective tool for investigating the interactions among climate, hydrological cycle, and vegetation (Roderick and Farquhar, 2011; Yang and Yang, 2011). Additionally, the parameter w is an empirical parameter controlling the shape of the Budyko curve and reflecting the impacts of other factors like land surface characteristics, which has strong effects on the propagation time from meteorological to hydrological drought. Some studies have found that the parameter w of the Budyko framework is associated with land surface characteristics such as soil types, vegetation cover, climate seasonality, as well as topography (Milly, 1993, 1994; Zhang et al., 2001, 2004; Yang et al., 2007, 2009; Shao et al., 2012; Williams et al., 2012). Hence, the parameter ω can be regarded as an integrated parameter to reveal the impacts of underlying surface characteristics on the propagation time from meteorological to hydrological drought. Therefore, the correlations between the propagation time and the parameter w of the Fu's equation were explored in this study aimed at revealing possible effects of the parameter w on the propagation time.

Arctic Oscillation (AO) is closely associated with the climate of middle and high latitudes regions (Hudgins and Huang, 1996). Many studies demonstrated that meteorological, agricultural, and hydrological droughts are closely linked with climate indices such as the El Niño Southern Oscillation (ENSO) and Atlantic Oscillation (AO) (Talaee et al., 2014). Evaporation is a complex parameter controlling mass and energy exchange in atmosphere and terrestrial ecosystems, playing a critical role in the mass and heat fluxes in the global atmospheric system. Hence, it can be adopted to monitor the variations of moisture and energy shifting from the ground to the atmosphere. Therefore, the large-scale atmospheric circulation anomaly such as ENSO and AO may impact the propagation time from meteorological to hydrological drought through affecting actual evaporation.

The primary objectives of this study are: (1) to inspect the relationships between meteorological and hydrological drought based on standard quantitative indexes; (2) to examine the propagation time from meteorological to hydrological drought; (3) to explore the potential influence factors on the propagation time from the perspectives of the atmospheric circulation anomaly such as El Niño Southern Oscillation (ENSO)/Arctic Oscillation (AO) and underlying surface characteristics.

2. Study area and data

2.1. The Wei River Basin

The Wei River Basin (WRB), as presented in Fig. 1, is selected as a case study in this study. It lies between 103.5E–110.5E and 33.5N–37.5N, covering a total area of nearly $1.35 \times 105\ \text{km}^2$. Located in a continental monsoon climate zone, the basin is characterized by rich precipitation and high temperature in summer, and dominated by sparse precipitation and low temperature in winter. Its annual average precipitation is approximately 559 mm (Zhang et al., 2008). Generally, its precipitation varies seasonally, which in flood season (from June to September) accounts for nearly 60% of annual precipitation. Its annual precipitation also varies obviously because of the unstable features of the intensity, duration and influencing area of the subtropical high pressure belt over the northern Pacific, which shows strong impacts on local precipitation. Topographically, the altitude decreases from its highest northwest mountainous areas to its lowest Guanzhong Plain located in the southeast and southern portions. It should be emphasized that the Guanzhong Plain is a very important agricultural production zone, and agriculture plays an important role in local economic development. Additionally, many industrial parks also have been built in this plain, whose normal operations need a large amount of water. Nevertheless, in recent decades, the runoff of this basin has significantly decreasing trends (Huang et al., 2014b), and it frequently suffers from droughts (Huang et al., 2014c). Thus, its available water resources are scarce, failing to satisfy the water demand of local socioeconomic and eco-environmental developments.

2.2. Data set

Daily precipitation data collected from 21 meteorological stations in the WRB and its adjacent areas were utilized in this study, whose locations are displayed in Fig. 1. Each station has precipitation data spanning January 1st, 1960–December 31st, 2008, which were acquired from the National Climate Center (NCC) of the China Meteorological Administration (CMA). The monthly Nino 3.4 Index time series covering 1960–2008 collected from the NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/data/correlation/nina34.data) was used to characterize ENSO events in this study. The monthly AO series during 1960–2008 was acquired from the National Oceanic and Atmospheric Administration (NOAA). Furthermore, Potential evapotranspiration (PET) values of the meteorological stations were calculated through the Penman-Monteith equation (Allen et al., 1998), whilst