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Drought structure based on a nonparametric multivariate standardized drought index across the Yellow River basin, China

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SUMMARY

Investigation of drought structure in terms of drought onset, termination, and their transition periods as well as drought duration helps to gain a better understanding of drought regime and to establish a reliable drought early warning system. In this study, a Nonparametric Multivariate Standardized Drought Index (NMSDI) combining the information of precipitation and streamflow was introduced to investigate the spatial and temporal characteristics of drought structure in the Yellow River basin (YRB). Furthermore, the correlations between the El Niño-Southern Oscillation (ENSO) events and NMSDI variations were explored using the cross wavelet technique. The results showed that (1) The variations of NMSDI were consistent with those of 6-month SPI (Standardized Precipitation Index) and SSFI (Standardized Streamflow Index), indicating that the proposed nonparametric multivariate drought index was reliable and effective in characterizing droughts. (2) The preferred seasons of drought onset were spring and summer, and winter was the preferred season of drought recovery in the YRB. The long-term average drought duration in the whole basin was nearly 5.8 months, which was clearly longer than the average drought onset and termination transition periods. (3) Overall, the drought structure in terms of drought duration, onset and termination transition periods in the YRB remained stable, and no appreciable change trend was found. (4) ENSO events exhibited a statistically negative correlation with NMSDI variations, suggesting that they showed strong impacts on drought evolutions in the YRB. Although the YRB was selected as a case study in this paper, the approach/indicator can be applied in other regions as well.

1. Introduction

Droughts are naturally recurring hazards that have considerable unfavorable impacts on social and economic development around the world, and their devastating impacts on eco-environmental system are still difficult to estimate (Wilhite, 2000; Mishra and Singh, 2010). Among all types of climate extremes, droughts are one of the costliest and least understood hazards (Wilhite, 2000). It has been reported that droughts led to the largest economic losses in China within the period 1949–1995 (Damage Report, 1995). With global warming, the global hydrological cycle is expected to intensify (Alan et al., 2003; Allan and Soden, 2008; Chang et al., in press), resulting in the increase in extremes such as drought and flood events.

Given the catastrophic nature of droughts, much attention has being drawn to the drought characteristics at regional and global scales (Wang et al., 2011; Huang et al., 2014a,b; Xu et al., in press). However, previous studies primarily focused on drought frequency analysis such as drought risk and return period as well as trend and period analysis through various drought indices (Ganguli and Reddy, 2012; Huang et al., 2014a; Bonaccorso et al., 2015). To date, only a few relevant studies have investigated drought structure characteristics in terms of drought onset, persistence and termination (Mo, 2011), which is a major gap in current drought-related knowledge. Because drought occurs slowly, a better understanding of conditions triggering drought onset helps to establish a reliable drought early warning system. If appropriate drought triggers are identified, they will substantially improve drought prediction accuracy (Steinemann and Cavalcanti, 2006), which is valuable to regional drought mitigation and water resources management. It is crucial to understand drought

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persistence characteristics, which have strong effects on the design of water supply systems (Mo, 2011; Bonaccorso et al., 2015). A good understanding of the drought persistence characteristics of a specific region is useful for further understanding its drought mechanisms, thus facilitating its agricultural development and drought mitigation. Therefore, it is important to explore the spatial and temporal characteristics of drought structure including the onset, persistence, and recovery of droughts, which helps to fully reveal the drought mechanism and lays a solid foundation for drought prediction.

Drought indices used in previous studies, such as the Standardized Precipitation Index (SPI, McKee et al., 1993, 1995), Standardized Streamflow Index (SSFI, Li et al., 2013), Crop Moisture Index (CMI; Palmer, 1968), and Soil Moisture Drought Index (SMDI; Hollinger et al., 1993) embody only one aspect of the shortages of water resources. The current consensus amongst a large number of studies is that developing drought indexes based on a single variable/indicator (e.g., precipitation, streamflow, or soil moisture) is likely to be insufficient for reliable drought risk assessment and reasonable decision-making. The drought status acquired from one indicator often does not match well with that obtained from a different indicator due to the complex physical interactions among evapotranspiration, base flow, direct runoff, infiltration, and groundwater flow. For example, Mo (2011) investigated drought onset and recovery over the United States using SPI and soil moisture percentile to characterize meteorological and agricultural droughts, respectively. The evolution characteristics of the onset and termination of meteorological drought were found to be different from those of agricultural drought, because the two drought indices are represented by different drought-related variables. Therefore, integration of information from multiple sources is urgently required for reasonable and reliable drought characterization and prediction, and investigation of drought structure based on an integrated drought index combining multivariate information deserves more effort.

Most recent drought indices rely on a representative parametric distribution function to fit sample data, and they tend to result in different tail behaviors (Farahmand and AghaKouchak, 2015). In fact, many problems will come up due to the assumption that sample data should follow a given distribution. Note that the complicated interactions among surface water, atmosphere, vegetation, soil, and groundwater have substantial impacts on hydrologic processes. Thus, any given distribution fails to accurately reflect the tail of drought distribution (Sadri and Burn, 2012). There is no universally accepted parametric distribution for meteorological and hydrological variables (Silverman, 1986; Smakhtin, 2001), and the use of a parametric distribution tends to result in a remarkable deviation in their low or high quantiles (Sharma, 2000). Hence, the application of a parametric drought index in drought assessment is another major gap in current drought-related studies. In this study, a nonparametric multivariate standardized drought index (NMSDI) coupled with information related to precipitation and streamflow was introduced to investigate the spatial and temporal features of drought structure in the Yellow River basin (YRB), China, without assuming representative parametric distributions.

The Yellow River is the second longest river in China and the sixth longest river in the world (Shiau et al., 2007). In northern China, the Yellow River is a major source of freshwater for nearly 107 million residents which account for approximately 8.7% of the total population in China (Wang et al., 2006). The YRB has been heavily plagued by droughts for a long time (She and Xia, 2013). After the 1970s, the zero-flow phenomena, which regularly occur in the downstream of the Yellow River, have drawn wide attention. The frequently interrupted flow during the past 30 years has led to extremely adverse effects on the social and ecological development in the region. Thus, it is important to reasonably and effectively characterize droughts based on a reliable drought index in the YRB.

The primary objectives of this study are: (1) to investigate spatial and temporal characteristics of drought structure in terms of drought onset, persistence and termination as well as their transition periods in the YRB; (2) to determine whether droughts across the YRB have a preferred season to start or end, and to determine the precursors of drought onset or termination; (3) to capture the correlations between the El Niño-Southern Oscillation (ENSO) events and NMSDI variations, along with their evolutionary characteristics in the YRB. Although the YRB was selected as a case study in this paper, the approach/indicator can be applied in other regions as well.

2. Study area and data

2.1. The Yellow River basin (YRB)

Fig. 1 shows the study area of this paper, the Yellow River basin (YRB), which is located between 95°E–119°E and 32°N–41°N. The Yellow River originates from the Qinghai-Tibet Plateau in the western portion of China. It first flows northward, turns south, then flows eastward, and finally discharges into the Bohai Sea. The total length of the Yellow River is approximately 5464 km, with a drainage area of 752,443 km^2. As Chinese ancestors have lived in this basin since prehistoric times, the Yellow River has always been called as the 'Mother River of China' (Fu et al., 2004). It should be mentioned that the Chinese Loess Plateau where water loss and soil erosion is extremely severe is situated in the middle of the YRB. Every year, approximately 1060 million tons of sediment is transported from the Loess Plateau to the Bohai Sea (Milliman and Meade, 1983). The climate of the YRB is influenced by the arid and semiarid continental monsoon (Wu et al., 2013). Annual precipitation in the YRB varies from 123 to 1021 mm, and annual pan evaporation ranges from 700 to 1800 mm (Shao et al., 2006). The mean annual precipitation is approximately 378 mm, which increases from the northwest to the southeast in the YRB (Wu et al., 2013). Due to the different climate types and topographies in the YRB, the precipitation distribution exhibits a noticeable regional discrepancy. To systematically investigate the characteristics of drought structure in the YRB, the whole basin was divided into eight sub-basins on the basis of the secondary basin boundary in China, and their zone numbers are 26, 28, 29, 31, 33, 36, 40, and 41, respectively (Fig. 1). The basin boundary map was obtained from the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (http://lake.geodata.cn/Portal/metadata/viewMetadata.jsp?id=210008-10263), and it was well used in our previous studies (Huang et al., 2015).

2.2. Data

The observed gridded monthly precipitation and simulated monthly runoff data from 1953 to 2012 based on the Variable Infiltration Capacity (VIC) model in the YRB were employed for analysis in this study. The VIC model (Liang et al., 1994) is a semi-distributed macro-scale hydrologic model characterized by representing sub-grid variability in precipitation, soil moisture storage capacity, topography, vegetation classes, etc. (Liang et al., 1994; Nijssen et al., 1997). Meteorological forcing (e.g., wind speed, precipitation, and temperature) for driving the VIC model was obtained from China Meteorological Administration (CMA), which was interpolated into 0.25 degree grid. The meteorological forcing obtained from CMA includes gauge-based observations (http://www.cma.gov.cn/2011qxfw/2011qsjgx/). Approximately 765 meteorological stations are available across the country, in