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Effects of non-linear temperature and precipitation trends on Loess Plateau droughts

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A B S T R A C T

In this study, we analysed the effects of non-linear temperature and precipitation trends on Loess Plateau droughts over the period of 1961–2010. The most commonly used drought index, the Palmer Drought Severity Index (PDSI), was used to represent the drought conditions in the study region. We first calculated the Loess Plateau PDSI using monthly temperature and precipitation from 53 meteorological stations and then determined trends in the PDSI, temperature, and precipitation using the ensemble empirical mode decomposition (EEMD) time series analysis method. Because of the different change characteristics and trends, precipitation plays an important role in the interannual variation in the PDSI, while temperature drives the PDSI trend change. The differences between the observed PDSI and the calculated results using the detrended temperature and observed precipitation, the observed temperature and detrended precipitation, and the detrended temperature and precipitation indicate that impact of the precipitation trend on droughts is smaller than the impact of the temperature trend. The increase in the observed temperature and limited decrease in the precipitation tend to increase drought in the Loess Plateau. The Loess Plateau will become drier and warmer in the future under climate change.

1. Introduction

Drought is one of the most damaging climate-related hazards, and it may significantly damage agricultural production and the natural environment, particularly in water scarce regions (Dai et al., 2004; Zou et al., 2005; Garbero and Muttarak, 2013). Drought obviously depends on precipitation, but it also relies on how much water infiltrates to deeper ground layers or runs off the land and how much is evaporated or transpired by plants (Trenberth et al., 2014). The frequency and intensity of droughts are likely to change rapidly under global warming (Zhang et al., 2012). Therefore, numerous scientists and governments have focused on studying the relationships between drought, precipitation and temperature, particularly under global warming (Hu and Willson, 2000; Zou et al., 2005; Easterling et al., 2007; Su and Wang, 2007a; Zhang et al., 2010; Dai, 2013).

The Loess Plateau is situated in the upper and central drainage basins of the Yellow River in northern China. Most areas have a sub-humid and semi-arid climate (Li et al., 2010). Many studies on changes in drought, precipitation and temperature and their relationships have been conducted (Zhang et al., 2008; Wang, 2008b; Xin et al., 2011; Zhang et al., 2012; Zhao and Wu, 2013). However, few studies have considered the effects of precipitation and temperature trends on drought in the Loess Plateau.

Several indices are designed to characterize drought, some of which are purely rainfall deficit indices. Typically, the indices are used for scientific and monitoring purposes by measuring both precipitation and evaporation. The most commonly used drought index is the Palmer Drought Severity Index (PDSI) (Palmer, 1965), which is calculated from a water-balance model forced with observed precipitation and temperature. The PDSI has been widely used in monitoring drought, studying aridity changes and reconstructing palaeoclimates (van der Schrier et al., 2006; Burke and Brown, 2008; Cook et al., 2010; Dai, 2011). The index has been universally applied in the Loess Plateau (Wang, 2008a; Zhang et al.,

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2012; Zhao and Wu, 2013) and in other regions in China (Zou et al., 2005; Ma and Fu, 2006; Zhang et al., 2007; Su and Wang, 2007a; Fang et al., 2009; Li et al., 2009), because it can reflect soil moisture and runoff very well (Su and Wang, 2007b; Dai, 2011).

Therefore, this study determines the effects of temperature and precipitation trends on drought in the Loess Plateau using the PDSI. First, we calculated the PDSI using meteorological data. Then, the changes in the PDSI, temperature and precipitation and their relationships were displayed. The non-linear trends in the three indices were calculated by the ensemble empirical mode decomposition (EEMD) time series analysis method. Finally, the effects of non-linear temperature and precipitation trends on the PDSI were analysed by comparing the PDSI variations under different scenarios.

2. Data and methods

2.1. Study area

The Chinese Loess Plateau lies between 33°43′–41°16′ N and 100°54′–114°33′ E, and the area is approximately 6.4×10^5 km^2 (Fig. 1). The plateau is 1000–1600 m above sea level, and its surface is covered by highly erodible loess layers that are an average of 100 m thick. The region is a transitional zone between the southeastern humid monsoon climate and the northwestern continental dry climate. This continental monsoon region has an annual average temperature of 4.3 °C in the northwest and 14.3 °C in the southeast. The annual rainfall ranges from 200 mm in the northwest to 700 mm in the southwest, and the rainfall is highly variable both spatially and temporally (Xin et al., 2011).

2.2. Data

In the Loess Plateau, 53 surface meteorological stations have continuous observations over 1961–2010 (Fig. 1). The initial datasets of the mean air temperature and precipitation amount at these stations were collected from the China National Meteorological Center. To eliminate the possible effects of artificial shifts caused by relocations of measurement sites or unknown reasons, each station's temperature or precipitation time series was checked for homogeneity (Menne and Williams, 2005). The stations available for this study are not uniformly distributed across the Loess Plateau (Fig. 1).

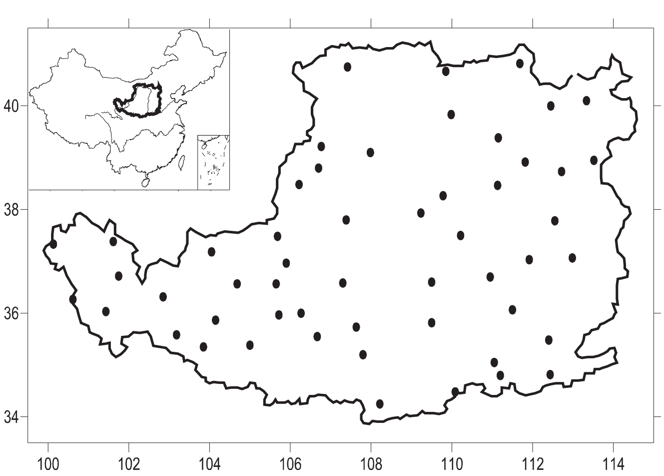

Fig. 1. Location of the Loess Plateau and distribution of the meteorological stations used in this study.

2.3. Methods

The nonparametric Mann-Kendall (MK) method (Mann, 1945; Kendall, 1975) was used to examine the nonlinear trend (Li et al., 2010), and a comparison analysis was performed at the 95% confidence level. The MK test has been widely used to test trends in climatology and hydrology (Burn et al., 2004; Dixon et al., 2006; Ma and Fu, 2006; Chen and Grasby, 2009; Kumar et al., 2009; Xin et al., 2011; Wang et al., 2012).

Ensemble empirical mode decomposition (EEMD) is an adaptive and temporally local time series analysis method designed for analysing non-linear and non-stationary data, such as climate data (Wu and Huang, 2004, 2009). The principle underlying the EEMD method is to obtain the arithmetic mean of multiple observations by adding multiple white noise realizations to the target data as a way to mimic a scenario of multi-trial observations for a single-trial observation. Using an ensemble, EEMD cancels various realizations of white noise added to each trial of the ensemble and obtains scale-consistent signals. Finally, the raw data are decomposed into finite intrinsic mode functions and a trend (Wu and Huang, 2009; Wu et al., 2009; Wang et al., 2014). The trend is used to display the characteristics of temperature, precipitation and drought in this study (Wu et al., 2007). In recent years, trends based on EEMD have been applied by scholars in many climate change studies (Qian et al., 2011; Wu et al., 2011; Yan et al., 2011; Qian et al., 2012; Ji et al., 2014).

Since the PDSI was proposed by Palmer (1965), it gradually became a standard for measuring meteorological drought. To use the traditional method objectively in each region across the globe, the self-calibrating Palmer Drought Severity Index (sc-PDSI) was proposed (Wells et al., 2004). In China, the model of calculating the sc-PDSI is the version revised by Liu et al. (2004) and is used in this research.

A detrended data series is generated by detrending an observed data time series by removing the non-linear trend. To maintain the detrended time series at a variation range similar to the observed series, we added a constant value, after subtracting the non-linear trend from the observed data at each year. The constant is the first value of the non-linear trend series, and it allows the detrended data series to remain the same with the observed series at the first data. The detrended series differs from the observed series from the second data. Through this detrending method, we can obtain the detrended data series for temperature, precipitation, and PDSI.

3. Results and discussion

3.1. Characteristics of the PDSI, temperature and precipitation in the Loess Plateau

The data at the 53 meteorological stations data were first aggregated to create one temperature and one precipitation time series for all months over 1961–2010 in the Loess Plateau. Then, the monthly PDSI series from January 1960 to December 2010 was calculated using monthly precipitation and temperature. Because the precipitation and temperature used for calculating the PDSI are monthly total precipitation and monthly averaged temperature, Fig. 2 shows the mean value of the monthly total precipitation, monthly averaged temperature and monthly PDSI for 12 months in a year. To determine the relationships among the PDSI, temperature and precipitation, the trends are also given in Fig. 2. Obvious decreases in the PDSI and increases in the temperature occur, and their trends pass the MK significant level test. The decreasing precipitation trend is not apparent and does not pass the MK test. However, to analyse the differences between the effects of temperature and precipitation on drought, all the trends are extracted

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