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Temporal and spatial evolution of the standardized precipitation evapotranspiration index (SPEI) in the Loess Plateau under climate change from 2001 to 2050

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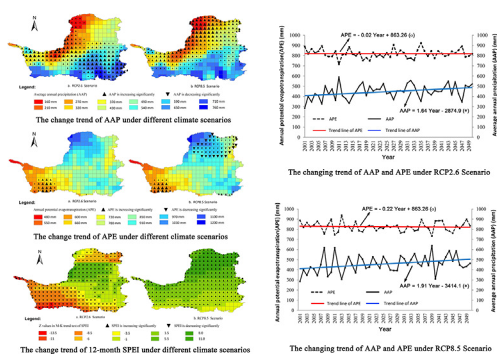
HIGHLIGHTS

- The evolution of precipitation, PET and SPEI from 2001 to 2050 was analyzed.
- The climate forecasted data are based on the CMIP5 data and RegCM4.0.
- The Loess Plateau is estimated to be wetter in the central part in RCP2.6 Scenario.
- The whole Loess Plateau is estimated to be wetter in RCP8.5 Scenario.
- The frequency of normal and wet event shows upward trend under climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Loess Plateau has great uncertainty on drought occurrence due to climate change. This paper analyzes the evolution of precipitation, potential evapotranspiration and standardized precipitation evapotranspiration index (SPEI) based on the Coupled Model Inter-comparison Project Phase 5 (CMIP5) data and regional downscaling model (RegCM4.0). Results indicate that, under RCP2.6 Scenario, the precipitation will increase significantly (5% confidence level) at the rate of 16.40 mm/10 a. However, the potential evapotranspiration is showing non-significant decreasing trend at the rate of 2.16 mm/10 a. Moreover, the SPEI will decrease in the south and northernmost area and increase in the central northern area of Loess Plateau. Under RCP8.5 Scenario, the precipitation will increase significantly (5% confidence level) at the rate of 19.12 mm/10 a. The potential evapotranspiration will non-significantly decrease at the rate of 2.16 mm/10 a and the SPEI is showing increasing trend almost in the whole Loess Plateau. Generally, Loess Plateau is becoming wetter in the central part under RCP2.6 Scenario and the wet area will be enlarged to almost the whole plateau under RCP8.5 Scenario. Based on the results, the water resources will increase under global warming, which may alleviate the water scarcity issue in the Loess Plateau.

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1. Introduction

Climate change may cause a series of frequent extreme weather events, including drought, heavy rains, and high temperature (Min et al., 2011; IPCC, 2013). The impact of drought climate events is mostly widespread, because drought is a natural and recurring feature of climate and occurs in almost all climatic regimes (Zarch et al., 2015). Various studies have proven that climate change is expected to increase drought intensity and frequency worldwide as a result of changes in precipitation patterns and temperature rising (Burke et al., 2006; Wanders and Wada, 2015).

To precisely assess the drought severity for the purpose of risk management, scientists have proposed many quantitative definitions of drought and related indexes (Burke et al., 2006). However, these indexes all have their own advantages and disadvantages (Keyantash and Dracup, 2002). The Palmer drought severity index (PDSI) is one of the mostly widely used drought indexes globally (Wang et al., 2015a). It has had great success in long-term drought monitoring, but is unsatisfactory for addressing short-term drought (Guttman, 1998). The standardized Precipitation Index (SPI) was developed to provide a better representation of wetness and dryness (Hayes et al., 1999), which is recommended as a better drought index because the required parameters are simple. Nevertheless, only the precipitation is considered in the index of SPI, which, to some extent, is specifically applicable to the meteorological drought. Vicente-Serrano et al. (2010) proposed the standardized precipitation evapotranspiration index (SPEI) for drought assessment. SPEI is good at detecting, monitoring and exploring the consequences of global warming on drought conditions (Dubrovsky et al., 2009).

China is a country seriously affected by drought in the world (Ma and Fu, 2003). The Loess Plateau is located in the arid areas of North China, which is an ecologically fragile area. With the rapid development of the social economy, more water is consumed in different sectors especially for domestic and industrial consumption. In this context, less water is available for ecology and agriculture, which poses a great threat to ecological sustainability and food security. As a consequence, the characteristics of water balance and drought evolution under global warming are extremely important for vegetation recovery and ecological sustainability in the Loess Plateau. Wang et al. (2015b) concluded that the drought frequency in the Loess Plateau was showing an increasing trend from 1961 to 2012. Nonetheless, Gao et al. (2017) found that the regional precipitation was showing an obvious increasing trend from 1990 to 2014. Zhang et al. (2015) showed that the annual mean potential evapotranspiration had a declining trend at the rate of 12.9 mm/10 a in the Yellow River Basin (including the Loess Plateau) of China from 1961 to 2012. However, Li et al. (2012) concluded that the potential evapotranspiration has increased obviously due to the downward trend in relative humidity and upward trend in temperature in the Loess Plateau during 1961–2009 and will continue increase in the 21st century. Among the existing drought-related studies, the research findings in the Loess Plateau are always inconsistent or contradictory due to the high uncertainty of the meteorological factors and the climate data from different sources used for analysis.

Based on the above analyses, this paper will study the characteristics of the drought evolution in the Loess Plateau under the future climate change. The main contents of this paper can be summarized as follows: (1) to analyze the spatial and temporal variation of precipitation and potential evapotranspiration from 2001 to 2050; (2) to calculate the index of SPEI and analyze the spatial and temporal variation of SPEI from 2001 to 2050; and (3) based on the above findings, to forecast the probability of dry events and wet events in the Loess Plateau under different climate change scenarios, which may be an important reference for the government to use when considering ecological protection in the future.

2. The study area and data

2.1. The study area

The Loess Plateau is a large ecological and agricultural zone of China, located in the upper and middle reaches of the Yellow River (as shown in Fig. 1). The Loess Plateau covers an area of 628,000 km^2, between 33°43'and 41°16′N and the longitude between 100°54'and 114°33′E, which is surrounded by Taihang Mountain to the east, Riyue-Helan Mountain to the west, Qinling Mountain to the south and Yinshan Mountain to the north (Gao et al., 2017).

The majority of the Loess Plateau belongs to sub-humid and semi-arid climates, with the average annual temperature ranging from 4.3 °C to 14.3 °C (Yu et al., 2015). The precipitation is mainly concentrated during summer, ranging from 200 mm in the northwest to 750 mm in the southeast, 65% of which is distributed from June to September. Solar energy resources are rich in the Loess Plateau, with 2200–2800 annual hours of sunshine and 5.0–6.3 $\times$ 10^9 J/m^2 annual total solar radiation. The annual potential evapotranspiration is estimated to be much higher than the precipitation, ranging from 865 mm to 1274 mm (Li et al., 2012).

2.2. Data source and collection

This study used two types of data: 1) the observed data from weather stations from 1961 to 2000. The data include daily precipitation, daily mean temperature, maximum temperature, minimum temperature, relative humidity, atmospheric pressure, radiation intensity, wind speed and other meteorological elements. These data were downloaded through the China Meteorological Sharing Network (http://data.cma.cn/) including 57 sites in the Loess Plateau; 2) the projected climate change data for the Loess Plateau from 1961 to 2050. The General Circulation Models (GCMs) data are from the World Climate Research Programmer's (WCRP) coupled model inter-comparison project phase 5 (CMIP5) multi-model dataset. The multi-model dataset is produced by a simple averaging method based on 21 global climate system models. The list of the basic information of the 21 GCM models and the associated institutions is shown in Supplementary material.

Based on the GCM data, the National Climate Center of China used RegCM4.0 for downscaling and obtained the projected climate data of different scenarios from 2001 to 2050 in the Loess Plateau with a resolution of 0.5°. Based on the 0.5° spatial resolution, the whole Loess Plateau is spatially divided into 315 grids. The projected climate data mainly include daily precipitation; daily mean, maximum and minimum temperature; daily mean relative humidity; daily mean atmospheric pressure; daily mean radiation intensity; and the daily mean wind speed. It must to be noted that CMIP5 divides the future greenhouse gas emission scenarios into four types (RCP2.6, RCP4.5, RCP6.0 and RCP8.5), and they are called the Representative Concentration Pathway (Zhang et al., 2016).

3. Methodologies

3.1. Calculation of the potential evapotranspiration (PET)

The Penman-Monteith (PM) method is one of the most widely accepted methods to calculate the PET, which is also a physical-based method recommended by Food and Agriculture Organization of the United Nations (FAO) in 1998 (Allen et al., 1998). The PM method has been adopted by the International Commission on Irrigation and Drainage (ICID), and the American Society of Civil Engineers (ASCE) as the standard procedure to compute PET (Vicente-Serrano et al., 2010). In combination with the PM method, Zhao et al. (2015) found that the SPEI index calculated based on the PM method was more reliable in arid areas of Northwest China. Therefore, the PM method is adopted in