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Spatial and temporal variability of drought in the arid region of China and its relationships to teleconnection indices

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SUMMARY

We studied the drought patterns in the arid region of northwestern China between 1960 and 2010 using the Palmer Drought Severity Index (PDSI). The general evolution of drought was obtained by empirical orthogonal function (EOF), rotated empirical orthogonal function (REOF), the Mann–Kendall test, and the continuous wavelet transform method. Additionally, relationships between rotated principal component time series (RPCs) and seven selected climate indices were analyzed. The results showed that: (1) Four moisture-related spatial patterns (North Xinjiang, western South Xinjiang, Central Xinjiang, and the Hexi Corridor) were objectively defined by REOF analysis. These patterns are related to distinct geographical areas and are associated with distinct temporal variations. (2) The PDSI increased significantly in most regions of Xinjiang, while decreased in the eastern Hexi Corridor. The significant 4–8 year band is the major period band for the annual and seasonal PDSI derived. (3) The seasonal REOFs (RPCs) and EOFs (PCs) have consistent spatial distribution patterns with the annual REOF. The seasonal trends of PDSI are also the same as the annual PDSI trends, indicating space–time consistency between annual PDSI and seasonal PDSI. (4) The drought evolution in this region is affected by the area of northern hemisphere polar vortex, the Arctic Oscillation, and the North Atlantic Oscillation. In addition, the changes of drought in South Xinjiang and the Hexi Corridor may also be associated with the Tibetan Plateau High. Changes in drought pattern are expected to have a strong impact on the economic livelihood of the region, especially for agricultural production.

1. Introduction

Drought is a stochastic natural hazard that is caused by intense and persistent shortage of precipitation (Zargar et al., 2011). Temperature, high winds, and low relative humidity also play a significant role in the occurrence of droughts (Mishra and Singh, 2010). Drought is regarded as one of the most serious environmental disasters, and large scale intensive droughts have been observed on all continents, affecting large areas of Europe, Africa, Australia, South America, and Asia (Mishra and Singh, 2010). One of the reasons for this is the usually large spatial extent of droughts, and their lengthy duration, sometimes reaching continental scales and lasting for many years (Ionita et al., 2012). China has suffered frequent severe droughts during the second half of the 20th century (Zou et al., 2005). Many studies have shown that much of northern China has experienced droughts since the 1950s, with the most severe and prolonged droughts having occurred since 1990 (Wang et al., 2011). Zou et al. (2005) found that more than 25% of the country was under drought threat almost every year. Zhai et al. (2010) also found a large increase in dryness over northern China after 1990. In the arid and semi-arid regions of northwestern China, due to soaring population growth and unreasonable environmental exploitation, the mainstreams and tributaries of many rivers are deprived of water, and the rivers are drying up (Chen et al., 2011). For example, in the Tarim River, due to the high intensity of water resource utilization in the upper reaches of the river basin, the downstream 321 km of the river dried up, and the terminal lakes of the Tarim River, i.e., Lop Nor Lake and Taitema Lake, dried up in 1970 and 1972, respectively, and the ground water level was greatly lowered. Thus, droughts are receiving an increasing amount of attention in areas, such as northwestern China, where greater demands on water supplies have emerged due to increases in population.

Spatial and temporal patterns of drought have been analyzed by several methods, ranging from satellite images to historical

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records; however, drought is generally identified by climate elements (Dai, 2011; Zargar et al., 2011). Drought indices are quantitative measures that characterize drought levels by assimilating data from one or several variables (indicators), such as precipitation and evapotranspiration, into a single numerical value (Zargar et al., 2011). A number of different indices have been developed to quantify droughts, each with its own strengths and weaknesses (Zargar et al., 2011). Among them, the Palmer Drought Severity Index (PDSI) (Palmer, 1965) is the most prominent index of meteorological drought used in the world (Mishra and Singh, 2010). The PDSI was one of the first procedures to demonstrate success at quantifying the severity of droughts across different climates. Instead of being based purely on precipitation, the PDSI is based upon a primitive water balance model. A common critique of PDSI is that the behavior of the index at various locations is inconsistent, making spatial comparisons of PDSI values difficult. The SC-PDSI (Self-calibrating PDSI) automatically calibrates the behavior of the index at any location by replacing empirical constants in the index computation with dynamically calculated values. An evaluation of the SC-PDSI at 761 sites within the U.S. states of Nebraska, Kansas, Colorado, Wyoming, Montana, North Dakota, and South Dakota, as well as at all 344 climate divisions, showed that it is more spatially comparable than the PDSI (Wells et al., 2004). Some other studies (Gobena and Gan, 2013; Sousa et al., 2011; van der Schrier et al., 2006a) also demonstrated that the SC-PDSI can improve upon the PDSI significantly and is more appropriate for comparing the drought severity of diverse climates. Regional studies, such as global (van der Schrier et al., 2013), Europe (Ionita et al., 2012), western Canada (Gobena and Gan, 2013), western Turkey (Durdu, 2013; Tunalioglu and Durdu, 2012), North America (van der Schrier et al., 2006b), and the river basins of China (Jia et al., 2014) have also indicated that the SC-PDSI can describe drought evolution well.

Drought is generally driven by extremes in the natural variations of climate, which are forced by internal interactions of the atmosphere and feedback from the oceans and land surface (Sheffield et al., 2009; Wu and Kinter, 2009). These are modulated by external forces, such as variations in solar input and atmospheric composition, either natural or anthropogenic. Research has highlighted a number of factors that may potentially impact drought occurrence in the arid region of northwestern China. So, the main objective of this study is to analyze the inter-annual and inter-decadal drought patterns, and to determine the relationships between drought and teleconnection indices. We first determine significant spatial patterns of annual and seasonal drought by using the empirical orthogonal function (EOF) and rotated empirical orthogonal function (REOF) methods. Then, temporal variability of time series corresponding to the significant patterns is explored in terms of long-term trends and periodic behavior by using the Mann–Kendall method and the Wavelet Transform (WT). Additionally, we investigate the relationships between the time variability of significant patterns and teleconnection indices.

2. Study area, data, and methods

2.1. Study area

The arid region of study is located in the innermost center of the Eurasia continent (Fig. 1), and comprises an area extending between 34 and 50°N, 73 and 108°E (2.53×10^6 km^2). The arid region of northwestern China includes the Uygur Autonomous Region of Xinjiang, Gansu Province, western Inner Mongolia, the northern Hui Autonomous Region of Ningxia, and the northern Qinghai Province. In these areas, basins lie west of the Helanshan Mountains in the Ningxi Hui Autonomous Region and west of the Ushaoling Mountains in Gansu Province. The climate of the arid region is typical of inner-continental land masses, with a wide temperature range, low precipitation, and low humidity. The climate is dominated by continental arid conditions with lesser effects from the East Asian Monsoon (Liu et al., 2010). Mean annual rainfall value in the whole study area is 172 mm. Annual rainfall in the area generally increased at the rate of 8.01 mm/decade during 1960–2010. The temperature in the arid regions has risen by 0.35 °C/decade, and the significantly increasing trends dominate throughout the whole year and in all seasons (Wang et al., 2013b).

2.2. Data

Monthly data (including monthly temperature and precipitation) from 76 weather stations (Fig. 1) were used, provided by

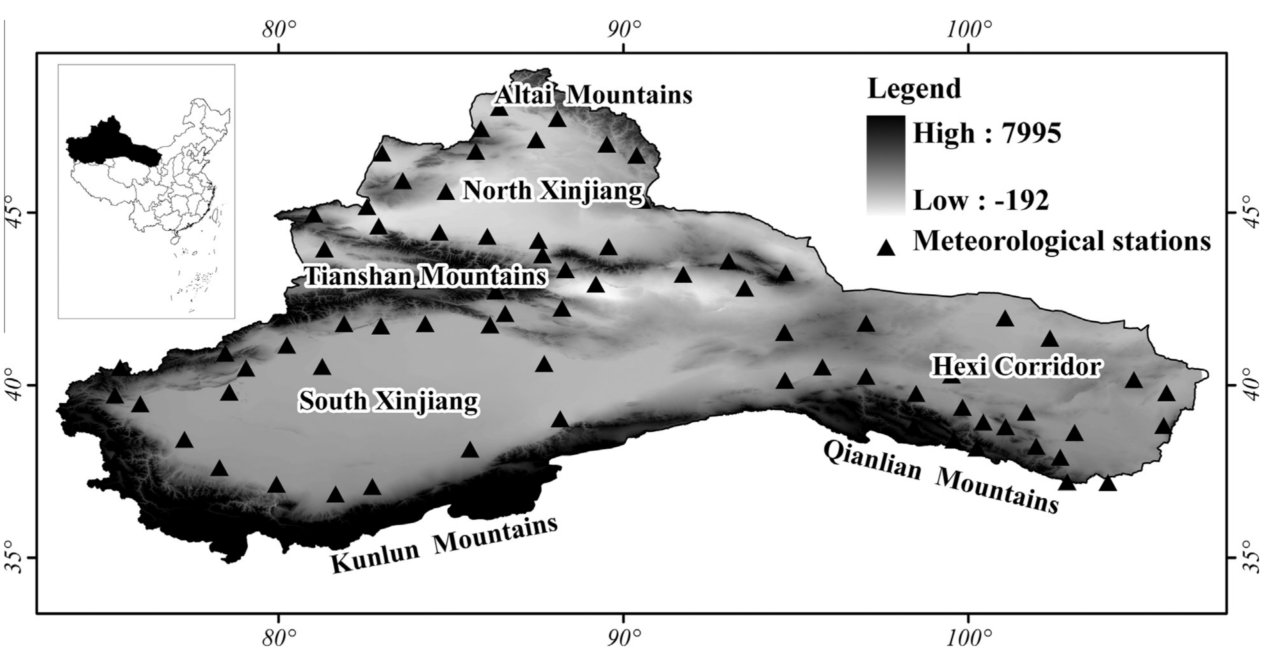

Fig. 1. Study area and weather station in the arid region of China.