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Anthropogenic warming has caused hot droughts more frequently in China

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ABSTRACT

Historical records have indicated an increase in high-impact drought occurrences across China during recent decades, but whether this increase is due to natural variability or anthropogenic change remains unclear. Thus, the shift toward dry conditions and their associated attributions across China are discussed in this study, primarily regarding the standardized precipitation evapotranspiration index (SPEI). The results show that drought occurrences across China increased consistently during 1951–2014, especially during the recent twenty years. Most of the increased drought events happened under warm-dry conditions that coincided with relatively high temperature anomalies but without large anomalies in annual precipitation, implying an increase in hot drought events across China. Further analysis revealed that the change in drought occurrences were mainly due to the combined activity of external natural forcings and anthropogenic changes across China. However, external natural forcings were mainly responsible for the variability of droughts and anthropogenic influences for their increasing trends, suggesting that anthropogenic warming has increased hot drought occurrences, associated risks and impacts across China. With continued warming in the future, the impact of anthropogenic warming on the increased hot drought events will be further amplified. The probability of warm years is projected to significantly increase, and the occurrence probability of hot drought events (SPEI < -1.0) will increase to nearly 100% by the year 2050, even though the annual precipitation is projected to increase across China in the future.

1. Introduction

In recent decades, China has suffered several prolonged extreme droughts, such as the ones from the autumn of 2009 to the spring of 2010 in Southwest China, from July to August of 2013 in Eastern China, and from July to August of 2014 in North China, which have resulted in large economic losses, ecosystem damage, and the disruption of society (e.g., Yang et al., 2012; Sun, 2014; Wang and He, 2015; Wang et al., 2015). According to Chinese governmental statistics, the severe drought in 2009/2010 in Southwest China caused a shortage of drinking water that impacted more than 21 million people and 11 million livestock, resulting in economic losses that reached nearly 30 billion US dollars (e.g., Yang et al., 2012). Additionally, the drought in North China in the summer of 2014 is considered to be the most serious event in the past six decades, resulting in a devastating reduction of agricultural production (Wang and He, 2015). Furthermore, the study by Yu et al. (2014) has revealed that severe and extreme droughts have become more serious since the late 1990s in China, and the dry areas were reported to increase by ~3.72% decade^{-1} in past decades. Thus, understanding the causes of the increasing severe drought events in China is urgently important for improving predictions and reducing economic losses.

Previous studies have revealed the possible physical mechanisms responsible for severe drought in China, through associated atmospheric circulation patterns and atmosphere/ocean modes (e.g., Wang, 2001; Ma, 2007; Gao and Yang, 2009; Yang et al., 2012; Wang and He, 2015). The weakening of the East Asian monsoon after the late 1970s has contributed to a dramatic decrease of monsoon rainfall in North China, resulting in the so-called "Southern Flood—Northern Drought" pattern over eastern China (Wang, 2001, 2002; Ding et al., 2009). The winter North Atlantic Oscillation (NAO) also showed an in-phase correlation with summer precipitation in eastern China, with the NAO directing precipitation for 2–3 years (Fu and Zeng, 2005). Furthermore, from a multi-decade

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perspective, the positive phase of the Pacific Decadal Oscillation (PDO) generally corresponds to a dry period over North China (Ma, 2007; Pei et al., 2015). The severe drought over Southwest China during the 2009/2010 autumn-winter was simultaneously accompanied by a strong negative-phase Arctic Oscillation and an El Niño Modoki event (Yang et al., 2012). The snow cover anomaly over the Tibetan Plateau and the activity of the Western Pacific Subtropical High are also considered as two important causes of the droughts in this region, especially the drought in the summer of 2006 (Zou and Gao, 2007). Additionally, some studies have emphasized the impacts of the upper tropospheric jet stream on precipitation anomalies over central-southern China (e.g., Wang et al., 2010).

Despite good insights into the causes of droughts based on large-scale atmospheric circulation anomalies, the influence of anthropogenic forcings on the occurrence probability of droughts has received less attention until recently (Li et al., 2015a; Zhao and Dai, 2015; Zhao et al., 2015). In early 2007, using a regional climate model study, Gao et al. (2007) showed that the precipitation decreased and the temperature increased when land use was modified by anthropogenic activities. Recently, Wang et al. (2013) implicated anthropogenic emissions as a prime driver of the "Southern Flood—Northern Drought" pattern in eastern China after the late 1970s. However, some recent analyses (Zhou et al., 2013; Song et al., 2014; Zhang and Zhou, 2015) from simulations of the Coupled Model Intercomparison Project phase 5 (CMIP5) argued that although the presence of aerosols can drive a weakened monsoon circulation, the responses from these models are far weaker than the observations. Moreover, the models failed to reproduce the observed precipitation changes as well as the drought trend in northern China. Therefore, they suggested that natural variability was the dominant factor that determined the drought changes in China and that the aerosol influence played only a complementary role. This discrepancy again raised the question of which factor is important for inducing the increasing droughts in China.

Precipitation deficits are a prerequisite for drought occurrences by any definition, and thus most previous efforts have evaluated the droughts using only precipitation anomalies (e.g., Yang et al., 2012; Chen et al., 2013; Zhang et al., 2013a; Li et al., 2015b). In addition, temperature anomalies are also considered to play an important role in drought occurrences, greatly amplifying evaporative demand and thereby increasing the overall drought intensity and impact (e.g., Dai et al., 2004; Dai, 2012; AghaKouchak et al., 2014; Chen and Sun, 2015a). In the past century, human activity has caused significant temperature increases. However, little attention has been given to the analysis of anthropogenic influences on droughts in China.

Therefore, on the basis of previous studies, this work focuses mainly on the discussion of changes in drought occurrences in China under warming conditions. More importantly, the possible impacts on the droughts from external natural and anthropogenic influences are separated and discussed. In addition, the probability of drought occurrence is also projected under continued future warming scenarios.

2. Data and methods

2.1. Datasets

The complete record sets, including monthly precipitation and temperature for the period from January 1951 to December 2014 from 160 first-order meteorological stations across China (Fig. 1), were used in this study. These stations are maintained by professional weather observers in China, and the data are collected and released by the National Climate Center along with their homogeneity and quality control processes. Because the climates in China vary across regions due to its complex topography, China is separated into six regions (Fig. 1) according to the China meteorological and geographical division handbook that was released by the National Meteorological Center of the China Meteorological Administration in 2006, which has been widely used in early studies (e.g., Chen et al., 2012a). These regions include Northeast China (NEC), North China (NC), South China (SC), Southwest China (SWC), eastern Northwest China (ENWC), and western Northwest China (WNWC). Analyses mainly focused on these six regions and are presented in the following sections. The time series were calculated from the averages of all stations for China as a whole and for each of six regions.

To assess the potential effects of natural and anthropogenic forcings on droughts, monthly outputs from 15 climate model simulations that include both external natural and human forcings ("Historical" experiment), only external natural forcings ("Natural" experiment; simply referring as NAT hereafter), and only anthropogenic influences ("GHG" experiment: Greenhouse Gases) were used in this study. Additionally, the 21st-century scenarios for future greenhouse gas emissions, RCP4.5 (Representative Concentration Pathways) and RCP8.5 as defined in Moss et al. (2010), were used in this study; 33 models from RCP4.5 and 28 models from RCP8.5 were selected to evaluate potential future changes of droughts in China. All these analyses in this study were based on the first ensemble member of each model, referred to as *r1i1p1* for all experiments. These outputs were extracted from the CMIP5 and are archived at the website of the Earth System Grid (ESG) gateway, hosted by the PCMDI (Program for Climate Model Diagnosis and Intercomparison). More information about these models is presented in Table 1. These monthly outputs were re-gridded into a common $2.5^\circ \times 2.5^\circ$ grid using a first-order conservative remapping procedure. The topographical adjustment was implemented for the re-gridded monthly temperature due to the different resolutions between models and the target grids.

2.2. Methods

Objectively quantification of drought occurrence, intensity, duration, and spatial extent is very complex. Thus, numerous studies have been devoted to improving drought detection and monitoring, and a few objective indices have been developed on the basis of readily available data (e.g. Palmer, 1965; McKee et al., 1993; Ma and Fu, 2001). Among these indices, the Palmer drought severity index (PDSI; Palmer, 1965) and the standardized precipitation index (SPI; McKee et al., 1993) are the two most widely used. However, more recent studies (e.g. Guttman, 1998; Dubrovsky et al., 2009; Vicente-Serrano et al., 2010; Beguería et al., 2014) have identified several deficiencies in these indices that limit their accuracies in both operational and research works. For example, the main shortcoming of the PDSI is its built-in fixed time scale of 9–12 months (Guttman, 1998), while for the SPI only precipitation variability is considered in its calculation, but the role of temperature is ignored (Vicente-Serrano et al., 2010). Therefore, a new standardized precipitation evapotranspiration index (SPEI) based on a simple water balance (i.e., the difference between precipitation P and potential evapotranspiration E) was developed by Vicente-Serrano et al. (2010) and further improved by Beguería et al. (2014).

The process of SPEI calculation can be summarized as follows. First, Vicente-Serrano et al. (2010) suggested the difference (Δ) of P and E to measure the water surplus or deficit:

$$\Delta_i = P_i - E_i \quad (1)$$

Second, Δ is aggregated at different time scale (n) as: