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Climate change impacts on meteorological, agricultural and hydrological droughts in China

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ABSTRACT

Bias corrected daily climate projections from five global circulation models (GCMs) under the RCP8.5 emission scenarios were fed into a calibrated Variable Infiltration Capacity (VIC) hydrologic model to project future hydrological changes in China. The standardized precipitation index (SPI), standardized runoff index (SRI) and standardized soil moisture index (SSWI) were used to assess the climate change impact on droughts from meteorological, agricultural, and hydrologic perspectives. Changes in drought severity, duration, and frequency suggest that meteorological, hydrological and agricultural droughts will become more severe, prolonged, and frequent for 2020–2049 relative to 1971–2000, except for parts of northern and northeastern China. The frequency of long-term agricultural droughts (with duration larger than 4 months) will increase more than that of short-term droughts (with duration less than 4 months), while the opposite is projected for meteorological and hydrological droughts. In extreme cases, the most prolonged agricultural droughts increased from 6 to 26 months whereas the most prolonged meteorological and hydrological droughts changed little. The most severe hydrological drought intensity was about 3 times the baseline in general whereas the most severe meteorological and agricultural drought intensities were about 2 times and 1.5 times the baseline respectively. For the prescribed local temperature increments up to 3 °C, increase of agricultural drought occurrence is predicted whereas decreases or little changes of meteorological and hydrological drought occurrences are projected for most temperature increments. The largest increase of meteorological and hydrological drought durations and intensities occurred when temperature increased by 1 °C whereas agricultural drought duration and intensity tend to increase consistently with temperature increments. Our results emphasize that specific measures should be taken by specific sectors in order to better mitigate future climate change associated with specific warming amounts. It is, however, important to keep in mind that our results may depend on the emission scenario, GCMs, impact model, time periods and drought indicators selected for analysis.

1. Introduction

Drought is a natural phenomenon mainly caused by below-normal precipitation over an extended period (Wilhite et al., 2000; Tallaksen et al., 2004; Mishra and Singh, 2010; Dai, 2012; Van Loon and Van Lanen, 2012). Droughts are complex events best characterized by a series of properties including their frequency, duration and intensity (Keyantash and Dracup, 2002; Mishra and Singh, 2010). Droughts can also take a variety of different forms depending on which part of the hydrological cycle they impact most strongly on. For example, a lack of precipitation over a prolonged period of time (several weeks to several years) manifests as a meteorological drought. Such droughts invariably propagate through the hydrologic cycle, however. Extended meteorological droughts tend to cause hydrological droughts, or droughts characterized by a reduction in stream flow that occurs from both the loss of stream flow and a reduced occurrence of groundwater top-up events. A further consequence of extended meteorological droughts is the occurrence of agricultural droughts. These occur when the soil moisture is reduced over time from an ongoing lack of rainfall (Wilhite and Glantz, 1985; Hisdal et al., 2001; Keyantash and Dracup, 2002; Sheffield and Wood, 2008; Hayes et al., 2007). All types of droughts can be detrimental to both natural and anthropogenic systems. For example, below-normal water availability in rivers, lakes and reservoirs can cause water scarcity and often occurs in association with increasing water demand. This along with reduced water available for irrigation and in the soil column on account of the drought can threaten food production while also damaging aquatic ecosystems as ever greater proportions of the remaining water available are extracted for human uses (Döll et al., 2009; Wisser et al., 2010). The significance of droughts cannot be understated with droughts ranking first among all

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natural hazards when measured in terms of the number of people affected and the economic losses associated with their occurrence (Wilhite, 2000).

China is a frequently drought-affected country in East Asia since the monthly, annual and inter-annual variations in precipitation and temperature are significant there (Ma and Fu, 2003; Dai et al., 2004; Zou et al., 2005). As reported by the Ministry of Water Resources of China (MWRC, 2011), extreme droughts occurred every 2 years on average for the period 1990–2007. The average grain loss associated with these droughts is nearly 39.2 billion kg annually, with the average economic loss accounting for 1.47% of the country's gross domestic product. During the past decade, droughts were common in all parts of China from south to north, and resulted in serious social, economic and environmental consequences (Wang et al., 2012). For example, the recent winter drought which hit the northeast of China in 2008–2009 left more than 10 million people struggling with water shortages and led to total economic losses of up to $2.3 billion (Wang et al., 2011a, 2011b). Other examples include, the record-breaking severe and sustained droughts occurred in 2006 (Li et al., 2009) and 2009–2010 (Yang et al., 2012) in Southwest China that caused devastating and far-reaching impacts to agriculture, society, the economy, and many ecosystems (Zhang et al., 2012a,b).

The devastating impacts of droughts in China have spurred many scientific studies, with focus on particular drought components, such as precipitation, runoff/stream flow, or soil moisture. For example, using the precipitation-based China-Z index, Wang and Zhai (2003) showed an expanding area of drought affected lands in agricultural regions of northern China during the past 50 years. Ma and Fu (2003) also revealed a drying trend in major parts of North China during 1951–1998 using a surface humidity index. These patterns are not confined to northern China only however. Indeed, Wu et al. (2011) reconstructed China's daily soil moisture values from 1951 to 2009 and showed that up to 30% of the total area of China is prone to drought and Wang et al. (2011a, 2011b) showed that over the past 60 years severe droughts in China grew increasingly common, suggesting an increasing risk on sustainable agricultural productivity across the whole nation. Zou et al. (2005) used the Palmer Drought Severity Index (PDSI) to investigate the variations in droughts over China, and Zhai et al. (2010) used both PDSI and standardized precipitation index (SPI) to identify tendencies in dry/wet conditions during recent decades over ten large regions in China. Both found an increasing trend of droughts across major regions of China in the past decades. Despite this intense research focus on droughts in China, a missing component of this research has been a consideration of the different types of droughts (namely meteorological, hydrological and agricultural). As each manifests differently and has unique implications for natural and anthropogenic systems, this is a significant omission. To fully understand and manage drought in China it is imperative to develop a more complete picture of how these different types of droughts operate and how their frequency, duration and intensity have been changing in the recent past and may continue to change in the future, particularly as a result of climate change.

It has observed that there has been an increase in drought risk globally since the late 1970s, due to enhanced evaporation (on account of increasing global temperatures) without any increase in precipitation in most locations (Sheffield and Wood, 2008; Zou et al., 2005; Dai, 2012; Trenberth et al., 2014). Within the context of future global warming as a result of an increase in greenhouse gases (IPCC, 2013), it is of great significance to assess the climate change impacts on droughts at the regional scale and, more importantly, to determine which types of droughts will be most affected (i.e., meteorological, hydrological and/or agricultural). Several studies have quantified the potential changes of hydrology and water resources in basins in North China (e.g., Xu et al., 2009c; Li et al., 2010; Yang et al., 2012), South China (e.g., Jiang et al., 2007; Qiu, 2010; Wang et al., 2014) and the whole country (e.g., Guo et al., 2002; Wang et al., 2012; Leng et al., in press). However, very few studies have examined the impacts of climate change on droughts at the river basin scale (e.g. Duan and Mei, 2014). There has also been little effort to explicitly examine the potential impacts of future climate change on droughts across the whole country, and especially, the sensitivities of various drought type (e.g. the meteorological, agricultural and hydrological droughts) responses to different climate warming amounts. Understanding whether certain types of droughts are more sensitive to projected climate change than others could potentially identify which sector(s) is most sensitive to changing drought frequencies, durations and intensities enabling more effective drought management plans to be developed. Indeed, results from such a comprehensive study over the whole country could be used not only to inform on potential impacts for specific sectors but also can be used to coordinate adaptation/mitigation strategies among different sectors/regions by the central government. Thus, the objective of this research is to assess the potential impacts of future climate change on drought characteristics in different domains of the hydrological cycle in China. To address this, we used bias-corrected daily outputs from state of the art climate models as inputs for a calibrated hydrologic model configured over the whole of continental China. Based on future water resource scenarios, drought characteristics were then assessed using various drought indices and the implications of the changes in drought characteristics are discussed.

2. Data and methodology

2.1. Bias-corrected climate projections

The fast-track of the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP) aims to quantify the uncertainty in climate scenarios, climate models, and impact models that project climate change impacts on water, biomes and agriculture (Warszawski et al., 2013). Within the framework of ISI-MIP, climate projections from 5 global circulation models (HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M, see Table 1 for details) driven by multiple Representative Concentration Pathway (RCP) scenarios were obtained at a 0.5° × 0.5° spatial resolution and a daily time step from 1950 to 2099 (Hagemann et al., 2013). These datasets were bias-corrected to the WATCH Forcing data (WFD) (Weedon et al., 2011) enabling us to adequately represent the effects of changes in climate variability in addition to changes in the climate mean (Hempel et al., 2013), which is important for the investigation of extreme hydrological events. The bias correction method is based on a distribution-based bias correction algorithm which was adopted in the WaterMIP/WATCH (Piani et al., 2010; Hagemann et al., 2011). Specifically, a multiplicative algorithm that preserves the relative changes (e.g. precipitation) and an additive approach that preserves the absolute changes (e.g. temperature) were first applied to the GCM data to match the WFD climatology. The residual or normalized data are then applied to a parametric quantile mapping approach for adjusting the daily variability of GCM data to match that of the WFD. Subsequently, the derived monthly correction

Table 1
Descriptions of the 5 global circulation models used in this study.

Model name	Institute acronyms	Institute full name
GFDL-ESM2M	NOAA GFDL	NOAA Geophysical Fluid Dynamics Laboratory
HadGEM2-ES	MOHC (additional realizations by INPE)	Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais
IPSL-CM5A-LR	IPSL	Institut Pierre-Simon Laplace
MIROC-ESM-CHEM	MIROC	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
NorESM1-M	NCC	Norwegian Climate Centre