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Climate change enhances the severity and variability of drought in the Pearl River Basin in South China in the 21st century

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ABSTRACT

Drought is expected to increase in frequency, severity, and duration in the future due to global warming and this will greatly threaten the future socio-economic development. This study evaluates the spatiotemporal variation of future drought (2016–2100) in the Pearl River Basin (PRB) using the Palmer drought severity index (PDSI), the Variable Infiltration Capacity (VIC) model, and future climate projections based on the general circulation models (GCMs) from phase 5 of the Coupled Model Intercomparison Project (CMIP5) under three representative concentration pathway (RCP) scenarios. The results show that future drought conditions are expected to be more serious than historical (1960–2015) drought conditions in the PRB, especially under RCP8.5. The severity and variability of future drought conditions are also higher than for the historical period. The west Guangxi and South Guizhou provinces exhibit the highest increment in drought severity under the three RCP scenarios. At the seasonal scale, drought severity shows the highest increment in the winter with little change in summer; the summer drought severity increases in most areas of the PRB but the increment of the drought severity is lower than the winter. The number of future drought events is expected to decrease but the duration and severity are expected to increase, especially in the mid-west PRB and under high greenhouse gas (GHG) emission scenarios. In summary, in most areas of the PRB, the severity and variability of drought are expected to increase in the 21 st century, especially in the mid-west PRB and an increase in evapotranspiration is assumed to be the main underlying cause. Irrigation projects and agricultural production in the PRB might face serious threats of drought in the future.

1. Introduction

Drought is one of the most frequent and hazardous disasters worldwide and has caused considerable agricultural and economic losses (Mishra and Singh, 2010; Piao, 2010; Lobell and Costa-Roberts, 2011). Recent global surface air temperatures have risen significantly due to global climate change and increases in greenhouse gas (GHG) emissions, which are expected to exacerbate future drought events (Dai, 2013; Cook et al., 2014). The 4th and 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (AR4 and AR5) has predicted an increase in global surface air temperatures of 0.3 ∼ 4.8 °C and associated changes in the spatial patterns of global precipitation in the 21st century. If global temperatures continue to rise, the area and intensity of drought may change dramatically.

General circulation models (GCMs), released by the Coupled Model Intercomparison Project (CMIP), provide information on long-term future climate projections (IPCC, 2013). The GCMs simulate different preset scenarios representing different future GHG emission levels and provide excellent tools for evaluating future changes in drought conditions. As the latest release of the GCM data by the CMIP, the CMIP Phase 5 project (CMIP5) provides more than 50 GCMs for the IPCC's AR5 from 24 institutes around the world (Taylor et al., 2011). The representative concentration pathway (RCP) scenarios (Moss et al., 2010) that include four scenarios (i.e., RCP2.6, RCP4.5, RCP6.0, and RCP8) with increasing levels of GHG emissions were adopted in the CMIP5 as well as the IPCC AR5. Using these GCMs, many studies have demonstrated an increase in future drought severities with increasing levels of GHG emissions (Wang, 2005; Sheffield and Wood, 2008; Li et al., 2012; Dai, 2011, 2013; Cook et al., 2014; Wang and Chen, 2014). These studies have characterized a general outline of future drought changes and pointed out the subsequent direction of the effort. However, most studies have only focused on a national or global scale,

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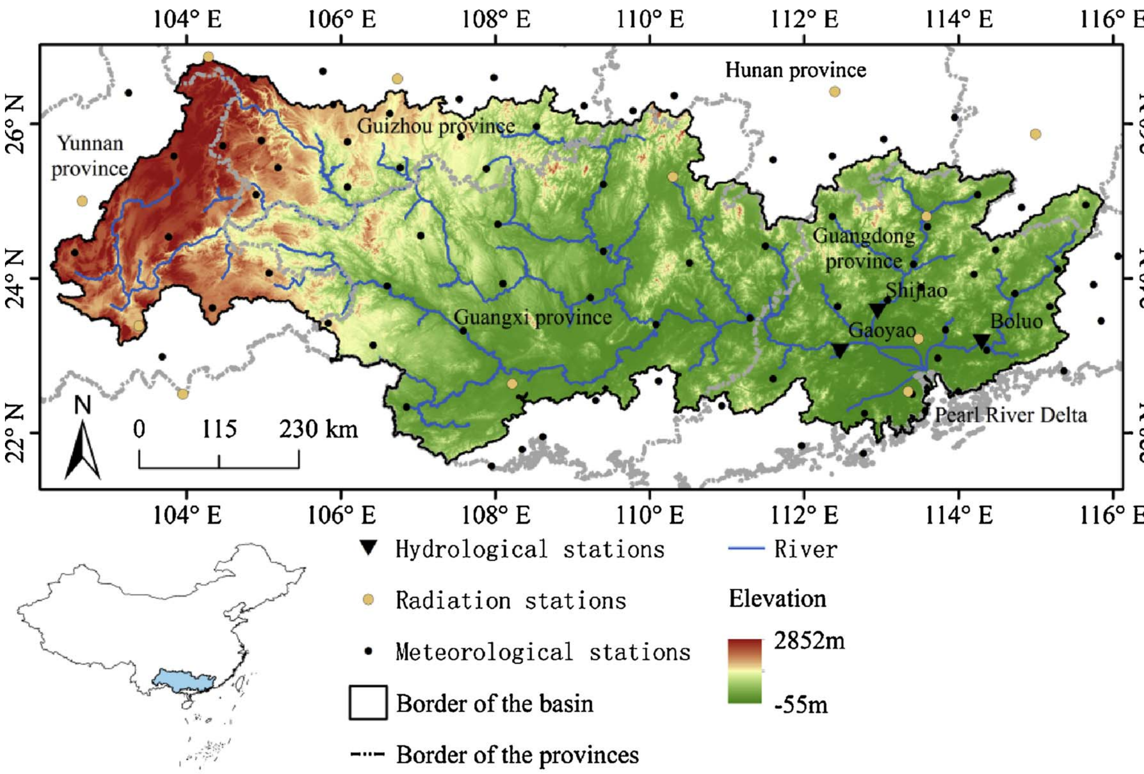

Fig. 1. Location, topography and stations of the Pearl River Basin (PRB).

impeding further understanding of varying patterns at a fine scale and applications. First, a coarse spatial resolution is usually inadequate for revealing the spatiotemporal pattern of a regional drought because only a fine spatial resolution enables the regional management of drought control, water resource allocation, and agricultural production. Second, the drought metrics that were used in the earlier studies, such as the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010) and the conventional Palmer drought severity index (PDSI) (Palmer, 1965), did not consider land surface factors (e.g., hydrological process, soil property, and vegetation), resulting in a lack of clarity regarding key change in future drought events.

It is well known that the conventional PDSI is calculated based on the water balance and thus has been widely applied to the study about climate change and impact on drought (Sheffield and Wood, 2008; Cook et al., 2014; Dai, 2013; Wang and Chen, 2014). However, in the conventional PDSI, the water budget is calculated using a simple two-layer bucket-type water balance model that does not consider land use and the spatial heterogeneity of soil properties (Zhang et al., 2012a,2012b). Despite a revision of the PDSI using a self-calibrating algorithm (scPDSI, Wells et al., 2004) to improve the portability and spatial comparability, the index is still inadequate for determining the actual drought conditions in detail. To solve this problem, distributed hydrological models that feature improved physical mechanisms and a wider consideration of land surface processes have been used to analyze drought change (Wu et al., 2011; Zhang et al., 2012a,b; Liu et al., 2015; Zhang and He, 2016). For example, Zhang et al. (2012a,2012b) and Liu et al. (2015) improved the PDSI by replacing the conventional two-layer bucket-type model with the variable infiltration capacity (VIC) hydrological model (Liang et al., 1994); in this approach the water budget of PDSI is calculated based on the VIC model's outputs (e.g. evapotranspiration, soil moisture, and runoff yield). This improvement represents a new direction for a more reliable evaluation of drought conditions.

As a widely used and grid-based macroscale distributed hydrological model, the VIC model not only simulates the land surface hydrological processes based on water and energy balances but also considers several other factors such as the sub-gridcell heterogeneity of the land cover, the root zone of the vegetation, and frozen soil. The model has been widely validated in different climatic regions, including arid and humid regions in China, and has been coupled successfully with downscaled GCMs to obtain future land surface process projections (Wu et al., 2014; Yan et al., 2015). Moreover, evidence has proved the reliability and rationality of this model based on calculations of the water budget of the PDSI (Wu et al., 2011; Zhang et al., 2012a,2012b; Liu et al., 2015; Zhang and He, 2016). Because it considers not only soil moisture but also evapotranspiration, the VIC-based PDSI is assumed to be a powerful tool for analyzing the future changes in drought conditions.

Even though the Pearl River Basin (PRB) is located in the subtropical humid monsoon region of South China, the area has suffered considerably from frequent and severe meteorological drought events. For example, a rare severe drought (the most severe drought disaster in China since 1951, Barriopedro et al., 2012) occurred in the upper PRB located in southwest China from the autumn of 2009 to the spring of 2010, causing an economic loss of more than 3.5 billion dollars and a crop loss of more than 1 million ha. A consensus has been reached that the historical droughts occurring in the PRB can be attributed to decreased precipitation (Barriopedro et al., 2012). However, a debate remains as to the factors driving the evolution and changes in future droughts events although Cook et al. (2014) believed that increased evapotranspiration in South China was a key factor. Therefore, further explorations of the major influencing factors on future drought events in the PRB are required.

In this study, the VIC model was used to calculate the VIC-based PDSI in the PRB for the evaluation of future drought conditions. Detailed objectives of the study include 1) to construct the VIC-based PDSI in the PRB, 2) to simulate the hydrological processes in a future period (2016–2100) using the VIC model with a downscaled multi-model ensemble (MME) of the GCM projections and calculate the PDSI based on the VIC outputs, and 3) to evaluate the spatiotemporal

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