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21st century drought outlook for major climate divisions of Texas based on CMIP5 multimodel ensemble: Implications for water resource management

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SUMMARY

Management of water resources in Texas (United States) is a challenging endeavor due to rapid population growth in the recent past coupled with significant spatiotemporal variations in climate. While climate conditions impact the availability of water, over-usage and lack of efficient management further complicate the dynamics of supply availability. In this paper, we provide the first look at the impact of climate change projections from an ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) on 21st century drought characteristics under three future emission trajectories: Representative Concentration Pathway (RCP) 2.6, RCP 4.5 and RCP 8.5, using the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI). In addition, we evaluate the performance of the ensemble in simulating historical (1950–1999) observations from multiple climate divisions in Texas.

Overall, the ensemble performs better in simulating historical temperature than precipitation. In semi-arid locations such as El Paso and Laredo, decreasing precipitation trends are projected even under the influence of climate policies represented by the RCP 4.5. There is little variability in the SPI across climate divisions and across RCPs. The SPEI, on the other hand, generally shows a decreasing trend toward the latter half of the 21st century, with multi-year droughts becoming the norm under the RCP 8.5, particularly in regions that are already dry, such as El Paso. Less severe droughts are projected for the sub-humid eastern edge of the state. Considering that state water planning agencies are already forecasting increased water shortages over the next 50 years, we recommend proactive approaches to risk management such as adjusting the planning tools for potential recurrence of multi-year droughts in regions that are already water-stressed.

1. Introduction

Droughts are a normal part of climate and occur in virtually all parts of the world. However, in recent years droughts have been experienced with greater frequency and severity globally (Nielsen-Gammon, 2008; Mishra and Singh, 2010; Texas Water Development Board [TWDB], 2012; Dai, 2013; Yu et al., 2014; Warren and Holman, 2012). Since the beginning of the 21st century, two major droughts in Texas, in 2006 and 2011, have already resulted in the loss of hundreds of lives, billions of dollars of agricultural losses via crop failure and thousands of square miles of land lost to wildfires (Combs, 2012; AghaKouchak and Nakhijiri, 2012). The 2011 drought was the worst 1-year drought in recorded history for much of Texas. By October 2011, nearly 90% of the state was classified in the exceptional drought category (Combs, 2012); conditions did not improve for much of the state until 2013. Water planners in the state are tracking the inflows for the recent years and concluding that some regions, such as Wichita Falls and West Texas are in the middle of a new and more severe critical drought or experiencing a drought very similar to the critical drought of the 1950s.

The effects of long-term droughts, such as the 1950s drought and the late 1990s drought are more widespread, as they impact the quantity of water available from surface and groundwater resources, impair water quality and riparian habitats, and negatively impact energy infrastructure (Riebsame et al., 1994; Wilhite and Svoboda, 2000; Wilhite and Knutson, 2008). As such, the frequency of drought is expected to increase worldwide

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because of increasing temperatures and rainfall events tending to be shorter but more intense (Alexander et al., 2006; Shili et al., 2014; Wuebbles et al., 2014). For instance, South-eastern Australia was subject to extreme dry conditions in the form of millennial drought (1997–2009), followed by the wettest recorded two-year period in 2010–2011 (CSIRO, 2012). Several studies (Norwine and John, 2007; Nielsen-Gammon, 2008; Banner et al., 2010; Liu et al., 2012; Jiang and Yang, 2012; Hernandez and Uddameri, 2014; Wuebbles et al., 2014) based on climate models have projected rising temperatures for Texas in the 21st century, albeit with no significant trends in precipitation, suggesting higher likelihood of droughts. Parts of the Southwestern United States, including Western Texas have already been identified as being climate change 'hotspots' or areas highly vulnerable to the impacts of climate change by Diffenbaugh et al. (2008).

On the demand side, the Texas Water Development Board (TWDB, 2012) projects that the water demand in Texas will rise by 22% by 2060, from about 18 million acre-feet per year to about 22 million acre-feet per year, creating more challenges for water supply planners. By 2060, urban areas are expected to have the largest increases in water demand due to increased municipal water consumption from rapid population growth. In particular, counties with major metropolitan areas, such as Harris County (Houston), Bexar County (San Antonio), Dallas, Tarrant, Denton and Collin Counties (Dallas-Fort Worth area) and Travis County (Austin) are anticipated to have the largest water deficits (difference between projected supplies and demands). During the same period, groundwater supplies are expected to diminish by ~30%, primarily due to decreased water availability from the Ogallala, over-usage, and pumping restrictions to curb land subsidence in the Gulf Coast aquifer (TWDB, 2012). Surface water supplies are projected to decline due to persistent dry conditions and decrease in inflows. Mace and Wade (2008) suggest that future changes in climate resulting in more frequent droughts may induce a greater reliance on groundwater, if surface water resources become less reliable.

Understanding the spatial and temporal characteristics of drought is thus critical for long-term water use planning, particularly in a water-stressed state such as Texas. Although different classifications of drought exist based on the hydroclimatic or socio-economic variable used to measure it, droughts generally result from lack of precipitation for a sustained period of time. Evapotranspiration (ET) may also play a significant role in drought by producing moisture deficits. Several drought indices, such as the Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Runoff Index (SRI; Shukla and Wood, 2008) and the Standardized Precipitation Index (SPI; McKee et al., 1993) have been applied to detect and monitor drought. The SPI has been widely-used in drought assessment studies (e.g., Turkes and Tath, 2009; Ibrahim et al., 2010) but only accounts for precipitation. Over the last few years new indices such as the Joint Deficit Index (JDI; Kao and Govindaraju, 2010) and the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al. (2010)) have been introduced to overcome some of the shortcomings of the SPI. The JDI is a probability-based index that has been developed using copulas and can be used to assess the combined effects of multiple hydrologic variables such as precipitation and streamflow. Its ability to capture emerging and prolonged droughts has been demonstrated (Kao and Govindaraju, 2010; Mirabbasi et al., 2013). The SPEI includes evapotranspiration (ET), the loss element of the water balance, while retaining the positive features of the SPI. By including ET, the SPEI accounts for the impact of trends in another important climatic variable, temperature. Although the SPEI is a recent development in drought assessment, it has already been recommended as an alternative to the SPI to evaluate climatic water imbalances by several authors (e.g. Potop and Mozny, 2011; Begueria et al., 2014; Stagge et al., 2014).

Recently, Hernandez and Uddameri (2014) applied the SPEI to two Coupled Model Intercomparison Project Phase 3 (CMIP3) global climate models (GCMs) under two scenarios (Special Report on Emission Scenarios (SRES) A1B and B1) across different locations in South Texas and projected long periods of drought, ranging from 5 to 8 years, in the second half of the 21st century. However, their projections of intensification of future drought is based the Thornthwaite method of estimating PET, a method that has been suspected of overestimating drying with increasing temperatures (Lockwood, 1999). As part of the Southern Climate Impacts Planning Program (SCIPP), Liu et al. (2012) applied a set of 16 CMIP3 GCMs to assess the effect of future climate change on the Southern United States. Of the six states included in the study, Texas was found to have the greatest decrease in annual precipitation in the 21st century; additionally, drier regions were projected to get drier. Jiang and Yang (2012) simulated future changes in hydroclimatic variables across Texas using a suite of CMIP3 GCMs. Under the A1B scenario, much of the state was projected to get drier toward the end of the 21st century. However, the authors point out that regional difference in climate factors such as moisture sources and topography across Texas strongly impact future patterns in temperature and precipitation and must be taken into account in drought assessment studies. The general conclusion from these studies is a drier regime toward the end of the 21st century. However, these projections are based on the SRES scenarios where the impacts of future regulations on emissions to have not been explored.

In response to the need for more sophisticated models and scenarios that capture the effect of policies, simulations from the new generation of GCMs have recently become available within the CMIP Phase 5 (CMIP5; Taylor et al., 2012). The CMIP5 models have higher spatial resolutions and are more comprehensive and as such provide new avenues for modeling the effects of climate change employing a wide range of alternative scenarios, known as Representative Concentration Pathways (RCPs) to aid in risk-based natural resource management. The simulation of climate from a single GCM is not sufficient to provide a thorough assessment of future hydrologic impacts or to adequately capture the uncertainties involved therein; the use of multi-model ensemble means has been shown to provide more vigorous projections of future changes and presents the most conservative approach from a risk-management perspective (Murphy et al., 2004; Raisanen, 2007; Tebaldi and Knutti, 2007; Sperna Weiland et al., 2012). The primary objective of this paper is, therefore, to provide the first look at the impact of climate change projections from an ensemble of CMIP5 GCMs on drought characteristics until the end of the 21st century under different mitigation scenarios in 10 cities, chosen as representative examples of the major climate divisions of Texas, using the SPI and SPEI. The novel feature of this study is that we have evaluated the performance of the ensemble in simulating historical observations at the chosen study locations and make recommendations on their suitability of application in the state.

2. Methodology

2.1. Study area characteristics

Owing to its sheer size and a number of local geographical influences, the climate of Texas is spatially diverse. There are ten distinct climatic regions as shown in Fig. 1a (GIS shapefile sourced from NCDC, 2015), each with their own seasonal weather patterns (Nielsen-Gammon, 2008). 10 major urban areas, namely (1) Abilene, (2) Dallas-Fort Worth, (3) El Paso, (4) Houston, (5) Laredo, (6) Longview, (7) Lubbock, (8) McAllen, (9) San Angelo, and (10) San Antonio were chosen as illustrative examples of the 10 major climatic divisions in Texas. Other major urban areas, such as Amarillo, Austin,