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Hydro-climatological Drought Analyses and Projection Using Meteorological and Hydrological Drought Indices: A Case Study in Blue River Basin, Oklahoma

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1. Introduction

Understanding the characteristics of the historical droughts will be beneficial to reveal the possible impacts of the future climate changes on such climatic extreme phenomenon (Edwards and McKee 1997). However, drought is difficult to be quantified due to its dependence on regional differences, needs, and disciplinary perspectives (McKee *et al.* 1993). For the past decades, various drought indices have been developed to assimilate thousands of bits of data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible big picture (Heim 2002; Wells *et al.* 2004; Jain *et al.* 2010). Therefore, the overarching goal of this study is to reconstruct the past drought situation and assess the future drought risks for a drought-prone Blue River Basin, Oklahoma, under a likely changing climate from three aspects, *i.e.*, intensity, duration and extent. This basin is located in Southeastern Oklahoma with a drainage area of 676 square miles (Fig. 1). It is a relatively small basin but has experienced several severe droughts in the past half century. The first objective of this study is to construct the past drought conditions and predict future drought scenarios for Blue River Basin using three types of drought indices, the Standardized Precipitation Index (SPI) (McKee *et al.* 1993), Palmer Drought Severity Index (PDSI) (Palmer 1965) and Standardized Runoff Index (SRI) (Vasiliades *et al.* 2010). These types are meteorological drought index, hydro-meteorological index and hydrological index, respectively. The second objective is to examine the relationships among the three indices. The third objective is to find the suitable drought index for Blue River Basin under a changing climate.

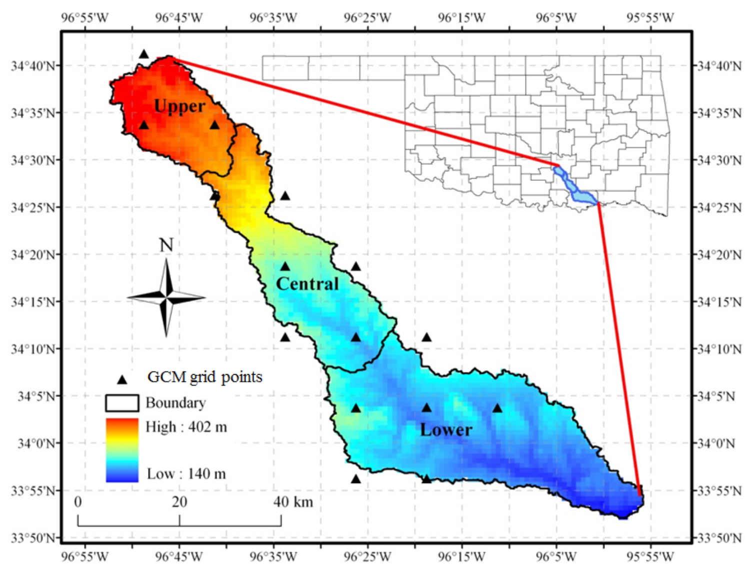

Fig. 1 The study area: Blue River Basin in Oklahoma.

2. Data, model and drought indices

2.1 Climate Data

Climate data of the study region were first extracted and later modeled for SPI, PDSI and SRI calculation. For this study, the observational data used were the gridded National Climatic Data Center (NCDC) Cooperative Observer station data, described by Maurer *et al.* (2002). The data cover the time period from 1950 to 1999 in a monthly time step. The observation data have climate variables of surface temperature (°C)

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and monthly precipitation (mm/day). The data domain covers the continental U.S. and portions of southern Canada and northern Mexico at a 1/8° (~12 km) resolution. Projection data are archived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase3 (CMIP3) multi-model dataset. CMIP3 has temperature and precipitation projections under three CO2 emission scenarios (A2, A1B and B1) for the period of 2010 to 2099, and this data share the same resolution and coverage with the NCDC observation data. The two scenarios of the 21st century for future greenhouse gas emissions used in this study were A2 and A1B as defined in the IPCC Special Report on Emissions Scenarios (IPCC 2007). According to IPCC (2007), scenario A2 is a higher emission path and describes a higher population world where technological change and economic growth are more fragmented and slower. Scenario A1B is a middle emission path known as business-as-usual and describes a balanced world where people do not rely too heavily on any one particular energy source.

2.2 Thornthwaite Monthly Water Balance Model

The hydrological model used to simulate the hydrologic process and generate runoff output for SRI calculation is the Thornthwaite Monthly Water Balance Model driven by a graphical user interface. It is named after C.W. Thornthwaite who used water budget in climate classification (Thornthwaite 1948). An updated description is given by McCabe and Markstrom (2007). Input for this model is monthly temperature and precipitation. Outputs from the model include potential evapotranspiration (PET), soil moisture, actual evapotranspiration (AET), snow storage, surplus, and runoff total.

3. Results and Discussions

3.1 Runoff Calibration

The Thornthwaite Monthly Water Balance Model was calibrated to generate future runoff under the A1B scenario. Manual calibration of the monthly water resources model was done to get the best agreement between observed and modeled runoff for the period of June 1936 through August 2006. The parameters used modeled the calibration period well with the Nash-Sutcliffe coefficient of efficiency being 0.78 and a root mean square error of 12.9. The modeled runoff was used to simulate past SRI and project future SRI.

3.2 Past and Future Drought

Blue River Basin is located within the state of Oklahoma, which survived the 1930s Dust Bowl and 1950s severe drought. Historical records show that Oklahoma experienced four major droughts in the 20th century: 1909-18, 1930-40, 1952-58, and 1962-72. According to Oklahoma Climatological Survey (OCS), “the drought of the 1930s is associated with the Dust Bowl of the Great Plains, when socioeconomic conditions, agricultural practices and drought forced the largest emigration of Oklahomans in state history.” “Statistically or meteorologically, for much of the ABRFC/Oklahoma, the droughts of the 1950s were more severe (record low SPI and PDSI) than the 1930s. However, the human toll (Socioeconomic Impact) was less severe.” “The lessons of the 1930s helped the next generation cope with the worse droughts of the 1950s: preparedness and mitigation embodied in crop selection, conservation strategies, and sound business decisions.” (Arndt 2002)

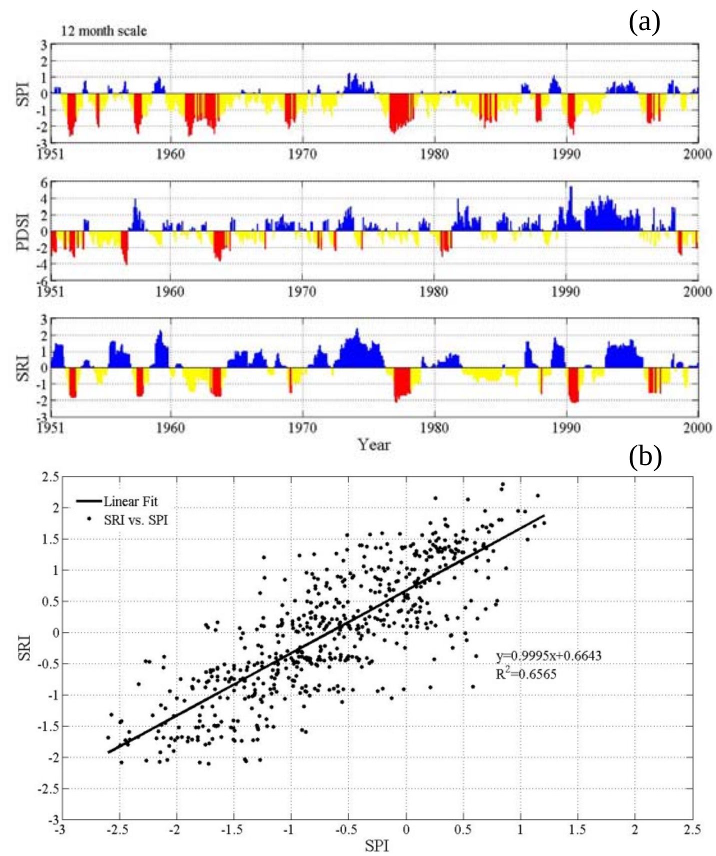

Fig 2. (a) Historical time series variation of SPI, PDSI and SRI (b) Scatter plot of SPI vs. SRI and the linear regression line.

As can be seen from Figure 2a top panel, SPI shows massive droughts from the beginning of 1950s to the end of the 1960s. 1950s droughts are interrupted by several wet spells which slightly relieved the drought severity. As shown on the figure, there was a long duration extreme drought between 1960 and 1965. This drought lasted almost 5 years without being interrupted by occasional wet spells. The drought was released slightly by some above average rains in 1965 and formed into another extreme drought by the end of 1960s. Other than the other mega drought near 1980, Blue River Basin experienced some normal dry spells and some wet spells after 1980.

PDSI provides somewhat different descriptions on Blue River Basin drought history (Fig. 2a, middle panel). The 1950s and 1960s drought were captured roughly, but the onset and severity were slightly different. The 1970s drought on SPI was totally missed on PDSI panel, and Blue River Basin is mostly under wet conditions after 1980 except for one severe drought around 1981. SRI, in this case, is very similar to SPI in terms of severity and timing of droughts. Figure 2b shows that SPI and SRI are highly correlated with correlation coefficient (CC) of 0.81. SRI is found out to have two month lag time from SPI (CC reaches highest value), which means hydrological drought doesn't happen until two months later after the meteorological drought took place. Although the wet spells look more significant on the SRI panel, SRI successfully captures all the major droughts except the one in mid 1980s. In general, droughts shown on SRI mostly have shorter duration than the same ones shown on SPI, and wet periods are longer than those on SPI panel.

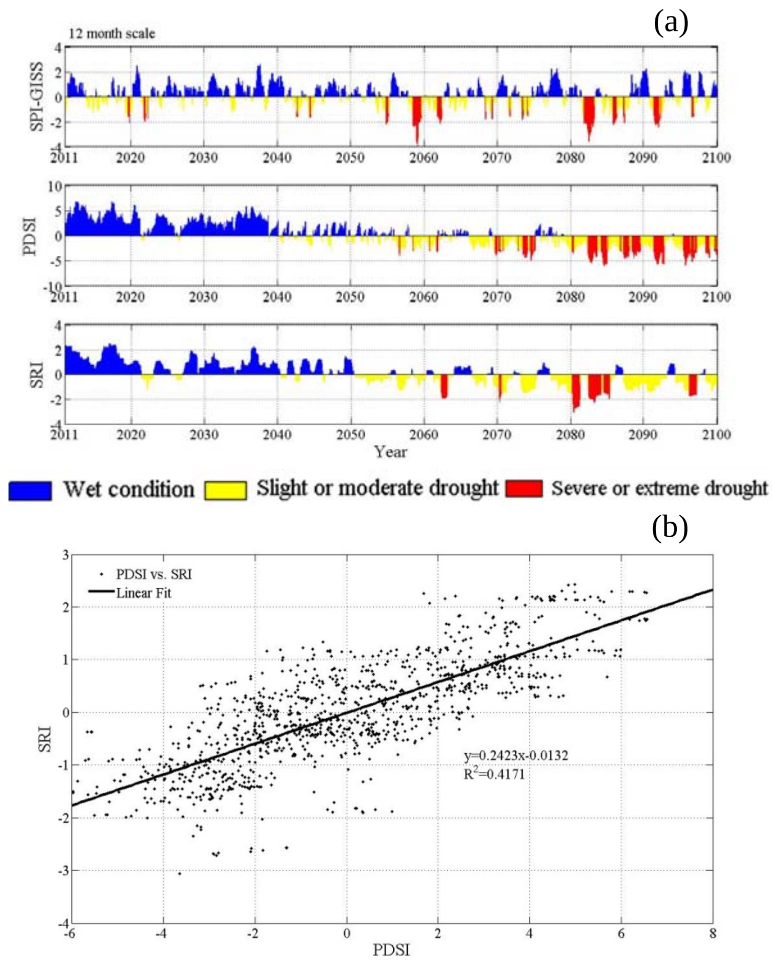

Fig. 3 (a) Future time series variation of SPI, PDSI and SRI (b) Scatter plot of SPI vs. SRI and the linear regression line.

For drought projection using SPI, ensemble mean monthly precipitation should not be used because the averaging process diminishes the monthly variation of precipitation which could generate misleading outputs. Therefore, one of the 16 GCMs --- GISS-ER is selected, because simulation from GISS-ER is proved to match the observation for the period of 1950-1999 with the most similarities from a statistical point of view from a previous study (Liu *et al.* 2011). Hence, future SPI is calculated based on GISS-ER projection data with the most confidence. Projections of drought conditions in Blue River Basin display quite some differences among the three indices (Fig. 3a). SPI indicates one minor drought in the early 2020s, and the frequency and intensity of drought appear to increase substantially after 2050. PDSI and SRI also display much more droughts after 2050, although PDSI and SRI show more similarity in time series. PDSI and SRI time series has correlation coefficient of 0.78 (Fig. 3b) and they do not exhibit any time lag from one another (CC reaches highest value at 0 month lag time). More drought events are displayed on PDSI panel than on the SRI panel, and severe droughts on PDSI are indicated to be more severe (PDSI<-5) than those on SRI. Blue River Basin is constantly under wet conditions before 2050 for both PDSI and SRI, with decreasing trend of wetness from

2011 to 2050. It is not surprising to see that both PDSI and SRI demonstrate more severe and frequent drought after 2050, although the magnitude of droughts is not exactly the same. Based on Thorthwaite Monthly Water Balance Model projection, Blue River Basin is going to have increasing trend of ET and decreasing trend in total runoff under A1B scenario. Actual ET is going to increase by up to 8% on average and runoff is going to reach below -10% of change by the end of the 21st century. Apparently, more water is going out as ET and less water will be available for surface runoff, so there is less recharge back to the ground.

Future droughts are getting more severe and frequent from SPI, PDSI and SRI perspectives. Table 1 shows the areas affected by severe or extreme droughts based on the basin division. Historically, the affected areas are almost equally distributed among the upper, central and lower Blue River Basin. Both SPI and PDSI display an average around 3% of the areas affected by severe/extreme droughts from 1950 to 1999, note that the lower region is slightly less affected than the upper and central regions. In terms of projection, SPI shows an average of 25.6%, 22.9% and 20.6% of areas affected in the upper, central and lower Blue River Basin throughout the 21st century. Results from PDSI are displayed in two half centuries: the first half century sees almost no droughts while the second half century sees an average of 23.5%, 23.5%, 22.2% of areas affected by severe or extreme droughts. Overall speaking, both SPI and PDSI exhibit larger areas being under severe or extreme droughts in the future period.

Blue River Basin	1950-1999		2010-2099			
	SPI	PDSI	SPI	PDSI (2010-2049)	PDSI (2050-2099)	PDSI (total)
Upper	3.5%	3.5%	**25.6%**	0.5%	**23.5%**	13.3%
Central	3.5%	2.8%	**22.9%**	0.5%	**23.5%**	13.6%
Lower	3.2%	2.7%	**20.6%**	0.83%	**22.2%**	12.8%

Table 1. Percent of areas under severe/extreme droughts for upper, central and lower Blue River Basin.

4. Conclusions

This study analyzed the historical drought of the Blue River Basin in the past 50 years and projected the possible drought status of the future 90 years under the A1B scenario, a very likely future climate in Southern US based on previous studies. Three types of drought indices (SPI, PDSI and SRI) all capture the major droughts documented in history. In terms of timing and severity, SPI and SRI perform better and exhibit higher inner correlation. The results projected by SPI, PDSI and SRI under the business as usual A1B scenario suggest that more drought events might occur in the second half of the 21st century. This could be caused by the fact that the precipitation predicted by GISS-ER shows a descending trend, while the temperature is slowly but constantly increasing after 2010. Moreover, the ET projected by the Thornthwaite Monthly Water Balance Model also has a significant increasing trend under such a warming climate. In the projection period, PDSI and SRI have a similar performance because they both take into account the factors of soil moistures and ET. Therefore, the drought of future Blue River Basin is very likely going towards a more frequent and more intensive situation.

In this study, SRI appears to be a better indicator for the study basin because: (1) SRI considers the changing climate factor which is playing a rather significant role in the future drought management; (2) Compared to PDSI which also considers temperature change, SRI provides drought information from a hydrological point of view, which makes more sense and is more applicable to water resources managers and local farming business; and (3) SRI is proved to function well in this research both for the past drought record reconstruction and for the future drought risk assessment under a changing climate.

In summary, this study found that the three indices (*i.e.* SPI, PDSI and SRI) captured the recorded droughts for the past 50 years and also suggested very likely more frequent and more severe droughts in the future 90 years over the Blue River Basin. This study also found that SRI has better agreements with the other two indices, with high CC of 0.81 (0.78) and 2-month (no appreciable) lag time from SPI (PDSI) over 1950-

2099 time period across the basin. Although this study recommended the PDSI and SRI are the more suitable indices to assess the future drought risks under an increasingly warming climate by taking into account of the ET and soil moisture in Blue River Basin, for further comprehensively analyzing the droughts, more drought indices from ecological and socioeconomic perspectives should be also investigated and inter-compared to provide a more complete picture of drought risks and its potential impacts on the dynamically coupled nature-human systems.

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