Analyzing Past and Predicting Future Drought with Comprehensive Drought Indices for Arkansas-Red River Basin

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ABSTRACT
This study is intended to examine the past drought and predict future drought scenarios for Arkansas-Red River Basin with comprehensive drought indices ranging from meteorology, hydro-meteorology to hydrology. In this proceeding, we present some early results and analysis with the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). Historical climate data within the 1900-2009 timeframe were archived to derive the drought indices calculations. The projected A2, A1B climate data modules from 16 statistically downscaled Global Climate Models (GCM) were applied in drought occurrence frequency and affected area prediction. The results from the SPI and PDSI show that widespread drought took place in the 1910s, 1930s, 1950s and 1960s, which agrees with the historical climate record. Both the SPI and PDSI indicate more frequent droughts in the second part of the 21st century, but predictions from the two indices were carried out under different scenarios. The two indices describe future drought characteristics from a temporal and a spatial perspective. Future SPI values indicate that there might be a 110 year period of drought cycles occurring in the Arkansas-Red River Basin under A2, and future PDSI shows more severe droughts in the western portions of the basin under A1B.

Categories and Subject Descriptors
A.0 [General Literature]: General –conference proceeding.

General Terms

Keywords
Arkansas-Red River Basin, drought index, climate change, GCMs

INTRODUCTION
Since the 1970s, intensive studies have been carried out on climate change and its impacts on various aspects of the Earth. Observations from various scopes of sciences have gradually directly or indirectly validated the assumption that the average temperature of the Earth is increasing. Global Circulations Models (GCMs) from around the world have been producing projections for the Earth’s future and all of these models have been showing a decent increasing trend of Earth’s average temperature in the coming 90 years (Kart et al., 2009). Studies on climate change impacts have consequently become not only scientifically valuable, but also economically and socially needed.

Drought is a normal, recurrent feature of global climate. It occurs virtually in all climate zones, and impacts the local ecological environment and the social environment (NIDIS, 2006). Many drought events have been observed and recorded in human history. Some of these droughts were so severe that they dried up major water resources and forced out civilizations from their settlements. Knowing when and where a drought might take place and how severe it is to become is very important for a society in terms of having substantial development. Future climate is changing all the time, and it is having quite an impact on the Earth’s atmosphere, hydrosphere, biosphere, and lithosphere. The research scope in this study is to analyze the climate change impacts on the occurrence of drought in terms of intensity, duration and extent. Understanding the pattern of droughts within historical record assists analyzing the future drought, thus revealing the climate change effects on this climate extreme phenomenon.

Drought is difficult to define due to the fact that it depends on differences in regions, needs, and disciplinary perspectives. Still, common definitions consider drought as a deficiency of precipitation over an extended period of time, resulting in a water shortage for some activity, group, or environmental sector. Since drought is covered under a plethora of different scientific categories, scientists place this phenomenon into four different classifications: meteorological drought, agricultural drought, hydrological drought, and socio-economic drought (NIDIS, 2006).

Drought is defined usually on the basis of the degree of dryness (in comparison to some “normal” or average amount) and the duration of the dry period. Meteorological drought is usually region specific since atmospheric conditions that result in
deficiencies of precipitation are highly variable from region to region (NIDIS, 2006). Agricultural drought considers whether the water quantity in soil meets the demand of plants at various growing stages. An agricultural drought occurs when the soil moisture fails to nourish the plants. This could result from a meteorological drought which caused by lacking of rainfall, or from the hydrological drought which is indicated by the dropping groundwater wetting head. Hydrological drought, as discussed, is associated with reservoirs or lake level. It is a basin-scale drought, which is initially caused by the deficits of rainfall. It is important to note however, that not every meteorological drought could lead to hydrological drought immediately due to the fact that reservoir levels are mainly constant without an extensive lack of inflow. It would take longer for major precipitation deficiencies to show up in components of the hydrological system. Socioeconomic drought is different from the previous three kinds of droughts. It is a demand-supply issue concerning water usage and water related industries. If the water supply fails to meet the demand of water usage such as hydroelectric power, food production, and fishery activities etc., a socioeconomic drought becomes in effect due to the demand-supply unbalance.

In this project, only meteorological and hydrological droughts were chosen for research within the Arkansas-Red River Basin (also known as ABRFC).

**Figure 1. Study region and the states covered.**

The ABRFC includes parts of seven states in and around Oklahoma and covers 208,000 square miles (Figure 1). The major aquifers (such as the Ogallala Aquifer within ABRFC) are the main water sources for agriculture and municipal water usage for the states. Major cities within the ABRFC area include Colorado Springs, CO; Dodge City and Wichita, KS; Oklahoma City, OK; and Amarillo, TX among others (NWS). It is therefore very important to study the water issues in the ABRFC from both hydrological and social-economical perspectives.

Since drought is difficult to quantify, people develop drought indices, assimilating thousands of bits of data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible big picture. The drought indices used in this study are the Standardized Precipitation Index (SPI) and the Palmar Drought Severity Index (PDSI). SPI is a meteorological index while PDSI is a hydro-meteorological drought index. Detailed discussions of the two indices are included in the following section.

### 2. DATA AND DROUGHT INDICES

#### 2.1 Climate Data

In order to calculate the SPI, PDSI and SRI, climate data of the region should first be extracted. 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 covers the time period from 1950 to 1999 in a monthly time step. The observation data contains surface temperature (°C) and monthly precipitation (mm/day) readings. The data realm covers the continental U.S. and portions of southern Canada along with northern Mexico at a 1/8° (~12 km) resolution. Another historical dataset is Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by Oregon State University. This dataset covers the U.S from 1900 to 2009 in a monthly time step with the resolution of 4km. Only precipitation data is available for archive at this phase though. PRISM data is archived in this study for comparison with the observations provided and it is also used to simulate drought conditions prior to 1950. Projection data is from The World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase3 (CMIP3) multi-model dataset. CMIP3 has temperature and precipitation projections by three CO₂ emission scenarios from 2000 to 2099 and this data shares the same resolution and coverage with 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 (Nakic’enovic’N et al., 2000). According to the IPCC AR4, scenario A2 is a higher emission path and describes a more populated 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. One thing worth noting is that in the coming IPCC AR5, A2 is considered the “business as usual” scenario instead of A1B. Still, the methodology used in this study is still applicable using the new scenarios under AR5.

#### 2.2 Drought Index

##### 2.2.1 SPI

Standardized Precipitation Index (SPI) is an indicator of meteorological drought which is mainly caused by a deficiency of precipitation and it was developed by McKee et al. (1993). The SPI is an index based on the probability of precipitation for any time scale. In McKee’s paper describing SPI, he calculated SPI for 3, 6, 12, 24, and 48-month time scales based on Fort Collins, CO precipitation data. An example of the SPI classification is shown in Tables 1 and 2. McKee pointed out that “The heaviness or lowness of a precipitation event in the SPI is relative to the rainfall characteristics of that area.” In order to calculate SPI, long-term precipitation record is needed to fit to a probability distribution, which is then transformed into a standard distribution. Therefore, the region specific deviation from the data is eliminated and precipitation data is standardized for research purpose.

<table>
<thead>
<tr>
<th>SPI</th>
<th>Cumulative Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.0</td>
<td>0.0114</td>
</tr>
<tr>
<td>-2.5</td>
<td>0.0082</td>
</tr>
<tr>
<td>-2.0</td>
<td>0.0022</td>
</tr>
<tr>
<td>-1.5</td>
<td>0.0016</td>
</tr>
<tr>
<td>-1.0</td>
<td>0.0587</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.3085</td>
</tr>
<tr>
<td>0.0</td>
<td>0.5000</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6915</td>
</tr>
<tr>
<td>1.0</td>
<td>0.8413</td>
</tr>
<tr>
<td>1.5</td>
<td>0.9132</td>
</tr>
<tr>
<td>2.0</td>
<td>0.9271</td>
</tr>
<tr>
<td>2.5</td>
<td>0.9358</td>
</tr>
<tr>
<td>3.0</td>
<td>0.9986</td>
</tr>
</tbody>
</table>
SPI is fairly easy to calculate compared to other indices. It can provide early warnings to help assess drought severity. The disadvantage of SPI is that it considers only precipitation but not evapotranspiration. This is a fairly important parameter in drought study and a more comprehensive index should also be used to serve as a comparison.

2.22 PDSI

The Palmer Drought Severity Index is an indicator of a hydro-meteorological drought that has been used for the last 45 years. This index gives water moisture information for certain regions. Instead of taking only precipitation into account, PDSI also considers temperature, which has a huge impact on evapotranspiration and soil moisture. This index provides a more comprehensive method to assess the impacts of climate change on drought since it requires more climate variables as input (Palmer, 1965).

PDSI is the first widely used comprehensive drought index in the U.S. The National Climate Prediction Center uses the PDSI to evaluate and predict drought. drought agencies allocate water resources during prolonged droughts based on the PDSI.

The PDSI is an indicator of prolonged soil moisture deficiency (Palmer, 1965). While it estimates soil moisture using a simple two layer soil description, it has been shown to be strongly correlated ($r = 0.5 - 0.7$) with measured soil moisture (Dai, 2004). The PDSI soil parameter used for a bucket water balance is the available water content (AWC). AWC is the difference between the soil moisture at field capacity and the wilting point. For this study, AWC was determined from the State Soil Geographic Database (STATSGO) for the top 100 cm of the soil profile. The STATSGO soil database has a spatial resolution of 1 km (Figure 2).

Figure 2. Available water content for the top 100 cm soil column.

Eq. 1 illustrates the components of the PDSI calculation; evapotranspiration ($ET$), recharge ($R$), runoff ($RO$), loss ($L$), potential evapotranspiration ($PE$), potential recharge ($PR$), potential runoff ($PRO$), and potential loss (PL). The deficit in soil moisture, $d_i$, at the end of each month measures the difference between precipitation and the required precipitation to maintain the long term monthly soil moisture (Wells, 2004). The software package provided by the University of Nebraska (Wells, 2005) calculated the PDSI on a monthly time step.

$$d_i = P - (\alpha PE + \beta PR + \gamma PRO + \delta PL)$$

Where \(\alpha = \frac{E[ET]}{E[PE]}\), \(\beta = \frac{E[R]}{E[PR]}\), \(\gamma = \frac{E[RO]}{E[PRO]}\), \(\delta = \frac{E[L]}{E[PL]}\)

The next step in the procedure is the climate characteristic value, $K$. $K$ helps standardize the index across varying climates. The moisture deficit between the desert and the tropical regions should be identified and found comparable for example. $K$ was defined by Palmer to relate the average moisture supply to the average moisture deficits.

$$K = \left[\frac{17.6}{\sum_{i=1}^{16} p_k} \left[\frac{E[PE] + E[R] + E[RO]}{E[P] + E[R]} + 2.8\right] + 0.5\right]$$

The climate characteristic, $K$, and deficit, $d$, are then combined to form the moisture anomaly index, $Z$. This indicator is

$$Z = K d$$

Finally, PDSI is computed using Eq. 4.

$$PDSI_i = 0.897PDSI_{i-1} + \frac{1}{3} Z_i$$

The coefficients 0.897 and 1/3 include the impacts of time on drought predictions. The weighting gives more importance to the previous month’s PDSI over short-term precipitation events that can increase $Z_i$.

3. RESULTS AND DISCUSSIONS

3.1 Past and Future Climate

The temperature and precipitation change over ABRFC in a yearly time step are shown in Figures 3 and 4. Temperature shows a decreasing trend from 1950 to 1975 and has a peaking point around 1955. The temperature increases lightly after 1975 and the trend continues from 2010 till 2099, during which the average temperature over the ABRFC increases almost 4 degrees under the A1B module and 5 degrees under A2. The results show that climate change (regional warming specifically) became noticeable since 1975. The trend continues throughout the 21st century.

Figure 3. Temperature anomaly noted over the ABRFC (Red line is the ensemble mean of 16 GCMs from the A1B scenario).
The Precipitation trends show more dramatic changes for the past 50 years (Figure 4). There was a big fall around 1955 and a giant leap around 1960. The overall trend for precipitation is slight increasing. This trend doesn’t appear obvious for 2010-2099 mainly because the projection is the ensemble mean of 16 GCMs. The big variations are mostly equal out by different GCMs. Still, A2 shows a slight decreasing trend after 2050 which might cause meteorological drought in the second half of the century.

[Image of precipitation anomaly over ABRFC]

Figure 4. Precipitation anomaly over the ABRFC (Red line is the ensemble mean of 16 GCMs from A1B scenario).

The spatial pattern of precipitation from 1950-1999 is shown in Figure 5. There is a large gradient between Northwestern portions of the ABRFC and Southeastern ABRFC, with the northwestern regions receiving around 300mm/per of rainfall and southwestern areas getting more than 1000mm/year. It seems that the precipitation pattern around Rocky Mountains displays some sort of abnormal behavior which could be explained by the fact that statistical downscaling methods have some difficulties illustrating mountainous rainfall characteristics.

[Image of precipitation pattern for ABRFC averaged from 1950-1999]

Figure 5. Precipitation pattern for the ABRFC averaged from 1950-1999.

### 3.2 Past Droughts

The SPI results for 1900-2009 based on PRISM data is shown in Figure 6 below. In this study, 1, 3, 12, 48 month scales are studied to see the intensity and duration of the major droughts in the ABRFC. As can be seen from Figure 5 for the 48 month panel, four major droughts took place in the 1910s, 1930s, 1950s, and 1960s. The most serious one is the 1950s drought which lasted for almost half a decade. The 1930s drought was made up of several intensive individual droughts with shorter durations. Historical records show that Oklahoma experienced three major droughts in the 20th century: 1909-1918, 1930-1940, 1952-1958, and 2001-2002. According to the Oklahoma Climatological Survey, "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) The duration of the 2001-2002 drought was only a few months, therefore, it was not shown on the 12 and 48 month scale. The 1 month scale panel does however, display this shorter duration drought. The length of the red bar around 2001 indicates that the drought is quite severe yet it does not last long enough to be displayed on the 12 or 48 month scale panel. These results indicate that SPI does capture the major droughts in the ABRFC with quite some confidence.

[Image of SPI projection from 1900-2099]

Figure 6. SPI over the ABRFC from 1900-2009 (Red bars mean severe or extreme drought).

In order to show the relationship among drought severity, frequency and area extent, a SAF (severity-area-frequency) curve was fitted based on historical SPI data (Figure 7).

[Image of Severity-Areal-Frequency curve for SPI from 1900-2009]

Figure 7. Severity-Areal-Frequency curve for SPI from 1900-2009.

As can be seen from the figure, the less frequent droughts (longer return period) were more likely to be more severe (lower SPI), and more widespread (larger area extent). This was more likely to be from an overall slight dryness (high SPI). The 1950s drought was devastating due to the fact that it lasted almost a decade and occurred over nearly the whole Southern Great Plains. Therefore, the 1950s drought is of low frequency (long return period).

SPI projection for the A2 scenario is shown in Figure 8, applying the 1, 3, 12, 48 month scales. The 48 month scale panel displays a severe drought in the late 2060s which lasts almost half a decade. This drought event has similar temporal patterns as the one in the 1950s. Identically, the 2060s drought is followed by a shorter duration 2080s drought which also resembles the 1960s drought
following the 1950s one. The similar pattern indicates a possible severe drought cycle of every 110 years in the ABRFC region.

![Figure 8. SPI over the ABRFC from 2010-2099 under the A2 scenario (Red bars mean severe or extreme drought).](image)

### 3.2 PDSI

The input data for computing PDSI is temperature and precipitation, therefore, PDSI is only computed from 1950 to 1999 since no temperature PRSIM data is available before 1950. Figure 9 shows the temporal pattern of PDSI from 1950-1999. Similarly, PDSI also captures the 1950s, 1960s, and 1980s major droughts. The historic time series shows that there has been an increasing trend in PDSI since the mid-1950s. There was a significant gyration in the series switching from a severe drought (-4 < PDSI < -3) to a moderate wet spell (2.0 < PDSI < 3.0). There was also an increase in the variance of PDSI after 1980. Figure 10 shows the spatial mean and variance for 1950-1999. The historic PDSI is -0.12 for the entire ABRFC region over this 50-year period. This indicates that the area tended to be in a drought over this time period. Still, the minimum and maximum PDSI for a single month in any given grid were -8.6 and +11.5 respectively. Over the entire basin the impacts of drought average out over this period, there are still locations within the basin that experienced severe dry and wet periods over the 50 years. The variance of PDSI showed that the western portions of the ABRFC region were more likely to experience larger fluctuations of drought during the 1950-1999 period. This corresponds with the areas that received less annual precipitation.

![Figure 9. Historic PDSI monthly time series for ABRFC region (1950-1999).](image)

Near the Rocky Mountains there are some areas that do not appear to experience significant variability. This could be due to the available water content that is approximately 2-30 cm near the mountain range. The PDSI in this region would most likely not be the best indicator of drought due to the uncertainty in the AWC.

![Figure 10. Historic PDSI for the ABRFC for 1950 – 1999.](image)

The projected PDSI for 2010-2100 was determined under the A1B scenario using ensemble means for precipitation and temperature. The study looks at the mean PDSI in 30-yr increments for 2010-2039, 2040-2069, and 2070-2099 (Figure 11). There appears to be a wetter period during the 2010-2039 timeframe, predominating more in the western regions (Texas and Colorado) of the ABRFC. During the 2040-2100 period, this same region experiences a more severe drought than the eastern region. This same area saw a higher variance during 1950-1999. A possible cause is the small amount of precipitation that falls over the region (Figure 5).

Near the Rocky Mountains there are some areas that do not appear to experience significant variability. This could be due to the available water content that is approximately 2-30 cm near the mountain range. The PDSI in this region would most likely not be the best indicator of drought due to the uncertainty in the AWC.

![Figure 11. PDSI for A1B scenario over the ABRFC region.](image)
Figure 12 displays the PDFs of PDSI for the past and the future. 1950-1999 shows a near normal distribution with mean value slightly above zero, while 2050-2099 displays an abnormal PDF with mean value below zero and left tail reaching towards much lower PDSI. This indicates that future drought is likely to get more severe and frequent, as projected by SPI under A2 scenario.

![Figure 12. PDF of PDSI for the ABRFC region under the A1B scenario.](image)

4. CONCLUSIONS

The temperature in ABRFC is going upward after 2010 and it is projected to increase by 4-5 degrees by the end of the century. Precipitation however, does not show a discernible trend overall, except that A2 shows a slight decreasing trend after the 2050s.

The two indicators both capture the major drought in the 1950s and the 1960s. SPI and PDSI reconcile quite well from 1950 to 1999 but not for the future period. The reasons might be: (1) Temperature before 2000 didn’t vary quite as much as after 2010. PDSI in this case is not greatly affected by temperature but after 2010, increasing evapotranspiration induced by high temperature leads to decreasing PDSI. (2) SPI, on the other hand, only considers precipitation. The decreasing pattern of SPI is mainly due to decreasing precipitation trend projected by the A2 scenario. SPI only gives drought information from a meteorological perspective.

According to the SPI, ABRFC is basically in wet conditions for the first half of the 21st century, but precipitation gets less abundant after 2060 which leads to a severe drought in the late 2070s. This indicates a possible drought cycle of 110 years. The simulation does however indicate that a wetter period will occur from 2010 - 2039. These simulations indicate that a greater strain will be put on the groundwater and surface water resources during the next 90 years.

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6. REFERENCES


