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Bridging drought and climate aridity

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ABSTRACT

Drought is a complex phenomenon, and tracing its periodicity is often a puzzle. In time and space, the frequency of drought events inspires suspicion of connections with local climate features including aridity gradients. The present study analyzes the connection between drought patterns and regional aridity gradients. Specially, the study addresses environmental water stresses in the Great Plains of the United States over the two time periods: 1951 to 1982 and 1983 to 2014. The regional aridity gradients were estimated then analyzed along with the time series of the standardized precipitation index. Employing a multivariate regression on principal components model, the study evaluates the connection between drought patterns and regional aridity gradients. The results indicate significant relationships between drought patterns and climate aridity over the time. The comparison of the aridity gradients of the Great Plains region over the two time periods indicates a wetter period from 1983 to 2014. Meanwhile, there is a shift of drought intensity, as the tendency for exceptional drought events increased significantly across the Great Plains during the period 1983 to 2014. The contrast observed with the wetting trend and the increased drought severity implies that exceptional droughts are not necessarily the cause of a drying climate. A consideration of this paradigm may help to better implement drought monitoring strategies at regional levels.

1. Introduction

The natural circulation of water between the hydrosphere, lithosphere, biosphere and atmosphere plays an essential role on the dynamism of terrestrial ecosystems. However, debates on climate and dryness raise multiple questions regarding the future of water resources (Cheng et al., 2016; Sohoulande Djebou and Singh, 2015). Indeed, changes in the climatic system are often accompanied by substantial effects on moisture circulation. In several regions of the globe, environmental dryness is now repeatedly reported with unusual intensity (Seager et al., 2015; Panu and Sharma, 2002). Such facts, entice debates on fresh water availability and drought. In particular, drought is reported as a major concern for human society and the terrestrial ecosystem (Sohoulande Djebou and Singh, 2015; Clark et al., 2002). The threats of drought on freshwater availability are frequently generalized at the global scale. However, the magnitude of the alert is not the same in all climate regions of the planet. Such disparity suggests the necessity to address drought using regional climate specificities. On a regional scale, the short and long-term availability of atmospheric moisture are often defined by drought and climate aridity. Although, both drought and aridity characterize environment dryness, these two concepts should be differentiated appropriately (Sohoulande Djebou et al., 2015; Salvati et al., 2012). Actually, the concept of aridity is related to the climate as it designates the long-term state of dryness of the environment. In contrast, drought is considered a natural hazard which refers to a temporary state of dryness of the weather (Mishra and Singh, 2010). Ultimately, aridity characterizes the climate while drought refers to abnormal temporal deficiencies of moisture in the environment. Probably, one may expect functional connections between climate aridity and drought patterns.

To date, notable studies undertaken on drought seem to implicitly neglect to emphasize regional climate aridity gradients. However, efforts aiming to address this gap would possibly be beneficial for adequate water resources and environment management at regional scale. The present study expounds the connection between drought patterns and climate aridity gradients in the Great Plains of the USA, and it also analyzes the interplay with drought categories. The paper revisits the concepts of drought

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and aridity from a water resources and environmental prospective. Specially, the leading indices used for drought and climate aridity characterization are reviewed. The study employs the time series of standardized precipitation index SPI of local stations across the Great Plains as well as the time series of atmospheric variables including temperature, precipitation and potential evapotranspiration. The atmospheric variables were employed to estimate the aridity gradients which were afterward analyzed along with the SPI time series using a multivariate regression on principal components.

This paper reports the essential outcomes of the study in five distinct sections following this introduction. The first section outlines the concepts of drought and climate aridity. The second section describes the study region and the data employed, then theoretically presents the method of analysis. The third section details the essential results of the study. The fourth section, the synthesis and discussion, showcases the meaning and relevance of the results obtained. Finally, the conclusion recaps the key findings of the study and provides a holistic insight on drought and climate aridity.

2. Concepts of drought and climate aridity

2.1. Drought

Drought refers to an abnormal deficiency of environmental moisture which is often the consequence of a low precipitation at a specific location (Mishra and Singh, 2010). However, drought has no unique functional definition (McKee et al., 1993). It is very difficult to provide an absolute interpretation for drought because its physical meaning varies depending on each region. For instance, an amount of precipitation causing drought in a humid climate region may not be low enough to cause drought in an arid climate region.

In practice, there are four variants of drought including meteorological drought, hydrological drought, agricultural drought and socioeconomic drought (Heim, 2002; Panu and Sharma, 2002; Mishra and Singh, 2010). The meteorological drought identifies an atmospheric condition characterized by a temporal deficiency of precipitation. The concept of agricultural drought is more complex since it involves soil moisture and characterizes the dryness of the root zone at the surface soil layers. At the watershed scale, abnormal reductions of the precipitation are likely to affect surface hydrological processes such as run-off, base-flow, evapotranspiration and infiltration. This scenario is known as hydrological drought. The overall effect of these types of drought can reflect on freshwater availability for the society and such case is referred to as socioeconomic drought. Virtually, socioeconomic drought is the most perceivable form to most people because it causes deficiencies in public water supply, and broadly affects the economy. Yet in reality, all the four types of drought can overlap and result in significant impacts on the natural ecosystem, the society and the economy (Heim, 2002). Fig. 1 presents the magnitude of the economic damages caused by drought in the continents of the globe during the last 6 decades. The data used in Fig. 1 are retrieved from the Emergency Events Database EM-DAT at the Centre for Research on the Epidemiology of Disasters CRED (Below et al., 2007). Particularly, during the period (2010–2015), the estimated economic damages of drought for America (all the continent), outweighs those of previous decades. In large part, this is due to the persistent droughts recently reported across the United States of America USA (Cheng et al., 2016; Seager et al., 2015).

Regardless of the types, specific parameters are regularly employed to characterize drought. These parameters of dry spells include the duration, intensity, setting (onset and demise), and areal coverage (Panu and Sharma, 2002). However, drought classification relatively depends on local moisture features and there is no universal index for assessing drought (Heim, 2002). Consequently, it is difficult to compare drought between two different regions unless these regions are assumed alike from a biophysical prospective. Moreover, the indices proposed for drought analysis do not address the same aspect of drought. Some indices are estimated based on very simplistic methods while others involve more sophisticated or complex procedures (Heim, 2002).

Within the climatic frame of the USA, the most widely used indices are the palmer drought severity index PDSI (Palmer, 1965; Alley, 1984; Dai et al., 2004) and the SPI (Guttman, 1999; McKee et al., 1993). SPI is reported to be a simpler index compared to PDSI (Guttman, 1998). Furthermore, in comparison with PDSI, the deficit of precipitation expressed by SPI is considered very informative on drought impacts (McKee et al., 1993). Indeed, the state of soil moisture, groundwater, snowpack, streamflow and reservoir in time and space can be traced using SPI. SPI is a probability based index, which expresses the standardized departure of precipitation from the normal probability distribution function associated with the long-term raw precipitation data at a given location (Keyantash and Dracup, 2002). SPI is also interpreted as the number of standard deviations by which precipitation anomalies deviate from the long-term mean (Keyantash and Dracup, 2002; Hayes et al., 1999). Aligning with the regional scope of this study, we employed monthly SPI time series to address drought patterns. SPI is a very practical index. McKee et al. (1993) defined a drought event as a period starting with a negative SPI and reaching a value of -1 or less. The defined drought period ends with a positive value of SPI. For functional purposes, the United States Drought Monitor USDM uses five levels to categorize drought intensity including “abnormal dry” = D0 when $-0.5 \leq \text{SPI} \leq -0.7$, “moderate drought” = D1 when $-0.8 \leq \text{SPI} \leq -1.2$, “severe drought” = D2 when $-1.3 \leq \text{SPI} \leq -1.5$, “extreme drought” = D3 when $-1.6 \leq \text{SPI} \leq -1.9$, and “exceptional drought” = D4 when $\text{SPI} \leq -2$. This study considers SPI as well as the thresholds of the USDM, then addresses drought in relation with climate aridity over the Great Plains of the USA.

2.2. Climate aridity

The circulation of water masses in the earth system is naturally influenced by climate factors. Generally, climate factors are periodic (e.g. seasonal, annual, decadal) and are thereby associated with return periods. The periodicity of these factors sustains multiple interactions with the environment and water resources. These interactions are essential for defining climate zones. Very often a minimum time period of three decades is sufficient to define the average climatology of a region. The climatology informs on the average state of dryness which is also designated by climate aridity. Technically, the climate aridity expresses the gap between the average annual potential evapotranspiration *PET* and the average annual precipitation. Hence, climate aridity particularly depends also on the amount of energy available for moisture evaporation (Arora, 2002).

Over the century, various indices were devised to address climate aridity (Paltineanu et al., 2007). For example, De Martonne (1926) proposed an aridity index I_{DM} which is defined as the ratio between the mean annual precipitation P (mm) and the annual mean temperature T (°C) scaled by 10 (see formula in Table 1). Later, Erinç (1965) substituted the temperature component of De Martonne formula and defined an aridity index I_m as the ratio between P (mm) and the annual maximum temperature $T_{\max}$, (°C). However, a significant improvement in the field of climate analysis took place with Budyko's aridity index (Arora, 2002; Budyko, 1974). Actually,