Journal of Hydrology 511 (2014) 838–849

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Analysis of watershed topography effects on summer precipitation variability in the southwestern United States

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ARTICLE INFO

Article history:
Received 21 April 2013
Received in revised form 11 November 2013
Accepted 12 February 2014
Available online 24 February 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Peter F. Rasmussen, Associate Editor

Keywords:
Summer precipitation
Variability
Watershed topography
Climate change

SUMMARY

With climate change, precipitation variability is projected to increase. The present study investigates the potential interactions between watershed characteristics and precipitation variability. The watershed is considered as a functional unit that may impact seasonal precipitation. The study uses historical precipitation data from 370 meteorological stations over the last five decades, and digital elevation data from regional watersheds in the southwestern United States. This domain is part of the North American Monsoon region, and the summer period (June–July–August, JJA) was considered. Based on an initial analysis for 1895–2011, the JJA precipitation accounts, on average, for 22–43% of the total annual precipitation, with higher percentages in the arid part of the region. The unique contribution of this research is that entropy theory is used to address precipitation variability in time and space. An entropy-based disorder index was computed for each station's precipitation record. The JJA total precipitation and number of precipitation events were considered in the analysis. The precipitation variability potentially induced by watershed topography was investigated using spatial regionalization combining principal component and cluster analysis. It was found that the disorder in precipitation total and number of events tended to be higher in arid regions. The spatial pattern showed that the entropy-based variability in precipitation amount and number of events gradually increased from east to west in the southwestern United States. Regarding the watershed topography influence on summer precipitation patterns, hilly relief has a stabilizing effect on seasonal precipitation variability in time and space. The results show the necessity to include watershed topography in global and regional climate model parameterizations.

1. Introduction

In recent decades, a number of studies have shown that the sustainability of the natural soil–water–atmosphere balance is threatened by climate change (Thomas et al., 2004; Junk et al., 2013). Several authors concur that an increase in sea surface temperature should induce an increase in atmospheric humidity (Huntington, 2006). However, there still remains a debate on whether, in general, climate change effects will result in decreased or increased precipitation amounts (Easterling et al., 2000; Salve et al., 2011). Nevertheless, it has been widely shown that climate change will result in higher frequencies of extreme events such as floods, droughts, extreme temperatures, high precipitation variability, and desertification (e.g., Groisman et al., 2004; Overpeck et al., 2011; Wehner et al., 2011; IPCC, 2012).

Under climate change, Oreskes et al. (2010) clearly designated summer precipitation as one of the critical components of climate affecting water supply, agricultural productivity, and risk of floods and droughts. In contrast, projections from general circulation models (GCMs) are not consistent enough for decision making at the local level (Oreskes et al., 2010). Worldwide, studies addressing seasonal and annual precipitation variability have focused more attention on the large-scale causes, such as El Niño and Southern Oscillation (ENSO), the Madden Julian Oscillation (MJO), and monsoons (Mohino et al., 2011; Giannini et al., 2003; Krishnamurthy and Shukla, 2000). At the regional scale, the potential forcing effect of the watershed topography has been less considered.

Changnon and Vogel (1981) indirectly indexed the role of watershed topography by indicating that, unlike cloud movement, storm movement is from upstream to downstream. It was suggested that the morphologic characteristics of the watershed were

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http://dx.doi.org/10.1016/j.jhydrol.2014.02.045
0022-1694/

a driving factor. Along similar lines, using warm-season precipitation events to examine the spatial variability of precipitation around Oklahoma City, Hand and Shepherd (2009) showed a significant effect of urbanization on spatial precipitation variability. However, again, at regional watershed scales the forcing effects of watershed biophysical characteristics have been less reported. This should also be a critical improvement to climate model parameterizations to improve simulations of future precipitation extremes under climate change (O'Gorman, 2012).

In addition to analyzing summer precipitation using an entropy/disorder approach, this study utilizes linear regression and later combines principal component and cluster analysis to investigate how the watershed topography affects disorder of summer precipitation patterns in both time and space. Of all the interactions between precipitation and terrain complexity, the impact of orography is one of the most well-documented phenomena (Roe, 2005). In the vicinity of large mountain barriers, orographic effects are so dominant that they sustain ecosystems and regional climates. Notable transitions can be observed between vegetation on the drier leeward flank, and the vegetation on the wetter windward side of mountain ranges (Roe, 2005). However, at the watershed scale and in regions which do not feature large mountain barriers, the terrain complexity's effects on precipitation patterns have not been documented. The aim of this study is to investigate the disorder in summer precipitation to uncover the potential interactions between summer precipitation variability and the physical watershed characteristics for regional watersheds in the southern United States.

2. Study area and importance of the JJA period

The spatial domain encompasses six states in the southwestern United States: Arizona, New Mexico, Texas, Oklahoma, Arkansas, and Louisiana. This region covers an area of 1,780,636 km^2 and represents more than 18% of the contiguous United States. As presented in Fig. 1, the regional watersheds within this domain are the Lower Colorado basin (United States Geological Survey Hydrologic Unit Codes USGS-HUC 15), Rio Grande (HUC 13), Texas Gulf (HUC 12), Arkansas Red-White (HUC 11), and Lower Mississippi (HUC 08).

The focus of our study is on JJA, because a large portion of the precipitation in the course of the year occurs during this period. This was determined by computing the yearly percentage of JJA precipitation over the period 1895–2011. We used climate division monthly precipitation from the Full Network Estimated Precipitation (FNEP) dataset (McRoberts and Nielsen-Gammon, 2011), released by the Atmospheric Sciences Department at Texas A&M University. Based on an equal-area weighted average among the climate divisions, statewide monthly and yearly precipitation values were computed for 1895–2011. Aggregating the yearly JJA precipitation amount, the yearly percentage was derived for each state over the entire period.

It was found that JJA seasonal precipitation accounts for a significant portion of the yearly total precipitation in the region. By way of example, Fig. 2 represents a time series of the yearly percentage of JJA precipitation amount over the period 1895–2011 for Arkansas, Texas, and New Mexico. During 1895–2011, the overall average yearly percentages of JJA precipitation amounts varied from 22 to 43% in the region. Fig. 3a presents the spatial distribution of long-term average annual precipitation totals and Fig. 3b presents the average percentage of yearly JJA precipitation amounts. Analyzing these two maps, it is evident that the contribution of the JJA precipitation to the yearly precipitation increases, moving westward from humid to arid regions. In addition, Table 1 shows the frequencies of JJA percentages of yearly precipitation in each state. Over the 117-year time period (1895–2011), the JJA precipitation contribution is very high in the far western and arid states (New Mexico, Arizona), while it decreases in the eastern and humid states (Louisiana, Arkansas). Meanwhile, Texas and Oklahoma show more transitional characteristics.

The importance of JJA precipitation in this region is due to the North American Monsoon (NAM). The NAM is a yearly phenomenon that controls the warm season climate over North America and causes summer precipitation in the southwestern regions (Higgins and Shi, 2001). The moisture originating from the Gulf of Mexico and Gulf of California is driven by the NAM over the desert areas including the states of Arizona and New Mexico (Higgins et al., 1997). Reviewing the southwestern United States climate, Sheppard et al. (2002) indicated that the July–August–September precipitation in Arizona and New Mexico account for 50% of the

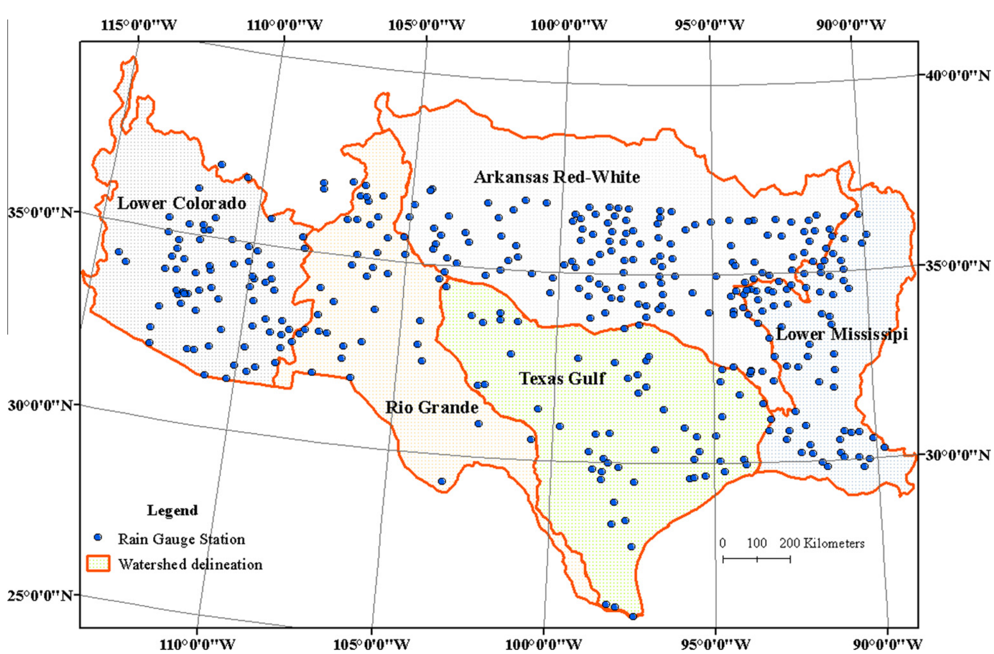

Fig. 1. Study region showing the watershed boundaries and the location of the rain gauge stations involved in the study.