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Holocene climate variability in Texas, USA: An integration of existing paleoclimate data and modeling with a new, high-resolution speleothem record

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ABSTRACT

Delineating the climate processes governing precipitation variability in drought-prone Texas is critical for predicting and mitigating climate change effects, and requires the reconstruction of past climate beyond the instrumental record. We synthesize existing paleoclimate proxy data and climate simulations to provide an overview of climate variability in Texas during the Holocene. Conditions became progressively warmer and drier transitioning from the early to mid Holocene, culminating between 7 and 3 ka (thousand years ago), and were more variable during the late Holocene. The timing and relative magnitude of Holocene climate variability, however, is poorly constrained owing to considerable variability among the different records. To help address this, we present a new speleothem (NBJ) reconstruction from a central Texas cave that comprises the highest resolution proxy record to date, spanning the mid to late Holocene. NBJ trace-element concentrations indicate variable moisture conditions with no clear temporal trend. There is a decoupling between NBJ growth rate, trace-element concentrations, and $\delta^{18}O$ values, which indicate that (i) the often direct relation between speleothem growth rate and moisture availability is likely complicated by changes in the overlying ecosystem that affect subsurface CO_2 production, and (ii) speleothem $\delta^{18}O$ variations likely reflect changes in moisture source (i.e., proportion of Pacific-vs. Gulf of Mexico-derived moisture) that appear not to be linked to moisture amount.

1. Introduction

Holocene climate (beginning 11.7 ka [thousand years ago]) was anomalously stable relative to the last glaciation and previous glacial–interglacial cycles, and late Holocene climate (4-0 ka) is a close analogue to the modern (20th and 21st century) climate state. Projections of 21st century climate change forecast global temperatures in excess of the warmest Holocene conditions, which is notable when considering that the development of human civilization has occurred entirely within the Holocene (Marcott et al., 2013). A comprehensive understanding of Holocene climate is relevant to predicting and mitigating future climate change effects.

Developing a comprehensive understanding of the nature and drivers of Holocene climate variability requires the reconstruction of past climate, beyond the instrumental record, from climate archives. There are many different types of climate proxies preserved in climate archives, each reflecting a distinct aspect of the climate system in a unique way. Compiling a comprehensive picture of regional climate for a given interval requires careful consideration of similarities and differences of available proxy records and the relative strengths and weaknesses of each proxy.

Delineating controls on climate variability in Texas is important and challenging for several reasons. According to the U.S. Census Bureau, Texas's economy and population are the second largest in the U.S., and both are among the fastest growing in the Nation (USA Today, 2014). Texas is prone to drought, and the 2011 drought, for example, resulted in agricultural damages of $9 billion (Austin American-Statesman, 2011). Climatic processes governing past, current, and future drought in Texas are poorly understood,

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however, in part because there is no one specific precipitation regime that dominates the climate. Instead, Texas is characterized by large year-to-year precipitation variability that is influenced by multiple precipitation regimes. These include the winter Pacific westerly storm track (Feng et al., 2014a; Seager et al., 2007), the North American Monsoon and Great Plains Low Level Jet that drive summer moisture patterns in the southwestern and midwestern U.S. (Higgins et al., 1997; Higgins, 1997), and the North Atlantic Subtropical High that influences summer precipitation in the southeastern U.S. (Hu et al., 2011).

High-resolution records of Holocene climate from proxy reconstructions pertaining to Texas are few compared to numerous glacial-deglacial records, including speleothem records (Feng et al., 2014a; Musgrove et al., 2001) and 20th century tree ring and speleothem records (Cleaveland et al., 2011; Feng et al., 2014b). Existing Holocene records from in and near Texas are largely discontinuous, with few age constraints, and for which proxies have a complex, and sometimes ambiguous, relation to the climate system. We present a new high-resolution speleothem (NBJ) reconstruction of mid to late Holocene climate (7–0 ka), and integrate our findings into a synthesis of Holocene paleoclimate proxy data from in and near Texas (including Oklahoma, southeastern New Mexico, and northern Mexico; hereafter, Texas) and existing static and transient paleoclimate model simulations that span the Holocene. We find that the NBJ $\delta^{13}C$ record corresponds well with the general evolution of Holocene climate indicated by other records from Texas (e.g., Nordt et al., 2002; Cooke et al., 2003; Ellwood and Gose, 2006). Paleoclimate model simulations are consistent with proxy data that indicate a warmer and drier mid (8.2-4 ka) to late Holocene (4-0 ka), relative to the early (11.7-8.2 ka) Holocene, but model results do not simulate late Holocene climate variability preserved in the proxy records. NBJ trace-element concentrations vary independently from $\delta^{18}O$ values, indicating a possible decoupling between moisture amount and supply. NBJ $\delta^{18}O$ variability does not correspond well with speleothem and sea surface temperature (SST) records from the broader region (including the Gulf of Mexico and the southwestern U.S.), but $\delta^{18}O$ variability is similar to a reconstruction of the Atlantic Meridional Overturning Circulation (Thornalley et al., 2009).

2. Controls on present day climate

Texas spans a transition region between sub-humid to semi-arid climates and is prone to drought (Larkin and Bomar, 1983). There is pronounced seasonality in temperatures (Fig. 1). Precipitation amounts are generally larger in spring and fall compared to summer and winter but vary greatly. The interannual variability of precipitation exceeds the intra-annual variability, indicating an absence of well-defined wet/dry seasons (Fig. 1). Spring and summer precipitation is associated with the Great Plains low-level jet that transports Gulf of Mexico (GoM) moisture to the continental U.S. (Higgins et al., 1997). Large precipitation events can occur in summer and early fall in association with tropical storms, which occasionally have an eastern tropical Pacific origin and a trajectory crossing the GoM. Late fall and winter precipitation is often triggered by the arrival of northern cold fronts associated with the Pacific winter storm track that also provides much of the western U.S. with the majority of its annual precipitation (Seager et al., 2007).

Studies of the principle sources of continental precipitation delineate several oceanic moisture sources for Texas. Forward-tracking models find that the GoM and Caribbean and the tropical north Atlantic are year-round moisture sources, though their influence is more pronounced during the summer (Gimeno et al., 2012; van der Ent and Savenije, 2013). These models also document that the northeastern Pacific is a winter-only source. These results are consistent with particle-tracking results indicating that the majority of summer and winter precipitation events in central Texas are associated with air masses with southeast-northwest and northwest-southeast trajectories, respectively (Feng et al., 2014a). Furthermore, forward-tracking and back-trajectory models describe the importance of recycled-continental moisture, which accounts for a greater proportion of precipitation during dry intervals (Dirmeyer and Brubaker, 2007; Gimeno et al., 2012). Quantitative estimates of annual contribution from oceanic sources vs. terrestrial recycling calculated from a water accounting model (van der Ent and Savenije, 2013) over Texas suggest that 23% of precipitation is sourced from the GoM, 9% from the tropical Pacific, 2% from the North Pacific, 5% from the eastern tropical Atlantic, and 29% from terrestrial recycling. The remainder (32%) likely results from more remote oceanic regions (van der Ent and Savenije, 2013).

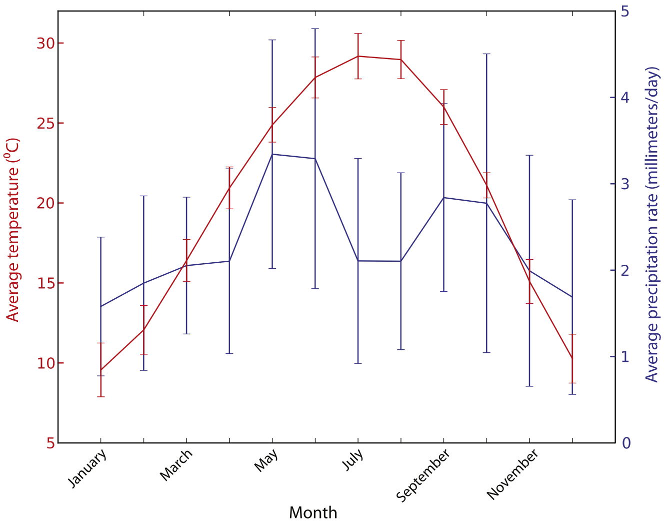

Fig. 1. Monthly temperature and rainfall climatology for Texas illustrating a strong seasonal cycle for temperature whereas precipitation exhibits small intraannual and large interannual variability. The latter is reflected by large error bars in monthly precipitation. Monthly averages calculated from data obtained from Modern-Era Retrospective Analysis for Research and Applications (MERRA; http://gmao.gsfc.nasa.gov/merra/) and the Global Precipitation Climatology Project (GPCP; http://precip.gsfc.nasa.gov/) for the latitude/longitude range of 28 N, 257E to 34 N, 266E for the interval spanning 1/1/1979 to 12/1/2010. Error bars demark two standard deviation (i.e., plus one standard deviation and minus one standard deviation).

Developing an understanding of processes governing precipitation extremes across the continental U.S. is a topic of much interest. Many studies have focused on land-sea connections, investigating the degree to which the El Niño/La Niña phases of the El Niño Southern Oscillation (ENSO) and warm/cold phases of the Pacific Decadal Oscillation (PDO) and Atlantic Meridional Oscillations (AMO) coincide with regional moisture extremes (Dong and Sutton, 2007; Feng et al., 2010; McCabe et al., 2008). In general, drier conditions occur across the southwestern and central U.S. during La Niña events due to the northward displacement of the Pacific winter storm track and a summer circulation regime that suppresses convective activity, respectively. The opposite occurs during El Niño events (Seager et al., 2010; Hu and Feng, 2001a). Not all La Niña events, however, induce droughts and not all droughts coincide with La Niña events, which indicates that ENSO effects are likely competing with those from other interannual oscillations (e.g., Arctic Oscillation, North Atlantic Oscillation) and may only be realized in a particular atmospheric state (Hu and Feng, 2001b; Feng et al., 2010).