Quaternary Science Reviews 102 (2014) 27–38

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Tropical Pacific forcing of Late-Holocene hydrologic variability in the coastal southwest United States

Matthew E. Kirby [a, *], Sarah J. Feakins [b, *], Christine A. Hiner [a], Joanna Fantozzi [a], Susan R.H. Zimmerman [c], Theodore Dingemans [d], Scott A. Mensing [d]

[a] *California State University, Fullerton, Department of Geological Sciences, Fullerton, CA 92834, USA*
[b] *University of Southern California, Department of Earth Sciences, Los Angeles, CA 90089, USA*
[c] *Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore CA 94550, USA*
[d] *Department of Geography, University of Nevada, Reno, NV 89557, USA*

A R T I C L E   I N F O

Article history:
Received 24 April 2014
Received in revised form
15 July 2014
Accepted 5 August 2014
Available online 3 September 2014

Keywords:
Climate
Runoff
Leaf wax
Hydrogen isotope
Drought

A B S T R A C T

Change in water availability is of great concern in the coastal southwest United States ($_{CSW}$US). Reconstructing the history of water pre–1800 AD requires the use of proxy data. Lakes provide long-lived, high-resolution terrestrial archives of past hydrologic change, and their sediments contain a variety of proxies. This study presents geochemical and sedimentological data from Zaca Lake, CA (Santa Barbara County) used to reconstruct a 3000 year history of winter season moisture source (δD_{wax}) and catchment run-off (125–2000 μm sand) at decadal resolution. Here we show that winter season moisture source and run-off are highly variable over the past 3000 years; superimposed are regime shifts between wetter or drier conditions that persist on average over multiple centuries. Moisture source and run-off do not consistently covary indicating multiple atmospheric circulation modes where wetter/drier conditions prevail. Grain-size analysis reveals two intervals of multi-century drought with less run-off that pre-date the "epic droughts" as identified by Cook et al. (2004). A well-defined wet period with more run-off is identified during the Little Ice Age. Notably, the grain size data show strong coherence with western North American percent drought area indices for the past 1000 years. As a result, our data extend the history of drought and pluvials back to 3000 calendar years BP in the $_{CSW}$US. Comparison to tropical Pacific proxies confirms the long-term relationship between El Niño and enhanced run-off in the $_{CSW}$US. Our results demonstrate the long-term importance of the tropical Pacific to the $_{CSW}$US winter season hydroclimate.

1. Introduction and Background

California is enduring extreme drought conditions during 2013–2014. Although the hydroclimate of the semi-arid region is inherently variable, with large interannual variability in precipitation (Dettinger et al., 1998), there is considerable concern that the recent dry years may be part of a drying trend (Williams et al., 2013). For the coastal southwest United States ($_{CSW}$US), future projections are for drier conditions with less frequent, but more intense precipitation (e.g., more atmospheric river events) and subsequent flood events (Dettinger, 2011; Das et al., 2013; Neelin et al., 2013; Pierce et al., 2013; Seager et al., 2013). This combination of hydroclimatic change represents a formidable challenge to the water resource and management infrastructure as well as to the ecology of the region (Tanaka et al., 2006; Loarie et al., 2008; Williams et al., 2013).

Understanding past hydroclimatic variability and its forcings provides a baseline understanding of the dynamics that drive the hydroclimatic system. This baseline is important for examining present change and assessing future predictions. Today, the $_{CSW}$US has an almost exclusively winter-season precipitation regime. Interannual variations in precipitation amount vary with the position of winter season storm tracks influenced by Pacific sea surface temperature (SST) patterns (Fig. 1) (Namias et al., 1988; Seager et al., 2005a; Herweijer et al., 2006; Graham et al., 2007; Cook et al., 2011; Gan and Wu, 2013) Variations in Pacific Ocean SSTs, including those associated with El Niño-Southern Oscillation (ENSO) as well as extra-tropical conditions such as that in the Kuroshio Extension region (northwest Pacific), have been shown to play important

* Corresponding authors.
E-mail addresses: mkirby@fullerton.edu (M.E. Kirby), feakins@usc.edu (S.J. Feakins).

http://dx.doi.org/10.1016/j.quascirev.2014.08.005
0277-3791/

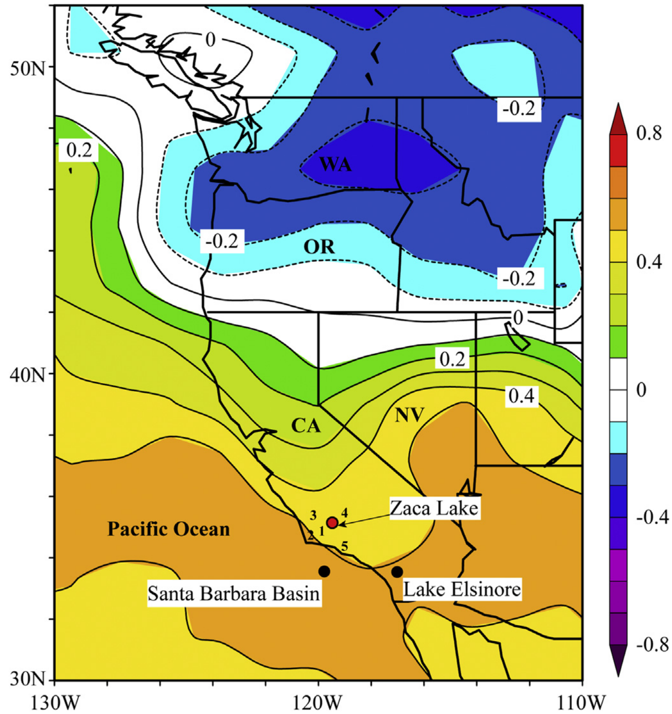

Fig. 1. Western United States showing correlation between November to March (1949–2008 AD) surface precipitation rates (Kalnay et al., 1996) to tropical Pacific SST 1st EOF (empirical orthogonal function) values (Hoerling et al., 2001). Precipitation sites are numbered on figure: 1) Los Alamos, 2) Lompoc, 3) Santa Maria, 4) Cuyama, 5) Santa Barbara. CA = California, NV = Nevada, OR = Oregon, WA = Washington.

roles in driving precipitation amount variability, including both droughts and pluvials, on interannual to multi-decadal timescales in the $_{CSW}$US (Andrews et al., 2004; Castello and Shelton, 2004; Cook et al., 2011; DeFlorio et al., 2013; McCabe-Glynn et al., 2013; Wang et al., 2013).

How the tropical Pacific will influence future hydroclimatic change in this region is of particular interest. Research indicates that the frequency and perhaps intensity of El Niño events may increase with projected future warming (Ashok et al., 2012; Santoso et al., 2013; Cai et al., 2014) ENSO plays a major role in modern winter climatology of the $_{CSW}$US (Schonher and Nicholson, 1989; Castello and Shelton, 2004; Seager et al., 2005a; Hanson et al., 2006). During the instrumental era, El Niño events are correlated with wetter than normal conditions in the $_{CSW}$US, which can produce extreme precipitation events and subsequent flooding (Cayan et al., 1999; Fye et al., 2004; Seager et al., 2005a; Dettinger, 2011); La Niña conditions are associated with drier than normal conditions (Castello and Shelton, 2004; Seager et al., 2005a; Herweijer et al., 2006; Graham et al., 2007). Paleoclimatic reconstructions can test the long-term relationship between ENSO and winter precipitation variability. Moreover, because winter season precipitation is the only significant contributor to the region's hydrologic budget, there is potential to study this unimodal climate regime without the noise associated with multi-season precipitation (e.g., in monsoon influenced areas). Finding long-lived, high-resolution terrestrial archives from the $_{CSW}$US is a challenge. Most hydroclimatic reconstructions spanning the past 3000 years from the $_{CSW}$US are limited to multi-decadal to centennial scale resolution at best (Davis, 1992; Kirby et al., 2004, 2010, 2012; Bird et al., 2010, 2012). Tree ring networks provide a millennial view of variability particularly sensitive to drought conditions (Herweijer et al., 2007); however, they are less useful for reconstructing pluvials, nor does the tree ring network fully resolve spatial patterns across the $_{CSW}$US, missing lowland areas below the tree-line (Meko et al., 1980; Macdonald and Case, 2005).

Here, we present sedimentological and geochemical results from Zaca Lake, CA to reconstruct hydroclimatic variability over the past 3000 calendar years (cal yrs BP) at ~decadal resolution. This site fills an important geographical gap in knowledge representing the $_{CSW}$US region with large population centers and scarce water resources. We use leaf wax hydrogen isotopes (δD_{wax}) and grain size (125–2000 μm sand) to infer changes in moisture source and run-off, respectively. Regime shift analysis is applied to variable proxy records to statistically discern shifts in the mean state and to assess the coupling between moisture source and precipitation amount through time. Hydroclimatic proxies from Zaca Lake are compared to ENSO-related proxies to evaluate the role of the tropical Pacific on late-Holocene hydrologic variability in the coastal southwest United States.

2. Study site and methods

2.1. Study site

Zaca Lake is a closed lake (0.08 km^2 lake area, 12 m water depth in July 2009) contained within a small (9 km^2), steep sided catchment (730–1320 masl) (Norris and Norris, 1994; Feakins et al., 2014; Fig. 2). The lake has a spill-over elevation approximately 9 m above present lake level to a second basin, Overflow Lake, which is currently dry. Zaca Lake sediments extend deeper than the present core based on seismic profiling (Kirby and Simms, unpublished data). Sedimentation history in the adjacent Overflow Lake basin has been dated to 7500 cal yrs BP with a charcoal sample from 450 cm depth (Padilla, 2010). The lake sits within the highly fractured and steeply dipping Monterey Formation. Consequently, a strong geomorphic contrast exists between the highly dissected, less vegetated south facing slopes and the more vegetated, less dissected north facing slopes (Fig. 2). There is also evidence for relict mass movement in the form of slumps and landslides as well as events documented within the historical record (Norris and Norris, 1994). Zaca Lake is a eutrophic, oligomictic lake with spring/summer $CaCO_3$ whiting events (Dickman, 1987; Sarnelle, 1992). Multi-month stratification produces hypolimnion anoxia and the build-up of H_2S, occasionally causing fish mortality during turnover (Sarnelle, 1992). The hydrologic balance of the lake depends on direct precipitation, evaporation, overland flow, and groundwater contributions from an up-valley spring (Feakins et al., 2014; Ibarra et al., 2014). In the late 19th Century (Libeus family homestead est. 1891 AD), before significant human modification, lake levels were observed to fluctuate approximately 0.5–1.0 m on a seasonal basis (Norris and Norris, 1994).

2.2. Age control and sediment analyses

Zaca Lake sediment core USC–ZACA09–1C (Z–1C) was obtained using a modified Livingston square rod piston corer. An intact sediment–water interface was collected on the first drive. The core was split, described, digitally photographed, and sub-sampled in the CSUF Paleoclimatology and Paleotsunami Laboratory. An overlapping core (Z–1D) was also obtained to confirm basin versus local sediment signals. The two cores have almost identical sedimentology. Seismic reflection data confirm that the core was extracted from a basin wide sediment unit (Kirby and Simms, unpublished data). All data presented in this paper come from the master core, Z–1C.

A combination of radiocarbon dating ($n = 21$) and reference horizon methods ($n = 4$) were used for age control. Discrete organic terrestrial macrofossils were picked under a binocular scope after