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Evidence for orbital and North Atlantic climate forcing in alpine Southern California between 125 and 10 ka from multi-proxy analyses of Baldwin Lake

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A B S T R A C T

We employed a new, multi-proxy record from Baldwin Lake (~125–10 ka) to examine drivers of terrestrial Southern California climate over long timescales. Correlated bulk organic and biogenic silica proxy data demonstrated high-amplitude changes from 125 to 71 ka, suggesting that summer insolation directly influenced lake productivity during MIS 5. From 60 to 57 ka, hydrologic state changes and events occurred in California and the U.S. Southwest, though the pattern of response varied geographically. Intermediate, less variable levels of winter and summer insolation followed during MIS 3 (57–29 ka), which likely maintained moist conditions in Southern California that were punctuated with smaller-order, millennial-scale events. These Dansgaard-Oeschger events brought enhanced surface temperatures (SSTs) to the eastern Pacific margin, and aridity to sensitive terrestrial sites in the Southwest and Southern California. Low temperatures and reduced evaporation are widespread during MIS 2, though there is increasing evidence for moisture extremes in Southern California from 29 to 20 ka. Our record shows that both orbital-scale radiative forcing and rapid North Atlantic temperature perturbations were likely influences on Southern California climate prior to the last glacial. However, these forcings produced a hydroclimatic response throughout California and the U.S. Southwest that was geographically complex. This work highlights that it is especially urgent to improve our understanding of the response to rapid climatic change in these regions. Enhanced temperature and aridity are projected for the rest of the 21st century, which will place stress on water resources.

1. Introduction

Throughout the U.S. Southwest, Great Basin, and California, climate model projections for the 21st century indicate that increased radiative forcing that will produce enhanced temperatures, aridity, and climate variability (Overpeck et al., 2013). These projections prompted our investigation of regional sensitivity to past climate change and potential forcing mechanisms over the past 125 ka, in a sector of the U.S. that is already water-stressed and increasingly populous (Georgescu et al., 2012). Retrospective studies are crucial for deepening our understanding of large-scale climate dynamics and teleconnections, and assessing the potential range of temperature and hydrological variability. Long-lasting droughts in the West during the Late Quaternary have been documented (e.g. Brunelle and Anderson, 2003; Heusser et al., 2015; MacDonald and Case, 2005; Mensing et al., 2013), most of which were associated with warm intervals (Woodhouse et al., 2010). Conversely, extreme wet events were also a feature of West Coast climates (e.g. Bird and Kirby, 2006; Kirby et al., 2013, 2012). These prolonged hydroclimatic events, on the order of

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several decades or centuries, have no analogue in the past 150 years of instrumental records.

A growing body of climatic records from the U.S. Southwest, Great Basin, and Southern California suggests regional sensitivity to a variety of climate drivers that include an atmospheric-oceanic teleconnection with the North Atlantic (Asmerom et al., 2010; MacDonald et al., 2008; Oster et al., 2014; Reheis et al., 2015; Wagner et al., 2010), Pacific Ocean (Hendy and Kennett, 2000a; Heusser, 1998; Lund and Mix, 1998) boreal insolation (Lachniet et al., 2014; Moseley et al., 2016), and migrating storm tracks (Garcia et al., 2014; Kirby et al., 2006; Owen et al., 2003). Offshore marine cores have documented long histories through several Marine Isotope Stages (MISs), but with dynamically different responses compared to terrestrial sites (Heusser and Basalm, 1977; Hooghiemstra et al., 2006). The longer-term climate history of terrestrial Southern California throughout past glaciations and multiple MISs is lesser-known, compared to abundant studies on the Holocene and last glacial (MIS 2).

In this study, a newly-acquired core from Baldwin Lake in the San Bernardino Mountains (SBM) that spanned 125 to 10 ka provided insight to the long-term temperature and hydrological variability of Southern California, and associated climatic drivers. We use this material to address the following questions: Is alpine Southern California sensitive to orbital and North Atlantic forcing over long timescales? How does the record of paleoenvironmental change and climatic variability at Baldwin Lake compare to other Southern California, Great Basin and Southwestern sites over the past 125 to 10 ka?

2. Setting

Located east of the Los Angeles Basin, the SBM are part of the Transverse Ranges and include some of the highest elevation peaks in Southern California. The SBM form a barrier between the interior Mojave and Sonoran Deserts, and the summer-dry, winter-wet Mediterranean conditions towards the coast. The San Andreas and Mill Creek Faults bound either side of the SBM range. Triassic-to Cretaceous-age granitic rocks dominate the SBM range (Morton and Miller, 2006), with other allocthonous sedimentary terranes of Precambrian and Mesozoic age (Dibblee, 1964). High relief valleys and slopes are often covered with Quaternary deposits, including alluvium, talus, and fanglomerates.

Baldwin Lake (34.275°N, 116.8°W) lies at an elevation of 2060 m in the Big Bear Valley of the SBM, approximately 160 km east of the Pacific coastline (Fig. 1). It is presently an intermittent lake, and one of two major lake basins in Big Bear Valley, with a 79 km^2 watershed (Big Bear Lake TMDL Task Force, 2012). To the west, the Big Bear Lake watershed is 96 km^2, and supported a lake throughout the Holocene (Kirby et al., 2012; Paladino, 2008). Sugarloaf Mountain to the south (3033 m) is the primary sediment source of the Baldwin basin, via the 14 km^2 Sugarloaf fan (Flint and Martin, 2012; Leidy, 2006). Smaller-scale faults occur throughout Big Bear Valley, including a thrust fault <1 km east of Baldwin Lake on Nelson Ridge (Flint and Martin, 2012). The highest elevations of the Transverse Ranges were glaciated during MIS 2; moraines still persist on the northern flank of Mt. San Gorgonio (3506 masl) and mark later Holocene readvances (Owen et al., 2003).

Mediterranean winter-wet and summer-dry conditions prevail throughout the SBM and Southern California, modulated by upwelling and currents on the North American Pacific margin. The configuration of the North Pacific High and North American Low, and westerly winds, drive this strong precipitation seasonality (Barron et al., 2003; Cayan and Peterson, 1989). Seasonal migration of the Polar Jet Stream (PJS) brings Pacific-derived moisture in the winter months, and Southern California's yearly precipitation averages 13–64 cm at lower elevations, and 64–150 cm in the mountains (National Oceanic and Atmospheric Administration, n.d.). Annual precipitation averages are comparatively higher in Big Bear Valley, averaging ~220 cm/yr (U.S. Climate Data, 2016) and the moisture is largely derived from North Pacific winter storms (Wise, 2010). Other precipitation sources include orographic uplift, lateral snow drift (Minnich, 1984), and occasional summer storms that result from convection or dissipating tropical cyclones (Tubbs, 1972). Average July high temperature at Big Bear City is 27.2 °C, and January's average high is 8.3 °C (U.S. Climate Data, 2016).

3. Materials and methods

3.1. Core recovery and Initial Core Description (ICD)

We re-cored Baldwin Lake in August 2012 at the basin depocenter (34°16.56633′, −116°48.61182′) with a CME-95 truck-mounted hollow stem auger drill. Prior coring at Baldwin Lake in 2004 yielded a 14.2 m sequence referred to as BLDC04-2 (Fig. 1; Kirby et al., 2006). We refer to the new sequence of cores as BDL12, which consisted of overlapping 2.5 foot sections from two separate holes totaling 27 m, now archived at UCLA. Cores were split at UCLA in 2013, then photographed and described at University of Minnesota's Limnological Research Center (LRC) in 2014, following conventions for Initial Core Description (ICD; Schnurrenberger et al., 2003). Key sedimentary structures and changes, described by depth from surface, have been summarized for the Supplemental Information.

3.2. Sedimentary analyses

Initial magnetic susceptibility (MS) data were collected at UCLA with a Bartington MS2e sensor, and later replicated at LRC. The GeoTek Multi-Sensor Core Logger at LRC collected 0.5-cm interval data. Loss-on-ignition (LOI) analysis at 1-cm intervals throughout BDL12 determined the bulk organic and carbonate content of the sediment (Dean, 1974; Heiri et al., 2001). Organic content was determined from the mass lost from1-cm^3 volume samples after 1-h burns at 550 °C in a muffle furnace, and carbonate content was calculated after subsequent 1-h burns at 950 °C. Core density was calculated from sample dry weight values recorded during LOI analysis. Bulk inorganic values were percentage values, calculated from the remaining sample weight after all LOI burns compared to the initial dry weight. Mass accumulation rates (MARs) were calculated by multiplying a horizon's dry density by the sedimentation rate derived from the age model (Rack et al., 1995). The 1-cm LOI and MS data were used to correlate the core sections, and determine a depth-below-surface value for each horizon of the sequence.

Grain size sampling was initially done at 50 cm intervals (Silveira, 2014), with later sampling that targeted the basal coarse-grained facies, and the slowly-deposited MIS 2 interval. Samples (n = 93) were digested in 30–35% H_2O_2 to remove organics, then 1N HCl to remove carbonates, and lastly 1M NaOH to remove biogenic silicates, with intermittent centrifuging. Analyses were performed on a Malvern Mastersizer 2000 laser diffraction grain size analyzer at California State University – Fullerton. The results were combined with high-resolution grain-size data from core BLDC04 (Blazevic et al., 2009) after re-aligning BLDC04's measured depths to correlate with BDL12 (see Supplemental Data). We reported the grain size mode (i.e., most frequently-occurring size) here in μm, after averaging values at 25-cm intervals for the core above 15 m, and at 50-cm intervals for the core section spanning 15–27 m. This was done to reduce noise and variable sampling resolutions throughout the ~27 m sequence. X-ray fluorescence