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Subtropical hydroclimate during Termination V (~430-422 ka): Annual records of extreme precipitation, drought, and interannual variability from Santa Barbara Basin

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ABSTRACT

Hydroclimate extremes are expected to become more frequent and intense with anthropogenic climate forcing, but future El Niño-Southern Oscillation (ENSO) behavior is unclear. Understanding of extreme hydroclimate variability and magnitude prior to human-influences is limited by short instrumental records, however, continuous sedimentary archives of past hydroclimate variability can complement and extend these records. Laminated Santa Barbara Basin (SBB) sediment cores MV0508-33JPC, −21JPC, and −29JPC preserve annually-resolved, multi-centennial-scale precipitation records from Termination V (T_V), the transition from glacial Marine Isotope Stage (MIS) 12 to interglacial MIS 11 at 424 ka. These records provide insights into the subtropical hydroclimate response to warming. Foraminiferal $\delta^{18}O$ variations indicate rapid warming and/or salinity changes, and were used to verify the T_V age assignment. A paleoprecipitation proxy was developed using the first principal component of scanning XRF elemental counts (PC1), which has high loadings for siliciclastic sediment-associated elements K, Ti, and Si. Sedimentary laminae couplets identified in PC1 were annually-tuned to investigate T_V paleoprecipitation variability, as modern SBB laminae represent annual deposits. Extreme flooding and decadal-to-centennial droughts were identified, with magnitudes exceeding modern observations. ENSO-like (2–7 year) paleoprecipitation periodicities coincide with wetter intervals, but ENSO variability is reduced during droughts. A 1500-year arid interval may be related to poleward shifting of general atmospheric circulation as ice sheets melted, such that the subtropical dry zone intersected California. Southern California paleoprecipitation reconstructions from past warm climates provide insight into precipitation variability and magnitude on interannual timescales, and can reduce uncertainties in predictions of interannual climate, including ENSO.

1. Introduction

Extreme weather events (e.g., heat waves, drought, floods) and interannual climate variability have considerable socioeconomic impacts, such as food and water stress and loss of life, and are likely to become more frequent and intense during the 21st century (IPCC, 2013). A crucial factor in assessing anthropogenic climate change risks is determining the influence of human-related emissions on recurrence frequency and magnitudes of extreme weather events (Stott et al., 2016). However, the short duration of instrumental records limits understanding of background climate variability, especially on interannual to sub-decadal timescales relevant to human perception of weather-climate conditions. It is difficult to attribute precipitation extremes to a particular forcing due to

Abbreviations: SBB, Santa Barbara Basin; T_V, Termination V; T_I, Termination I; MIS, Marine Isotope Stage; XRF, X-ray fluorescence; PC1, first principal component; PDO, Pacific Decadal Oscillation; AR, atmospheric river; MCT, Mid-Channel Trend; 04BC, sediment core SPR0901-04BC; 29JPC, sediment core MV0508-29JPC; 21JPC, sediment core MV0508-21JPC; 33JPC, sediment core MV0508-33JPC; ONI, Oceanic Niño Index; ENSO, El Niño-Southern Oscillation.

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inaccuracies in model representations, and because the relationship between variability and anthropogenic climate change is not well understood (Stott et al., 2016). Insights from continuous, annually-resolved paleoclimate archives provide a broader perspective of natural climate variability and weather extremes that can aid in reducing model uncertainties, and recognizing and mitigating human vulnerability to damaging climate and weather events.

Marine Isotope Stage (MIS) 11 is considered to be a close analogue to the Holocene interglacial due to its similar orbital configuration and pre-industrial atmospheric CO_2 concentrations (Loutre and Berger, 2003; Siegenthaler et al., 2005), and thus is relevant for examining interannual climate variability. Termination V (T_V), the transition from glacial MIS 12 to interglacial MIS 11 (424 ka), was one of the largest magnitude deglaciations of the Pleistocene (Lisiecki and Raymo, 2005b). Climate fluctuations observed in marine and continental paleoclimate records from this time (Candy et al., 2014) are similar to those recorded in the last glacial-interglacial cycle, Termination I (T_I). Marine sediment cores from the North Atlantic and Iberian Margin document ice-rafting events and millennial and (inter)stadial-type temperature oscillations during T_V (Barker et al., 2015; Kandiano et al., 2012, 2017; Oliveira et al., 2016; Oppo et al., 1998; Rodrigues et al., 2011; Vázquez Riveiros et al., 2013; Voelker et al., 2010). A lacustrine record from the Sulmona Basin, Italy indicates increasing precipitation through T_V into MIS 11 (Regattieri et al., 2016), while marine sediments from Northwest Africa record aridity during T_V and wet conditions during MIS 11 (Helmke et al., 2008). In the American Southwest, North American Monsoon strength generally increased (decreased) during warm (cool) substages of MIS 11 (Cisneros-Dozal et al., 2014; Fawcett et al., 2011). This region also experienced drought episodes spanning centuries to millennia during much of MIS 12 and during the warmest phase of MIS 11, attributed to a combination of less winter precipitation as mid-latitude westerly winds shifted poleward, and reductions in summer precipitation (Fawcett et al., 2011).

Capturing interannual hydroclimate variability during T_V may provide insights into the response of precipitation variability and extremes during a warming climate interval with similar orbital forcing to the Holocene but without anthropogenic drivers. However, reconstructing T_V paleo-interannual hydroclimate variability is difficult because few continuous, multi-centennial, annually-resolved archives exist. Ice core and typical marine sediment records from this time interval are generally low-resolution, preventing interannual climate investigations. Santa Barbara Basin (SBB), located offshore of southern California, preserves a varved annual archive that records modern and Holocene hydroclimate variability (Hendy et al., 2013, 2015; Schimmelmann et al., 1990, 1992, 1998, 2006, 2013; Schimmelmann and Kastner, 1993; Schimmelmann and Tegner, 1991; Soutar and Crill, 1977). A suite of cores recovered from a truncated anticline in SBB contains laminated sediments deposited during Quaternary interglacials, including T_V, providing a unique high-resolution archive that captures both weather and climate change (Afshar, 2011; Behl et al., 2005, 2007; Dean et al., 2015; Hopkins et al., 2006; Marshall, 2012; White et al., 2013).

Southern California is situated at the boundary between mid-latitude climate and subtropical dryness (Polade et al., 2017), and is therefore in a critical location for assessing hydroclimate variability and general atmospheric circulation shifts in response to a warming climate. Fluctuations in Pacific ocean-atmosphere conditions are robustly coupled with extreme weather and interannual to decadal precipitation variability in the Pacific Ocean basin, including in southern California (Hendy et al., 2015; Mantua et al., 1997; Polade et al., 2017; Ropelewski and Halpert, 1987). On an interannual scale, the El Niño-Southern Oscillation (ENSO; 2–7 year periodicity) influences weather around the globe (Ropelewski and Halpert, 1987), and California precipitation is particularly sensitive to ENSO intensity (Hoell et al., 2016). Climate models have trouble simulating ENSO and its teleconnections because of the difficulty in distinguishing predicted changes from natural modulations, making future changes in ENSO intensity and spatial patterns unclear (Cai et al., 2015; IPCC, 2013). Thus, proxy records are needed to elucidate natural interannual climate variability (e.g., ENSO). Climate oscillations within the ENSO bandwidth have been observed in annually laminated MIS 11 lacustrine sediments from Germany (Koutsodendris et al., 2011), a location far afield from the tropical Pacific. Decreased ENSO frequency was observed in Papua New Guinea during MIS 11, however this study was limited to the 35-year lifetime of one clam (Ayling et al., 2015). Multi-centennial paleoclimate archives preserved in SBB provide a broader temporal perspective of natural Pacific Basin ocean-atmosphere conditions and interannual hydroclimate needed to assess and improve climate model forecasts.

Here we investigate the natural hydroclimate variability of southern California during T_V, targeting extreme events and the interannual ENSO-influenced frequency bandwidth using a paleoprecipitation proxy developed for SBB laminated sediments (Hendy et al., 2015). Annually-resolved scanning X-ray fluorescence (XRF) elemental counts record high (low) siliciclastic sediment-associated elemental counts attributed to precipitation and runoff (drought) into SBB (Supplementary Material [SM]; SM Figs. 1–7). Elemental variations have been used to identify 20th century ENSO events in SBB sediments (Hendy et al., 2015), demonstrating the utility of these records for the examination of interannual hydroclimate variability. We present a sequence of multi-centennial paleoprecipitation records from SBB sediment core MV0508-33JPC, resolved at the annual scale, and identify dominant interannual-to-centennial hydroclimate cyclicities and extremes. This study provides an important perspective on extreme weather and interannual hydroclimate variability during a transition from a cool glacial to a warm interglacial climate (T_V, ~430–422 ka).

2. Regional setting

Southern California has a Mediterranean climate with cool, wet winters and warm, dry summers. The positions of the subpolar Aleutian Low and subtropical North Pacific High pressure systems control moisture transport into western North America (Lora et al., 2016). In summer, the North Pacific High inhibits storm landfall. In winter, the high pressure system is displaced southwest, tracking moisture-laden storms into California (Lu et al., 2003). The region's hydroclimate varies between extreme precipitation or drought (Dettinger et al., 2011). Variations in the extremes are linked to interannual and interdecadal climate oscillations. El Niño (La Niña) events in southern California are associated with increased (decreased) precipitation (Hoell et al., 2016) (see SM). Regional hydroclimate is further influenced by decadal climate variability, as precipitation events occur more frequently during the Pacific Decadal Oscillation (PDO) positive phase (Verdon and Franks, 2006). Additionally, extreme precipitation in California is associated with atmospheric rivers (ARs), narrow plumes (<1000 km wide, >2000 km length) of tropically-sourced atmospheric water vapor (Dettinger et al., 2011). Intense precipitation associated with these ARs is responsible for nearly half of California's total annual precipitation (Dettinger et al., 2011). ARs are responsible for a larger-than-average fraction of precipitation in southern California when they occur during El Niño events within the positive PDO phase (Dettinger et al., 2011).

The semi-enclosed SBB is located within the southern California