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Stable isotopic evidence of El Niño-like atmospheric circulation in the Pliocene Western United States

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Abstract

Understanding how the hydrologic cycle has responded to warmer global temperatures in the past is especially important today as concentrations of CO_2 in the atmosphere continue to increase due to human activities. The Pliocene offers an ideal window into a climate system that has equilibrated with current atmospheric $p\mathrm{CO}_2$. During the Pliocene the Western United States was wetter than modern, an observation at odds with our current understanding of future warming scenarios, which involve the expansion and poleward migration of the subtropical dry zone. Here we compare Pliocene oxygen isotope profiles of pedogenic carbonates across the Western US to modern isotopic anomalies in precipitation between phases of the El Niño Southern Oscillation (ENSO). We find that when accounting for seasonality of carbonate formation, isotopic changes through the late Pliocene match modern precipitation isotopic anomalies in El Niño years. Furthermore, isotopic shifts through the late Pliocene mirror changes through the early Pleistocene, which likely represents the southward migration of the westerly storm track caused by growth of the Laurentide Ice Sheet. We propose that the westerly storm track migrated northward through the late Pliocene with the development of the modern Cold Tongue in the East Equatorial Pacific, then returned southward with widespread glaciation in the Northern Hemisphere – a scenario supported by terrestrial climate proxies across the US. Together these data support the proposed existence of background El Niño-like conditions in Western North America during the warm Pliocene. If the Earth behaves similarly with future warming, this observation has important implications with regard to the amount and distribution of precipitation in Western North America.

1 Introduction

As the Earth's climate continues to respond to the anthropogenic input of greenhouse gasses to the atmosphere, understanding potential regional responses of the hydrologic cycle becomes vital for effective freshwater resource management and natural hazard mitigation policies. This problem is particularly relevant in water-vulnerable areas such as the Southwest United States where the amount of water used is similar to the amount of water available (Meehl et al., 2007). The current suite of Earth system models predicts an intensified hydrologic cycle with increasing global temperatures (Meehl et al., 2007). For many regions, this temperature increase is associated with increased precipitation. However, in the mid-latitudes where evaporation currently dominates precipitation such as in the Southwest US, a temperature increase results in decreasing precipitation due to the poleward expansion and enhanced aridification of the Hadley cell margin (Seager et al., 2007; O'Gorman and Schneider, 2010). This predicted regional response conflicts with reconstructed wetter-than-modern conditions in the southwest during pre-Quaternary warm periods, particularly in the Pliocene epoch.

It is then of great importance to study the mechanisms behind increased precipitation during pre-Quaternary warm periods in regions that are projected to dry over the coming decades as a result of modern climate change. Herein, we examine terrestrial stable isotope records for the Pliocene of Western North America in order to better understand the causes of these wetter-than-modern conditions despite higher global temperatures and a potentially strengthened hydrologic cycle.

The Pliocene epoch (5.33–2.58 Ma), with similar-to-modern boundary conditions including atmospheric $p\mathrm{CO}_2$ of ~ 400 ppm (Pagani et al., 2010) and global geography (Zachos et al., 2001; Haug et al., 2001), affords us a unique view of a globally warmer equilibrium state of the Earth system (Jansen et al., 2007). During the Pliocene, global temperatures were 3–4 °C higher than today (Ravelo et al., 2005), and major ice sheets were absent from the Northern Hemisphere (Zachos et al., 2001). In addition, much of the Western and Southern US were characterized by wetter-than-modern conditions, while a few areas in the Pacific Northwest were drier than modern (Fig. 1).

A number of studies have suggested that these anomalous wet conditions may have been the result of the temperature structure of the tropical Pacific. In the Pliocene, sea surface temperatures (SSTs) in the West Equatorial Pacific were similar to modern, while SSTs in the East Equatorial Pacific (EEP) were 3–5 °C warmer with evidence of a much deeper thermocline (Wara et al., 2005; Dekens et al., 2007; Etourneau et al., 2010). In the modern climate, this temperature structure characterizes the El Niño phase of ENSO. This observation has led many studies to conclude that the Pliocene was characterized by a background El Niño-like state, though the nature of interannual variability is poorly constrained (Ravelo et al., 2004; Wara et al., 2005).

During modern El Niño years, North America is particularly affected by atmospheric teleconnections, as anomalous atmospheric conditions propagate poleward from the Equatorial Pacific via planetary waves. Major changes in North American hydrology are primarily facilitated by a deeper Aleutian low, which forces the subtropical jet and westerly storm track equator-ward (Bjerknes, 1969; Trenberth et al., 1998). Qualitative spatial patterns of reconstructed Pliocene precipitation (wetter/drier) based on terrestrial proxy records match modern El Niño teleconnection patterns (Molnar and Cane, 2002) (Fig. 1), and GCM experiments have shown that forced permanent El Niño-like SSTs result in a south-shifted subtropical jet and increased moisture convergence across the Western and Southern US (e.g. Barreiro et al., 2006; Shukla et al., 2009; Brierly and Federov, 2010; Vizcaíno et al., 2010; Goldner et al., 2011).

It has also been suggested that these wet conditions may have been the result of lower topography in the North American Cordillera (Bonham et al., 2009) based on PRISM 2 (Pliocene Research, Interpretation and Synoptic Mapping) boundary conditions. The assumption of lower topography, however, is not supported by paleoaltimetry studies of the US, which show that large-scale topography reached modern elevations by the early Miocene (e.g. Mulch et al., 2006; Mix et al., 2011; Chamberlain et al., 2012). More recently, Pliocene boundary conditions provided by PRISM 3 and used as part of the PlioMIP (Pliocene Model Intercomparison Project) have been amended to include near-modern topography across the Western US (Sohl et al., 2009; Bragg et al., 2012). Results of PlioMIP ensembles using these updated boundary conditions indeed show enhanced precipitation rates over the Western US likely resulting from the reduced zonal temperature gradient across the tropical Pacific, though there appear to be discrepancies with proxy-based reconstructions of precipitation across the Southeastern US (Haywood et al., 2012).

In this study, we seek to characterize atmospheric circulation over the US to test the validity of this proposed mechanism of wetter-than-modern conditions. We compare two new and three previously published Plio-Pleistocene oxygen isotopic profiles across the Western US measured in pedogenic carbonates with modern observations of isotopes in precipitation across two phases of ENSO (Neutral and El Niño) at 77 stations across the country (Welker, 2012). Unlike floral-, faunal-, and sediment-based reconstructions that record only local environmental conditions, isotopes in precipitation recorded in authigenic minerals are controlled by a combination of local and upstream conditions and therefore offer unique insights into synoptic-scale atmospheric circulation.

2 Methods

2.1 Pedogenic carbonates

We sampled two well-dated sections composed of Pliocene paleosols and fluvial deposits that contain abundant pedogenic carbonate: (1) the San Timoteo Badlands of Southern California (Albright, 1999) on the windward corner of the intersection of the Transverse and Peninsular ranges, and (2) the Glenns Ferry, Tuana Gravels, and Bruneau formations located in Hagerman, ID (Hart et al., 1999; Sadler and Link, 1996; Amini et al., 1984). We collected calcareous sand- and mudstones showing no physical signs of weathering or re-precipitation of carbonate. Milled carbonate samples were reacted with phosphoric acid through a Kiel III carbonate device. Carbon and oxygen isotope ratios were then measured on a Thermo Finnigan MAT 252. Precision of carbonate $\delta^{18}O$ values is ~ 0.06 ‰ based on repeated analyses of NBS-19 and M-2 carbonate standards. These isotope values are given in Supplement Table S1.

In addition to these new isotope records, we compiled three previously published isotopic profiles of pedogenic carbonates that are found in Plio-Pleistocene sections in the Western US. These profiles were collected from Camp Rice, NM (Mack et al., 1994), Meade, KS (Fox and Koch, 2003), and St. David, AZ (Wang et al., 1993) (Fig. 1). Taken together, these locations cover a wide spatial area of the Western US, allowing us to compare regional isotopic shifts across the Plio-Pleistocene.

Isotope values are left as $\delta^{18}O_{\text{carbonate}}$ for analysis rather than converting to $\delta^{18}O_{\text{precip}}$, as regional temperature evolution over this time period is poorly constrained. As a result, our comparisons between paleo and modern data are limited to relative changes rather than absolute values. We correct for changing $\delta^{18}O$ of seawater due to the initiation of terrestrial Northern Hemisphere glaciation. This correction involves a linear increase in $\delta^{18}O_{\text{sea}}$ of 0.39 ‰ between 3.6 and 2.4 Ma based on mean ocean records (Mudelsee and Raymo, 2005).

2.2 Modern isotopes in precipitation

Weekly precipitation samples collected as part of the National Atmospheric Deposition Network were analyzed for $\delta^{18}O$ and δD values as part of the United States Network for Isotopes in Precipitation (USNIP) (Welker, 2000, 2012). We use this dataset in our analysis as it represents over 10 000 samples of weekly precipitation collected from 77 sites across the US between 1989 and 1995 (Welker, 2012). We binned these samples into El Niño and Neutral Phases based the Southern Oscillation Index. We then subdivided these phases into JFM (winter), AMJ (spring), JAS (summer), and OND (fall) seasons. Seasonal average $\delta^{18}O$ was calculated for each site using precipitation amount-weighted averages of raw weekly isotopic values. The El Niño isotopic anomalies given in this paper are the difference between El Niño and Neutral seasonal averages at each site ($\Delta\delta^{18}O$). Finally, we used a twelve-point spherical kriging interpolation in ArcGIS to generate seasonal maps of precipitation $\delta^{18}O$ anomalies.

3 Results

3.1 Pedogenic carbonates

Oxygen isotopic records are presented in Fig. 2a–e. These records show two contrasting trends that are dependent upon geographic location. First, in the Southwest US we observe a decrease in δ^{18}O of carbonate through the late Pliocene followed by an increase through the early Pleistocene. For example, in section located at St. David, AZ, δ^{18}O decreases by 3 ‰ through the late Pliocene, then increases by 2 ‰ through the early Pleistocene. Similarly, δ^{18}O decreases by 4 ‰ through the late Pliocene in sections at San Timoteo, CA, and increases by 3 ‰ through the early Pleistocene in Camp Rice, NM.

In contrast, δ^{18}O values in the Great Plains and Northwest Interior increase through the late Pliocene and decrease through the early Pliocene. The δ^{18}O values of pedogenic carbonates from Meade, KS, increase by 2 ‰ through the late Pliocene, then decrease by 2 ‰ through the early Pleistocene. Three δ^{18}O values of carbonate from this section are excluded at ~ 2.4 Ma, as these values are anomalously high (by 6–9 ‰) and clearly represent extensive evaporative enrichment that mask changes in precipitation (Fox and Koch, 2003). Finally, though temporal coverage is relatively poor, δ^{18}O values in Hagerman, ID increase by as much as 4 ‰ across the late Pliocene and decrease by ~ 1 ‰ across the early Pleistocene.

One feature that is consistent between all of the locations that span both the late Pliocene and early Pleistocene is a characteristic "V" shape with a local min/max within estimated dating errors of the Pliocene-Pleistocene boundary. Consequently, carbonate δ^{18}O values in the mid-Pleistocene (ca. 1 Ma) approach mid-Pliocene (ca. 4.0 Ma) values in these sections regardless of the direction of change. Isotopic trends in the San Timoteo, CA and Camp Rice, NM sections also reverse initially around the Plio-Pleistocene boundary.

The structure of the isotope records and the fact that the direction of changes is regionally dependent strongly suggests that oxygen isotope signals are primarily affected by atmospheric circulation changes rather than changes in temperature or local rainfall amount. Regional temperature evolution through this time period is not well-constrained, though global reconstructions show temperature decreased across the late Pliocene on the order of 1.1–1.6 °C (see Pagani et al., 2010). The temperature effects on $\delta^{18}O_{\text{calcite}}$ values are approximately 0.35 ‰ °C^{-1}, based on the combined relationships between temperature of precipitation and its oxygen isotope composition (Rozanski et al., 1993) and the equilibrium isotopic fractionation between carbonate and water (Kim and O'Neil, 1997). Assuming a liberal 2 °C of cooling across the late Pliocene, this should translate into a decrease in $\delta^{18}O$ values of ∼ 0.7‰ at all sites, which if present, is masked under the larger observed signals.

Additionally, terrestrial proxy-based climatic reconstructions show similar decreases/increases in rainfall amount at or in the vicinity of all isotope localities through the Pliocene/Pleistocene (Thompson, 1991). We would then expect to observe increasing/decreasing $\delta^{18}O$ through the Pliocene/Pleistocene at all locations based on the local "amount effect". As we do not observe this, we eliminate local rainfall amount as a dominant driver of isotopic change across this time interval.

3.2 Modern isotopes in precipitation

Modern seasonal precipitation $\delta^{18}O$ anomalies during El Niño years as compared to Neutral years from 1989–1995 are shown in Fig. 3 (Welker, 2012). During the fall months (OND), negative $\delta^{18}O$ anomalies occur primarily in the Southwest and Great Plains, and are on the order of −4 ‰ to −3 ‰ . During El Niño winters (JFM), negative anomalies on the order of −3 ‰ to −2 ‰ occur over the West coast and around the Great Lakes. Large positive anomalies on the order of 3–6 ‰ characterize the Southwest, while small negative anomalies occur over the Eastern US in the Spring (AMJ). Anomalies are minimal during the summer (JAS) with small positive anomalies over Southern Idaho/Northern Utah and small negative anomalies over North Dakota. It is important to note that for specific regions, isotopic anomalies are seasonally distinct.

For examples, the Southwest experiences large negative anomalies in the fall and large positive anomalies in the spring.

While we incorporate over 10 000 separate weekly measurements of isotopes in precipitation in our analysis of modern ENSO signals, the time interval of observations is only 6 yr and does not include large El Niño events such as took place in 1997–1998. In order to validate these observed signals as robust features of ENSO teleconnections, we compared observations to reanalysis-driven isotope-tracking model data from 1950–2003 and found modeled ENSO signals over the past half-century largely match those observed from 1989–1995 (see Supplement for full discussion).

4 Discussion

4.1 Seasonality of carbonate formation

In order to compare modern observations of isotopes in precipitation with isotopes of pedogenic carbonates, we must consider seasonal biases of pedogenic carbonates at each locality, as modern soil carbonates have been shown to form during discreet seasonal intervals that are regionally distinct (Breecker et al., 2009; Stevenson et al., 2010). Accounting for the seasonal bias in the soil carbonate records presented is of particular importance considering regional δ^{18}O anomalies in El Niño precipitation are seasonally dependent.

Pedogenic carbonate formation occurs as soils dry, both through the associated decrease in soil $p\mathrm{CO}_2$ as microbial respiration rates slow and as carbonate becomes increasingly saturated in soil water through evapotranspiration, following the wet season and peak primary productivity (Breecker et al., 2009; McFadden and Tinsley, 1985; McFadden et al., 1991; Retallack, 2005). Evidence for carbonate formation during times of drying of soils is supported by depth profiles of oxygen isotopes in soils. Typical soil profiles show increasing $\delta^{18}\mathrm{O}_{\mathrm{carbonate}}$ values near the soil surface (Quade et al., 1989; Liu et al., 1996), an effect caused by the upward wicking of soil water and downward diffusion of the isotopically heavier water as a soil dries (Barnes and Allison, 1983). We therefore assign carbonate growth to occur as monthly precipitation reaches a minimum and soil moisture decreases.

In the Southwest region including the San Timoteo, CA, St. David, AZ, and Camp Rice, NM localities, monthly precipitation reaches a minimum and soil moisture decreases dramatically in the spring (AMJ) following the winter westerly storms (Fig. 4). This observation is consistent with the empirical finding of Breecker et al. (2009) that carbonate formation in the Southwest occurs primarily in the spring. In the Great Plains including the Meade, KS locality, minimum monthly precipitation and decreasing soil moisture occurs primarily in the fall (OND) following the wet summer growth season (Fig. 4). Finally in the Northwest Interior including the Hagerman, ID locality, soil moisture decreases as monthly precipitation reaches a minimum in the summer (JAS) (Fig. 4). However, an empirical study of this region found that dry areas (MAP < 400 mm) with weak seasonality of rainfall form carbonates in the winter as well (Stevenson et al., 2010). We then model the season of carbonate formation at Hagerman, ID as both summer and winter as two possible end-member scenarios.

4.2 Comparison of Pliocene and modern isotope signals

A comparison of the observed Plio-Pleistocene changes in carbonate δ^{18}O with calculated changes in δ^{18}O between El Niño and Neutral years ($\Delta\delta^{18}$O) at each locality based on observed seasonal El Niño anomalies and the estimated season of soil carbonate formation is shown in Fig. 5. Observed $\Delta\delta^{18}$O of pedogenic carbonates across the late Pliocene matches calculated changes associated with a shift from El Niño to Neutral circulation in the modern climate at three of the four analyzed localities – Meade, KS, St. David, CA, and San Timoteo, CA. The Hagerman, ID site presents a more complicated scenario, however. If carbonate δ^{18}O is representative of winter precipitation, as it most likely is in the modern climate based on regional empirical analyses of carbonate formation in this region (Stevenson et al., 2010), then the change in δ^{18}O at the Hagerman, ID site is consistent with the observed change from El Niño to Neutral background circulation across the late Pliocene. If carbonate δ^{18}O is representative of summer precipitation, potentially due to higher Pliocene mean annual precipitation, however, the observed shift does not support the transition from El Niño to Neutral circulation at the Hagerman site.

4.3 Comparison of Pliocene and Pleistocene isotope signals

In addition to this line of evidence, comparisons between carbonate δ^{18}O values from mid-Pliocene and mid-Pleistocene paleosols also support the idea that wetter-than-modern Pliocene conditions in the Western US were a product of El Niño-like circulation. The Plio-Pleistocene boundary is characterized by the initiation and rapid expansion of glaciation in the Northern Hemisphere (Zachos et al., 2001). Northern Hemisphere glaciation, independent of the longitudinal location of ice sheet growth, causes a series of atmosphere-ocean teleconnections that propagate to the tropics resulting in a south-shifted ITCZ (Intertropical Convergence Zone) in all three major ocean basins (Chiang and Bitz, 2005). A south-shifted ITCZ in turn creates a deeper Aleutian low and shifts the Pacific jet southwards across the Western US (Trenberth et al., 1998; Chiang and Bitz, 2005), similar to El Niño circulation. Studies that reconstruct climate during periods of Northern Hemisphere glaciation in the Quaternary with both proxy data and models observe a deeper Aleutian low and subsequent southward shifted Pacific jet, which enhances moisture delivery to the Southwest (e.g. Clark et al., 1999; Wagner et al., 2010; Asmerom et al., 2010).

The fact that mid-Pliocene δ^{18}O values are similar to mid-Pleistocene values at all sites that span this time interval suggests that atmospheric circulation in the mid-Pliocene resembled that of the mid-Pleistocene. Specifically, the Pacific subtropical jet was displaced farther South allowing the enhanced delivery of moisture to the Southwest. In the absence of large-scale glaciation during the mid-Pliocene, the observed El Niño-like SST structure of the equatorial Pacific provides a well-understood mechanism that causes this circulation regime over the Western US.

In our proposed scenario, the “V” pattern of δ^{18}O observed in Plio-Pleistocene pedogenic carbonates represents the poleward migration of the subtropical jet with the decay of El Niño-like SSTs and development of the EEP Cold Tongue through the late Pliocene (Fig. 2f), followed by a southward redirection of the subtropical jet beginning at the Plio-Pleistocene boundary by the large-scale expansion of glaciation in the Northern Hemisphere (Fig. 2g). This interpretation of climatic evolution across the Plio-Pleistocene fits well with compilations of faunal-, floral-, pollen-, and sediment-based climate reconstructions, as well. Across the Western US, there is a general pattern of wetter-than-modern conditions through the Pliocene, followed by a period of increased aridity around the Pliocene-Pleistocene boundary, and finally a return to wetter-than-modern conditions by the mid-Pleistocene (Thompson, 1991) (Fig. 2).

5 Conclusions

In summary, we have compared δ^{18}O values from pedogenic carbonates at multiple sites across the Western US through the Plio-Pleistocene with modern δ^{18}O changes in precipitation between phases of the El Niño Southern Oscillation. From our analysis, the isotope records of pedogenic carbonate display regionally dependent, synchronous changes across the Plio-Pleistocene. Comparisons between the δ^{18}O of Pliocene pedogenic carbonate and modern observations of δ^{18}O of precipitation reveal that at three of our four localities the isotopic trends across the Pliocene match local trends between El Niño and Neutral years. In addition, convergence on mid-Pliocene δ^{18}O values during the mid-Pleistocene in pedogenic carbonates at localities that cover the interval suggests similar circulation conditions during these two time intervals. Circulation during the mid-Pleistocene is currently better constrained and was characterized by a deep Aleutian low and south-shifted Pacific jet, similar to El Niño circulation. Together, we see these as strong evidence that wetter-than-modern conditions in the Pliocene Western US despite warmer global temperatures, were a product of the background El Niño-like temperature structure of the tropical Pacific.

This finding is broadly consistent with the initial results of PlioMIP ensemble data run with PRISM 3 boundary conditions, which show increased precipitation over the Western US as a result of the reduced zonal temperature gradient across the tropical Pacific (Haywood et al., 2012). Future work addressing the nature of tropical Pacific teleconnections encapsulated in these ensemble data along with the use of isotope-enabled GCM's run with PlioMIP boundary conditions will allow for an unprecedented level of data-model comparison.

Finally, while idealized GCM experiments have demonstrated the dynamical effects of a background El Niño-like tropical Pacific on Pliocene climate (e.g. Barreiro et al., 2006; Shukla et al., 2009; Brierly and Federov, 2010; Vizcaíno et al., 2010; Goldner et al., 2011), the mechanisms leading to this state are still debated (e.g. Federov et al., 2006, 2010). The identification of these mechanisms and their relevance to modern climate change is of the utmost importance to freshwater resource management in the Western US as well as other regions affected by atmospheric teleconnections from the tropical Pacific.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/8/5083/2012/cpd-8-5083-2012-supplement.zip.

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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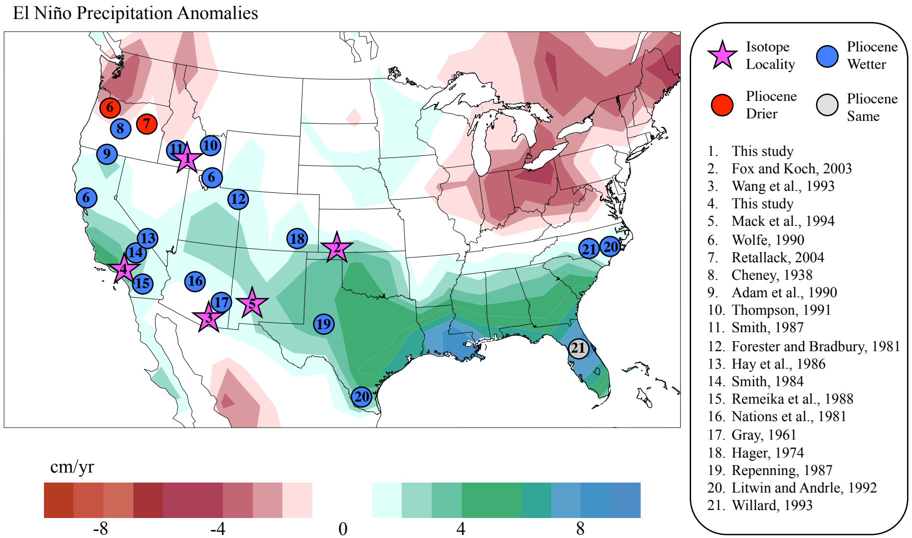

Fig. 1. Modern El Niño precipitation anomalies, isotope localities, and reconstructed Pliocene conditions. Anomalous annual El Niño precipitation calculated with CMAP precipitation data from 1979–2008; CMAP precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA, from their Web site at http://www.esrl.noaa.gov/psd/. Purple stars show isotope record localities used in this study. Blue circles represent reconstructions of wetter-than-modern Pliocene conditions, and red circles represent reconstructions of drier-than-modern Pliocene conditions.

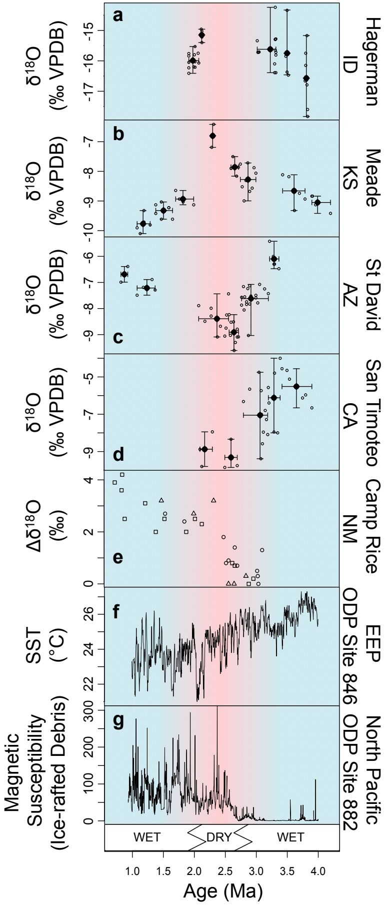

Fig. 2. Caption on next page.

Fig. 2. Isotope stratigraphies from **(a)** Hagerman, ID, **(b)** Meade, KS (Fox and Koch, 2003), **(c)** St. David, AZ (Wang et al., 1993), **(d)** San Timoteo, CA, and **(e)** Camp Rice, NM (Mack et al., 2003). Open circles in **(a–d)** represent individual samples, filled circles represent binned averages, and error bars represent bin ranges. Camp Rice, NM values normalized to sub-locality minimum values, and circles, triangles, squares represent sub-localities Hatch Siphon, Rincon Arroyo, Luccro Arroyo, respectively. **(f)** Reconstructed SSTs in the East Equatorial Pacific ODP Site 846 show development of the modern cold tongue (Lawrence et al., 2006). **(g)** Magnetic Susceptibility at ODP Site 882 in the North Pacific shows Ice-Rafted debris and expansion of NH glaciation through the Pleistocene (Maslin et al., 1995). Climatic conditions (wet/dry) in the Western US shown at the bottom and in blue and red background based on compilation of proxy-based reconstructions (Thompson, 1991).

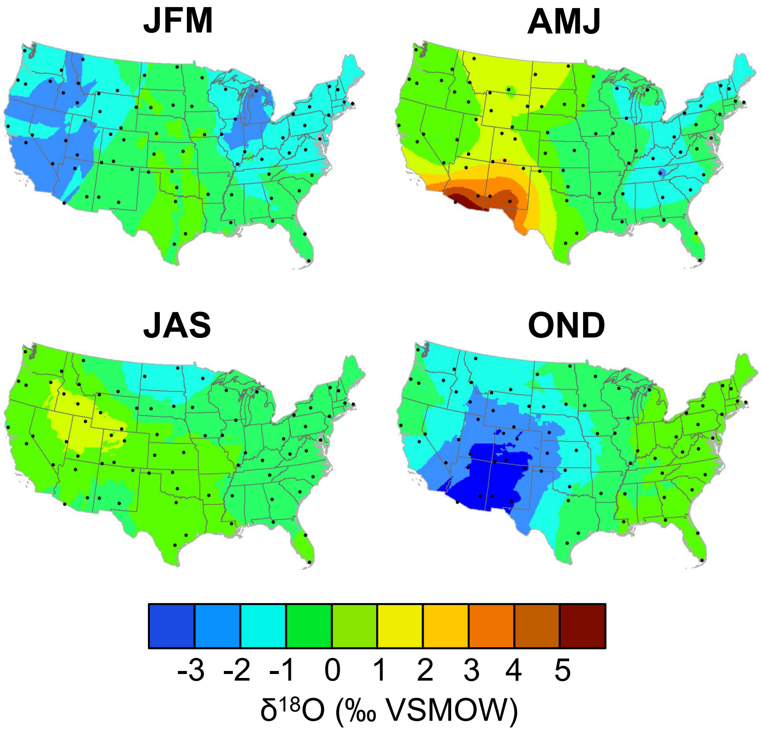

Fig. 3. Modern seasonal El Niño isotope anomalies. Black circles represent USNIP station sites. Figure modified from Welker (2012).

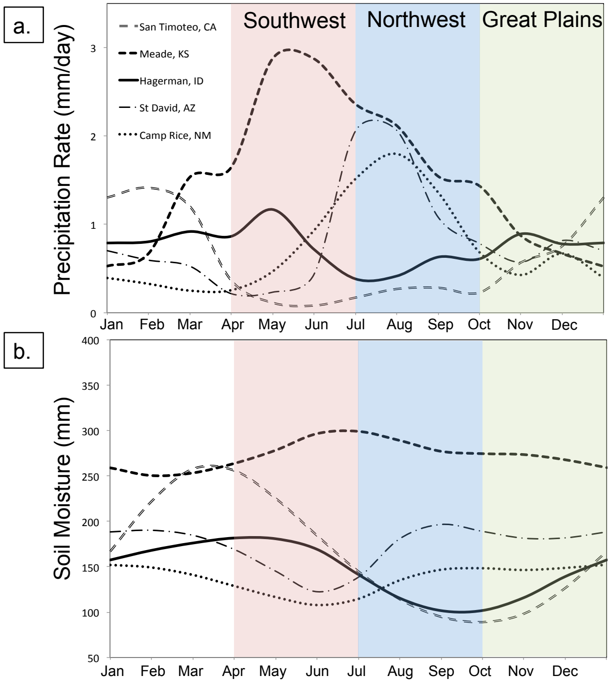

Fig. 4. (a) Average monthly precipitation rates from CMAP 1979–2000 (ref. in Fig. 1) and **(b)** soil moisture from NOAA Climate Prediction Center 1971–2000 (van den Dool et al., 2003) at each of the isotope localities. Shaded regions show predicted seasonality of carbonate formation in the Southwest (red), Northwest (blue), and Great Plains (Green) based on minimum monthly precipitation and decreasing soil moisture.

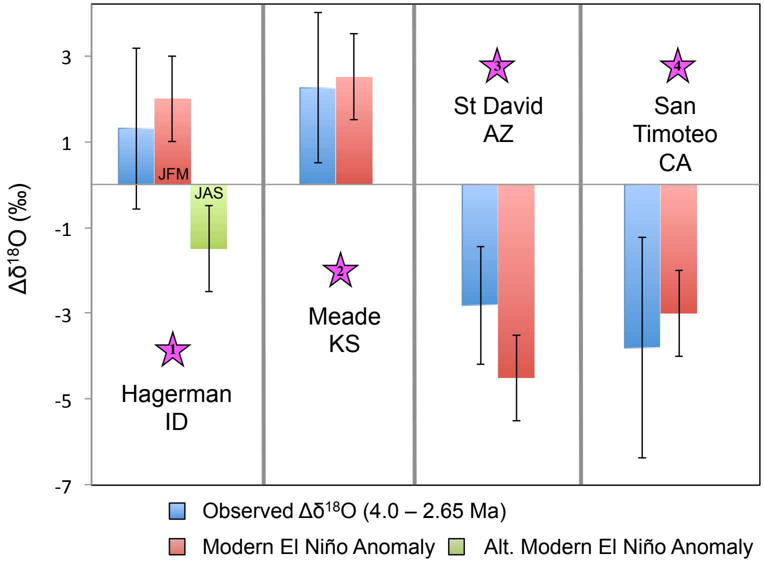

Fig. 5. Comparison of observed Pliocene $\Delta\delta^{18}$O with modern El Niño δ^{18}O anomalies Error bars in observed $\Delta\delta^{18}$O values show 95 % confidence intervals in differences between relevant sample bins. Numbered stars correspond to labeling in Fig. 1.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion