Supplementary Information

Modern ENSO $\delta^{18}O_{precip}$ Signals

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 years and does not include large El Niño events such as took place in 1997-8. In order to validate these observed signals as features of ENSO teleconnections, we analyze model output of $\delta^{18}O$ from the Stable Water Isotope Intercomparison Group (SWING) publically available on their website (http://atoc.colorado.edu/~dcn/SWING/datab-ase.php). We use data from the ECHAM-4 results of the S1b Experiment in which the model is forced with varying SST from the HadlSST data set.

Seasonal El Niño $\delta^{18}O$ anomalies based on the Niño 3.4 Index from 1950-2003 are shown in SFIG 1. In the winter (JFM), there are positive anomalies located in the Southwest and Northern US along with negative anomalies along the Southeast coast. This is in contrast to modern observations, which show negative anomalies along the West Coast. Similarly in the spring (AMJ), the Southwest and Northern US are characterized by positive anomalies. These regional signals match those observed in the modern dataset and are particularly relevant to the Southwest sites as is discussed in Section 4.1 of the main text. In the summer (JAS) there is a less coherent pattern of anomalies. Though small positive anomalies extend across portions of the Southern US, much of the US does not experience anomalies $\delta^{18}O$ similar to the observational data. Finally in the fall (OND), the model shows a large zone of negative anomalies extending across the Southern US. This signal is shifted east compared to observational data, though the signals match over the Great Plains region. This is relevant to the Meade, KS site as discussed in Section 4.1 of the main text.

While there are some discrepancies between observed and modeled signals, there is very good agreement on the isotopic changes relevant to our discussion based on seasonality of carbonate formation at each locality (see discussion in main text). Therefore, we regard the isotopic anomalies observed in modern precipitation used in our analysis to be a robust feature of modern ENSO teleconnections.

Pliocene Topography

The isotope records presented do not appear to be primarily driven by changes in topography. In this section, we will describe the topographic environment of each site, expected signals of uplift, and previous research on regional topography. In addition, we present a new record of topography from the Southern Sierra Nevada.

Moisture that reaches Hagerman, ID is advected west from the Pacific across the Cascades and Columbia Plateau. As such, the site is located in a zone of relatively low $\delta^{18}O_{precip}$ that is representative of upstream orographic rainout to the west. Across the late Pliocene, we observe a $\Delta\delta^{18}O$ of approximately 1‰, a signal that cannot be explained by the rise of upstream topography. Moreover, it has been shown that the Cascade Range developed in the mid-Miocene and the isotopic rain shadow has persisted since then (Kohn et al., 2002; Takeuchi and Larson, 2005; Takeuchi et al., 2010).

The Meade, KS locality is situated on the eastern edge of the central Rocky Mountains, and in terms of modern precipitation, the site is located within a steep $\delta^{18}O$ gradient (Kendall and Coplen, 2001). We expect topographic rise to manifest as decreasing $\delta^{18}O$ values across the Pliocene with decreasing efficiency of moisture delivery to the western Great Plains from the Gulf of Mexico. Instead, we observe increasing $\delta^{18}O$ values through the late Pliocene, similar to Hagerman, ID and at odds with rising topography. More importantly, however, the concept of rising of large-scale topography in this region is also in conflict with isotopic paleoaltimetry studies that have demonstrated the full development of modern $\delta^{18}O$ gradients on the eastern edge of the Rockies by the late Eocene to Oligocene (39-29 Ma) (Mix et al., 2011; Chamberlain et al., 2012).

The Camp Rice, NM and St David, AZ isotopic records are located at the southern edge of the Colorado Plateau. While Camp Rice carbonates do not cover the late Pliocene, St David carbonates record decreasing $\delta^{18}O$, which could be interpreted as decreasing efficiency of inland moisture transport with rising topography. This would conflict with a number of studies, however, that have shown stable or decreasing Colorado Plateau elevations since the Paleogene (Horton and Chamberlain, 2006; Mix et al., 2011;

Huntington et al., 2010; Chamberlain et al., 2012).

The San Timoteo, CA section is located at the windward corner of the Transverse and Peninsular ranges. There is sedimentological evidence that this region was tectonically active throughout the Pliocene, though it is debated whether this entailed the uplift or lateral translation of the Transverse Ranges (Albright, 1999; Weldon et al., 1993; Matti and Morton, 1993). Based on empirical relationships between precipitation isotopes and elevation (Poage and Chamberlain, 2001), the observed decrease in $\delta^{18}O$ translates to ~1.5 km uplift in 1 million years – a scenario that, to our knowledge has not been proposed in previous research. This empirical relationship, however, is not valid at windward positions. Uplift or lateral translation may account for a portion of the observed signal through infiltration of high elevation waters to the lower, windward section of the basin or by elevation-induced increases in upstream precipitation (Galewsky, 2009). As the isotopic signals of these effects are reduced relative to the empirical leeward relationship, we do not believe the amount of inferred uplift is plausible (>3km); therefore, the observed signal cannot be fully explained by changes in elevation.

Finally, conflicting evidence exists as to whether or not the Southern Sierra Nevada experienced uplift through the Pliocene (e.g.: Chamberlain et al., 2012), which may have impacted moisture delivery to the western US interior. In order to address this question, we collected lacustrine carbonates from the Coso formation of Owens Lake Valley, CA (Bacon et al., 1992) from 6 - 2 Ma located ~10km leeward of the Southern Sierra Nevada (SFIG 2). Methods used to analyze isotopic values are described in Section 2.1, main text, and isotopic values are included in Supplementary Table 1. This location is ideally situated to study topographic uplift for two reasons: 1) A recent study of storm trajectories has shown that moisture travelling inland will avoid pathways across high elevation when possible, so that only locations immediately leeward of high elevation will be isotopically sensitive to uplift (Lechler and Galewsky, 2013). 2) This location is situated north of the large spring and fall El Niño $\delta^{18}O$ anomalies and is therefore insensitive to changes in the Pacific jet that may act to mask changes in uplift (FIG 3, main text). We include this data in the supplement rather than the main text as it does not pertain to El Niño signals and because minerals are lacustrine rather than pedogenic and as such reflect different formation processes.

The isotopic evolution of the Coso formation is displayed in SFIG 2. With progressive uplift through the Pliocene, we would expect to observe clearly decreasing $\delta^{18}O$ on the order of 3-6‰ based on the empirical $\delta^{18}O$ v. elevation relationship (Poage and Chamberlain, 2001) and depending on the amount of uplift (~1-2.5 km). Instead, we observe a slight trend of increasing $\delta^{18}O$ from 5 - 3 Ma on the order of ~1‰ followed by even higher values from 2.5 – 2.0 Ma that range from -14 to -10‰. The anomalously high values suggest potential evaporative enrichment, concurrent with regional drying during this time period discussed in the main text. These data suggest stable topography in the Southern Sierra Nevada through the Pliocene epoch.

References

Albright, L. B.: Magnetostratigraphy and biochronology of the San Timoteo Badlands, southern California, with implications for local Pliocene-Pleistocene tectonic and depositional patterns, Geol. Soc. Am. Bull., 111, 1265-1293, 1999.

Bacon, C. R., Giovanetti, D. M., Duffield, W. A., Dalrymple, G. B., Drake, R. E.: Age of the Coso formation, Inyo County, California. Geological Survey Bulletin, 1527, 1-18, 1992.

Bonham, S., Haywood, A., Lunt, D., Collins, M., and Salzmann, U.: El Niño-Southern Oscillation, Pliocene climate and equifinality, Philos. T. Roy. Soc. A., 367, 127-156, 2009.

Chamberlain, C. P., Mix, H. T., Mulch, A., Hren, M. T., Kent-Corson, M. L., Davis, S. J., Horton, T. W., and Graham, S.A.: The Cenozoic climatic and topographic evolution of the western North American Cordillera, Am. J. Sci., 312, 213-262, 2012.

Galewsky, J.: Orographic precipitation isotopic ratios in stratified atmospheric flows: Implications for paleoelevation studies, Geology, 37, 791-794, 2009.

Horton, T. W. and Chamberlain, C. P.: Stable isotopic evidence for Neogene surface downdrop in the central Basin and Range Province, Geol. Soc. Am. Bull, 118, 475-490, 2006.

Huntington, K. W., Wernicke, B. P., and Eiler, J. M.: Influence of climate change and uplift on Colorado Plateau paleotemperatures from carbonate clumped isotope thermometry, Tectonics, 29, TC3005, 2010.

Kendall, C. and Coplen, T.B.: Distribution of oxygen-18 and deuterium in river waters across the United States, Hydrol. Process, 15, 1363-1393, 2001.

Kohn, M. J., Miselis, J. L., and Fremd, T. J.: Oxygen isotope evidence for progressive uplift of the Cascade Range, Oregon, Earth. Planet. Sc. Lett., 204, 151-165, 2002.

Lechler, A., Galewsky, J.: Refining Paleoaltimetry reconstructions of the Sierra Nevada, California, using air parcel trajectories, Geology, 41, 259-262, 2013.

Matti, J. C. and Morton, D. M.: Paleogeographic evolution of the San Andreas Fault in Southern California: A reconstruction based on a new cross-fault correlation, in: The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution, edited by: Powell, R. E., Weldon, R. J., and Matti, J. C., Geol. Soc. Am. Mem., 178, 107–159, 1993.

Mix, H. T., Mulch, A., Kent-Corson, M. L., and Chamberlain C. P.: Cenozoic migration of topography in the North American Cordillera, Geology, 39, 87-90, 2011.

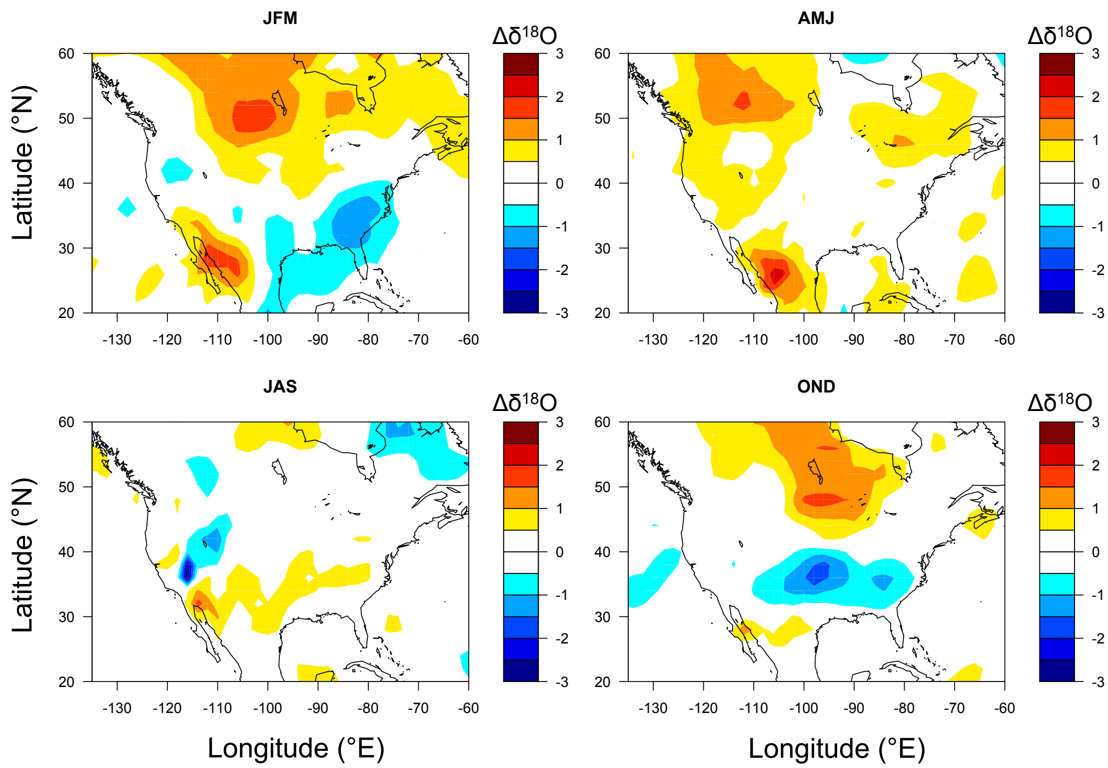
Poage, M. A. and Chamberlain, C. P.: Empirical relationships between elevation and the stable isotope composition of precipitation and surface waters: Considerations for studies of paleoelevation change, Am. J. Sci., 301, 1-15, 2001.

Sohl, L. E., Chandler, M. A., Schmunk, R. B., Mankoff, K., Jonas, J. A., Foley, K. M., and Dowsett, H. J.: PRISM3/GISS topographic reconstruction, U.S. Geological Survey Data Series, 419, 6 pp., 2009.

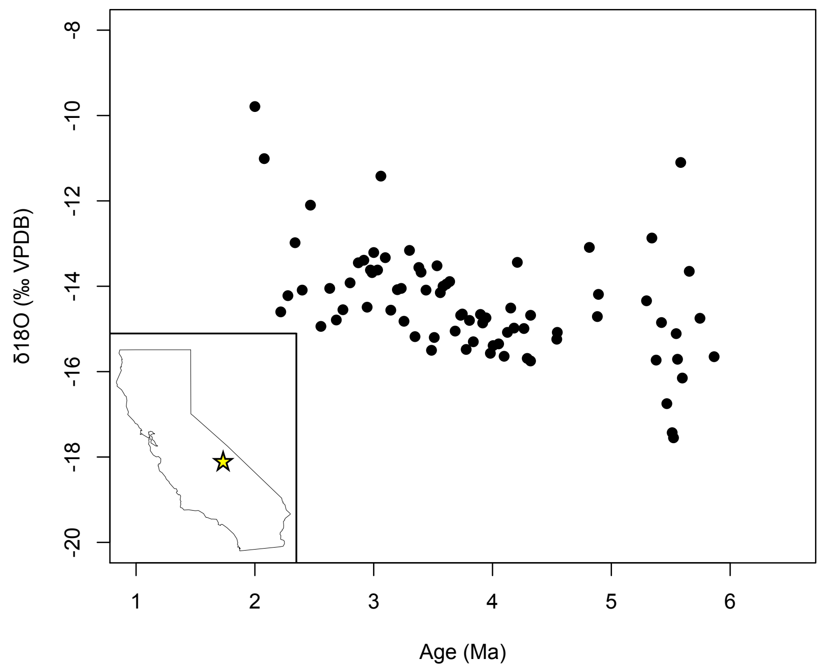
Takeuchi, A. and Larson, P. B.: Oxygen isotope evidence for the late Cenozoic development of an orographic rain shadow in eastern Washington, Geology 223, 127-146, 2005.

Takeuchi, A., Hren, M. T., Smith, S. V., Chamberlain, C.P., and Larsen, P. B.: Pedogenic carbonate carbon isotopic constraints on paleoprecipitation: Evolution of desert in the Pacific Northwest, USA, in response to topographic development of the Cascade Range, Chemical Geology, 277, 323-335, 2010.

Weldon, R. J., Meisling, K. E., and Alexander, J.: A speculative history of the San Andreas Fault in the central Transverse Ranges, California, in: The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution, edited by: Powell, R. E., Weldon, R. J., and Matti, J. C., Geol. Soc. Am. Mem., 178, 161–198, 1993.



Supplementary Figure 1. Seasonal El Niño anomalies of modeled $\delta^{18}O_{precip}$ based on the Niño 3.4 Index from 1950-2003. Isotope data taken from Stable Water Isotope Intercomparison Group (SWING) [reference in text].



Supplementary Figure 2. $\delta^{18}O$ values measured in lactustrine carbonates from the Coso formation in Owens Valley, CA. The location is represented by the gold star in the inset.