

## ***Interactive comment on “Stable isotopic evidence of El Niño-like atmospheric circulation in the Pliocene Western United States” by M. J. Winnick et al.***

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We would like to thank the reviewer for their thoughtful comments and suggestions. We agree with the two major comments given by the reviewer and will revise the paper to address: 1) potential topographic change in the Sierra Nevada; and 2) our assumption of Pliocene seasonality. Major proposed changes include: an expansion of literature review on Pliocene topography in the western US, the inclusion of two new isotope stratigraphies that show evidence of stable topography in the Pliocene Sierra Nevada, and a justification of our assumption of Pliocene seasonality based on an analysis of published Pliocene GCM output. We address specific comments below:

The reviewer could not find referenced supplementary material:

This reference to supplementary material was from the originally submitted draft and was removed before posting to the discussion section. Somehow the reviewer received this older version, while receiving the updated version of the Supplementary Information. Changes between these two drafts are relatively minor, though do involve an expansion of this specific paragraph to discuss recent modeling efforts of the PRISM 3 project using near-modern topographical boundary conditions.

The reviewer commented on the question of Sierra Nevada uplift:

This is a very good point, and one on which the bulk of our revisions will focus via the following changes:

1) Our statement that topography in the western US has remained largely unchanged since the Miocene was too vague. In order to rectify this, we will reinsert the Supplementary Discussion referenced above, including a detailed summary of literature on specific topographical features (i.e.: Eastern Rockies, Colorado Plateau, Cascades, Sierra Nevada) and how they may interact with each of sites.

2) We agree that the question of recent uplift of the Southern Sierra is an open one, and our group is currently studying this question in collaboration with Dr.'s Joe Galewsky, Matthew Huber, and Andreas Mulch. Since the submission of this paper, we have collected and analyzed two additional sequences located in a zone with no modern El Niño precipitation isotope anomalies and immediately leeward of the Sierra Nevada in Owen's Valley, CA and in Fish Lake Valley, NV. In these isotope stratigraphies, we observe no evidence of uplift over the Pliocene. We will include this new data in a revised manuscript.

3) Finally, recent work as a part of this collaboration has resulted in a paper currently in press in Geology that analyzes air parcel trajectories across the Southern Sierras

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[Lechler and Galewksy, in press]. The finding of this paper is that air parcels crossing the Sierras avoid pathways across high topography so that locations significantly downstream of the Sierras [ $>150$  km, i.e.: the St David, AZ site in this paper] are isotopically insensitive to uplift. We will include these recent findings in our discussion of possible topographical signals in our data.

Page 3, line 6-9

The reviewer disagrees with a sentiment expressed in the introduction:

We agree with the reviewer that the greatest challenge when working with isotopes in precipitation is separating local signals from upstream signals, and we will amend the statement according. In addition we will provide references of other paleoclimate studies showing isotope records that reflect upstream rainout and moisture transport rather than local effects (e.g.: Pausata et al., 2011; Poulsen et al, 2010). We address the actual issue of separating these effects in detail in Section 3.1 based on the synchronicity of signals across all sites and an analysis of local environmental factors from previous studies proximal to each of our sites.

Page 3, lines 28-29

The reviewer comments on the limitations of only having 5 sites:

The line in the paper to which the reviewer refers asserts that these sites are representative of regional signals, and we agree that this statement should not be made before our justification of it later in Section 3.1. We will rephrase this line to state that these locations offer comparisons of isotopic signals over a wide spatial range, which to our knowledge has not been previously attempted with oxygen isotopes from the Pliocene. In addition, we will address the limitation of having only 5 locations by including data from two additional locations as described above.

Page 4, line 2

The reviewer commented on our statement regarding regional temperature evolution:

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We will expand on this statement in a revised manuscript. As stated, global temperatures decreased on the order of  $\sim 1.5^{\circ}\text{C}$  across the time interval, likely due to decreasing atmospheric  $\text{pCO}_2$  (Pagani et al., 2010). Conversely, a number of modeling studies suggest that increased moisture convergence over the Southern US due to tropical Pacific SST's may have led to increased atmospheric albedo and slight warming ( $\sim 1\text{--}3^{\circ}$  [Barreiro et al., 2006; Briery, et al., 2010; Vizcaíno et al., 2010]) with the establishment of modern tropical Pacific zonal temperature gradients. To our knowledge, there have been no studies of the interaction of these competing effects across the late Pliocene. We will address the issue of Pliocene seasonality later in this response.

Page 4, lines 9-20

The reviewer commented on the lack of presentation of La Niña isotope anomalies in modern precipitation:

There were no SOI + (La Niña) years contained in the modern dataset. We do however start with the assumption that only El Niño is relevant and will clarify this in the Introduction (Section 1). The reason behind this assumption is that reconstructions of Pliocene tropical Pacific SST's show a reduced zonal temperature gradient, resembling the modern El Niño phase of ENSO (e.g.: Wara et al., 2005; Etourneau et al., 2010; Scroxton et al., 2011). In addition, a number of previous studies have hypothesized that North American hydrology was primarily controlled by these El Niño-like conditions in the tropical Pacific via atmospheric teleconnections (e.g.: Molnar and Cane, 2002; Goldner et al., 2011). We assume the relevance of El Niño in order to test this hypothesis, and we will clarify these intentions in a revised manuscript. To our knowledge, there has only been one study that suggests La Niña may be relevant to the Pliocene, in which reconstructed SST's from two ODP cores in the West and East tropical Pacific suggest an increased zonal temperature gradient (Rickaby and Halloran, 2005). However, this study used only one data point to represent the Pliocene warm period, and a subsequent high-resolution study of the same core sections do in fact show reduced zonal SST gradients (Wara et al., 2005).

The reviewer inquired as to the potential effects of elevation on El Niño anomalies:

This is a good question. While elevation does have an effect on the absolute value of  $\delta^{18}\text{O}$  in precipitation at specific sites, we see no evidence in the observational or simulated datasets that El Niño isotopic anomalies are dependent on site elevation. Instead, our analysis suggests that these anomalies are features of regional-scale air masses. We will include this in Section 3.2.

The reviewer commented on the limitations of kriging:

We agree with the reviewer on the importance of not over-interpreting the exact shapes of kriging contours as these are particularly sensitive to the type of covariance model used. We do not suspect that this is an issue with respect to the paleo sites in Arizona, New Mexico, Kansas, or Idaho as each of these sites falls proximal to (<150 km w/ no major topographic boundaries between) modern sites. The California site, however, is not proximal to a modern site (~250 km). To address this, we will calculate the kriging error at each location and analyze the associated uncertainty in Sections 3.2 and 4.2.

Pages 5 and 6

The reviewer commented on our statement that all of our sites experienced increased precipitation relative to modern in the late Pliocene:

We agree with the reviewer that there is inherently heterogeneity in the magnitude of precipitation anomalies across the US during the Pliocene and will amend our statement accordingly. The idea that each site experienced wetter-than-modern conditions, however, is based on previous studies of local environmental conditions proximal to each of the sites as shown in Figure 1. In addition, a number of modeling studies that force permanent El Niño-like conditions in the tropical Pacific in order to study the associated teleconnections observe a ubiquitous increase in precipitation across the Southern US (Barreiro et al., 2006; Briery, et al., 2010; Vizcaíno et al., 2010; Goldner et al., 2011), providing a dynamical mechanism for the observed uniformity in direction

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of change.

Page 5, lines 20-26

The reviewer commented on the temporal limitations of the modern dataset:

We agree with the reviewer that the observational dataset is limited and clearly state this limitation in the manuscript (Page 8, lines 1-7). Incorporating over 10,000 separate analyses, this dataset represents multiple years of laboratory work and is significantly larger than those used in similar studies looking at isotopes in precipitation across the United States (e.g.: Kendall and Coplen, 2001; Liu et al., 2010; Liu et al., 2012). As the reviewer acknowledges, we address this limitation through a comparison of measured data to simulations of isotopes in precipitation from 1950-2003. This comparison is preliminary and will be the focus of future research, however, initial results discussed in the Supplementary Information show that observed signals relevant to our discussion match the simulated results.

Pages 7 and 8

The reviewer questioned our assumptions of Pliocene seasonality:

We agree with the reviewer regarding the necessity of expanding the justification for assumptions on the seasonality of Pliocene carbonate formation, and will revise the text accordingly. As stated in the text, soil carbonates form primarily as soils dry following strong seasonal precipitation (Breecker et al., 2009; Peters et al., 2013). While there were undoubtedly changes in precipitation in the western US during the Pliocene, a survey of Pliocene GCM studies suggest that the overall patterns of precipitation seasonality were similar to today in the regions relevant to our study. In the Southwest, models predict wetter winter conditions, while spring-summer conditions were similar to or drier than modern (Barreiro et al., 2006; Vizcaino et al., 2010; Goldner et al., 2011), resulting in a strengthened version of the modern seasonality pattern. In the Great Plains region, models predict increases in summer precipitation with little to no

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change in fall-winter precipitation (Barreiro et al., 2006; Haywood et al., 2007; Shukla et al., 2009; Vizcaino et al., 2010; Goldner et al., 2012), again strengthening the modern pattern of seasonality. In each of these cases, increased precipitation during the wet season may have caused soils to dry slightly later in the year, which could have amplified observed El Niño signals through a shift to incorporate a higher proportion of summer-heavy/winter-light precipitation in the Southwest/Great Plains. This is, however, only speculative and cannot be quantified.

Pages 8 and 9

The reviewer questioned the paper's conclusions:

It appears that we were not clear enough in this section about the connections between our isotopic data and conclusions from previous studies. We will rephrase this section to reflect the following: We do not attempt to reconstruct the position of the EEP Cold Tongue with terrestrial sites; this is instead based on SST reconstructions from ODP cores (e.g.: Wara et al., 2005; Etourneau et al., 2010) as represented by Figure 2f. Based on a number of idealized GCM experiments cited in the manuscript (e.g.: Barreiro et al., 2006; Briery, et al., 2010; Vizcaíno et al., 2010; Goldner et al., 2011), the development of the EEP through the late Pliocene is predicted to cause the northward migration of the subtropical jet. The isotopic signals we observe are consistent with this predicted response of the subtropical jet in terms of direction, magnitude, and timing. Our observed signals are also consistent with the wet-dry-wet temporal evolution of the western US as concluded in Thompson (1991) based on a compilation of local environmental reconstruction from sites across the western US.

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