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Invited review article

Lake oxygen isotopes as recorders of North American Rocky Mountain hydroclimate: Holocene patterns and variability at multi-decadal to millennial time scales

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ABSTRACT

Lake sediment oxygen isotope records (calcium carbonate-$\delta^{18}O$) in the western North American Cordillera developed during the past decade provide substantial evidence of Pacific ocean–atmosphere forcing of hydroclimatic variability during the Holocene. Here we present an overview of 18 lake sediment $\delta^{18}O$ records along with a new compilation of lake water $\delta^{18}O$ and $\delta^{2}H$ that are used to characterize lake sediment sensitivity to precipitation-$\delta^{18}O$ in contrast to fractionation by evaporation. Of the 18 records, 14 have substantial sensitivity to evaporation. Two records reflect precipitation-$\delta^{18}O$ since the middle Holocene, Jellybean and Bison Lakes, and are geographically positioned in the northern and southern regions of the study area. Their comparative analysis indicates a sequence of time-varying north–south precipitation-$\delta^{18}O$ patterns that is evidence for a highly non-stationary influence by Pacific ocean–atmosphere processes on the hydroclimate of western North America. These observations are discussed within the context of previous research on North Pacific precipitation-$\delta^{18}O$ based on empirical and modeling methods. The Jellybean and Bison Lake records indicate that a prominent precipitation-$\delta^{18}O$ dipole (enriched-north and depleted-south) was sustained between ~3.5 and 1.5 ka, which contrasts with earlier Holocene patterns, and appears to indicate the onset of a dominant tropical control on North Pacific ocean–atmosphere dynamics. This remains the state of the system today. Higher frequency reversals of the north–south precipitation-$\delta^{18}O$ dipole between ~2.5 and 1.5 ka, and during the Medieval Climate Anomaly and the Little Ice Age, also suggest more varieties of Pacific ocean–atmosphere modes than a single Pacific Decadal Oscillation (PDO) type analogue. Results indicate that further investigation of precipitation-$\delta^{18}O$ patterns on short (observational) and long (Holocene) time scales is needed to improve our understanding of the processes that drive regional precipitation-$\delta^{18}O$ responses to Pacific ocean–atmosphere variability, which in turn, will lead to a better understanding of internal Pacific ocean–atmosphere variability and its response to external climate forcing mechanisms.

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1. Introduction

North American Rocky Mountain winter precipitation, principally stored as snowpack, is the primary water resource for the surrounding semiarid regions (Wise, 2012). North American precipitation patterns and corresponding snowpack distributions reflect synoptic scale winter storm tracks and the upper level atmospheric flow (Changnon et al., 1993; L'Heureux et al., 2004; Shinker and Bartlein, 2009; Miyasaka et al., 2014). Significant snowpack variance is explained by ocean–atmosphere climate modes, which are internal to the climate system and operate on interannual to multi-decadal times-scales, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Dettinger et al., 1998; Cayan et al., 1998; Brown and Comrie, 2004; Mote, 2006; Brown, 2011; Pederson et al., 2011). Changing atmospheric flow provides a potential mechanistic explanation for correlations between precipitation distributions (both spatial and temporal) and internal climate modes such as ENSO and PDO.

The role and significance of internal ocean–atmosphere climate variability, and its responses to external forcing mechanisms, such as changes in Earth's orbital configuration, volcanism, and anthropogenic activity, are prominently featured in questions about the future of water resources in western North America (Pederson et al., 2013; McCabe and Wolock, 2009; Wise, 2010; Byrne et al., 1999; Clark et al., 2001; Salathé, 2006; Hoerling et al., 2010; Abatzoglou, 2011). However, application of multi-decadal climate mode concepts is complex because such atmospheric behavior emerges in the climate system even in the absence of external forcing and thereby comprises background climate variability, or noise, which is inherently stochastic (Alexander, 2010; Schneider and Cornuelle, 2005; Overland et al., 2008).

Estimates of future responses of western North American water resources to anthropogenic warming are provided by General Circulation Models (GCMs) (Barnett and Pierce, 2009; Seager et al., 2007). GCMs accurately capture many aspects of the climate system, including the global response to external forcing, which provide important insight into the dynamics associated with past and future climate change. However, many GCMs consistently appear to either suppress or inaccurately represent internal ocean–atmosphere variability and should not be exclusively relied upon to investigate future climate change scenarios for regions that are strongly influenced by internal climate modes such as western North America (Alder and Hostetler, 2014; Bartlein et al., 2014; Collins, 2005; Deser et al., 2012; Harrison et al., 2014, 2015; Schmidt et al., 2005; Sun, 2010).

Holocene climate proxy records provide abundant evidence for changes in internal ocean–atmosphere climate variability related to external forcing (e.g., Cobb et al., 2013; Koutavas and Joanides, 2012; Li et al., 2011; Moy et al., 2002). Here we review evidence that internal ocean–atmosphere climate variability affects hydroclimate in western North America in response to external forcing from spatially distributed lake isotope records (carbonate-$\delta^{18}O$) with an emphasis on the records that reflect the oxygen isotope composition of precipitation (precipitation-$\delta^{18}O$). Such records provide insight on past changes in atmospheric flow, moisture source areas, rainout efficiency, and the temperature of condensation (Ingraham, 1998; Darling et al., 2006). We propose that with a process-based understanding of regional climate controls on precipitation-$\delta^{18}O$, inferred precipitation patterns and corresponding atmospheric flow from spatially distributed precipitation-$\delta^{18}O$ paleorecords will elucidate the changing influence of North Pacific ocean–atmosphere variability on Rocky Mountain snowpack on multi-decadal to millennial time scales.

To achieve our objectives, we evaluate 18 lake carbonate-$\delta^{18}O$ records within the greater western North American Cordillera from Alaska to Colorado (Fig. 1). Our evaluation is based on a compilation of lake water isotope values ($\delta^{18}O$ and δ^2H) that provide a framework for understanding the $\delta^{18}O$ relationships between lake-sediment carbonate (endogenic calcite and aragonite), lake water, and precipitation. This allows us to characterize each of the lake carbonate-$\delta^{18}O$ records as an "isometer" of the climate processes that control precipitation, precipitation minus evaporation (P − E), or a mixture of both. We then use the Holocene precipitation-$\delta^{18}O$ records to examine north–south precipitation-$\delta^{18}O$ patterns on multi-decadal to millennial timescales. From this comparative analysis we consider how internal Pacific ocean–atmosphere modes varied throughout the Holocene and influenced hydroclimate in the western North American Cordillera in relation to external forcing by solar insolation. This comparison necessitates a review of previous research on precipitation-$\delta^{18}O$ in the North Pacific and Gulf of Alaska region.

2. Lake water-$\delta^{18}O$ and carbonate-$\delta^{18}O$

We focus this analysis on the interior Rocky Mountain region where there are strong continental rainout fractionation effects on precipitation-$\delta^{18}O$ (Winnick et al., 2014). The lake carbonate-$\delta^{18}O$ records are distributed from northern Alaska (~68°N) to southern Colorado (~37°N), and we also include a discussion of the Mount Logan ice-$\delta^{18}O$ record in the Yukon Territory (Fisher et al., 2004, 2008), the Oregon Caves National Monument (NM) speleothem-$\delta^{18}O$ record (Ersek et al., 2012), and the Gulf of Alaska (GoA) foraminiferal-$\delta^{18}O$ record EW0408-85JC (Praetorius and Mix, 2014) (Fig. 1a, Table 1). Additional lake and speleothem carbonate-$\delta^{18}O$ records from the desert environments of the Great Basin (Benson et al., 2002, 2003; Lachniet et al., 2014; Yuan et al., 2004, 2013), and the Sierra Nevada in California (McCabe-Glyn et al., 2013) are not included in the present analysis, which we have limited to intermountain regions with higher precipitation amounts.

The intermountain lake records span a range of climates indicated by the ratio of precipitation (P) to potential evaporation (PE) derived from the National Centers for Environmental Prediction North American Regional Reanalysis (NCEP-NARR). The NARR is a three-dimensional atmospheric model forced with observed climate from surface measurements and atmospheric soundings (Mesinger et al., 2006). The model is fundamentally similar to global reanalysis products but is projected onto a 0.3° × 0.3° horizontal grid that makes it particularly useful for studies of topographically complex environments. The large-scale P/PE patterns (Fig. 1a) reflect topographic effects on the amount of precipitation where regions with the highest ratios, indicative of a wetter climate, occur in low elevation coastal areas and particularly along the coastal mountain ranges, largely due to higher P. Lower P/PE ratios, which indicate a drier climate, occur in leeward rain shadows of mountain ranges: these are found in eastern Washington, the southwest Yukon Territory, and low elevation regions of Colorado and Utah, due to low P and high PE. Intermediate ratios typically reflect areas with highly uneven seasonal precipitation distributions where the amount