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# Oxygen isotope records of Holocene climate variability in the Pacific Northwest

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ABSTRACT

Oxygen isotope ($\delta^{18}O$) measurements of authigenic carbonate from Cleland Lake (southeastern British Columbia), Paradise Lake (central British Columbia), and Lime Lake (eastern Washington) provide a ~9000 year Holocene record of precipitation-evaporation balance variations in the Pacific Northwest. Both Cleland Lake and Paradise Lake are small, surficially closed-basin systems with no active inflows or outflows. Lime Lake is surficially open with a seasonally active overflow. Water isotope values from Cleland and Paradise plot along the local evaporation line, indicating that precipitation-evaporation balance is a strong influence on lake hydrology. In contrast, Lime Lake water isotope values plot on the local meteoric water line, signifying minimal influence by evaporation. To infer past hydrologic balance variations at a high temporal resolution, we sampled the Cleland, Paradise, and Lime Lake sediment cores at 1–60 mm intervals (~3–33 years per sample on average) and measured the isotopic composition of fine-grained (<63 μm) authigenic $CaCO_3$ in each sample. Negative $\delta^{18}O$ values, which indicate wetter conditions in closed-basin lakes, occur in Cleland Lake sediment from 7600 to 2200 years before present (yr BP), and are followed by more positive $\delta^{18}O$ values, which suggest drier conditions, after 2200 yr BP. Highly negative $\delta^{18}O$ values in the Cleland Lake record centered on ~2400 yr BP suggest that lake levels were high (and that the lake may have been overflowing) at this time as a result of a substantially wetter climate. Similarly, Paradise Lake sediment $\delta^{18}O$ values are relatively low from 7600 to 4000 yr BP and increase from ~4000 to 3000 yr BP and from ~2000 yr BP to present, indicating that climate became drier from the middle through the late Holocene. The $\delta^{18}O$ record from Lime Lake, which principally reflects changes in the isotopic composition of precipitation, exhibits less variability than the closed-basin lake records and follows a generally increasing trend from the mid-Holocene to present. These results are consistent with several proximal reconstructions of changes in lake-level, precipitation amount, and precipitation isotopic composition and may also reflect the establishment of modern El Niño Southern Oscillation (ENSO) variability in the late Holocene, as inferred from proxy evidence of synoptic ocean-atmosphere changes in the Pacific basin. Results from mid-Holocene (6000 yr BP) climate model simulations conducted as part of the Paleoclimate Modeling Intercomparison Project Phase 3 (PMIP3) indicate that in much of western North America, the cold season (October–March) was wetter and the warm season (April–September) was considerably drier relative to the late Holocene, leading to an overall drier climate in western North America with enhanced hydroclimatic seasonality. This is consistent with inferences from the Cleland and Paradise $\delta^{18}O$ records, which lake modeling experiments indicate are strongly influenced by cold season precipitation-evaporation balance. This also explains apparent inconsistencies between the lake $\delta^{18}O$ records and other proxies of hydroclimatic change from the greater Pacific Northwest region that are less sensitive to cold season climate and thus indicate relatively drier conditions during the mid-Holocene. The abrupt negative excursion at ~2400 yr BP in the Cleland Lake $\delta^{18}O$ data, as well as the marked shift to more positive values after this time, demonstrate

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that gradual changes in ocean-atmosphere dynamics can produce abrupt, non-linear hydroclimate responses in the interior regions of western North America.



## 1. Introduction

Changes in the Pacific and Atlantic ocean-atmosphere systems during the Holocene produced substantial variations in the climate of western North America. Currently, the El Niño Southern Oscillation (ENSO) (Brown and Comrie, 2004; Cayan et al., 1999, 1998; Dettinger et al., 1998; McCabe and Dettinger, 2002, 1999; Wise, 2010), the closely associated Pacific Decadal Oscillation (PDO) (Barlow et al., 2001; Biondi et al., 2001; Bond and Harrison, 2000; Gedalof, 2002; Hare and Mantua, 2001; Hidalgo, 2004; MacDonald and Case, 2005; Mantua and Hare, 2002; Mantua et al., 1997; Sung et al., 2014; Whitfield et al., 2010), and the Northern Annular Mode (NAM) (which is expressed through the Arctic Oscillation or AO) (McAfee and Russell, 2008; Wallace and Thompson, 2002; Wang et al., 2006) are the primary drivers of North American hydroclimate variability on inter-annual to multidecadal timescales. These synoptic climate systems affect the strength and trajectory of the westerly winds and summer monsoonal air masses that deliver water vapor from the Pacific and Atlantic basins to the interior of North America. Other modes of ocean-atmosphere variability, such as the Pacific North American Pattern (Ge et al., 2009; Leathers and Palecki, 1992; Leathers et al., 1991; Lee et al., 2012; Liu et al., 2014, 2013, 2011; Minobe and Mantua, 1999; Trouet and Taylor, 2010), and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001; Feng et al., 2008; Hidalgo, 2004; Kim et al., 2004; McCabe et al., 2008, 2004; Mo et al., 2009), also influence climate in North America and are related to the aforementioned climate modes either directly or through global teleconnections. For example, various lines of research have revealed close relationships between ENSO and the PDO (Di Lorenzo et al., 2010; Newman et al., 2003; Verdon and Franks, 2006; Vimont, 2005) as well as connections between predominant climate modes in the Pacific and Atlantic basins (e.g., ENSO and AMO) (Alexander et al., 2002; Dong et al., 2006; Timmermann et al., 2007; Zhang and Delworth, 2007). Our current understanding of how these modes of variability influence western North America is based largely on analyses of historical observations, which typically span less than a century, and climate model simulations, which exhibit inter-model inconsistency both in terms of regional ENSO climatology and responses to external forcing (Diffenbaugh et al., 2006; Harrison et al., 2003, 2014; Schmidt et al., 2014; Shin et al., 2006). Investigations of paleoclimate change in ENSO sensitive regions expand our temporal perspective on terrestrial climate responses to internal and external forcing and provide a baseline for evaluating climate model hindcasts.

The oxygen isotopic composition of authigenic carbonate minerals (i.e., calcite and aragonite) in lacustrine sediments provides paleo-hydroclimate information on a wide range of timescales (from inter-annual to millennial) and therefore can be used to assess Holocene climate variability (Leng and Marshall, 2004; Talbot and Kelts, 1990; Talbot, 1990). This proxy is particularly informative as a drought/pluvial indicator in lake systems where the lake hydrologic budget is strongly influenced by shifts in precipitation-evaporation balance, and for which evaporation is a substantial component of total water loss (i.e., evaporation + outseepage) (Gat, 1995; Jones and Imbers, 2010; Shapley et al., 2008; Steinman and Abbott, 2013; Steinman et al., 2010a, 2010b). Most closed-basin lakes possess these traits and when located in a catchment with calcareous substrate often precipitate carbonate minerals from the water column (Kelts and Hsu, 1978; Koschel, 1997; Shapley et al., 2005), thereby providing an archive of lake water isotope variability in response to climate driven changes in hydrologic balance. In contrast, open-basin lakes are not substantially influenced by evaporation and instead have a water isotopic composition controlled by that of through-flowing, meteoric water. Carbonate mineral ($CaCO_3$) oxygen isotope records from open-basin lakes can therefore provide information on past changes in the isotopic composition of precipitation, which complements the paleoclimate perspective obtained from closed-basin sediment oxygen isotope records.

Given the many factors that influence lake water isotopic composition (e.g., climate variations, lake morphometry, and the groundwater through-flow rate), qualitative attempts to interpret sediment core oxygen isotope records may inadequately characterize lake responses to climate change (Jones et al., 2005; Leng and Marshall, 2004; Steinman and Abbott, 2013; Steinman et al., 2013, 2010b). To address this issue, lake hydrologic and isotope mass balance models can be used to provide a framework for interpretation that quantitatively accounts for the many influences on lake hydrology and isotope dynamics. Such models provide a robust approach to interpreting lake sediment isotope records and have been used to provide insight into potential climate states capable of producing measured sediment core geochemical values and inferred past lake levels (Anderson et al., 2007; Benson and Paillet, 2002; Benson et al., 1996; Jones and Imbers, 2010; Jones et al., 2007, 2005; Li and Morrill, 2013; Morrill et al., 2006; Phillips et al., 1994, 1986; Rowe and Dunbar, 2004; Shapley et al., 2008; Stansell et al., 2012; Steinman et al., 2013, 2012; Vassiljev, 1998a).

We present lake sediment oxygen isotope ($\delta^{18}O$) records of past precipitation-evaporation balance from Cleland Lake (closed-basin; southeastern British Columbia), Paradise Lake (closed-basin; central British Columbia) and Lime Lake (open-basin; eastern Washington) that span the last ~9000 years before present (yr BP) and provide insight into western North American climate system responses to ocean-atmosphere forcing on inter-annual to millennial timescales. To reconstruct hydroclimate variability at a high temporal resolution, we analyzed the isotopic composition of 2246 samples collected at ~1 mm resolution from the Cleland Lake sediment cores, and 651 samples (combined) from the Paradise and Lime lake cores. We support our interpretation of these records using sensitivity simulations conducted with a lake hydrologic and isotope mass balance model (based on that of Steinman et al., 2010b). The objective of the mass-balance model simulations is to determine the long-term hydrologic and isotopic sensitivity of Cleland and Paradise to seasonal temperature and precipitation changes. These analyses provide insight into the evolution of middle to late Holocene hydroclimate variability in the Pacific Northwest as well as variability in the constraining internal and external forcing mechanisms. We then compare the lake isotope series to other records of hydroclimatic change from the greater Pacific Northwest region (which we define as British Columbia, Washington, Oregon, northern Idaho, and western Montana) as well as ocean sediment, coral, and lake sediment based proxies of