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Key Points:
- Lake sediment isotope records exhibit coherent centennial timescale variability
- The Little Ice Age was dry in much of the Pacific Northwest
- Climate model simulations support drought patterns evinced by lake sediment data

Supporting Information:
- Text S1
- Tables S1–S4 and Figures S1–S10

Correspondence to:
B. A. Steinman,
bas56@psu.edu

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Ocean-atmosphere forcing of centennial hydroclimate variability in the Pacific Northwest

Byron A. Steinman[1], Mark B. Abbott[2], Michael E. Mann[3], Joseph D. Ortiz[4], Song Feng[5], David P. Pompeani[2], Nathan D. Stansell[6], Lesleigh Anderson[7], Bruce P. Finney[8], and Broxton W. Bird[9]

[1]Department of Meteorology and Earth and Environmental Systems Institute, Pennsylvania State University, University Park, Pennsylvania, USA, [2]Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, [3]Department of Meteorology and Earth and Environmental Systems Institute, Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA, [4]Department of Geology, Kent State University, Kent, Ohio, USA, [5]Department of Geosciences, University of Arkansas, Fayetteville, Arkansas, USA, [6]Department of Geology and Environmental Geosciences, Northern Illinois University, De Kalb, Illinois, USA, [7]U.S. Geological Survey, Denver Federal Center, Denver, Colorado, USA, [8]Department of Geosciences, Department of Biological Sciences, Idaho State University, Pocatello, Idaho, USA, [9]Department of Earth Sciences, Indiana University-Purdue University at Indianapolis, Indianapolis, Indiana, USA

Abstract Reconstructing centennial timescale hydroclimate variability during the late Holocene is critically important for understanding large-scale patterns of drought and their relationship with climate dynamics. We present sediment oxygen isotope records spanning the last two millennia from 10 lakes, as well as climate model simulations, indicating that the Little Ice Age was dry relative to the Medieval Climate Anomaly in much of the Pacific Northwest of North America. This pattern is consistent with observed associations between the El Niño–Southern Oscillation (ENSO), the Northern Annular Mode, and drought as well as with proxy-based reconstructions of Pacific and Atlantic ocean-atmosphere variations over the past 1000 years. The large amplitude of centennial variability indicated by the lake data suggests that regional hydroclimate is characterized by longer-term shifts in ENSO-like dynamics and that an improved understanding of the centennial timescale relationship between external forcing and drought is necessary for projecting future hydroclimatic conditions in western North America.

1. Introduction

The response of regional hydroclimate to external forcing is the subject of considerable scientific interest due to its potential impact on global water availability. Analyses of observational data [*Dettinger et al.*, 1998; *Wang et al.*, 2006; *Wise*, 2010] indicate that interannual- to decadal-scale drought patterns in the American West are largely controlled by the interplay of the El Niño–Southern Oscillation (ENSO) and the Northern Annular Mode (NAM) (Figures 1 and S1 in the supporting information), which climate models and paleoclimate proxy data suggest are affected by external forcing [*Cook et al.*, 2004; *Seager et al.*, 2008; *Graham et al.*, 2011]. The timing and magnitude of drought in much of the American West during the Little Ice Age (LIA) (defined by the Intergovernmental Panel on Climate Change as ~1450–1850 A.D.) and the Medieval Climate Anomaly (MCA) (defined as ~900–1300 A.D.) have been reconstructed using a variety of proxy data [e.g., *Cook et al.*, 2004, 2010; *Steinman et al.*, 2012], but significant questions remain about the magnitude, spatial coherence, and causes of drought in the greater Pacific Northwest, particularly on multidecadal to centennial timescales. It is likely, for example, that mean state hydroclimatic shifts lasting multiple centuries occurred in the past due to synoptic climate (e.g., ENSO/NAM) responses to external (i.e., solar and volcanic) forcing and that such shifts could occur in the future with profound socioeconomic implications. Investigating the temporal patterns and driving mechanisms of such lower frequency climate change is therefore of critical importance to the development of sustainable water resource management strategies. To this end, we analyze paleoclimate proxy data including 10 lake sediment oxygen isotope ($\delta^{18}O$) records [*Stevens et al.*, 2006; *Anderson et al.*, 2007; *Stevens and Dean*, 2008; *Shapley et al.*, 2009; *Nelson et al.*, 2011; *Steinman et al.*, 2012] and tree ring records [*Cook et al.*, 2004, 2010] from western North America as well as climate model simulation results (supporting information). The resulting synthesis of paleoclimate data provides insight into the influence of Pacific and Atlantic ocean-atmosphere variability and external forcing on decadal- to millennial-scale climate change.

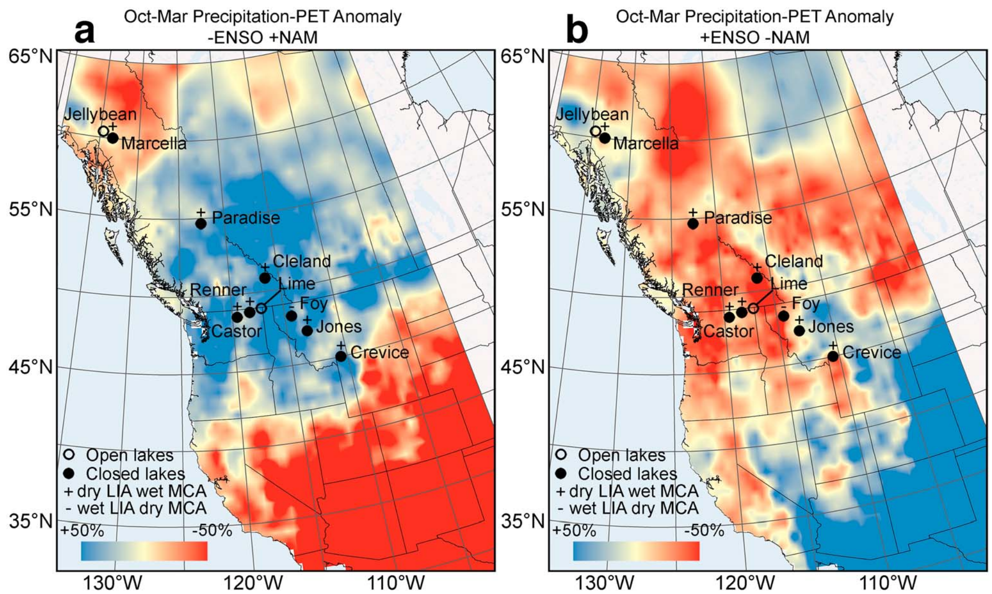

Figure 1. Average percent change in October–March precipitation minus PET (relative to total October–March precipitation) during (a) years of negative ENSO and positive NAM and (b) vice versa (supporting information). Plus (minus) signs represent a drier (wetter) LIA relative to the MCA in the lake isotope records.

2. Regional Climate

ENSO and the Pacific Decadal Oscillation (PDO) influence precipitation amounts and temperature in the Pacific Northwest by modifying the strength and position of the Aleutian Low and North Pacific high-pressure systems and the westerly winds that deliver water vapor to the continental interior in late fall and winter. Wet periods often occur during the negative phase of ENSO (i.e., La Niña, as defined by the Niño3/3.4 index) when the Aleutian Low weakens (or shifts to a more westerly position) and promotes a more northerly storm track, and vice versa [*Dettinger et al.*, 1998; *Wise*, 2010] (Figures 1 and S1). The NAM also influences climate in North America, with positive NAM phases characterized by a greater pressure difference between extratropical high- and low-pressure centers and a stronger midlatitude jet stream that produces more zonal westerly winds [*Wang et al.*, 2006]. Positive NAM phases often produce wetter conditions in the Pacific Northwest, with a stronger influence at higher latitudes. Precipitation patterns in this region (Figure S2) vary from north to south with the majority of rain/snowfall occurring during the warm season and cold season, respectively.

3. Methods and Results

To account for chronologic uncertainties, a Monte Carlo-based randomization method [*Marcott et al.*, 2013] was applied to the 10 lake sediment records (Figure S3 in the supporting information). One hundred individual age model realizations were produced for each record by randomly selecting dates from the 2σ uncertainty range of each age control point. To account for variability in the isotopic composition of precipitation, isotopic anomalies in the open lake (Jellybean and Lime) records were subtracted from proximal closed lake series (i.e., Marcella, Castor, and Renner) [*Anderson et al.*, 2007; *Steinman et al.*, 2012]. The resulting $\Delta\delta$ records (Castor-Lime, Renner-Lime, and Marcella-Jellybean) represent changes in the oxygen isotopic composition ($\delta^{18}O$) of lake water corrected for the influence of variability in $\delta^{18}O$ of precipitation. Each lake record realization was interpolated at a 10 year time step (the average sampling interval) (Table S1) and standardized by mean centering and dividing each mean-centered value by the standard deviation of the series (Figure 2). The standardized (*z* scores) series were then averaged to produce the regional records (i.e., Eastern and Western; Figures 2c and 2f). The 2σ uncertainty range for each stacked record is defined by the standard deviation of the 100 series at each time step. The Palmer Drought Severity Index (PDSI) data (Version 2a) from the grid points corresponding with each lake location

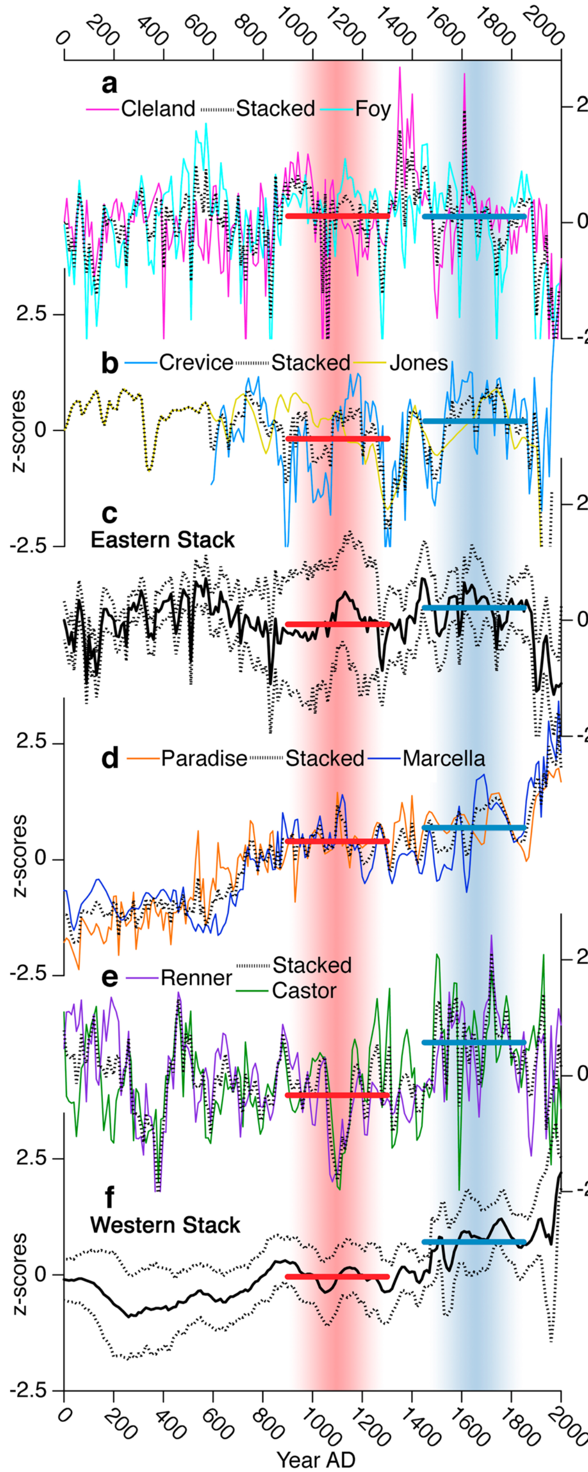

Figure 2. Sediment oxygen isotope *z* scores with independent age models (Figure S10) from (a) two of the northern sites in the Rocky Mountains (Cleland and Foy) [*Stevens et al.*, 2006], (b) two of the southern sites in the Rocky Mountains (Crevice and Jones) [*Stevens and Dean*, 2008; *Shapley et al.*, 2009], (c) Eastern stacked composite produced by averaging the standardized (*z* score) values of the Rocky Mountain data sets (excluding Jones because of limited age model control), (d) northern sites (Paradise and Marcella-Jellybean) [*Anderson et al.*, 2007], and (e) Washington sites (Renner-Lime and Castor-Lime) [*Nelson et al.*, 2011; *Steinman et al.*, 2012] plotted with (f) the Western stacked composite produced by averaging the standardized (*z* score) values of the northern and Washington data sets. Mean values from the MCA and LIA are shown by the red and blue bars, respectively. The dashed lines in Figures 2c and 2f represent the 2σ uncertainty range based on the assessment of age model uncertainty.

were standardized and averaged in the same manner but were not interpolated. *T* tests establish the significance of the difference between mean values from the LIA and MCA in each of the 100 realizations of the Eastern and Western Stacked series (Figure S4). We did not conduct *t* tests on the tree ring data because the difference between mean values from the MCA and LIA are negligible (e.g., the difference in the Western PDSI stack is <0.02).

Average *z* score values from the LIA are greater than values from the MCA in seven of the eight closed lake records (Figure 2), indicating drier conditions. The Washington lakes (Castor-Lime and Renner-Lime) exhibit the largest magnitude difference between the MCA and LIA, whereas the Rocky Mountain records (Cleland, Foy, Jones, and Crevice) exhibit the smallest difference between the two time periods. *T* test comparisons reveal that the difference between the mean LIA and MCA values in the Western *z* score composite (Figures 2 and S4) is significant ($p < 0.05$) and that the difference between the two time periods in the Eastern *z* score series is also likely significant (although with a larger uncertainty range during the MCA).

4. Discussion and Conclusions

Lake hydrologic and isotopic responses to climate change depend on lake size (e.g., volume and surface area) and the proportion of water lost though groundwater outflow, overflow, and evaporation. Hydrologically closed lakes lose the majority of water through evaporation and are more isotopically enriched relative to open lakes, which lose water primarily through nonfractionating outflows such as overflow and groundwater seepage. Closed lakes that lose all water through evaporation reach the limit of isotopic enrichment, and open lakes that lose no (or very little) water through evaporation maintain an isotopic composition similar to that of meteoric water [*Steinman and Abbott*, 2013]. Physical modeling studies of small, surficially closed lake systems at multidecadal resolution indicate that higher δ^{18}O values reflect lake isotopic responses to drier conditions, reduced groundwater inflow rates, and warmer temperatures [*Shapley et al*., 2009; *Steinman et al*., 2010; *Steinman et al*., 2012]. Lower δ^{18}O values result from the opposite set of conditions. Reddening of the isotopic signal in sediment from small lake systems (i.e., similar to those studied here) does not affect average isotopic values on multidecadal to centennial timescales due to short lake water residence times. In contrast, large lakes can exhibit a reddened isotopic response, due to much larger equilibration times, that leads to mean isotopic values that are not contemporaneous with hydroclimatic conditions [*Benson et al*., 2002]. Model simulations of the isotopic and hydrologic mass balance of Castor Lake demonstrate a strong isotopic sensitivity to winter (November–February) precipitation and lesser control by precipitation and temperature in all other seasons [*Steinman et al*., 2012]. Other model simulations indicate that low-frequency hydroclimatic variations produce water isotopic changes in groundwater throughflow lakes and that the seasonality of precipitation can also affect water and sediment isotopic composition [*Shapley et al*., 2009]. In general, modeling studies [e.g., *Shapley et al*., 2009; *Steinman et al*., 2010] indicate that lake sensitivity to seasonal climate forcing is dependent on the local climatic and hydrologic setting and that all lakes with considerable water loss through evaporation are sensitive to hydroclimate variability regardless of the season in which it occurs. On this basis, the large (greater than 0.5‰) differences between the LIA and MCA in several of the records (e.g., Castor, Marcella, and Crevice) (Figure S3) are thought to have occurred due to appreciable changes in net precipitation/evaporation balance [*Anderson et al*., 2007; *Steinman et al*., 2012].

Inferred colder temperatures during the LIA [*Galloway et al*., 2011] cannot explain higher isotope values in lake sediment from this time. This is because temperature decreases produce lower evapotranspiration rates and greater water availability, a scenario that leads to positive hydrologic fluxes, lower water and sediment δ^{18}O values and is therefore inconsistent with the lake records. Furthermore, subtracting the open lake isotope anomalies from the Castor, Renner, and Marcella records removed the influence of changes in the δ^{18}O of precipitation, as well as the effect of varying temperatures on equilibrium carbonate mineral fractionation, from the closed lake δ^{18}O series [*Anderson et al*., 2007; *Steinman et al*., 2012]. A possible limitation of the $\Delta\delta$ method is that open lakes could also exhibit isotopic responses to large hydroclimate anomalies that affect evaporation rates (e.g., exceptionally warm summers). However, the low magnitude of variability in the Lime and Jellybean records indicates that such responses either did not occur, or were short lived, over the past 2000 years. Thus, changes in net precipitation-evaporation balance are likely the principal control on closed lake hydrology and the corresponding sediment oxygen isotope values presented here.

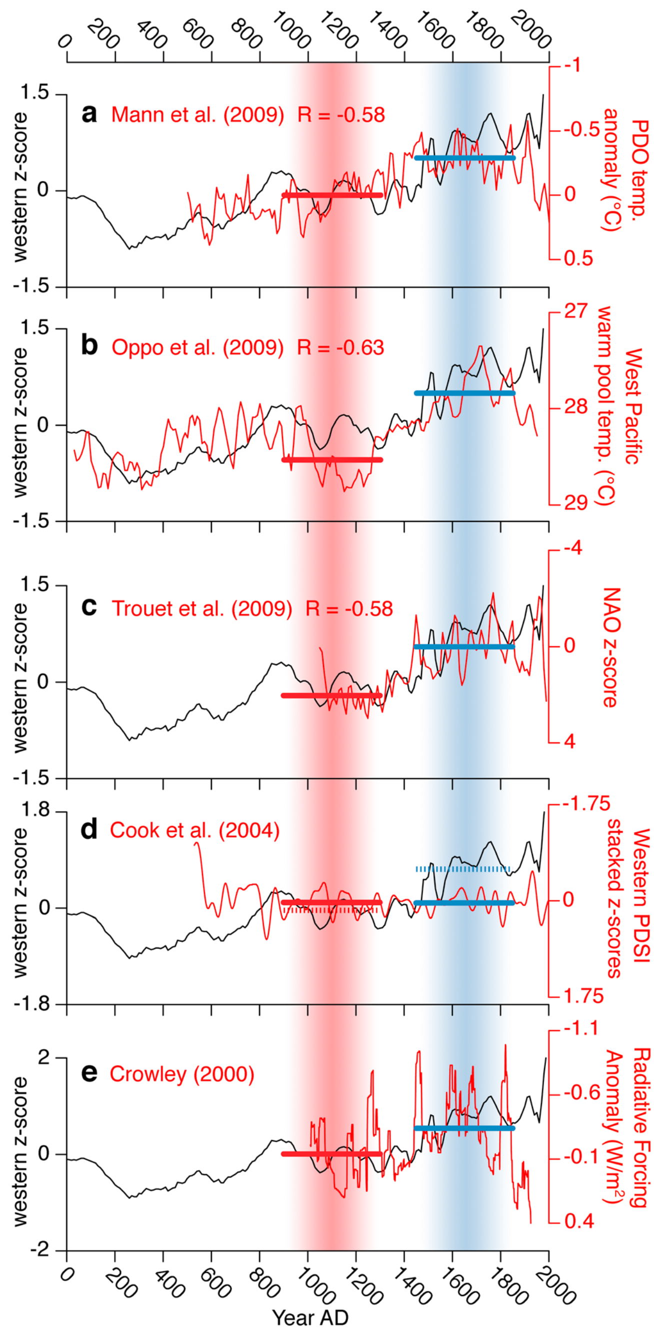

Figure 3. Western stacked (averaged *z* scores) lake sediment isotope record (Figure 2f) compared with (a) PDO temperature anomalies [*Mann et al*., 2009], (b) West Pacific warm pool temperatures [*Oppo et al*., 2009], (c) NAO *z* scores [*Trouet et al*., 2009], (d) composite PDSI reconstructions from the grid points corresponding with each western lake location [*Cook et al*., 2004] (Version 2a) (50 year low-pass filter), and (e) total radiative forcing anomalies [*Crowley*, 2000] (25 year moving average). PDO, West Pacific SST, and NAO data were interpolated at 10 year intervals. Correlations were calculated using 50 year moving averages of interpolated data. Mean values from the MCA and LIA are shown by the red and blue bars, respectively (lake isotope mean values in Figure 3d are dashed).

The composite lake sediment oxygen isotope data indicate that drier conditions prevailed during the LIA and that the MCA was relatively wetter (Figure 2). This implies that substantial variability occurred in the mean state of the Pacific ocean-atmosphere system on centennial timescales. This result is consistent with a multiproxy PDO reconstruction [*Mann et al*., 2009] that provides insight into North Pacific responses to low-frequency ENSO dynamics and signifies generally negative (cool phase) PDO conditions during and prior

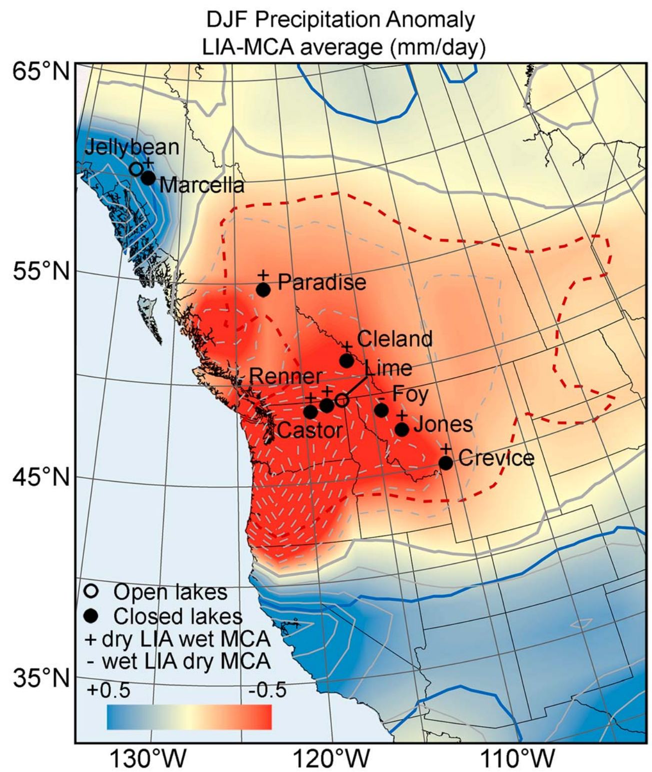

Figure 4. CAM results: the difference between simulated December–February precipitation anomalies (mm/d) forced by SSTs during the LIA (LIA_g) and MCA (MCA_g) (LIA average minus MCA average) (Table S2). The red and blue lines enclose regions where the precipitation differences are significant at the 95% confidence level by a two-tailed *t* test. Grey contours are spaced in 0.2 mm/d intervals. The thick contour line depicts a value of 0.

to the MCA and a more positive (warm phase) PDO thereafter (Figure 3). This PDO pattern is in turn consistent with inferred warmer (cooler) central and western Pacific Ocean temperatures resulting from a La Niña-like (El Niño-like) Pacific Ocean mean state. Tropical Pacific sea surface temperature (SST) reconstructions from the West Pacific warm pool and the Niño3.4 region support this assessment [*Cobb et al.*, 2003; *Oppo et al.*, 2009].

The lake isotope trend toward more positive values (i.e., drier conditions) during the past millennium is consistent with long-term trends in proxy records of Pacific and Atlantic ocean-atmosphere variability (Figure 3), suggesting that the observed interannual to decadal relationship between ENSO and winter precipitation-evaporation balance in the Pacific Northwest (Figure 1) operates on centennial timescales. The drying trend is evident in the lake sediment data until the past ~200 years when the Washington and Yukon records diverge (supporting information). Instrumental data indicate that winter precipitation-evaporation responses to ENSO/NAM in northwestern British Columbia and the southern Yukon are opposite to those of inland Washington and the Rocky Mountain sites. The similar LIA/MCA trend in the Marcella Lake data relative to those of the Washington records may therefore be due to large warm season hydroclimate anomalies (Figures 1 and S1). Shifts in mean tropical Pacific Ocean conditions may have resulted from more frequent and persistent El Niño and La Niña anomalies during the LIA and the MCA, respectively [*Li et al.*, 2011]. Given the dynamical connection between ENSO and the PDO [*Verdon and Franks*, 2006], such changes in ENSO frequency and/or magnitude likely affected average Pacific Northwest hydroclimate, particularly in the cold season when ENSO teleconnections are strongest [*Dettinger et al.*, 1998; *Wise*, 2010].

Experiments using the National Center for Atmospheric Research Community Atmosphere Model (CAM) support the hydroclimate patterns evinced by the lake data (supporting information). Two sets of experiments were conducted in which (i) global and (ii) tropical mean sea surface temperature anomalies from the MCA were used to force the model (Figure S5 and Table S2). The simulations reproduced reduced cold season precipitation during the LIA relative to the MCA in the Pacific

Northwest (Figures 4 and S6). Furthermore, the largest LIA precipitation anomalies are observed in Washington and decrease inland toward the Rocky Mountains and to the north, a pattern that is consistent with the lake $\delta^{18}O$ data. Additional similarities include a difference between LIA and modern precipitation amounts that is larger than the difference between mean MCA and modern precipitation and warm season precipitation anomalies during the MCA and LIA that are opposite in sign of the cold season anomalies (Figures S7 and S8). The use of global rather than tropical SSTs to force the model produced larger precipitation changes, but the spatial patterns of the two tests are largely consistent. This suggests that the tropical Pacific is the primary driver of North American precipitation anomalies in the model simulations.

Comparison of the low-frequency variability evident in lake sediment and tree ring based Palmer Drought Severity Index (PDSI) reconstructions reveals several disparities (Figures 3 and S9 and Table S3). Across all of the lake regions, average reconstructed PDSI values from the MCA and LIA are ±0.30 or well within the range (of ± 0.5) of near-normal conditions as defined by the PDSI. This implies that hydroclimate has not varied substantially on centennial timescales over the last 1000 years and is in stark contrast to the considerable centennial-scale hydroclimatic variations indicated by the composite lake sediment isotope records. This finding may be a result of different seasonal sensitivities of the lake and tree-ring proxies [*St. George et al.*, 2010; *St. George and Ault*, 2014] and the limited ability of some tree-ring records to capture climate variations on longer (multicentennial to millennial) timescales [*Esper et al.*, 2012]. It has been shown, for example, that in much of the Pacific Northwest, tree-ring growth is most strongly influenced by soil moisture content during the growing season [*St. George et al.*, 2010], whereas lake isotope values are strongly influenced by cold season precipitation [*Steinman et al.*, 2012].

Changes in extra-Pacific synoptic dynamics with different impacts on climate during different seasons could explain the disparity between the tree-ring and lake sediment records. For example, multiproxy data from the Atlantic basin indicate a weakening of the North Atlantic Oscillation (NAO) over the last two millennia (Figure 3) [*Trouet et al.*, 2009] (supporting information). Observational data indicate that when the NAM/NAO is in a positive phase (January–March average) and ENSO is in a negative phase (June–November average), warm season precipitation minus potential evapotranspiration (PET) amounts (at a lag of 10 months from the prior June) are smaller on average in the southern Pacific Northwest [*McAfee and Russell*, 2008] and greater in much of the northern Pacific Northwest (Figure S1). In the CAM simulations, warm season precipitation rates are higher during the LIA and lower during the MCA in much of western North America (a pattern opposite that of the cold season) (Figure S8). Such a hydroclimatic scenario of wetter winters with simultaneously drier summers, and vice versa, explains the apparent inconsistency between the two proxies in the Washington region, in which lakes are strongly influenced by October–March precipitation [*Steinman et al.*, 2012]. This could also explain why the lake isotope records from the Rocky Mountains, which are subject to larger summer precipitation anomalies (due to a larger proportion of annual precipitation occurring during summer), do not universally exhibit a large disparity between mean isotope values from the MCA and LIA. Nevertheless, the lake data indicate that perturbations in the mean state of the tropical Pacific forced larger century timescale hydroclimatic shifts in much of the Pacific Northwest than can be inferred from the tree-ring data.

Modeling [*Mann et al.*, 2005; *Graham et al.*, 2011] and proxy data [*Mann et al.*, 2009; *Marchitto et al.*, 2010; *Ersek et al.*, 2012] comparisons show links between mean tropical Pacific Ocean conditions and radiative forcing [*Crowley*, 2000] that provide insight into potential future responses of the ocean-atmosphere system to greenhouse gas forcing. Studies of proxy data sets including tree rings [*Cook et al.*, 2004, 2010] and speleothems [*Asmerom et al.*, 2007] suggest connections between inferred solar activity maxima, La Niña-like conditions in the tropical Pacific, and reduced water availability in the American Southwest. Lake sediment data from the Pacific Northwest reveal an opposite pattern in which centennial periods of lower solar activity correspond with dryness, and vice versa, similar to the north-south antiphased pattern of drought that occurs on annual to decadal timescales in response to ENSO (Figures 1 and 4). Proxy data therefore reveal a climatic response that is consistent with the hypothesized "ocean dynamical thermostat" mechanism in which increases in radiative forcing produce a cooling of the eastern tropical Pacific [*Mann et al.*, 2005, 2009; *Marchitto et al.*, 2010]. The large magnitude of centennial variability revealed by the lake sediment data implies that the climate system is characterized by longer-term shifts in ENSO-like dynamics and further that a better understanding of Pacific and Atlantic Ocean-atmosphere responses to external climate forcing is necessary for projecting future hydroclimatic conditions in western North America.

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