Millennial-to-centennial patterns and trends in the hydroclimate of North America over the past 2000 years

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Abstract. A synthesis of 93 hydrologic records from across North and Central America, and adjacent tropical and Arctic islands, reveals centennial to millennial trends in the regional hydroclimates of the Common Era (CE; past 2000 years). The hydrological records derive from materials stored in lakes, bogs, caves, and ice from extant glaciers, which have the 20 continuity through time to preserve low-frequency (>100 year) climate signals that may not be well represented by other shorter-lived archives, such as tree-ring chronologies. The most common pattern, represented in 46 (49%) of the records, indicates that the centuries before 1000 CE were drier than the centuries since that time. Principal components analysis indicates that millennial-scale trends represent the dominant pattern of variance in the southwest and northeast U.S., the mid-continent, Pacific Northwest, the Arctic, and the tropics, although not all records within a region show the same direction of 25 change. The Pacific Northwest, Greenland, and the southernmost tier of the tropical sites tended to dry toward present, as many other areas became wetter than before. Twenty-two records (24%) indicate that the Medieval period (800-1300 CE) was drier than the Little Ice Age (1400-1900 CE), but in many cases the difference was part of the longer millennial-scale trend, and, in 25 records (27%), the Medieval period represented a pluvial (wet) phase. Where quantitative records permitted a comparison, we found that centennial-scale fluctuations over the Common Era represented changes of 3-7% of the modern 30 inter-annual range of variability in precipitation, but the accumulation of these long-term trends over the entirety of the Holocene caused recent centuries to be significantly wetter, on average, than most of the past 11,000 years.

1 Introduction

Hydroclimate extremes characterize the Common Era (CE; the past two millennia) across North America (Cook et al., 2007; Woodhouse and Overpeck, 1998) and the Northern Hemisphere (Ljungqvist et al., 2016). The patterns of wet and dry conditions shifted at annual to multi-decadal scales (Fye et al., 2003; Pederson et al., 2011; Woodhouse et al., 2009), with

5 notable periods of "mega-drought," defined by severe moisture reductions lasting for multiple decades and covering large areas of the continent (Cook et al., 2004, 2010; Stahle et al., 2000). The Medieval period (800-1300 CE), in particular, included several decades-long droughts that have been widely analyzed to assess the underlying mechanisms (Coats et al., 2014; Cook et al., 2004; Herweijer et al., 2007; Meko, 2007; Routson et al., 2016a; Seager et al., 2007a), although earlier portions of the Common Era may have been at least as dry (Routson et al., 2011). Throughout this interval, the observed

10 hydroclimate changes had important consequences for people, landscapes, and ecosystems (Heusser et al., 2015; Jones and Schwitalla, 2008; Mason et al., 2004). As a result, the Common Era provides a useful baseline for considering future hydroclimatic changes and their impacts (Cook et al., 2015; Seager et al., 2007b).

Little is known, however, about the low-frequency trends that lasted for centuries or longer and slowly altered the hydroclimate of North America during the Common Era. Trends persisting for centuries to millennia were probably small

15 compared to inter-annual variability and may have fallen within the uncertainties of reconstructions at annual scales (e.g., a 0.01 mm/yr multi-century trend in effective precipitation at Mina Lake, Minnesota over the past >800 years; St. Jacques et al., 2008, 2015). However, small changes that are imperceptible at annual scales can substantially affect hydrologic baselines when they accumulate over time scales of >100 years, reaching magnitudes at millennial scales equivalent to historic droughts, such as the 1930s Dust Bowl (Shuman et al., 2010).

20 Tree-ring records have generated rich insight into annual to centennial-scale climate variability, but, with the exception of a small number of chronologies comprised of long-lived individual series, most do not thoroughly preserve evidence of low-frequency (>100 year) changes (Ault et al., 2013; Cook et al., 1995; Sheppard et al., 1997). Instead, materials that have accumulated in lakes, bogs and caves, and ice stored in extant glaciers, can be used to evaluate centennial or longer trends, even if they often lack annual-scale age control or resolution (Marlon et al., 2016). The strength of these

25 longer-lived archives resides in the continuous, multi-millennial time series that circumvent issues, such as those associated with the short individual series lengths inherent to most tree-ring records (Cook et al., 1995).

Here, we present a dataset of 93 records of hydroclimate change during the Common Era in North America, Central America, and the adjacent islands from the tropics to the Arctic (Fig. 1). All the records are published and span >1000 years. Many approach decadal-scale resolution, but they all have a mean resolution of at least one sample per century. The records

30 represent a wide range of different physical, biotic, and geochemical variables. Because they derive from multiple archives and measurable variables, they record different characteristics of local hydrological changes and yield a diverse matrix of information about factors ranging from lake levels and soil moisture to evaporation (Table 1). Annual precipitation has been inferred from 14 fossil pollen records (15% of the records), but most other records (58 or 62%) have been interpreted to

preserve evidence of changes in effective moisture (precipitation minus evaporation). Twenty-five records (27%) provide calibrated reconstructions of hydroclimatic variables (e.g., millimeters of precipitation), but most represent relative indices of hydrologic change. Therefore, to simplify treatment of this diverse data matrix, we discuss the patterns in the data in terms of relative changes from wet to dry conditions, broadly defined.

5   We use this dataset to identify the major trends, if any, that characterize the hydroclimate of North America over the past two millennia. Using data binned by century, we evaluate the patterns associated with commonly referenced periods, such as the Medieval Climate Anomaly (MCA) from 800–1300 CE (1150-650 BP) and the Little Ice Age (LIA) from 1400-1900 CE (550-50 BP), but we also describe other first-order hydroclimate trends represented by the data. In doing so, we assess evidence for major regional contrasts that may represent important circulation patterns or dynamics (e.g., Mock, 1996;

10   Shinker and Bartlein, 2010; Wise and Dannenberg, 2014), and, where possible, we consider the magnitude of Common Era trends in the context of the Holocene.

2. Data and Methods

2.1. Dataset

2.1.1 Overview

15   The 93 lake, bog, cave, and glacial records span nine different regions of North and Central America, Greenland, and the Caribbean islands, with variable spatial densities of sites among regions (Fig. 1, Table 1). Most of the records have been calibrated to a specific hydrologic variable, such as annual precipitation, lake or bog water depth, lake salinity, snow accumulation rate, or represent a geochemical index related to hydrology, such as oxygen and carbon stable isotope concentrations or other elemental ratios reflective of evaporative concentration of ions in soil or lake water. We have not

20   included any fossil datasets (e.g., pollen or diatom percentages) as only relative or qualitative indices, and only 9 out of 93 records represent relative indices based on sedimentological properties that record phenomena, such as runoff or dust deposition. In two cases, Deep Pond, Massachusetts and Castor Lake, Washington, we included two reconstructions based on different independent analyses or cores, but most sites are represented by a single time series. To focus on multi-century trends in the mean hydroclimate, we also have not included sedimentary records of extreme events, such as hurricanes or

25   floods (Donnelly et al., 2015; Munoz et al., 2015).

        We compiled the data from publically available sources and solicited additional published records from the original authors. Many of the records derive from NOAA's Paleoclimatology database (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets).

2.1.2. Lake datasets: biotic, geochemical, sedimentological

The vast majority of records (77%) come from lake sediments, which are available from all regions except the southern Plains and southeastern U.S. (Fig. 1, Table 1). These records represent a range of different approaches to hydrologic reconstruction. Fossil pollen data have been used to infer past precipitation changes, and we include published

5 reconstructions where they are site specific rather than regional averages (e.g., Gajewski, 1988). Likewise, we also include records of paleolimnological status inferred from transfer functions applied to fossil diatoms and other microfossil assemblages. These inferences include variables sensitive to moisture balance, such as water salinity and water depth (e.g., Laird et al., 1996; Schmieder et al., 2011).

In addition to the biotic records, we include sedimentological datasets, which typically are used to infer changes in

10 lake depth (Fig. 1). In some cases, the sedimentological data have been converted to quantitative estimates of lake level (e.g., Pribyl and Shuman, 2014), which, in a subset of these records, have been used to calculate changes in precipitation minus evaporation (e.g., Marsicek et al., 2013). In others, the data provide a relative index of lake status. In a few cases, lake sedimentology has also been used as a relative measure of precipitation-related run-off and aeolian activity (Dean, 1997; Kirby et al., 2010; Routson et al., 2016b).

15 Finally, we include geochemical records, focusing on the original authors' interpretation of the analyses. The geochemical records range from sulfur concentrations in lake sediments indicative of evaporative concentration and associated water-level change (Hodell et al., 2001) to Mg/Ca and oxygen isotope analyses of lake carbonates indicative of evaporative losses from the lakes (Tian et al., 2006; Yu and Ito, 1999). Oxygen isotope datasets from lakes also have been used to infer changes in precipitation seasonality or source (e.g., importance of the local snowpack versus direct

20 precipitation)(e.g., Anderson, 2011; Steinman et al., 2012). Other compounding factors also influence these records (Anderson et al., 2016; Steinman and Abbott, 2013), but most of the lake sediment isotope records have been used as relative indices of high versus low effective moisture. However, to focus on the patterns of local hydrologic changes, we excluded records thought to have been dominated by local temperature effects or large-scale circulation changes rather than their local hydrologic effects (e.g., Anderson et al., 2005).

2.1.3 Peat sequences

In raised ombrotrophic bogs in Minnesota, Michigan, Maine, and Quebec, variability in precipitation and evaporation changes the surface wetness of the bog and, thus, the water-table depth, which influences the community composition of testate amoebae (Booth, 2010). Like biotic indicators from lake sediments, testate amoebae leave identifiable remains, which

30 can be used along with extensive networks of modern samples to reconstruct past water-table depths (Booth, 2008). Water-table-depth reconstructions are often detrended to minimize the influence of autogenic bog processes and to emphasize decadal-to-centennial-scale events, attributable to climate rather than wetland evolution (Booth, 2010). Other evidence of

hydrologic change can be derived from peatlands, but only calibrated estimates of water table depth from testate amoebae records are included here.

2.1.4 Speleothems and other cave deposits

5 Sediments and carbonate speleothems from caves also preserve oxygen and carbon isotopes, and trace-element chemistry (Mg/Ca, Sr/Ca), which can be used to infer past hydroclimates. In our data compilation, we include eight of these records from Central America and scattered sites at latitudes <42° N in North America. Like oxygen isotopes from lake sediments, many different processes can affect these records, but we followed the interpretations of the original publications.

2.1.5 Glacier ice

We include four annual ice-layer-accumulation records from the Greenland ice sheet (Meese et al., 1994; Andersen et al., 2006). These cores were dated by counting annual layers as determined from visual stratigraphy, laser light scattering from dust, chemistry, and electrical conductivity, with cross-checking using known volcanic eruptions. These accumulation records were then corrected for densification and ice-layer thinning due to ice flow, and we use them as direct measure of

15 past precipitation.

2.2. Statistical Analyses

2.2.1 Binning, normalization and infilling

To compare the time series from these disparate sources, we averaged them into discrete bins and standardized them over the

20 Common Era. The bins were calculated for each record at 100-yr intervals, averaging all the points within each century. Binning emphasizes long trends and removes age-uncertain sub-centennial variations from each record. We standardized each binned record over the 2000-year interval of the Common Era, or the entire length of the record if shorter than the analysis period. To do so, we subtracted each record's mean and divided by its standard deviation to calculate z-scores. Bins with missing data were infilled for cluster and empirical orthogonal function and principal components (EOF/PCA) analyses

25 using singular spectrum analysis (SSA) to estimate the values of missing data (Ghil et al., 2002). Missing bins were infilled with SSA using a 5-bin (500yr) moving window. This methodology is well suited for filling gaps in bins with no observations.

2.2.2 Cluster analyses

Hierarchical cluster analysis (HCA) was used to organize the records into a binary tree that subdivides groups of records with similar temporal patterns (Bar-Joseph et al., 2001; Eisen et al., 1998). Cluster analysis has been widely applied in paleoecology to divide samples into stratigraphic zones (Grimm, 1987), but we use HCA to group paleoclimate datasets by

5   their dominant temporal patterns (e.g., Kaufman et al., 2016). The HCA and associated heat map was computed with the clustergram.m program in Matlab, using Euclidian pairwise distances between records for clustering and average linkages for the dendrogram. The composites were then generated by averaging the binned time series from each cluster. The 95% bootstrap confidence intervals on the composites were generated over 500 replicates of sampling-with-replacement from the records contributing to each cluster (Boos, 2003).

2.2.3 EOF/PCA

Principal component analysis (PCA) and empirical orthogonal function (EOF) analysis were used to characterize the dominant modes of variability in the North American hydroclimate dataset, as well as to characterize regional patterns of variability. The PCA was conducted on regional subsets of sites, based on regions represented by polygons in Figure 1, and

15   was applied using base functions in R (R Core Development Team, 2009).

2.2.4 Epoch difference and trend analyses

Epoch differences were used to map broad-scale changes in the hydrological interferences between time periods. We used this method to examine two pairs of time periods: 1) the MCA 800–1300 CE minus the LIA 1400-1900 CE, and 2) the

20   second millennium (1000-2000 CE) minus the first millennium (1-1000 CE). Additionally, we fit generalized linear models to records that have been calibrated to provide quantitative hydroclimate time series to determine the magnitude of trends over the Common Era. The models were fit to binned data while accounting for correlation in the error terms using a first-order autoregressive model in the nlme package in R (Pinheiro et al., 2017).

25 **3. Results**

3.1 Temporal patterns

A heat map shows the individual records and their departures from the mean of the Common Era (Fig. 2A). Cluster analyses of these data identify three major groups that differ in their long-term trends (Fig. 2B-D). The averaged time series of the records (n = 25) included in one of the clusters indicates wet conditions from 800-1500 CE (including during the MCA)

followed by drying to present (Fig. 2B). The wet phases at individual sites varied in time, but most often occurred from 800-1200 CE (blue in Fig. 2A, top). This cluster primarily includes sites in the Great Lakes region, the northeastern U.S., and adjacent areas (Fig. 2E). Because few data exist for some regions, such as the southeast U.S. (Fig. 1), the absence of any patterns may be a function of data availability.

5   A second cluster includes records (n = 22) that have weak or no long-term trends but that show evidence of drought from 900-1300 CE during the MCA (Fig. 2C). A sub-set of these data also indicates wet conditions early in the Common Era before 500 CE (Fig. 2A). Overall, the sites that comprise this cluster are broadly distributed. It includes the majority of records in the Arctic and boreal Canada, but these patterns are also characteristic of a few sites in western North America (Fig. 2F).

10   The third cluster includes sites with a prevailing trend from dry to wet over the Common Era (Fig. 2D). Excluding the detrended bog records, which by definition cannot capture millennial-scale changes, this cluster represents 53% (46 of 87 records) of our dataset. The 46 records include the majority of records in the northeast U.S., the mid-continent, the Rocky Mountains, and the Yucatan Peninsula, as well as along the western margin of North America (Fig. 2G).

15 **3.2 EOF results**

The pattern and interpretation of the first EOF is similar to that of the third cluster. It indicates that overall millennial-scale trends, particularly those amplified by a transition at ca. 900-1200 CE, explain the largest amount of coherent variance in the data (Fig. 3A-B). The first EOF loads positively and most strongly at sites in the northeast U.S., the western mid-continent, the western margin of North America, and the Yucatan Peninsula. It also loads negatively in many regions (Fig. 3A), but few

20 individual records show strong drying trends to present (Fig. 2A), and the weak or negative loadings appear to primarily indicate records with little or no trend. Proportionally, however, the variance explained by EOF 1 is small (29.4%).

The second EOF emphasizes contrasts between ca. 1000 CE and the last few centuries and accounts for 18.1% of variance in the data (Fig. 3C-D). Like clusters 1 and 2, EOF 2 highlights the Medieval-age anomalies in the records, but they neither dominate the variability within the dataset nor are they consistently of the same sign. The EOF loads negatively (dry

25 at ca. 1000 CE and wet today) across large areas of western and tropical North America, whereas positive loadings (wet at ca. 1000 CE and dry today) appear most commonly in the northeast U.S. and in Greenland, consistent with the pattern of sites that comprise cluster 1 (Fig. 2B).

The third EOF is the only other EOF to explain >10% of the variance (11.8% explained, Fig. 3E-F), and it highlights sites where the 19th and 20th centuries contrast with earlier periods (like the first cluster in Fig. 2A). It loads most

30 heavily and positively (dry today, wet LIA) in the northeast U.S., central Rocky Mountains, and Central America and has negative loadings (wet today, dry LIA) across northwestern North America from Washington to Alaska and Manitoba (Fig. 3E).

Overall, the total variance explained by the first three EOFs (59.3%) is slightly more than half, which indicates that no one pattern consistently dominates the dataset. Thus, more than half of the variance attributable to these dominant EOFs is associated with synoptic-scale trends (EOF 1), but nearly half of the total variation also can be attributed to site-specific changes and heterogeneity within regions (Fig. 2A).

3.3 Epoch differences

A map of the differences between the mean z-scores for the LIA (1400-1900 CE) and the MCA (800-1300 CE) highlights the extent of low-frequency drying during the MCA (Fig. 4A), which is not consistently the same as the patterns of individual annual to multi-decadal droughts during the same time (Herweijer et al., 2007). Red symbols on the map represent

10 a dry MCA: sites with higher z-scores (wetter) during the LIA than during the MCA. Reduced moisture during the MCA extended from southern California through the central Rocky Mountains to areas of the mid-continent (Fig. 4A). Dry conditions also affected the northeast U.S. and Yucatan, but the difference between 800-1300 CE and 1400-1900 CE at many sites simply reflects the millennial-scale wetting trend over the Common Era (Fig. 2D).

A map contrasting the first and second millennia CE (Fig. 4B) shares many features of the LIA-MCA difference

15 map and the patterns of EOF 1, which emphasize the long-term trends (Fig. 3A-B). Red symbols indicate where the first millennium CE was drier than the second, and blue symbols show the reverse (where the mean z-scores for the second millennium CE were higher, wetter, than those for the first millennium). A wetter first millennium CE was most prominent in the Pacific Northwest and in Central America (blue, Fig. 4B), whereas the first millennium was drier over portions of the Yucatan, California, the Rocky Mountains, the mid-continent, and the northeast U.S. (red, Fig. 4B).

3.4 Regional correlations and contrasts

Time series of first principal component (PC) scores, derived from the records within each region in Fig. 1, indicate that similar long-term changes affected multiple regions (Fig. 5). In particular, many regional PC scores represent large differences between the two millennia and show evidence of a rapid transition at ca. 1000 CE. These differences in time

25 explain about a third of the variance in most regions (27-41%, Fig. 5).

The regional scores are correlated (absolute magnitude of $r > 0.55$, $p \leq 0.01$), but in most cases, the correlations only represent long-term autocorrelated trends. Based on the maps (Fig. 4) and loadings, the changes represented by the correlated scores generally trended in the opposite direction in the Pacific Northwest, the Arctic and parts of the tropics compared to the other regions. The Pacific Northwest tended to become drier toward present as large portions of the

30 Southwest, northeast U.S., and the mid-continent became wetter than during the first millennium CE (Fig. 4B). Generalized least squares models including a first-order autoregressive term indicate that the PC scores only correlate significantly

between the Southwest and two other regions, the northeast U.S. (slope, β = 0.68±0.13, p = 0.0001) and the Pacific Northwest (β = 0.38±0.14, p = 0.0193).

3.5 Holocene context

5   A subset of Common Era records extends at least 6000 years into the Holocene and has a similar geographic distribution as the overall Common Era dataset. The Holocene records indicate that the dominant wetting trend over the past 2000 years began early in the Holocene (Fig. 6). Maps reveal that individual regions, such as portions of northwestern and tropical North America, did not always follow the mean pattern, but the Holocene-length records facilitate comparisons of the mean trends for both time scales (Fig. 6A). On average, the Holocene-long records (n = 36) show a long-term increase in

10   moisture leading to the Common Era (Fig. 6B). The period from 1000-1500 CE, specifically, was the wettest of the Holocene based on this set of data. By contrast, the average z-scores were 5 standard deviations below the mean of the Common Era during the early Holocene.

3.6 Magnitudes of change

15   Moisture-balance changes inferred from past lake levels, pollen-inferred annual precipitation, and ice accumulation rates provide constraints on the magnitudes of the low-frequency hydroclimate changes. Such data are not widespread, but, where they exist, they reveal the magnitude of the fluctuations described above (Fig. 7). Overall, the reconstructions indicate changes equivalent to net changes in precipitation on the order of 0-100 mm over the Common Era. Negative trends (red, Fig. 7A) are uncommon in this subset of the records and have smaller magnitudes than the positive trends (blue, Fig. 7A).

20   Consequently, the inferred rates of change before 1500 CE (before potential land use effects on the pollen records) equal -0.01 to +0.07 mm/yr (Fig. 7B).

In the northeast U.S., where the greatest density of quantitative records exists, the lake-level and pollen records indicate an increase in annual effective precipitation of 25-50 mm, about 2-5% of mean annual precipitation in the region today, since the early part of the first millennium CE (Gajewski, 1988; Marsicek et al., 2013; Newby et al., 2014). Trends

25   range from having magnitudes similar to those in northeast to no significant trends in pollen-inferred precipitation reconstructions from the Great Lakes region (Gajewski, 1988; St. Jacques et al., 2008). In the Rocky Mountains, lake-level reconstructions from Wyoming also indicate an increase of ~20 mm (4%) since 100 CE, when conditions were approximately as dry as during the MCA (Pribyl and Shuman, 2014). The changes in the northeast U.S. and Wyoming equal about 3-7% of the range of inter-annual variability in annual precipitation, as represented by climate division data since 1948

30   CE (NCDC, 1994). Trends in Greenland ice core accumulation rates have magnitudes near zero; the largest and most significant trend equals -0.005±0.002 mm/yr (p = 0.07) at GRIP (Andersen et al., 2006).

4. Discussion

4.1 Prominent low-frequency patterns

Multi-century fluctuations and trends appear to be important features of the hydroclimatic history of North America during the Common Era. The causes and consequences of these low-frequency (centennial to millennial scale) hydrologic changes

5   need to be considered as part of the full spectrum of changes during recent millennia, in addition to the annual to decadal variability that has been the focus of other syntheses of Common Era climate patterns (Ault et al., 2013). An overall trend from dry to wet dominates >50% of the records (Fig. 2) and is evident in the first EOF, which explains 29.4% of the variance in the available dataset of 93 records (Fig. 3A-B). Additional multi-century patterns, represented by clusters 1-2 and EOFs 2-3, also express coherence across sets of records and multiple regions and indicate that long wet periods were as frequently

10   recorded as prolonged dry intervals, such as the MCA (Fig. 2A-B). Overall, periods like the MCA were not unusual, because the hydroclimate fluctuations created periods that were both wetter and drier than present, although few centuries appear to have been as wet as the 20th century.

The spatial heterogeneity in the temporal patterns (Fig. 3-5) may represent real sub-regional complexity of hydroclimate, consistent with the variability associated with historic hydroclimatic changes (Cook et al., 2007; Dai et al.,

15   1998; Groisman and Easterling, 1994). Non-hydroclimatic influences on the proxy records and site-level factors also may explain much of the 40.7% of the variance unattributed to EOFs 1-3, and these influences are also likely embedded in the first three EOFs as well. Differences among archives, such as their sensitivities to annual versus seasonal hydroclimate, also may explain why Medieval drying from 900-1300 CE (1150-650 BP) can appear in one sub-set of records from a given region (Fig. 2C), while long trends from dry to wet dominate another sub-set from the same area (Fig. 2D). One potential

20   implication is that long-term trends (>100-1000 years) affected more of North America than is apparent from our dataset, but some archives (e.g., detrended bog records) do not preserve such signals. Some records may act as stringent low-pass filters (e.g., sedimentary records of lake-level change; Newby et al., 2014), but others may be better suited to recording discrete events (e.g., bogs in the northeast U.S.; Booth et al., 2006).

Furthermore, the climate signals were weak relative to our ability to reconstruct them. When considered over the

25   entire Holocene, the data show pronounced trends in hydroclimate that far exceed those of the Common Era (Fig. 6), but, at the scale of individual millennia or centuries such as those of the last 2000 years, the signal-to-noise ratio in many records may be relatively low. For example, independent lake-level and pollen-derived estimates of Common Era changes can correlate closely (Marlon et al., 2016; Marsicek et al., 2013), but the root mean squared error of pollen-inferred annual precipitation equals ~165 mm compared to trends of <50 mm over 2000 years (Fig. 7).

30   The small magnitudes of past hydroclimate fluctuations reveal, however, the unusual character of the changes taking place in some regions today. For example, in Massachusetts in the northeast U.S., multiple pollen and lake-level datasets indicate that effective annual precipitation increased by <50 mm over 2000 years or <0.025 mm/yr (Fig. 7B)(Marsicek et al., 2013). By comparison, annual precipitation in that area has increased by 2.7 mm/yr since 1948 CE

(NCDC, 1994; Pederson et al., 2013). More generally, annual precipitation increases of 13% over southern Canada and 4% over the U.S. during the 20th century (Groisman and Easterling, 1994) could represent at least an order-of-magnitude amplification of the regional trends of <5% during the entire Common Era (Fig. 7). Additional work is required, however, to thoroughly compare the magnitudes and rates of past and ongoing trends.

4.2 Medieval drying and low-frequency records

Our data confirm that during the MCA, average moisture decreased over large areas of North America (Fig. 2C, 6). However, at many sites, the MCA was drier than the LIA or other more recent periods, simply because of the long-term trend, such that earlier periods tended to be drier than later periods (e.g., cluster 3 in Fig. 2D; EOF 1, Fig. 3A-B). As a result,

10   the dry periods in the early portions of some dendroclimatic records that extend back <1000 years might capture only part of a trend that would have extended further back in time (e.g., Pederson et al., 2013).

The 25 records included in cluster 1 also indicate that unusually wet conditions characterized some regions during the MCA (Fig. 2A-B), which is consistent with several multi-decadal pluvials in dendroclimatic reconstructions in western North America (Routson et al., 2016a). Furthermore, long drying trends in regions, such as the Pacific Northwest, resulted in

15   a LIA that was drier than the MCA (Fig. 4-5). However, in the northeast U.S., where many records fall into cluster 1 (Fig. 2E), the pollen assemblages that provide much of the evidence for the inferred drying since the MCA are influenced by land use since ca. 1600 CE and should be interpreted cautiously (Fuller et al., 1998; Marsicek et al., 2013; St. Jacques et al., 2015; Webb et al., 1993). The importance of ragweed (*Ambrosia*) and other herb pollen in the upper portions of these records result in modern analogs that derive from drier prairie regions, which may explain why pollen-inferred precipitation

20   reconstructions deviate significantly from lake-level reconstructions (within cluster 3, Fig. 2D) only during the LIA (Marsicek et al., 2013). If so, the land-use effects on the pollen-derived reconstructions may artificially truncate multi-millennial moistening trends otherwise found in the northeast U.S. (Fig. 2G). Nonetheless, anomalously wet regional conditions during the MCA highlight the complex nature of hydroclimate during this interval in general.

25   ### 4.3 Differences between the first and second millennia

The long trends apparent in our dataset typically indicate that the mean state of the first and second millennia differed (Fig. 4B) and that low-frequency trends differed between regions (Fig. 5). These contrasts have parallels to those observed in instrumental and dendroclimatic data, particularly in the western U.S. where the Pacific Northwest and southwest U.S. often exhibit anti-phased moisture anomalies, because of factors, such as tropical and northern Pacific sea-surface temperatures,

30   which can influence the position of the jet stream (Dettinger et al., 1998; Routson et al., 2016a; Wise, 2010, 2016). The differences could indicate a tendency for storms to follow more southern tracks since 1000 CE than before, which resulted in

general drying of the Northwest, likely due to a reduction in precipitation rather than a negative evapotranspiration-driven effect from temperature (PAGES 2k Consortium, 2013; Trouet et al., 2013; Wahl et al., 2012).

Placed in the context of the Holocene (Fig. 6), the difference between moisture levels of the two millennia of the Common Era is modest and consistent with longer-term multi-millennial trends. Changes in global forcing, such as slow

5   changes in seasonal insolation and greenhouse gases, can explain many of the Holocene-scale trends (Shuman and Marsicek, 2016). Climate models run with mid-Holocene (4050 BCE or 6000 YBP) forcings simulate extensive drying, which must have been followed by moistening towards the present, because of dynamical responses of the atmosphere to seasonal insolation change, sea-surface conditions in the tropical Pacific and Atlantic, and surface-atmosphere feedbacks (Diffenbaugh et al., 2006; Harrison et al., 2003; Shin et al., 2006). Because of the responses to external forcing, the Common

10 Era and especially the second millennium CE stand out as the wettest periods of the Holocene over much of North America, despite the decadal "mega-droughts" that occasionally punctuated the persistence of the relatively wet conditions. Understanding how the multi-centennially trends, which are expressed weakly at annual scales, interacted with such extremes at decadal scales warrants further investigation.

5. Conclusions

15 Hydrologic reconstructions from across North and Central America, and adjacent islands, indicate that the hydroclimates of the first and second millennia CE differed significantly. Many regions, such as the northeast U.S., the mid-continent, the Rocky Mountains, the western margin of North America, and the northern Yucatan Peninsula experienced an overall wetting trend over the Common Era. Not all portions of North America experienced this trend, however, and the Pacific Northwest and the southern tropics, in particular, were characterized by drying toward present. In many areas, the changes continue

20 trends that persisted for millennia during the Holocene, and the patterns may indicate the continuation of long-term, low-frequency responses of Hadley circulation, the position and influence of the subtropical high systems, and the major westerly storm tracks to orbital and greenhouse gas forcing (Braconnot et al., 2007; Harrison et al., 2003).

The millennial-scale trends equal changes of <5% in annual precipitation over the Common Era and only 3-7% of the historic range of inter-annual precipitation variability. However, they represent trends that allowed the Common Era to

25 become the wettest portion of the Holocene in many areas. Multi-decade "mega-droughts" of the MCA were associated with low-frequency (>100-yr) departures from more recent wet conditions, but the low moisture levels of the MCA were commonly part of the long-term trends that made early periods drier than later portions of the Common Era. Now, however, increases in precipitation in many portions of North America have substantially accelerated the long-term trends.

Data availability:

(1) Input data used for the analysis: Upon publication, we will include data citations to the original data. If the data are not currently archived, then we will generate text files to archive in the NOAA Paleoclimatology database. The files contain the full data time series and important metadata.

(2) Output time series: Through the NOAA Paleoclimate database, we will also archive a spreadsheet with the 100-year binned raw data for each record and one with the standardized 100-year binned data, along with the regional averages. This will enable future users to try different standardization approaches and also to compare our composites with subsequent studies.

Author contributions:

All of the authors contributed to data compilation, study design, data interpretation, and manuscript preparation. NM, DK, and BS coordinated the workshops that facilitated the project. CR and NM processed the dataset and, with BS, conducted the final statistical analyses and generated figures and tables. BS led the manuscript writing.

15 **Competing Interests:**

The authors declare that they have no conflict of interest.

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Table 1. Hydroclimate record data including latitude (Lat), longitude (Long), and elevation (Elev). Records sensitive to annual precipitation (P) and effective moisture (P-E) are indicated as are records that have been calibrated to provide quantitative reconstructions (Cal). Sign refers to whether the variable has a positive or negative relationship to the hydroclimate inference (e.g., to effective moisture).

Site name	Political Unit	Lat	Long	Elev (m)	Archive	Variable	Sign	P	P-E	Cal	Reference
Abbott Lake	California	36.23	-121.48	286	lake	particle size	+				Hiner et al., 2016)
Basin Pond	Maine	44.46	-70.05	132	lake	pollen	+	X		X	Gajewski (1988)
Bat Cave	New Mexico	32.20	-104.40	1300	speleothem	$\delta^{13}C$	-		X		Asmerom et al. (2013)
Beaver Lake	Nebraska	42.46	-100.67	905	lake	diatom	+		X		Schmieder et al. (2011)
Berry Pond	Massachusetts	42.51	-73.32	631	lake	pollen	+	X		X	Marsicek et al. (2013)
Big Lake	British Columbia	51.67	-121.45	1030	lake	diatom	+		X		Cumming et al. (2002)
Bison Lake	Colorado	39.76	-107.35	3255	lake	$\delta^{18}O$	-				Anderson (2011)
Blood Pond	Massachusetts	42.08	-71.96	214	lake	pollen	+	X		X	Marsicek et al. (2013)
Buckeye Creek Cave	West Virginia	37.98	-80.40	600	speleothem	Sr/Ca	-				Springer et al. (2008)
Bufflehead Pond	Minnesota	44.99	-93.54	515	lake	stratigraphy	-		X		Shuman et al. (2009b)
Laguna de Felipe	Dominican Republic	18.80	-70.88	1005	lake	$\delta^{18}O$	-		X		Lane et al. (2009)
Castor Lake	Washington	48.54	-119.56	594	lake	reflectance	-		X		Nelson et al. (2011)
Castor Lake	Washington	48.54	-119.56	594	lake	$\delta^{18}O$	-		X		Steinman et al. (2012)
Chauvin Lake	Alberta	52.68	-110.10	625	lake	diatom	-		X		Laird et al. (2003)
Lake Chichancanab	Quintana Roo	19.83	-88.75	15	lake	sulphur	-		X		Hodell (1995)
Chilibrillo Cave	Panama	9.20	-79.70	60	speleothem	$\delta^{18}O$	-		X		Lachniet et al. (2004)
Clear Lake	New York	43.74	-74.20	587	lake	pollen	+	X		X	Gajewski (1988)
Coldwater Lake	North Dakota	46.01	-99.08	594	lake	diatom	-		X		Fritz et al. (2000)
Conroy Lake	Maine	46.29	-67.88	136	lake	pollen	+	X		X	Gajewski (1988)
Crevice Lake	Montana	45.00	-110.58	1713	lake	$\delta^{18}O$	-		X		Stevens and Dean (2008)
DYE3	Greenland	65.18	-43.83	2479	ice	accumulation	+	X		X	Andersen et al. (2006)
Davis Pond	Massachusetts	42.14	-73.41	214	lake	stratigraphy	-		X	X	Newby et al. (2011)
Deep Pond	Massachusetts	41.56	-70.64	23	lake	stratigraphy	-		X	X	Marsicek et al. (2013)
Deep Pond	Massachusetts	41.56	-70.64	23	lake	pollen	+	X		X	Marsicek et al. (2013)
Dixie Lake	Ontario	49.83	-93.95	398	lake	diatom	+		X		Laird et al. (2012)
ELA Lake 239	Ontario	49.67	-93.73	386	lake	diatom	+		X		Laird et al. (2012)
ELA Lake 442	Ontario	49.77	-93.82	411	lake	diatom	+		X		Laird et al. (2012)

East Lake	Nunavut	74.53	-109.32	5	lake	varve	+				Cuven et al. (2011)
Elk Lake	Minnesota	47.11	-95.13	457	lake	geochemical	-		X		Dean et al. (1994)
Lake Elsinore	California	33.67	-117.35	379	lake	particle size	+				Kirby et al. (2010)
Emerald Lake	Colorado	39.15	-106.41	3053	lake	stratigraphy	-		X		Shuman et al. (2014)
Fish Lake	Colorado	37.25	-106.68	3718	lake	composite	-				Routson et al. (2016b)
Foy Lake	Montana	48.17	-114.35	1006	lake	$\delta^{18}O$	-		X		Stevens et al. (2006)
Fresh Pond	Rhode Island	41.16	-71.58	28	lake	pollen	+	X		X	Marsicek et al. (2013)
GISP2	Greenland	72.60	-38.50	3209	ice	accumulation	+	X		X	Meese et al. (1994)
GRIP	Greenland	72.58	-37.64	3237	ice	accumulation	+	X		X	Andersen et al. (2006)
Gall Lake	Ontario	50.23	-91.45	365	lake	diatoms	+		X		Laird et al. (2012)
Lago El Gancho	Nicaragua	11.90	-85.92	44	lake	$\delta^{18}O$	-		X		Stansell et al. (2012)
Hells Kitchen Lake	Wisconsin	46.19	-89.70	502	lake	pollen	+	X		X	Gajewski (1988)
Hidden Lake	Colorado	40.51	-106.61	2708	lake	stratigraphy	-		X		Shuman et al. (2009a)
Humboldt Lake	Saskatchewan	52.13	-105.10	552	lake	diatom	-		X		Laird et al. (2003)
Irwin Smith Bog	Michigan	45.03	-83.62	223	bog	testate amoeba	-		X		Booth et al. (2012)
Jenning Cave	Florida	29.20	-82.20	30	cave	lipid $\delta^{13}C$	-				Polk et al. (2013)
Jones Lake	Montana	47.05	-113.14	1248	lake	$\delta^{18}O$	-		X		Steinman et al. (2012)
Juxtlahuaca Cave	Guerrero	17.40	-99.20	934	speleothem	$\delta^{18}O$	-				Lachniet et al. (2012)
Lac le Caron	Quebec	52.28	-75.83	248	bog	testate amoeba	+		X		Loisel and Garneau (2010)
Lake of the Woods	Wyoming	43.48	-109.89	2820	lake	stratigraphy	-		X	X	Pribyl and Shuman (2014)
Lime Lake	Washington	48.87	-117.34	780	lake	$\delta^{18}O$	+	X		X	Steinman et al. (2012)
Little Pond Royalston	Massachusetts	42.68	-72.19	302	lake	pollen	+	X		X	Marsicek et al. (2013)
Little Raleigh	Ontario	49.45	-91.89	457	lake	diatom	+		X		Laird et al. (2012)
Little Windy Hill	Wyoming	43.48	-109.89	2821	lake	stratigraphy	-		X	X	Pribyl and Shuman (2014)
Lower Bear Lake	California	34.25	-116.91	2059	lake	C/N	+				Kirby et al. (2012)
MB01	Nunavut	69.81	-112.08	290	lake	pollen	+	X		X	Peros and Gajewski (2008)
Marcella Lake	Yukon Territory	60.07	-133.81	749	lake	$\delta^{18}O$	-				Anderson et al. (2007)
Meekin Lake	Ontario	49.82	-94.77	353	lake	diatom	+		X		Laird et al. (2012)
Oro Lake	Saskatchewan	49.78	-105.33	686	lake	diatom	-		X		Michels et al. (2007)
Minden Bog	Michigan	43.61	-82.83	240	bog	testate amoeba	-		X		Booth et al. (2012)

Minnetonka Cave	Idaho	42.09	-111.52	2346.96	speleothem	$\delta^{13}C$	+			Lundeen et al. (2013)
Lake Miragoane	Nippes	18.40	-73.05	14	lake	$\delta^{18}O$	-		X	Hodell et al. (1991)
Moon Lake (ND	North Dakota	46.32	-98.16	444	lake	diatom	-		X	Laird et al. (1996)
N14	Greenland	59.98	-44.18	101	lake	BSi	+			Andresen et al. (2004)
NGRIP	Greenland	75.10	-42.32	2922	ice	accumulation	+	X		X	Andersen et al. (2006)
New Long Pond	Massachusetts	41.85	-70.68	29	lake	stratigraphy	-		X	X	Newby et al. (2009)
No Bottom Lake	Nantucket	41.29	-70.11	8	lake	pollen	+		X	X	Marsicek et al. (2013)
Nora Lake	Manitoba	50.47	-99.94	638	lake	diatom	-		X		Laird et al. (2003)
Lake Athabasca	Alberta	58.80	-110.71	213	lake	C/N	+			Wolfe et al. (2011)
Ongoke Lake	Alaska	59.25	-159.42	75	lake	diatom	+		X		Chipman et al. (2008)
Oregon Caves	Oregon	42.08	-123.42	1390	speleothem	$\delta^{13}C$	+			Ersek et al. (2012)
Path Lake	Nova Scotia	43.87	-64.93	15	lake	pollen	+	X		X	Neil et al. (2014)
Lake Peten-Itza	Peten	16.92	-89.83	110	lake	$\delta^{18}O$	-		X		Curtis et al. (1998)
Pinhook Lake	Indiana	41.61	-86.85	259	bog	testate amoeba	-		X		Booth et al. (2012)
Lake Punta Laguna	Yucatan	20.63	-87.62	14	lake	$\delta^{18}O$	-		X		Curtis et al. (1996)
Pyramid Lake	California	40.02	-119.56	1157	lake	$\delta^{18}O$	-		X		Benson et al. (2002)
Renner Lake	Washington	48.78	-118.19	754	lake	$\delta^{18}O$	-		X		Steinman et al. (2012)
Rice Lake	North Dakota	48.01	-101.53	620	lake	Mg/Ca	-		X		Yu and Ito (1999)
Rogers Lake	Connecticut	41.21	-72.17	12	lake	pollen	+	X		X	Marsicek et al. (2013)
Round Lake	North Dakota	48.42	-101.50	1064	lake	diatom	+		X		Schmieder et al. (2011)
SS1381	Greenland	67.01	-51.10	196	lake	mineral	+		X		Anderson et al. (2012)
SS16	Greenland	66.91	-50.46	477	lake	diatom	+		X		Perren et al. (2012)
Saco Bog	Maine	43.55	-70.46	45	bog	testate amoeba	-		X		Clifford and Booth (2013)
Sidney Bog	Maine	44.39	-69.78	91	bog	testate amoeba	-		X		Clifford and Booth (2013)
South Rhody Bog	Michigan	46.56	-86.07	290	bog	testate amoeba	-		X		Booth et al. (2012)
Steel Lake	Minnesota	46.97	-94.68	415	lake	$\delta^{18}O$	-		X		Tian et al. (2006)
Swan Lake	Nebraska	42.16	-99.03	702	lake	diatom	+		X		Schmieder et al. (2011)
Tzabnah Cave	Yucatan	20.75	-89.47	20	speleothem	$\delta^{18}O$	-		X		Medina-Elizalde et al. (2010)
Victoria Island	Nunavut	69.80	-112.06	290	lake	pollen	+	X		X	Peros and Gajewski (2008)
Lake Winnipeg	Manitoba	50.57	-96.83	217	lake	$\delta^{18}O$	-		X		Buhay et al. (2009)

Yellow Lake	Colorado	39.65	-107.35	3170	lake	$\delta^{18}O$	-		Anderson (2012)
Yok Balum Cave	Toledo	16.21	-89.07	366	speleothem	$\delta^{18}O$	-	X	Kennett et al. (2012)
Zaca Lake	California	34.78	-120.04	737	lake	particle size	+		Kirby et al. (2014)
Dune Lake	Alaska	64.42	-149.90	134	lake	$\delta^{13}C$	-	X	Finney et al. (2012)
Takahula Lake	Alaska	67.35	-153.67	275	lake	$\delta^{18}O$	-	X	Clegg and Hu (2010)
Wolverine Lake	Alaska	67.10	-158.91	85	lake	accumulation	-	X	Mann et al. (2002)
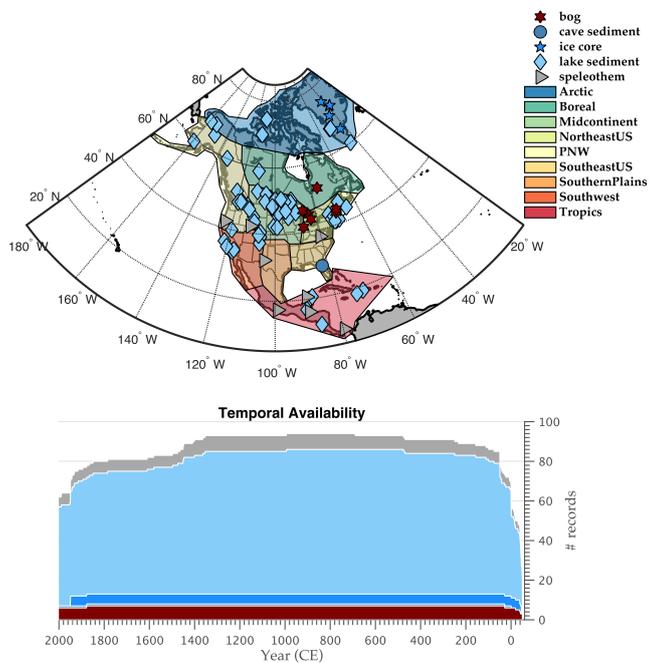
Figure 1: Temporal and spatial distribution of the North American paleo-hydroclimate records used in this study. Top: geographical distribution by archive type indicated by symbol colors and shapes. The differently colored areas on the map delimit the regions used for principal components analyses (e.g., PNW, Pacific Northwest). Bottom: The temporal distribution of records in the dataset. Colors correspond to the archive types in the map.
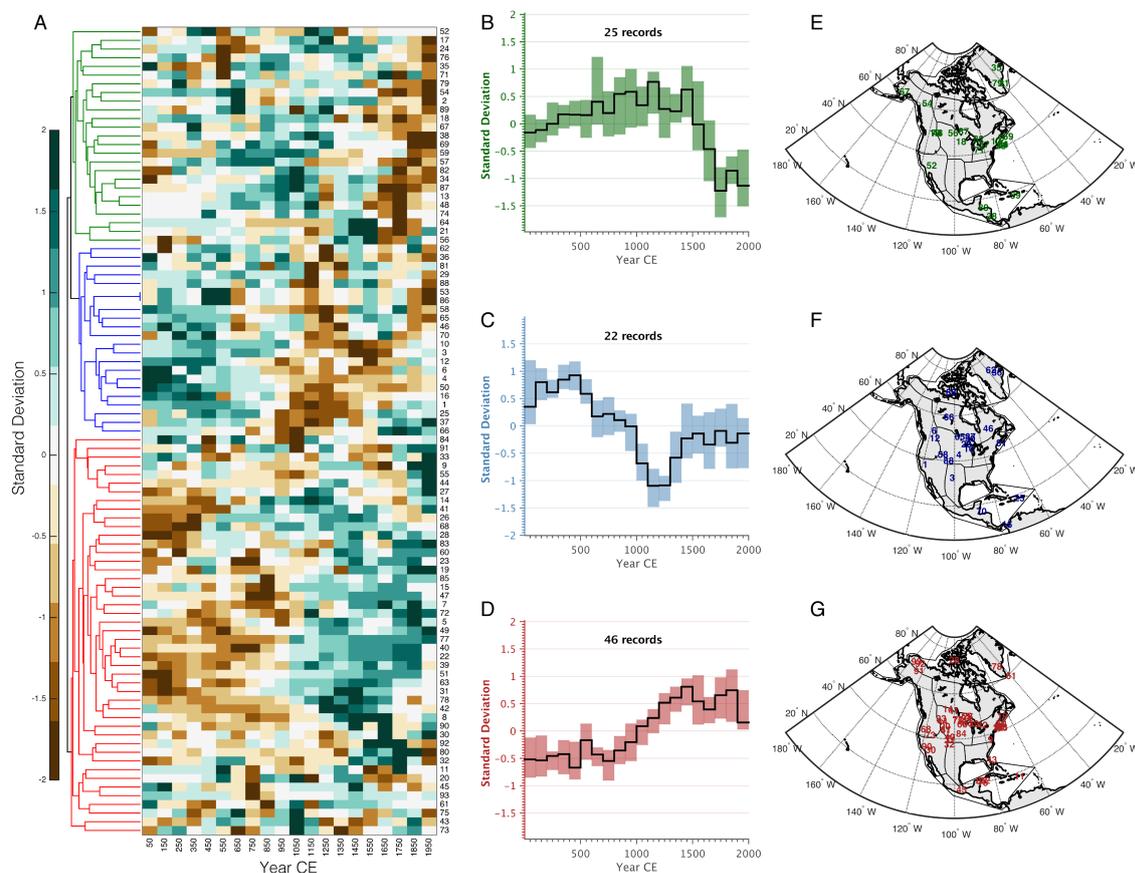
Figure 2: A) Heat map, cluster analysis, and dendrogram of the standardized hydroclimate records used in this study. The clustering shows the dominant groups of temporal patterns represented by the hydroclimate records. B-D) Average composites of the respective colored clusters in panel A. The shading shows the 95% bootstrap confidence intervals with 500 iterations. E-F) The spatial distribution of records in each cluster; numbers correspond with those in panel A.
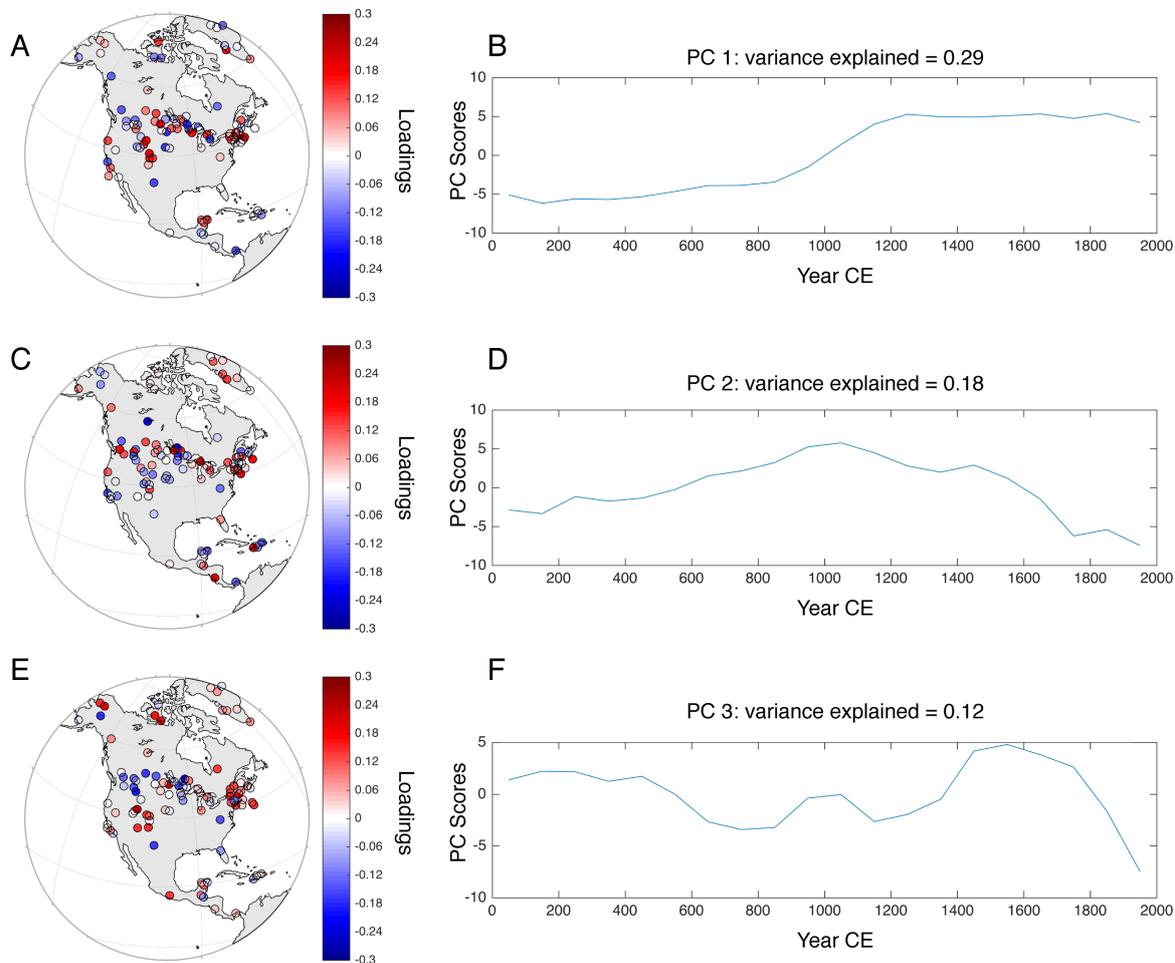
Figure 3: Results of empirical orthogonal function analysis (EOF) of the North American hydroclimate dataset showing (left) loadings associated with the first EOF, and (right) the average time series for each EOF.
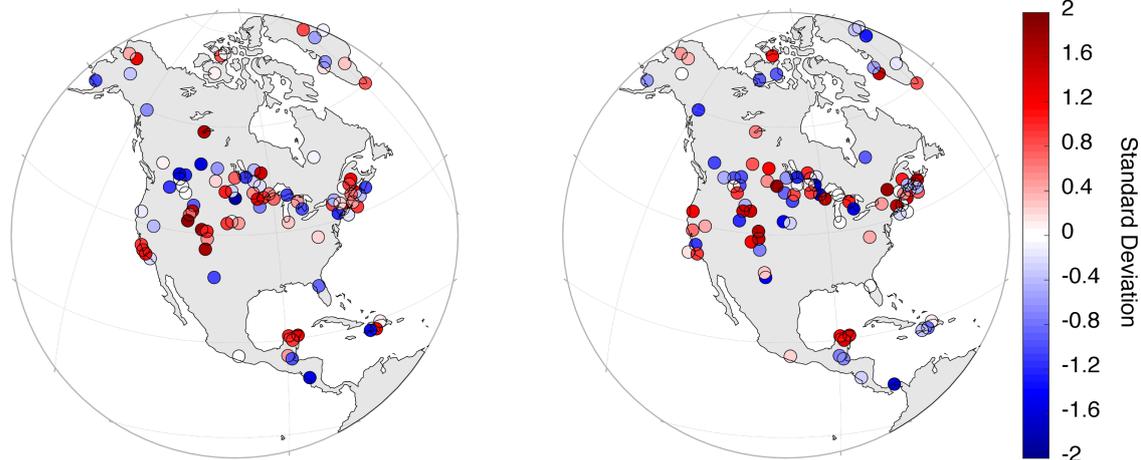
Figure 4: Epoch differences showing A) the average standardized value (SD) of the second millennium (1000-2000 CE) minus the average of the first millennium (0-1000 CE), and B) the average of the Little Ice Age (1400-1900 CE) minus the average of the medieval climate anomaly (800-1300 CE). Red symbols indicate that the older interval (epoch) was drier than the younger interval.
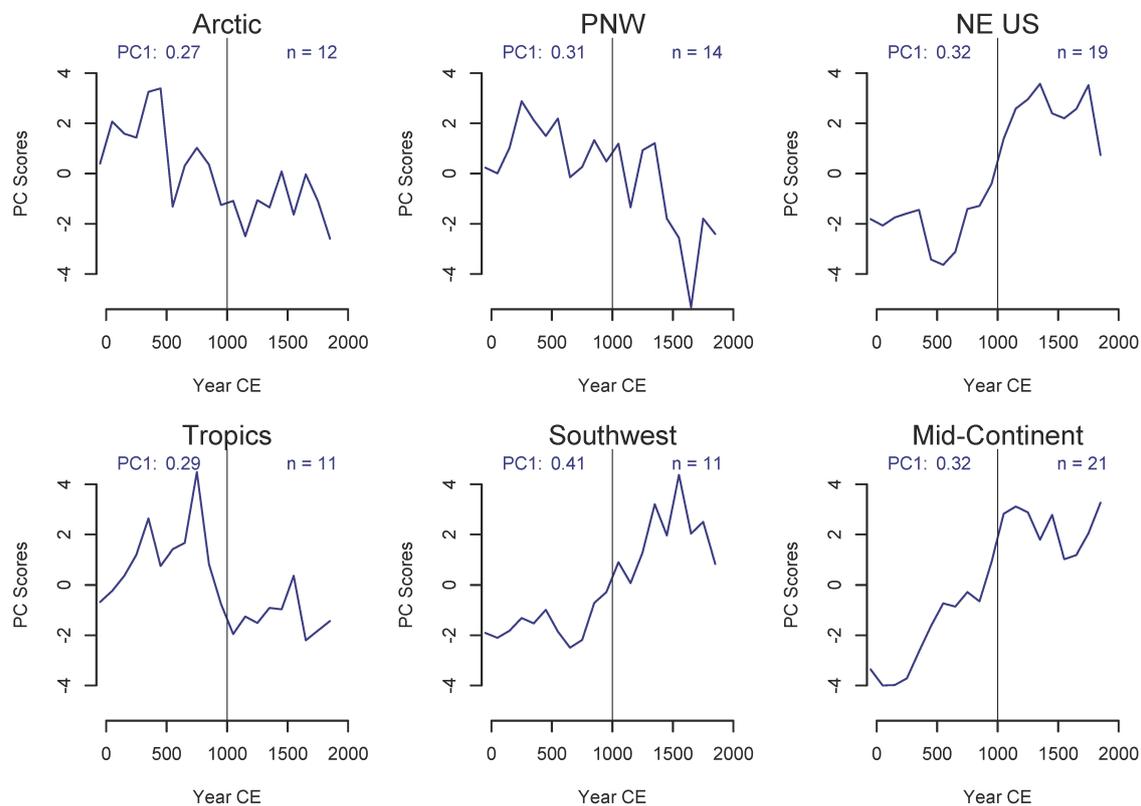
Figure 5: Regional principal components analysis (PCA) scores showing the dominant modes of variability in six North American hydroclimate regions delineated in Figure 1. Numbers on the left represent the fraction of the variance explained by PC1 in each region. Vertical lines mark 1000 CE.
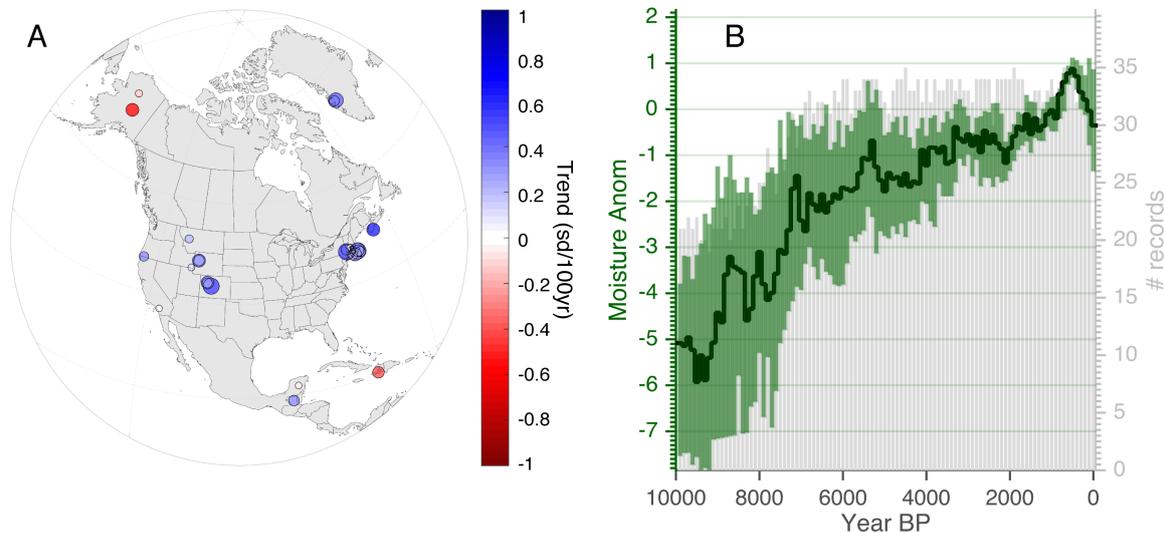
Figure 6: Holocene context including records that extend 6000 years or longer in the North American hydroclimate dataset. **A:** Maps of Holocene-length trends. Blue colors show wetting trends, red colors show drying trends and the size of the symbol reflects the magnitude of the trend. **B:** The median Holocene composite of the z-scores of the Common Era records (Fig. 1), with 95% bootstrapped confidence intervals. Units represent standard deviations from the mean of the Common Era. Grey bars show the number of available records through time.
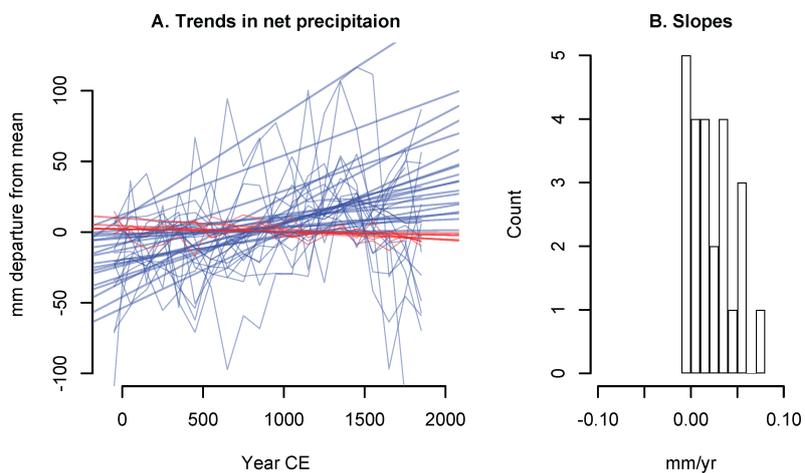
Figure 7: Time series and trends of all quantitative records presented as mm departures from their mean over the Common Era. Net precipitation is used here to include pollen-inferred annual precipitation, precipitation minus evapotranspiration changes estimated from lake levels, and ice core accumulation rates (calibrated records in Table 1). Blue time series indicate those with positive linear trends from 1-1500 CE; red time series have negative linear trends. Trend lines in A were fit using generalized linear models with a first-order autoregressive term. The slopes of the models appear as a histogram in B.