The Structure of Holocene Climate Change in Mid-Latitude North America

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14 **ABSTRACT (198 words)**

15 A sequence of long-term and rapid changes during the Holocene appears in a network of 40 well-
16 resolved paleoclimate datasets from mid-latitude North America, including records of pollen-inferred
17 temperatures, alkenone-derived sea-surface temperatures (SSTs), lake-level changes, dust
18 accumulation, and lake isotopes from Idaho to Maine. Statistical analyses reveal that changes in
19 insolation and the Laurentide Ice Sheet explain 51.7% of the variance in the records, especially multi-
20 millennial trends, but peak rates of change indicate additional rapid changes at ca. 10.8, 9.4, 8.3, 7.0,
21 5.5-5.2, 4.7, 2.1, and 0.9 ka. Step changes between 9.4 and 8.3 ka relate to ice sheet dynamics that
22 warmed much of the region, and changes at 5.5 ka were the largest since the demise of the ice sheet.
23 The shift at 5.5 ka initiated widespread cooling and increases in effective moisture, which culminated
24 in the coolest, wettest millennia in most areas after 2.1 ka. Replicated evidence from multiple records
25 also shows a spatially-varied set of multi-century fluctuations including 1) low temperatures and high
26 effective moisture at 5.5-4.8 ka in the mid-continent and 2) repeated phases of low SSTs, cool
27 summers, and drought superimposed upon long cooling, moistening trends in eastern North American
28 since 5.5 ka.

29

30

31 **1. INTRODUCTION**

32 Efforts to understand Holocene climate change have demonstrated the importance of insolation, ice
33 sheet, and greenhouse gas changes at multi-millennial scales (e.g., COHMAP, 1988; Kaufman et al.,
34 2004; Liu et al., 2014; Marcott et al., 2013; Renssen et al., 2009), but millennial-to-centennial
35 variations and events also shaped Holocene climates (Alley et al., 1997; Booth et al., 2005; deMenocal
36 et al., 2000; Fleitmann et al., 2008; Magny and Haas, 2004; Magny et al., 2006; Martin-Puertas et al.,
37 2012; Neff et al., 2001; van Geel et al., 2000). Changes composed smooth temporal trends when
38 averaged at global-to-continental scales (Marcott et al., 2013), but long waves in the westerlies

guarantee that many mid-latitude changes were expressed as mosaics of regional anomalies of different sign and magnitude (Donders et al., 2008; Morrill et al., 2013; Renssen et al., 2009) and with different multivariate characteristics (Morrill et al., 2013; Rach et al., 2014). Diagnosing the full spectrum of Holocene climate changes, therefore, requires comparisons of many complementary paleoclimate records (Mayewski et al., 2004; Wanner et al., 2011, 2008).

In mid-latitude North America, Holocene climate history differed from that of other regions because of a specific combination of long-term trends (e.g., Bartlein et al., 2011; Viau et al., 2006), regime shifts (Shuman et al., 2002; Williams et al., 2010), and variability at annual to multi-centennial scales (Booth et al., 2006; Grimm et al., 2011; Nelson et al., 2011; Newby et al., 2014; Nichols and Huang, 2012). Here, we attempt to integrate multiple temperature, moisture, and isotopic records to describe the most coherent and robust Holocene paleoclimate signals. We use a network of 40 records to document the relative sequence and covariance, i.e., the structure, of temperature and moisture trends, steps, and events from the Rocky Mountains to the Atlantic coast (Fig. 1). We define trends as progressive, multi-millennial changes; steps as non-reversing changes that took place within centuries; and events as temporary (reversing) fluctuations that lasted less than ~1000 years.

Individual datasets cannot detect all regionally-significant changes because any given change may be spatially heterogeneous and may not affect all sites (Cook and Krusic, 2004; Mann et al., 2009; Williams et al., 2010). Likewise, individual parameters (e.g., temperature or drought severity) cannot represent the full complexity of the climate history (Rach et al., 2014). For these reasons, we follow Alley's (2003) suggestion to use multiply-replicated, multi-parameter analyses as a way to improve reliability and confidence in the paleoclimate signals. We focus on four types of records that have been consistently measured at multiple locations and that can be readily interpreted as representing key climate variables. In particular, we use the multi-site, multi-record evidence to evaluate when and

64 where steps and events punctuated the well-documented long trends.

65

66 To do so, we produce regional and sub-regional averages (stacks) of 1) pollen- and alkenone-inferred
67 summer temperatures; 2) quantified lake-level changes; 3) relative dust accumulation rates; and 4)
68 lake-sediment isotopic values. We use the regional and sub-regional means of each data type to filter
69 local ecological, hydrological, or geochemical factors and to clarify common climate signals that
70 extend beyond individual sites. Correlations among variables further confirm where and when
71 important climate signals have been detected by multiple independent approaches. We calculate rates of
72 change and use principal components to identify common periods and patterns of changes. The relative
73 significance and sequences of change can help to diagnose the North American climate dynamics that
74 were important for ecological, geomorphic, and cultural changes during the Holocene (e.g., Foster et
75 al., 2006; Halfen and Johnson, 2013; Kelly et al., 2013; Munoz et al., 2011).

76

77 **2. METHODS**

78 **2.1 Data**

79 Our analysis uses a network of 40 records from 38 sites between the Rocky Mountains (Colorado,
80 Wyoming, Idaho) and the North Atlantic coast (including two marine records from off Virginia and
81 Nova Scotia). They represent the region influenced by Atlantic-derived moisture and air masses in mid-
82 latitude North America, and span the west-to-east North American moisture gradient (Bryson, 1966;
83 Liu et al., 2010). Annual temperatures vary little across the region today, but seasonal temperature
84 differences decline and annual precipitation increases from <400 mm to >1100 mm from west to east
85 (NCDC, 1994). Mean July temperatures do not vary systematically by longitude within the study area,
86 but range from 18°C at the northern sites to 24°C in the south (NCDC, 1994).

87

88 Most records were either generated by us or were publically available (Fig. 1; Table 1). Each was

required to have spanned from <0.6 to >10.0 ka for the purpose of consistent statistical power throughout the Holocene, and as a result, we excluded some relevant and well-resolved isotope datasets that did not extend to before 9 ka (e.g., Anderson, 2012; Smith et al., 2002). To evaluate sub-regional differences, we divided the datasets into four sub-regions: western (Colorado to North Dakota); west-central (South Dakota to Illinois); east-central (Ontario); and eastern (New York to Maine). Groupings were predominantly geographical, but were modified based on clusters of records identified using principal components analyses (see Section 2.2).

2.1.1. Temperature records

Of the 40 records, nineteen document changes in the mean temperature of the warmest month (MTWM). The MTWM records derive from well-resolved pollen-inferred reconstructions (>70 samples/11,000 years) from North Dakota to Maine (Table 1), and are supplemented by a temperature reconstruction based on two pollen records from northern Wyoming (Kelly et al., 2013; Shuman, 2012a) to extend the geographic coverage. We focus on regional averages of the reconstructions because they represent the common temperature signals and average out local ecological influences (e.g., local disturbances), but we also discuss where individual records either deviate from or provide support for the mean patterns.

The reconstructions were generated using a widely applied space-for-time substitution (modern analog) technique (Overpeck et al., 1985), which assigned temperatures to each fossil sample based on comparisons with >4000 modern pollen samples from across North America (Whitmore et al., 2005). We followed methodological suggestions from Williams and Shuman (2008) including a) averaging the MTWM values from the seven best modern analogs for each sample, b) using 64 regionally-split taxa for the comparisons, and c) applying the squared chord distance as the measure of comparison. We place the MTWM reconstructions in the context of other paleoenvironmental records to assess the

114 coherency of the climate signals and the nature of moisture and isotopic changes that coincided with
115 the regional temperature changes.

116

117 As an additional comparison and to further extend the geographic coverage of temperature records, we
118 also include two sea-surface temperature (SST) reconstructions derived from alkenone
119 paleothermometry from the margin of eastern mid-latitude North America (Sachs, 2007). We linearly
120 detrended (and evaluate the detrending of) the original temperature series, however, because the raw
121 SST reconstructions contain a large magnitude trend that indicates that late-Pleistocene (Younger
122 Dryas) temperatures were 5°C greater than today (Sachs, 2007) and that may have resulted from
123 nutrient, light, seasonality, or depth biases in alkenone production (Kim et al., 2004; Prahl et al., 2006).
124 At a minimum, the large trends were not likely representative of conditions on the continent where late-
125 Pleistocene cold is well documented (Levesque et al., 1997; Mott et al., 1986; Peteet et al., 1990), but
126 the additional variability may be relevant and is, therefore, evaluated here.

127

128 2.1.2. Moisture records

129 Nine records provide quantified estimates of Holocene lake-level changes. Several of the records from
130 closed basin lakes have been used with mass-balance approaches to quantify precipitation minus
131 evapotranspiration (P-E) through time (Marsicek et al., 2013; Newby et al., 2014; Pribyl and Shuman,
132 2014; Shuman et al., 2010), but P-E cannot be easily produced for overflowing lakes (i.e., Upper Big
133 Creek and Lower Paintrock Lakes in Colorado and Wyoming, Table 1) or for the two other effective
134 moisture records used here (relative dust accumulation rates from Elk and Steel Lakes, Minnesota).
135 Therefore, and because the P-E reconstructions are simply linear transformations of the lake-level
136 histories (Pribyl and Shuman, 2014), we transform all of the moisture records to z-scores. Z-scores
137 measure deviations from the Holocene mean of each record in terms of standard deviations, and
138 account for the different units in lake and dust records as well as the different magnitudes of water level

139 change in lakes and watersheds of different sizes.

140

141 The lake-level reconstructions all rely on the same technique (Digerfeldt, 1986; Pribyl and Shuman,
142 2014), which uses transects of sediment cores and on-shore sediment profiles (supplemented with
143 geophysical surveys) to track the elevation and lateral position of near-shore sediments as a direct
144 measure of shoreline position. At each lake, sediment characteristics from 2-5 radiocarbon-dated cores
145 from different water depths were systematically analyzed using a decision-tree approach applied in R
146 (R Core Development Team, 2009) to determine intervals containing near-shore sediments
147 (paleoshoreline deposits). Water-level changes were then reconstructed systematically in R based on
148 the changing elevations of the near-shore sediments at each site (Pribyl and Shuman, 2014).

149

150 The two lake-sediment mineralogy datasets from Minnesota (Dean, 1997; Nelson and Hu, 2008)
151 provide an index of aeolian dust accumulation based on the sediment fraction of fine quartz and
152 feldspars measured by x-ray diffraction (XRD). Aeolian dust accumulation likely reflects regional
153 aridity because low effective moisture (P-E) reduces vegetation cover and facilitates aeolian erosion
154 (Forman et al., 2001; Kohfeld and Harrison, 2000). Because dust flux can relate to aridity in a non-
155 linear fashion (e.g., potential dust-source areas may change exponentially in extent during drought) and
156 because the data are not normally distributed, we log transformed the XRD data for all plots and
157 analyses. Despite potential complexities, such as the role of winds and changing sources of fine
158 particulates (Mason et al., 2003; McKean et al., 2015; Muhs et al., 2008), we use the records because
159 they provide an opportunity to evaluate the fidelity of the signals in replicated records from the same
160 area. They also provide detailed information about the relative sequence of hydroclimate changes in a
161 sub-region without the type of quantitative lake level records used elsewhere.

162

163 2.1.3. Stable hydrogen and oxygen records

164 We compare the temperature and moisture records with seven stable hydrogen and oxygen isotope
165 datasets from lake sediments, which are distributed across our four sub-regions. Six stable isotope
166 datasets (Bear, Bison, O'Brien, Crawford, Fayetteville Green, and Grinnell lakes) represent the oxygen
167 isotope composition of bulk carbonate sediments (Anderson, 2011; Bright et al., 2006; Henne and Hu,
168 2010; Kirby et al., 2002; Yu et al., 1997; Zhao et al., 2010), whereas one (Berry Pond) represents the
169 hydrogen isotopic composition of C₂₂ *n*-acid, an organic compound primarily derived from emergent
170 aquatic plants (Hou et al., 2007; Shuman et al., 2006). Many interacting hemispheric to local scale
171 processes can influence individual lake-sediment stable isotopes (Gibson and Edwards, 2002; Gibson
172 et al., 2002; Henderson and Shuman, 2009; Jasechko et al., 2013; LeGrande and Schmidt, 2009;
173 Schlaepfer et al., 2014; Smith and Hollander, 1999; Steinman and Abbott, 2013), but networks of lakes
174 can retain important patterns related to climate and atmospheric circulation (e.g., Henderson and
175 Shuman, 2009; Shanahan et al., 2015). As with the other types of records, our comparisons reveal the
176 regional fidelity of the embedded signals.

177

178 **2.2 Analyses**

179 Regional and sub-regional mean temperature and moisture histories were calculated where multiple
180 records could be averaged. We plot standard errors to show the confidence in the mean patterns of
181 change, but also assessed the signals in combinations of records by also generating means for all
182 factorial combinations of the individual datasets. Doing so reveals the sensitivity of the mean record to
183 inclusion of any individual record and its particular age uncertainties, sample spacing, and
184 reconstruction errors. Likewise, we completed 100 bootstrapped iterations of principal components
185 analysis (PCA) in R to quantify the amount of variance common across 1) all datasets and 2) three
186 categories of data: temperature, effective moisture (lake-level and dust accumulation), and isotope
187 records. To do so, we randomly selected (with replacement) from the relevant pool of records to

188 generate 100 random combinations for PCA. We conducted the PCA on correlation matrices except
189 when analyzing temperatures alone. For temperature, the covariance matrix was used to retain the
190 magnitude of the signals in degrees C. We also used the PCA loadings to identify regional groups of
191 correlated datasets and to recognize outliers before calculating regional means of the different
192 variables.

193

194 We defined abrupt changes as times when the rates of change over 200 year intervals rose above 85%
195 of the background rates. We computed the rates of change in terms of the absolute change in z-scores
196 from the beginning to end of each 200-year interval. Mean rates were calculated for each data type, and
197 then a mean of the data-type means was used as a summary index to avoid biases associated with
198 differences in the number records of each data type. We focus on the periods of major abrupt changes
199 identified in the summary index, but also use peaks in the rates of change from the different types of
200 records, sub-regions, and principal components to identify periods of abrupt changes as expressed by
201 these other metrics. For this reason, we provide different ages for some changes depending on the
202 metric being discussed.

203

204 We also calculated correlations among records, regional and subregional means, and PCA scores to
205 assess the coherency of the signals. We applied linear regression and Granger causality tests in R to
206 further quantify the relationships. Linear models quantify the amount of variance in one time series that
207 can be explained by another or by important forcing functions (i.e., time series of insolation and glacial
208 extent)(Berger and Loutre, 1991; Dyke, 2004), but because autocorrelation within time series data can
209 produce spurious correlations, we use the Granger tests to evaluate whether a given predictor provides
210 more information than expected from autocorrelation alone (Granger, 1969).

211

212 To complete these analyses, all data were first interpolated to 50-yr time intervals in calendar years. We

used published age models for the isotope, dust, and SST records, but developed age models for temperature and lake level records using *Bchron*, a Bayesian tool for incorporating calibrated radiocarbon uncertainties and sample spacing into age models (Haslett and Parnell, 2008; Parnell et al., 2008). Doing so enabled us to include updated chronological information for some of the sites (Grimm et al., 2009).

3. RESULTS

3.1 Major patterns of temperature, moisture, and isotopic change

3.1.1. Mean regional changes

The record of regional mean temperatures (derived from pollen and alkenones) and effective moisture (from lake level and dust flux) confirms that the Holocene climate history of mid-latitude North America included a combination of long-term trends, abrupt shifts, and multi-century events (Fig. 2). Mean temperatures of the warmest month for the region rose progressively by $>1.5^{\circ}\text{C}$ to a maximum at 7 ka and have since declined by $>0.5^{\circ}\text{C}$ (Fig. 2A). Mean effective moisture levels across the region, however, have only recently achieved their maximum based on Holocene-scale changes in lake levels and dust flux of >1.5 sd (Fig. 2B).

Prominent accelerations of the long-term trends decreased temperatures and increased effective moisture at 5.5-4.7 and 2.1-1.8 ka (Fig. 2). The multi-century changes equaled about 50% of the magnitude of the long-term trends since 7 ka, but were $>140\%$ as rapid. The mean rate of change across all datasets exceeded 85% of the rates (0.26 sd/200 yrs) seven times: at 10.9-10.5, 9.4, 8.3, 5.5, 5.2, 4.7, and 0.9-0.6 ka (Fig. 3, top panel). During these intervals, abrupt century-scale shifts in temperature and effective moisture (vertical dashed lines, Fig. 2) punctuated the progressive background trends, which had a mean background rate of change of 0.18 ± 0.09 sd/200 yr.

238 Several of the rapid changes cluster in the early Holocene (Fig. 2-4). Effective moisture and
239 temperature increased rapidly by 10.5 ka, and then shifted stepwise at ca. 9.3-9.1 and 8.4-8.0 ka
240 respectively. Effective moisture declined stepwise at 9.3-9.1 ka by 0.2 sd/200 yr, which is more than
241 twice the mean background rate of lake-level change of 0.08 ± 0.07 sd/200 yr and especially prominent
242 in the median of the moisture records (thin black line, Fig. 2B). The step change initiated a new multi-
243 millennial mean that persisted until 6 ka (Fig. 2B). The second principal component of the moisture
244 records emphasizes that the shift represents part of a large moisture change from 9.3 to 7.4 ka (Fig.
245 4B). Temperatures experienced a similar stepwise increase of 0.2°C to a new multi-millennial mean at
246 8.4-8.0 ka (Fig. 2A). PCA confirms that temperature changes at 8.4-8.0 ka included both a cool event
247 (Fig. 4A, lower panel) and a step change (Fig. 4A, upper panel).

248 The most prominent interval of anomalously low temperatures developed at 5.5-4.7 ka after the
249 single largest and most coherent increase in effective moisture in the Holocene record (Fig. 2-4). The
250 largest change in the ensemble of stable isotope records also took place at this time (Fig. 4C); PC1 of
251 isotopic records contrasts the distribution of values before 5.2 ka with more recent values. PCA of the
252 temperature records indicates, however, that the net regional cooling at 5.5-4.7 ka may be a
253 combination of two different patterns: peak rates of cooling at many sites by 4.8 ka (Fig. 4A, top) as
254 well as a brief cool event when temperatures were $\sim 0.5^{\circ}\text{C}$ lower than the mid-Holocene mean for ca.
255 400 years from 5.2 to 4.8 ka (Fig. 4A, bottom). The highest mid-Holocene rates of mean regional
256 temperature change bracketed this later event (Fig. 3B), and median temperatures reached two minima
257 at 5.5-5.2 and 5.0-4.8 ka (thin black line, Fig 2A).

258

259 Warming combined with widespread drought at 4.7 ka to end the anomalously cool, wet conditions that
260 began after 5.5 ka (Fig. 2). Afterwards, mean regional temperatures changed little until 2.9 ka, except
261 for a minimum from 3.9-3.5 ka and a maximum at 3.0 ka; both events shifted the distribution of boot
262 strapped temperatures (gray lines, Fig. 2A). The extensive drought after 4.7 ka persisted until 4.0 ka

(with median moisture levels reaching a minimum from 4.2-3.9 ka), but the drought was followed by a progressive increase in effective moisture to present (Fig. 2B, 4B). Additional drought episodes at 3.6-3.3 and 3.0-2.4 ka had sufficient severity across records to also temporarily decrease the median and mean effective moisture z-scores relative to the long-term increase, but the events did not achieve the magnitude or extent of the aridity reconstructed at 4.7-4.0 ka (Fig. 2B).

Later shifts in both temperature (cooling) and effective moisture (increasing) at 2.6-1.8 ka represent a final acceleration of the long-term trends (Fig. 2, 4), although they were not sufficiently rapid or synchronous to produce major peaks in the mean rates of change (>0.25 sd/200 yrs; Fig. 3). The transitions resulted in the establishment of modern-like conditions for the remainder of the Holocene, except for a prominent warm, dry episode from 0.80-0.35 ka (1150-1600 AD).

3.1.2. Common signals across variables

The temperature and moisture datasets share a significant amount of signal at multi-millennial to multi-century scales despite deriving from different types of records and from different sites. Over the last 7 ka, the mean regional temperature and moisture time series (Fig. 2) correlate significantly ($r = -0.90$; 1 sd range = -0.53 to -0.95). Granger causality tests indicate that each series contributes significantly more to predicting the other than autocorrelation within either series alone (moisture as a predictor of temperature: $F = 10.86$, $p = 0.0013$; temperature as a predictor of moisture: $F = 2.96$, $p = 0.087$). Rates of change confirm that departures from the long trends often influenced multiple variables simultaneously, although they also confirm differences among the sequences of moisture and temperature changes.

PCA of the entire multivariate dataset reveals that all four data types contribute similarly to the first three components, which explain $>65\%$ of the variance in the data (Table 2). The first component

288 explains 34.9% of the variance (Fig. 5A), and the second explains an additional 21.0% (Fig. 5B).
289 Together, they reveal two major long-term patterns: PC1 correlates ($r = 0.83$) with orbitally driven
290 changes in seasonal insolation (red line, Fig. 5A) and PC2 correlates ($r = 0.91$) with the area of the
291 Laurentide Ice Sheet (blue line, Fig. 5B). Removing the insolation trend from PC1 produces residuals
292 that also correlate ($r = 0.97$) with the area of the ice sheet (gray line, Fig. 5B). Linear models show that
293 insolation and ice sheet area explain 69.0% and 29.2% of the variance in PC1 respectively; ice sheet
294 area explains 83.0% of PC2. Insolation and ice sheet area, therefore, explain at least 24.0% and 27.7%,
295 respectively, of the total variance in our spatially distributed, multivariate dataset.

296

297 PC1 and PC2 also show a series of common features at multi-century scales (Fig. 5C-D). Both
298 components show a stepwise deviation from the insolation and ice area trends at 9.3 ka, which was
299 progressively reversed over the course of the Holocene by a long trend and a series of rapid steps and
300 fluctuations of >0.5 sd at 8.4, 7.0, 5.3, and 2.1 ka.

301

302 **3.2. Sub-regional changes**

303 The major trends, abrupt changes, and multi-century events affected all of our sub-regions in different
304 ways (Fig. 6). In all of the sub-regions, temperature trends after 8 ka correlated significantly but
305 negatively with the moisture trends ($r = -0.58$ to -0.89). As mean regional temperatures declined,
306 effective moisture rose (Fig. 6). For example, correlations and Granger tests indicate that temperature
307 changes at Steel Lake, Minnesota (Fig. 6B, thin black line) usefully predict the effective moisture
308 trends inferred from dust changes there (Fig. 6B, middle row): $r = -0.52$; $F = 9.26$, $p = 0.0027$.

309

310 The independent datasets consistently reconstructed multiple multi-century events (e.g., a mid-
311 continental cold period at ca. 5.5-4.8 ka, Fig. 7), but the sequence of multi-century events and step
312 changes observed in the mean regional record (Fig. 2) does not represent a widely or consistently

313 expressed signal at sub-regional scales (Fig. 6). Rather, the events and steps in the mean record (Fig. 2)
314 often represent positive interference among sub-regional patterns with different, but overlapping,
315 periods of anomalous conditions. For example, cool events ($>0.4^{\circ}\text{C}$ and >200 yrs) interrupted the
316 warming before 8.0 ka at different times in different regions: a) in the west from 9.7-8.5 ka; b) at Steel
317 Lake and other west-central sites at 8.6-8.1 and 8.0-7.5 ka respectively; c) in Ontario at 9.3-8.9 ka; and
318 d) in SSTs at 9.5-9.1 ka (Fig. 6). Some of these events overlap in time and may only differ due to age
319 uncertainties, but others are potentially out of phase with each other (e.g., Fig. 6B). Despite the
320 differences, the data widely record a subsequent step change at 8.2-8.0 ka that produced near stationary
321 maximum temperatures until at least 6.8 ka in central and eastern areas (Fig. 6B-D).

322
323 In the eastern coastal region, the MTWM reconstruction correlates ($r = 0.77$) with the detrended SST
324 record (Fig. 6D). Both indicate warming of $1\text{-}2^{\circ}\text{C}$ with important, but different, multi-century
325 fluctuations before 7 ka. By contrast, the raw SST reconstructions, which retain a large linear trend
326 (Sachs, 2007), indicate that the early Holocene and Younger Dryas (YD) chronozone (12.7-11.7 ka)
327 were $>5^{\circ}\text{C}$ warmer than today, which is inconsistent with the magnitudes of the various isotopic
328 changes and with the pollen-inferred temperatures from all of the sub-regions (top, Fig. 6). In fact, the
329 southern tier of west-central sites from Pickerel Lake, SD to Chatsworth Bog, IL, were at least as cool
330 as today until after 4.8 ka even though Steel Lake, MN to the north warmed to higher than modern
331 temperatures after 8.2 ka (Fig. 6B). PC1 loadings indicate opposing directions of temperature change
332 (cooling versus warming since 7 ka) in northern (e.g., Mansell Pond, Maine; Scotian margin SSTs) and
333 southern reconstructions (e.g., Chatsworth Bog, Illinois) as well as a geographically crosscutting zone
334 with small trends (loadings <0.1) from North Dakota and southern Minnesota to Wisconsin and
335 southern Ontario (Table 2).

336
337 The directions of some major moisture changes also differed between western and eastern areas (Fig.

6). Lake levels from inland (Fig. 6C) and coastal Massachusetts (Fig. 6D) increased by >1 sd before 9.0 and 8.2 ka respectively, but moisture levels in the west rose to an early Holocene maximum by 10 ka and then rapidly declined to their lowest levels of the past 10 ka at 9.3 ka (Fig. 6A). Effective moisture also declined after an early Holocene maximum (>9.3 ka) in the west-central region based on short-lived peaks and attendant stepwise increases in dust deposition at 9.3 and 8.2 ka at Elk and Steel Lakes, MN (Fig. 6B, note inverted scale). The dust records only extend to <11 ka, but their mean correlates with the mean lake-level record from Wyoming over the common period of record ($r = -0.57$; Fig. 6B-C); Granger tests show that the mean dust record contributes significantly to predicting the Wyoming lake changes ($F = 5.25$, $p = 0.023$). Taken together the various records show that the east-west moisture gradient had been weaker than today before ca. 9 ka because effective moisture was low in the east and high in the west. The gradient then steepened as the west dried relative to the east by ca. 8 ka.

3.2.1 Mid-Holocene events

In the west (Fig. 6A) and coastal east (Fig. 6D), stepwise cooling of $>0.4^{\circ}\text{C}$ at 5.7-5.0 ka marked a permanent end to the period with maximum temperatures, which had ended in Ontario at 7.0-6.8 ka (Fig. 6C). Likewise, oxygen and hydrogen isotope values from Steel Lake, O'Brien Lake, Crawford Pond, Fayetteville Green Lake, and Berry Pond (Henne and Hu, 2010; Kirby et al., 2002; Nelson and Hu, 2008; Shuman et al., 2006; Yu et al., 1997) show rapid stepwise declines in delta values at ca. 5.5 ka (Fig. 4C). Because the changes are equivalent to a $>0.5\text{‰}$ change in $\delta^{18}\text{O}$, the shift would be consistent with cooling of $>0.35^{\circ}\text{C}$ based on the Dansgaard (1964) temperature- $\delta^{18}\text{O}$ relationship although numerous other factors almost certainly also influenced the isotope ratios. The shifts are synchronous within the current age uncertainties of each record (following Parnell et al., 2008).

362 In the central region, the change at 5.5 ka initiated a prominent millennial-scale fluctuation in
363 temperature and moisture (Fig. 7). A reduction in dust accumulation, and by inference an increase in
364 effective moisture, at Elk and Steel Lakes, Minnesota, from 5.6-4.8 ka coincided with a reduction in
365 pollen-inferred temperatures in the same region (Fig. 6B), particularly at Sharkey Lake, Lake West
366 Okoboji, and Chatsworth Bog (Fig. 7). Varve counts from Elk Lake indicate that the changes there
367 could have taken place within centuries or less at 5.49-5.39 and 4.81-4.54 varve ka.

368

369 The event from 5.6-4.8 ka also included hydroclimatic changes in the other sub-regions (Fig. 6). In the
370 Rocky Mountain west, a narrowing of the uncertainty around the mean lake-level series indicates a
371 coherent increase in moisture levels by >0.8 sd from 5.8 to 5.1 ka (Fig. 6A). Of all of the moisture
372 records examined here, only Davis Pond from the inland highlands of western Massachusetts did not
373 rise at this time (Fig. 6C), but it experienced a phase of anomalously low water constrained by similar
374 bracketing ages: 5.7-4.9 ka (Fig. 6C).

375

376 3.2.3 Late Holocene

377 Changes after 5.7 ka marked the beginning of cooling and moistening trends in many areas, which
378 persisted until present and were punctuated by a series of multi-century events (Fig. 6). In the coastal
379 east, multi-century moisture variations of the last >5.7 ka coincided with terrestrial and marine
380 temperature changes (Fig. 8). Warm/dry and cool/moist deviations from the long-term trends appear to
381 represent the dominant modes of variability. The warm, dry phases became progressively cooler and
382 wetter toward present, such that the most recent warm, dry periods (e.g., 1.3-1.2 ka) had absolute
383 temperatures and moisture levels equal to the earliest of the intervening cool, wet phases (e.g., 4.6-4.2
384 ka).

385

386 The SST and MTWM records skillfully predict the moisture trends based on a linear model of the mean

lake level changes (red line, Fig. 8; $p < 2.2 * 10^{-16}$, adjusted $R^2 = 0.84$). Granger tests spanning the period since 8 ka also show that mean SSTs and MTWM predict each other more than the autocorrelation in each series alone (SST as a predictor of MTWM: $F = 16.16$, $p = 0.00009$; MTWM as a predictor of SST: $F = 10.88$, $p = 0.00004$). The temperatures have a similar relationship to the lake level changes (e.g., MTWM as a predictor of lake level: $F = 5.2$, $p = 0.024$; lake level as a predictor of MTWM: $F = 7.97$, $p = 0.0054$). Consequently, the three different data types from nine different sites in the eastern sub-region contain a well-replicated signal of drought and warming at 4.9-4.6, 4.2-3.9, 2.9-2.1, and 1.3-1.2 ka.

Sharp cooling at 2.1-1.8 ka of 0.25-0.5°C coincided with a rapid rise in water levels (>0.25 sd), and produced the dominant climate of the Common Era (0-1950 AD). SSTs and MTWMs during the preceding 800 years (the “2.7-ka event” from 2.9-2.1 ka) as well as during a pair of cool, moist periods in the millennium from 3.9 to 2.9 ka were 0.2-0.4°C higher than during even the warmest portion of the Common Era (1.5-1.2 ka). Consequently, the Common Era represents the coolest and wettest portion of the last 9.3 ka in the coastal east (Fig. 8) and likely, in much of the study region except possibly in central areas such as Minnesota, Iowa, and Illinois (Fig. 6B).

4. DISCUSSION

4.1 Coherency of the records

Signals in our dataset confirm that the Holocene climate history of mid-latitude North America included a combination of coherent long-term trends (Fig. 5A-B); regime shifts at ca. 9.3, 8.0, 7.0, 5.3, and 2.1 ka (Fig. 5B-D); and multi-century events, such as at 8.3-8.0, 5.2-4.9, and 1.3-0.8 ka (Fig. 5C-D). Many of the trends, steps, and events affected both temperature and effective moisture patterns (Fig. 2, 6, 8), and despite some differences among records, were recorded repeatedly and independently by sediment stratigraphies, geochemical changes, and biotic assemblage changes. The shared signals

412 validate the robustness of many of the multi-millennial to multi-centennial features of the records.

413

414 Multi-century variability composes an important part of the spectrum of mid-latitude climate changes
415 (Fig. 8), but some events described in other studies, such as at ca. 4.2 and 2.7 ka (Booth et al., 2005;
416 Martin-Puertas et al., 2012; van Geel et al., 2000; Walker et al., 2012), do not consistently appear as
417 prominent features in our study region (Fig. 2, 4, 6). They may have been a) more important in other
418 parts of the world than mid-latitude North America, b) composed of complex multivariate signals, or c)
419 narrower in spatial extent than the largest events and abrupt changes detected by our rates of change
420 and principal component analyses (Figs. 3-5). Changes and events, such as at 5.6-4.8 ka, stand out
421 more prominently than these events in our sub-regions (e.g., Fig. 6), just as other well-studied events,
422 such as at ca. 8.2 ka (Alley et al., 1997) and 9.3 ka (Fleitmann et al., 2008), appear to have different
423 characteristics here than elsewhere (e.g., manifesting as more consistently as step changes rather than
424 events).

425

426 Common signals exist at low frequencies, in part, because all of the records act as low-pass filters on
427 the climate history via factors such as tree longevity, watershed-scale hydrologic response times, and
428 sediment mixing. None of the archives used here, however, have a substantially greater lag or bias
429 towards low frequency components than the others (e.g., alkenone-, pollen-, and sediment-derived
430 datasets in Fig. 8). Indeed, the comparability of the records reveals that even small climate changes,
431 such as temperature changes of $\sim 0.2^{\circ}\text{C}$, produced meaningful ecological changes that affected both
432 terrestrial vegetation and marine plankton (Fig. 8A-B), while also altering the sediment and
433 geochemical dynamics in small lakes and ponds (Fig. 8C).

434

435 The comparability of multiple records from within individual sub-regions (e.g., Figs. 7-8) indicates that
436 additional differences among sub-regions (Figs. 6) and variables (Fig. 3-4) likely represent underlying

climatic heterogeneity and structure much like that that exists during modern droughts or other variations. The records examined here differ most often, and contain poorly replicated features, at centennial and shorter scales where radiocarbon uncertainties, sample spacing, and reconstruction error may all be factors. However, by averaging across multiple records in each sub-region, we have reduced the random sources of error and the remaining disparities will require more detailed analyses to diagnose.

4.2 Uncertainties and sources of error

Some important differences among records probably arose from non-climatic factors. For example, raw (not detrended) alkenone-based SST reconstructions indicate, and may faithfully capture, a substantial background cooling trend of $>5^{\circ}\text{C}$ in the western Atlantic during the Holocene (Sachs, 2007), but our MTWM reconstructions only correlate well with the SST records once the SSTs have been linearly detrended (Fig. 6D). Both the MTWM and SST reconstructions indicate maximum warmth relative to any background trend from ca. 8-5 ka, which is consistent with macrofossil evidence that tree species in the northeastern U.S. grew at higher elevations at the time than today (Jackson and Whitehead, 1991; Shuman et al., 2004; Spear et al., 1994). In contrast, greater than modern temperatures in the raw SST records during the YD, just prior to the start of a large magnitude Holocene cooling trend (Sachs, 2007), differ from terrestrial inferences about the YD drawn from pollen, chironomid, lake productivity, and stable isotope data from the Atlantic coast of North America (Hou et al., 2007; Levesque et al., 1997; Peteet et al., 1990). Other paleoceanographic records also do not confirm the magnitude of the subsequent Holocene cooling (Kim et al., 2007, 2004; Solignac et al., 2004; Thornalley et al., 2009). Consequently, a linear or similar trend in the raw SST reconstructions may have been generated by nutrients or other factors (Prah et al., 2006) or may represent a temperature trend unique to the region of the Labrador Current (Sachs, 2007). Only the superimposed variability correlates with other regional records (Fig. 6D, 8). If the detrended SST signal (Fig. 6D) is the most

climatically meaningful component of the record, then mean Holocene temperature reconstructions that incorporate the raw SST reconstructions (i.e., Marcott et al., 2013) may be artificially too high in the early Holocene (Liu et al., 2014).

The different long-term trends in the MTWM and raw SST records do not reflect a lag or similar bias in the pollen data, because such biases would have delayed, dampened, or removed the signal of the abrupt changes and multi-century events (Webb III, 1986), which we have identified as a replicated component of the dataset. The same multi-century events in the pollen-inferred data appear in the SST and lake-level reconstructions (Fig. 8); pollen-inferred precipitation changes from these sites also show a strong coherence with the lake-level reconstructions (Marsicek et al., 2013). Correlations among variables in the modern pollen analog dataset (e.g., MTWM with winter temperatures or annual precipitation; Williams and Shuman, 2008), however, may have produced other erroneous trends in our records, especially if winter temperature or effective moisture signals were erroneously translated to the summer temperature reconstructions (Telford and Birks, 2005; Williams and Shuman, 2008).

4.3 Insolation and ice sheet effects

As many studies have suggested for the past several decades, the most robust long-term features and abrupt changes in the regional record (Fig. 2) can be directly attributed to the effects of insolation and the Laurentide Ice Sheet (Fig. 5). Long-term temperature trends conform with expectations derived from climate model simulations, which show that the albedo, topography, and freshwater flux changes associated with the remnant Laurentide Ice Sheet could have kept many regions cool in the early Holocene by altering regional energy budgets and synoptic circulation patterns (Alder and Hostetler, 2015; Liu et al., 2014; Renssen et al., 2009). As a result, peak Holocene temperatures, particularly during the warmest months, were not achieved in most sub-regions until 7 ka when the thermal effects of summer insolation anomalies dominated (compare Fig. 2A with results from Liu et al., 2014).

487

488 Short-lived temperature, moisture, and isotopic events between ca. 9.5 and 8.0 ka (Fig. 4-6) may
489 represent part of the North American expression of hemispheric cool events at ca. 9.3 and 8.2 ka (Alley
490 et al., 1997; Fleitmann et al., 2008; Morrill et al., 2013), which were associated with glacial meltwater
491 floods and routing changes driven by ice sheet dynamics (Barber et al., 1999; Yu et al., 2010). The
492 events appear to be less significant and more spatially variable in North America than coincident
493 climatic step changes (Fig. 4-6), which probably represent the consequences of rapid, non-reversing
494 changes in ice sheet height and extent (Dyke, 2004; Shuman et al., 2002; Williams et al., 2010). Similar
495 step changes have been documented at these times in other regions as well (Adkins et al., 2006), but
496 their importance in North America relative to the cold events conforms with expectations that
497 meltwater-related changes in North Atlantic circulation would have produced events centered
498 downwind of the North Atlantic (LeGrande and Schmidt, 2008; Wagner et al., 2013), while non-
499 reversing changes in the height and area of the ice sheet likely produced climatic changes centered on
500 North America (Alder and Hostetler, 2015; Felzer et al., 1996; Pausata et al., 2011).

501

502 **4.4 Additional multi-century variability**

503 The repeated multi-century warm/dry events indicated by SST-, MTWM-, and lake-level records in the
504 east over the past 8 ka also represent a robust aspect of the Holocene record (Fig. 8), but their spatial
505 extent and the character of similar multi-century variability in other regions requires more study.
506 Similar variability appears in other datasets (Fig. 6), but outside of the east, few opportunities currently
507 exist to develop a similar multi-site, multi-parameter evaluation of the signals. One exception is the
508 cold event in the mid-continent (Fig. 7) that coincided with reduced dust deposition in Minnesota at ca.
509 5.6-4.8 ka (Fig. 6B).

510

511 **4.5 Changes at ca. 5.5 ka**

512 The most prominent deviations from the long-term temperature and moisture trends since 7 ka took
513 place at 5.6-4.8 ka (Fig. 2). Stepwise transitions at ca. 5.7-5.2 ka, particularly in effective moisture,
514 terminated extensive mid-continent aridity and the “Holocene thermal maximum” across much of our
515 study region (Fig. 6). They, thus, widely reversed the effects produced by the decay of the ice sheet and
516 its meltwater before ca. 7 ka (Fig. 6). Some regions such as Ontario had begun to cool before 5.5 ka
517 (Fig. 6), but even there, the largest changes in the available isotope records (Fig. 3C, 4C) likely indicate
518 important changes in atmospheric circulation at ca. 5.5 ka (Kirby et al., 2002; Yu et al., 1997; Zhao et
519 al., 2010). Many of the hydroclimate changes began synchronously at 5.7 ka (see synchrony analyses
520 by Newby et al., 2014; Shuman et al., 2014).

521

522 Explanations for non-reversing shifts at 5.5 ka include amplification of orbital and greenhouse gas
523 forcing by surface-atmosphere interactions, such as related to vegetation or sea ice changes (Claussen
524 et al., 1999; Crucifix et al., 2002), or intrinsic ocean dynamics, such as driven by salt and heat fluxes in
525 the North Atlantic (Goosse et al., 2002; Jongma et al., 2007; Thornalley et al., 2009). Such mechanisms
526 have been proposed and debated as an explanation for the end of the African Humid Period at ca. 5.5 ka
527 (deMenocal et al., 2000; Kropelin et al., 2008; McGee et al., 2013; Shanahan et al., 2015; Tierney and
528 deMenocal, 2013), but changes at this time extended across the Northern Hemisphere (Magny and
529 Haas, 2004; Magny et al., 2006; Oppo et al., 2003; Shuman, 2012b; Thornalley et al., 2009). Our
530 results confirm their importance for mid-latitude North America.

531

532 **4.6 Climates of the Common Era**

533 The past 2000 years (the ‘Common Era’) represent the period with the highest average effective
534 moisture and coolest summers since the decay of the ice sheet (Fig. 2). The rates of cooling and
535 moistening accelerated by ca. 2.1 ka, and the changes have many similarities to those at ca. 5.5 ka (Fig.

2, 5). Consequently, the conditions of the Common Era were not representative of conditions that had persisted for much of the Holocene, and medieval warmth and drought that punctuated the conditions of the Common Era, especially in portions of the east (Fig. 8), rarely reached the magnitude of earlier events (Figs. 6, 8).

The climate changes of the Common Era differed, however, across sub-regions (Fig. 6), and thus further confirm the importance of spatial patterning of Holocene climate variations at centennial to millennial scales. Temperatures from Wyoming to Illinois, like dust accumulation rates in Minnesota, were lower before 1 ka than afterward (Fig. 6A,B). Elsewhere, the lowest temperatures and highest effective moisture levels were achieved after 1 ka and then again after the multi-century phase of high temperatures and drought during medieval times, which appears most prominently in MTWM, SST, and lake-level records from the east (Fig. 8). Although the medieval anomaly appears to have been earlier in the coastal east than elsewhere (Fig. 6A-C), the duration of the event is also short relative to the associated temporal uncertainty and the age differences cannot be verified.

5. CONCLUSIONS

The consistent climate signals detected across regions and diverse (sedimentary, geochemical, biotic) paleoenvironmental records (Fig. 2-5) indicate an integrated sequence of slow trends, abrupt shifts and accelerations, and multi-century events during the Holocene climate history of mid-latitude North America. The sequence of events captured by our mean temperature and moisture records (Figs. 2 & 6), rate-of-change analyses (Fig. 3), and principal component analyses (Figs. 4-5) confirms that a series of abrupt shifts and transient fluctuations produced important modifications of orbital and ice sheet driven climate trends from the Rocky Mountains to the North Atlantic. However, the same details do not apply to all locations or records (Fig. 6), and >30% of the variance in the data derives from local to sub-regional climate patterns (Table 2).

561

562 Within the context of sub-regional variation (Fig. 6), widespread, multi-parameter replication of the
563 structure of the climate history indicates that abrupt events had magnitudes equal to about 25-50% of
564 the long-term changes. They included both positive and negative interference with the long trends, and
565 despite their modest magnitudes, must have produced significant ecological (vegetation/pollen) and
566 geomorphic (lake/dust) consequences to enable detection by the records examined here. Rapid
567 transitions from ca. 9.3-8.2 ka coincided with the declining influence of the Laurentide Ice Sheet and
568 its meltwater, but additional step changes and acceleration of long-term trends at ca. 5.5 and 2.1 ka
569 were equally as important and may have resulted from far-field feedbacks related to Northern
570 Hemisphere cooling. The replicated evidence for multi-century, multivariate climate changes provides
571 a benchmark for comparison with simulations aimed at understanding the full spectrum of climate
572 variations, but more detailed data are required to fully map and understand the structure of these
573 spatially varied changes.

574

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581

582

583 **Table 1. Site Table**

584 “MTWM” refers to mean temperature of the warmest month; “SST” to sea-surface temperatures;
585 “18O” to oxygen isotope records; and “2H” to hydrogen isotope records.

586

587 **Table 2. Principal Component (PCA) loadings**

588 Sites are sorted by loadings of the variable-specific PCAs.

589

590 **Figure Captions**

591

592 Figure 1. A map of the North American paleoclimate records used here. Numbers correspond with
593 those in Table 1.

594

595 Figure 2. A. Mean (solid black line) and median (dashed black line) of all of the pollen- and alkenone-
596 inferred temperature time series from the region (black circles, Fig. 1). Gray lines shows each of the
597 means from all possible factorial combinations of records. B. Mean (solid black line) and median
598 (dashed black line) of all of the effective moisture (lake level and dust) records, plotted as z-scores.
599 Gray lines show all possible factorial combinations. Vertical dashed lines indicate the timing of
600 maxima in the mean rate of change across all data types (Fig. 3A).

601

602 Figure 3. Mean rates of change over 200-yr intervals plotted by data type compared with each other.
603 Panel A represents the mean of all of the time series (B-E) below, which show the mean absolute
604 magnitude of change in the various categories of data. The vertical scale indicates +1 z-score (standard
605 deviation) units above each of the horizontal lines, which mark zero for the time series above. The
606 horizontal dashed line in A marks the threshold for distinguishing major episodes of abrupt change
607 (0.26 sd/200 yrs; 85% of the rates) at 10.9-10.5, 9.4, 8.3, 5.5, 5.2, 4.7, and 0.9-0.6 ka, which are also

608 indicated by vertical dashed lines (as in Fig. 2). Peaks within 300 years of each other are treated as
609 single events.

610

611 Figure 4. First (top) and second (bottom) principal component (PC) scores plotted by time for A) all
612 temperature reconstructions, B) all moisture reconstructions, and C) all isotope records. Thick lines
613 indicate the scores based on PCA of all datasets, and gray lines indicate scores based on 100 iterations
614 of the PCA using bootstrapped subsets of the data. Red lines in C represent a PCA that included two
615 datasets (Fayetteville Green Lake and Bison Lake), which otherwise did not have sufficient duration
616 for inclusion in our analyses. Vertical lines indicate maxima in the absolute magnitude of the rate of
617 change in the component scores for each data type; solid lines indicate rates of >1.5 units per 200
618 years, and dashed lines indicate 0.9 units per 200 years.

619

620 Figure 5. PC scores plotted by time based on the complete dataset. A) Scores for the first component
621 (PC1) are shown with the June insolation trend for 45°N (Berger and Loutre, 1991) in red. B) Scores
622 for the second component (PC2) as well as the residuals of PC1 minus the June insolation trend (gray
623 line) are shown with the area of the Laurentide ice sheet (Dyke, 2004) in blue. C-D) Residual scores for
624 PC1 (top) and PC2 (bottom) after both insolation (PC1 only) and ice area trends (PC1 & 2) have been
625 removed.

626

627 Figure 6. Stacks of temperature (top) and moisture (bottom) records from the A) western, B) west-
628 central, C) east-central, and D) eastern sub-regions. All temperature records are shown as deviations in
629 degrees C from their most recent value; all moisture records are shown as z-scores (anomalies in
630 standard deviations from their mean). Shading indicates the standard error about the mean for all stacks
631 (except, for simplicity, SSTs shown in red in D); time series from individual sites are shown without
632 uncertainty. Sites names included in each stack are listed. MTWM indicates mean temperature of the

633 warmest month; SST indicates detrended sea-surface temperatures.

634

635 Figure 7. Pollen-inferred mean temperatures of the warmest month (as anomalies relative to present)

636 for three sites from the west-central sub-region.

637

638 Figure 8. Trends and multi-century climate variability in the eastern sub-region over the past 8000

639 years. Time series (which are the same as shown in Fig. 6D) represent the means of the available

640 reconstructions of A) sea-surface temperatures (SST), B) mean temperature of the warmest month

641 (MTWM), and C) lake level. The red line in C represents the linear model of the mean lake-level

642 changes based on the mean of the temperature records (both SSTs and MTWM); for comparison, blue

643 shading shows the standard error about the mean lake-level reconstruction. Gray shading indicates

644 multi-century deviations from the long-term temperature trends. Vertical lines indicate the beginning

645 (tan) and end (blue) of multi-century droughts reconstructed in coastal Massachusetts, based on the

646 mode of the age distributions calculated for regional drought events by Newby et al. (2014).

647

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Table 1

Number Site	State/Province	Latitude	Longitude	14C dates	Samples	Temperature	Lake Level	Isotope	Dust	Pollen citation	Citation for reconstruction
1 Rainbow Lake	WY	44.94	-109.50	29	220		X				Shuman and Serravezza, unpub.
2 Lower Paintrock Lake	WY	44.39	-107.38	39	220		X				Serravezza (2016)
3 Lake of the Woods	WY	43.48	-109.89	21	220		X				Pribyl and Shuman (2014)
4 Little Windy Hill Pond	WY	41.43	-106.33	18	220		X				Minckley et al. (2012)
5 Upper Big Creek Lake	CO	40.91	-106.62	7	220		X				Shuman and Pribyl (2015)
6 Emerald Lake	CO	39.15	-106.41	29	220		X				Shuman et al. (2014)
7 Davis Pond	MA	42.14	-73.41	31	220		X				Newby et al. (2011; 2014)
8 New Long Pond	MA	41.85	-70.68	52	220		X				Newby et al. (2009; 2014)
9, 27 Deep Pond	MA	41.56	-70.64	53	125/220	MTWM	X			Foster et al. (2006)	Marsicek et al. (2013)
10a Buckbean Bog	WY	44.30	-110.26	4	45	MTWM				Baker (1976)	Shuman (2012)
10b Sherd Lake	WY	44.27	-107.01	2	48	MTWM				Burkart (1976)	Shuman (2012)
11 Rice Lake	ND	48.01	-101.53	14	81	MTWM				Grimm (2001)	This study
12 Moon Lake	ND	46.86	-98.16	14	144	MTWM				Laird et al. (1996)	This study
13 Pickerel Lake	SD	45.50	-97.33	3	73	MTWM				Watts and Bright (1968)	This study
14, 32 Steel Lake	MN	46.97	-94.68	35	119	MTWM			X	Wright et al. (2004)	This study
15 Sharkey Lake	MN	44.59	-93.41	9	163	MTWM				Camill et al. (2003)	This study
16 Lake West Okoboji	IA	43.33	-95.20	9	93	MTWM				Van Zant (1979)	This study
17 Devils Lake	WI	43.42	-89.73	12	98	MTWM				Maher (1982)	This study
18 Chatsworth Bog	IL	40.68	-88.34	9	55	MTWM				King (1981)	This study
19 Nutt Lake	ON	45.22	-79.45	10	83	MTWM				Bennett (1987)	This study
20 Hams Lake	ON	43.24	-80.41	10	80	MTWM				Bennett (1987)	This study
21 Graham Lake	ON	45.18	-77.35	6	207	MTWM				Fuller (1997)	This study
22 High Lake	ON	44.52	-76.60	8	189	MTWM				Fuller (1997)	This study
23 Spruce Pond	NY	41.24	-74.20	9	141	MTWM				Maenza-Gmelch (1997)	This study
24 Sutherland Pond	NY	41.39	-74.20	11	140	MTWM				Maenza-Gmelch (1997)	This study
25 Little Pond-Royalston	MA	42.68	-72.19	7	83	MTWM				Oswald et al. (2007)	Marsicek et al. (2013)
26 Blood Pond	MA	42.08	-71.96	15	125	MTWM				Oswald et al. (2007)	Marsicek et al. (2013)
28 Mansell Pond	ME	45.04	-68.73	10	110	MTWM				Almquist-Jacobson and Sanger (1995)	This study
29 OCE326-GGC30	(Nova Scotia)	44.00	-63.00	8	141	SST					Sachs (2007)
30 CH0798-GGC19	(Virginia)	36.87	-74.57	5	165	SST					Sachs (2007)
31 Elk Lake	MN	45.87	-95.80	Varves	162				X		Dean (1997)
33 Bear Lake (cores 96-1/96-2)	UT/ID	41.98	-111.33	34	157			18O			Bright et al. (2006)
34 Bison Lake	CO	39.77	-107.35	9	284			18O			Anderson (2011)
35 O'Brien Lake	MI	44.64	-83.88	16	66			18O			Henne and Hu (2010)
36 Crawford Pond	ON	43.47	-79.95	4	73			18O			Yu et al. (1997)
37 Fayetteville Green Lake	NY	43.03	-75.97	6	998			18O			Kirby et al. (2003)
38 Grinnell Pond	NJ	41.10	-74.63	7	334			18O			Zhao et al. (2010)
39 Berry Pond	MA	42.51	-73.32	16	35			2H			Shuman et al. (2006)

Table 2

			All		Temperature		Moisture		Isotopes	
Component:			1	2	1	2	1	2	1	2
Percent of Variance:			34.92	21.07	35.23	28.54	51.10	19.34	42.30	23.63
Buckbean Fen/Sherd Lake	WY	T	0.25	-0.07	0.61	-0.23				
GGC30 (Nova Scotia)		SST	0.24	0.01	0.39	-0.04				
Mansell Pond	ME	T	0.22	0.01	0.26	0.04				
Steel Lake	MN	T	0.06	0.32	0.22	0.70				
Nutt Lake	ON	T	0.23	-0.03	0.19	-0.04				
Blood Pond	MA	T	0.10	0.17	0.15	0.25				
High Lake	ON	T	0.16	0.19	0.12	0.12				
Little Pond	MA	T	0.14	-0.14	0.12	-0.07				
Graham Lake	ON	T	0.13	0.17	0.11	0.10				
Sutherland Pond	NY	T	0.19	0.13	0.11	0.06				
Devils Lake	WI	T	0.15	0.21	0.09	0.09				
Moon Lake	ND	T	0.16	0.02	0.08	0.02				
GGC19 (Virginia)		SST	0.05	0.26	0.06	0.25				
Spruce Pond	NY	T	0.07	0.30	0.06	0.20				
Sharkey Lake	MN	T	0.07	0.25	0.04	0.18				
Rice Lake	ND	T	0.05	0.03	0.03	0.01				
Hams Lake	ON	T	-0.03	0.16	-0.01	0.17				
Deep Pond	MA	T	-0.06	0.20	-0.07	0.21				
Pickerel Lake	SD	T	-0.20	0.05	-0.18	0.05				
Lake West Okoboji	IA	T	-0.10	-0.05	-0.20	-0.19				
Chatsworth Bog	IL	T	-0.16	0.12	-0.38	0.31				
Upper Big Creek Lake	CO	LL	-0.05	0.13			-0.03	0.10		
Little Windy Hill Pond	WY	LL	0.09	0.14			0.18	0.24		
Lower Paintrock Lake	WY	LL	0.04	-0.22			0.19	-0.46		
Steel Lake	MN	D	0.23	0.15			0.23	0.50		
Elk Lake	MN	D	0.22	0.10			0.28	0.39		
New Long Pond	MA	LL	0.10	-0.30			0.30	-0.40		
Lake of the Woods	WY	LL	0.21	0.03			0.31	0.18		
Davis Pond	MA	LL	0.19	-0.23			0.38	-0.23		
Rainbow Lake	WY	LL	0.25	-0.05			0.38	0.16		
Deep Pond	MA	LL	0.20	-0.23			0.39	-0.21		
Emerald Lake	CO	LL	0.25	-0.13			0.42	-0.01		
Bear Lake	ID/UT	18O	-0.16	0.08					-0.42	0.32
Berry Pond	MA	2H	0.05	0.07					0.12	0.80
O'Brien Lake	MI	18O	0.20	0.19					0.40	0.47
Grinnell Lake	NJ	18O	0.19	-0.05					0.56	-0.19
Crawford Pond	ON	18O	0.22	-0.17					0.57	-0.07

Temperature, Lake Level, Dust, and Isotope Records

○ Lake level (1-9) ● Temperature (10-30) □ Dust (31-32) ■ Isotope (33-39)

Shuman and Marsicek - Figure 4

Shuman and Marsicek - Figure 6