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The structure of Holocene climate change in mid-latitude North America

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A B S T R A C T

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

1. Introduction

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

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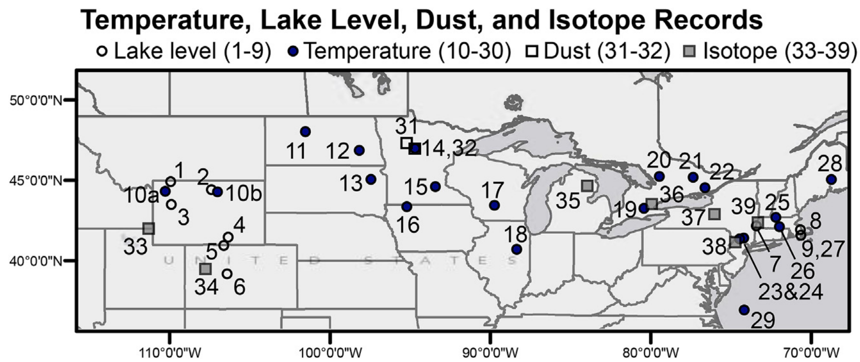

Fig. 1. A map of the North American paleoclimate records used here. Numbers correspond with those in Table 1.

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

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

2. Methods

2.1. Data

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

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

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