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Holocene climate changes in eastern Beringia (NW North America) — A systematic review of multi-proxy evidence

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ABSTRACT

Reconstructing climates of the past relies on a variety of evidence from a large number of sites to capture the varied features of climate and the spatial heterogeneity of climate change. This review summarizes available information from diverse Holocene paleoenvironmental records across eastern Beringia (Alaska, westernmost Canada and adjacent seas), and it quantifies the primary trends of temperature- and moisture-sensitive records based in part on midges, pollen, and biogeochemical indicators (compiled in the recently published Arctic Holocene database, and updated here to v2.1). The composite time series from these proxy records are compared with new summaries of mountain-glacier and lake-level fluctuations, terrestrial water-isotope records, sea-ice and sea-surface-temperature analyses, and peatland and thaw-lake initiation frequencies to clarify multi-centennial- to millennial-scale trends in Holocene climate change. To focus the synthesis, the paleo data are used to frame specific questions that can be addressed with simulations by Earth system models to investigate the causes and dynamics of past and future climate change. This systematic review shows that, during the early Holocene (11.7–8.2 ka; 1 ka = 1000 cal yr BP), rather than a prominent thermal maximum as suggested previously, temperatures were highly variable, at times both higher and lower than present (approximate mid-20th-century average), with no clear spatial pattern. Composited pollen, midge and other proxy records average out the variability and show the overall lowest summer and mean-annual temperatures across the study region during the earliest Holocene, followed by warming over the early Holocene. The sparse data available on early Holocene glaciation show that glaciers in southern Alaska were as extensive then as they were during the late Holocene. Early Holocene lake levels were low in interior Alaska, but moisture indicators show pronounced differences across the region. The highest frequency of both peatland and thaw-lake initiation ages also occurred during the early Holocene. During the middle Holocene (8.2–4.2 ka), glaciers retreated as the regional average temperature increased to a maximum between 7 and 5 ka, as reflected in most proxy types. Following the middle Holocene thermal maximum, temperatures decreased starting between 4 and 3 ka, signaling the onset of Neoglacial cooling. Glaciers in the Brooks and Alaska Ranges advanced to their maximum Holocene extent as lakes generally rose to modern levels. Temperature differences for averaged 500-year time steps typically ranged by 1–2 °C for individual

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records in the Arctic Holocene database, with a transition to a cooler late Holocene that was neither abrupt nor spatially coherent. The longest and highest-resolution terrestrial water isotope records previously interpreted to represent changes in the Aleutian low-pressure system around this time are here shown to be largely contradictory. Furthermore, there are too few records with sufficient resolution to identify sub-centennial-scale climate anomalies, such as the 8.2 ka event. The review concludes by suggesting some priorities for future paleoclimate research in the region.

1. Introduction

As sea level rose during the transition from the Pleistocene to the Holocene, the vast non-glaciated landmass extending from northeastern Siberia to northwestern Canada (Beringia) was transformed. The dry, treeless landscape was replaced by the present-day mosaic of boreal forest, peatlands and thaw lakes bordered by epicontinental seas – an environment dramatically different from any during the preceding 100,000 years. Compared to the dramatic transformation that preceded it, the environmental changes of the Holocene, and the climate changes that drove them, were relatively minor. Nonetheless, these changes reveal how the climate system behaves when boundary conditions are similar to present. This similarity adds confidence to interpretations of Holocene paleoclimate archives, many of which are based on knowledge of the relation between modern climate and environmental conditions. On the other hand, the relatively small climate signal challenges our paleoclimate indicators. All paleoclimate archives are influenced to some extent by factors other than climate, and they often represent a combination of climate variables, including their seasonality. In addition, the sub-millennial-scale features of Holocene climate are likely to be overlooked in natural archives without extraordinarily high sample resolution (generally sub-centimeter scale), and accurate century-scale geochronology.

Considering the substantial challenges involved in reconstructing Holocene climate change, we must explore all available evidence from a wide variety of sources. And considering the diversity of the climatologies encompassed by the vast area of eastern Beringia (about 5×10^6 km^2), we must consider evidence from as many sites as possible in order to capture the spatial heterogeneity of climate change and to discern real variability from uncertainties. Fortunately, the Holocene environmental and climate history of eastern Beringia has received extensive research attention over the past five decades. The enormity of this previous work, however, and the evolving scientific understanding that it represents, challenges us to organize, extract and apply the most reliable information it holds. To address this goal, this systematic review builds on the recent comprehensive compilation of Arctic Holocene proxy climate records (Sundqvist et al., 2014) by revealing the prominent trends represented by the records within the database alongside paleoclimate evidence from archive types that cannot be adapted to fit a database of continuous time series. After summarizing evidence from multiple sources, we find that no single archive type provides a superior proxy for past climate, but that, by comparing evidence from diverse indicators, we can investigate proxy biases while revealing any common signals.

1.1. Research questions

This review focuses on the observational evidence for Holocene climate changes in eastern Beringia, but to understand the *causes* of the changes, and how they relate to the global climate system, requires an investigation of climate-forcing mechanisms and climate-feedback processes. One fruitful approach to investigating the causes of climate change involves simulations by Earth system models. This review does not consider the output of climate models, but rather addresses research questions that should help inform future investigations using Earth system models to elucidate the causes and dynamics of past and future climate change. Addressing these questions requires that we qualify the most robust features of the full range of proxy records over the large region of eastern Beringia – a scale that is commensurate with the resolution of global models:

- What are the primary differences between the climate of the early and late Holocene?
- Is there evidence for a mid-Holocene thermal maximum around 6 ka? If so, how much warmer was it?
- What was the magnitude of temperature variability at the site level during the middle and late Holocene?
- Is there evidence for a widespread and rapid climate transition during the Holocene that might represent a step-wise shift in the mode of ocean-atmospheric circulation?
- Is there evidence in the region for an abrupt climate reversal at 8.2 ka, as has been observed elsewhere?

1.2. Scope

This review summarizes the available evidence for Holocene climate change across eastern Beringia (Fig. 1) as expressed through a variety of proxy types, including physical, chemical and biological, from marine and terrestrial archives. It includes the first quantitative synthesis of the proxy records within the Arctic Holocene database (Sundqvist et al., 2014), focusing on Alaska (north of 58° N latitude), Yukon and western Northwest Territories (west of 125° W longitude). We herein update the Arctic Holocene database from version 2 (Sundqvist et al., 2014) to version 2.1 by including the recently published records from Corser Bog (Nichols et al., 2014) and the midge-based paleoclimate reconstruction from Upper Fly Lake (Bunbury and Gajewski, 2009), which was previously overlooked. In addition, we include the new record from Kurupa Lake (Boldt et al., 2015), a highly resolved temperature reconstruction from northern Alaska that fills a large gap in spatial coverage, although it extends back to only 5.7 ka. All other records from eastern Beringia in the Arctic Holocene database extend back to at least 6 ka; most (75%) extend to at least 9 ka, and half (47%) extend back to 11.5 ka. Of the 105 study sites from both marine and terrestrial settings that were considered from the region, only 32 (Table 1) met the criteria for resolution (at least one data point every 400 years on average), duration (at least 6–2 ka), and geochronology (at least one control point every 3000 years). A comprehensive and systematic approach to selecting the time series is fundamental to an unbiased and reproducible synthesis of available information. The data and metadata for all versions of the Arctic Holocene database are available at NOAA Paleoclimatology (http://ncdc.noaa.gov/paleo/study/15444).

In addition to a synthesis of the records that meet the criteria for