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Younger-Dryas cooling and sea-ice feedbacks were prominent features of the Pleistocene-Holocene transition in Arctic Alaska

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ABSTRACT

Declining sea-ice extent is currently amplifying climate warming in the Arctic. Instrumental records at high latitudes are too short-term to provide sufficient historical context for these trends, so paleoclimate archives are needed to better understand the functioning of the sea ice-albedo feedback. Here we use the oxygen isotope values of wood cellulose in living and sub-fossil willow shrubs ($\delta^{18}O_{wc}$) (*Salix* spp.) that have been radiocarbon-dated (^{14}C) to produce a multi-millennial record of climatic change on Alaska's North Slope during the Pleistocene-Holocene transition (13,500–7500 calibrated ^{14}C years before present; 13.5–7.5 ka). We first analyzed the spatial and temporal patterns of $\delta^{18}O_{wc}$ in living willows growing at upland sites and found that over the last 30 years $\delta^{18}O_{wc}$ values in individual growth rings correlate with local summer temperature and inter-annual variations in summer sea-ice extent. Deglacial $\delta^{18}O_{wc}$ values from 145 samples of subfossil willows clearly record the Allerød warm period (~13.2 ka), the Younger Dryas cold period (12.9–11.7 ka), and the Holocene Thermal Maximum (11.7–9.0 ka). The magnitudes of isotopic changes over these rapid climate oscillations were ~4.5‰, which is about 60% of the differences in $\delta^{18}O_{wc}$ between those willows growing during the last glacial period and today. Modeling of isotope-precipitation relationships based on Rayleigh distillation processes suggests that during the Younger Dryas these large shifts in $\delta^{18}O_{wc}$ values were caused by interactions between local temperature and changes in evaporative moisture sources, the latter controlled by seaice extent in the Arctic Ocean and Bering Sea. Based on these results and on the effects that sea-ice have on climate today, we infer that ocean-derived feedbacks amplified temperature changes and enhanced precipitation in coastal regions of Arctic Alaska during warm times in the past. Today, isotope values in willows on the North Slope of Alaska are similar to those growing during the warmest times of the Pleistocene-Holocene transition, which were times of widespread permafrost thaw and striking ecological changes.

1. Introduction

Rapid climate changes often involve strong positive feedbacks, and in the Arctic the most important of these is the albedo change caused by reductions in the extent of sea ice in summer and early autumn (Serreze and Francis, 2006). Over the last 40 years, coverage of multi-year sea ice in the Arctic Ocean has decreased by 11% per decade (Screen and Simmonds, 2010), which is an alarming trend because general circulation models suggest a seasonally ice-free Arctic Ocean will have strong effects on global climate (Deser

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et al., 2010). Recent observations of unusual convective storms traversing the Arctic Ocean and intense winters in mid-latitudes tend to support this prediction (Vihma, 2014; Klein et al., 2015a). Recent declines in sea ice have been forced by and acted to enhance warming air temperature trends in Arctic Alaska, including a 2.9 °C rise in mean annual temperature at Barrow (Fig. 1) since CE 1900 (Wendler et al., 2010), and a 0.5–2 °C rise in mean annual permafrost temperature over the last several decades (Smith et al., 2010; Jeffries et al., 2012). Sea-ice-enhanced warming of air temperatures could thaw permafrost and release its vast stores of ancient carbon downstream and to the atmosphere, which in turn could change global carbon budgets and influence climate and ecosystems across a wide range of spatial and temporal scales (Jorgenson et al., 2006; Schuur et al., 2008; Post et al., 2009; Bhatt et al., 2014).

A deeper historical context is needed to understand the potential magnitude, sensitivity, geographic extent, and ecological ramifications of the ice-albedo feedback. Land-based paleoclimatic records that are sensitive to both abrupt climate change and sea-ice-processes can provide this additional perspective with precisely dated paleo-records whose chronologies are not complicated by the ^{14}C-reservoir effects in marine records. The prehistoric precedents most comparable in their rates and magnitudes to the changes in sea-ice cover and climate occurring today occurred 17,000 to 8000 calendar ^{14}C years ago (17.0–8.0 ka) during the last deglaciation (Ruddiman, 2001).

The most notable of the warming events occurring during the last deglaciation was the termination of the Younger Dryas cold period at 11.7 ka when temperatures in Greenland warmed by at least 5 °C within a few decades (Alley, 2000). A sea-ice albedo feedback caused by the retreat of sea ice in the North Atlantic is thought to have amplified this post-Younger Dryas warming. The isotopic signature of this sea-ice retreat is recorded as a shift to both higher δ^{18}O values and deuterium excess values in Greenland ice cores as the evaporative source areas of Greenland-bound moisture moved northward over the Atlantic Ocean (Jouzel et al., 2005; Klein et al., 2015a).

Resolving the deglacial climate history in the Alaska–Siberia sector of the Arctic and how it compared with the North Atlantic region is critical for understanding the teleconnections and feedbacks of paleoclimatic events at high latitudes (i.e. Kaufman et al., 2004; Melles et al., 2012; Praetorius and Mix, 2014; Kaufman et al., 2016). Compared to the North Atlantic, much less is known about the postglacial climate history of the region surrounding the North Pacific, and the climate history of the Arctic Ocean and its adjacent lands remains a large gap in our understanding of paleoclimatic events (Polyak et al., 2010; Jakobsson et al., 2014).

In this study, we fill some of these knowledge gaps by building on the pioneering work of Epstein (1995) by using δ^{18}O values in modern and sub-fossil willow shrub (*Salix* spp.) cellulose ($\delta^{18}O_{wc}$) as a proxy for past climate change. Our focus is on the last deglaciation, 13.5 to 7.5 ka. We start by testing how climate variables affect the spatial and temporal patterns of $\delta^{18}O_{wc}$ values in living willows, and then, after compiling a record of ancient $\delta^{18}O_{wc}$ values, we infer how these climate variables changed during the Pleistocene–Holocene transition. Finally, we use this record to explore how abrupt deglacial climate changes both drove and were driven by Arctic sea-ice feedbacks.

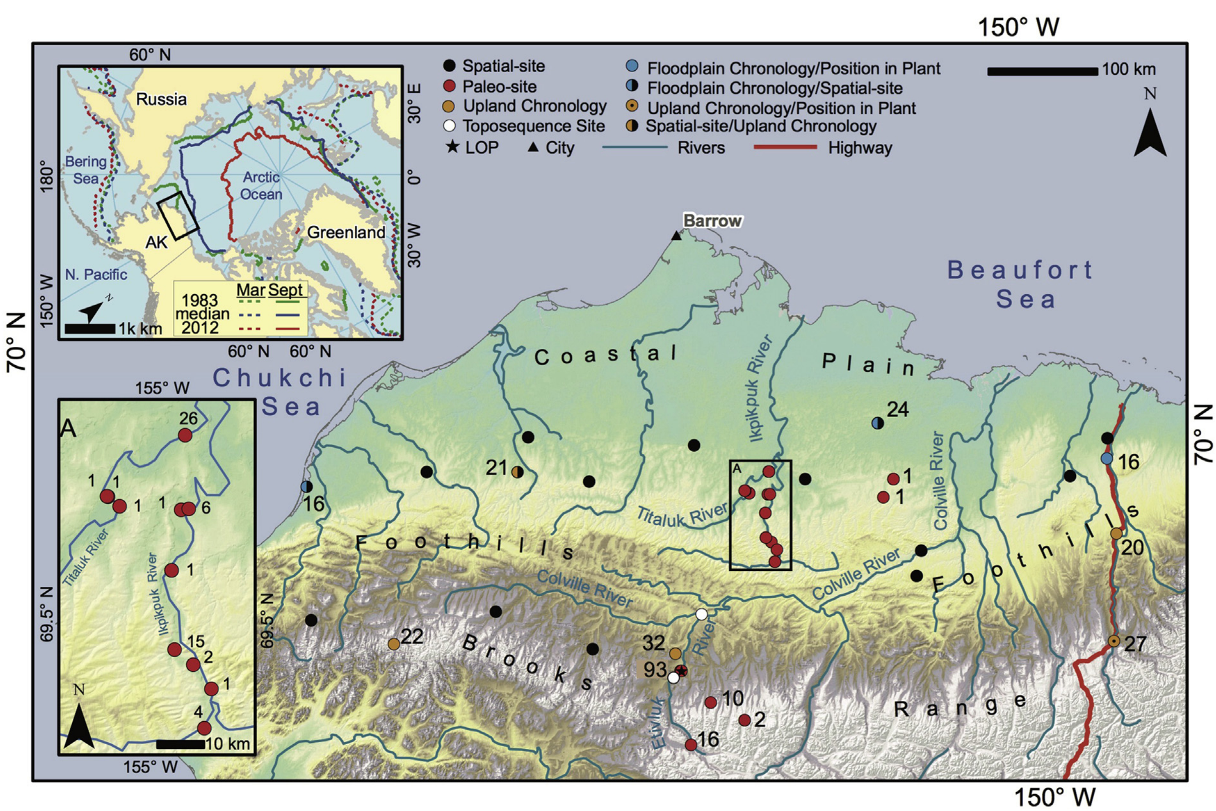

Fig. 1. Alaska's North Slope showing sampling locations. See text for site descriptions. Numbers next to 'paleo' and 'chronology' sites indicate how many sub-fossil (total = 179), and individual rings (total = 178) were analyzed for $\delta^{18}O_{wc}$ from these locations. Top left inset shows maximum (March; dashed line) and minimum (September; solid line) sea-ice extent during 1983 (green lines) and 2012 (red lines), which represent the most and least extensive sea-ice years since record keeping began in 1976. Also shown is the median sea ice extent since 1976 (blue lines; from Fetterer et al., 2002).