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Holocene atmospheric circulation in the central North Pacific: A new terrestrial diatom and $\delta^{18}O$ dataset from the Aleutian Islands

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A B S T R A C T

The North Pacific is a zone of cyclogenesis that modulates synoptic-scale atmospheric circulation, yet there is a paucity of instrumental and paleoclimate data to fully constrain its long-term state and variability. We present the first Holocene oxygen isotope record ($\delta^{18}O_{diatom}$) from the Aleutian Islands, using siliceous diatoms preserved in Heart Lake on Adak Island (51.85° N, 176.69° W). This study builds on previous work demonstrating that Heart Lake sedimentary $\delta^{18}O_{diatom}$ values record the $\delta^{18}O$ signal of precipitation, and correlate significantly with atmospheric circulation indices over the past century. We apply this empirical relationship to interpret a new 9.6 ka $\delta^{18}O_{diatom}$ record from the same lake, supported by diatom assemblage analysis. Our results demonstrate distinct shifts in the prevailing trajectory of storm systems that drove spatially heterogeneous patterns of moisture delivery and climate across the region. During the early-mid Holocene, a warmer/wetter climate prevailed due to a predominantly westerly Aleutian Low that enhanced advection of warm ^{18}O-enriched Pacific moisture to Adak, and culminated in a $\delta^{18}O_{diatom}$ maxima (33.3‰) at 7.6 ka during the Holocene Thermal Maximum. After 4.5 ka, relatively lower $\delta^{18}O_{diatom}$ indicates cooler/drier conditions associated with enhanced northerly circulation that persisted into the 21st century. Our analysis is consistent with surface climate conditions inferred from a suite of terrestrial and marine climate-proxy records. This new Holocene dataset bridges the gap in an expanding regional network of paleoisotope studies, and provides a fresh assessment of the complex spatial patterns of Holocene climate across Beringia and the atmospheric forces driving them.

1. Introduction

Numerous paleoenvironmental studies now contribute to a global synthesis and understanding of Holocene climate change over the past 11.7 ka (Mayewski et al. 2004; Marcott et al. 2013; Rehfeld et al. 2018). By comparing common trends between individual proxy records, these studies provide a means to infer the timing, scale, and spatial extent of major Holocene climatic features. These include stepwise climate transitions, intervals exceeding twentieth century warmth, and the low-frequency behaviour and modes of natural climate variability. At broad (i.e. global) spatial and temporal scales these trends are relatively coherent and unambiguous, yet at finer spatial scales, climate variability is more pronounced due to local and regional factors. Such variability is highlighted in two recent paleoclimate syntheses focused on west and eastern Beringia – the region extending from northeast Siberia to northwest Canada (Fig. 1a) (Brooks et al. 2015; Kaufman et al. 2016). While general circulation models (GCM) typically emphasise insolation as the key driver of millennial-scale Holocene climate change (Renssen et al. 2009), these compilations indicate a more complex and spatially heterogeneous climate

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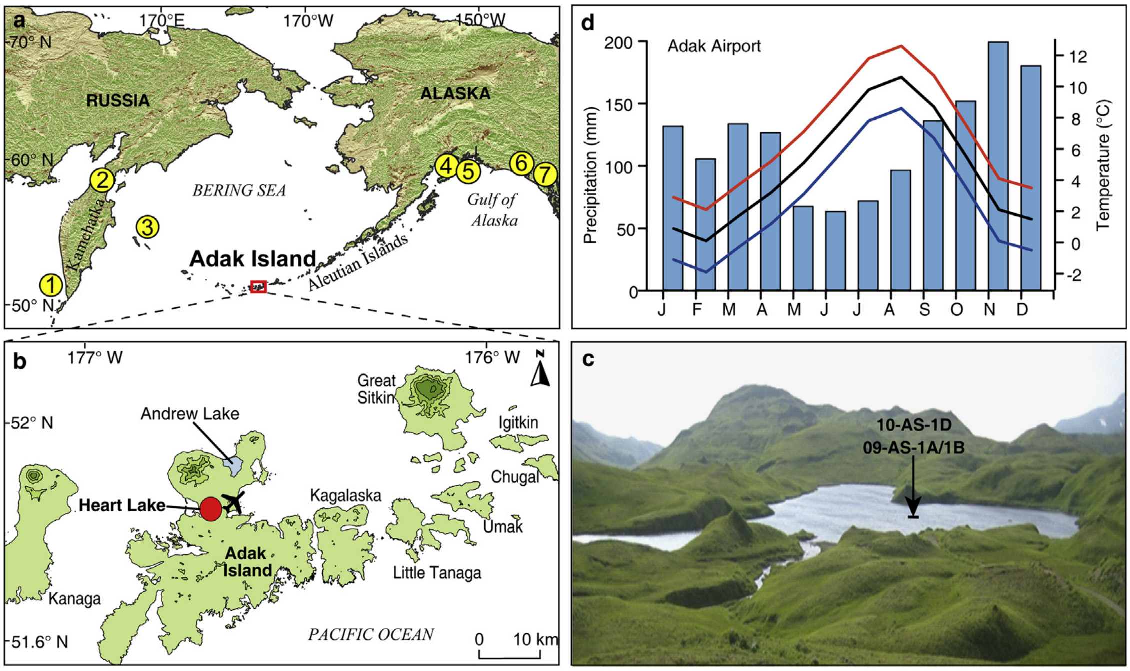

Fig. 1. Location of (a) Adak Island in the central Aleutian Islands, (b) Heart Lake and Andrew Lake, (c) oblique north west view of Heart Lake with the inflow channel visible in the foreground [credit: Yarrow Axford], and (d) monthly mean precipitation (blue bars) and surface air temperature at Adak airport (1949–2016), whereby solid lines depict mean (black), minimum (blue) and maximum (red) temperatures (NOAA, 2017). Numbered circles in 1a indicate key sites referred to in text: (1) LV29-114-3 (Max et al. 2012), (2) Pechora Lake (Hammarlund et al. 2015), (3) SO201-12-77KL (Max et al. 2012), (4) Horse Trail Fen (Jones et al. 2014), (5) Mica Lake (Schiff et al. 2009), (6) Mount Logan (Fisher et al. 2008), and (7) Jellybean Lake (Anderson et al. 2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

evolution than implied by linear insolation forcing alone. For example, major climatic features previously considered ubiquitous, such as a prominent Holocene thermal maximum (HTM) (Kaufman et al. 2004), are now recognised to be spatially asynchronous across this vast region (Kaufman et al. 2016). Moreover, existing terrestrial water isotope records are also shown to be ambiguous and contradictory during the Holocene (Kaufman et al. 2016), and the most recent suite of model-data comparisons reveal significant mismatches between simulated and reconstructed Holocene temperatures in Alaska (Zhang et al. 2017).

At the synoptic scale, Beringia is located within the main centre of influence of the Aleutian Low; one of the most dominant ocean-atmospheric systems in the Northern Hemisphere and of global climate significance (Rodionov et al. 2007). However, virtually all available terrestrial paleoclimate data are restricted to mainland Alaska and eastern Russia (Sundqvist et al. 2014; Brooks et al. 2015; Kaufman et al. 2016), and compared to lower latitude regions, paleoisotope reconstructions are sparse (Kaufman et al. 2016). This partly reflects a lack of base-line water isotope measurements for constraining the regional water isotope cycle [e.g. Welker, 2000; Anderson et al. 2016), as well as a paucity of lake core studies with continuous sequences of carbonate-rich sediments – or suitable alternatives – for isotopic analysis. Hence, to elucidate past and future climate in this region, there is an outstanding requirement for greater spatial coverage of highly resolved and accurately dated paleoclimate datasets, as well as an empirical-based understanding of the atmospheric and environmental controls driving them.

To address this, we present the first Holocene oxygen isotope record from the Aleutian Islands in south west Alaska. Our isotope measurements derive from siliceous diatoms ($\delta^{18}O_{diatom}$) preserved in the sediments of Heart Lake, on Adak Island (Fig. 1b), and are supported by diatom assemblage analysis of the same sedimentary sequence. We build on earlier work by Bailey et al. (2015) who demonstrate that Heart Lake $\delta^{18}O_{diatom}$ values correlate significantly with North Pacific climate indices over the past hundred years ($r = 0.43$; $p < 0.02$, $n = 28$). Here, we apply this empirically-derived understanding to interpret new $\delta^{18}O_{diatom}$ data from a longer Heart Lake sediment core which extends back to 9.6 ka. The primary aims are to: (1) investigate the forcing and response of this remote region to a warming climate system as it transitioned from the last glacial period; (2) develop a Holocene reconstruction of North Pacific atmospheric circulation; and (3) bridge the gap in the regional network of proxy records to synthesise and assess complex spatio-temporal patterns of natural climate variability across Beringia.

2. Regional setting

Heart Lake is a small (~0.25 km^2), freshwater through-flow system on Adak Island in the central North Pacific (51.85° N, 176.69° W) (Fig. 1c). The island is volcanic and forms part of the 1900-km-long Aleutian archipelago extending from mainland Alaska to the Russian-Kamchatka Peninsula. The lake watershed area is ~8 km^2 and is situated in low-relief hills surrounded by mountainous terrain (Fig. 1c). There is a single lake basin with a maximum depth of 8 m. One stream inflows from two larger lakes and a small outflow channel drains to the Bering Sea ~2 km to the west. Lake volume is ~8 $\times$ 10^5 m^3 and water retention is an estimated two weeks, based on the available stream gauge inflow data (TDX, 2013). Inspection of available satellite imagery reveals that Heart Lake freezes over in winter and this ice surface remains into spring (USGS, 2017).

Adak Island has a mild maritime climate compared to mainland Alaska and is strongly affected by persistent fog and light rain in the summer, and frequent storms and strong winds during winter (Rodionov et al. 2007). Mean annual air temperature is 4.3 °C, and mean winter (December–February) and summer (June–August) values are 1.0 °C and 9.0 °C, respectively (1949–2016) (NOAA,