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Holocene temperatures and isotopes of precipitation in Northwest Greenland recorded in lacustrine organic materials

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ABSTRACT

Reconstructions of Holocene lake water isotopic composition based upon subfossil aquatic organic material offer new insights into Arctic climate. We present quantitative estimates of warmth during the Holocene Thermal Maximum in northwest Greenland, inferred from oxygen isotopes of chironomid head capsules and aquatic moss preserved in lake sediments. $\delta^{18}O$ values of chironomids from surface sediments of multiple Greenland lakes indicate that these subfossil remains record the $\delta^{18}O$ values of the lake water in which they grow. Our lake water $\delta^{18}O$ reconstruction is supported by downcore agreement with $\delta^{18}O$ values in aquatic moss and chironomid remains. $\delta^{18}O$ of both organic materials from Secret Lake decrease after 4 ka (ka = thousands of years ago) by 3‰ into the Neoglacial. We argue that lake water at Secret Lake primarily reflects precipitation $\delta^{18}O$ values, which is strongly correlated with air temperature in NW Greenland, and that this signal is biased towards summer and early autumn conditions. Other factors may have influenced Secret Lake $\delta^{18}O$ values through the Holocene, including evaporation of lake water and changing seasonality and source of precipitation. The maximum early Holocene summer and early autumn-biased temperature anomaly at Secret Lake is 2.5–4 °C warmer than present from 7.7 (the beginning of our record) to ~6 ka. The maximum late Holocene cold anomaly (which includes the Little Ice Age) is 1.5–3 °C colder than present. These ranges of possible temperature anomalies reflect uncertainty in the $\delta^{18}O$ – temperature relationship for precipitation at the study site through the Holocene.

1. Introduction

By the end of this century, temperatures are predicted to increase in the Arctic between 2 and 9 °C (Stocker et al., 2013). Reducing the uncertainty around these estimates has important societal implications, and studies of past climate conditions can help clarify how climate change may occur in the Arctic. During an early to middle Holocene Thermal Maximum (HTM), summers were warmer than present across most of the Arctic between 9 and 5 ka, driving the most extensive retreat of the Greenland ice sheet (GrIS) since the end of the last glacial maximum at ~11 ka (Lecavalier et al., 2014). This time period provides an opportunity to test the sensitivity of the GrIS to the most recent sustained warm period in the Arctic, however the magnitude and spatiotemporal expression of the HTM in Greenland (and the Arctic as a whole) was heterogeneous and is not yet fully characterized (Briner et al., 2016; Kaufman et al., 2016). Climate records in northwest Greenland are sparse, leaving the timing and magnitude of the HTM in this sector of the Arctic largely unresolved. Estimates of sea surface temperatures in nearby Baffin Bay (Levac et al., 2001) and air temperature estimates based upon oxygen isotopes ($\delta^{18}O$) in the Agassiz ice core (Lecavalier et al., 2013, 2017) and pollen in lake sediments (Gajewski, 2015) provide evidence for temperature shifts at nearby sites during the Holocene, but differ in the timing and magnitude of past warmth. Additional proxy records from beyond the Greenland Ice Sheet will aid in clarifying the region's climate response to solar insolation trends.

To reconstruct a Holocene climate history for the Thule region of northwest Greenland, we employ $\delta^{18}O$ values from analyses of subfossil aquatic organic material in lake sediments. We measured $\delta^{18}O$ of chironomid larval head capsules and aquatic moss stems

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preserved in the sediments of a precipitation-fed lake to infer past lake water isotopic composition and, by extension, interpret possible climatic controls on precipitation $\delta^{18}O$. Previous work has demonstrated that $\delta^{18}O$ values of chironomid head capsules reflects the isotopic composition of the water in which they grow in both laboratory culturing experiments and modern lakes (Mayr et al., 2015; Verbruggen et al., 2011; Wang et al., 2009; Wooller et al., 2004), and we report chironomid $\delta^{18}O$ values from surface sediments of four Greenland lakes that further support this observation. Additionally, parallel downcore measurements of bulk carbonate and chironomid head capsule $\delta^{18}O$ values yielded very similar reconstructions of lake water isotopes through the late glacial at Rotsee (Switzerland) (Verbruggen et al., 2010). Given the fidelity of chironomid oxygen isotopes as a proxy for lake water, and the relationship between oxygen isotopes of precipitation and air temperature, we employ our down core record of oxygen isotopes measured from chironomids in Secret Lake to constrain the amplitude and timing of Holocene temperature trends and HTM warmth in northwest Greenland. This record also provides estimates of shifts in the stable isotopes of precipitation over northwest Greenland through the Holocene, providing an independent comparison with $\delta^{18}O$ records from nearby ice cores obtained from northern Greenland and the eastern Canadian Arctic.

2. Methods, study sites and materials

2.1. Study sites and field work

Modern lake water and surface (top 1 cm) sediment samples containing aquatic organic material from four Greenland lakes were collected in the summers of 2014 and 2015. Two lakes are in northwest Greenland, near Thule, and two are in southwest Greenland, near Nuuk (Table 1). Results from these new lakes add to existing datasets describing modern chironomid $\delta^{18}O$ – lake water relationships (Mayr et al., 2015; Verbruggen et al., 2011). Surface sediments were recovered using a 6″ x 6” Ekman dredge. Water samples from lakes, their inflows and, when available, precipitation were collected at surface sediment sites. Lake water and inflow samples were collected in 10 mL zero headspace glass vials or 30 mL HDPE Nalgene bottles, and taped to prevent evaporation. Samples from lakes and inflows were collected by hand up to 30 cm below the water surface. Snow from a single storm in 2014 was gathered from the ground (<12 h after snowfall in late August) into a 1000 mL Nalgene bottle and taped.

Secret Lake (informal name; 76.5798°N, 68.6619°W, Fig. 1) is a shallow (3.4 m maximum depth) 0.05 km^2 lake, situated 250 m above sea level and above the local marine limit. The lake is < 2 km from Wolstenholme Fjord and ~50 km from the open waters of Baffin Bay. Secret Lake is currently precipitation fed by a 0.5 km^2 watershed. This catchment includes several small (1 m^2) connected pools along the main inflow NE of the lake, all of which are precipitation fed as well. The active layer of Thule's continuous permafrost is between 0 and 2 m (Bjella, 2013). Additionally, Secret Lake's small catchment is elevated well above local river systems (Fig. 1), precluding inputs from any other source, including outlet glaciers of the GrIS. Since regional deglaciation around 10.7 ka, there is no evidence that the ice sheet, now 13 km away, advanced far enough to enter the present day watershed (Corbett et al., 2015, 2016). The lake is ice-covered for much of the year but overflows into a surface outflow stream during the ice-free summer months, including during our visits to the site in late August of both 2014 and 2015. All of these aforementioned catchment characteristics make Secret Lake an excellent candidate to reconstruct past isotopes of precipitation.

We recovered a 1.44 m sediment core (core 14-SEC-N1) from 3.36 m water depth in Secret Lake using a hammer driven Nesje piston system in August 2014. Coring stopped when we met resistance and repeated hammering did not advance the core tube further into the sediment. We bagged the top 2–3 cm of sediment, including the sediment water interface while recovering the core in the field. Basal sediments are dense diatomaceous clay with abundant aquatic moss material. We also acquired an accompanying surface sediment sample (top 0–1 cm) using an Ekman dredge less than 2 m from the core site.

Despite the shallow depth of the lake, and wind storms in excess of 70 knots that occurred less than 1 week prior to sampling, wave action does not appear to have disturbed surface sediments, as laminated stratigraphy is intact in the top 5 cm of a nearby surface core. Water column clarity measured shortly after the storm using a Secchi disk was ~3 m, further evidence that widespread suspension of sediments by wave action is not problematic even in this relatively shallow lake.

Secret Lake is less than 6 km distance and less than 100 m different in elevation from Thule Air Base (TAB), where long term historical climate monitoring provides valuable information for interpreting our modern and paleo $\delta^{18}O$ record. Daily temperatures, relative humidity and precipitation are available from the TAB meteorological station from 1951 to 2012. Mean annual air temperatures (MAAT), mean July temperatures (MJT) and mean annual precipitation (MAP) at TAB are -11 ± 1.3 °C, 6 ± 1.2 °C and 184 ± 56 mm mean water equivalent per year (mm w.e. yr^{-1}) respectively. Additionally, an International Atomic Energy Agency (IAEA) monitoring station at TAB collected monthly temperature and $\delta^{18}O/\delta D$ values of precipitation from 1966 to 1971, accessible through the IAEA's Global Network of Isotopes in Precipitation online portal (IAEA/WMO, 2015).

2.2. Geochronology

The 14-SEC-N1 chronology is based upon six AMS ^{14}C ages on cleaned, hand-picked aquatic moss remains. Ages were calibrated using Calib 7.1 and IntCal13 (Reimer et al., 2013; Stuvier et al., 2005). The age-depth model was developed with the Bacon package in R, which uses Bayesian statistics to calculate probable sedimentation rates (Blaauw and Christen, 2011). The final age depth model output is produced using over 7 million iterations (Fig. 2).

2.3. Preparation of chironomids for $\delta^{18}O$ measurements

Two to 4 g aliquots of bulk sediment, representing 0.5–1.5 cm of

Table 1
Greenland lakes where surface sediments and lake-water were sampled in August 2014 or 2015.

Lake Name	Latitude (°N)	Longitude (°W)	Depth (m)	Surface Elevation (m a.s.l.)	$\delta^{18}O_{lake\ water}$	$\delta D_{lake\ water}$	$\delta^{18}O_{chironomids\ (0–1\ cm)}$
Secret Lake	76.58021	−68.65907	3.2	250	−18.5	−143.3	3.8
Stardam	76.66512	−67.94100	5.25	221	−19.2	−151.1	2.9
T1	63.757	−51.356	9	25	−15.2	−104.5	10.5
T2	63.757	−51.364	11	43	−15.3	−104.7	9.3

T1 and T2 are informal names. All lakes are isolated from glacial meltwater. $\delta^{18}O/\delta D$ values are reported in per mil, relative to VSMOW.