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Medieval warmth confirmed at the Norse Eastern Settlement in Greenland

G. Everett Lasher and Yarrow Axford
Department of Earth and Planetary Sciences, Northwestern University, 2145 Sheridan Road, Evanston, Illinois 60208, USA

ABSTRACT

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INTRODUCTION AND MOTIVATION

Abundant evidence exists across much of northern Europe for warm conditions during the Medieval Climate Anomaly (MCA, ca. 950–1250 CE) (Solomina et al., 2016), however climate during this time was more variable elsewhere in the Northern Hemisphere (PAGES 2k Consortium, 2013). This period is of interest in Greenland because favorable climate conditions are often associated with Norse settlement of the island at 985 CE (Jones, 1986). Cooling and increased climate variability is conventionally implicated in the collapse of the Norse settlements at ca. 1450 CE, however non-climatic explanations have also been proposed (Dugmore et al., 2012; Hartman et al., 2017). Data constraining local climate within the settlement areas during this period are limited (Millet et al. 2014), and it is unclear whether they support climatic explanations for Norse settlement history in Greenland.

Many glaciers around South and West Greenland and Baffin Island advanced after the MCA, reaching their maximum late Holocene extents during the Little Ice Age (LIA, ca. 1250–1850 CE) (Larsen et al., 2016; Miller et al., 2012). In contrast, recent investigations also found mountain glacier advance comparable to that of the LIA between 975 and 1275 CE on Baffin Island and in West Greenland (Jomelli et al., 2016; Young et al., 2015). Marine records around Baffin Bay also give contrasting views of conditions for the past 2000 yr. Some results indicate a warm MCA relative to the LIA (e.g., Perner et al., 2012), while others find expanded sea-ice cover and cool sea-surface temperatures (SSTs) during the MCA (e.g., Sha et al., 2017). Quantitative proxy records of Greenland climate are sparse, and nearly all high-resolution records are from ice cores documenting conditions over the Greenland Ice Sheet. Most terrestrial records from Greenland are too coarse to resolve the MCA and LIA, and those with adequate temporal resolution suggest spatial heterogeneity in the climatic expression of these periods. For example, West Greenland lake records show pronounced cold conditions during the LIA (Axford et al., 2013), but 250 km south, temperatures are highly variable over the past 3000 yr with no clear MCA or LIA expression (D'Andrea et al., 2011). The alkenone-based record of D'Andrea et al. (2011) was found to be antiphased with a speleothem $\delta^{18}O$ record from Ireland, suggesting contrasting climates between West Greenland and Europe. If similar antiphasing with Europe led to cool conditions in South Greenland during Medieval times, this would contradict the hypothesis that climatic warming facilitated Norse settlement there.

One mechanism proposed to explain the MCA in Europe, and now evidence for coeval antiphased cooling around Baffin Bay, is the North Atlantic Oscillation (NAO). Based upon a tree ring– and speleothem-based NAO reconstruction, Trouet et al. (2009) hypothesized that a dominantly positive NAO (NAO+) mode persisted during the MCA, delivering warm air masses to northern Europe. Observations of NAO variability suggest that a positive mode could result in cool conditions in South Greenland–West Greenland–Baffin Bay during the MCA and perhaps explain glacial advance there (Young et al., 2015). However, other studies contradict the notion of persistent NAO+ conditions throughout this time period (e.g., Ortega et al., 2015) (Fig. DR1 in the GSA Data Repository[1]).

To test whether South Greenland experienced cold conditions during the MCA due to dominant NAO+ conditions, we reconstruct $\delta^{18}O$ of precipitation over the past 3000 yr at a site within the western dipole of the NAO and within the Norse Eastern Settlement (Fig. 1). At our study site, both temperature and moisture sources are influenced by the NAO, and both affect precipitation $\delta^{18}O$ values in the same direction, amplifying rather than obscuring the isotopic signature of warming or cooling.

[1]GSA Data Repository item 2019096, Figure DR1 (comparative North Atlantic Oscillation reconstructions), Figure DR2 (age-depth model for SL core 16-LOW-U2), Figure DR3 (isotopes of precipitation and lake water in South Greenland), and Table DR1 (radiocarbon ages from Scoop Lake), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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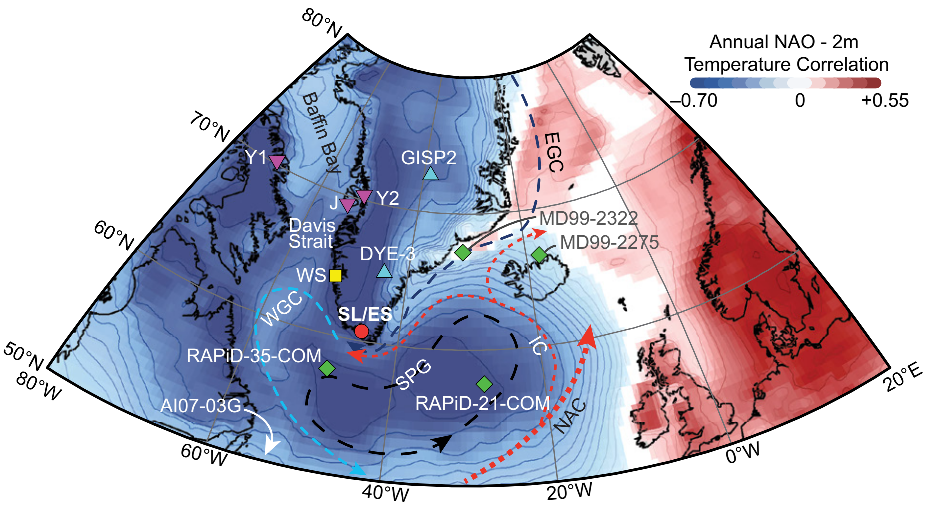

Figure 1. Sites, ocean currents, and atmospheric patterns in Greenland and North Atlantic discussed in text. NAO—North Atlantic Oscillation; SL/ES—Scoop Lake and Norse Eastern Settlement; WS—Western Settlement; blue triangles are ice cores (Alley, 2004; Vinther et al., 2010); green diamonds are marine records (Sicre et al., 2014; Miettinen et al., 2015; Moffa-Sanchez and Hall, 2017); purple triangles are West Greenland and Baffin Bay moraine records from Young et al. (2015; Y1 and Y2) and Jomelli et al. (2016; J); NAC—North Atlantic Current; SPG—subpolar gyre; EGC—East Greenland Current; WGC—West Greenland Current; IC—Irminger Current.

METHODS AND APPROACH

We isolated and analyzed δ¹⁸O of subfossil chironomids (the aquatic larvae of Insecta: Diptera: Chironomidae) preserved in lake sediments. Scoop Lake (60.697°N, 45.419°W) is a 7-m-deep, ~0.05 km², remote, nonglacial, through-flowing lake located at 477 m above sea level on sparsely to unvegetated granodiorite bedrock. We recovered a 156-cm-long gyttja core (16-LOW-U2), with an intact sediment-water interface and intact horizontal stratigraphy throughout (Fig. DR2), in August 2016 and analyzed the upper 80 cm of the core for a high-resolution late Holocene sequence. Eight aquatic plant macrofossils were accelerator mass spectrometry ¹⁴C dated from this zone (Table DR1 in the Data Repository). Chironomid head capsules (CHCs) were prepared following the methods described in Lasher et al. (2017) and analyzed on a thermal conversion elemental analyzer coupled to an isotope ratio mass spectrometer. δ¹⁸O values are reported as per mil (‰) relative to Vienna standard mean ocean water (VSMOW); analytical 1σ = 0.4‰.

CHC δ¹⁸O values reflect that of the water they grow in (van Hardenbroek et al., 2018), and water source and lake hydrology determine growth-water δ¹⁸O. Scoop Lake water collected in late August 2016 plots on the global meteoric water line, indicating minimal evaporation (Fig. DR3). The δ¹⁸O value of CHCs in Scoop Lake surface sediment (0–1 cm), representing the last ~40 yr, is 10.8‰ ± 1‰ (n = 3). Using the demonstrated CHC–lake water enrichment factor (+22.5‰) (van Hardenbroek et al., 2018), average lake water δ¹⁸O over the past 40 yr is –11.7‰. This value is near identical to mean measured precipitation δ¹⁸O of summer precipitation collected over three weeks in August 2016 (–11.9‰), and to the amount-weighted annual average of historical (1961–1974 CE) precipitation (–12.0‰) from Kangilinnguit, Greenland (150 km northwest) (IAEA/WMO, 2017). Estimated residence time of water in Scoop Lake is 1–3 yr. Considering these factors, we argue that CHC δ¹⁸O from Scoop Lake is a strong proxy for annual precipitation δ¹⁸O values over South Greenland.

Precipitation δ¹⁸O values in the high latitudes are strongly correlated with surface air temperatures, and in South Greenland are also influenced by SSTs and moisture source (Bonne et al., 2014; Sodemann et al., 2008). In South Greenland, moisture source is strongly influenced by the configuration of the NAO. Models and observations suggest lower δ¹⁸O precipitation values in South Greenland during NAO+ modes, due to higher-latitude (and thus colder) air-mass trajectories influencing condensation temperatures (Sodemann et al., 2008; Vinther et al., 2010). If the NAO was in a sustained positive mode during the MCA, CHCs should record more negative δ¹⁸O precipitation values at our study site. Reconstructed δ¹⁸O at Scoop Lake would record some combination of changing temperatures and prevalence of high-latitude air masses over time. Due to the meteorological setting of our site, these signals are additive, so we interpret changes in δ¹⁸O at Scoop Lake as maximum constraints on mean annual temperature changes over time.

RESULTS

Five ¹⁴C ages were used to develop the age-depth model using the R software package rbacon v. 2.3.4 (Blaauw and Christen, 2018) (Fig. DR1), after rejection of three outliers falling outside the 95% confidence intervals of a model containing all dates (Table DR1). Given sedimentation rates, each 1-cm-thick sample integrates an average of 40 yr. δ¹⁸O values measured from CHCs decrease by 2.5‰ from the beginning of the record 3000 yr ago to 900 CE (Fig. 2A). This trend is interrupted at 900 CE when δ¹⁸O values increase by 1.5‰. The period between 900 and 1400 CE is characterized by overall more positive δ¹⁸O values than both the previous and following four centuries. A brief (<200 yr) period of lower values is centered at 1150 CE The 15th century marks the transition to overall lower values and exhibits the highest variability of the record. Low δ¹⁸O values persist between 1500 and 1900 CE. δ¹⁸O values from surface sediments are 2‰ higher than average values between 1600 and 1900 CE, indicating an increase in precipitation δ¹⁸O values during the last century.

We estimate temperature from inferred precipitation δ¹⁸O using two relationships: the global δ¹⁸O-temperature relationship of 0.67‰/°C (Dansgaard, 1964), and a similar relationship observed at coastal high-latitude North Atlantic International Atomic Energy Agency (IAEA) sites (0.71‰/°C; Arppe et al., 2017). These relationships translate into Neoglacial cooling of ~2 °C between 3000 and 1500 yr ago (Fig. 2D). This cooling trend was interrupted by warming of ~1.5 °C between 900 and 1400 C.E., punctuated by a multi-decadal cooling event. Consistent LIA cooling, 1.5 °C colder than the preceding warmth, lasted between 1500 and 1900 CE and was followed by a warming of 2 °C to present.

DISCUSSION

The hypothesized antiphase cold expression over Greenland during the MCA from a dominant NAO+ configuration is not supported by our results. Neoglacial cooling in South Greenland is interrupted by warmer, albeit variable, temperatures between 900 and 1400 CE. Ice-core temperature reconstructions in central Greenland are similar in timing and magnitude to those at our site, particularly over the past 1000 yr (Fig. 2D) (Alley, 2004). The magnitude of temperature shifts over South and central Greenland is generally higher than in multi-proxy reconstructions of temperature for the whole Arctic (e.g., Christiansen and Ljungqvist, 2012), suggesting either amplified local temperature change or that isotopes here also reflect changes in dominant moisture source that accompanied past temperature changes. The timing of Greenland Ice Sheet fluctuations around South Greenland agrees

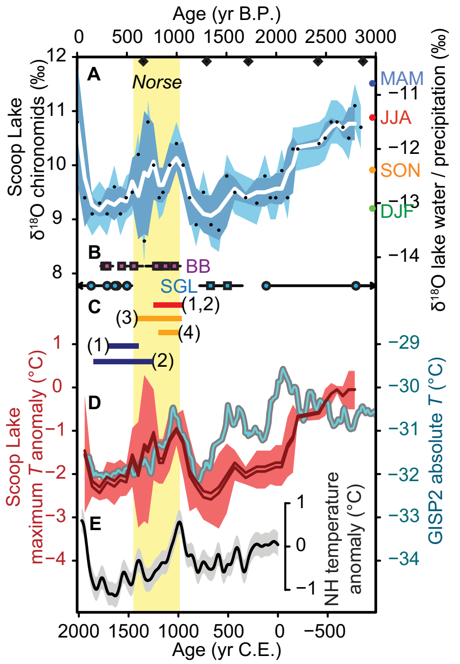

Figure 2. Results and temperature interpretations from Scoop Lake, South Greenland. Norse settlement of Greenland shown as yellow band (yr B.P is relative to 2016). A: Left axis is measured $\delta^{18}O$ values of Scoop Lake chironomids (black dots; light blue band shows $\delta^{18}O$ analytical 1σ) and three-point moving average (white line; dark blue band shows moving-average 1σ). Circles on right axis are 1961–1974 CE seasonal mean precipitation $\delta^{18}O$ values from South Greenland (MAM—March-April-May; JJA—June-July-August; SON—September-October-November; DJF—December-January-February) (IAEA/WMO, 2017). Black diamonds on top axis are ^{14}C samples. B: South Greenland (SGL) and Baffin Bay region (BB) late Holocene maximum glacier extent. Circles are glaciers present in South Greenland lake watersheds (Larsen et al., 2016). Squares are ^{10}Be-dated late Holocene glacial extent (Jomelli et al., 2016; Young et al., 2015; Winsor et al., 2014). C: Durations of Medieval Climate Anomaly (red), Little Ice Age (blue) (1—Moffa-Sánchez and Hall, 2017; 2—Solomina et al., 2016), and peak SSTs (orange) off north Iceland (3—Sicre et al., 2014) and southeast Greenland (4—Miettinen et al., 2015). D: Scoop Lake maximum temperature (*T*) anomaly inferred from chironomid $\delta^{18}O$ (red), and temperatures inferred at Greenland Ice Sheet Project 2 (GISP2, blue; Alley, 2004). E: Extratropical Northern Hemisphere (NH) temperature (Christiansen and Ljungqvist, 2012).

well with temperature trends at Scoop Lake. Neoglacial advance nearby culminated by 1.8 ka, with subsequent retreat then advance at 500 CE (Larsen et al. 2016) (Fig. 2B). An outlet glacier near Narsarsuaq (50 km north of Scoop Lake) reached its late Holocene maximum between 500 and 800 CE, coincident with inferred cool temperatures (Fig. 2B) (Winsor et al., 2014). However, across the broader western dipole of the NAO, proxy records paint a complex picture of MCA conditions. We propose and explore explanations for these seemingly conflicting patterns.

1. There was no prolonged, dominantly NAO+ configuration during the MCA. More positive water vapor and precipitation $\delta^{18}O$ values—such as those observed during most of the MCA at our study site—are delivered to South Greenland during NAO– configurations (Bonne et al., 2014). Additionally, while several mountain glacier records show LIA-comparable advance during the MCA, no centennially resolved terrestrial proxy records from Greenland or Baffin Island show four centuries of cold Medieval conditions. The isotope record at Scoop Lake shows 1.5 °C of warming beginning at 900 CE and a generally warm MCA, but with variable conditions including cooler decades around 1150 CE. Brief cold spells during overall milder temperatures following 1500 yr of insolation-forced Neoglacial cooling may have permitted LIA-equivalent advance of some sensitive mountain glaciers during the MCA. This explanation does not require that the NAO was in a dominant negative configuration during the MCA, but rather suggests that South Greenland warmed via another mechanism. Our results support a recent proxy-informed NAO model reconstruction that found no positive anomaly during the MCA (Ortega et al., 2015).
2. Late Holocene climate in coastal South Greenland was modulated by subpolar gyre circulation, which could explain warming there during the MCA. Enhanced Labrador Sea deep-water formation associated with a strong subpolar gyre between 1000 and 1400 CE could have enhanced warm-water delivery to coastal areas around South Greenland via the Irminger Current, raising SSTs and coastal air temperatures. Coeval SST anomalies of approximately the same magnitude as temperatures at Scoop Lake are documented off the north Icelandic shelf and southeast Greenland (Figs. 1 and 2C) (Miettinen et al., 2015; Sicre et al., 2014). Cold-biased benthic foraminifera decrease between 1000 and 1300 CE in Igaliku fjord, <10 km from Scoop Lake, providing local evidence for warm Irminger Current influence (Lassen et al., 2004).

Strong warming from changes in the subpolar gyre was likely localized around South Greenland and Iceland, with less influence north of Davis Strait and the Norse Western Settlement. Much of the warm Irminger Current component of the West Greenland Current, responsible for South Greenland's mild climate, is diverted south of Davis Strait (Seidenkrantz, 2013) (Fig. 1). This geographically variable influence of the West Greenland Current helps explain modern climatic heterogeneity in the region, and likewise could contribute to spatial variability in past climate trends. SST decreases off Labrador (Canada), and indicators of Labrador Sea water south of Iceland support a vigorous subpolar gyre and enhanced cold Labrador Current during the MCA (Moffa-Sánchez and Hall, 2017; Sicre et al., 2014), which could have driven contrasting cool conditions favorable for glacier advance on Baffin Island.

CONCLUSIONS AND IMPLICATIONS

We conclude from our reconstruction of oxygen isotopes of precipitation that the MCA in southernmost Greenland near the Norse Eastern Settlement was generally warmer between 900 and 1400 CE, reversing 1500 yr of Neoglacial cooling and overlapping with the arrival of Norse settlers at 985 CE (Jones, 1986). Cold conditions following the MCA began with a period of exceptional climate instability (the period of highest sample-to-sample variability in our isotope record) from 1350 to 1450 CE that preceded Norse abandonment ca. 1450 CE. Multiple factors have been linked to Norse settlement and abandonment of Greenland, including climate change, food shortages, and cultural dynamics (Dugmore et al., 2012; Hartman et al., 2017). Our results now provide direct evidence for major contemporaneous climate shifts within the Eastern Settlement.

The climate of South Greenland over the past 1500 yr has been largely in phase with that of northern Europe and has probably been strongly influenced by major subpolar ocean currents. Warm MCA temperatures in South Greenland, inferred here from a proxy sensitive to NAO-related changes in atmospheric circulation, do not support the hypothesis that the MCA was a period of dominantly positive NAO conditions. MCA glacier advances documented on the coasts of northern Baffin Bay may be compatible with warmth in South Greenland due to different effects of the subpolar gyre north of Davis Strait, or those advances could record regional short-term cooling superimposed over general MCA warmth. Additional studies reconstructing subcentennial climate variations around Greenland and its coastal margins are needed to diagnose the complex mechanisms of climate change there. This is especially urgent given the critical role that this region, home to vulnerable components of the Atlantic overturning circulation and to a dynamic sector of the Greenland Ice Sheet, will play in future global change.

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