Quaternary Science Reviews xxx (2016) 1–10

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Alkenone-based reconstructions reveal four-phase Holocene temperature evolution for High Arctic Svalbard

Willem G.M. van der Bilt [a, b, *], William J. D'Andrea [c], Jostein Bakke [a, b], Nicholas L. Balascio [d], Johannes P. Werner [a, b], Marthe Gjerde [a, b], Raymond S. Bradley [e]

[a] *Department of Earth Science, University of Bergen, Allégaten 41, 5007, Bergen, Norway*
[b] *Bjerknes Centre for Climate Research, Bergen, Norway*
[c] *Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA*
[d] *Department of Geology, College of William & Mary, Williamsburg, VA 23185, USA*
[e] *Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA*

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form
12 October 2016
Accepted 14 October 2016
Available online xxx

Keywords:
Svalbard
Holocene
Paleothermometry
Alkenones
U_{37}^{K}

ABSTRACT

Situated at the crossroads of major oceanic and atmospheric circulation patterns, the Arctic is a key component of Earth's climate system. Compounded by sea-ice feedbacks, even modest shifts in the region's heat budget drive large climate responses. This is highlighted by the observed amplified response of the Arctic to global warming. Assessing the imprint and signature of underlying forcing mechanisms require paleoclimate records, allowing us to expand our knowledge beyond the short instrumental period and contextualize ongoing warming. However, such datasets are scarce and sparse in the Arctic, limiting our ability to address these issues. Here, we present two quantitative Holocene-length paleotemperature records from the High Arctic Svalbard archipelago, situated in the climatically sensitive Arctic North Atlantic. Temperature estimates are based on U_{37}^{K} unsaturation ratios from sediment cores of two lakes. Our data reveal a dynamic Holocene temperature evolution, with reconstructed summer lake water temperatures spanning a range of ~6–8 °C, and characterized by four phases. The Early Holocene was marked by an early onset (~10.5 ka cal. BP) of insolation-driven Hypsithermal conditions, likely compounded by strengthening oceanic heat transport. This warm interval was interrupted by cooling between ~10.5–8.3 ka cal. BP that we attribute to cooling effects from the melting Northern Hemisphere ice sheets. Temperatures declined throughout the Middle Holocene, following a gradual trend that was accentuated by two cooling steps between ~7.8–7 ka cal. BP and around ~4.4–4.3 ka cal. BP. These transitions coincide with a strengthening influence of Arctic water and sea-ice in the adjacent Fram Strait. During the Late Holocene (past 4 ka), temperature change decoupled from the still-declining insolation, and fluctuated around comparatively cold mean conditions. By showing that Holocene Svalbard temperatures were governed by an alternation of forcings, this study improves our understanding of Arctic climate dynamics.

1. Introduction

Arctic surface temperatures have increased twice as fast as the global average over recent decades (Screen and Simmonds, 2010). This so-called Arctic amplification of warming has also been predicted by models and reconstructed from proxy archives and thus seems a persistent feature of the Arctic climate system (Serreze and Barry, 2011). Consequently, even modest changes in forcing have the potential to drive large climate responses in the region. The Arctic therefore provides a uniquely sensitive environment to study past natural climate variability beyond the short (±100 yrs) instrumental period. Doing so allows us to capture the envelope of natural climate variability, providing a valuable context to assess the future implications of ongoing warming.

To do this requires the investigation of geological archives of past climate, which remain few and far between in the Arctic (Wanner, 2014). Furthermore, available datasets often have inadequate resolution to resolve rapid shifts (Sundqvist et al., 2014), such as those unfolding at present. Therefore, the climate history of the

---

* Corresponding author. Department of Earth Science, University of Bergen, Allégaten 41, 5007, Bergen, Norway.
E-mail address: willemvanderbilt@gmail.com (W.G.M. van der Bilt).

http://dx.doi.org/10.1016/j.quascirev.2016.10.006

present Holocene interglacial remains poorly constrained on sub-orbital timescales (Wanner et al., 2011 and references therein). However, available high-resolution records reveal complex spatio-temporal Holocene climate patterns in the Arctic on multi-centennial timescales, seemingly influenced by external forcing mechanisms (e.g. solar activity and ice-sheet induced cooling) as well as internal dynamics (e.g. reorganization of Atlantic oceanic and atmospheric circulation patterns) (e.g. Bond et al., 2001; Darby et al., 2012; Debret et al., 2007; Olsen et al., 2012; Rohling and Pälike, 2005; Yu et al., 2010).

The High Arctic Svalbard archipelago is particularly sensitive to such climate shifts due to its location near the interface of warm Atlantic and cold Arctic waters (Werner et al., 2015). Compounded by sea ice feedbacks (Müller et al., 2009; Pithan and Mauritsen, 2014), shifts in the relative contribution of these water masses in the Fram Strait west of Spitsbergen can significantly impact ocean-atmosphere heat fluxes and thus regional temperature. Here, we present two quantitative Holocene-length terrestrial temperature reconstructions from Svalbard, based on alkenone paleothermometry (U^K_{37}) from sediments of two lakes on northwestern Spitsbergen. Comparing these records to other regional paleoclimate evidence, we examine the evolution and drivers of Holocene summer temperature in the Nordic Seas region of the Atlantic Arctic.

2. Setting

We investigated two lakes on coastal northwest Svalbard, Lake Hakluyt (Hakluytvatnet) on Amsterdam Island (79.77°N, 10.74°E) and Lake Hajeren on the Mitra peninsula of Spitsbergen (79.26°N, 11.52°E) (Fig. 1B). The former lies adjacent to the ocean at 12 m a.s.l. and measures 0.10 km^2 (Gjerde et al., this issue). Lake Hajeren is situated further inland, has a surface area of 0.23 km^2 and is situated at 35 m a.s.l (van der Bilt et al., 2015b). Both sites are above reported Holocene marine limits (Landvik et al., 2013; Salvigsen, 1979), but Hakluytvatnet is only separated from the ocean by a SW-NE-trending beach ridge (Fig. 2B). Two small cirque glaciers (North and South) drain into Lake Hajeren (Fig. 2A), while the Hakluytvatnet catchment has been glacier-free throughout the Holocene (Gjerde et al., this issue; van der Bilt et al., 2015a). Although largely unvegetated, both catchments fall within the same bioclimatic unit of mesic Arctic Tundra (Elvebakk, 2005). The nearest meteorological station at the settlement of Ny Ålesund (Fig. 1B) recorded an average annual air temperature of −5.2 °C between 1981 and 2010 (Førland et al., 2011), while summer (JJA) conditions have been characterized by a mean of 3.8 °C. Instrumental observations go back to 1898 and reveal a 2.6 °C per century warming trend (Nordli et al., 2014). As stated, local climate is strongly influenced by the interplay between the warm Atlantic waters of the West Spitsbergen current and the cold Arctic East Spitsbergen current (e.g. Werner et al., 2015) (Fig. 1B). Attendant climate responses are amplified by sea-ice feedbacks (Müller et al., 2009), controlling heat fluxes between ocean and atmosphere (Screen and Simmonds, 2010).

3. Methods

3.1. Analyses

To quantify changes in Holocene summer (JJA) lake water temperature, we employed biomarker-based paleothermometry, using the alkenone-unsaturation index U^K_{37} after Brassell et al. (1986) (Eq. (1)). The U^K_{37} index varies with alkenone production temperature and is used for paleothermometry in marine and lacustrine sediments, including High Arctic lakes on Greenland and Svalbard (D'Andrea et al., 2011; D'Andrea et al., 2012).

$$U^K_{37} = \frac{C37:2 - C37:4}{C37:2 + C37:3 + C37:4} \quad (1)$$

Samples were extracted in 1 cm intervals from Hajeren core HAP0212 (n = 100) and Hakluytvatnet core AMP112 (n = 84) (Fig. 2). Both were extracted in the summer of 2012 with the use of a piston coring device. Lithological descriptions are presented by van der Bilt et al. (2015b) and Gjerde et al. (this issue), respectively. After freeze-drying, samples were weighted, homogenized and solvent-extracted with a Dionex ASE350 for lipid extraction using 9:1 dichloromethane (DCM): methanol. Sample blanks (pre-combusted sand) were routinely used to monitor contamination.

Total Lipid Extracts (TLE) were evaporated in a Biotage TurboVap under a stream of nitrogen gas. After transferring TLE to 4 ml vials, flash silica-gel chromatography (100% active silica gel) was used to further isolate constituent lipids. Samples were eluted with 4 bed volumes (~4 ml) of hexane (F1), DCM (F2), and methanol (F3). All lipid fractions were then collected in 2 ml vials.

After separation, the F2 fraction, containing alkenones, was saponified overnight at 75 °C using 0.5M KOH in 95% methanol/H_2O. Alkenones were recovered by liquid-phase separation (three rinses for each sample) using toluene. Subsequently, extracts were transferred back into 2 ml vials, evaporated under a stream of nitrogen gas and brought up in toluene to the necessary dilution for analysis with a Thermo TRACE Ultra Gas Chromatograph Flame Ionization Detector (GC-FID). Samples for down-core analysis were measured using a DB-1 column (60 m, 0.25μm ID, 0.1 μm film thickness). Representative samples were also analyzed down-core using a VF200MS column to identify the presence and quantify the fractional abundances of tri-unsaturated isomers (Longo et al., 2013). An alkenone standard was injected every six samples to monitor analytical precision of the U^K_{37} measurements, which was better than ~0.0045 (2σ) over the course of analysis.

4. Chronology

We used the terrestrial macrofossil-derived radiocarbon ages published by van der Bilt et al. (2015b) for Lake Hajeren (n = 21) and Gjerde et al. (this issue) for Hakluytvatnet (n = 28) to date the investigated sediment cores. To capture and acknowledge the full range of calibration uncertainty inherent to our age-depth models, we calibrated these dates with the Bacon 2.2 package (Blaauw and Christen, 2011) (Fig. 3A and B), using the IntCal13 curve and considering all generated age-depth iterations (Reimer et al., 2013). This approach allows us to assess the degree similarities between both proxy time series within the prescribed ranges of uncertainty. The age-depth model for Lake Hajeren that was published by van der Bilt et al. (2015b) falls within this envelope of chronological uncertainty.

5. Results and discussion

5.1. Temperature calibration

The similar C37 distributions of alkenones from Lake Hajeren and Hakluytvatnet suggest that the producer in each site is the same haptophyte (Wang et al., 2015) (Figs. 4 and 5). Specifically, the high abundance of tetra-unsaturated isomers in both populations as well as the presence of both ethyl and methyl C38 alkenones suggests that this species belongs to the lacustrine Group I phylotype (Figs. 4 and 5) (D'Andrea et al., 2016). Also, samples in both lakes contain two tri-unsaturated C37 isomers, a characteristic that

Please cite this article in press as: van der Bilt, W.G.M., et al., Alkenone-based reconstructions reveal four-phase Holocene temperature evolution for High Arctic Svalbard, Quaternary Science Reviews (2016), http://dx.doi.org/10.1016/j.quascirev.2016.10.006