Quaternary Science Reviews 126 (2015) 201–218

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Reconstruction of glacier variability from lake sediments reveals dynamic Holocene climate in Svalbard

Willem G.M. van der Bilt [a, b, *], Jostein Bakke [a, b], Kristian Vasskog [b, c], William J. D'Andrea [d], Raymond S. Bradley [e], Sædis Ólafsdóttir [a, b]

[a] Department of Earth Science, University of Bergen, Allégaten 41, 5007, Bergen, Norway
[b] Bjerknes Centre for Climate Research, Allégaten 55, 5020, Bergen, Norway
[c] Uni Climate, Uni Research, Allégaten 55, 5007 Bergen, Norway
[d] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
[e] Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA

ARTICLE INFO

Article history:
Received 26 May 2015
Received in revised form
24 August 2015
Accepted 1 September 2015
Available online xxx

Keywords:
Holocene climate
Svalbard
Glacier activity
Lake sediments
Numerical analyses

ABSTRACT

The Arctic is warming faster than anywhere else on Earth. Holocene proxy time-series are increasingly used to put this amplified response in perspective by understanding Arctic climate processes beyond the instrumental period. However, available datasets are scarce, unevenly distributed and often of coarse resolution. Glaciers are sensitive recorders of climate shifts and variations in rock-flour production transfer this signal to the lacustrine sediment archives of downstream lakes. Here, we present the first full Holocene record of continuous glacier variability on Svalbard from glacier-fed Lake Hajeren. This reconstruction is based on an undisturbed lake sediment core that covers the entire Holocene and resolves variability on centennial scales owing to 26 dating points. A toolbox of physical, geochemical (XRF) and magnetic proxies in combination with multivariate statistics has allowed us to fingerprint glacier activity in addition to other processes affecting the sediment record. Evidence from variations in sediment density, validated by changes in Ti concentrations, reveal glaciers remained present in the catchment following deglaciation prior to 11,300 cal BP, culminating in a Holocene maximum between 9.6 and 9.5 ka cal BP. Correspondence with freshwater pulses from Hudson Strait suggests that Early Holocene glacier advances were driven by the melting Laurentide Ice Sheet (LIS). We find that glaciers disappeared from the catchment between 7.4 and 6.7 ka cal BP, following a late Hypsithermal. Glacier reformation around 4250 cal BP marks the onset of the Neoglacial, supporting previous findings. Between 3380 and 3230 cal BP, we find evidence for a previously unreported centennial-scale glacier advance. Both events are concurrent with well-documented episodes of North Atlantic cooling. We argue that this brief forcing created suitable conditions for glaciers to reform in the catchment against a background of gradual orbital cooling. These findings highlight the climate-sensitivity of the small glaciers studied, which rapidly responded to climate shifts. The start of prolonged Neoglacial glacier activity commenced during the Little Ice Age (LIA) around 700 cal BP, in agreement with reported advances from other glaciers on Svalbard. In conclusion, this study proposes a three-stage Holocene climate history of Svalbard, successively driven by LIS meltwater pulses, episodic Atlantic cooling and declining summer insolation.

1. Introduction

Instrumental observations suggest that the Arctic has been changing faster than any other region on the Northern hemisphere over the past decades (Serreze and Barry, 2011). This amplified response has consistently been simulated by climate models for a future with increased atmospheric greenhouse gas concentrations (Pithan and Mauritsen, 2014). But though albedo and temperature feedbacks have been suggested (Screen and Simmonds, 2010), the drivers of Arctic climate variability have yet to be fully constrained (Miller et al., 2010). It is important to improve our understanding of

* 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.2015.09.003

forcing mechanisms, as the Arctic has a disproportionately large influence on global climate (McGuire et al., 2006; Solomon, 2007). As the paradigm of a stable Holocene climate has shifted (Bond et al., 2001; Overpeck et al., 1997), Holocene proxy time-series are increasingly considered as potential analogues for future climate, and may help assess the range of natural Arctic climate variability (McKay and Kaufman, 2014; Wanner et al., 2011).

However, Arctic climate proxy datasets are scarce and unevenly distributed (Wanner et al., 2011). Moreover, records often cover only parts of the Holocene and lack robust chronological control (Sundqvist et al., 2014). Continuous, well-dated and high-resolution archives are required to resolve the temporal and spatial signature of Holocene Arctic climate variability. Glaciers are ubiquitous in the Arctic and rapidly respond to shifts in summer temperature and winter precipitation (Oerlemans, 2005; Østrem and Liestøl, 1964). This sensitive response to climate change is captured by variations in minerogenic rock-flour production and may be recorded in lacustrine sediment archives of downstream glacier-fed lakes (Karlén, 1976, 1981). Monitoring data demonstrate that variations in the flux of minerogenic sediments into glacier-fed lakes provide a robust high-resolution record of glacier activity and size (Leemann and Niessen, 1994a; Liermann et al., 2012; Roland and Haakensen, 1985). The signature of rock-flour in lacustrine sediments therefore serves as a climate proxy that has been widely applied (Bakke et al., 2010; McKay and Kaufman, 2009; Rosqvist and Schuber, 2003; Simonneau et al., 2014). Indeed, sediment records from glacier-fed lakes are rated among the best continuous high-resolution terrestrial proxy archives available (Ashley, 1995; Carrivick and Tweed, 2013). Here, the conceptual model described above has been further developed into a multi-proxy approach that integrates physical (Bakke et al., 2005), magnetic (Paasche et al., 2007) and geochemical tools (Bakke et al., 2009), in combination with numerical techniques (Bakke et al., 2013; Vasskog et al., 2012).

We present a sediment record from glacier-fed Lake Hajeren in northwest Spitsbergen that encompasses the entire Holocene. This region sits at the crossroads of Arctic and Atlantic water masses and is therefore sensitive to climate shifts (Rasmussen et al., 2014; Werner et al., 2013). Nonetheless, the coverage of high-resolution terrestrial climate proxy records in the area is sparse. The main goal of this study is to provide a reconstruction of Holocene glacier activity that will improve our understanding of centennial-scale Arctic climate variability. To this end, we apply a multi-proxy toolbox to ensure rigor in our interpretations. The methods also enable us to detect other catchment and lake processes that leave an imprint in the lake sediment record. Accurate detection of sediments reflecting glacier activity requires a full understanding of these processes, which include, but are not limited to, paraglacial redeposition (Ballantyne, 2002), mass wasting (Vasskog et al., 2011), lake stratification (Leemann and Niessen, 1994a; Richards et al., 2012) and redox processes (Lamoureux and Gilbert, 2004). Moreover, to ensure the chronological robustness required to resolve centennial climate variability (Sundqvist et al., 2014), we have used a combination of radiocarbon dating and Paleomagnetic Secular Variations (PSV). Finally, we integrate this study into a regional paleoclimatic context by comparing our site-specific findings to other high-resolution proxy records from the Arctic sector of the North-Atlantic.

2. Setting

Hajeren, the distal glacier-fed lake investigated in this study, measures 0.23 km^2 and is located on the Mitrahalvøya Peninsula in Northwest Spitsbergen (79°15′33.47″N 11°31′4.25″E) (Fig. 1). Bathymetric profiling reveals two basins with a maximum depth of 19.5 m (Fig. 2). The lake's surface elevation is 35 m a.s.l., placing Hajeren slightly above the local marine limit reported by Landvik et al. (2013) (32 m a.s.l.).

The catchment of Lake Hajeren covers 2.96 km^2 of which 0.25 km^2 is presently glacier-covered. Two northwest-facing cirque glaciers drain into the lake (Fig. 1), which will henceforth be referred to as North and South glaciers. Based on field observations (Van der Bilt et al., 2015), the North Glacier (0.8 km^2) is believed to be polythermal, while the South Glacier (0.17 km^2) may have turned cold-based due to recent thinning. Based on documented past glacier front positions (NPI, 2015) and a lack of geomorphic evidence (e.g. tectonised sediments and looped moraines), we argue that both glaciers are not surging. Also, using a historical aerial photographs (NPI, 1936), both have been retreating for at least 78 years and likely since the Little Ice Age (LIA). This period of favorable conditions for glacier growth commenced after 1.3 ka cal BP and culminated on Svalbard during the 19th century (Salvigsen and Høgvard, 2006). Lake Hajeren is drained by an ephemeral spillway, enhancing its capacity to retain glacigenic suspended load (Dahl et al., 2003).

The glacial geomorphology of the catchment is characterized by two sets of terminal moraine deposits that are indicated as stages 1 and 2 in Fig. 1. Based on aerial photographs from 1936 (NPI, 1936), Stage 2 moraines were deposited during the culmination of the Little Ice Age (LIA). The more distal Stage 1 moraines are exclusively found in front of the more erosive polythermal North glacier and comprise a complex of mounds (Van der Bilt et al., 2015). Their weathered appearance and position outside Stage 2 moraine deposits suggests that they were possibly deposited during a pre-LIA glacier maximum, in agreement with findings from nearby catchments (Reusche et al., 2014; Røthe et al., 2015).

Bedrock geology comprises Proterozoic protoliths of the Krossfjorden group that were metamorphosed during the Grenvillian orogeny (Dallmann, 2015). Local bedrock predominantly consists of NNW–SSE trending Signehamna formation schists that are horizontally overlain by marble belonging to the Generalfjellet formation in southern Mitrahalvøya (Krasilšcikov, 1975).

Climate in Spitsbergen is influenced by the West and East Spitsbergen currents (Rasmussen et al., 2014). The former transports warm and saline Atlantic waters northwards (Aagaard-Sørensen et al., 2014), while the latter brings in cold water from the Arctic Ocean (Loeng, 1991). The interplay between these distinctly different water masses create a climate that is highly sensitive to shifting oceanic and atmospheric conditions (Rasmussen et al., 2014) as well as changes in sea ice extent (Benestad et al., 2002; Müller et al., 2012). At present, Northwest Spitsbergen has a maritime polar climate with an average annual temperature of −5 °C and 427 mm of annual precipitation measured at nearby Ny Ålesund for the 1980–2010 period (Førland et al., 2012). Temperatures have been recorded since 1898 and reveal highly variable, but generally warming conditions during the 20th century (Nordli et al., 2014). Moreover, the last 30 years are characterized by continuous warming with the warmest years on record occurring during the past decade (Nordli, 2010).

3. Material & methods

3.1. Coring and mapping

In August 2012, a seismic survey was carried out on Lake Hajeren, using a Malå Ground Penetrating Radar (GPR) system fitted with a 50 Mhz antenna. Post-processing of these data using the RadExplorer software package revealed a fairly homogeneous distribution of soft sediments over two sub-basins henceforth referred to as North and South basins, with water depths of 13 and