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The Island of Amsterdamøya: A key site for studying past climate in the Arctic Archipelago of Svalbard

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ABSTRACT

This paper introduces a series of articles assembled in a special issue that explore Holocene climate evolution, as recorded in lakes on the Island of Amsterdamøya on the westernmost fringe of the Arctic Svalbard archipelago. Due to its location near the interface of oceanic and atmospheric systems sourced from Arctic and Atlantic regions, Amsterdamøya is a key site for recording the terrestrial response to marine and atmospheric changes. We employed multi-proxy approaches on lake sediments, integrating physical, biogeochemical, and isotopic analyses to infer past changes in temperature, precipitation, and glacier activity. The results comprise a series of quantitative Holocene-length paleoclimate reconstructions that reveal different aspects of past climate change. Each of the four papers addresses various facets of the Holocene climate history of north-western Svalbard, including a reconstruction of the Annabreen glacier based on the sedimentology of the distal glacier-fed lake Gjøavatnet, a reconstruction of changing hydrologic conditions based on sedimentology and stratigraphy in Lake Hakluytvatnet, reconstruction of summer temperature based on alkenone paleothermometry from lakes Hakluytvatnet and Hajeren, and a hydrogen isotope-based hydrological reconstruction from lake Hakluytvatnet. We also present high-resolution paleomagnetic secular variation data from the same lake, which document important regional magnetic field variations and demonstrate the potential for use in synchronizing Holocene sedimentary records in the Arctic. The paleoclimate picture that emerges is one of early Holocene warmth from ca. 10.5 ka BP interrupted by transient cooling ca. 10-8ka BP, and followed by cooling that mostly manifested as two stepwise events ca. 7 and 4 ka BP. The past 4ka were characterized by dynamic glaciers and summer temperature fluctuations decoupled from the declining summer insolation.

1. Introduction

There is no region on Earth where climate is changing as fast as in the Arctic, as the effects of global greenhouse forcing are strengthened by regional feedbacks (e.g. sea-ice) (Miller et al., 2010). The rapid climate transition underway in the Arctic is observed as temperatures rising twice as fast as the global average (Screen and Simmonds, 2010), as well as by increases in precipitation (Boisvert and Stroeve, 2015; Masson-Delmotte et al., 2013). By increasing the surface area of open water, on-going sea-ice retreat enhances evaporation and heat fluxes from the surface ocean, intensifying the regional hydrological cycle and amplifying warming (Bintanja and Selten, 2014; Boisvert and Stroeve, 2015; Screen and Simmonds, 2010). Indeed, climate model projections suggest that Arctic precipitation may increase by more than 50% during the 21st century (Bintanja and Selten, 2014), while temperatures could rise by 11 °C above the 1986–2005 mean (Van Oldenborgh et al., 2013). The anticipated climatic changes will pose significant challenges to societies in the Arctic and beyond.

Despite the observed rates of change and its anticipated impacts, our knowledge of the *natural* variability of the Arctic climate system remains limited due to the scarcity of data and the relatively

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short period (≤100 yrs) of instrumental observations. These natural variations will be superimposed on anthropogenic change, and should therefore be part of any assessment of future climate. Furthermore, an evaluation of the spatiotemporal patterns of past natural variability is necessary to determine the sensitivities and connections within the climate system. Hence, an informed understanding of the history, causes, and impacts of natural arctic climate variations is imperative assessment of future change. This notion has given rise to a number of critical questions in the scientific community: what is the range of natural Arctic climate variability on societally relevant (i.e. multi-decadal to centennial) timescales? What external and internal forcing mechanisms and boundary conditions influence the timing and patterns of natural climate variability in the Arctic? How can the past provide useful analogues to the future state of Arctic climate?

Compared to the glacial periods, the Holocene has been characterized by large-scale climatic boundary conditions (e.g. albedo, sea-level, ice-sheet configuration, oceanography) similar to the present and thus represents a critical reference period when trying to understand teleconnections and feedbacks that may drive future change in the Arctic. For example, the North Atlantic Oscillation (NAO), the Atlantic sector manifestation of the Arctic Oscillation (AO), is the leading mode of climate variability (ignoring the global warming signature) recognized in instrumental observations from the North Atlantic Arctic. This atmospheric phenomenon represents changes in the distribution of atmospheric mass between high- and mid-latitudes and has a major impact on the distribution of heat and moisture throughout the Arctic (Thompson and Wallace, 1998). Paleoenvironmental reconstructions have revealed the importance of these systems with respect to past variability in the Arctic system, extending our understanding beyond just the recent instrumental period (Darby et al., 2012; Funder et al., 2011; Olsen et al., 2012; Renssen et al., 2009). The spatial climate patterns associated with the AO/NAO provide just one example of the importance of internal climate dynamics in determining Arctic climate. The development of a greater number of spatially distributed climate reconstructions is critical to document the connections and sensitivities within the Arctic climate system. Our aim is to fill part of the knowledge gap through our cross-disciplinary paleoclimate investigations of Amsterdamøya. In this special issue, we have collated lacustrine sedimentary records that record changes in Holocene temperature, precipitation and glacier activity – key parameters of atmospheric climate, on Svalbard – strategically located at the dynamic interface of competing Arctic and Atlantic influences. To extract this sensitive climate signal from the investigated sediments, we used a range of analytical techniques, including novel sedimentological, organic geochemical, and isotope approaches.

2. Study area

The Island of Amsterdamøya (N79°46′, E10°45′) (Fig. 1) is one of the northernmost islands in the Arctic Archipelago of Svalbard. It was discovered by Dutch explorer Willem Barents in 1596 CE and was later occupied by Dutch whalers, who built a seasonal whaling station on the Island during the peak of their operations in the 17th century. The main Dutch settlement called Smeerenburg (Fig. 1) (Dutch for "blubber town") occupied a flat area on the eastern side of the island. The island measures 18.8 km^2 and is characterized by glacially eroded cirques, steep cliffs, and flat valley floors. The mountain plateau Hollendarberget (Fig. 1) is the highest point on the Island (472 m a.s.l.) and is covered by an allochthonous block field.

Exposure ages on glacial erratics found in the block field at Hollendarberget indicate that the summits of Amsterdamøya have remained ice-free since >80 ka BP, although the valleys were glaciated until 18–15 ka BP (Landvik et al., 2003). Annabreen (0.4 km^2), the largest glacier on the Island, is located in a north-facing valley. There are also two smaller glaciers, Hiertabreen (0.1 km^2) and Retziusbreen (0.2 km^2). The island contains a number of lakes, the largest of which are Gjøavatnet (2 m a.s.l.) and Hakluytvatnet (12 m a.s.l.). Gjøavatnet is supplied by meltwater from Annabreen glacier, while Hakluytvatnet is fed by two perennial snow patches located south of the lake. There are no morphological features indicating the marine limit (ML) on the island, and it is believed to be close to present day sea level (Boulton and Rhodes, 1974; Landvik et al., 1998; Salvigsen, 1979). There has been little postglacial emergence in north-western Svalbard, and neither Amsterdamøya nor Danskøya (to the south) (Fig. 1) display patterns of post-glacial uplift relative to sea level (Boulton and Rhodes, 1974; Landvik et al., 1998; Salvigsen, 1977). Therefore, Gjøavatnet and Hakluytvatnet contain sedimentary accumulation spanning most of the Holocene, despite their proximity to sea level.

The climate of Amsterdamøya is moderated by the West Spitsbergen Current (WSC), the northernmost limb of the Norwegian Atlantic Current (NwAC), which transports warm Atlantic water along the NW coast of Svalbard along its route to the Arctic Ocean (Fig. 1). The warm WSC, and its warming influence on air masses, results in warmer temperatures, greater precipitation, and less sea ice on the western coast of the Svalbard Archipelago than on the eastern coast, which is influenced by the cold East Spitsbergen Current (ESC) (Fig. 1). In addition, the alternating westerlies and the polar-front jet stream, both affected by the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), modulate the present climate of Amsterdamøya.

3. Terrestrial paleoclimate evidence

Our research presented in this special issue builds upon decades of terrestrial studies on Svalbard. The archipelago's glaciation history and its deglaciation have been intensely examined by a combination of stratigraphic studies, (cosmogenic) dating, analysis of offshore marine sediment cores, and bathymetric mapping of submerged glacial landforms (e.g. Gjermundsen et al., 2015; Ingólfsson and Landvik, 2013; Jessen et al., 2010; Landvik et al., 1998). Interestingly, there is no equivocal terrestrial evidence for any significant glacial advance during the Younger Dryas (12.9–11.7 ka BP). Mangerud and Landvik (2007) hypothesize that the most recent episode of glacier advance (i.e., the so-called Little Ice Age (LIA) may have overridden the Younger Dryas front position based on the stratigraphic relationship between dated shorelines and moraines. However, retarded glacio-isostatic uplift rates (Forman et al., 1987; Landvik and Salvigsen, 1987) and changes in fjord sedimentation (Forwick and Vorren, 2009) suggest that glaciers re-advanced in Younger Dryas time, similar to those in Scandinavia (Bakke et al., 2009).

Holocene climatic variations on Svalbard have been examined by many researchers over the past decades. Most Holocene terrestrial paleoclimate studies on Svalbard have focussed on glaciers because they are ubiquitous and act as sensitive climate recorders with the potential to resolve seasonal climate variations (e.g. Humlum et al., 2005; Reusche et al., 2014; Røthe et al., 2015; Svendsen and Mangerud, 1997; van der Bilt et al., 2015; Werner, 1993). A great deal of attention has been focused on studies of the Linné catchment on western Spitsbergen (Fig. 1), a valley occupied by a glacier and downstream lake of the same name. Pioneering work by Svendsen et al. (1987) revealed that the lacustrine sediment record from Lake Linné captured changes in glacier size. A robust chronology published by Snyder et al. (1994) afforded new possibilities for studying the lake record, enabling

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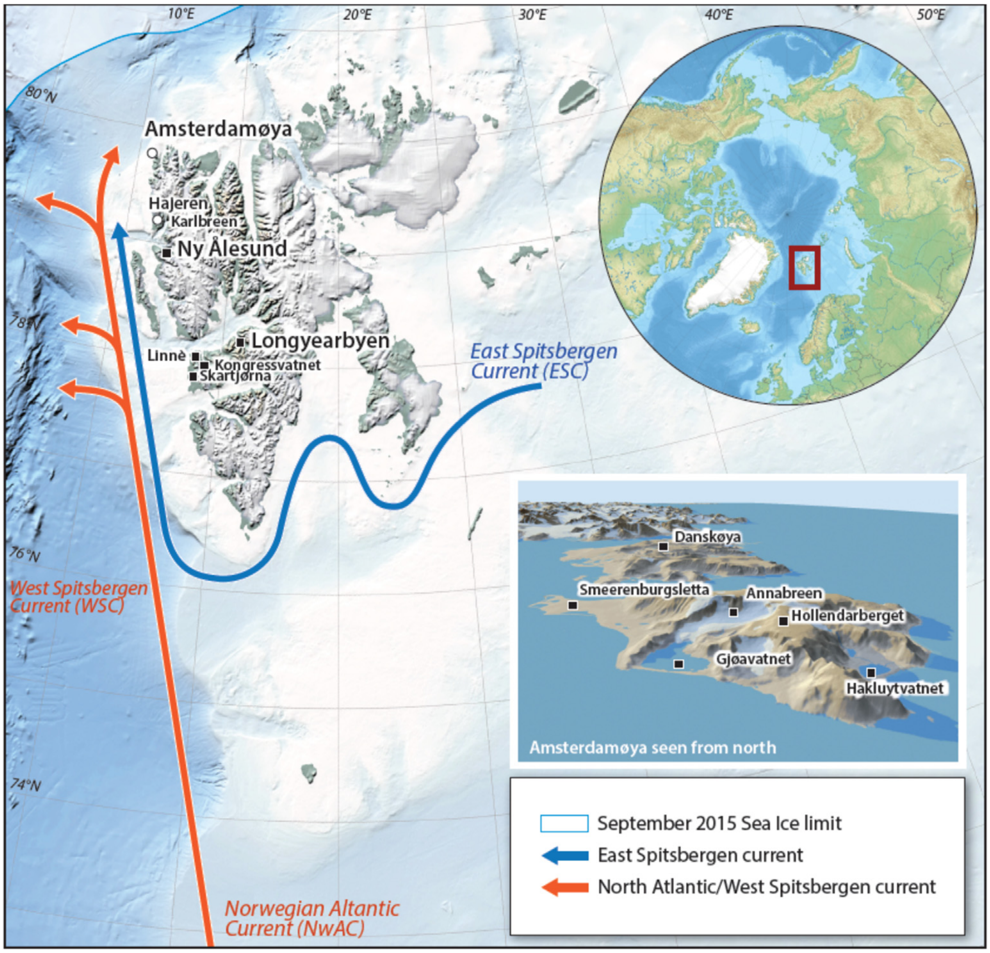

Fig. 1. The Arctic Archipelago of Svalbard and the main ocean currents affecting the climate of Svalbard. The Island of Amsterdamøya (small map) consist of undulating mountain plateaus incised by cirques, carved out by past and present glaciers on the island. At present the largest glacier is Annabreen, calving into lake Gjøavatnet.

Svendsen and Mangerud (1997) to provide the first framework of Holocene glacier change on Svalbard. Changes in sedimentation, lamination and coal content revealed a three-stage glacier history, marked by Early Holocene retreat around 9.7 ka BP, an ice-free Middle Holocene followed by regrowth after 3 ka BP (Neoglacial), which culminated in the 19–20th centuries. Complementing the paleolimnological reconstructions are moraine studies within the Linné catchment. Werner (1993) undertook an ambitious survey of Neoglacial moraines on Svalbard, including those fronting Linnébreen glacier. Lichenometric dating revealed multiple periods of moraine formation (interpreted as glacier advance) during the Neoglacial around ca. 1500, 1000, and between 650 and 200 yr. BP. Reusche et al. (2014) refined this work using cosmogenic nuclide exposure dating of moraine boulders, while hypothesizing about the climatic signature of glacier change. Adding to this picture of dynamic glaciers on Svalbard is the study by Humlum et al. (2005), in which relict vegetation was dated under the glacier Longyearbreen, indicating that the glacier has advanced from about 3 km to its present length of about 5 km during the last 1100 years.

Additional lake-sediment based studies have refined the outlined paleoclimate framework. Røthe et al. (2015) integrated lake sediment-based evidence and geomorphological evidence of glacier changes to provide a continuous reconstruction of equilibrium line altitude (ELA) changes for the Karlbreen valley glacier on north-western Spitsbergen (Figs. 1 and 2). The record, which spans the past 3.5 ka, reveals multiple Neoglacial advances of a similar magnitude to the LIA, in agreement with the observations of Werner (1993) and Reusche et al. (2014). Moreover, a study by Røthe et al. (2015) hint at an Early Holocene glacier maximum prior to 6.7 ka BP, based on the association of an ice-cored moraine system and a lacustrine slumping event. A study by van der Bilt et al. (2015) from the adjacent glaciated catchment of Hajeren Lake support this and indicate a phase of sustained Early Holocene glacier activity until 6.7 ka BP. This lake-sediment-based reconstruction, which targeted small glaciers with a short (decadal) response time, captures two short-lived cycles of glacier growth and melt around 4.3 and 3.1 ka BP. These events, which coincide with phases of glaciers advancing in other mid-high latitude sites of the Northern Hemisphere (Wanner et al., 2008), highlight the sensitivity of the Svalbard cryosphere to rapid climate perturbations.

In addition to the outlined glacier studies, a number of lake-sediment based studies have explored the potential of different paleoecological tools to reconstruct environmental (climate) change on Svalbard. One lake in particular, Skartjørna on western Spitsbergen (Fig. 1), has been the subject of numerous detailed Holocene studies. Birks (1991) presented a plant macrofossil-based study going back more than 8 ka BP. Based on assemblage changes, this study suggests that Early Holocene mean July temperatures were more than 2 °C warmer than today. Velle et al. (2011) report a chironomid-based temperature reconstruction that shows little to no cooling in summer lake water temperature during the past 1800

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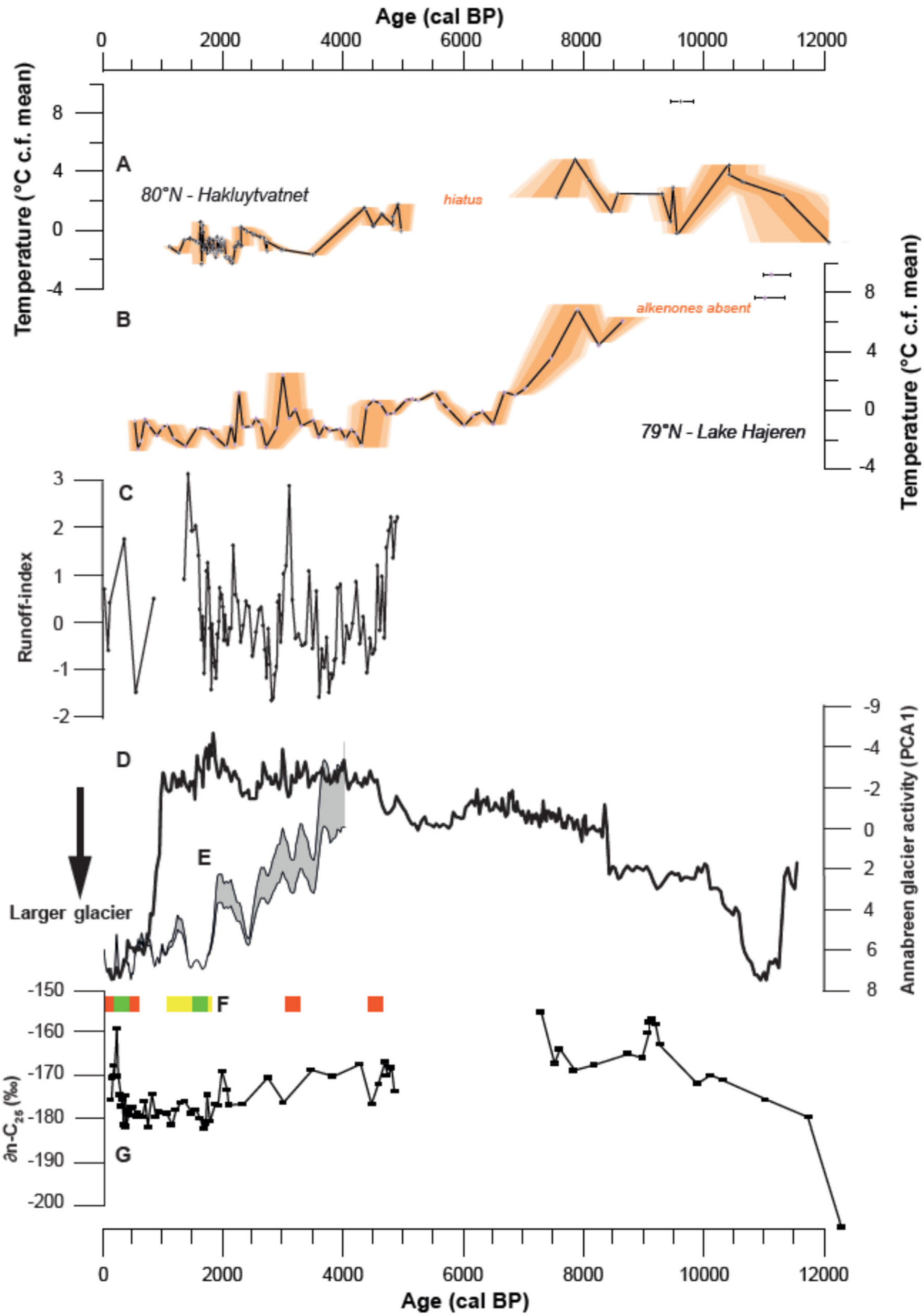

Fig. 2. Summary of findings at the island of Amsterdamøya. In A and B two different alkenone based temperature records plotted with 95%, 90% and 70% confidence intervals in shades of orange (dark-light) and in black the temperature estimate (van der Bilt et al.,2017). In C a runoff proxy based on grain-size fluctuations in lake Hakluytvatnet (Gjerde et al., 2017), in D reconstruction of glacier activity in the Annabreen as recorded in the distal glacier-fed lake Gjøavatnet (de Wet et al., 2017). In E, a previous published glacier reconstruction from the west coast of Svalbard (Røthe et al., 2015); in F (red) glacier activity in recorded in the distal glacier-fed lake Hajeren (van der Bilt et al., 2015), (green) moraines dated with cosmogenic dating in front of Linnébreen (Reusche et al., 2014) and (yellow) timespan when the glacier Longyearbreen was situated up valley from present front position as recorded by macrofossils found in subglacial channels (Humlum et al., 2005); in G hydrogen isotope data from lake Hakluytvatnet interpreted to indicate changes in the isotopic composition of lake water (Balascio et al., 2017).

years. Similarly, using the UK37 alkenone paleothermometer on lake sediments from Lake Kongressvatnet on western Spitsbergen (Fig. 1.), D'Andrea et al. (2012) reported stable lake water temperatures and no evidence for a cooling trend during the past 1800 years. These findings also suggest that summer temperatures during the 18–19th centuries, when glaciers occupied their greatest Holocene positions, weren't particularly cold, while highlighting the extraordinary rates and amplitude of ongoing warming.

4. Marine paleoclimate evidence

Considering the dynamical oceanographic conditions and maritime setting of the investigated sites, paleoceanographic studies offshore of north-western Svalbard (Eastern Fram Strait and wider Nordic Seas region) provide important paleoclimate context for new sediment records from Amsterdamøya. The climate at Amsterdamøya responds rapidly to a reduction in Atlantic inflow due to anticipated sea-ice expansion (Werner et al., 2013). Such shifts in sea ice also have the potential to distress the precipitation patterns in northwestern Svalbard, and (related) mass balance of glaciers (Müller et al., 2012).

Marine-based Holocene paleoclimate reconstructions indicate that the Early Holocene was marked by the arrival of warm, ameliorating Atlantic surface waters after 10 ka BP (Rasmussen et al., 2014; Ślubowska-Woldengen et al., 2007). The influence of warm water at this time is supported by the widespread expansion in the range of thermophilous molluscs (Salvigsen et al., 1992). Maximum Holocene temperatures, attributed to a maximum in Atlantic water advection and summer insolation, were reached prior to 9 ka BP (Risebrobakken et al., 2011; Werner et al., 2015 and references therein). Early Holocene waters in Fram Strait were dominated by the sub-polar planktic foraminifera species *Turborotalia quinqueloba*, indicating the presence of Atlantic Water at least as far as 79°N (near Amsterdamøya). At the same time, high foraminifera and diatom productivity rates suggest that the Arctic Front was nearby (Aagaard-Sørensen et al., 2014). Regional surface water conditions cooled after 8 ka BP. Sarnthein et al. (2003) and Rasmussen et al. (2012) infer cooling of Atlantic water south of Svalbard after 7.4 ka BP, while Werner et al. (2013) report a 3.5 °C (summer) cooling of surface waters in the eastern Fram Strait between 7.2 and 7 ka BP in the eastern Fram Strait. In addition, increases in the polar planktic foraminifera species *Neogloboquadrina pachyderma* (*sinistral).* around 8.2, 6.9 and 6.1 ka BP indicate short-lived cooling phases (Werner et al., 2013). Persistent cooling commenced after 6 ka BP (Werner et al., 2015), synchronous with widespread sea-ice expansion in Fram Strait (Müller et al., 2012) and set against a backdrop of gradually decreasing summer insolation (Huybers, 2006). Cold conditions characterized the late Holocene (Neoglacial), particularly between 5.2 and 2.0 ka BP (Werner et al., 2013). Aagaard-Sørensen et al. (2014) infer an increase in warm Atlantic water inflow penetrating the Svalbard shelf after 3 ka BP. However, Sarnthein et al. (2003) report a number of centennial-scale cooling events that interrupted the warmth associated with strengthening Atlantic water influence. Sea-ice reconstructions also indicate the prevalence of dynamic conditions during the latest Holocene, marked by fluctuations of the sea-ice margins (Müller et al., 2012). In addition, Werner et al. (2015) propose that stratification caused the decoupling of surface and sub-surface waters offshore Svalbard after 3 ka BP, and interpretation that can reconcile the seemingly conflicting evidence of a strengthening Atlantic influx coupled with low sea surface temperatures.

5. Our findings

Our investigation encompasses analyses of lake sediment records from Hakluytvatnet and Gjøavatnet on Amsterdamøya as well as Hajeren on the nearby Mitrahalvøya Peninsula (Fig. 1). To gain a comprehensive and well-resolved understanding of terrestrial paleoclimate, we applied multiple high-resolution proxy techniques and generated robust radiocarbon-based chronologies (Fig. 2). The approaches include physical sedimentology (e.g. bulk density, grain size, organic matter content), scanning XRF-based elemental analysis, alkenone paleothermometry, and leaf wax distribution as well as hydrogen isotope measurements. Three papers in this issue focus on the analysis of sediment cores from Hakluytvatnet (Balascio et al., 2017; Gjerde et al., 2017; van der Bilt et al., 2017) and one on sediments of Gjøavatnet (de Wet et al., 2017).

Gjerde et al. (2017) describe changes in sediment properties since the Younger Dryas that reflect the response of the lake and its catchment to regional climate changes (Fig. 2C). This study indicates that the lake was a nutrient-poor environment during the early Holocene, and that it completely desiccated during the middle Holocene, c. 7.2–5.0 ka BP. At 5.0 ka BP, an apparently abrupt change in moisture balance allowed the lake to fill with water once more and after this time it became dominated by aquatic mosses. Sedimentation over the last 5.0 ka was punctuated by periodic inwashing of minerogenic sediment, which are interpreted to reflect rapid snowmelt events associated with regional climate changes.

Balascio et al. (2017) present leaf wax data from Hakluytvatnet to reconstruct regional hydroclimate during the Holocene. Distinct paleoenvironmental intervals are defined based on changes in the distribution and hydrogen isotopic composition of mid- and long-chain length *n*-alkanes (Fig. 2G). Their data indicate that the lake experienced significant evaporative enrichment from 12.8 to 7.5 ka BP. This is attributed to a greater influence of sub-polar air masses during the early Holocene, c. 12.8–9.5 ka BP, which was followed by a period of generally warm but unstable conditions from c. 9.5–7.5 ka BP, prior to desiccation of the lake. Over the last 5.0 ka BP, an overall decline in lake water δD values is attributed to a progressive increase in the influence of polar air masses, colder conditions, and/or increased length of seasonal ice cover.

Further quantitative analysis of the Hakluytvatnet record is provided by van der Bilt et al. (2017), who present lake water temperature reconstructions using alkenone paleothermometry (Fig. 2A&B). They define four-phases of regional temperature change during the Holocene based on data from Hakluytvatnet and nearby Lake Hajeren. They found strong similarities between the two alkenone-based records, which reveal the warmest temperatures during the early Holocene, except for an interval of cooler temperatures c.10.5–8 ka BP that is attributed to cooling effects from the melting Northern Hemisphere ice sheets. Temperatures then declined from the mid-to late Holocene during two distinct cooling steps, 7–5 ka BP and 4.4–3.5 ka BP. These changes are attributed to the strength of regional oceanic heat transport, sea ice, and conditions in Fram Strait.

de Wet et al. (2017) analysed sedimentation in Gjøavatnet and present a reconstruction of the Annabreen glacier (Fig. 2D). The record indicates that the Annabreen glacier persisted in the catchment during the early Holocene from c. 11.1–8.4 ka BP, and completely melted away, or was at least restricted in size, from 8.4 to 1.0 ka BP when organic matter accumulation significantly increased and minerogenic input decreased. This period was punctuated by at least three abrupt intervals of colder conditions marked by reduced organic matter accumulation (5.9–5.0, 2.7–2.0, and 1.7–1.5 ka BP), but the data suggest that the Annabreen glacier

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did not significantly re-advance until 1.0 ka BP, similar to interpretations from other regional glacier reconstructions.

Together, the records reveal warm conditions in the early Holocene, c. 11–9 ka BP, which is supported by alkenone temperatures, the retreat of the Annabreen glacier, and a period of evaporative enrichment of Hakluytvatnet. The mid to late Holocene is marked by progressive cooling that seems to have occurred in discrete steps and at times associated with dry conditions, at least in one interval that led to the desiccation of Hakluytvatnet. Continued cooling over the last 5.0 ka BP is captured by alkenone-derived temperatures and changes in precipitation isotopes showing the greater influence of polar air masses and reduced oceanic heat transport to the region. Regional cooling eventually resulted in the re-growth of Annabreen c. 1.0 ka BP, as well as the advance of other regional glaciers, prior to present retreat driven by anthropogenic warming.

6. Conclusions

- Amsterdamøya, on the northwest coast of Svalbard and located near the interface of oceanic and atmospheric systems sourced from Arctic and Atlantic regions, is a key site for recording the terrestrial response to marine and atmospheric change.
- We have employed different (multi)proxy approaches on investigated lake sediments, integrating physical, biogeochemical and isotopic analyses with advanced chronological tools such as radiocarbon dating on microfossils and PSV to infer past changes in temperature, precipitation and the cryosphere.
- The results comprise a series of quantitative Holocene-length paleoclimate reconstructions that reveal different aspects of natural climate change.
- The results indicate a three-phased Holocene climate evolution; warm but unstable early Holocene (10.5ka – 7.8k BP); gradual, stepwise cooling until c. 4 ka BP until the onset of the Neoglacial.
- Our findings identifies distinct intervals of rapid change. These transitions underscore the dynamic non-linear behavior of regional climate, confirming the potential for abrupt climate transitions.
- We recommend intensified research in the Arctic with a particular focus on high-resolution climate reconstructions to further investigate *tipping points* in the Arctic climate system, a discussion relevant for placing present day changes into a longer time perspective.

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