
3-1-2018

The Island of Amsterdamøya: A Key Site for Studying Past Climate in the Arctic Archipelago of Svalbard

Jostein Bakke
Universitetet i Bergen

Nicholas Balascio
William & Mary

Willem G.M. van der Bilt
Universitetet i Bergen

Raymond Bradley
University of Massachusetts Amherst

William J. D' Andrea
Lamont-Doherty Earth Observatory

See next page for additional authors

Follow this and additional works at: https://scholarworks.smith.edu/geo_facpubs



Part of the [Geology Commons](#)

Recommended Citation

Bakke, Jostein; Balascio, Nicholas; van der Bilt, Willem G.M.; Bradley, Raymond; D' Andrea, William J.; Gjerde, Marthe; Ólafsdóttir, Sædís; Røthe, Torgeir; and De Wet, Greg, "The Island of Amsterdamøya: A Key Site for Studying Past Climate in the Arctic Archipelago of Svalbard" (2018). Geosciences: Faculty Publications, Smith College, Northampton, MA.
https://scholarworks.smith.edu/geo_facpubs/149

This Article has been accepted for inclusion in Geosciences: Faculty Publications by an authorized administrator of Smith ScholarWorks. For more information, please contact scholarworks@smith.edu

Authors

Jostein Bakke, Nicholas Balascio, Willem G.M. van der Bilt, Raymond Bradley, William J. D' Andrea, Marthe Gjerde, Sædís Ólafsdóttir, Torgeir Røthe, and Greg De Wet

Introduction to special issue in Quaternary Science Reviews:

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

Jostein Bakke¹, Nicholas Balascio², Willem G. M. van der Bilt¹, Raymond Bradley³, William J. D`Andrea⁴, Marthe Gjerde¹, Sædis Òlafsdottir¹, Torgeir Røthe¹ and Greg De Wet³

¹ Department of Earth Science and Bjerknes Centre for Climate Research, University of Bergen, Allègaten 41, 5007, Bergen, Norway

² Department of Geology, College of William & Mary, Williamsburg, VA 23187, USA

³ Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA

⁴ Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA

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 five papers in this issue 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 reconstruction from lake Hakluytvatnet. We also present high-resolution paleomagnetic secular variation data from these sites, which document important regional magnetic field variations and demonstrate the potential for use in synchronizing Holocene sedimentary records. 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.

Keywords:

Svalbard, Holocene, Paleoclimatology, Continental biomarkers, Glacier reconstruction, Hydrology, Arctic, Lake sediments

1.0 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 the anticipated impacts, our knowledge of the *natural*/variability of the Arctic climate system remains limited due to the scarcity of data and the relatively short period (≤ 100 yrs) of instrumental observations. Future anthropogenic climate changes will be superimposed on these natural variations, so a full understanding of on-going climate trends must also incorporate the role of natural climate variability. Furthermore, evaluating 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 to adequately assess 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?

Relative 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 modern day and thus represents a relevant reference period when trying to understand teleconnections and feedbacks that may be important in anticipating future changes 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; Olsen et al., 2012; Renssen et al., 2009) **(ADD FUNDER)**. The spatial climate patterns associated with the AO/NAO provide just one example of the importance of internal climate dynamics, as opposed to simple insolation forcing, in determining Arctic climate. The development of a greater number of spatially distributed climate reconstructions is critical to documenting 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 on Svalbard, an important location within the North Atlantic sector of the Arctic. We use a range of analytical techniques, including sedimentological, organic geochemical, and isotope approaches.

2.0 Study area

The Island of Amsterdamøya (N79°46', E10°45') is one of the northernmost islands in the Arctic Archipelago of Svalbard. It was discovered by Dutch explorer Willem Barents in AD 1596 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 (Dutch for "blubber town") occupied a flat area on the eastern side of the island. The island measures 18.8 km² and is characterized by glacially eroded cirques, steep cliffs, and flat valley floors. The mountain plateau Hollendarberget 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 (Fig. 1) 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 (0.4km²), the largest glacier on the Island, is located in a north-facing valley. There are also two smaller glaciers, Hiertabreen (0.1km²) and Retziusbreen (0.2km²). 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 on Amsterdamøya.

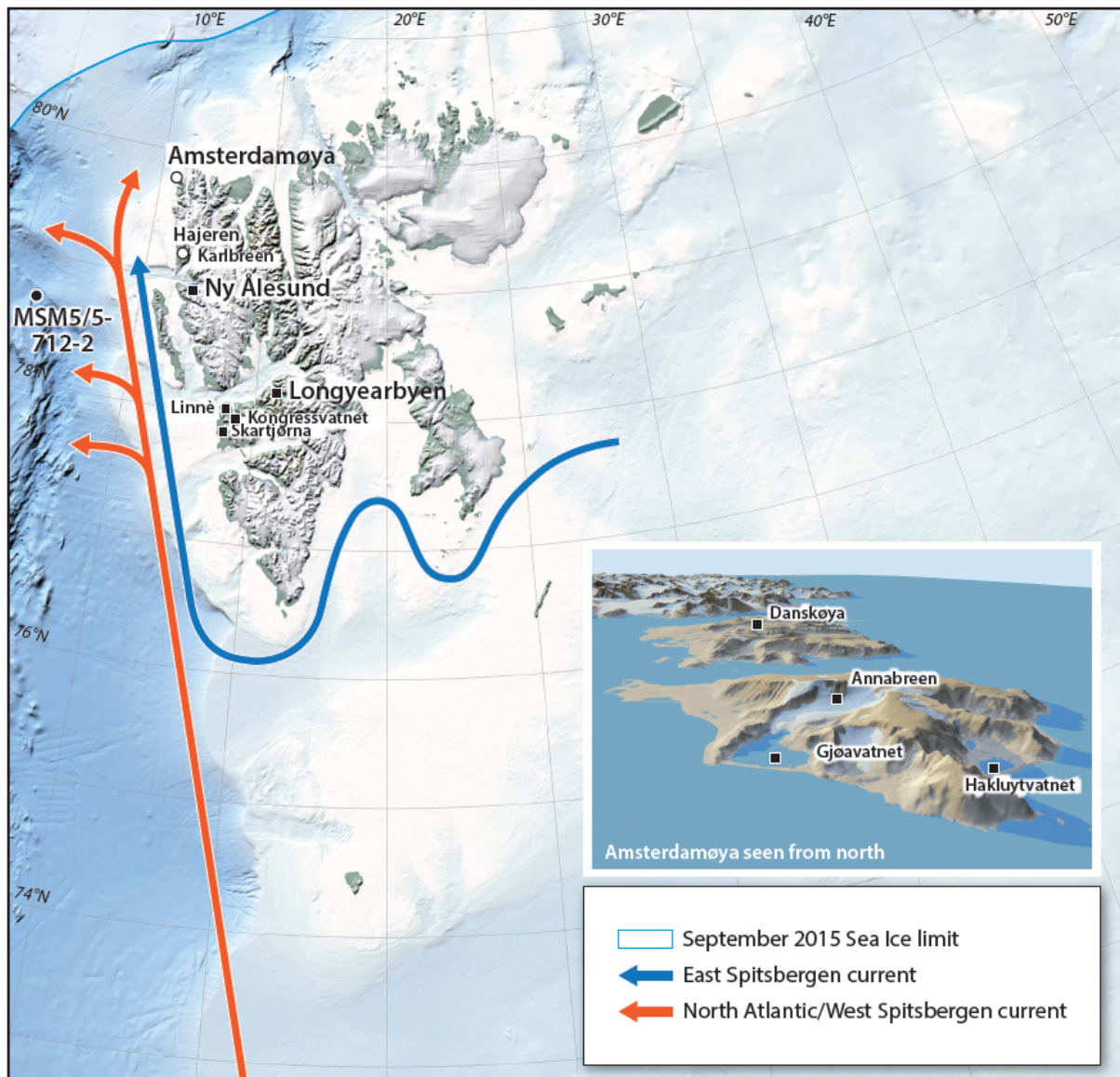


Figure 1. The Arctic Archipelago of Svalbard and the main ocean currents affecting the climate of Svalbard. The Island of Amsterdamøya (small map) consist of undulating mountain plateaus incised by cirques, carved out by past and present glaciers on the island. At present the largest glacier is Annabreen,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

3.0 Terrestrial paleoclimate evidence

Our research presented in this special issue build upon decades of earlier 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 high resolution 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 & 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. Werner, 1993; Svendsen and Mangerud, 1997; Humlum et al., 2005; Reusche et al., 2014; Røthe et al., 2015; van der Bilt et al., 2015). 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 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), culminating 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, ca. 1500, 1000, and between 650-200 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 they date relict vegetation under the glacier Longyearbreen, indicating that the glacier has increased in length from about 3 km to its present size of about 5 km during the last 1100 years.

Additional lake-sediment based studies have contributed to the available terrestrial paleoclimate data. 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 (Fig. 1 & 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, the findings of 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 these findings 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 1,800 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. Their 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.

4.0 - 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. Hence, the climate at Amsterdamøya would respond 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., 2014a). 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 7.2-7 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 5.2-2.0 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.

5.0. Our findings

Our investigation included analysis of lake sediment records from Hakluytvatnet and Gjøavatnet on Amsterdamøya, and Hajeren on the nearby Mitrahalvøya Peninsula, constrained by radiocarbon-based chronologies and interpreted using data collected by multiple techniques, to gain a comprehensive, well-resolved understanding of terrestrial paleoclimate conditions. 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 and hydrogen isotope measurements. Four papers in this issue focus on the analysis of sediment cores from Hakluytvatnet (Balascio et al., this issue; Gjerde et al., this issue; van der Bilt et al., this issue; Ólafsdóttir et al. this issue) and one on sediments of Gjøavatnet.

Gjerde et al. (in press) describe changes in sediment properties since the Younger Dryas that reflect the response of the lake and its catchment to regional climate changes. 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 in-washing of minerogenic sediment, which are interpreted to reflect rapid snowmelt events associated with regional climate changes.

Balascio et al. (in press) 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. Their data indicate that the lake experienced significant evaporative enrichment from 12.8-7.5 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. (in press), who present lake water temperature reconstructions using alkenone paleothermometry. 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 in two 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. (in press) analysed sedimentation in Gjøvatnet and present a reconstruction of the Annabreen glacier. 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 8.4-1.0 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 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 the influence of anthropogenic warming in the 20th century.

Ólafsdóttir et al. (in press) used paleomagnetic secular variations as a tool for synchronising multiple Holocene sediment records from Svalbard. Directions of the characteristic remanent magnetization were derived from vector analyses of the results from alternating field demagnetization, yielding reliable records for the Holocene. The Paleomagnetic Secular Variations (PSV) from these locations reveals magnetic features that can be correlated throughout the North Atlantic. This, along with detailed radiocarbon chronology from two of the lakes (Lake Hakluytvatnet and Lake Hajeren), allows synchronization and provides constraints for depth-age models from sediment archives where radiocarbon dating is problematical, such as those with low organic content or hard water effects. Development of high precision PSV-chronologies are important for future climate research and open up new avenues for developing reliable chronologies from other polar regions.

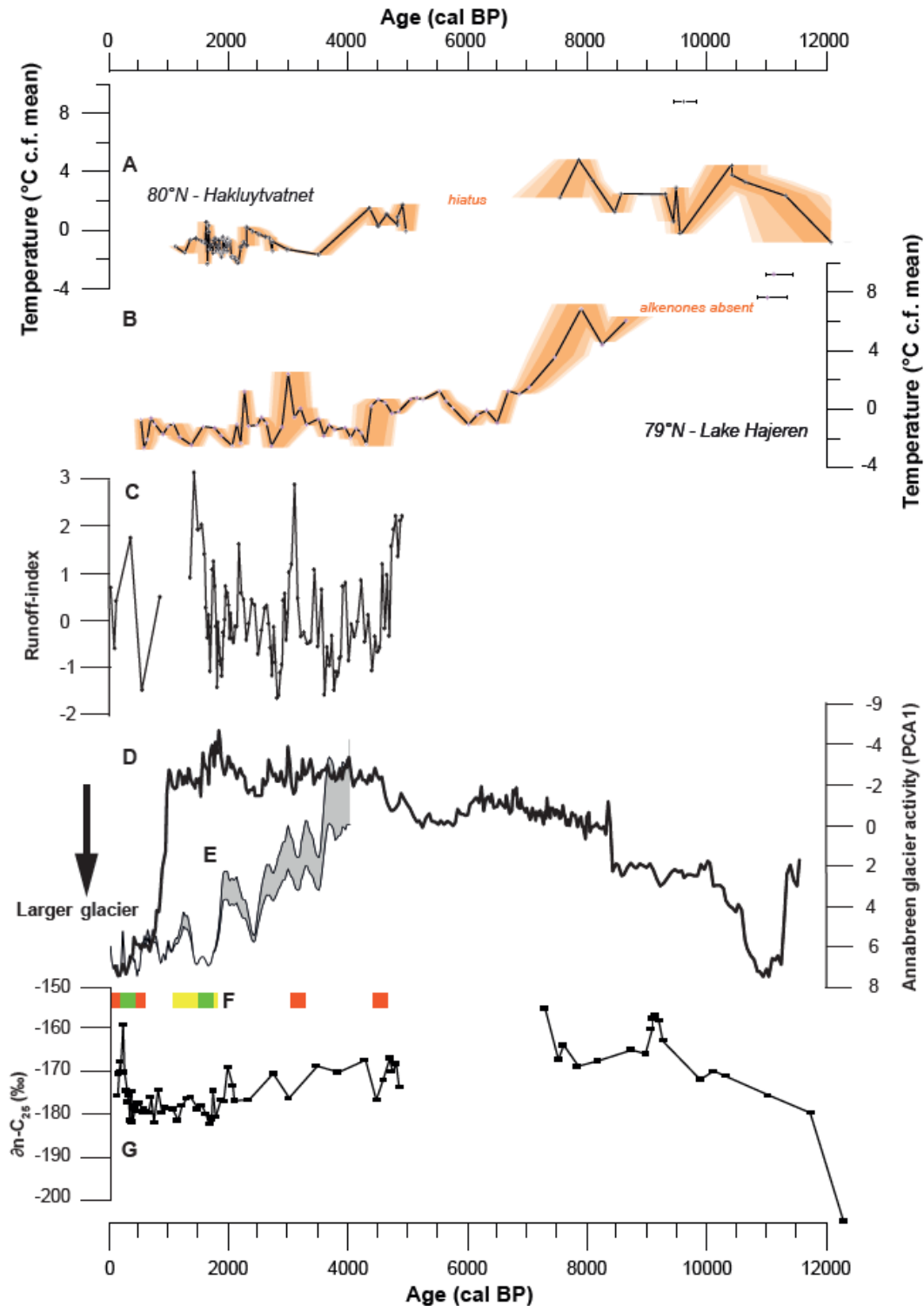


Figure 2. Summary of findings at the island of Amsterdamøya. In A and B two different alkenone based temperature records plotted with 95%, 90% and 70% confidence intervals in shades of orange (dark-light) and in black the temperature estimate (van der Bilt et al., in press). In C a runoff proxy based on grain-size fluctuations in lake Hakluytvatnet (Gjerde et al., 2016), in D reconstruction of glacier activity in the Annabreen as recorded in the distal glacier-fed lake Gjøvatnet (de Wet et al., in press). 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., 2002); in G hydrogen isotope data from lake Hakluytvatnet interpreted to indicate changes in the isotopic composition of lake water (Balascio et al., in press).

5.0 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 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 past 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 study identifies distinct paleoclimate intervals that at times deviate from the slow changes in insolation forcing. This underscores the dynamic response of the regional climate system in the North Atlantic sector of the Arctic and confirms the potential for abrupt climate transitions.
- We recommend intensified research in the Arctic with a particular focus on the last two millennia to further investigate tipping points in the Arctic climate system, a discussion relevant for placing present day changes into a longer time perspective.

6.0 References:

- Aagaard-Sørensen, S., Husum, K., Hald, M., Marchitto, T., Godtlielsen, F., 2014. Sub sea surface temperatures in the Polar North Atlantic during the Holocene: Planktic foraminiferal Mg/Ca temperature reconstructions. *The Holocene* 24, 93-103.
- Bakke, J., Lie, Ø., Heegaard, E., Dokken, T., Haug, G.H., Birks, H.H., Dulski, P., Nilsen, T., 2009. Rapid oceanic and atmospheric changes during the Younger Dryas cold period. *Nature Geoscience* 2, 202-205.
- Balascio, N., D'Andrea, W., Gjerde, M., Bakke, J., in press. Leaf wax hydrogen isotopes reveal high Arctic hydroclimate variability during the Holocene. *Quaternary Science Reviews*???
- Bintanja, R., Selten, F.M., 2014. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature* 509, 479-+.
- Birks, H.H., 1991. Holocene vegetational history and climatic change in west Spitsbergen-plant macrofossils from Skardtjørna, an Arctic lake. *The Holocene* 1, 209-218.
- Boisvert, L.N., Stroeve, J.C., 2015. The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. *Geophysical Research Letters* 42, 4439-4446.
- Boulton, G.S., Rhodes, M., 1974. Isostatic uplift and glacial history in northern Spitsbergen. *Geological Magazine* 111, 481-500.
- D'Andrea, W.J., Vaillencourt, D.A., Balascio, N.L., Werner, A., Roof, S.R., Retelle, M., Bradley, R.S., 2012. Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. *Geology* 40, 1007-1010.
- Darby, D.A., Ortiz, J.D., Grosch, C.E., Lund, S.P., 2012. 1,500-year cycle in the Arctic Oscillation identified in Holocene Arctic sea-ice drift. *Nature Geoscience* 5, 897-900.
- de Wet, G., Bakke, J., Balascio, N., D'Andrea, W., Bradley, R., Perren, B., in press. Holocene climate change reconstructed from proglacial lake Gjøavatnet on Amsterdamøya, NW Svalbard. *Quaternary Science Reviews*???
- Forman, S.L., Mann, D.H., Miller, G.H., 1987. Late Weichselian and Holocene relative sea-level history of Brøggerhalvøya, Spitsbergen. *Quaternary Research* 27, 41-50.
- Forwick, M., Vorren, T.O., 2009. Late Weichselian and Holocene sedimentary environments and ice rafting in Isfjorden, Spitsbergen. *Palaeogeography, Palaeoclimatology, Palaeoecology* 280, 258-274.
- Gjerde, M., Bakke, J., D'Andrea, W., Balascio, N., Hormes, A., Bradley, R., Vasskog, K., Olafsdottir, S., Røthe, T., B, P., in press. Late Glacial and Holocene multi-proxy environmental reconstruction from Lake Hakluyvatnet, Amsterdamøya Island, Svalbard. *Quaternary Science Reviews*???

Gjermundsen, E.F., Briner, J.P., Akçar, N., Foros, J., Kubik, P.W., Salvigsen, O., Hormes, A., 2015. Minimal erosion of Arctic alpine topography during late Quaternary glaciation. *Nature Geoscience* 8, 789-792.

Humlum, O., Elberling, B., Hormes, A., Fjordheim, K., Hansen, O.H., Heinemeier, J., 2005. Late-Holocene glacier growth in Svalbard, documented by subglacial relict vegetation and living soil microbes. *Holocene* 15, 396-407.

Huybers, P., 2006. Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science* 313, 508-511.

Ingólfsson, Ó., Landvik, J.Y., 2013. The Svalbard–Barents Sea ice-sheet – Historical, current and future perspectives. *Quaternary Science Reviews* 64, 33-60.

Jessen, S.P., Rasmussen, T.L., Nielsen, T., Solheim, A., 2010. A new Late Weichselian and Holocene marine chronology for the western Svalbard slope 30,000–0 cal years BP. *Quaternary Science Reviews* 29, 1301-1312.

Landvik, J.Y., Bondevik, S., Elverhøi, A., Fjeldskaar, W., Mangerud, J., Salvigsen, O., Siegert, M.J., Svendsen, J.-I., Vorren, T.O., 1998. The last glacial maximum of Svalbard and the Barents Sea area: ice sheet extent and configuration. *Quaternary Science Reviews* 17, 43-75.

Landvik, J.Y., Brook, E.J., Gualtieri, L., Raisbeck, G., Salvigsen, O., Yiou, F., 2003. Northwest Svalbard during the last glaciation: Ice-free areas existed. *Geology* 31, 905-908.

Landvik, J.Y., Salvigsen, O., 1987. The Late Weichselian and Holocene shoreline displacement on the west-central coast of Svalbard. *Polar Research* 5, 29-44.

Masson-Delmotte, V., M. Schulz, A.Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, and, X.S., Timmermann, A., 2013. Information from Paleoclimate Archives, in: Stocker, T.F., D. Qin, Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Miller, G.H., Alley, R.B., Brigham-Grette, J., Fitzpatrick, J.J., Polyak, L., Serreze, M.C., White, J.W.C., 2010. Arctic amplification: can the past constrain the future? *Quaternary Science Reviews* 29, 1779-1790.

Müller, J., Werner, K., Stein, R., Fahl, K., Moros, M., Jansen, E., 2012. Holocene cooling culminates in sea ice oscillations in Fram Strait. *Quaternary Science Reviews* 47, 1-14.

Ólafsdóttir, S., Bakke, J., Stoner, J., Bradley, R., Gjerde, M., in press. Paleomagnetic secular variations as a tool for synchronizing Holocene Arctic lake sediment records at Svalbard. *Quaternary Science Reviews*????

Olsen, J., Anderson, N.J., Knudsen, M.F., 2012. Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* 5, 808-812.

Rasmussen, T.L., Forwick, M., Mackensen, A., 2012. Reconstruction of inflow of Atlantic Water to Isfjorden, Svalbard during the Holocene: Correlation to climate and seasonality. *Marine Micropaleontology* 94–95, 80-90.

Rasmussen, T.L., Thomsen, E., Skirbekk, K., Ślubowska-Woldengen, M., Klitgaard Kristensen, D., Koç, N., 2014. Spatial and temporal distribution of Holocene temperature maxima in the northern Nordic seas: interplay of Atlantic-, Arctic-and polar water masses. *Quaternary Science Reviews* 92, 280-291.

Renssen, H., Seppa, H., Heiri, O., Roche, D.M., Goosse, H., Fichefet, T., 2009. The spatial and temporal complexity of the Holocene thermal maximum. *Nature Geoscience* 2, 410-413.

Reusche, M., Winsor, K., Carlson, A.E., Marcott, S.A., Rood, D.H., Novak, A., Roof, S., Retelle, M., Werner, A., Caffee, M., 2014. ¹⁰Be surface exposure ages on the late-Pleistocene and Holocene history of Linnébreen on Svalbard. *Quaternary Science Reviews* 89, 5-12.

Risebrobakken, B., Dokken, T., Smedsrud, L.H., Andersson, C., Jansen, E., Moros, M., Ivanova, E.V., 2011. Early Holocene temperature variability in the Nordic Seas: The role of oceanic heat advection versus changes in orbital forcing. *Paleoceanography* 26.

Røthe, T.O., Bakke, J., Vasskog, K., Gjerde, M., D'Andrea, W.J., Bradley, R.S., 2015. Arctic Holocene glacier fluctuations reconstructed from lake sediments at Mitrahavøya, Spitsbergen. *Quaternary Science Reviews* 109, 111-125.

Salvigsen, O., 1977. Radiocarbon datings and the extension of the Weichselian ice-sheet in Svalbard. *Norsk Polarinstitutt Årbok* 1976, 209-224.

Salvigsen, O., 1979. The last deglaciation of Svalbard. *Boreas* 8, 229-231.

Salvigsen, O., Forman, S.L., Miller, G.H., 1992. Thermophilous molluscs on Svalbard during the Holocene and their paleoclimatic implications. *Polar Research* 11, 1-10.

Sarnthein, M., Kreveld, S., Erlenkeuser, H., Grootes, P., Kucera, M., Pflaumann, U., Schulz, M., 2003. Centennial-to-millennial-scale periodicities of Holocene climate and sediment injections off the western Barents shelf, 75 N. *Boreas* 32, 447-461.

Screen, J.A., Simmonds, I., 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* 464, 1334-1337.

Ślubowska-Woldengen, M., Rasmussen, T.L., Koç, N., Klitgaard-Kristensen, D., Nilsen, F., Solheim, A., 2007. Advection of Atlantic Water to the western and northern Svalbard shelf since 17,500 calyr BP. *Quaternary Science Reviews* 26, 463-478.

Snyder, J., Miller, G., Werner, A., Jull, A., Stafford, T., 1994. AMS-radiocarbon dating of organic-poor lake sediment, an example from Linnévatnet, Spitsbergen, Svalbard. *The Holocene* 4, 413-421.

Svendsen, J.I., Landvik, J.Y., Mangerud, J., Miller, G.H., 1987. Postglacial marine and lacustrine sediments in Lake Linnévatnet, Svalbard. *Polar Res* 5, 281-283.

Svendsen, J.I., Mangerud, J., 1997. Holocene glacial and climatic variations on Spitsbergen, Svalbard. *The Holocene* 7, 45-57.

Thompson, D.W.J., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters* 25, 1297-1300.

van der Bilt, W., D'Andrea, W., Bakke, J., Balk, in press. Alkenone-based reconstructions reveal four-phase Holocene temperature evolution for High Arctic Svalbard. *Quaternary Science Reviews*?????

van der Bilt, W.G.M., Bakke, J., Vasskog, K., D'Andrea, W.J., Bradley, R.S., Ólafsdóttir, S., 2015. Reconstruction of glacier variability from lake sediments reveals dynamic Holocene climate in Svalbard. *Quaternary Science Reviews* 126, 201-218.

Van Oldenborgh, G., Collins, M., Arblaster, J., Christensen, J., Marotzke, J., Power, S., Rummukainen, M., Zhou, T., 2013. Annex I: atlas of global and regional climate projections. *Climate change*, 1311-1393.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T.J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., 2008. Mid-to Late Holocene climate change: an overview. *Quaternary Science Reviews* 27, 1791-1828.

Werner, A., 1993. Holocene moraine chronology, Spitsbergen, Svalbard: lichenometric evidence for multiple Neoglacial advances in the Arctic. *The Holocene* 3, 128-137.

Werner, K., Müller, J., Husum, K., Spielhagen, R.F., Kandiano, E.S., Polyak, L., 2015. Holocene sea subsurface and surface water masses in the Fram Strait—Comparisons of temperature and sea-ice reconstructions. *Quaternary Science Reviews*.

Werner, K., Spielhagen, R.F., Bauch, D., Hass, H.C., Kandiano, E., 2013. Atlantic Water advection versus sea-ice advances in the eastern Fram Strait during the last 9 ka: Multiproxy evidence for a two-phase Holocene. *Paleoceanography* 28, 283-295.