Past Precipitation on Svalbard

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Austre Nevlingen in northern Spitsbergen, August 14, 2015. A pilot study was conducted on sediment cores from this lake. View towards northeast.

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Abstract

The recent years' events of extreme precipitation (rain) with associated mudslides and debris flows on Svalbard calls for more knowledge about past precipitation. Are the observed extreme rainfalls really extreme in a longer time perspective covering the Holocene (the last *c*. 11,700 years)? Has Svalbard experienced periods of high summer precipitation in the past? We studied lake sediment cores from Svalbard to answer key research questions about one of the main climate parameters: precipitation. The Holocene Arctic precipitation record has hitherto been challenging to reconstruct and little is known how it has affected Svalbard through time. Leaf wax hydrogen isotopes (δ^2H) provide a new innovative way to address this issue. A pilot study of sediment cores from Austre Nevlingen, a lake in northern Spitsbergen, shows that the terrestrial and aquatic δ^2H at the site reflect different precipitation seasonality in the Holocene. The reconstructions from Austre Nevlingen also suggest that the most prominent Holocene precipitation changes occurred in winters. A possible reason is that Early Holocene warming reduced sea ice, intensified the local evaporation (mostly in winter) and increased the atmospheric moisture available for precipitation. Our findings from Austre Nevlingen support models suggesting that sea-ice loss causes increased Arctic winter precipitation.

Introduction

Liquid precipitation (rain) delivers heat to the surface and in extreme amounts, it can trigger debris flows and mud slides such as seen in Svalbard in recent years. Additionally, glacier variations are governed by precipitation (and temperature). Hence, Arctic precipitation is a major environmental parameter and one of the main controls on the mass balance of glaciers, including when it occurs and whether it falls in the form of snow or rain. The distribution and variation of sea ice also control Arctic precipitation (Bintanja & Selten, 2014; Thomas et al., 2016). Increasing temperatures in the Arctic during the last decades have caused a reduction in sea-ice cover, mainly in fall and winter, which leads to lowered albedo and increased absorption of heat in the ocean. Because open water provides a source of evaporation, the reduced sea-ice cover leads to increased winter precipitation in the Arctic, including Svalbard (Bintanja & Selten, 2014). Another process contributing to increasing Arctic precipitation is greater poleward moisture transport from lower latitudes, a process mainly occurring in summer (Vázquez et al., 2016). This calls for more knowledge about Arctic precipitation dynamics, especially focusing on how and why it varies between the seasons.

Svalbard is one of few land masses in the Arctic, and due to its location, it is of particular interest for studies of changes in the atmospheric and oceanic circulation. Svalbard is characterized by large climate gradients because humid and warm air masses from the Atlantic meet cold, polar air masses from the Arctic Ocean (Førland et al., 2009). The North Atlantic Current (the Gulf Stream) splits in two south of Svalbard; the West Spitsbergen Current and the North Cape Current which transport warm and saline water along the west coast of Svalbard and into the Barents Sea (Fig. 1A). Depending on the relative strength of these air and water masses, the location of the polar front varies. This affects the climate of Svalbard, and feedback mechanisms between the atmosphere, cryosphere and the ocean make the climate dynamics complex.

Because of large spatial and temporal variations, and the lack of relevant geological paleoclimate archives (proxies), little is known about Arctic precipitation variations and seasonality through geological time. This project aims to provide new knowledge about past precipitation in Svalbard by applying analyses of stable hydrogen isotopes (δ^2H) in leaf waxes extracted from Holocene lake sediment cores. The Holocene is our present geological period and includes the last *c*. 11,700 years, i.e., the time since the end of the last ice age. It is characterized by a relatively stable climate. Studies of leaf wax hydrogen isotopes have successfully provided new knowledge about past precipitation elsewhere in the Arctic, e.g., in Canada (Thomas et al., 2012), Greenland (Balascio et al., 2013; Thomas et al., 2016, 2020), northeast Russia (Wilkie, 2012), as well as one site in Svalbard (Balascio et al., 2018).

Leaf waxes are a type of biomarker, i.e., organic compounds that can be linked to a specific type of organism and the environmental conditions the organism experienced. The waxes are lipids (fats), and consist of long carbon chains with hydrogen atoms attached to them. Leaf waxes are produced by both terrestrial and aquatic plants and record the hydrogen isotopic composition (δ^2H) of the source water during photosynthesis: lake water for aquatic plants and soil water for terrestrial plants. Eventually, the waxes are washed off the leaves, transported by surface runoff and end up in lakes, where they are preserved in the sediments. By extracting the leaf waxes (fatty acids) from the sediments, we can measure leaf wax δ^2H and get information about the source water δ^2H and ultimately precipitation δ^2H (Sachse et al., 2012). Terrestrial plants use soil water, which is mainly recharged by rain during the growing season (Cooper et al., 1991), therefore reflecting summer precipitation δ^2H. Aquatic plants use lake water, coming from snowmelt and/or summer precipitation depending on how often the water in the lake is replaced (Thomas et al., 2020). They can therefore reflect mean annual or summer precipitation δ^2H. Terrestrial plants produce longer hydrocarbon chains than aquatic plants (e.g., Ficken et al., 2000; Sachse et al., 2012), which makes them possible to distinguish from each other, and by analyzing both terrestrial (δ^2H_{terr}) and aquatic (δ^2H_{aq}) leaf waxes we can investigate precipitation seasonality.

Climate modelling predicts that the future winter precipitation will increase in the Arctic, in pace with the reduction of the sea-ice cover (Bintanja & Selten, 2014). Studies from Greenland show that this also occurred in the Middle Holocene when the winter precipitation increased due to higher air temperatures and reduced sea-ice cover (Thomas et al., 2016). We hypothesize that Svalbard experienced similar changes in the Early-Middle Holocene, and test this by analyzing leaf waxes extracted from our collection of lake sediment cores covering the Holocene. This is highly relevant in order to understand the natural variation in precipitation over long time scales. Further, it provides an opportunity to understand whether the recent extreme precipitation events in Svalbard are also ’extreme’ in a geological perspective, and whether comparable events have occurred earlier in the Holocene.

The project ‘Past Precipitation on Svalbard’ aims to reconstruct Holocene precipitation seasonality on Svalbard and to investigate how this in turn has influenced the environment. We focus our investigations along a southwest-northeast oriented climatic transect from Isfjorden to Nordaustlandet (Fig. 1B).

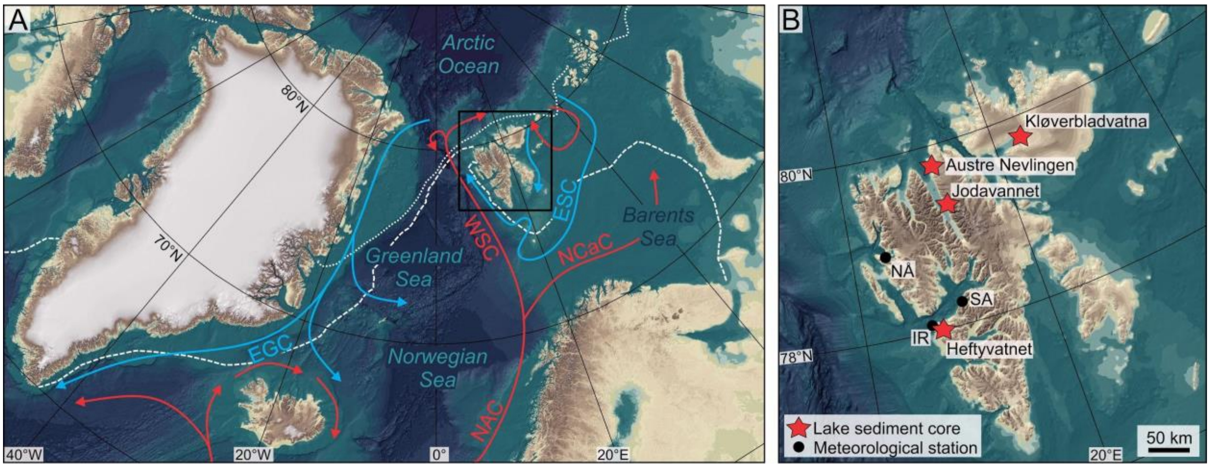

Fig. 1. A. Map showing the location of Svalbard (black box), with ocean surface currents (warm in red, cold in blue; NAC = North Atlantic Current; NCaC = North Cape Current; WSC = West Spitsbergen Current; ESC = East Spitsbergen Current; EGC = East Greenland Current), and median winter (white dashed line) and summer (white dotted line) sea-ice extent AD 1981-2010 (National Snow and Ice Data Center, 2019). B. Map of studied lakes and meteorological stations (IR = Isfjord Radio; NÅ = Ny-Ålesund; SA = Svalbard Airport).

Methods

In this project we applied a new method to reconstruct precipitation, measuring the hydrogen isotopic composition (δ^2H) of leaf wax compounds in lake sediments. Four lakes were selected from our collection of lake sediment cores, sampled since 2015. The lakes were chosen based on preliminary results, sediment composition and the lakes' geographical locations. Heftyvatnet is located on the west coast of central Spitsbergen close to Longyearbyen, Jodavannet and Austre Nevlingen in the more arid central part of northern Spitsbergen and Kløverbladvatna on Nordaustlandet (Figs 1-2). To record modern conditions and differences in chain length distribution between different plant groups, we collected lake water samples and leaves from a selection of the most common plants growing on Svalbard today. This was done during a field campaign in August 2018 (Svalbard Environmental Protection Fund, project 17/114).

Data from Kløverbladvatna and Jodavannet have already been presented by Schomacker et al. (2019) and Voldstad et al. (2020), whereas this is the first investigation of Austre Nevlingen and Heftyvatnet, the latter also being studies for tephra (Farnsworth et al., in prep.). All cores were split open and analyzed using an ITRAX core scanner to record visual and radiographic imagery and elemental profiles, measured using X-ray fluorescence (XRF; e.g., Kylander et al., 2011). The total organic content was determined through loss on ignition (LOI; Heiri et al., 2001). Sediment samples were dried at 110 °C for 24 h and combusted at 550 °C for 4 h. To establish the chronologies of the cores, plant macrofossils were handpicked from sieved core material and dated through accelerator mass spectrometry (AMS) radiocarbon dating at the Ångström Laboratory, Uppsala University and Lund University Radiocarbon Dating Laboratory, Sweden. All radiocarbon ages have been calibrated and are presented in calibrated years before present (cal. yr BP; BP = 1950). To combine data from several sediment cores collected from the same lake, we aligned them in AnalySeries (v. 2.0.8; Paillard et al., 1996), using tie points in the elemental data.

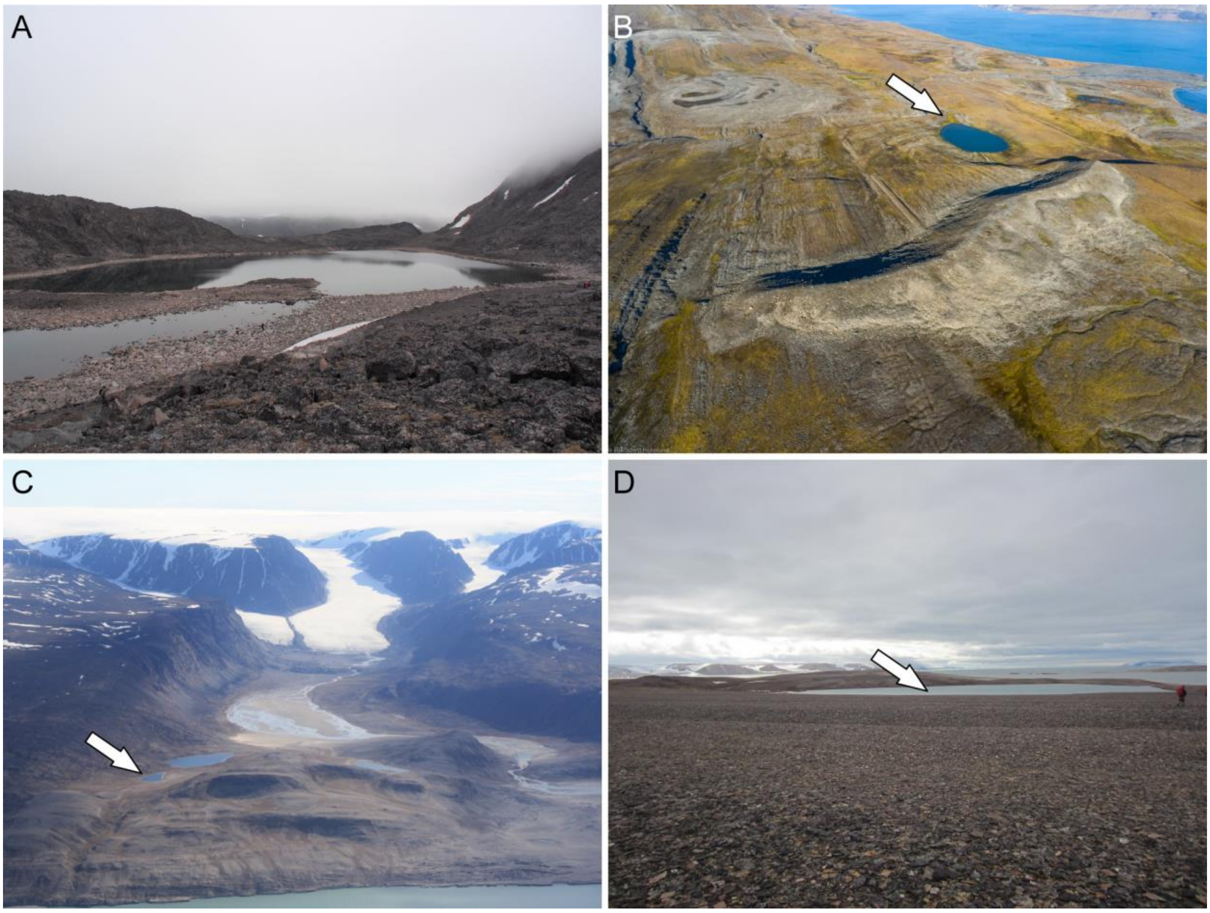

Fig. 2. Views of the lakes from which sediment cores were collected. Austre Nevlingen, northern Spitsbergen (A), Heftyvatnet, central Spitsbergen (B), Jodavannet, northern Spitsbergen (C), and Kløverbladvatna on Nordaustlandet (D). Photographs: Ó. Ingólfsson (A), E. S. Mannerfelt (B), S. E. Kjellman (C), and A. Schomacker (D).

The leaf wax analyses were performed in the Organic and Stable Isotope Biogeochemistry Laboratory at the University at Buffalo, NY, USA. A first batch of samples was extracted and analyzed by Kjellman during a research stay in Buffalo in autumn 2018, financed by the Svalbard Environmental Protection Fund. A second batch was planned to be analyzed by Kjellman in spring 2020, but had to be postponed due to the COVID-19 outbreak. Because of prevailing travel restrictions, these samples were instead analyzed by one of project partner Elizabeth K. Thomas' students in winter 2020-2021. Additional samples will be analysed in 2021 as part of project 20/36, which is a continuation of project 17/101.

Sediment samples were collected every 2.5-8 cm (corresponding to on average every 220-460 year), freeze-dried and homogenized. Lipids were extracted from the sediments using an Accelerated Solvent Extractor, and the fatty acids were separated from other compounds and purified using flash-column chromatography (Fig. 3). With this technique, compressed gas is used to push solvent through the column. Different solvents are used to remove different compounds, based on their polarity. Biomarker quantification was made through gas chromatography and the isotopic composition was measured using mass spectrometry. To incorporate age uncertainty into our biomarker records, we entered data into Linked PaleoData (LiPD) files (McKay and Emile-Geay, 2016) and analyzed them using the GeoChronR package (McKay et al., 2018) in R (v. 3.6.3; R Core Team, 2020).

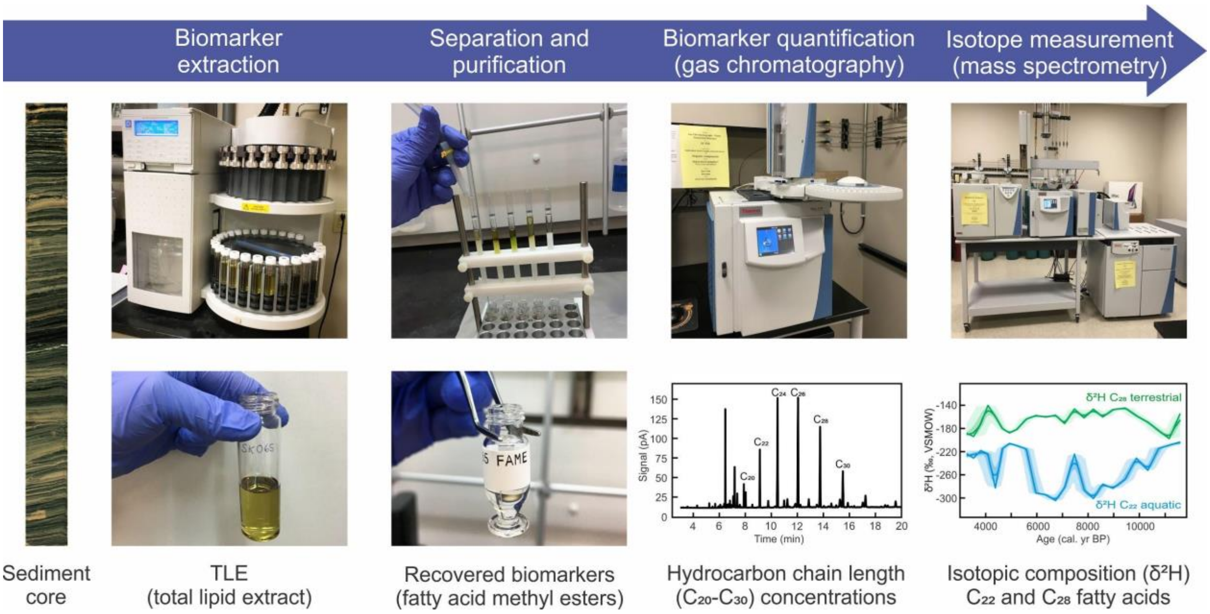

Fig. 3. Methodology for leaf wax biomarker extraction, purification and analyses.

Preliminary results

We have analyzed all four lake sediment records for leaf wax hydrogen isotopes (Fig. 4). The records from Jodavannet, Heftyvatnet and Austre Nevlingen start over 11,000 years ago and cover most of the Holocene. Austre Nevlingen is missing the last *c*. 1500 years, and the Kløverbladvatna δ^2H records only cover the last *c*. 5400 years, since this it when the basin was uplifted above sea level and isolated from the fjord (Schomacker et al., 2019). So far, we have focused on securing high enough temporal resolution for all records, and on interpreting the Austre Nevlingen record. We are currently awaiting additional samples from Heftyvatnet to be analyzed and are working to improve the age-depth model for that record.

Since this method is new to Svalbard, we used Austre Nevlingen as a pilot study to give an insight into how leaf wax compounds can be used in this region. Previously, one lake sediment record has been analyzed for *n*-alkanes (Balascio et al., 2018), but our study is the first one using fatty acids (*n*-alkanoic acids). One challenge with the Austre Nevlingen record was to compare two sediment cores from the same lake, since they gave somewhat contradicting δ^2H_{aq} values in the later part of the record (Fig. 5A). Large shifts in the aquatic isotopes can reflect changes in the local conditions, if the lake water isotopes can shift between recording the mean annual and the summer precipitation δ^2H.

Our results from Austre Nevlingen have been published in Quaternary Science Reviews (Fig. 5; Kjellman et al., 2020). In the article we discuss how variations in regional sea surface temperature and sea-ice extent affect the seasonal variation in precipitation on northern Spitsbergen. Austre Nevlingen does not receive enough meltwater to get completely flushed by spring melt. We can therefore use the aquatic plant waxes (recording the mean annual precipitation δ^2H) together with terrestrial plant waxes (representing summer precipitation δ^2H) to reconstruct precipitation seasonality. In our Austre Nevlingen records, the most notable precipitation changes took place in winter, reflected in the greater variability in the aquatic than terrestrial leaf wax hydrogen isotope ratios (Fig. 5A-B).

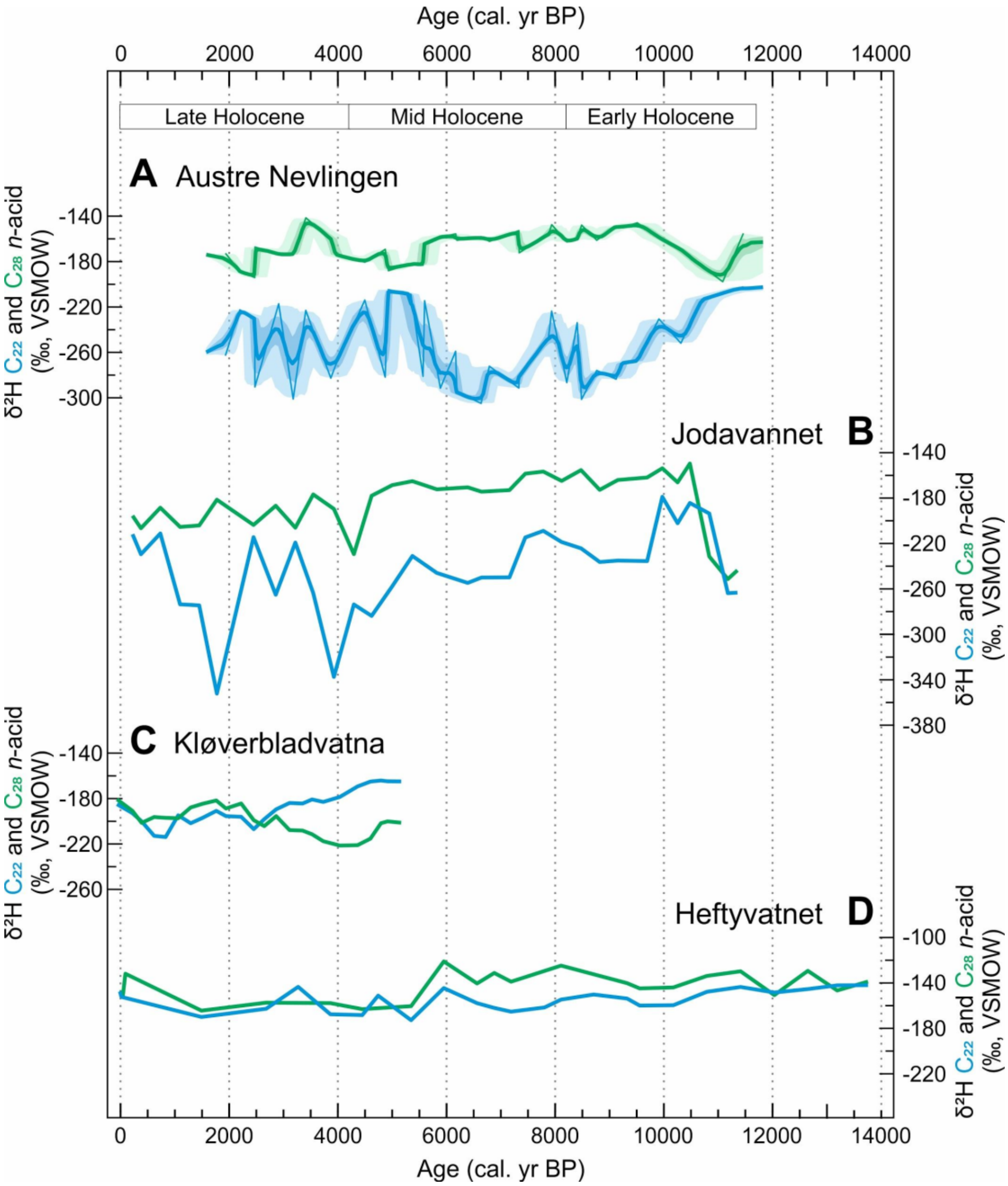

Fig. 4. Leaf wax hydrogen isotopic signal (δ^{2}H) for C_{22} (blue; aquatic) and C_{28} (green; terrestrial) fatty acids from Austre Nevlingen (A), Jodavannet (B), Kløverbladvatna (C) and Heftyvatnet (D). In A, fine lines show the raw data plotted on the median of each age point, bold lines represent median values of the age model ensembles, and the light and dark shading 1σ and 2σ age uncertainty, respectively (McKay et al., 2018).

In the Early Holocene, high summer insolation, warm ocean surface temperatures and reduced sea-ice extent contributed to greater winter evaporation and more winter precipitation (decreasing δ$^2H_{aq}$; Fig. 5). Increasing δ$^2H_{terr}$ between 11,000-9500 cal. yr BP supports an Early Holocene warming, suggesting enhanced evaporative enrichment and/or more proximal moisture sources during summer. After 9500 cal. yr BP, δ$^2H_{terr}$ stabilized, indicating stable summer conditions. The low δ$^2H_{aq}$ trend continued until *c*. 6000 cal. yr BP,

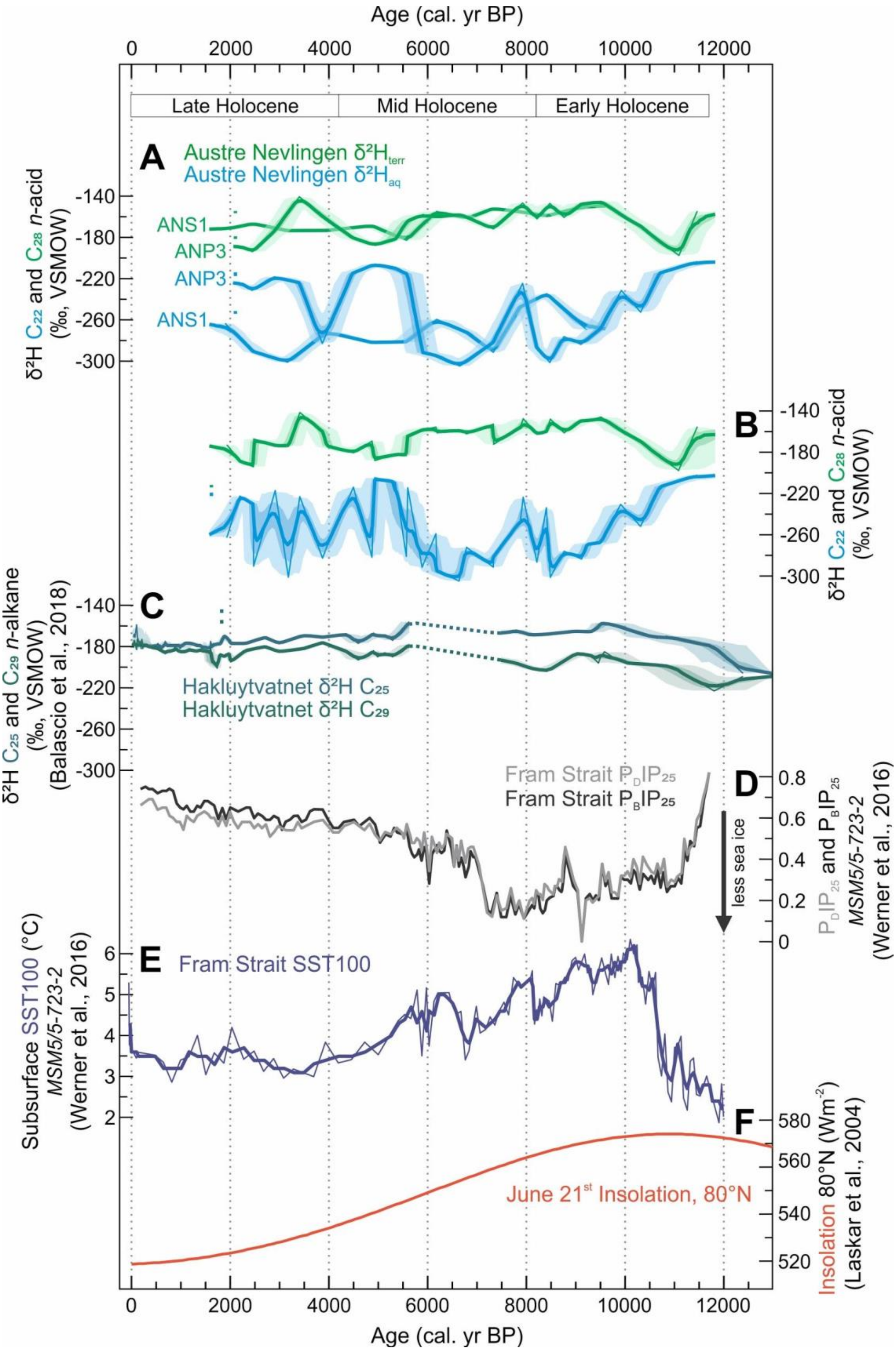

Fig. 5. Results from Austre Nevlingen (A-B) and other regional climate records (C-F; Laskar et al., 2004; Werner et al., 2016; Balascio et al., 2018). In A-C, vertical colored bars represent the average proxy uncertainty (standard error of the mean), and lines and shadings are shown as in Fig. 4. From Kjellman et al. (2020).

after which δ^2H_{aq} varies more, and the climate signal is more difficult to distinguish. We have interpreted these large fluctuations to partly reflect influence by local conditions in the lake (e.g., lake ice duration), suggesting that we need to be careful when choosing study sites. Slightly lower δ^2H_{terr} values after 5600 cal. yr BP suggests gradual cooling and less summer evaporation.

The next step is to interpret the three remaining records, and compare them all. The Jodavannet record (50 km south of Austre Nevlingen) resembles the one from Austre Nevlingen, with more negative aquatic than terrestrial δ^2H, and higher amplitude variability in the later part of the record. The sediment core from Jodavannet has also been analyzed for sedimentary ancient DNA (*sed*aDNA) with the aim of reconstructing the vegetation history (Voldstad et al., 2020). The *sed*aDNA record indicates an early warm postglacial period with high species richness, lasting until *c*. 6400 cal. yr BP. After 6400 cal. yr BP, there was a shift from moist snowbed communities to also include semi-dry heath vegetation, suggesting a reduced moisture supply in the Middle Holocene. Good control on changes in dominating vegetation throughout the record will help us interpret changes in the leaf wax hydrogen isotopes. Kløverbladvatna and Heftyvatnet display less variation in both the aquatic and terrestrial δ^2H and have less negative δ^2H values than the other records, indicating differences in moisture source and/or seasonality reflected in δ^2H_{aq}.

Conclusions

- Leaf wax hydrogen isotopes from the pilot study from Austre Nevlingen suggest large variability in precipitation seasonality on northern Spitsbergen throughout the Holocene. We are able to extract both the summer and mean annual precipitation signal. This is possible because terrestrial and aquatic plants at this site use source water (soil water and lake water, respectively) with different seasonality.
- The Austre Nevlingen data suggest that Early Holocene regional warming had a strong effect on moisture availability and precipitation seasonality in northern Svalbard. High summer insolation and strong Atlantic water influx contributed to reduced sea ice, which we suggest favored greater local winter evaporation leading to increasing winter precipitation.
- Our results from Austre Nevlingen indicate that the precipitation seasonality in northern Spitsbergen is strongly linked to regional ocean surface conditions. As a result, the positive trend in winter precipitation observed in Svalbard today, may amplify because of warming ocean surface waters and reduction in sea ice.
- Our four lake records span a climate transect from central Spitsbergen in southwest to Nordaustlandet in northeast, allowing us to investigate how different parts of Svalbard have received precipitation from different moisture sources and/or with different transport histories throughout the Holocene.
- By targeting lakes with different lake water residence times (i.e., with lake water during the growing season reflecting summer or mean annual precipitation δ^2H), we can extract information on different parts of the hydrological cycle, such as seasonality and aridity.
- The approach of using leaf wax hydrogen isotopes for reconstructing precipitation seasonality on Svalbard requires high-resolution sedimentary records in order to decipher past short-term precipitation dynamics. Ideally, modern annually laminated

sediment should be studied along with isotope analyses of modern precipitation and vegetation to provide a baseline for interpreting the geological record.

- A continuation of this project aims to improve the temporal resolution of the results (Svalbard Environmental Protection Fund, project 20/36).

Dissemination of project results

Scientific publications

Kjellman, S. E., Schomacker, A., Thomas, E. K., Håkansson, L., Duboscq, S., Cluett, A. A., Farnsworth, W. R., Allaart, L., Cowling, O. C., McKay, N. P., Brynjólfsson, S., & Ingólfsson, Ó., 2020. Holocene precipitation seasonality in northern Svalbard: Influence of sea ice and regional ocean surface conditions. *Quaternary Science Reviews 240*, 106388, 1-15. https://doi.org/10.1016/j.quascirev.2020.106388.

Scientific presentations

Kjellman, S. E., Schomacker, A., & Thomas, E. K., 2020. Lake Water Isotope Gradients in Arctic Norway, Sweden and Finland: Implications for Proxy-based Precipitation Reconstructions. American Geophysical Union Fall Meeting 2020. *iPoster.*

Kjellman, S. E., 2020. Holocene precipitation seasonality in Svalbard inferred from δ^2H of sedimentary leaf waxes. CHESS Annual Meeting 2020. *Presentation.*

Kjellman, S. E., Schomacker, A., Thomas, E. K., Håkansson, L., Duboscq, S. M., Cluett, A., Farnsworth, W. R., Allaart, L., & Cowling, O., 2019. Leaf wax hydrogen isotope reconstruction of Holocene precipitation seasonality in High Arctic Svalbard. 49th International Arctic Workshop. *Presentation.*

Kjellman, S. E., Schomacker, A., Håkansson, L., & Thomas, E. K., 2018. Holocene Arctic precipitation and its response to sea ice extent – using leaf wax hydrogen isotopes as a proxy. IPA-IAL Joint Meeting. *Poster.*

Popular scientific communication

Kjellman, S. E., 2020. Formidlingskonkurransen 2020. Geoforskning. Hydrogenisotopenes hemmelighet. https://www.geoforskning.no/nyheter/klima-og-co2/2287-hydrogenisotopenes-hemmelighet *Popular scientific article (in Norwegian).*

Kjellman, S. E., 2019. Science for schools, Arctic Frontiers 2019. Nordnorsk vitensenter, Tromsø. “Arktiske innsjøer som klimaarkiver - Hva kan gjørme og bladvoks fortelle om tidligere klima på Svalbard?”. *Presentation (in Norwegian).*

Work in progress

Kjellman, S. E., Schomacker, A., Thomas, E. K. et al. (in prep.). Holocene precipitation seasonality along a climatic gradient from western Spitsbergen to Nordaustlandet, Svalbard (working title). Expected publication 2022.

Kjellman, S. E. (in prep.). Reconstructing Holocene precipitation seasonality in Svalbard using organic geochemical and stable isotope proxies (working title). UiT The Arctic University of Norway. PhD thesis. Expected publication 2022.

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