

Diatom-based reconstructions of climate and ocean conditions from Svalbard and Baffin Bay since the Last Glacial Maximum

MIMMI OKSMAN

ACADEMIC DISSERTATION

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Abstract

The recent changes in the Arctic region, e.g. decreased Arctic sea ice cover and accelerated ice mass loss from the Greenland ice sheet, have an alarming rate and magnitude. The ongoing climate warming has a profound impact on the sensitive Arctic region known as polar amplification. To better understand the changes taking place in the Arctic region, and to project the future impacts of the ongoing climate change, we need to look into the past in order to obtain analogues of past climate conditions and past interactions between climate system components (ocean, ice sheet, and atmosphere).

High-latitude marine proxy records provide indirect information of past long-term oceanic conditions and climate variability. Paleoceanographic records, from the vicinity of ice margins, can be employed to investigate past interactions between the ocean and ice sheets, which are crucial in order to understand the future impacts of the ocean surface warming on the marine terminating parts of ice sheets.

This work examines ocean surface conditions (August sea surface temperatures, sea ice and ocean surface water masses) from high northern latitudes after the Last Glacial Maximum using marine fossil diatom assemblages. Long-term paleoclimatic and -oceanographic records are obtained from two study sites (northern Svalbard and central-eastern Baffin Bay) using quantitative and qualitative diatom analyses, and sediment grain size distribution analysis. An additional focus of this work was to study the ecology of common northern North Atlantic diatom species and define their relationship to environmental variables (August sea surface

temperatures and April sea ice) in order to identify the best indicator species for these environmental variables and to improve their reliability as paleoceanographic indicators for high latitude paleoclimatic reconstructions.

The Baffin Bay study site was investigated for the deglacial period (10–14 kyr BP), and the results suggest a warmer ocean surface in central-eastern Baffin Bay during the cold Younger Dryas period (11.7–12.9 kyr BP) indicating that the ocean was out of phase with atmospheric conditions over Greenland. The warmer conditions were caused by enhanced inflow of Atlantic-sourced waters and increased solar insolation on the Northern Hemisphere, which amplified seasonality over Baffin Bay and had a significant role triggering the retreat of the Jakobshavn Isbræ ice stream in West Greenland, which is visible in the sedimentological evidence. The paleoceanographic record from northern Svalbard represents the late Holocene (last ca. 4 200 years), and the results show a clear climate shift at 2.5 kyr BP, as the study location changed from stable, glacier-proximal conditions into fluctuating glacier-distal conditions, emphasizing the sensitivity of the Arctic environment to climate oscillations.

Diatoms are widely used as indicators for past climate change, which emphasizes that understanding the species' relationship to environmental variables is essential when employing diatoms as a paleoclimate proxy. The study of the main northern North Atlantic diatom taxa's ecology and responses to environmental variables identifies robust indicators for cold, temperate and warm waters and for sea ice. The

results show that not all sea ice-associated species have a statistically significant relationship to sea ice within the large calibration dataset used. Only *Actinocyclus curvatus*, *Coscinodiscus oculus-iridis*, *Fragilariopsis oceanica* and *Porosira glacialis* were found to have a statistically significant relationship to sea ice, whereas the widely used sea ice indicator *Fragilariopsis cylindrus* shows no significant relationship to sea ice. While this species is often found in sea ice and in the marginal ice zone, its ecology appears to be more complex.

This work presents paleoceanographic and – climatic records from high latitude oceans that give new insights to our current knowledge of past climate variability, and reform some of our current understanding of the past climate conditions on a local scale. This work also improves the applicability of the key northern North Atlantic diatom taxa as paleo-indicators, questioning previous knowledge on the ecology of some species and highlighting some important taxonomic issues. These issues need to be resolved in the future, as they might affect ecological interpretations and climate reconstructions.

Tiivistelmä

Viimeaikaiset muutokset arktisessa ympäristössä, kuten merijään laajuuden pieneneminen sekä Grönlannin mannerjäätikön sulaminen, ovat tapahtuneet hälyttävällä nopeudella ja intensiteetillä. On selvää, että nykyisellä ilmastomuutoksella on vakavia vaikutuksia ilmastollisesti herkkään arktiseen alueeseen. Tutkimalla menneitä ilmastovaihteluita, ilmasto-olosuhteita sekä vuorovaikutuksia ilmastosysteemin komponenttien (meri, mannerjäätikkö, ilmakedä) välillä, löydetään mahdollisia analogioita nykyiselle ilmastomuutokselle. Menneisyyden ilmastotiedon avulla voidaan siis paremmin ymmärtää nykyisiä muutoksia arktisessa ympäristössä sekä arvioida tulevia ilmastomuutoksen vaikutuksia.

Merenpohjan sedimenttisarjat tarjoavat epäsuaa tietoa menneistä pitkän aikavälin ilmastovaihteluista sekä meren pintaveden olosuhteiden muutoksista. Jäätikön reunan läheisyydestä saatavan tiedon avulla pystytään tutkimaan muinaisia meren ja jäätikön välisiä vuorovaikutuksia, mikä on erittäin tärkeä ymmärtää arvioitaessa nykyisen meren pintaveden lämpenemisen vaikutuksia Grönlannin mereen päättyviin jäätikköihin.

Tässä työssä tutkitaan edellisen jääkauden jälkeisiä merenpinnan olosuhteiden (meriveden pintalämpötilan, merijään ja merivirtojen) vaihteluita korkeilla pohjoisilla leveysasteilla käyttäen meressä eläviä piilevyhteisöjä. Pitkän aikavälin vaihteluita ilmastossa ja merenpinnassa tutkitaan kahdelta eri tutkimusalueelta Pohjois-Huippuvuorilta sekä Baffininlahdelta. Työssä käytetään piilevyhteisöihin perustuvia kvantitatiivisiä ja kvalitatiivisiä metodeja. Lisäksi sedimentin raekoko-analyysiä

käytetään tutkittaessa meren ja jäätiköiden välistä vuorovaikutusta. Työssä tutkitaan myös yleisempien pohjoisella Pohjois-Atlantilla esiintyvien piilevien ekologiaa sekä vasteita yleisimpiin ympäristömuuttujiin; meriveden pintalämpötilaan ja merijäähän. Lajikohtaisia ympäristövasteita tutkimalla pyritään selvittämään parhaimmat indikaattorilajit tutkituille ympäristömuuttujille sekä edistämään lajien käyttömahdollisuuksia paleotutkimuksissa.

Baffininlahdelta tutkittiin deglasiation aikaisia (10 000–14 000 vuotta sitten) muutoksia. Tulokset osoittavat että meren pintavedet olivat lämpimiä kylmän Nuorempi Dryas-kauden aikana (11 700–12 900 vuotta sitten), mikä viittaa siihen että meren pintaosien olosuhteet poikkesivat Grönlannissa vallinneista ilmasto-olosuhteista. Nämä lämpimät olosuhteet aiheutuivat alueella lisääntyneestä Atlanttisesta merivirtauksesta sekä pohjoisella pallonpuoliskolla lisääntyneestä auringon säteilystä mikä puolestaan voimisti vuodenaikaisuutta. Raekoon muutos meren pohjasedimentissä osoittaa että lämpimällä merivedellä oli suuri vaikutus Länsi-Grönlannissa sijaitsevan Jakobshavn Isbræ-jäätikkövirran romahtamiseen. Pohjois-Huippuvuorilta tutkittu sedimenttisarja kattaa noin viimeisen 4 200 vuoden ajanjakson. Tuloksien perusteella Pohjois-Huippuvuorilla tapahtui merkittävä muutos noin 2 500 vuotta sitten kun ilmasto vaihtui melko tasaisesta hyvin vaihtelevaksi. Sedimenttiarkiston perusteella alueella sijainnut jäätikkö vetäytyi samaan aikaan tutkimusalueen läheisyydestä kauemmaksi. Muutos korostaa Arktisen alueen herkkyyttä ilmastovaihteluille.

Piilevät ovat hyviä indikaattoreita paleoilmastotutkimuksissa, ja siksi on erityisen tärkeää tuntea piilevien ekologiaa ja lajikohtaisia vasteita ympäristömuuttujiin. Tutkimus piilevien lajikohtaisista ympäristövasteista ja ekologiasta jakaa lajit kylmän-, lämpimän- ja lauhkeanveden indilaattoreiksi sekä merijää-indikaattoreiksi. Tutkimus osoittaa että kaikilla merijäähän yhdistetyillä lajeilla ei ole tilastollisesti merkittävää suhdetta merijäähän. Tuloksissa ainoastaan lajit *Actinocyclus curvatulus*, *Coscinodiscus oculus-iridis*, *Fragilariopsis oceanica* ja *Porosira glacialis* osoittavat tilastollisesti merkittävää vastetta merijäähän, kun taas aiemmin yleisesti merijää-indikaattorilajina käytetyllä *Fragilariopsis cylindrus*-lajilla ei ole tilastollisesti merkittävää vastetta merijäähän. Vaikka tämä laji esiintyy yleisesti merijäessä ja jääreunan edustan avovesialueella, sen ekologia on luultua monimutkaisempi.

Kokonaisuudessaan työ esittelee menneitä meren pintaosissa ja ilmastossa tapahtuneita vaihteluita pohjoisilta leveysasteilta, mikä lisää ymmärrystämme ja uudistaa joitakin aiempia käsityksiämme menneistä paikallisista ilmastovaihteluista. Lisäksi tutkimus vahvistaa nykyistä tietämystämme Pohjois-Atlantin piilevälajiston ympäristövasteista, mutta myös kyseenalaistaa joidenkin lajien nykyistä käyttöä indikaattoreina paleotutkimuksissa, sekä tuo esiin taksonomisia ongelmia jotka vaativat selvitystä tulevaisuudessa, sillä ne voivat mahdollisesti vääristää tulkintoja ja aiheuttaa virheellisiä ilmastorekonstruktioita.

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Papers I–III

List of original publications

This thesis is based on the following publications:

- I Oksman, M., Juggins, S., Miettinen, A., Witkowski, A., Weckström, K. 2017. The biogeography and ecology of common diatom species in the northern North Atlantic, and their implications for paleoceanographic reconstructions. (Submitted to *Marine Micropaleontology*).
- II Oksman, M., Weckström, K., Miettinen, A., Juggins, S., Divine, D.V., Jackson, R., Telford, R., Korsgaard, N.J., Kucera, M. 2017. Younger Dryas ice margin retreat triggered by ocean surface warming in central-eastern Baffin Bay. *Nature Communications* 8:1017, doi:10.1038/s41467-017-01155-6.
- III Oksman, M., Weckström, K., Miettinen, A., Ojala, A.E.K., Salonen, V.P. 2017. Late Holocene shift towards enhanced oceanic variability in a High Arctic Svalbard fjord (79°N). *Arktos* 3:4, doi:10.1007/s41063-017-0032-9.

The publications are referred to in the text by their roman numerals.

Authors' contribution to the publications

Paper I The idea for the study came from K. Weckström and was further developed with M. Oksman and A. Miettinen. The statistical analyses were done by S. Juggins and data was provided by A. Miettinen. M. Oksman took light microscopy images and A. Witkowski contributed to diatom identifications. Results were interpreted by M. Oksman and K. Weckström. M. Oksman was responsible for preparing the manuscript, while all authors commented and contributed

Paper II The study was planned by M. Oksman, K. Weckström and A. Miettinen. M. Oksman carried out the diatom and the grain size distribution analyses. The statistical analyses were done by S. Juggins and D. Divine. R. Jackson constructed the chronology. R. Telford and N.J. Korsgaard contributed with their expertise on age-modelling and glaciology. M. Kucera provided sediment material. M. Oksman was responsible for preparing the manuscript, while all authors commented and contributed

Paper III The study was planned by M. Oksman, K. Weckström, A. Miettinen and V.-P. Salonen. M. Oksman carried out the diatom analysis. V.P. Salonen provided sediment material and the grain size distribution data. A. Ojala contributed on revising the chronology. M. Oksman was responsible for preparing manuscript, while all authors commented and contributed. .

Abbreviations

AMOC	Atlantic Meridional Overturning Circulation
AMS	Accelerator mass spectrometry
BC	Baffin Current
Cal yr BP	Calibrated radiocarbon years before present
EGC	East Greenland Current
ESC	East Spitsbergen Current
GrIS	Greenland Ice Sheet
IC	Irminger Current
IRD	Ice rafted detritus
LC	Labrador Current
LGM	Last Glacial Maximum
MIZ	Marginal Ice Zone
NAC	North Atlantic Current
SST	Sea surface temperature
YD	Younger Dryas
WA-PLS	Weighted averaging partial least square
WGC	West Greenland Current
WSC	West Spitsbergen Current

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1 Introduction

1.1 Arctic climate change

Through the Earth's geological history, climate has undergone multiple fluctuations with time scales ranging from centennial to millennial. The ongoing climate change has special characteristics; the exceptional rate of changes and the major impact on the Arctic region, seen as the polar amplification (Kaufman et al. 2009; Serreze and Barry 2011). The Arctic sea ice cover has declined rapidly in extent and volume over the last few decades (Polyak et al. 2010; Stroeve et al. 2012; IPCC 2013). The global mean surface temperature has increased steadily since the late 19th century (Hartmann et al. 2013). The Greenland Ice Sheet (GrIS) has lost ice mass over the past decade (Rignot et al. 2011) and the rate of ice mass loss has accelerated since 1992 (Vaughan et al. 2013). In 2013, IPCC reported that the spring snow cover extent in the Northern Hemisphere has decreased and permafrost temperatures have increased since the 1980s (Vaughan et al. 2013). All recent high-latitude environmental and climate fluctuations have considerable importance, because they have a global influence through ocean–ice sheet–atmosphere interactions. Particularly crucial is the ice loss in the Arctic region, since it has a direct influence on the global ocean circulation and a large control on the global sea level. Bamber et al. (2012) showed that the recent freshwater discharge from the GrIS accounts now for a third of the entire freshwater flux from the Arctic, underlining the importance of the ice sheet meltwater to the North Atlantic circulation. Several studies have shown that the ocean has an important role regulating ice sheet stability, as the ocean has a direct connection to the ice sheet through the

marine terminating outlet glaciers (Holland et al. 2008; Nick et al. 2013). These marine-terminating outlets produce one-third of the yearly GrIS mass loss through ice discharge (Enderlin et al. 2014), whereas the other two thirds are lost through negative surface mass balance (surface melt). Hanna et al. (2013) correlated changes in sea surface temperatures (SSTs) around Greenland to changes in runoff and suggest that the ocean may have an effect on the local atmosphere, which regulates the surface melt, indicating that the ocean could play a role in both GrIS's ice loss mechanisms. The oceanic heat clearly interacts with the ice margin, and plays an important role in the accelerated ice loss from the GrIS, but this process is not as well understood in Greenland as it is, for instance, in the Antarctic (Joughin et al. 2012). For assessing impacts of climate variability and for projecting future climate development, there is a profound need to understand the natural past climate variability and its rate, magnitude and mechanisms behind it. In addition, the Arctic climate system is a combination of sensitive components (ocean, ice sheet, atmosphere) coupling with each other. Without understanding the coupling between these components, it is difficult to precisely project the ice loss' future impact on the sea-level. Marine sediments are excellent climate archives, since they generally provide long, and continuous records of past climate variability. Especially valuable are records at the high latitude regions in ice margin proximity for detecting ocean-ice sheet interactions.

1.1.1 Sea surface temperatures and Atlantic meridional overturning circulation

Because of the ocean's enormous heat

capacity and ability to transport heat via ocean currents and through water mixing, most of the human-produced excess heat in the Earth's climate system has been stored in the oceans (Levitus et al. 2001). Measurements show that the upper ocean (0–700 m) has warmed significantly between the years 1971–2010 (Fig. 1; Levitus et al. 2009) and this warming is more prominent in the Northern Hemisphere and, especially, in the North Atlantic region (Rhein et al. 2013). Higher SSTs impose a direct threat to the dynamics of the GrIS through the ice sheet's marine-terminating outlets, alongside other controlling factors (ice thickness, subglacial topography and bathymetry) (Holland et al. 2008; Motyka et al. 2011). Sea surface temperatures in the high latitudes of the North Atlantic Ocean modulate climate in northwest Europe and winter sea ice extent in the Arctic (Årthun et al. 2016). Nevertheless, despite the general warming trend, one obscure feature of the climate change is the

subpolar North Atlantic cooling anomaly, that has been suggested to be caused by the reduced Atlantic Meridional Overturning Circulation (AMOC) (Drijfhout et al. 2012; Rahmstorf et al. 2015). As AMOC is an important component of the North Atlantic climate system, the weakening has large-scale impacts on the meridional heat and carbon transport and on deep-water formation. Smeed et al. (2014) reported recent weakening of the AMOC based on observations made between the years 2004 and 2012, and climate models have projected that AMOC will slow down even more in the next decades (Rhein et al. 2013). The global warming affects the ocean's hydrological cycle as fresh water export from the Arctic increases. And the increased freshwater flux to the North Atlantic is significant, as it has been suggested to be responsible for the AMOC decline and for the regional subpolar North Atlantic cooling anomaly (Rahmstorf et al. 2015; Sévellec et al. 2017).

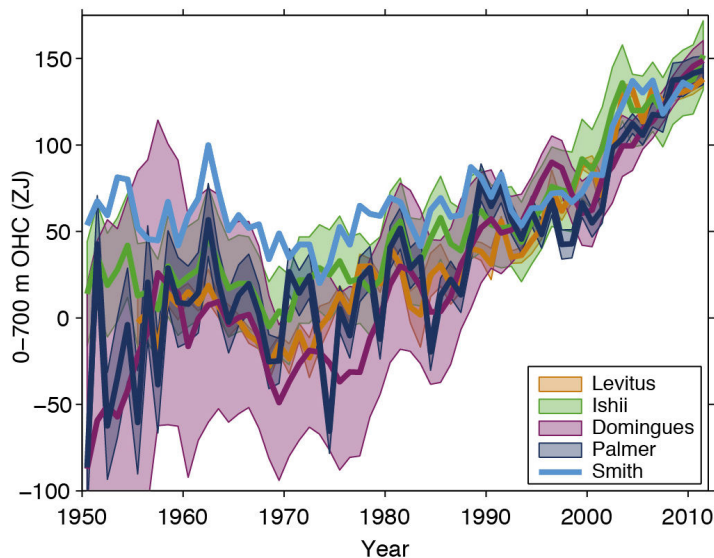


Figure 1. Observation-based estimates of annual global mean upper (0–700m) ocean heat content (OHC) in ZJ (1 ZJ=10²¹ Joules). Modified from Rhein et al. (2013) and original data from Levitus et al. (2012), Ishii and Kimoto (2009), Domingues et al. (2008), Palmer et al. (2007) and Smith and Murphy (2007).

1.1.2 Arctic sea ice

Sea ice is a crucially important component of the Arctic climate system, as it regulates heat transfer from the ocean to the atmosphere and changes the surface albedo. Further, sea ice has its significance for polar ecosystems, and it is a habitat for sea ice-associated animals and plants. Sea ice is very sensitive to atmospheric and oceanic heat variability. In August 2017, the Arctic sea ice extent was 5.51 million square kilometers having decreased drastically by 10.5 % per decade over the last four decades (Fig. 2, National Snow and Ice Data Center). Climate model projections are even more alarming, as they project that the Arctic Ocean may be ice-free during summers by 2030s (Wang and Overland 2012). Despite the fact that decreased Arctic sea ice cover has been found to provide some positive opportunities (mostly economic), the decline is assessed to pose major climatic and ecological threats. Sea ice decrease has multiple consequences for the ocean; increasing SSTs (as open water has stronger heat absorption) resulting in sea surface anomalies, decreasing surface albedo, freshening of the surface water layer of the northern North Atlantic, and increasing fresh water fluxes to the North Atlantic which affect the ocean circulation. The reason for the weakening of the AMOC (Smeed et al. 2014) has not been fully understood and the weakening has been linked to sea ice decline as part of the ongoing climate warming and as a result of surface water freshening (Sévellec et al. 2017). The open water season and its duration at high latitudes has also its importance as solar insolation can significantly increase SSTs during the short open water period (Bendtsen et al. 2017). This has a larger-scale impact on the GrIS as the sea ice retreat and the duration of

the open water season in front of tidewater outlet glaciers have been shown to control the melting of outlet glaciers (Bendtsen et al. 2017).

1.2 Reconstructing past sea surface conditions in the North Atlantic using fossil diatom assemblages

Since instrumental climate records generally only cover the last few decades, studying past natural climate variability becomes important in many aspects. Information of past climate variability is used to tune and validate climate models and it adds to the understanding of the ongoing climate change and future climate development. In addition, rate, causal mechanisms, and impacts of the changes can be evaluated using paleoclimate records, and the anthropogenic impact on the present climate change can be defined by comparing the magnitudes of natural climate variability to the ongoing climate change. Especially valuable are long-term and high-resolution climate records, since they can be used for detecting both short- and long-term variability, but finding archives that include both these characteristics is challenging.

Paleoclimatic and –oceanographic variability can be reconstructed through several different physical, biological and chemical proxies, but in this work, the focus is on marine fossil diatoms (Bacillariophyceae) preserved in ocean sediments. Diatoms are widely used for environmental reconstructions in the North Atlantic region as they are a highly abundant and diverse group, they show good analogue relations to modern oceanic water masses, and they are generally resistant to degradation (e.g. Koç et al. 1993; Jiang et al. 2001; Birks and Koç 2002; Andersen et al. 2004a, 2004b;

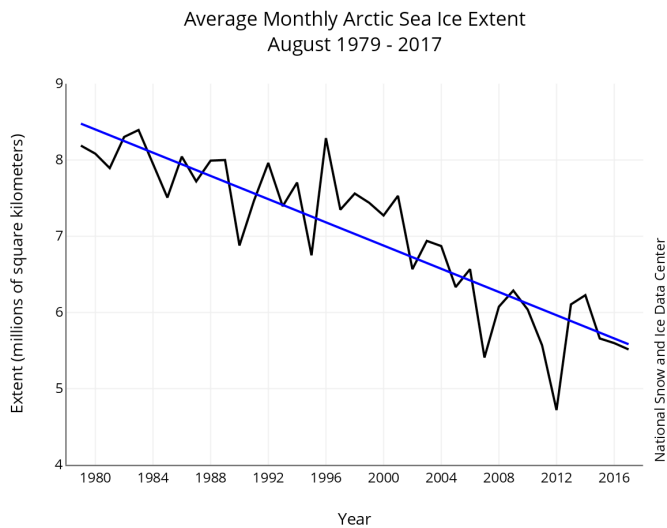
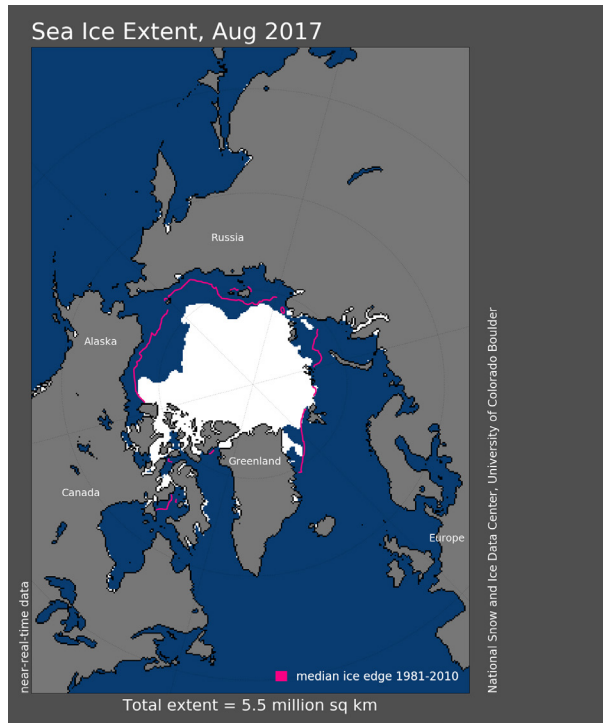


Figure 2. Arctic sea ice extent in August 2017 (August average extent for the years 1981-2010 is shown by the magenta line) and monthly August sea ice extent for the years 1979-2017 (National Snow and Ice Data Center).

Justwan et al. 2008; Berner et al. 2008, 2011; Miettinen et al. 2012, 2015). Marine diatom records thus allow a good assessments of past oceanic conditions and estimates of ocean current variability. Earlier diatom studies have mostly been conducted using qualitative methods that are based on the relative abundances of diatom species and on the knowledge that diatoms are strongly influenced by oceanic conditions like surface water temperature and sea ice cover (Williams 1990; Hasle and Syvertsen 1996; von Quillfeldt 2001). Koç Karpuz and Schrader (1990) presented the first quantitative diatom based SST reconstruction from the North Atlantic region that was based on a transfer function method and a calibration dataset that included 43 species and 104 surface sediment samples from the Greenland, Iceland and Norwegian Sea. This diatom calibration dataset was used for reconstructing surface ocean conditions in the North Atlantic region in Koç Karpuz and Jansen (1992) and Koç et al. (1993). Later, the same dataset was modified by Birks and Koç (2002) as the number of surface sediment samples was increased to 139 samples including samples from the Labrador Sea and Fram Strait region. Andersen et al. (2004a) revised the taxonomy in the calibration dataset and set the number to 52 species that has remained to present day. The calibration dataset was then used in several diatoms studies in the North Atlantic region (Berner et al. 2008, 2011; Justwan et al. 2008; Justwan and Koç 2009; Miettinen et al. 2011, 2012) until the number of surface sediment samples was increased to 184, as Miettinen et al. (2015) extended the dataset to cover colder regions from the East Greenland, West Spitsbergen margins, Greenland basin, Fram Strait and Baffin Bay. During the last two decades,

also three smaller and more regional North Atlantic diatom-based calibration datasets have been published by Jiang et al. (2001) with 53 surface sediment samples around Iceland, Sha et al. (2014) with 72 surface sediment samples from Baffin Bay, Labrador Sea and around Iceland, and by Krawczyk et al. (2016) with 87 surface sediment samples from Baffin Bay.

Offshore diatoms live both in the uppermost part of the water column (ca. 0–50 meters) and in/associated with sea ice (Ehrenberg 1841), and thus have a potential to be used as indicators for SSTs and sea ice. Sea ice diatoms are found in brine pockets, float directly under the ice, or are attached to the ice forming strands into water column (Horner 1985). Marginal Ice Zone (MIZ) assemblage diatoms live both in sea ice and in open water, but MIZ-species occur mainly in the early summer and bloom in the cold, fresher surface meltwater layer (von Quillfeldt 2003; Caissie 2012). Diatom-based transfer functions for sea ice were first developed for the Southern Ocean (e.g. Pichon et al. 1987; Crosta et al. 1998) and in the recent decade they have also been developed for the North Atlantic region (Justwan and Koç 2008; Sha et al. 2014; Miettinen et al. 2015; Krawczyk et al. 2016). Quantitative reconstructions of several environmental variables using a single proxy (diatoms) requires profound understanding of each species' ecology and species' responses to the investigated environmental variable.

The past SST variability has been widely studied in the North Atlantic region using quantitative diatom-based methods (e.g. Andersen et al. 2004a; Justwan et al. 2008; Berner et al. 2011; Jiang et al. 2015; Miettinen et al. 2015; Krawczyk et al. 2016). However, these records mainly cover the Holocene

period, whereas reconstructions reaching further back to the deglacial time (ca. 21–11 cal. kyr BP) are sparse and only qualitative records exist (Williams 1993; Koç and Jansen 1994; Koç et al. 2002; Müller et al. 2009; Hoff et al. 2016). The records spanning over the deglacial time hold valuable information of the ice sheet decay and ocean-ice sheet interactions under a warming climate, which could provide potential analogues for the modern climate warming, although the somewhat different boundary conditions will have to be taken into account.

1.3 Aims of this study

Diatoms have previously been used to study sea surface conditions at lower latitudes of the North Atlantic (e.g. Koç et al. 1993; Jiang et al. 2001; Birks and Koç 2002; Andersen et al. 2004a, 2004b; Justwan et al. 2008; Justwan and Koç 2008; Berner et al. 2008, 2011; Miettinen et al. 2012, 2015; Sha et al. 2014), but quantitative records of ocean conditions are missing from the high northern latitudes. Because past climate dynamics at high latitudes are not well understood despite being crucial concerning the ongoing environmental change in the region, there is a clear demand for long-term climate records.

The first aim of this work was to produce high-resolution records of paleoclimate and –oceanographic variability in the Northern Hemisphere high latitude areas using fossil diatom assemblages. The methods used include the quantitative reconstruction of August sea surface temperatures (aSSTs), Q-mode factor analysis and qualitative diatom assemblage analysis. The second aim was to assess the common North Atlantic diatom taxa as paleoceanographic indicators and to investigate their response to environmental variables (SSTs and sea ice

cover) and identify robust indicator species for the studied variables. The third aim was to assess past ocean-ice sheet interactions. To do this, grain size distribution analysis was added to the tool kit to further elucidate glacial history. In this work, marine sediment records are presented from two climatically sensitive Arctic regions, Baffin Bay and northern Svalbard.

More specifically the aims of this work were:

- i) To generate high-resolution climate records of August sea surface temperature and sea ice variability in Svalbard and Baffin Bay (Paper II and III).
- ii) Determine the past variability of the main ocean surface currents in Svalbard and Baffin Bay (Paper II and III).
- iii) Examine past interactions between the ocean and the Greenland Ice Sheet (Paper III).
- iv) To examine the common northern North Atlantic diatom taxa's responses to environmental gradients (sea surface temperature and sea ice) and identify the best indicators for these two variables (Paper I).

2 Regional setting

2.1 North Atlantic surface sediment calibration dataset

This work is largely based on a Northern Hemisphere diatom calibration dataset that was first published by Koç Karpuz and Schrader (1990), and later modified by Birks

and Koç (2002), Andersen et al. (2004a) and Miettinen et al. (2015). In this work, the diatom calibration dataset was used for investigating the ecology and biogeography of the common northern North Atlantic diatom taxa in Paper I, and employed for the aSST reconstructions in Papers II and III. The used North Atlantic diatom calibration dataset is so far the spatially largest dataset from the Northern Hemisphere, including

183 surface sediment samples around the North Atlantic (one sample was removed as an outlier). Samples are from between the latitudes of 42°N and 79°N, from the Nordic Seas, Fram Strait, West Spitsbergen margin, the Greenland basin, the Labrador Sea, Davis Strait and Baffin Bay (Fig. 3).

2.2 Downcore sites

Two marine sediment records from the

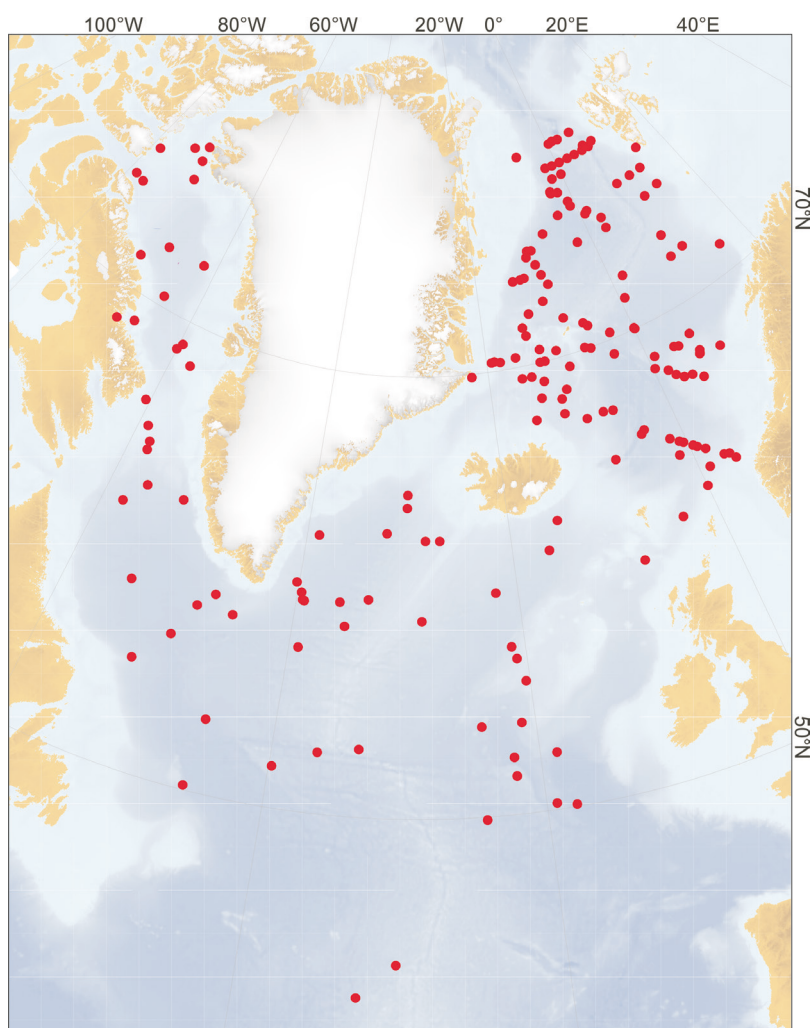


Figure 3. The locations of the 183 surface sediment samples from the North Atlantic included in the North Atlantic diatom calibration dataset.

northern high latitude ocean, central-eastern Baffin Bay and northern Svalbard (Fig. 4), were analyzed in this work (Papers II and III). The Baffin Bay sediment record represents the deglacial period (14–10.2 kyr BP), whereas the record from northern Svalbard covers the late Holocene (last ca. 4 200 years). Despite the spatial and temporal differences between the two records, both sites are very sensitive to climate fluctuations as they are situated in

the gateways between the Atlantic and Arctic water masses, where sea ice cover has an important role regulating the local climate; temperature and precipitation.

2.2.1 Baffin Bay

The modern ocean surface circulation in Baffin Bay is characterized by a counter-clockwise Baffin Bay gyre (Tang et al. 2004), which is dominated by the northward-

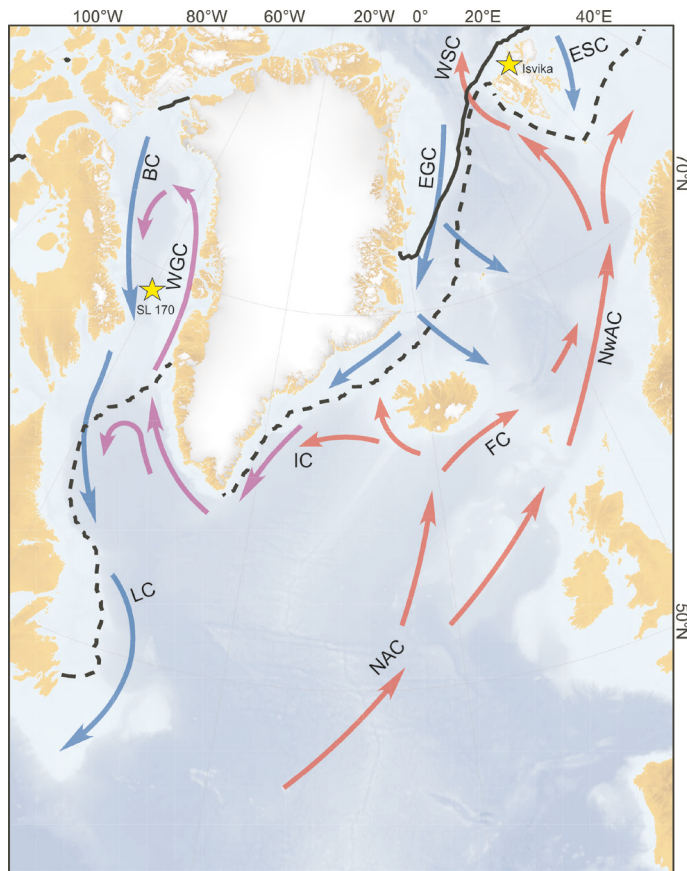


Figure 4. Map of the North Atlantic showing the locations of the two study sites (marked with yellow stars); core SL 170 (68°58.15'N; 59°23.58'W) and Isvika Bay (79°57.43'N; 18°34.24'E). Warm, cold and temperate ocean currents are indicated with red, blue and purple arrows respectively. NAC=North Atlantic Current, NwAC=Norwegian Atlantic current, FC=Faroes Current, ESC= East Spitsbergen Current, WSC=West Spitsbergen Current, EGC= East Greenland Current, IC=Irminger Current, WGC=West Greenland Current, BC=Baffin Current, LC=Labrador Current. Modern sea ice extent (average for the years 1981-2010) is indicated with a black dashed line for the winter maximum and with a black full line for the summer minimum (Fetterer et al. 2017).

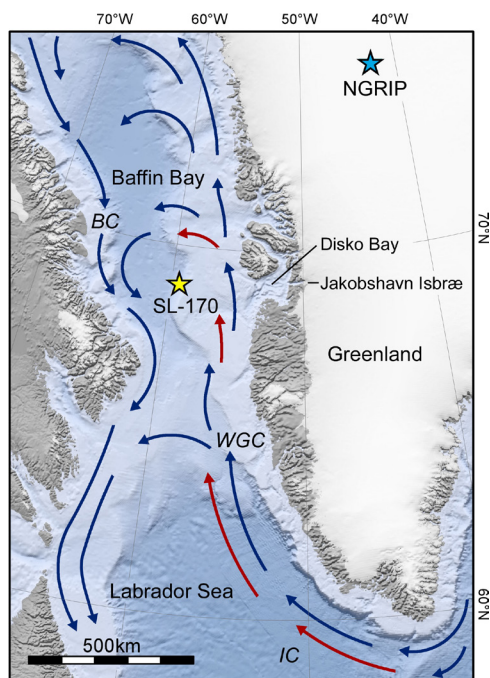


Figure 5. Map of the Baffin Bay showing the location of core SL 170 site (yellow star). Major surface currents in modern Baffin Bay; IC=Irminger Current, WGC=West Greenland Current and BC=Baffin Current.

flowing West Greenland Current (WGC) (Fig. 5). The WGC consist of relatively warm and saline Atlantic-sourced waters from the Irminger Current (IC) and of cold and low-salinity polar waters from the East Greenland Current (EGC). The water masses from IC and EGC mix together off South Greenland and enter Baffin Bay through Davis Strait. The relatively warm WGC flows northward and influences the west coast of Greenland. Most of the waters turn westwards forming the Baffin Bay gyre and only a small fraction continues up to the northernmost parts of Baffin Bay (Knudsen et al. 2008). Cold and low-saline Arctic waters enter the Baffin Bay from the Arctic Ocean through Nares Strait, Jones Sound and Lancaster Sound, and form the Baffin Current (BC). These waters mainly flow southward into the Labrador Sea

partly forming the Labrador Current (LC). The average summer (July) air temperature in the area is below 10°C and surface water temperature is ca. 5°C (Boertmann et al. 2013). Baffin Bay is covered by sea ice most of the year, the sea ice maximum occurs in February and the minimum in August-September (Tang et al. 2004). The sea ice distribution is affected by ocean circulation and sea ice prevails longest on the western side of the bay along the Canadian coast, whereas the eastern and the central part of the bay are affected by the generally warmer WGC, and only drift ice remains there during the summers.

The study site (68°58.15'N 59°23.58'W) is located on the Disko Shelf in central-eastern Baffin Bay (Fig. 5), which is under the influence of the WGC, as well as fresh water and iceberg discharge from Disko Bay. The study site is a deep marine environment and the core was obtained from the deepest ploughmark on the outer shelf.

2.2.2 Svalbard

The Svalbard archipelago (76°–81°N and 10°–30°E) is located in the northern North Atlantic and is surrounded by the Arctic Ocean, the Barents Sea, the Greenland Sea and the Norwegian Sea. Climate in Svalbard is largely regulated by the main ocean current, the West Spitsbergen Current (WSC), which carries warm and saline waters from lower latitudes as a continuation of the North Atlantic Current (NAC) (Fig. 6). Another important ocean current around Svalbard is the East Spitsbergen Current (ESC) that travels along the east side of the archipelago and carries cold, low-saline waters exiting from the Arctic Ocean.

The study site, Isvika Bay (79°57.43'N 18°34.24'E) is located in the southeastern

part of the Murchisonfjorden, which is situated on the west coast of Nordaustlandet (Fig. 6). Nordaustlandet is situated NE from the main island Spitsbergen and the two islands are separated by the Hinlopen Strait. Nordaustlandet is at the northernmost boundary of the area that receives warm and saline Atlantic-sourced waters. Isvika Bay is relatively shallow (ca. 100 meters deep) and today, the study area is sheltered from the open sea by large islands that rise 50 m above sea level (Kubischta 2011). River Hågglomelva runs to Isvika Bay discharging glacial meltwater that originates from the Vestfonna ice cap, which is today situated ca. 10 km from Isvika. The mean summer (June-August) air temperature in Svalbard is above 2.5°C (Bednorz and Kolendowicz 2013) and the mean annual temperature around -8°C (Pohjola et al. 2011). Modern summer (August) SST is between 1°C and 4°C.

3 Material and methods

3.1 Sediment sampling and chronology

Sediment core SL 170 was retrieved using a gravity corer from aboard the research vessel *Maria S. Merian* during the cruise MSM09/2 in September 2008. The core is 683 cm long and was obtained from 1 078 m water depth. After recovery, the core was split in two halves lengthways for the working and archive halves. The sediment core is stored at <4°C at the IODP Core Repository in Bremen, Germany.

The Isvika sediment core was collected in August 2009 using a modified Kullenberg corer. Two sediment cores Isvika 2 and Isvika 3 were taken from close vicinity on board *M/S Horyzont II* during an expedition to Nordaustlandet (Kubischta et al. 2011; Ojala et al. 2014). Cores were taken from

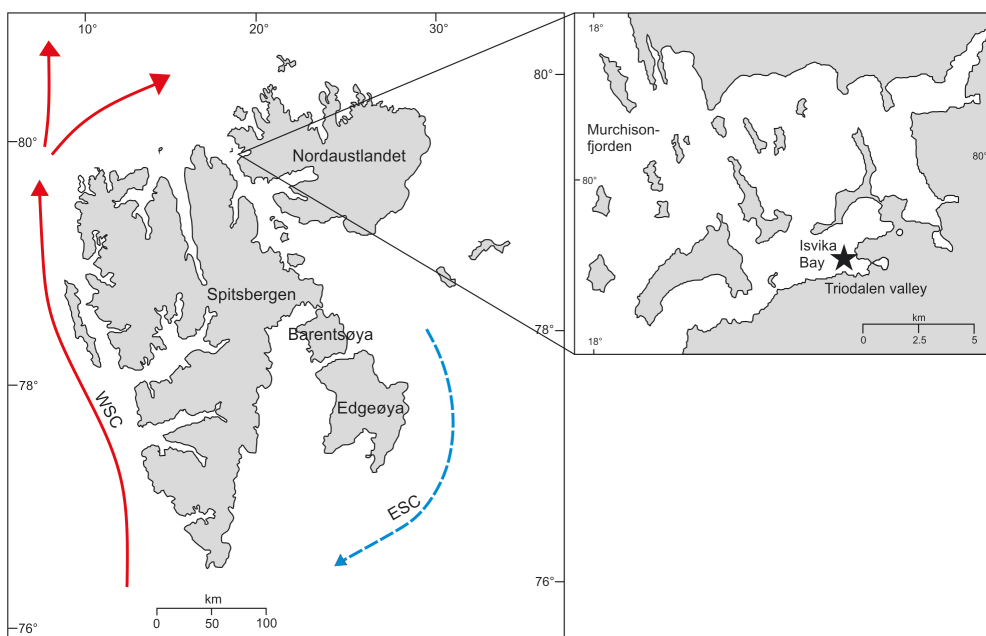


Figure 6. Map of Svalbard and map of Murchisonfjorden showing the coring location (79°57.43'N; 18°34.24'E) of Isvika core (black star). Major surface currents around modern Svalbard; WSC=West Spitsbergen Current and ESC=East Spitsbergen Current.

the deepest part of the basin, from ca. 100 m water depth. After recovery, the two cores were stored at +4°C at the Geological Survey of Finland and halved into archive and working halves. Later, the cores Isvika 2 and Isvika 3 were combined into one 250 cm long composite core (discussed in this work and in Paper III as Isvika core) due to a well-preserved upper part in Isvika 2 and a longer sediment record in Isvika 3.

Chronologies of the two cores were constructed using Accelerator Mass Spectrometry (AMS) ^{14}C dating conducted at the Laboratory for Ion Beam Physics, ETH Zurich (SL 170) and in the Laboratory of Chronology at the University of Helsinki (Isvika core). Chronology for core SL 170 is based on 18 AMS 14 ages from planktonic or mixed benthic foraminifera samples (Table 1). The radiocarbon dates were calibrated using CALIB Rev 7.0.4 program (Stuiver and Reimer 1993), and the age-depth model was constructed using BACON software (Blaauw and Christensen 2011) with the Marine13 calibration curve (Reimer et al. 2013) and a local reservoir correction (ΔR) of 140 ± 35 years (Lloyd et al. 2011). Previous studies from Baffin Bay have employed a ΔR from 0 to 400 years (Levac et al. 2001; Knudsen et al. 2008; Ledu et al. 2010; Gibb et al. 2015); the ΔR of 140 ± 35 years has been employed in several studies in the Disko Bay region (e.g. Perner et al. 2011, 2013; Jennings et al. 2014; Ouellet-Bernier et al. 2014; Hogan et al. 2016; Sheldon et al. 2016) and is in line with the regional reservoir correction ($\Delta\text{R}=150\pm 60$ years) in the southeast Baffin Island region (Coulthard et al. 2010). As the ΔR age is known to vary through time, and is poorly constrained for the deglacial period, several test-chronologies were run to justify the chosen ΔR age. The test-chronologies

were run keeping the same settings in BACON software and varying a constant ΔR age (0 ± 0 years, 200 ± 100 years, 400 ± 100 years and 1000 ± 100 years), and by running chronologies with ΔR age of 140 ± 35 years for the early Holocene and Bølling-Allerød and varying ΔR ages (200 ± 100 years, 400 ± 100 years and 1000 ± 100 years) over the Younger Dryas (YD) period. To summarize these experiments, eight additional age-depth models were created and in most of them the age shift was minimal having no effect on the interpretation of the results, as the onset of the warm SST period (13.4 kyr BP) remained inside the uncertainty interval and the YD period remained within the reconstructed warmer oceanic conditions. Only in one scenario (with a very high ΔR of $1\ 000\pm 100$ years), the warming of the ocean surface post-dates the YD period. However, the radiocarbon chronology is also strengthened by detrital carbonate-rich layers identified in the sediment core (Jackson et al. 2017). These layers were correlated to known Baffin Bay Detrital Carbonate Events (Andrews et al. 1995; 1996; 1998; 2014; Simon et al. 2012; 2014) and thus can be used as independent time markers. Utility of the very high ΔR age ($1\ 000\pm 100$ years) would clearly change the timing of these known events, and was thus reliably rejected.

The chronology of the Isvika core is based on six AMS 14 ages from benthic foraminifera (Table 1). The AMS 14 dates were calibrated, and the age-depth model was constructed using Oxcal program, version 4.2 (Bronk Ramsey and Lee 2013), Marine13 calibration curve (Reimer et al. 2013) and a local reservoir correction (ΔR) of 99 ± 39 years that was calculated using known Svalbard ΔR values (CHRONO 2010 Marine Reservoir Database <http://calib.qub.ac.uk/marine>). A chronology

Table 1. Radiocarbon dates and modelled ages from SL 170 and Isvika core. Dates marked with * are not included in the age-depth models.

Core	Sample ID	Material	Core depth (cm)	14C age (yr BP)	Calibrated age range (cal. yr BP), 95% confidence (2 σ uncertainty)	Modelled age (cal. yr BP)
SL 170	55678.1.1	Mixed benthic foraminifera	24-27	9 668 \pm 112	9 930-10 432	10,225
SL 170	55679.1.1	Mixed benthic foraminifera	35-37	9 460 \pm 80	10 094-10 500	10,309
SL 170	55680.1.1	Mixed benthic foraminifera	55-57	9 833 \pm 83	10 376-10 746	10,571
SL 170	55681.1.1	Planktic foraminifera (N. pachyderma)	74-76	9 901 \pm 82	10 651-10 966	10,796
SL 170	55682.1.1	Mixed benthic foraminifera	74-76	10 028 \pm 87		
SL 170	55682.2.1	Mixed benthic foraminifera (duplicate)	74-76	10 090 \pm 97		
SL 170	55683.1.1	Mixed benthic foraminifera	98-100	10 243 \pm 80	10 876-11 199	11,058
SL 170	55683.2.1	Mixed benthic foraminifera (duplicate)	98-100	10 232 \pm 137		
SL 170	55684.1.1*	Planktic foraminifera (N. pachyderma)*	116-118	11 042 \pm 107*		
SL 170	55685.1.1	Mixed benthic foraminifera	116-118	10 274 \pm 86	11 012-11 470	11,213
SL 170	Beta-344504*	Mollusc fragments*	136-139	10 080 \pm 50*		
SL 170	55686.1.1*	Mixed benthic foraminifera*	136-139	12 990 \pm 117*		
SL 170	58351.1.1	Mollusc fragments	159-160	10 755 \pm 85	11 379-11 973	11,693
SL 170	58352.1.1	Mixed benthic foraminifera	159-160	10 905 \pm 85		
SL 170	58353.1.1	Mixed benthic foraminifera	180-181	10 671 \pm 85	11 515-12 105	11,845
SL 170	55687.1.1	Mixed benthic foraminifera	266-269	11 267 \pm 100	12 250-12 656	12,498
SL 170	58354.1.1	Mixed benthic foraminifera	288-290	11 150 \pm 75	12 413-12 738	12,600

SL 170	55688.1.1	Planktic foraminifera (N. pachyderma)	399-402	11 597 ± 104	13 040-13 368	13,213
SL 170	55689.1.1	Mixed benthic foraminifera	399-402	11 944 ± 92		
SL 170	KIA 40766	Planktic foraminifera (N. pachyderma)	484-488	12 730 ± 60	13 879-14 572	14,137
SL 170	58355.1.1	Planktic foraminifera (N. pachyderma)	636-637	14 640 ± 130	16 434-17 462	16,991
Isvika	Hela-2440	Foraminifera	0-7	687±25	315-445	380
Isvika	Hela-2441*	Mollusc shell*	39-40	1 113±25*		
Isvika	Hela-2442*	Mollusc shell*	52-53	47 101±971*		
Isvika	Hela-2443	Foraminifera	85-89	2 739±29	2 463-2 720	2,591
Isvika	Hela-2607	Foraminifera	100-102	3 342±33	3 139-3 366	3,252
Isvika	Hela-2444*	Mollusc shell*	119-120	7 634±33*		
Isvika	Hela-2445*	Mollusc shell*	121-124	7 471±36*		
Isvika	Hela-2606	Foraminifera	150-153	5 506±47	5 836-6 112	5,974
Isvika	Hela-2446	Foraminifera	169-175	6 758±32	7 247-7 424	7,335
Isvika	Hela-2447*	Mollusc shell*	203	9 085±36*		
Isvika	Hela-2512*	Mollusc shell*	215.5	8 952±38*		
Isvika	Hela-2511	Foraminifera	245-250	10 374±42	NA	NA

for the Isvika core has been previously published by Kubischta et al. (2011) and Ojala et al. (2014). The original chronology was constructed using six ^{14}C ages on benthic foraminifera and six ^{14}C ages on shell fragments (Table 1) and older version of the marine calibration curve, Marine09 (Reimer et al. 2009). The previous chronology was found to include uncertainties related to the ^{14}C ages from the shell fragments, as shell fragments can be unreliable and likely to be re-deposited in the study area (Blake 1961; 1989). For the new chronology, all the ^{14}C ages from shell fragments were excluded and a newer version of the Marine calibration curve was employed.

The sediment cores for the surface sediment samples have been collected between latitudes 42° and 79°N during multiple cruises. All cores are obtained using a box-corer or a multicorer from variable water depths (Paper I; Appendix 1). The majority of the samples, 80 samples, have been collected before the year 1990 (Koç Karpuz and Schrader 1990) and no detailed information of the year of collection is available (Paper I; Appendix 1). 57 samples were collected between the years 1990 and 2000, and the remaining 46 samples were collected between the years 2006 and 2008 (Birks and Koç 2002; Miettinen et al. 2015; Paper I; Appendix 1). The surface samples

represent the topmost 1 cm layer of the core. Only a portion of the samples have been dated, but all the samples have been visually verified to represent the topmost sediment layer (Miettinen, A. personal communication).

The values for modern August SSTs are from the World Ocean Atlas 2001 (Stephens et al. 2002) including all observations since the year 1900 (Miettinen et al. 2015). The modern monthly sea ice data are from the National Snow and Ice Data Center (NSIDC, www.nsidc.com; Cavalieri et al. 1996). The sea ice data from years 1979–1999 was used for the samples collected before year 2000, and sea ice data from years 1979–2006, 1979–2007 and 1979–2008 for the samples taken in 2006, 2007 and 2008, respectively (Miettinen et al. 2015).

3.2 Laboratory analysis

3.2.1 Fossil diatom analysis

For diatom analysis, subsamples of circa 1 cm³ were extracted from the core SL 170 and from the Isvika core. Diatoms were analysed from core SL 170 at 1 cm intervals between the depths 24 and 195 cm (10.2–11.9 kyr BP) and at 5 cm intervals between 195 and 475 cm (11.9–14.0 kyr BP) resulting in a time resolution from 5 to 57 years (avg. 16 years). The Isvika core was analysed at varying depth intervals (intervals varying between 1.5 and 5.5 cm, 2.9 cm on average) resulting in a time resolution from 35 to 207 years (avg. 95 years). All samples for diatom analysis were prepared using a procedure that consist of HCl- and H₂O₂-treatments to remove carbonates and organic matter from the bulk sediment, and a separation of clay particles by settling (Koç et al. 1993). Diatom slides were prepared according to method

described in Koç Karpuz and Schrader (1990) and mounted with Naphrax. Identification of diatom species was conducted following the counting procedure described in Schrader and Gersonde (1978) and a minimum of 300 diatom valves (excluding *Chaetoceros* resting spores) were identified and counted using 1000x magnification. Diatom concentrations (10⁶ valves/g/dry sediment) were calculated from core SL 170 (Paper II) using microspheres on selected samples representing a ca. 100 year resolution. Diatom valves were photographed from the slides using a Zeiss Imager.M2 microscope and an Axiocam MRc5 digital camera (Paper I).

3.2.2 Sedimentological analysis

As an independent and supporting proxy for glacial history, the grain size distribution analysis was conducted from both sediment cores (Papers II, III). Focus was placed on the relative percentage of >63µm fractions as they are considered to be ice rafted and transported by icebergs. Although icebergs can carry ice-rafted debris (IRD) over relatively long distances, the bulk IRD is considered to accumulate close to the source and reflects the local ice dynamics (Andrews et al. 1997; Andresen et al. 2012). The proportion of the bulk sediment in the small size fraction (<63 µm) was used as a proxy for the influence of the glacier meltwater suspension plume in Paper II. All the grain size analysis measurements were conducted at the University of Helsinki using a Malvern Mastersizer 2000(G) particle size analyser. From the sediment cores, subsamples of ca. 0.5 cm³ were taken and before measuring treated with H₂O₂ and HCl in order to remove organic material and carbonates.

3.3 Statistical analyses

The North Atlantic calibration dataset and a weighted averaging partial least squares (WA-PLS) transfer function method (ter Braak and Juggins 1993) were employed to reconstruct aSSTs using the C2 program in Papers II and III. The statistical performance of the WA-PLS model was evaluated using *h*-block cross-validation (Burman et al. 1994; Trachsel and Telford 2016). The 2-component model used in papers II and III has a root mean square error (RMSE) of 1.14°C, the coefficient of determination between observed and inferred values (r^2) of 0.92 and a maximum bias of 2.81°C. The RMSE is slightly larger and the r^2 slightly lower than the corresponding values (0.80°C and 0.96, respectively) in Miettinen et al. (2015), where the performance was estimated using the leave-one-out cross-validation method, which does not allow for spatial autocorrelation and underestimates the prediction error because of effective pseudoreplication.

In Paper I, ecological response models for the two main environmental variables (August SST and April sea ice cover) were developed for the common North Atlantic diatom taxa, which include 21 diatom species listed in Table 2. The selected species (Table 2) are abundant in the North Atlantic region and commonly occur in paleoceanographic literature. The type and significance of each species' response to the studied environmental variables were assessed by fitting a series of hierarchical response models by Jansen and Oksanen (2013). The Weighted Average (WA)-method was employed to calculate each species' temperature optima from the calibration dataset, and the temperature ranges were estimated based on species occurrence in the

Table 2. 21 common northern North Atlantic species

Northern North Atlantic species

<i>Actinocyclus curvatulus</i>
<i>Bacteriosira bathyomphala</i> spore
<i>Coscinodiscus marginatus</i>
<i>Coscinodiscus oculus-iridis</i>
<i>Coscinodiscus radiatus</i>
<i>Fragilariopsis cylindrus</i>
<i>Fragilariopsis oceanica</i>
<i>Porosira glacialis</i>
<i>Rhizosolenia hebetata</i> f. <i>hebetata</i>
<i>Rhizosolenia hebetata</i> f. <i>semispina</i>
<i>Thalassionema nitzschioides</i>
<i>Thalassiosira angulata</i>
<i>Thalassiosira anguste-lineata</i>
<i>Thalassiosira gravida</i>
<i>Thalassiosira antarctica</i> var. <i>borealis</i> spore
<i>Thalassiosira hyalina</i>
<i>Thalassiosira nordenskiöldii</i>
<i>Thalassiosira oestrupii</i>
<i>Thalassiosira pacifica</i>
<i>Thalassiosira trifulta</i>
<i>Thalassiotrix longissima</i>

calibration dataset. The R 3.4.1 software (R Core Team 2017) with the package eHOF (Jansen and Oksanen 2013) was used for modelling ecological responses, while the C2 program was used for the WA-analysis.

The relative abundance of the Marginal Ice Zone (MIZ) –diatom assemblage was used to qualitatively reconstructing sea ice variability and meltwater events (Papers II and III). This assemblage includes the species *Porosira glacialis*, *Actinocyclus curvatulus*, *Coscinodiscus oculus-iridis* and *Fragilariopsis oceanica*. The MIZ-assemblage diatoms are associated to sea ice and occur both in sea ice and in the open-water phytoplankton at the marginal ice zone.

These species bloom in the cold and fresher surface water layer produced by melting sea ice/glaciers (Ligowski et al. 1992; von Quillfeldt et al. 2003).

The variability of different ocean water masses was explored using a Q-mode factor analysis (Imbrie and Kipp 1971) (Paper II). The Q-mode factor analysis was applied to the calibration dataset to group the taxa into factors or “assemblages” that are indicative of specific hydrographic conditions and distinct water masses/ocean currents. These factors were then applied to down-core diatom assemblages to assess the variability of ocean currents in time. The studied factors are the Marginal Ice Zone, the Arctic Waters, the Greenland Arctic Waters, the East-West Greenland Current, the Transitional Waters, the Sub-Arctic Waters, the North Atlantic Current Waters and the Norwegian Atlantic Current Waters. This method is described in more detail in the original publications (Imbrie and Kipp 1971; Andersen et al. 2004b; Berner et al. 2008). In Paper II, the name of the Marginal Ice Zone assemblage is changed from its original name “Sea Ice assemblage” presented in Andersen et al. (2004b), as the name Marginal Ice Zone reflects more adequately the species’ ecology, as the species are typical for the cold and fresher water layer associated with the ice-proximal environment of the marginal ice zone area.

4 Summary of original papers

4.1 Paper I

Paper I focuses on investigating twenty-one common diatom species in the northern North Atlantic, many of which are used as indicator

species in paleoceanographic studies, using a spatially extensive calibration dataset from the North Atlantic. The study aims to assess the species’ responses to environmental gradients and thus add to the knowledge of their implications for the northern North Atlantic paleoclimate/-oceanographic reconstructions. Emphasis was put on examining two, climatically important, environmental variables at northern latitudes; August sea surface temperatures (aSSTs) and April sea ice concentrations. Using the large North Atlantic calibration dataset, the species’ abundance and geographical distribution, species’ temperature range and calculated optima are presented alongside ecological response models for aSST and sea ice. In addition, high-quality light microscopy images of each species are presented to aid with species identification. The results of the study identify indicators for cold, warm and temperate waters and for sea ice. While the results in many cases strengthen current knowledge of the relationship of these species to their environment, they also challenge some previous interpretations. Most surprisingly, *Fragilariopsis cylindrus*, a widely used sea ice indicator species, did not show a statistically significant relationship with sea ice in this large dataset. On the other hand, *Coscinodiscus oculus-iridis* – a species more rarely used as a sea ice indicator, could prove to be a robust indicator of sea ice. Other identified robust indicator species with statistically significant relationships to sea ice were *Actinocyclus curvatulus*, *Fragilariopsis oceanica* and *Porosira glacialis*. The species response models for sea ice emphasize that not all sea ice-associated species have a statistically significant relationship to sea ice, although they are found at high abundances in high sea ice concentrations, emphasizing

for caution when using these species as paleoceanographic indicators.

4.2 Paper II

In paper II, deglacial ocean surface conditions were investigated using fossil diatom assemblages from a high-resolution sediment core SL 170 recovered from central-eastern Baffin Bay. The aim was to investigate ocean surface conditions and interactions between the ocean and the West Greenland ice margin during 14.0–10.2 kyr BP. From the diatom record, aSSTs were quantitatively reconstructed using a weighted-averaging partial least squares (WA-PLS) transfer function (ter Braak and Juggins 1993), and the variability of different water masses was examined using Q-mode factor analysis (e.g. Andersen et al. 2004a). In addition, sediment grain size distribution was measured to study changes in IRD depositions and the vicinity of the glacial meltwater suspension plume (Bartels et al. 2017). The results show warmer oceanic conditions during the YD period and strong interaction between the ocean and the ice margin that led to the collapse of Jakobshavn Isbræ at ca. 12.2 kyr BP. Such warmer oceanic conditions have so far only been hypothesized, but not been supported by data (e.g. Rinterknecht et al. 2014). Comparison of the aSST record with the North Greenland Ice Core Project (NGRIP) $\delta^{18}\text{O}$ record (Rasmussen et al. 2006) shows that the ocean surface was out of phase with atmospheric temperatures over Greenland during the YD period. The increase in aSSTs at 13.4 kyr BP, was followed by an increase in sedimentation rates and deposition of coarser material (i.e. dropstones) indicating enhanced calving from the retreating Jakobshavn Isbræ ice stream. The MIZ-assemblage suggest less severe sea ice conditions during that time than

previously suggested for Baffin Bay (Jennings et al. 2014). The factor analysis shows higher scores for the East-West Greenland Current (EWGC) assemblage indicating stronger inflow of warmer Atlantic-sourced waters which correlates with observations of intensified IC at the time (Kuijpers et al. 2003; Jennings et al. 2006). Stronger inflow of warm Atlantic waters coincides with increased solar insolation in the northern Hemisphere (Berger and Loutre 1991) implying intensified seasonality in Baffin Bay. The results emphasize the importance of the interactions between the ocean and the GrIS under modern climate warming, and show that the warming of ocean surface may have a significant influence on the marine-terminating glaciers of Greenland.

4.3 Paper III

Paper III presents a record of late Holocene paleoclimatic and –oceanographic variability from a high-Arctic fjord in northern Svalbard. The studied marine sediment record, Isvika core, was obtained from the relatively shallow and sheltered Isvika Bay in the western part of Nordaustlandet. Both aSSTs (quantitative) and sea ice variability (MIZ-diatoms, qualitative) were reconstructed from the downcore diatom assemblages. The produced record of ocean surface conditions was combined with high-resolution sedimentological proxies (grain size distribution and IRD) from the same core. Additionally, the chronology for the already previously studied sediment core was revised and presented in this paper. The results demonstrate a climatic shift at 2 500 cal. yr BP, as the marine environment changed from stable, cold, and glacier-proximal conditions to fluctuating, slightly warmer ice-distal conditions. The MIZ-

diatom assemblage indicates that during this climate shift, meltwater input increased and sea ice cover became more extensive compared to ocean conditions during the early part of the late Holocene (4 200–2 500 cal. yr BP). During the latter part of the late Holocene (2 500–250 cal. yr BP), aSST and sea ice are oscillating and negatively co-varying. Detected warm and cold periods can be correlated to the known Northern Hemisphere climate fluctuations, such as the Medieval Climate Anomaly (at ca. 900–600 cal. yr BP) and the Little Ice Age (at ca. 500–200 cal. yr BP). An increase in the relative abundance of species *Thalassionema nitzschioides* suggests stronger inflow of Atlantic water in the area during the last 600 years. The climate shift at 2 500 cal. yr BP could be linked to extensive sea ice cover in Fram Strait (Müller et al. 2012), that has been suggested to control glacier growth in Svalbard (van der Bilt et al. 2015), implying coupling between the ocean, ice sheets and the atmosphere. The distinct paleoceanographic shift and the oscillating conditions during the late Holocene underline that the Arctic region is very sensitive even to minor climate fluctuations and such fluctuations might be amplified under the projected climate warming.

5 Discussion

5.1 Warmer deglacial ocean surface conditions in Baffin Bay (Paper II)

High-resolution studies of deglacial ocean surface conditions are scarce and only a few high-resolution marine records span the whole YD period (Pearce et al. 2013; Müller and Stein 2014). The most conspicuous result

of this work is the reconstruction of a warmer ocean surface in Baffin Bay during the YD period (Fig. 7). The significance of the warmer oceanic conditions is emphasized, as they are driving the collapse of the Jakobshavn Isbræ ice stream (discussed in chapter 5.3). The warmer YD aSSTs contradict other YD SST-records from the eastern Norwegian Sea area (Birks and Koç 2002; Bakke et al. 2009) and the $\delta^{18}\text{O}$ -record from the North Greenland Ice Core Project (NGRIP) (Rasmussen et al. 2006), which display cold marine conditions and cold atmospheric temperatures over Greenland during the YD period (Fig. 7). As the YD in general is known as a cold-climate period, the warmer ocean surface in Baffin Bay was clearly out of phase with atmospheric temperatures and with other SST records (Birks and Koç 2002; Bakke et al. 2009) obtained east of Greenland.

Warmer oceanic conditions along the West Greenland coast over the YD have been earlier proposed by Rinterknecht et al. (2014) and Sheldon et al. (2016), and are also evident from the data in Gibb et al. (2015), however this is the first time that such conditions are clearly demonstrated using a quantitative approach. In contrast, dinocyst data in Jennings et al. (2014) points to an extensive sea ice cover and nearly perennial sea ice conditions indicating very cold conditions. As discussed in Paper II, Rinterknecht et al. (2014) proposed a hypothesis stating that warm water inflow via the WGC combined with reduced AMOC (McManus et al. 2004) caused amplified SST seasonality resulting in a warmer ocean surface off West Greenland over the YD. The results from SL 170 partly corroborate Rinterknecht's hypothesis, however some of the earlier suggestions, e.g. the AMOC reduction playing a role in increasing SSTs,

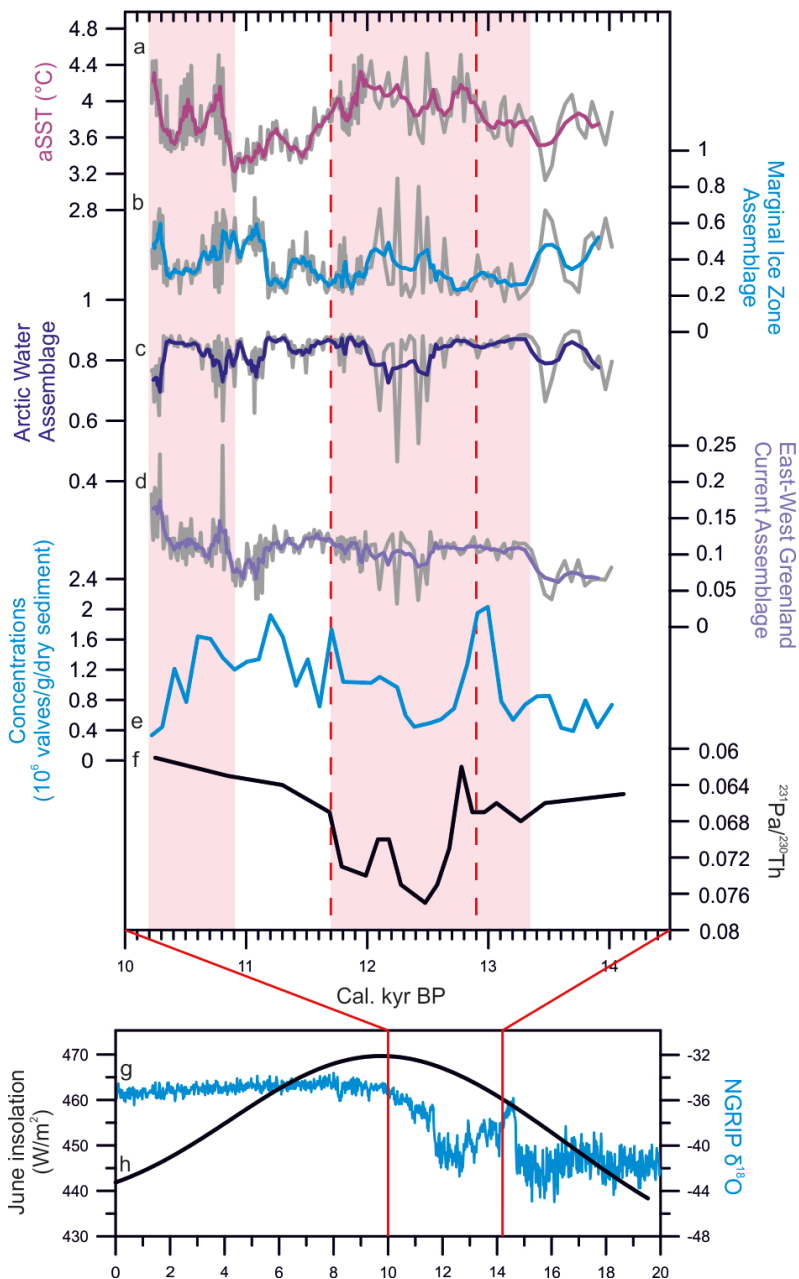


Figure 7. Results from core SL 170 compared with relevant paleoclimate data. a) aSST reconstruction (°C). b) MIZ assemblage factor. c) Arctic Water assemblage factor. d) EWGC assemblage factor. Colored lines in panels a, b, c and d indicate smoothed records (5 pts weighted average). e) Diatom concentrations (10⁶ valves/g dry sediment). f) AMOC rate presented as sedimentary ²³¹Pa/²³⁰Th from the subtropical North Atlantic Ocean (McManus et al. 2004). g) Stable oxygen isotope δ¹⁸O record from the NGRIP (Rasmussen et al. 2006). h) Mean monthly insolation values for June at 68°N for the last 20 kyr (Berger and Loutre 1991). Red shaded areas indicate of warm SST periods in the SL 170 record and the red dashed line marks the limits of YD (12.9–11.7 kyr BP) based on NGRIP (Rasmussen et al. 2006).

can be rejected as the aSST increase clearly precedes the AMOC reduction (Fig. 7). The factor analysis shows high scores for the EWGC assemblage at the onset of the warming around 13.4 kyr BP (Fig. 7), which suggest enhancement of the IC component in the WGC. Intensification of the IC during and after the YD has been suggested in previous studies and warmer IC waters have been considered to cause ice retreat on SE and SW Greenland coasts (Kuijpers et al. 2003; Jennings et al. 2006; Knutz et al. 2011; Dyke et al. 2014; 2017). The intensification of the IC component in the WGC is not solely responsible for increased aSSTs in Baffin Bay as the warming is also linked to increased solar insolation in the Northern Hemisphere and to increased seasonality (Fig. 7). The stronger insolation is shown to drive surface water warming (Andersson et al. 2010), yet the amplified seasonality has so far only been demonstrated from terrestrial proxies around Baffin Bay (Björck et al. 2002; Denton et al. 2005; Young et al. 2012). The warm summer (August) SSTs and relatively high diatom concentrations (Fig. 7) suggest warmer summer conditions implying that the cold YD conditions were restricted to winters.

Another significant finding of this work is that the MIZ-assemblage suggests less extensive sea ice cover and a longer open water period for the YD (Fig. 7) than earlier proposed for Baffin Bay (Jennings et al. 2014). In contrast, studies from Fram Strait and North of Iceland show extensive sea ice cover and prolonged sea ice duration (Müller and Stein 2014; Xiao et al. 2017), which suggest that the warm water inflow to the Nordic Seas and Fram Strait must have been weaker than to Baffin Bay. The Northern Hemisphere ocean circulation system during the deglaciation is not well known

and imposes important questions for future research. The changes in the Baffin Bay ocean surface conditions are likely a response to ocean current dynamics in the North Atlantic region that caused restricted inflow of Atlantic waters to the Nordic Seas and Fram Strait, and intensified the IC and warm-water transport to Baffin Bay. Knudsen et al. (2008) showed that in Baffin Bay deglacial inflow of warmer waters did not follow the modern-day gyre pattern, but the warmer waters were able to continue higher northwards. During the LGM and deglaciation, Nares Strait was blocked by massive ice sheets (Dyke et al. 2002) and the Arctic water inflow to Baffin Bay from the Arctic Ocean was most likely prevented or at least very limited allowing stronger inflow of Atlantic-sourced waters to higher latitudes until the opening of Nares Strait was initiated after 10 kyr BP (Jennings et al. 2011). The SL 170 record demonstrates another strong inflow of Atlantic-sourced waters around 10.9 kyr BP (Fig. 7) and this inflow is exceptionally strong when compared to the modern factor values of the EWGC in Baffin Bay (Paper II, supplementary). The strong Atlantic-water inflow is also evident in the northernmost part of Baffin Bay (Knudsen et al. 2008) and in the east-central Canadian Arctic Archipelago (Pieńkowski et al. 2014), and possibly linked to ice retreat in SE Greenland at the time (Dyke et al. 2014).

5.2 Late Holocene environmental change in northern Svalbard (Paper III)

The Isvika sediment core represents the entire Holocene epoch (last ca. 10 kyr BP), however due to the poor preservation of diatoms in the early and mid-Holocene sections, only the late Holocene (last ca. 4.2 kyr BP) was studied in this work. The results show a

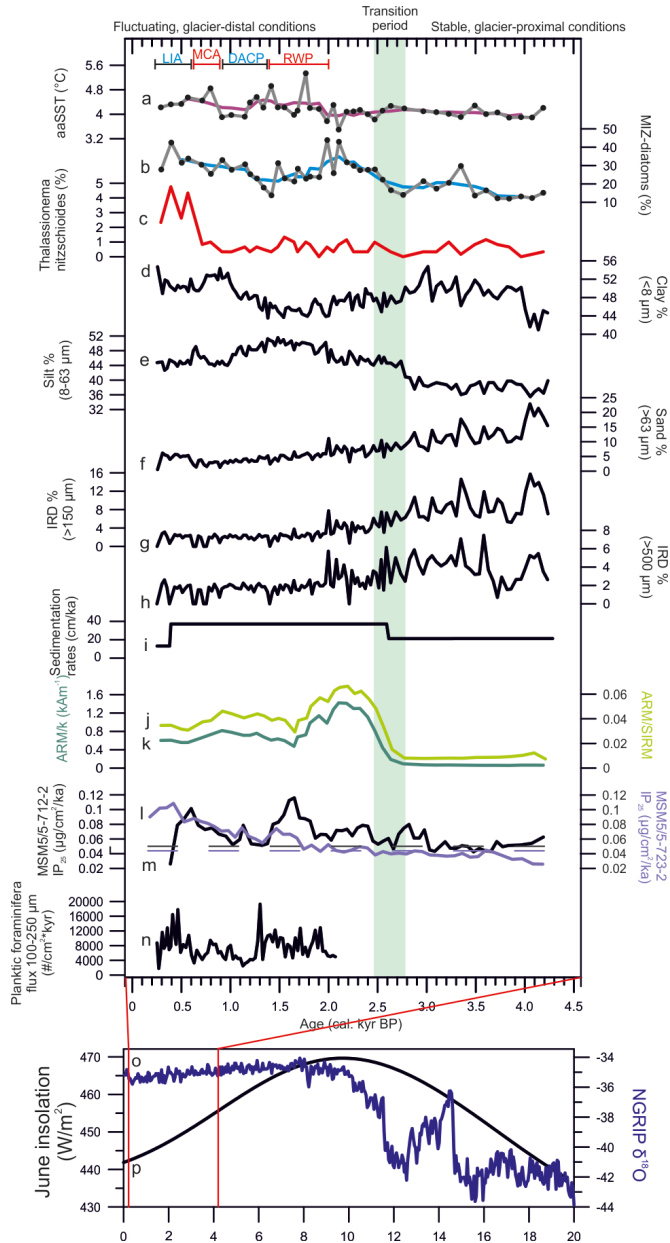


Figure 8. Results from Isvika core compared with relevant paleoclimate data. a) aSST reconstruction ($^{\circ}\text{C}$). b) Relative abundance of MIZ diatoms (%). Colored lines in panels a and b indicate smoothed records (5 pts weighted average). c) Relative abundance of Atlantic water indicator *Thalassionema nitzschioides* (%). d) Vol. % of clay ($<8\ \mu\text{m}$). e) Vol. % of silt ($8\text{--}63\ \mu\text{m}$). f) Vol. % of sand ($>63\ \mu\text{m}$). g) Vol. % of IRD ($>150\ \mu\text{m}$). h) Vol. % of IRD ($>500\ \mu\text{m}$). i) Sedimentation rates (cm/ka). j) Magnetic mineral ration ARM/SIRM (Ojala et al. 2014). k) Magnetic mineral ratio ARM/k (kAm^{-1}) (Ojala et al. 2014). l) IP_{25} accumulation rate ($\mu\text{g/cm}^2/\text{kyr}$) from sediment core MSM5/5-723-2 and m) MSM5/5-712-2 (Müller et al. 2012). Dashed lines show the calculated mean level for the records in Müller et al. (2012). n) Planktic foraminifera flux $100\text{--}250\ \mu\text{m}$ ($\#\text{cm}^2/\text{kyr}$) from core MSM5/5-712-1 (Werner et al. 2011). o) $\delta^{18}\text{O}$ (‰) values from the NGRIP ice core (NGRIP Members 2004). p) Mean monthly insolation values for June at 68°N for the last 20 kyr (Berger and Loutre 1991). Green shaded area indicates transition period from in the environmental shift. The RWP (2–1.4 kyr BP), DACP (1.4–0.9 kyr BP), MCA (0.9–0.6 kyr BP) and LIA (0.6–0.2 kyr BP) are indicated in the figure.

clear climate shift from a relatively stable environment into fluctuating conditions at 2.5 kyr BP. This shift is associated to the transition from a glacier-proximal to a glacier-distal environment, which is reflected in the grain size composition of the sediment (Fig. 8). The early part of the late Holocene (4.2–2.5 kyr BP) is characterized by longer open-water conditions where icebergs, likely originating from the active ice stream in NE Murchinsonfjorden (Hormes et al. 2011), were drifting and depositing IRD under cool surface water conditions. Several climate studies suggest a cooling trend for the late Holocene in the Arctic region (NGRIP Members; Kaufman et al. 2009; Miller et al. 2010) that correlates with decreasing Northern Hemisphere solar insolation (Berger and Loutre 1991). Based on the accumulation rates of the sea ice proxy IP_{25} , Müller et al. (2012) showed that the eastern Fram Strait had extensive, but fluctuating sea ice cover during the late Holocene, which was most pronounced after ca. 3 kyr BP when accumulation rates of IP_{25} are generally over the calculated average (Fig. 8). The reduced solar insolation and weaker Atlantic-water influence have been suggested to decrease the SSTs in the Nordic Seas and adjacent areas (Jiang et al. 2002; Andersen et al. 2004a) and promoting sea ice formation in the Fram Strait region. Further, the extensive sea ice cover is considered to maintain a dry and warmer climate over northern Svalbard limiting glacier growth (van der Bilt et al. 2015). Such a scenario corroborates the oscillating climate record from Isvika Bay and could explain the transition from the glacier-proximal to the glacier-distal environment through ocean-climate coupling. The oceanic conditions have fluctuated in Isvika Bay during the last 2 kyr, and aSST and sea ice records show a clear

negative correlation (Fig. 8). The oceanic oscillations roughly correlate with other oceanic (Werner et al. 2011) and terrestrial (van der Bilt et al. 2015) records, and with the known Northern Hemisphere climate fluctuations; the Roman Warm Period (RWP) at 2–1.4 kyr BP, the Dark Ages Cold Period (DACP) at 1.4–0.9 kyr BP, the Medieval Climate Anomaly (MCA) at 0.9–0.6 kyr BP and the Little Ice Age (LIA) at 0.6–0.2 kyr BP (e.g. Spielhagen et al. 2011, Fig. 6). During the last 600 years, the relative abundance of *Thalassionema nitzschioides* increases remarkably indicating stronger inflow of Atlantic waters. The Atlantic water increase is not evident in the reconstructed aSSTs as the AW in the Fram Strait was relatively cool during the LIA (Spielhagen et al. 2011). Similar intensification of Atlantic water has been recorded in foraminiferal assemblages from Isvika and around Svalbard (Kubischta et al. 2011; Jernas et al. 2013).

5.3 Ocean-ice sheet interactions (Paper II)

The core SL 170 from Baffin Bay has an ideal location at the maximum post-LGM extent of Jakobshavn Isbræ ice stream and the sedimentary record well reflects the interactions between the ocean and ice sheet. The present day GrIS mass loss is accelerating and a significant part of the ice loss is due to oceanic forcing (Joughin et al. 2012). The ocean's potential role in the retreat of present-day Greenland's marine-terminating outlet glaciers is well described in e.g. Holland et al. (2008), while Paper II clearly shows ocean-triggered retreat during the YD. The ice retreat is evident in the sediment of SL 170 after the aSST increase at 13.4 kyr BP (Fig. 7) as sedimentation rates increase, more coarse-grained material is deposited

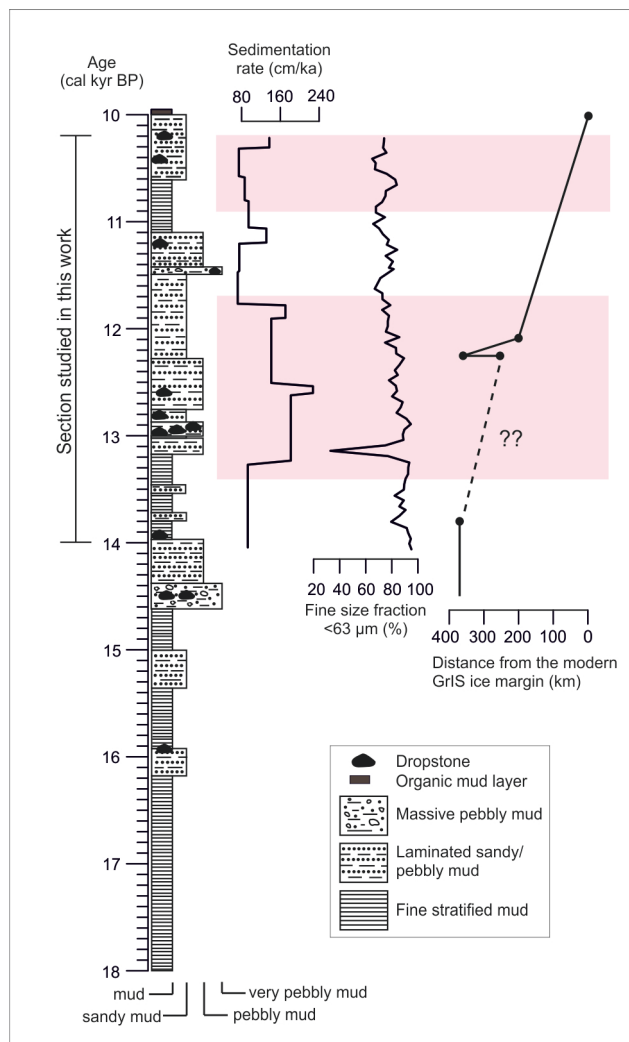


Figure 9. Lithostratigraphy of core SL 170. Sedimentation rates (cm/ka), fine grain size fraction $<63 \mu\text{m}$ (%) and time-distance diagram of Jakobshavn Isbræ extent modified from Ó Cofaigh et al. (2013). Distances are calculated from the modern GrIS margin. Black circles indicate ^{14}C dates, and for the dashed line the ice margin position is unknown. Red shaded areas indicate of warm aSST periods in the SL 170 record.

and the portion of $<63 \mu\text{m}$ grain fractions decrease (Fig. 9). As discussed in Paper II, these indicate a calving ice margin as the meltwater suspension plume, typical for a glacier front (Bartels et al. 2017), is moving further from the study location. The results from core SL 170 support the hypothesis put forward by Rinterknecht et al. (2014), which states that the ocean was the principle driving

mechanism for the Jakobshavn Isbræ retreat. A stronger IC during the YD (Kuijpers et al. 2003; Jennings et al. 2006; Dyke et al. 2017) has been suggested to be one of the major controlling factors for ice retreat together with topography and bathymetry (Dyke et al. 2014). This is demonstrated on SE Greenland as a north-south progression of ice margin retreat that follows the IC flow (Dyke et

al. 2017). Nevertheless, the asynchronous character of GrIS ice streams (Ó Cofaigh et al. 2013; Hogan et al. 2016) suggests that the ocean did not modulate ice retreat alone, but alongside with other controlling factors like topography and ice dynamics. Hogan et al. 2016 proposed that topography and ice dynamics controlled the retreat of Jakobshavn Isbræ, however, paper II shows that in addition to the topographic features, also the ocean governed the retreat. Ó Cofaigh et al. (2013) showed based on geophysical and geological data that Jakobshavn Isbræ suddenly advanced before collapsing at 12.2 kyr BP (Fig 9). They suggested that the advance represents a surge that led to dynamic thinning making the ice stream more susceptible for retreat. This emphasizes that despite the ocean having an important role in the collapse of the Jakobshavn Isbræ, also other controlling factors were at play. It appears that Jakobshavn Isbræ's retreat occurred by calving during the "cold atmosphere – warmer ocean" conditions, whereas during warmer periods before and after the YD the retreat occurred more strongly via surface and subsurface melting (Fig. 7).

The two study sites represent entirely different marine environments; core SL 170 from Baffin Bay is from a deep-marine environment on the outer shelf, whereas the Isvika core is from a shallow bay in Nordaustlandet that is sheltered by islands. During the deglacial time the coring site of SL 170 was surrounded by massive ice sheets extending to the outer shelf (Dyke et al. 2002; Ó Cofaigh et al. 2013; Simon et al. 2014) thus making it ideal for studying ocean-ice sheet interactions. In northern Svalbard, the glacial history is poorly constrained and previous studies suggest that

the main deglaciation would have occurred in the early Holocene (Kaakinen et al. 2009; Luoto et al. 2011) preceding the studied time period. The results from the Isvika core suggest that in the early part of the late Holocene the ice cap was situated relatively close to the bay, yet the marine-terminating part may have been located in the NE part of the Murchinsonfjorden. These settings do not allow interpretations of ocean-ice sheet-atmosphere coupling in northern Svalbard. However, on a speculative level, as hypothesized in Paper III, the extensive sea ice cover in Fram Strait (Müller et al. 2012) that has been suggested to have restricted glacier growth in northern Svalbard (van der Bilt et al. 2015) could explain the glacier retreat in the Isvika bay area. This would indicate that the environmental change in Isvika bay is a response to regional changes further underlining the importance of sea ice variability as a regulator of the sensitive high-Arctic climate. To better understand the effects of Northern Hemisphere climate variability on the oceanic environment and impacts on the ocean-ice sheet-atmosphere coupling, more high-resolution records revealing Arctic environmental dynamics and environmental responses are needed.

5.4 Common northern North Atlantic diatoms (Paper I)

Although the number of quantitative diatom-based reconstructions has increased significantly during the last decade (e.g. Jiang et al. 2002, 2005, 2015; Miettinen et al. 2011, 2012, 2015; Sha et al. 2014, 2016; Krawczyk et al. 2016), the calibration datasets, which these studies are based on, have not so far been thoroughly described or used for studying the ecology of diatoms. The number of quantitative diatom-based

paleoclimate reconstructions from high northern latitudes can be expected to increase in the near future as the need to model impacts of the ongoing climate warming in the Arctic requires long-term records of natural climate variability. The results of Paper I present the geographical distribution and ecological responses of 21 common North Atlantic diatoms species (Table 2) to main environmental gradients (August SST and April sea ice) and identifies indicator species for August SST and sea ice. These 21 species are generally common at high northern latitudes and they form 96.5–100% (avg. 98.7 %) of the diatom assemblages found in the Isvika core samples and 95–100% (avg. 99 %) of diatom assemblages in the core SL 170 samples. Although the aim of paper I was to investigate the common northern North Atlantic diatom taxa, some common North Atlantic species were left out of the study. The excluded species include for example *Chaetoceros* resting spores and *Paralia sulcata*. *Chaetoceros* resting spores are very dominant in the North Atlantic diatom assemblages but as they have negligible sensitivity to SSTs (Koç Karpuz and Schrader 1990) they have been left out of the calibration dataset and have not been counted in the surface sediment samples. *Paralia sulcata* has a very broad temperature tolerance and was also excluded from the calibration dataset (Miettinen, A. personal communications). Two common sea-ice associated species, *Fossula arctica* and *Fragilariopsis reginae-jahniae*, are included in the counts, but included in the total counts of *Fragilariopsis oceanica*. As taxonomic knowledge regarding these species has in recent years increased, it would be recommended to analyse them separately in future, as they are different species and may

show different ecological preferences that also need to be further investigated.

Based on the August SST response curves, the studied species were grouped into cold, warm and temperate water indicators (Paper I). The April sea ice response curves show that 11 species have statistically significant relationship with spring sea ice concentrations, of which 4 species (*Actinocyclus curvatus*, *Coscinodiscus oculus-iridis*, *Fragilariopsis oceanica* and *Porosira glacialis*) are robust indicators for relatively high April sea ice concentrations and 4 species (*Rhizosolenia hebetata* f. *semispina*, *Thalassionema nitzschioides*, *Thalassiosira angulata* and *T. oestrupii*) are good indicators for low concentrations/ice-free conditions. The rest of these 11 species (*Thalassiosira anguste-lineata*, *T. gravida* and *T. hyalina*) fall in between these extremes. One of the important findings of Paper I is the identification of (7) species that are abundant in high sea ice concentrations (i.e. sea ice-associated) but do not have a statistically significant relationship with sea ice. At least some of these species, e.g. *Fragilariopsis cylindrus* have been used as a sea ice indicator (e.g. Miettinen et al. 2015), yet caution should be taken as these species are as abundant (or even more abundant) in low to zero sea ice concentrations (Paper I).

All of the studied 21 diatom species were present in core SL 170 from Baffin Bay (Fig. 10), whereas *Coscinodiscus oculus-iridis*, *Thalassiosira angulata* or *Thalassiosira oestrupii* were not found in the samples from the Isvika core (Fig. 11). As shown in Paper I, *C. oculus-iridis* is not very abundant in the modern assemblages around Svalbard, but it is more abundant in Baffin Bay, whereas, *T. angulata* and *T. oestrupii* are generally abundant in the northern Nordic Seas and

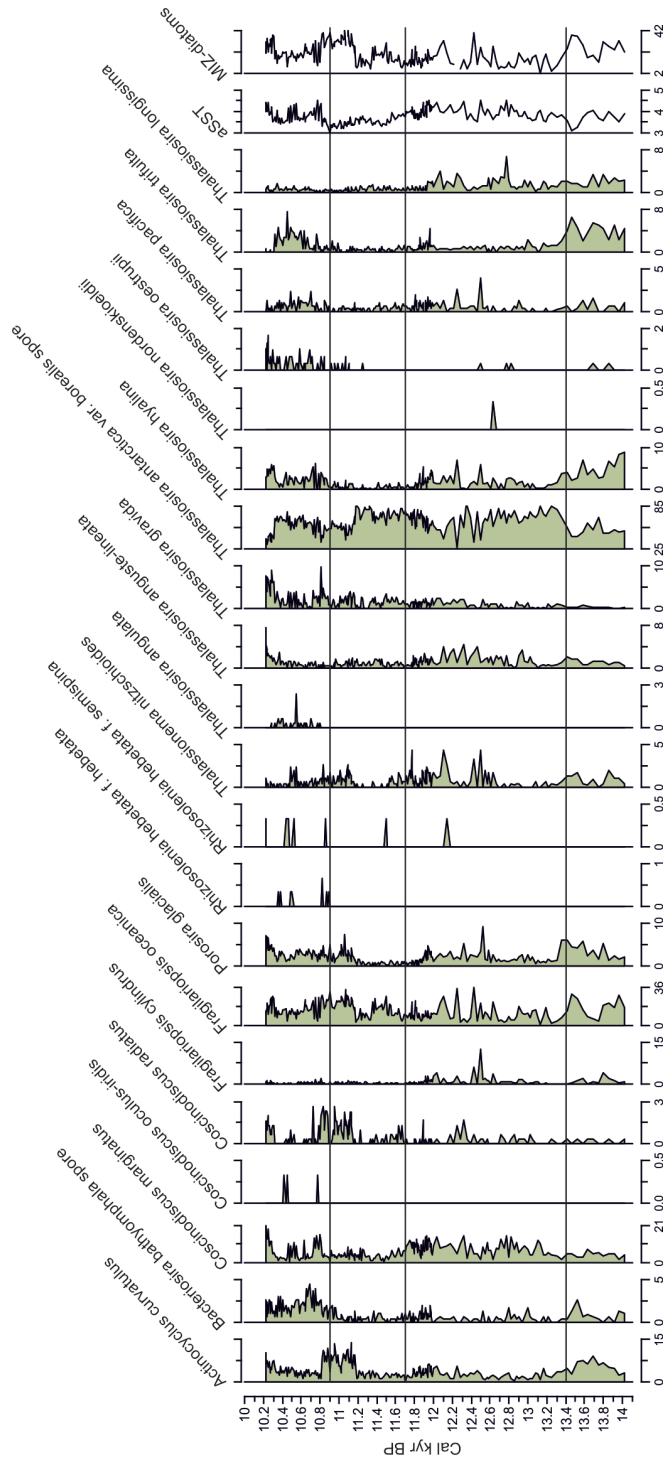


Figure 10. Relative abundances (%) of 21 common diatom species in core SL 170, reconstructed aSST and the relative abundance of MIZ-diatoms (%). Horizontal lines mark the onset of aSST warming at 13.4 and 10.9 kyr BP and onset of the cool aSST period at 11.7 kyr BP.

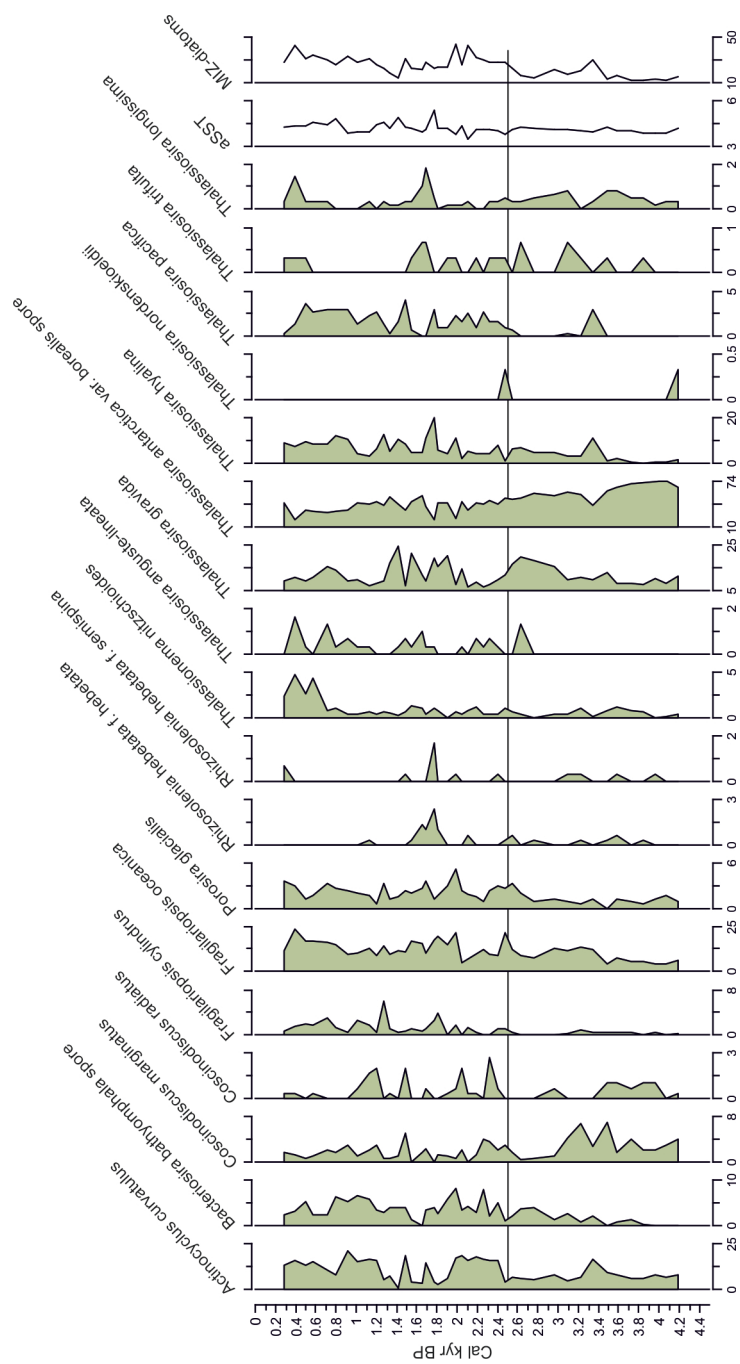


Figure 11. Relative abundances (%) of 18 common diatom species in Isvika core, reconstructed aSST and the relative abundance of MIZ-diatoms (%). Horizontal line marks the climate shift at 2.5 kyr BP.

especially in the lower latitudes of the North Atlantic, as they reflect influences of the Norwegian Atlantic Current (NwAC) and the NAC, respectively (Koç Karpuz and Schrader 1990; Andersen et al. 2004b). The absence of these two species (*T. angulata* and *T. oestrupii*) in the Isvika core and the decrease of *Coscinodiscus marginatus* – another Atlantic water indicator species (De Sève et al. 1999) – after 2.5 kyr BP suggests less Atlantic inflow during the latter part of the late Holocene, except for the last ca. 600 years where the relative abundance of *Thalassionema nitzschioides* increases. This corroborates several previous studies suggesting reduced Atlantic water inflow for the Late Holocene in Wester Svalbard as a result of reduced insolation (e.g. Hald et al. 2007; Rasmussen et al. 2012). In contrast, the appearance of *Thalassiosira anguste-lineata* in the record after ca. 2.6 kyr BP (Fig. 11) can be interpreted as an indication of enhanced Arctic Water inflow to the Isvika area as in Paper I, the geographical distribution and SST-response curve of *T. anguste-lineata* suggests that it is associated with areas receiving cold Arctic-water inflow.

Fragilariopsis cylindrus is commonly used as a sea ice indicator species (e.g. Hasle and Syvertsen 1996; Jiang et al. 2001; von Quillfeldt 2001), however the species does not have a statistically significant relationship with sea ice in the large northern North Atlantic calibration data set (Paper I). On the other hand, *C. oculus-iridis* is not commonly used as sea ice indicator, but in this calibration dataset it shows a strong statistically significant relationship with sea ice and could have potential as a robust sea ice indicator in areas where it is sufficiently abundant. *F. cylindrus* is not very common in the two core records, especially if compared

to the relative abundances of *F. oceanica*, which is one of the most abundant species in both cores (Figs. 10 and 11). In core SL 170 the MIZ-assemblage is dominated by *F. oceanica* (Fig. 10) whereas in the Isvika core, the MIZ-assemblage equally reflects the distribution of the three MIZ-diatoms; *Actinocyclus curvatulus*, *Porosira glacialis* and *F. oceanica*.

The warm aSST periods reconstructed from the core SL170 (at 13.4–11.7 and 10.9–10.2 kyr BP) are clearly evident in the diatom assemblage as an increase in the species, *C. marginatus*, *C. radiatus*, *Thalassionema nitzschioides*, *T. angulata*, *T. gravis* and *T. oestrupii*, that have relatively warm SST optima and have been used as temperate/warm water indicators in previous works (Hasle and Syvertsen 1996; De Sève et al. 1999; Andersen et al. 2004b; Berner et al. 2008). The abundances of these species in the modern Baffin Bay is relative low (Paper I, Paper II; supplementary figure 4)

6. Conclusions

The Arctic environment and its components are particularly sensitive to climate fluctuations. Sea ice and sea surface temperatures are important variables, and variations in these two have a large-scale effect as they alter the Arctic ice mass balance, albedo, ecosystem and the climate in North Europe. In this work, North Atlantic diatoms were employed to reconstruct paleoceanographic and –climatic variability in the Arctic region from two sites. In addition, the ecology of the diatom taxa was investigated via their responses to two gradients; August sea surface temperature and April sea ice cover. The main findings of this work are summarized below:

- The ecological response models for sea ice demonstrate that *Actinocyclus curvatulus*, *Coscinodiscus oculus-iridis*, *Fragilariopsis oceanica* and *Porosira glacialis* have a statistically significant relationship with April sea ice cover and are found in high sea ice concentrations (>50%), which makes them robust sea ice indicator species. *Rhizosolenia hebetata* f. *semispina*, *Thalassionema nitzschioides*, *Thalassiosira angulata* and *T. oestrupii* also have a statistically significant relationship with April sea ice cover but are associated with low concentrations or ice-free conditions.
- Seven species that are sea ice associated and abundant in high sea ice concentrations, including the widely used sea ice indicator species *Fragilariopsis cylindrus*, do not have a statistically significant relationship with sea ice, which emphasizes that a better understanding of their ecology and responses to environmental variables is needed, and caution should be taken when these species are used for paleoceanographic reconstructions.
- Reconstructions of sea surface conditions from Baffin Bay demonstrate warmer sea surface temperatures over the cold Younger Dryas period, implying that the ocean was out of phase with atmospheric temperatures over Greenland. The warming was caused by enhanced inflow of Atlantic-sourced waters and increased solar insolation on the Northern Hemisphere amplifying seasonality. Diatom assemblages indicate that deglacial sea ice cover in Baffin Bay was less extensive than previously suggested. The YD ocean surface record from Baffin Bay contradicts other climate records from the North Atlantic region and emphasizes the need for high-resolution records from Arctic regions in order to better understand the large-scale (Northern Hemisphere) ocean circulation system during this sensitive climate period.
- The response of the large Jakobshavn Isbræ ice stream to ocean surface warming underlines the ocean's role in triggering the retreat together with other controlling factors (topography and ice dynamics). The results of Paper II show that the ice retreat occurred via two processes; by calving under the cold YD atmosphere controlled by the warm ocean surface, and by surface and subsurface melt during the warm atmosphere periods preceding and following the YD, which highlights the possible dynamic response of the GrIS under future climate change scenarios.
- The late Holocene climate record from northern Svalbard clearly demonstrates climate shift at ca. 2.5 kyr BP. The sediment lithology and reconstruction of ocean surface conditions suggest a transition

from a stable, glacier-proximal environment with seasonal open-water conditions into a fluctuating, glacier-distal environment with more extensive sea ice cover. These environmental changes are likely caused by build-up of an extensive sea ice in the Fram Strait and around Svalbard that have been shown to drive climate in northern Svalbard. The climate shift underlines the sensitive character of the Arctic environment.

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