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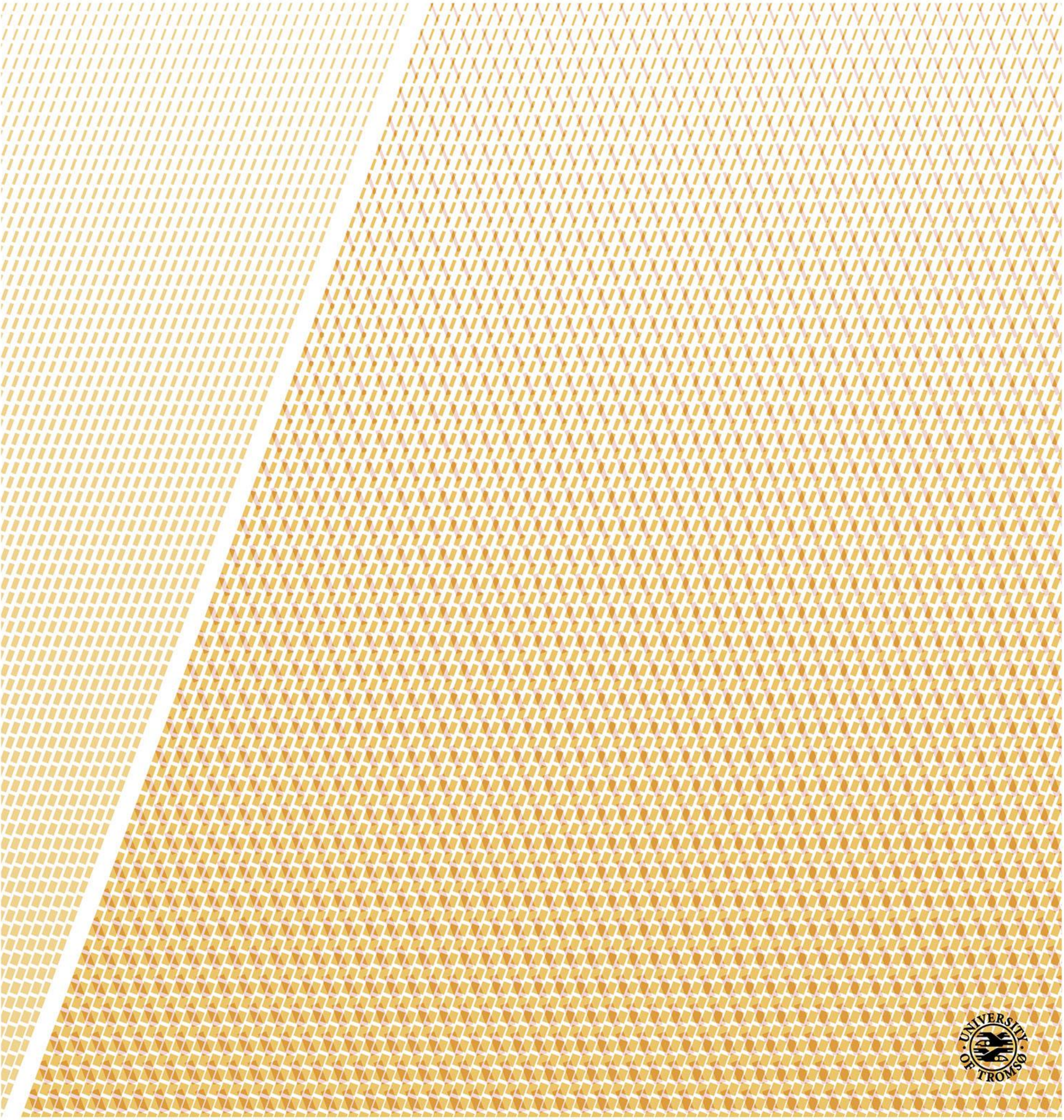
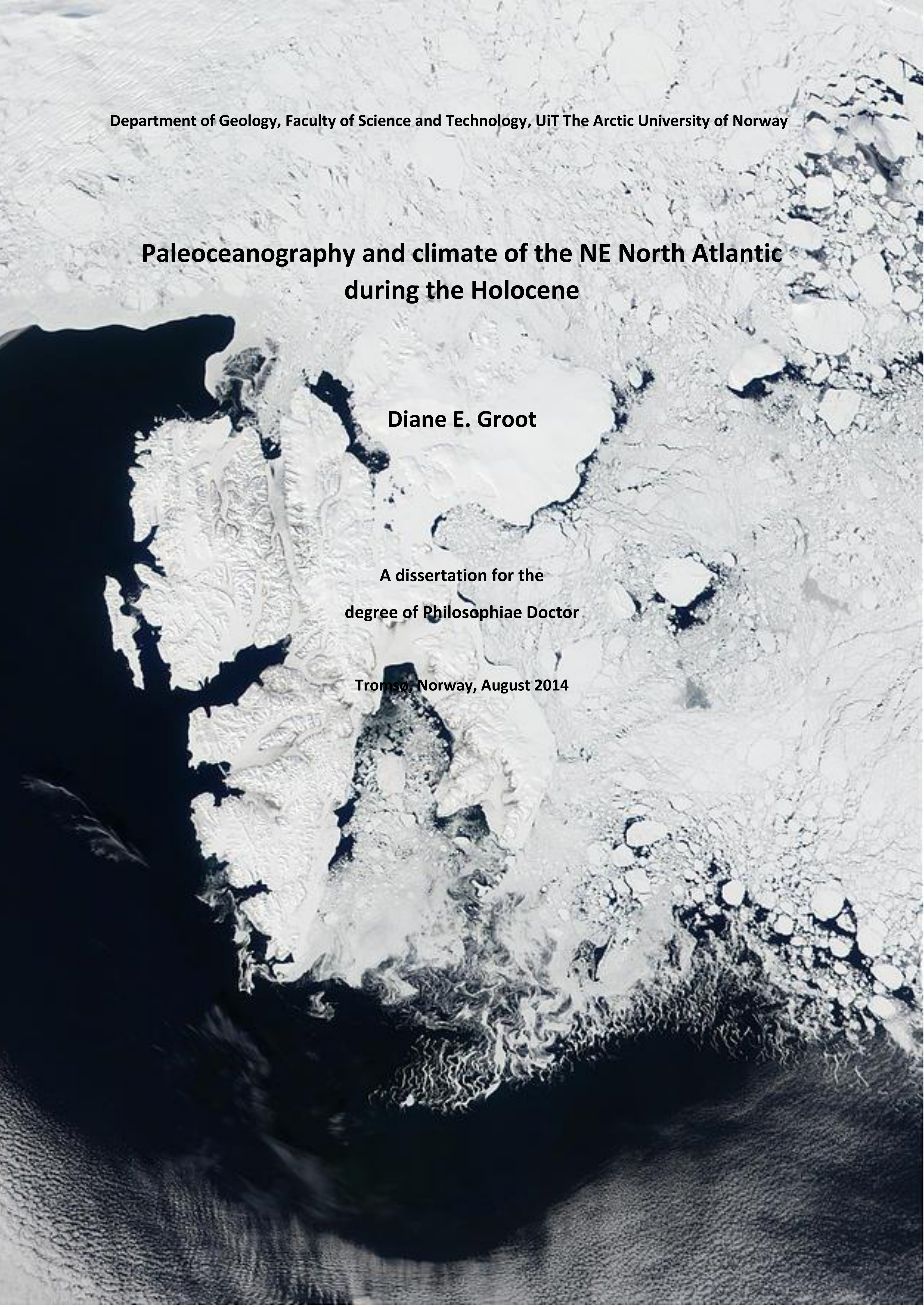
Paleoceanography and climate of the NE North Atlantic during the Holocene

Diane E. Groot
A dissertation for the degree of Philosophiae Doctor – August 2014





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Preface

This thesis is the result of a 3 year PhD study at the Department of Geology, UiT, the Arctic University of Norway, Tromsø, Norway. The work was supervised by Prof. Morten Hald, Dr. Katrine Husum and Dr. Steffen Aagaard-Sørensen. The doctoral thesis was carried out from January 2011 until July 2014. The PhD project was funded by the European Community's 7th Framework Program FP7, 2007/2013, Marie-Curie Actions, Grant Agreement No. 238111 and was part of the Marie Curie Initial Training Network CASE '*The Changing Arctic and Subarctic Environment'.* The CASE network provided progress meetings and training sessions hosted by the partner institutions. The Research Council of Norway provided a Marie Curie 'toppfinansiering'. The Norwegian Research School in Climate Dynamics (ResClim) provided funding to participate in the international PAGES YSM and OSM 2013 and in two international courses within the field of marine geology.

During the PhD study, results were presented in poster presentations and talks at national and international workshops and conferences (e.g. European Geological Union 2012, PAGES OSM 2013).

This thesis consists of an introduction and three scientific papers. The papers deal with the investigation of the variability of Holocene intermediate and bottom water conditions in the NE North Atlantic by applying benthic foraminifera.

The three scientific papers are:

Paper I

Groot, D.E., Aagaard-Sørensen, S., Husum, K. 2014**. Reconstruction of Atlantic Water variability during the Holocene in the western Barents Sea.** Climate of the Past 10, 51-62.

Paper II

Groot, D.E., Hald, M., Wilson, L.J., Husum, K., Aagaard-Sørensen, S., Godtliebsen, F., Salomonsen, G.R. **Late Holocene temperature variability of Atlantic Water from the northern Norwegian continental margin.** To be submitted to Boreas.

Paper III

Groot, D.E., Hald, M., Aagaard-Sørensen, S., Husum, K. **Deep water mass evolution of the last two millennia in the eastern Fram Strait, Polar North Atlantic.** Manuscript.

Acknowledgements

Starting a PhD and moreover finishing one is certainly not something you can do alone, and therefore I would like to thank all people who helped and supported me throughout my studies.

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The CASE group made all the traveling for courses and progress meetings something to look forward to. Thanks for all the good discussions and for making all the meetings so much fun. A special thanks goes to Sarah, Frazer, Michael, Johan, Gesa, Christian and Patricia. Thanks also to the Principal Investigators Jacques Giraudeau, Robert Spielhagen, Simon Belt, Jochen Knies, Katrine Husum and Hans Renssen for providing all the interesting training courses and wonderful stays at your institutions.

Collecting all the data would not have been possible without the help of the ’lab ladies’: Trine Dahl, Edel Ellingsen, Ingvild Hald, Kari Skirbekk and Julia Sen. Thanks for spending so many hours behind the microscope for me. Jan P. Holm made many maps for me which are used in this thesis.
Many friends and colleagues at the Department of Geology were there for providing scientific support but most importantly for providing ‘social support’. It was great to share our PhD’s together and to be distracted from them by all the social activities outside of work. Thanks to Noortje for making Tromsø feel like home when I first came here and to Marianne, Nicole and Eythor.

I especially want to mention Pati and Kari, thank you girls for all the foram and non-foram talk when it was most needed! Bénédicte, thank you for all the squash/peptalk sessions. Many thanks to Andreia, for making sure I also spent some time away from the computer and to Calvin and Carly for the numerous bike rides and coffee breaks in the final phases of the PhD.

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And of course, thanks to ‘het thuisfront’. To my parents Gerard and Liesbeth and to Linda, Susanne, Bas, Gilles and Frank. Thank you for encouraging me to do a PhD even when it meant to move to Norway for it, for all the support, interest, for exploring Norway together with me during your numerous visits and patiently listening to me during the many skype calls. For always making it such a pleasure to come back home.

Table of contents

1 Introduction

Recent warming of the climate system is unambiguous, as evidenced by increasing global mean air and ocean temperatures, reduction in Arctic sea-ice extent and globally rising sea levels (Intergovernmental Panel on Climate Change (IPCC), 2013). Warming is expressed in particularl in the high northern latitudes where average Arctic temperatures have increased at almost twice the global rate in the past 100 years and the sea-ice extent has declined considerably. Climate models predict that warming in the Arctic regions will continue to exceed the global average in the near and long-term future due to polar amplification, with concomitant reductions in sea-ice and terrestrial ice masses and increasing rates of sea level rise (Miller et al., 2010; IPCC, 2013).
The recent warming is often attributed to the increasing levels of greenhouse gases due to the burning of fossil fuels. In order to identify the anthropogenic impact on climate, it is necessary to study the natural climate variability beyond the era of instrumental measurements which can be estimated by the use of climate proxies.

The Nordic Seas are a key component of the global climate system due to the exchange of water masses from the Arctic and North Atlantic Oceans. Within the Nordic Seas, the warm and saline northward flowing Atlantic Water masses (carried by the North Atlantic Current, NAC) encounter the southward flowing Polar water masses, carrying sea-ice. The interaction with cold Polar air and water masses leads to a cooling and density increase of the Atlantic Waters and their subsequent descent into the deep basins of the Nordic Seas (Hansen and Østerhus, 2000). Deep waters formed in the Nordic Seas return southward as a major component of North Atlantic Deep Water (NADW) (Hansen and Østerhus, 2000). Through these processes, the Nordic Seas play a fundamental role in the Atlantic Meridional Overturning Circulation (AMOC). The AMOC helps to maintain the present mild climate of northwestern Europe through its meridional heat transport and plays an important role in global heat distribution (Broecker,1991; Hansen and Østerhus, 2000). A reduced AMOC would transport less heat northwards, leading to a cooling in the north and, at the same time, a buildup of heat in the south (Stocker, 1998). Since the North Atlantic Current is the main contributor of heat and salt to the European Arctic, any past variability in the NAC is relevant for variations in the paleoceanography of the Nordic Seas. To understand the past variability of the NAC and AMOC system is of great importance in terms of predicting future climate.
During the Holocene, considerable climate variability on decadal (e.g. Hansen and Østerhus, 2000) to millennial timescales (e.g. Bond et al., 1997; Bianchi and McCave, 1999) has been observed in the North Atlantic and Nordic Seas on top of a long-term temperature decline (e.g. Andersen et al., 2004;

Moros et al., 2004). The Early to Mid Holocene Thermal Maximum and the subsequent temperature decline throughout the Mid and Late Holocene (e.g. Hald et al., 2007) has been linked to the general decrease in summer insolation (Berger and Loutre, 1991). Millennial scale climate variability was observed by Bond et al. (1997) who identified a ca. 1500 year cycle of sea-ice expansion, linked to varying solar activity and diminished activity of the AMOC. The decadal climate variability observed in the North Atlantic and Nordic Seas can be related to the North Atlantic Oscillation (NAO) (Hurrell, 1995). This mode of atmospheric circulation is defined as the difference in atmospheric pressure at sea level between the Icelandic low and the Azorean high (Hurrell, 1995). It controls the strength and direction of westerly winds and storm tracks across the North Atlantic and exerts an influence on the influx of Atlantic Water into the Nordic Seas (Hurrell, 1995; Olsen et al., 2012). Further, the Early Holocene was interrupted by several short lived cooling events such as the Preboreal Oscillation (e.g. Hald and Hagen, 1998) and the 8.2 event (e.g. Kleiven et al., 2008). These events are suggested to be triggered by freshwater pulses causing a salinity decrease and a reduced deep return flow leading to a more sluggish AMOC (e.g. Kleiven et al., 2008). Finally, the last 2000 years are characterized by climate fluctuations such as the 'Dark Ages Cold Period' (DACP), 'the Medieval Warm Period' (MWP) and the cooling of the 'Little Ice Age' (LIA) (e.g. Lamb, 1965; Lamb 1977; Bradley, 2000) which had major implications for human settlements around the Nordic Seas (e.g. D'Anjou et al., 2012). These climate fluctuations of the last two millennia have been attributed to e.g. anomalies in total solar irradiance (Delaygue and Bard, 2011), volcanic eruptions (e.g. Crowley, 2000) and shifts in the NAO mode (Trouet et al., 2009).

In the NE North Atlantic, one of the key proxies for paleoceanographic reconstructions is benthic foraminifera. They have a widespread occurrence and abundance in a broad variety of environments such as fjords, shelf seas and the deep-sea. The distribution of benthic foraminifera can be used to provide information on e.g. bottom water temperature, currents, and surface productivity (e.g. Sejrup et al., 2004; Murray, 2006). Benthic foraminifera have been used in a number of studies in the Nordic Seas region (e.g. Duplessy et al., 2001; Mikalsen et al., 2001; Hald et al., 2004; Duplessy et al., 2005; Ślubowska-Woldengen et al., 2008; Rasmussen and Thomsen, 2010; Knudsen et al., 2012; Jernas et al., 2013), showing that benthic foraminiferal fauna distributions and abundances in combination with stable oxygen and carbon isotopes capture paleoceanographic changes.

The overall objective of this thesis is to improve our knowledge of the oceanographic variability in the NE North Atlantic during the Holocene. More specifically, the focus of this thesis is on the northward advection of Atlantic Water along the Norwegian and Svalbard continental margins and on the paleoceanography of the deep water masses of the Nordic Seas on multi-decadal to millennial timescales. In order to achieve this aim, sediment cores from high accumulation areas on the Norwegian and Barents Sea shelf and the west Spitsbergen slope were investigated using several paleoceanographic proxies. These include benthic foraminiferal fauna distributions, measurements of stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) and lithological parameters such as grain size distribution, and chemical analyses of bulk sediment carbon content.

2 Study area and oceanographic setting

This study is based on the analyses of marine sediment cores retrieved from the Norwegian continental shelf, the western Barents Sea margin and the eastern Fram Strait (Figure 1). The first two locations are affected by the inflow of warm and saline Atlantic Water whereas the third location is influenced by the Norwegian Sea Deep Water (NSDW).

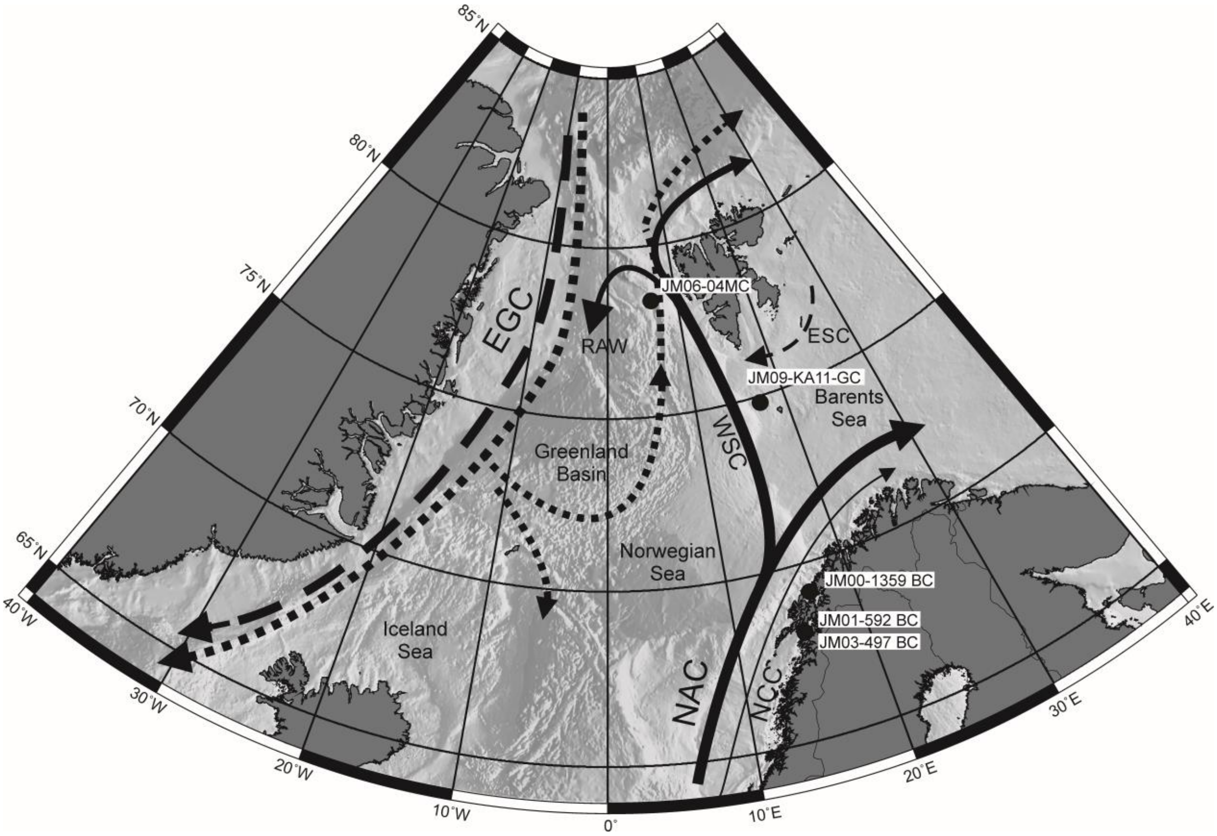

Figure 1. Map of the Nordic Seas and Barents Sea showing the major current systems and core locations. NAC, North Atlantic Current; NCC, Norwegian Coastal Current; WSC, West Spitsbergen Current; ESC, East Spitsbergen Current; RAW, Recirculating Atlantic Water; EGC, East Greenland Current.

Warm and saline Atlantic Water masses are advected into the Nordic Seas primarily over the Iceland-Faroe ridge and through the Faroe-Shetland Channel (Hansen and Østerhus, 2000). The Atlantic Water masses are topographically steered along the Norwegian continental margin by the North Atlantic Current (NAC; > 3°C, > 35 psu; Hopkins, 1991) and splits north of Norway into a meridional branch, the West Spitsbergen Current (WSC) (Aagaard et al., 1987) and a zonal component, the North Cape Current (NCaC) (Loeng, 1991). The WSC flows northwards along the Barents Sea and west

Spitsbergen slopes into the Arctic Ocean via the eastern Fram Strait. In eastern Fram Strait, the warm core of the WSC is situated over the upper part of the Svalbard continental slope, down to ca. 500 m water depth (Rudels et al., 2005). At intermediate and abyssal depths NSDW is found (-1.1 - 0°C; 34.91 psu; Schlichtholz and Houssais, 1999) which dominates the deep water inflow in eastern Fram Strait. The NSDW in eastern Fram Strait forms by mixing of some older NSDW derived from the Nordic Seas with Arctic Ocean Deep Water (AODW) (Schlichtholz and Houssais, 1999). In the western Fram Strait the East Greenland Current (EGC) (Aagaard and Greisman, 1975) transports cold and fresh Polar Water masses southwards into the Nordic Seas.

The Norwegian continental shelf is dominated by the Norwegian Coastal Current (NCC) overlying the Atlantic water masses in a westward thinning wedge that becomes narrower and shallower during summer (50-100 m water depth) than during winter (< 200 m water depth) (Sætre, 2007). This allows Atlantic Water to expand onto the shelf and to flow into the fjords (Gade and Edwards, 1980; Sætre, 2007).

The northward flow of the temperate Atlantic Waters forms part of the large global circulation system known as the meridional overturning circulation. Simplified, the Atlantic part of the meridional overturning circulation (AMOC) consists of a warm and salty northward surface flow and a cold deep return flow. In the northern North Atlantic and GIN Seas (Greenland-, Iceland-, and Norwegian Seas) the surface waters cool, sink and return southwards. The AMOC is in part driven by the density gradients in the ocean. Due to the atmospheric cooling of the salty southern derived waters, the density increases, leading to the descent of the surface waters. The newly formed deep water masses spread away from the source and pump warm waters from the south. This density driven part of the AMOC is known as the thermohaline circulation (THC).

3 Material and methods

Sediment cores analyzed in this thesis are retrieved from the western Barents Sea margin, the northern Norwegian continental margin, and eastern Fram Strait by gravity-, multi- and box corers (Table I). In this chapter, the material and methods applied in this PhD project are described.

Table I. Information on sediment cores used in this thesis and references to previous studies of the cores.

Core ID	Location	Latitude Longitude	Water depth (m)	Studied time interval	Previous study	Paper
JM09-KA11-GC	Western Barents Sea (Kveithola)	74°52.48’N 16°29.08’E	345	0-12,000 cal yr BP	Rüther et al. (2012)	1
JM03-497 BC	North Norwegian Margin (Sagfjorden)	67°58.17’N 15°21.73’E	547	1250-2003 CE		2
JM01-592 BC	North Norwegian Margin (Vestfjorden)	68°03.27’N 14°56.01’E	428	700-2001 CE		2
JM00-1359 BC	North Norwegian Margin (Andfjorden)	69°16.23’N 16°20.90’E	488	1300 BCE - 2000 CE		2
JM06-WP-04 MC	Eastern Fram Strait	78°54.93’N, 06°46.01’E	1497	460 BCE-2006 CE	Zamelczyk et al. (2013)	3

3.1 Sediment cores and sampling

Gravity core JM09-KA11-GC (Paper I) retrieved from the western Barents Sea, was sampled continuously in 0.5 cm slices. The three box cores (JM00-1359, JM01-592, JM03-497) retrieved from the northern Norwegian continental margin (Paper II), were sampled in 3 mm thick slices. Multicore JM06-WP-04 MC (Paper III) from eastern Fram Strait was sampled in 3 mm thick slices (Zamelczyk et al., 2013). All sediment samples were freeze-dried and wet sieved at >63 µm, >100 µm and >1 mm size fractions. Before and after freeze drying, weight of the sediment samples was determined. The >1 mm fraction was considered as ice rafted debris (Papers I, III).

3.2 Chronology

The chronology of the sediment core used in Paper I is based on previously published radiocarbon dates (Table I) (Rüther et al., 2012), complemented with new radiocarbon dates. The chronologies of the sediment cores used in Paper II are based on a combination of radiocarbon dates and ^{210}Pb and ^{137}Cs analyses. Radiocarbon dates were measured at the Radiocarbon Laboratory in Trondheim, Norway and Uppsala, Sweden and at Beta Analytic Inc. in Miami, Florida, US. The ^{210}Pb a ^{137}Cs analyses were performed at the Gamma Dating Center, University of Copenhagen, Denmark.

All radiocarbon dates were converted into calibrated ages using Calib version 7.0 (Stuiver et al., 2005) and the Marine13 calibration curve (Reimer et al., 2013). A local reservoir correction (ΔR) of 67 ±34 was applied for sediment core JM09-KA11 GC (Paper I) and a ΔR of 71 ±21 (Mangerud and Gulliksen, 1975; Mangerud et al., 2006) for the sediment cores used in Paper II. Age models were established by linear interpolation between the calibrated ages using the mid-point of the 2σ range as tie points in the interpolation. In the uppermost parts of the sediments cores of Paper II, ages were assigned using the CRS model (Constant Rate of Supply) (Appleby, 2001). In Paper III the age model developed by Zamelzcyk et al. (2013) was used.

3.3 Geochemical analyses

The weight percentages of total carbon (TC) and total organic carbon (TOC) were determined at sample intervals of ca. 4 cm (Paper I). TC and TOC were measured using a LECO CS 2000 induction furnace at the University of Tromsø. The $CaCO_3$ content was calculated using the following equation: $CaCO_3 = (TC-TOC) \times 100/12$.

3.4 Foraminiferal analyses

Benthic foraminiferal analyses were conducted on the 100 µm – 1mm size fraction (Paper I and III). At least 300 specimens were counted per sample and identified to species level when possible, following the guidelines from Knudsen (1998). The species were identified based on the classification in Feyling-Hanssen (1964), Feyling-Hanssen et al. (1971) and Loeblich and Tappan (1988). The accepted nomenclature as referred to in the World Register of Marine Species (WoRMS) is used. Species from the *Buccella* genus were combined and referred to as *Buccella* spp., and the morphologically similar species *Islandiella helenae* and *Islandiella norcrossi* were combined and referred to as *Islandiella* spp. (Paper I). Agglutinated foraminifera were excluded from further analysis due to their poor preservation potential. The relative abundance and concentration of the identified species was calculated in relation to all calcareous specimens per sample. In addition, the flux of calcareous benthic foraminifera was calculated following the methods described by Ehrmann and Thiede (1985). Species diversity (Paper III) is expressed by the Shannon index H(S) (Buzas and Gibson, 1969).

3.5 Stable isotope analyses ($\delta^{18}O$ and $\delta^{13}C$)

Stable isotopes were measured on the benthic foraminiferal species *C. neoteretis* (Paper I and II), *C. laevigata* (Paper II) and *C. wuellerstorfi* (Paper III) from the >100 µm fraction. Measurements were performed at the Geological Mass Spectrometer Laboratory at the University of Bergen (Paper I, II and III), and at Leibniz-Laboratory at the University of Kiel (Paper II). The $\delta^{18}O$ values were corrected for the ice volume effect (Fairbanks, 1989) (Paper I). A vital effect correction was applied for *C. laevigata* (Paper II) and *C. neoteretis* (Paper I) (Poole, 1994).

The oxygen isotopic ratio incorporated into the foraminiferal test reflects the $\delta^{18}O$ of the ambient sea water ($\delta^{18}O_w$) in which the foraminifera calcify, and the temperature dependent fractionation during the calcification process (e.g. Katz et al., 2010). The $\delta^{18}O$ of the sea water is in turn a function of global ice volume and regional/ local fresh water input. Incorporated carbon isotopes reflect the $\delta^{13}C$ of the dissolved inorganic carbon in the water mass which is controlled by carbon sources and sinks (e.g. Katz et al., 2010).

3.6 Temperature and salinity reconstructions

Bottom water temperatures (BWT) and salinities (BWS) were reconstructed by transfer functions applying the database of Sejrup et al. (2004) (Paper I). A weighted average partial least squares (WA-PLS) model was used for reconstructing temperature and salinity values. The reconstruction was performed using the C2 program (Juggings, 2010). The reconstructed bottom water temperatures were used to calculate $\delta^{18}O_w$ and to determine the salinity driven impact on the measured $\delta^{18}O_{calcite}$ (Paper I). In paper II, bottom water temperatures were calculated from the stable oxygen isotopes (assuming a constant $\delta^{18}O_w$) using the paleotemperature equation of Shackleton (1974).

3.7 Statistical analyses (Paper II)

Statistically significant features in the stable oxygen isotope records were evaluated by SiZer (Significance of Zero Crossings of the Derivative) analyses (Chaudhuri and Marron, 1999).

This method allows the identification of significant features at different time scales, i.e. at different levels of time resolution. By applying different levels of smoothing of the data set true underlying curves at particulate levels of resolution are identified and insignificant variability is eliminated. This method includes a graphical presentation of statistically significant derivatives from zero (i.e. true increases or decreases) and displays these over age and scale.

4 Summary of papers

Paper I

Groot, D.E., Aagaard-Sørensen, S., Husum, K. (2014). **Reconstruction of Atlantic Water variability during the Holocene in the western Barents Sea.** Climate of the Past 10, 51-62.

The overall goal of this paper is to enhance our understanding of the variability of Atlantic Water inflow in the high latitude North Atlantic throughout the Holocene. The study is based on the top 130 cm of gravity core JM09-KA11-GC, recovered from the Kveithola Trough at the western Barents Sea margin, close to the present day position of the Arctic Front. Paleoceanographic reconstruction of the western Barents Sea is based on high resolution down-core distribution patterns of benthic foraminiferal faunas and benthic stable isotopes. Bottom water temperatures and salinities were quantitatively reconstructed using transfer functions. Furthermore, total carbon (TC), total organic carbon (TOC) and $CaCO_3$ were determined on bulk sediment samples.

Four time periods have been identified which represent the varying oceanographic conditions in the western Barents Sea during the Holocene. During a transition period from the Younger Dryas into the Holocene (11 800 - 11 500 yr BP), the benthic foraminiferal fauna composition and stable oxygen isotopes suggests prevailing glaciomarine conditions with extensive sea-ice cover. Harsh environmental conditions are indicated by low benthic foraminiferal fluxes and IRD input. Meltwater lowered the salinity values of the bottom waters in Kveithola Trough. During the Early Holocene the enhanced inflow of Atlantic Water and/ or insolation by the sea-ice cover resulted in higher bottom water temperatures. The transition from the Early to the Mid Holocene is characterized by a local shift in current regime, possibly connected to a lowered influence of Arctic Water masses occupying the shallow banks enclosing Kveithola Trough. Increasing stable oxygen isotope values throughout the Mid Holocene indicate a slight cooling trend, thereby following the declining summer insolation. During the last 1500 years coarser grain-size fractions suggest a strengthened inflow of Atlantic Water. However, climatic conditions also became more unstable and periodically colder which may be related to periods of increased influence of Arctic Water.

Paper II

Groot, D.E., Hald, M., Wilson, L.J., Husum, K., Aagaard-Sørensen, S., Godtliebsen, F., Salomonsen, G.R. **Late Holocene temperature variability of Atlantic Water from the northern Norwegian continental margin.** To be submitted to Boreas.

The aim of this paper is to reconstruct bottom water temperatures during the Late Holocene from benthic foraminiferal stable oxygen isotopes, reflecting the temperature variability of Atlantic Water. More particularly, we aim to compare the modern warming of the last 100 years to preceding climate fluctuations of the Late Holocene such as the Medieval Warm Period and the Little Ice Age. Three box cores were retrieved from fjord basins in northern Norway. The deep-silled fjords as selected for this study allow for an open connection between the Atlantic Water prevailing on the shelf and the fjord basins, thus providing a regional climate signal that reflects changes in the heat flux of the North Atlantic Current. Stable oxygen isotopes measured on benthic foraminifera were compared to nearby located instrumental temperature time series. A close comparison between the $\delta^{18}O$ records and the instrumental data demonstrated that the proxy records reflect bottom water temperatures and that the salinity effect on $\delta^{18}O$ is minimal. The Late Holocene temperature development differs between the records, reflecting either a long-term temperature increase or decrease throughout the studied time intervals, which may be attributed to their specific locations. The well-known cooling of the LIA is reflected in all three records and fluctuates around the lowest temperatures of the last 800 and 1300 years in two of them. Over the last ca. 80 years a ca. 1°C warming of the bottom waters is observed in all records and this appears to be the warmest period of the last 3300 years.

Paper III

Groot, D.E., Hald, M., Aagaard-Sørensen, S., Husum, K. **Deep water mass evolution of the last two millennia in the eastern Fram Strait, Polar North Atlantic.** Manuscript.

The purpose of this study is to elucidate the Late Holocene paleoceanographic deep water conditions in the eastern Fram Strait. A sediment core from 1497 m water depth has been analyzed for benthic foraminiferal assemblages and benthic stable isotopes.

The benthic foraminiferal assemblages consists of species that are typical for the deep sea environments of the Nordic Seas and changes in the species distribution over the last 2400 years appears to be mostly affected by shifts in food availability. Fluctuations in the stable oxygen isotope record from 400 BCE to 1870 CE may be attributed to a strengthened influence of Atlantic Water and an associated increased volume transport which either caused a temperature increase of the bottom water masses of forced the low saline water masses of Arctic Intermediate Water down to the core location. Within the last ca. 150 years pronounced changes are observed in all analyzed parameters. Rapidly increasing benthic foraminiferal fluxes point to enhanced primary productivity. Within the last 20 years the relatively high sedimentation rates at the study area probably led to a stressed environment as suggested by the significant declines in benthic foraminiferal flux values and species diversity. Circulation changes within the Fram Strait are suggested by decreasing $\delta^{18}O$ values over the last ca. 150 years which in addition may indicate a slight warming of the bottom water masses.

5 Synthesis

The main objective of this study was to improve our knowledge of the paleoceanographic variability in the Nordic Seas throughout the Holocene. More specifically, the aim of this study was to assess the decadal to millennial variability of the Atlantic Water inflow and to elucidate the deep water variability of the Nordic Seas. Atlantic Water advection is the main transporter of heat and salt towards the north and is of great importance for the deep water convection.
Sediment cores from high-resolution areas which are under the influence of Atlantic Water masses (Papers I and II) or under the influence of deep water masses (Paper III) have therefore been studied. Special emphasis has been put on studying the natural climate variability of the last 2000 years (Papers II and III). The boundary conditions of the last two millennia are regarded closest in resembling the present conditions and presumably the conditions of the near future. Further, the climate forcing mechanisms are reasonably well known (McCarroll, 2010). Paleoclimate records from this time period are thus appropriate for testing and validating climate models and to assess the anthropogenic impact on climate. Benthic foraminiferal assemblages and benthic stable isotopes in combination with lithogenic and geochemical parameters were analyzed in order to elucidate the past oceanographic variability. Transfer functions were applied to quantify bottom water temperature and salinity changes in the Atlantic Water masses during the Holocene.

The following main conclusions were reached based on the results presented in this thesis:

- Atlantic Water masses have continuously been present at the western Barents Sea margin throughout the Holocene and governed the benthic foraminiferal fauna distributions. In the Early and Late Holocene the area experienced a stronger influence of Arctic Water masses associated with the presence of sea-ice. A mid Holocene cooling trend correlates with the paleoceanographic development of the Nordic Seas and the declining summer insolation (Paper I).

- Applying transfer functions to quantitatively estimate temperature may lead to an overestimation of temperatures when including species that are controlled by food supply rather than by temperature (Paper I).

- Temperature reconstructions from benthic stable oxygen isotope records document a ca. 1°C warming within the last century. This modern warming appears to be unprecedented over the past 3300 years and is most likely linked to the polar amplification of global warming (Paper II). In order to obtain absolute temperature values from stable oxygen isotope records, local relationships between salinity and $\delta^{18}O_{water}$ would have to be established.

- During the last ca. 150 years a significant shift in the deep water mass properties of the eastern Fram Strait occurred, which probably can be ascribed to changing modes of deep water convection in the Nordic Seas and circulation changes within the Fram Strait (Paper II).

6 Outlook

Benthic foraminifera are used in a wide variety of environments and time scales to reconstruct paleoenvironments. They have been related to e.g. flux of organic matter, water depth, turbidity of the water column, oxygen availability and grain size of the seabed. Further, benthic foraminiferal distributions are dependent on temperature and salinity and by applying transfer functions on the foraminiferal fauna, temperature and salinity values can be reconstructed (Sejrup et al., 2004). In Paper I transfer functions were applied in combination with stable oxygen isotopes. The results from Paper I demonstrate the strong influence food availability has on an assemblage and subsequently on the temperature reconstructions. The database could be adjusted by omitting species that are controlled more by food supply than by water temperature as was done for instance by Rasmussen et al. (2014). Another approach could be the use of an independent temperature reconstruction method, i.e. Mg/Ca ratios. So far, no Holocene temperature reconstruction based of Mg/Ca ratios for the Barents Sea has been undertaken. Not only could this method be able to capture the small temperature variability's that are not reflected in the transfer function based reconstructions but also, in combination with stable oxygen isotope measurements, enable quantitative reconstructions of salinity. This could especially be applicable in time periods or areas where freshwater input could have influenced the stable oxygen isotope signal. Application of this method does necessitate the development of Mg/Ca temperature calibrations for Arctic benthic foraminifera, which is currently being undertaken by Skirbekk et al. (in prep).

In Papers I and III interpretations on current speeds have been made based on the occurrence of benthic species that are associated with higher energy environments such as *C. wuellerstorfi*, *L. lobatula* and *A. gallowayi* in combination with the grain size distribution obtained from sieving over 1 mm, 100µm and 63µm size fractions. Interpretations on current speeds could be greatly improved by analyzing the sortable silt content. The use of mean sortable silt (10-63µm) as a current speed indicator is well established (e.g. McCave et al., 1995; McCave and Hall, 2006) and has been used to study the overflow strength of the deep waters from the Nordic Seas into the North Atlantic (Thornalley et al., 2013) for example. In areas were sea-ice occurs, a possible contamination of the current-sorted grain size fraction by IRD input should be taken into account (Hass, 2002).

Further, the sediment core studied in Paper III raised the question of how well benthic foraminiferal tests are preserved in the fossil record and whether or not this may differ among species. In the sediment core planktic foraminifera are affected by (selective) dissolution (Zamelczyk et al., 2013). The benthic tests showed signs of dissolution but the implications this may have on the faunal compositions and possible geochemical analyses should be further explored.

7 References

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Paper I

Reconstruction of Atlantic Water variability during the Holocene in the western Barents Sea.

Groot, D.E., Aagaard-Sørensen, S., Husum, K. 2014.
Climate of the Past 10, 51-62.

Paper II

Late Holocene temperature variability of Atlantic Water from the northern Norwegian continental margin.

Groot, D.E., Hald, M., Wilson, L.J., Husum, K., Aagaard-Sørensen, S., Godtliebsen, F., Salomonsen, G.R.
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Paper III

Deep water mass evolution of the last two millennia in the eastern Fram Strait, Polar North Atlantic.

Groot, D.E., Hald, M., Aagaard-Sørensen, S., Husum, K.

Manuscript