Faculty of Science and Technology

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A multi-proxy approach for reconstructing oceanographic dynamics during the Holocene

Development and Application of benthic foraminifera as proxies in the Polar North Atlantic

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A dissertation for the degree of Philosophiae Doctor – September 2014

Til Edel, for at du alltid har troen på det rare og snurrige. Din overbevisning om at to og to bare blir fire sånn av og til, innimellom alt det andre, er alltid til stor inspirasjon.

Veien blir til mens du går deg vill (Dag Evjenth)

Acknowledgements

Wow! Sitting here ready to submit I am amazed I was able to spell that right. It has been an intense and frustrating time finishing up, but mostly fun, inspiring and educational. After being in limbo for a long time while waiting for my results, it is almost unreal to finally be here. There are quite a few people I would like to thank before I press the submit button, and a few to whom I simply feel immensely grateful.

Firstly I would like to thank my main supervisor, Professor Morten Hald, for excellent guiding and fruitful discussions during my Ph.D. I have been impressed by your capability to always stay positive and constructive (yet strict), and I have really appreciated that you always listen to ideas and help take them further. I also thank my co-supervisor Dr. Juho Junttila for support and supervision during the project, countless cups of coffee, and a never-ending amount of extremely bad jokes while drinking it. Highly appreciated! To Dorthe Klitgaard-Kristensen, Katrine Husum and Lindsay Wilson, who were shortly involved as supervisors - thank you for constructive discussions and collaboration.

I would like to thank the technical and administrative staff at the Department of Geology; the lab chicks Trine Dahl, Ingvild Hald and Edel Ellingsen for their professional guidance and all the laughs at the lab – a fantastic combination; the men in black Steinar Iversen, Knut Sandaker and Bjørn Runar Olsen for assistance and patience during cruises, Jan Petter Holm for helping out with figures and posters, Annbjørg Johansen, Margrethe Lindquist and Inger Solheim for help with the paper mill, and the IT-crowd Bjørn Ivar Evje and Rolf Andersen for RAM & stuff. I also would like to thank the crew on R/V Jan Mayen (now Helmer Hansen) for their willingness to help during cruises.

Thanks to Professor Tom Marchitto for instruction and assistance at the Trace Element lab and with data processing, and to Anne Jennings for nerdy foraminifera discussions during my research stay at INSTAAR.

Big thanks to Steffen Aagaard Sørensen for always keeping his door and his mind open, when I desperately and with no warning, jumped into his office to discuss my data. Also to the rest of the paleo-crew - always good to have smart and knowledgeable people around: Tine Rasmussen, Giuliana Panieri, Patrycja Jernas, Kasia Zamelczyk, Noortje Dijkstra, Sarah Berben, Simon Pind Jessen and Mohammed Ezat. And also to Diane Groot for many frantic and helpful discussions while we were both finishing up.

Big thanks and lots of love to my ever faithful fan-club: Edel, Ingvild, Trine, Juho (?), Henrik and Iver – thank you for the good times, the laughter and all the unscientific and often slightly inappropriate discussions.

I am also grateful to Henry for being quite patient with me and also QUITE helpful in the finishing part of my PhD (I have learned that any word stronger than “quite” will be interpreted as sarcasm by a British person, so pardon the monotonous mode of expression). Anyway, THANK YOU (I quite mean it).

Finally, I would like to thank my family for being there for me and for all their support. Mamma og Pappa, finalizing my thesis would simply not have been possible without your help and support during this last summer and in general. Tusen takk for at dere har tatt så godt vare på Sigmund, og gjort det mulig for meg å flytte inn på kontoret i denne avslutningsperioden. Savnet har selvsagt vært stort, men jeg er utrolig takknemlig for at dere har lagt egne planer til side og dedikert sommeren til meg og Sigmund, og det uten å klage et eneste sekund. Dere er utrolige!

Og Sigmund Siggy, my sunshine, you keep me amazed with your strange ways and everyday reflections. Thank you for your contribution to the front page!

Contents

Preface

This thesis is a contribution to the project ForArc (Assessment of benthic foraminifera as environmental proxy in the Arctic region), and has been financed by the Norwegian Research Council (3 years) and the Arctic University of Norway, University of Tromsø (UIT) (1 year). The goal for the project was two sided; firstly to improve the utility of benthic foraminifera as an environmental and climatic proxy for the Arctic region; secondly to apply the improved methodology on Holocene paleo-records, in order to improve our knowledge on climatic fluctuations in the recent past. The execution of the project has been in collaboration between the Norwegian Polar Institute (NPI) and Department of geology, UiT.

The one year financed by UiT was used for so called "duty work" for the Geological Department. This included teaching in undergraduate classes, planning and organizing a PhD course, outreach activities during the "National Science Week", assisting on scientific cruises with R/V Jan Mayen, administrative work with Cristin (a system for documenting research results, information and academic activities) and some other administrative tasks.

During the 2008/2009 I participated in six scientific cruises with R/V Jan Mayen and R/V Lance, with the purpose of collecting data for this PhD-project. Between March and October 2012, I went on a 7 months research visit to INSTAAR (Institute for Arctic and Alpine Research), University of Colorado at Boulder, working with Professor Thomas Marchitto Jr. A large portion of the data analysis was performed at the ICP-MS Trace Element Laboratory at INSTAAR.

The project and preliminary results has been presented in 9 national and international conferences/workshop, 4 as first author (38th annual Arctic Workshop, Boulder 2008; The 33rd International Geological Congress, Oslo 2008; Third International APEX Conference and Workshop, Copenhagen 2009; AGU 45th Annual Fall Meeting, San Francisco 2012.

The work has resulted in two published papers (one as first author) and two manuscripts in preparation for publication:

Skirbekk, Kari; Klitgaard-Kristensen, Dorthe; Rasmussen, Tine Lander; Koc, Nalan; Forwick, Matthias. Holocene climate variations at the entrance to a warm Arctic fjord: evidence from Kongsfjorden Trough, Svalbard. *Geological Society Special Publication* 2010; Volume 344: 289-304.

Skirbekk, Kari; Hald, Morten; Marchitto, Thomas; Junttila, Juho; Klitgaard Kristensen, Dorthe. Mg/Ca-thermometry in an Arctic setting: temperature calibrations for three species of benthic foraminifera and implications on seasonality. *In preparation*

Skirbekk, Kari; Hald, Morten; Husum, Katrine ;Junttila, Juho. Oceanographic development the last 1700 years along the Atlantic Water – Arctic Water boundary in the Polar North Atlantic, inferred from bottom water temperature and salinity. *In preparation.*

Rasmussen, Tine Lander; Thomsen, Erik; Skirbekk, Kari; Slubowska-Woldengen, Marta; Klitgaard Kristensen, Dorthe; Koc, Nalan. Spatial and temporal distribution of Holocene temperature maxima in the northern Nordic seas: interplay of Atlantic-, Arctic- and polar water masses. *Quaternary Science Reviews* 2013; Volume 92: 280-291.

1. Background and objectives

The prevailing trend of global warming in the Arctic is manifested through a variety of observations including increased air temperatures, rising sea temperatures, glacial melting, reduction of sea-ice thickness and extent, and reduction of permafrost covered areas (ICPP 2013). The increase in air temperatures appear highly amplified in Arctic regions compared to the global average (Miller et al. 2010, Collins et al. 2013). Subsequently, the configuration of oceanographic patterns are also changing, possibly having long term effects on the Atlantic Meridional Overturning Cell (AMOC) and the northbound flow of Atlantic Water (AW), which appear to be getting stronger, warmer and saltier (Pardaens et al. 2007).

Interglacial periods are generally associated with relatively stable climatic conditions. Nevertheless, the warming trend experienced over the last century is not the only strong signature climatic event of the Holocene. Following deglaciation of the Late Weichselian ice sheet, northern Europe and the Arctic experienced warmer summer temperatures than present during a period referred to as the Holocene climatic optimum (Davis et al. 2003, Kaufman et al. 2004). In The Polar North Atlantic this general warming typically peaked at approximately 10-8 ka BP(Klitgaard-Kristensen et al. 2001, Hald et al. 2004, Ślubowska et al. 2005, Rasmussen et al. 2007, Ślubowska-Woldengen et al. 2007, Ślubowska-Woldengen et al. 2008). After this a deteriorating climate evolved, leading to the onset of the Neoglacial in Arctic and Sub-Arctic areas (Werner 1993, Matthews and Dresser 2008). This general climatic trend of the Holocene was only interrupted by relatively short-lived excursions of cooler periods; the pre boreal oscillation (PBO) and the 8.2-event. These events are linked to the drainage of large ice-dammed lakes into the North Atlantic Ocean (Barber et al. 1999, Teller et al. 2002 , Meissner and Clark 2006). However, significant climate instabilities have continued through to the latter part of the Holocene - a period where the melting of large ice sheets no longer had a major effect on the climate dynamics and where insolation was reduced compared to the Early Holocene. Several climate variability events, large enough to significantly influence the everyday life of Northern Europe's habitants, have been described: The Roman Warm Period (RWP, AD 50-400); the Dark Ages Cold Period (DACP, AD 400-800); the Medieval Warm Period (MWP, AD 800-1300), the Little Ice Age (LIA, AD 1300-1900), and finally the warming observed over the last 100 years referred to as the Modern Warming (Eiriksson et al. 2006).

The climate of northern Europe today is largely influenced by the inflow of warm Atlantic Water (AW), which continuously releases heat to the atmosphere along its path (Kushnir 1994, Smedsrud et al. 2013). Its effects are readily exemplified by a simple comparison of climatic conditions at similar latitudes of northern Norway and Svalbard, and Baffin and Ellesmere Islands in Arctic Canada, where the present climate is dramatically cooler and harsher. Recent climate anomalies in the northern Atlantic have been associated with fluctuations of Atlantic Water inflow (Kushnir 1994, Gray et al. 2004, Sutton and Hodson 2005, Knight et al. 2006, Folland et al. 2009, Robson et al. 2012, Sutton and Dong 2012). In this context it is of interest to reconstruct variations in AW inflow during the Holocene. Studying the dynamics of the oceanographic currents can also supply information on how the oceanographic system has responded to changes in the past.

The oceanographic system in the Polar North Atlantic is dominated by two main water masses of dissimilar properties (Figure 1); the warm saline Atlantic Water of the Northern Atlantic Current, with all its branches, and the colder and fresher Arctic Water of the East Spitsbergen Current (ESC). The boundary between these two water masses is called the Polar Front. The position of the Polar Front is known to fluctuate through time, reflecting varying AW inflow to the area (Ingvaldsen et al. 2004, Ingvaldsen 2005, Ślubowska et al. 2005, Ślubowska-Woldengen et al. 2007). Previous work has shown that the Atlantic Water influence along the Barents Sea and Svalbard shelf and fjords have fluctuated throughout the Holocene, indicating variations within the main current system (Hald et al. 2004, Ślubowska et al. 2005, Rasmussen et al. 2007, Ślubowska-Woldengen et al. 2007, Rasmussen and Thomsen 2010, Risebrobakken et al. 2010, Rasmussen et al. 2012). However, there are still unanswered questions, particularly regarding the oceanographic dynamics and interplay between the water masses in the region. Quantitative reconstructions of temperature variations are also sparse in the Arctic region.

Knowledge of past climates and environments, beyond the time of instrumental records, can be gained by the application of proxies. Several commonly used proxies are based on fossilized benthic foraminifera. Benthic foraminifera are unicellular, calcifying organisms, and they are the most abundant marine protozoa in the benthic realm (Barbieri et al. 2006). They are known to inhibit most marine habitats, and they have strong environmental and climatic preferences (Hald and Steinsund 1992, Corliss and Silva 1993, Hunt and Corliss 1993, Jennings and Helgadottir 1994, Hald and Korsun 1997, Korsun and Hald 1998, Wollenburg and Mackensen 1998, Gustafsson and Nordberg 1999, Korsun and Hald 2000, Mackensen et al. 2000, Wollenburg and Kuhnt 2000, Gustafsson and Nordberg 2001, Polyak et al. 2002, Rytter et al. 2002, Jennings et al. 2004, Pogodina 2005, Lloyd 2006, Murray 2006, Saher et al. 2009, Zajaczkowski et al. 2010). This makes them ideal tracers of paleo-environments. Also, their calcified tests can contain information on the physical and chemical properties of the ambient water masses, both via isotopic compositions and incorporated trace elements.

A commonly used temperature proxy in marine studies is oxygen isotopes ($\Delta^{18}O$) derived from foraminiferal tests. However, isotope values recorded in the foraminiferal tests depend on the oxygen-isotopic composition and temperature of the ambient water masses. This oxygen-isotope composition of

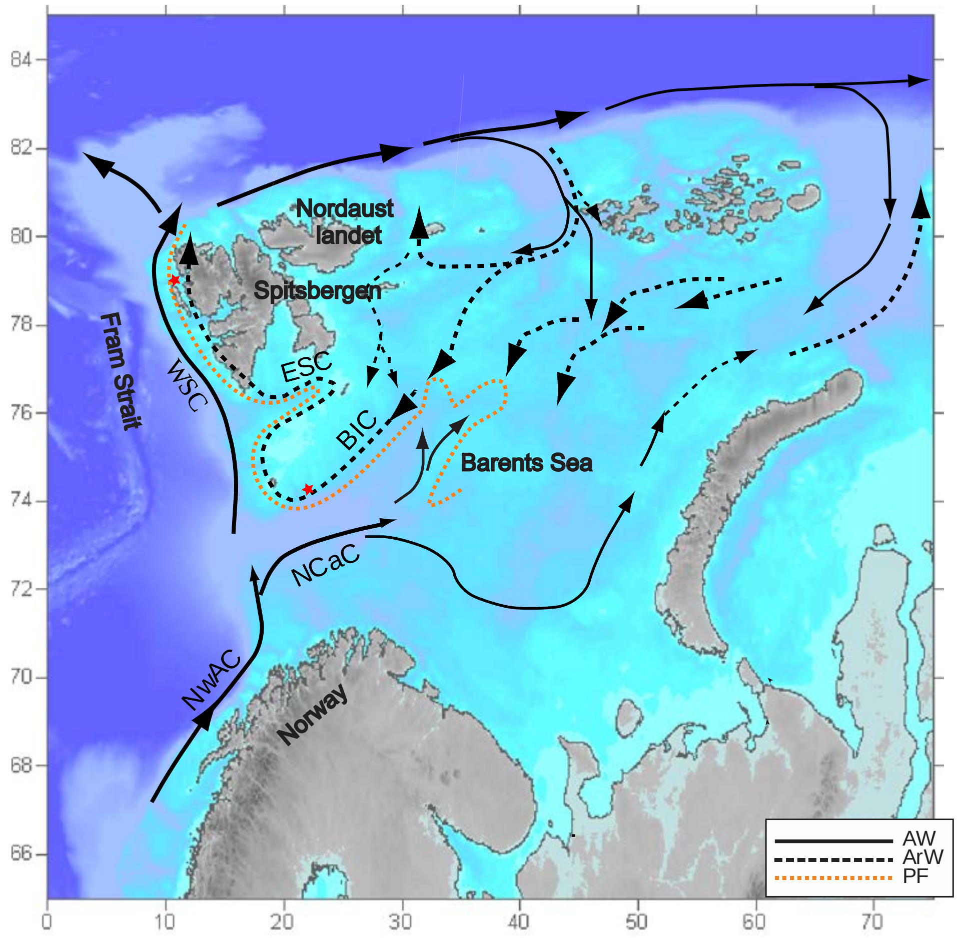

Figure 1. Overview map showing the Northen North Atlantic. Red star indicate main study sites; Kongsfjorden, western Svalbard, and western Barents Sea. Oceanic current patterns for the two main water masses, Atlantic water (NwAC: Norwegain Atlantic Current; NCaC: North Cape Current; WSC: West Spritbergen Current) and Arctic water (ESC: East Spritbergen Current; BIC: Bear Island Current), are indicated by arrows and letters. The oceanic front between the Atlantic and the Arctic water masses are called the Polar front (orange dashed line). (Modified from Kristensen et al. (2013)).

the ambient water masses is also correlated to the salinity, indicating that in an oceanographic setting with potential large salinity fluctuations this proxy may be imprecise. It has been shown that a 0.23 ‰ change in Δ^{18}O is equivalent to a 1°C temperature change (Shackleton 1974). Conversely, a 0.6 ‰ change in Δ^{18}O equals a 1 ‰ change in salinity (Craig and Gordon 1965). This implies that a 1‰ change in salinity could be interpreted as a 2-3°C temperature change. Transfer functions based on modern data from Arctic European continental margin also exist (Sejrup et al. 2004), but there are indications that they are not always decisive in Arctic regions (Groot et al. 2014). Also, they reconstruct a temperature based on the entire fauna, thus representative of an annual or sub-annual average. Hence, a reliable temperature proxy is needed in order to make plausible temperature reconstructions in these areas.

Mg/Ca-ratios in foraminiferal tests is a temperature proxy that has been developed during the last 15 years, as temperature seems to be the main control of magnesium incorporation into calcite tests (Nürnberg 1995, Nürnberg et al. 1996, Rosenthal et al. 1997, Branson et al. 2012). Mg/Ca-temperature calibrations have been developed for several species of marine, benthic foraminifera (Rosenthal et al. 1997, Toyofuku et al. 2000, Lear et al. 2002, Martin et al. 2002, Marchitto and deMenocal 2003, Marchitto et al. 2007, Bryan and Marchitto 2008, Groeneveld and Filipsson 2013, Izuka 1988), though few studies of cold water species exist (Kristjánsdóttir et al. 2007, Quillmann et al. 2012).

The main aim of this thesis is to enhance our understanding of the evolution and dynamics of Atlantic Water inflow to the Polar North Atlantic throughout the Holocene, with an emphasis on the unstable latter part, and how this correlates to known climatic events. For this purpose, study sites in proximity to the Polar Front were chosen; the western Barents Sea, and Kongsfjorden, western Spitsbergen. Both study sites are presently influenced by AW on a seasonal basis; hence, it is likely that they will reflect variation of AW influence in paleo-records as well. A secondary aim of the thesis is to improve/develop a temperature proxy for the Arctic region that could allow for better paleo-oceanographic reconstructions. Five species of benthic foraminifera were tested for a correlation between temperature and Mg/Ca-ratios, in order to derive temperature equations that could subsequently be applied on fossil material.

2. Study Area

2.1 Barents Sea and Western Svalbard Shelf

The initial study area for this work included a transect along the Norwegian – Barents Sea- Svalbard shelf, an area influenced by warm and salty Atlantic Water masses, flowing north via the Norwegian Atlantic Current (NAC) and its branches. The main areas of investigations were Malangen, northern Norway, the Western Barents Sea and Kongsfjorden, Svalbard. Due to challenges and difficulties during laboratory work, some data was lost and some was omitted. Therefore, only the Barents Sea and Kongsfjorden, western Spitsbergen will be presented here.

The Norwegian Atlantic Current flows north along the coast of Norway, and this has strong implications on climate as it continuously release heat to the atmosphere on its northbound path (Smedsrud et al. 2013). At approximately 70 °N it braches into two main currents; the North Cape Current (NCaC) flowing northeast along the Bear Island Trough; and the West Spitsbergen Current (WSC) flowing north along the shelf off Western Spitsbergen. As the AW flows north it becomes both cooler and fresher as a result of heat loss to the atmosphere and water mass mixing processes (Piechura et al. 2001); along the mid-Norwegian margin it holds properties of >35 psu and >6°C (Haugan et al. 1991); when it reaches the Barents Sea it typically holds temperatures around <6 °C and 35.1 psu; west of Spitsbergen it holds temperatures >2°Ca and salinities ≤35 psu (Ferre et al. 2012). In addition to the AW, the other main water mass of the Barents Sea - Spitsbergen area is the cooler and fresher Arctic Water (ArW), typically holding properties of <3°C and >34,4 psu (Ferre et al. 2012). The Arctic water flow south on the eastern side of Svalbard, rounds the southern tip, and continues north along the coast of Western Spitsbergen. It flows east of the WSC. It is referred to as the East Spitsbergen Current., and it is influenced by run-off, calving and melting processes from Spitsbergen. A branch of the ESC deflects from this part and flows south close to Bear Island, and is referred to as the Bear Island Current (BIC).

The oceanic front between the Atlantic Water and the Arctic Water is called the Polar Front (PF), sometimes referred to as the Arctic Front along the coast of western Spitsbergen (Swift 1986, Saloranta and Svendsen 2001). The PF is controlled by differences in temperature and salinity between the two water masses (Loeng 1991, Svendsen et al. 2002). In the Barents Sea its position is mainly controlled by topography (Johannessen and Foster 1978, Harris et al. 1998) , but within this framework, it is known to fluctuate over time (Ingvaldsen 2005). These fluctuations may occur both on a seasonal (Ingvaldsen et al. 2004) and an inter-annual basis (Ingvaldsen 2005), and may not be consistent throughout the water column (Aagaard and Greisman 1975, Harris et al. 1998, Lind and Ingvaldsen 2012). During periods of high AW inflow, the position of the Polar Front in the Barents Sea is displaced northwards (Ingvaldsen 2005). Variability in the AW inflow is strongly correlated to the strength of regional wind fields (Ådlandsvik and Loeng 1991, Loeng et al. 1997, Blindheim et al. 2000, Orvik et al. 2001). For the Barents Sea the strongest annual inflow of AW is mostly seen during winter (Ingvaldsen et al. 2004). However, there are some local variations for this seasonal pattern; in some areas maximum AW inflow is seen in June, implying complex oceanography in the area. Typical for the entire PF is an AW minimum during early spring, shifting the Polar Front southwards, as the Arctic Water influence increase (Ingvaldsen et al. 2004). For western Spitsbergen the AW typically linger out on the shelf break during winter, due to a strong density gradient towards the Arctic Water. This gradient is destabilized during spring, and the AW flow onto the shelf. No inter-annual front migration has been reported for Western Spitsbergen in modern oceanographic studies, but paleo-studies from the shelf suggest that its position varies through time (Ślubowska et al. 2005, Ślubowska-Woldengen et al. 2007). Along the Polar front water mass mixing is continuously occurring (Loeng 1991).

2.2 Kongsfjorden

Kongsfjorden is a 20 km long and 4-10 km wide, east-west oriented fjord, situated at approximately 79 °N on the coast of western Spitsbergen. The fjord is a glacially eroded trough, but no distinct sill is found at its entrance (Elverhøi et al. 1983). It consists of several basins (maximum 394 m depth) confined by shallow sills. A shallow sill situated at the fjord mouth at ~250 meters depth was deposited ~13000 ^{14}C years BP, and the fjord was deglaciated around 9000 ^{14}C years BP (Lehman and Forman 1992). At the present its inner part is occupied by four tidewater glaciers; Blomstrandbreen, Kongsvegen, Kronebreen and Conwaybreen, several of which are surge-type glaciers (Hagen et al. 1993). Due to the unpronounced sill at the fjord entrance, external water masses like Atlantic Water (AW) and Arctic Water can flow readily into the fjord (Elverhøi et al. 1983). In addition to these, the Kongsfjorden water masses include internal water masses (Winter-Cooled-Water, Local Water and Surface Water) and mixed water masses (Transformed Atlantic Water and Intermediate Water) (Cottier et al. 2005). The Local Water (LW) resembles the properties of ArW. Most of the AW masses influencing the bottom waters in Kongsfjorden are Transformed Atlantic Water (TAW; >34.7 psu; >1° C). The inflow to the fjord occurs along the southern side, and the outflow along the northern side; both the surface layer and the deeper layer follow this circulation pattern.

High Arctic areas like Kongsfjorden experience a strong seasonal gradient throughout the year. During the 116 days long polar night, the temperatures are low and a~ 0.7 meter thick sea ice is formed in the inner part of the fjord (Gerland and Renner 2007). Throughout this period the water column is cooled down and homogenized, and these un-stratified water masses create a density driven (barostraphic) front toward the shelf, inhibiting shelf water inflow (Svendsen et al. 2002, Cottier et al. 2005). Bottom water temperatures and salinities are typically around -1 to 1 ° C and ~35 psu (Jernas et al. 2012). In May the water column begin to stratify as a result of melt water input and sequential warming of the surface layer (Svendsen et al. 2002). Runoff season in Kongsfjorden normally lasts from June to September (Hop et al. 2002, Svendsen et al. 2002) and has the largest influence in the inner parts of the fjord. By midsummer Atlantic water typically propagates from the shelf into the fjord, topographically steered, as the strong density field created in winter is weakened, initially by the stratification and secondly by up-fjord winds (Cottier et al. 2005). Atlantic water continues to intrude the fjord throughout the summer and reaches a stable mode in September (Cottier et al. 2005). No wintertime studies show when the shelf-fjord advection terminates, but in late October/early November the temperatures on the AW and TAW in Kongsfjorden is still relatively high (Tverberg et al. 2007, Jernas et al. 2012). In December winter conditions again prevail (Rokkan Iversen and Seuthe 2011).

3. Material and Methods

3.1 Material - field work and sub-sampling

JM05-001 BC was collected south east of Bjørnøyrenna (74°09.49´N, 21°08.71´E; 350 m depth) during a scientific cruise with R/V Jan Mayen July 2005, using a box corer.

The core was 40 cm long. Material from the core, including an age model, stable isotopes and benthic foraminiferal distributions, has previously been published in Wilson et al., 2011. The core comprised the last 1400 years and and was sampled every 0.5 cm. Previously published stable isotope measurements preformed on *Melonis barleeanus* and age model is used in the present study (Wilson et al. 2011). In addition *Buccella frigida* and *Islandiella helenae/norcrossi* was sampled for Mg/Ca-measurements.

NP05-11-21 GC was collected in outer Kongsfjorden (79°03. 07'N, 11°05.40'E ; 327 m depth) during a scientific cruise with R/V Lance in July 2005, using a gravity corer.

Physical properties was measured using a multi sensor core logger (MSCL), x-ray images of reference halves was taken, samples from 10 depths (8 mono-specific *Nonionella labradorica* and two with mixed benthic species) was taken out for AMS dating. The core was sub-sampled every 10 cm (except from 160–240 cm depth when it was sub-sampled every3-4 cm and 400–515 cm when it was sub-sampled every 2–3 cm), giving a total of 104 samples. For the 104 samples IRD > 0.5 cm were counted, faunal distributions of benthic foraminifera was analysed and samples of *Elphidium excavtum* and *Cassidulina reniforme* was picked for Mg/Ca measurements.

NP05-11-21 MC: The upper 11 cm of a multicore taken concurrently with the Kongsfjorden gravity core, was sampled in order to get an undisturbed top for the record. This core was used for a Late Holocene high resolution study. The upper 11 cm of the multi core was connected to the gravity core at 5 cm depth (see Jernas et al. (2013) for details). Samples were taken out every cm down to 62 cm depth. *Nonionella labradorica* and *I. helenae/norcrossi* were sub-sampled for Mg/Ca analysis and *N. labradorica* for oxygen isotopes. A previously published age model, based on 6 AMS dates (mono-specific *N. labradorica*), and ^{210}Pb dating for the upper 14 cm, was used (Jernas et al. 2013).

JM99-1197 BC, retrieved during a cruise with R/V Jan Mayen in 1999 and **JM02-59GC**, retrieved from a cruise with R/V Jan Mayen in 2002, at the same position in Malangen, northern Norway, were combined to make a Late Holocene record with an undisturbed top. Samples were taken out every ~6 cm, a total of 42 samples. *E. excavatum* and *C. reniforme* were sub-sampled for Mg/Ca-measurements. Stable isotopes and age model had previously been published for the combined cores in Hald et al. (2011).

Core-top samples and CTD-casts: During the years 2005-2010 a large amount of Multi cores and Box cores were collected during various cruises with R/V Jan Mayen and R/V Lance, with the purpose of studying living foraminifera. Most of the samples were retrieved from stations in Kongsfjorden and the neighbouring fjord Krossfjorden. Some samples from other Svalbard fjords were also included in the dataset, in addition to 4 samples from Malangen, northern Norway. The samples were collected during three different seasons; April/May, July/August and October/November. The fluffy layer (organic rich, water saturated layer) typically being 1-2 cm thick were always sampled, and for most cores, the cm underneath this layer was also sampled. The samples were immediately added a mixture of Rose Bengal and ethanol, with the purpose of staining specimens of foraminifera that was living at the time of sampling (Boltovskoy and Wright 1976).

CTD (conductivity, temperature, depth) -measurements was performed at every location, to provide physical information from the water column

A total of 54 core-top samples were used for the present study. When present in sufficient numbers, sub-samples of living *E. excavatum*, *C. reniforme*, *N. labradorica*, *I. helenae/norcrossi* and *B. frigida* were picked out for Mg/Ca analysis.

3.2 Laboratory work

Faunal assemblages: For benthic foraminifera faunal distributions the samples were dry picked from 100µm mesh size. If possible a minimum of 300 specimens were identified to species level. The faunal distributions are presented as relative abundances. Benthic foraminiferal concentrations were calculated as flux values (no. of specimens (cm^2 ka^{-1})) using the bulk sediment density and sedimentation rate. A diversity index, which indicate the number of species that constitutes 95% of a fauna, was used to calculate faunal diversity (Walton 1964).

Stable Isotope Analysis: The stable isotope analysis for JM05-001 BC and JM99-1197 BC/JM02-59GC has been previously published (Hald et al. 2011, Wilson et al. 2011).

For the NP05-11-21MC/GC Late Holocene record, samples of *N. labradorica* was analysed using a Finnigan MAT 251 mass spectrometer, located at the Geological Mass Spectrometer (GMS) laboratory at the University of Bergen.

Mg/Ca-ratios: All Mg/Ca measurements are performed on a Thermo Finnigan Element 2, an inductively coupled plasma mass spectrometer (ICP-MS), located at INSTAAR, University of Colorado at Boulder. Ideally ~50 individuals were picked, but if this was not possible, all available material was picked. The samples were carefully crushed between two glass plates under a microscope, in order to crack open all chambers prior to cleaning. Any obvious contamination like pyrite or mineral grains was removed mechanically. A three step cleaning procedure was then carried out; a clay removal step where methanol (three repetitions) and MilliQ (4 repetitions) was added to the samples, ultrasonicated and siphoned out (7 total repetitions); a reductive step where citric acid, NH_4OH and anhydrous hydrazine was added to the sample, in order to remove any secondary coatings/overgrowths on the tests. The samples were put in the solution and kept in a hot bath for 30 minutes, while it was frequently ultrasonicated, before thoroughly rinsed; a oxidative step where NaOH and H_2O_2 was added to the samples in order to remove any organic material. It was heated and ultrasonicated in a three repetitions, before it was rinsed thoroughly. After the cleaning procedure, the samples were transferred to new vials and put in a weak acid leach (weak HNO_3), before they were rinsed and all solution was removed. Prior to measurements, the samples were dissolved in strong, ultrapure HNO_3. For the core top samples, only foraminifera that were stained in ≥90% of the chambers were used. In addition to the cleaning procedure described above, these samples were bleached with the purpose of removing the rose bengal. They were left in bleach overnight, and then thoroughly rinsed.

3.3 Data Processing

Temperature reconstructions from Oxygen isotopes

For the late Holocene records of NP05-11-21GC/MC and JM05-001 BC , oxygen isotope derived temperature calculations done using a modified version of Shackleton (1974), which included a SMOW-PDB conversion (Lubinski et al. 2001). To determine a $\delta^{18}O_{water}$ values, a salinity values of 34.9 was inserted to a salinity mixing line published by MacLachlan et al. (2007). This gave a $\delta^{18}O_{water}$ of 0.357 Oxygen isotope values from *N. labradorica* samples were corrected for a vital effect of 0.28 and *M. barleeanus* were corrected for a vital effect of -0.41 (Ivanova et al. 2008).

Temperature reconstructions from Mg/Ca-ratios: The present study attempted to develop new temperature calibration curves for five species of benthic foraminifera, by correlating species specific Mg/Ca-ratios from core-top samples to bottom water temperatures derived from CTD-casts. The five species was *E. excavatum*, C. *reniforme*, *I. helenea/norcrossi, N. labradorica* and *B. frigida*. Unfortunately, the material for *E. excavatum* and *C. reniforme* was lost during cleaning procedures. For the other three species, no correlation between BWT and Mg/Ca was seen initially. However, when grouping the data based on season, a significant correlation was seen (see paper 2&3 for details). Samples containing less than 15, juvenile and poorly stained specimens, were omitted from the dataset. Samples that showed indications of low $CaCO_3$-mass (<5µg) were omitted from the dataset, if the Fe/Ca and Al/Ca-ratios showed signs of contamination (Barker et al. 2003). This together with the seasonal grouping led to a far smaller data source than intended.

The temperature equations derived from the presented modern database were subsequently used to reconstruct temperatures in the paleo-records. Since no temperature equations was made for *E. excavatum* and *C. reniforme*, due to loss of data, no Mg/Ca temperature reconstructions could be made for the full Holocene record from NP05-11-21GC (Kongsfjorden) and the Late Holocene records from JM99-1197 BC/JM02-59GC (Malangen). Both *E. excavatum* and *C. reniforme* had been prepared for Mg/Ca- measurements for both records.

Salinity reconstructions derived from combined Mg/Ca and oxygen isotope records: For the Late Holocene records of NP05-11-21GC/MC and JM05-001 BC, an attempt was made to reconstruct bottom water salinities, by combining Mg/Ca-ratios and oxygen isotope data. As the temperature equation for $\delta_{18}O_{calcite}$ has two unknowns: temperature and $\delta_{18}O_{water}$. The temperatures derived from Mg/Ca, was inserted into the temperature equation used for oxygen isotopes (Lubinski et al. 2001). This gave a record of $\delta_{18}O_{water}$, which was subsequently inserted to the regional mixing line equation (MacLachlan et al. 2007), giving a salinity record. We realize that this combination likely gives some sources for errors in the calculations. Still, as the reconstructed salinities give values which are likely for both areas, they are notified as absolute salinity values. For NP05-11-21GC (Kongsfjorden) the salinity reconstructions is based on measurements on *N. labradorica*. For JM05-001 BC (Bear Island Trough) they are based on a combination of *I. helenae/norcrossi* (Mg/Ca) and *M. barleeanus* (oxygen isotopes), which are thought to reproduce and grow synchronously (Kristjánsdóttir et al. 2007). A combination of *B. frigida* (Mg/Ca) and *M. barleeanus* (oxygen isotopes) was also tested, but this reconstructed highly unlikely temperatures.

Age Models

For the full Holocene record (NP05-11-21GC) of Paper I, the dated levels were calibrated using Calib 5.0.2. (STUVIER % REIMER1993) and the calibration dataset Marine 04 (HUGHEN 2004). A reservoir age of 360 and a ΔR of 105±24 were used (MANGERUD). The age model was based on peaks of the probability curves, which all where within the 1σ range. Constant accumulation rates were assumed between the dated levels. In the full Holocene record as presented din paper IV, two dates of the age model from paper I were omitted, as they appeared as outliers compared to the other records it was being compared with. The two dates were from depth 270-271 cm (8760 cal. Years BP) and 320-321cm (10150 cal. Years BP). Form this follow that the age model in Paper I differ from that in Paper IV between 8000 and 10 700 cal. Years BP.

The age models of NP05-11-21MC/GC and JM05-001BC is based on a combination of AMS and ^{210}PB datings, which are previously published in Jernas et al. (2013) and Wilson et al. (2011). However, all AMS dates were recalibrated using Calib 7.0.2 (Stuiver and Reimer 1993) and the Marine13 calibration curve (Reimer et al. 2013). A ΔR of 71±21 were used for the Western Barents Sea and of 105±24 for Kongsfjorden (Mangerud et al. 2006). Calibrated ages were calculated as the mean within the 2σ range. Age models were recalculated according to this, and a constant accumulation rate was assumed between the dated levels.

4. Summary of Papers

Paper I

The primary aim of this paper was to reconstruct Holocene environmental development in Kongsfjorden, and to evaluate how the inflow of Atlantic Water (AW) compared to changes out on the shelf, which have been directly associated with changes in the Arctic Front position. Secondarily, it aimed to see how variations in AW inflow interacted with glacial activity. For this purpose, benthic foraminifera faunal distributions and IRD analysis were performed on a sediment core comprising the last 12000 years. Kongsfjorden is situated at a climatic junction; on one hand it is highly affected by glacial processes and cold water conditions as four glaciers connected to Spitsbergen ice caps drain into it; on the other hand it is highly influenced by the inflow of warm and salty AW originating from the Gulf Stream. This makes it an ideal location to study the dynamics and interplay between glacial and oceanographic driven processes.

A glacier proximal environment was evident for the final part of the Younger Dryas. Around 11.8 ka BP, AW inflow to the fjord is increased. Following this was a period of intensified glacial activity related to the final deglaciation of the fjord. The period of strong AW-inflow and high IRD delivery was interrupted by a 250 year long cold spell, during which the fauna changed profoundly, including several species known for low salinity tolerance. Concurrently, the IRD delivery paused, indicating the presence of sea ice. This cold event was correlated to the Pre Boreal Oscillation. After 10.6 ka BP a distinct shift from glacier proximal to glacier distal conditions happened concurrently with a stronger AW influence. These conditions prevailed until 7 ka BP, when the influence of AW diminished. Increased glacial activity is not observed until approximately 3.5 ka BP. Except for the cold spell during the PBO, the climatic development follows the trend of the insolation curve. The inflow of AW to Kongsfjorden is with few exceptions in phase with the migration of the Arctic Front out on the shelf.

Paper II

This paper aimed to develop Mg/Ca temperature calibrations for five species of cold water benthic foraminifera, as few such had been previously established. The species were chosen based on their presence both in modern Arctic environments and Weichselian and Holocene records. Samples containing living benthic foraminifera were retrieved from mainly Kongsfjorden, also in addition to a few samples from other Svalbard and northern Norwegian fjords. Concurrently, CTD measurements were carried out in order to obtain information about the bottom water temperature (BWT). Material was retrieved from several stations during several years and three different seasons. Mg/Ca-analysis was performed on mono-specific samples of living foraminifera (> 20 specimens) and coupled with BWT. Initially, no correlating was seen between the two parameters. However, when confining the data to specific seasons, an Mg/Ca-ratio – temperature relationship was observed. This implies that the different species have specific growing seasons. The timing of their reproduction and calcification is probably linked to certain ecological trigger mechanisms, as benthic foraminifera are known to have specific environmental and climatic preferences. *I. helenae/norcrossi* appeared to represent the July/August-oceanographic spring; hence a temperature equation based on spring samples was established for this species. At this time a strong pycnocline is developing in the fjord, relatively cold local fjord water is present on the bottom, while Atlantic Water inflow is initiating. This also coincides with the yearly bloom of the ice diatoms in Kongsfjorden. *I. helenae/norcrossi* is typically associated to areas of seasonal sea ice; hence sea ice diatoms could be a likely trigger mechanism for their growth. The dataset of *B. frigida* indicated a growing season lasting from July-November, and an equation based on July/August-spring and October/November-summer was presented. This period coincides with the time AW is typically present in Kongsfjorden; it enter the fjord in July, and reaches the highest temperatures in October/November. *B. frigida* is an Arctic species, but is often associated with the climatically favourable side of Arctic environments. We speculate that it can be an AW indicator in these areas, as it seems to thrive during AW influence. *N. labradorica* appear to have a dual growing season; a minor in April/May-winter and a mayor in October/November-summer. A temperature equation was derived from both winter and summer data. *N. labradorica* is typically associated with high organic fluxes. The calcifying seasons coincide with two events that are related to enhanced organic fluxed; the spring phytoplankton bloom (April/May) and the maximum inflow of Atlantic Water masses to the fjord. The knowledge of species specific calcifying seasons can contribute to better understand and interpret the temperatures being reconstructed. In high seasonality areas of where significantly different temperatures are seen throughout a seasonal cycle, this information can be crucial.

Paper III

The aim of this paper was to reconstruct temperature development and oceanographic dynamics from two sites along the Atlantic Water-Arctic Water boundary of the European Arctic. Mg/Ca and Oxygen Isotope data from sediment cores retrieved from the Bear Island Trough and Kongsfjorden, Spitsbergen, were used to produce temperature and salinity reconstructions. The oceanography on both sites is dynamic as the proximity to the Polar Front allow for water mass fluctuations between distinctively different water masses both on an annual (seasonal) and an inter-annual (long term) level. The large potential salinity change associated with a shift from Atlantic Water to Arctic Water makes temperature calculations based on Oxygen Isotopes unreliable, as a 1‰ change in psu can mimic a 2-3 °C temperature change (Craig and Gordon 1965, Shackleton 1974). Two Mg/Ca-temperature records from each site were used, reconstructing the temperature of different seasons/water masses, as suggested by Skirbekk et al. (in prep). The Barents Sea site appeared to reconstruct a regional oceanographic signal, while the Kongsfjorden site was affected by water mass mixing and glacial processes.

For the Barents Sea site one record mostly representing AW and one record representing ArW was presented. They indicated three intervals of northward Polar Front migration and increased Atlantic Water inflow during the last 1500 yr; AD 700-1000, AD 1200-1500 and AD 1700-present. For the rest of the time the AW-record indicated the presence of mixed AW-ArW water masses except for AD 1650-1750 when a southward shift of the Polar Front, large enough to suppress any AW influence to the site, occurred. The Kongsfjorden records seem to be out of phase with the changes seen in the Barents Sea until ~AD 1100. Before this the records imply no significant AW influence, except pulses of increased AW mixing into the ArW. After this AW inflow to Kongsfjorden seems to follow the same trend as for the Barents Sea, only with lower temperature amplitude. This is likely related to water mass mixing processes. The Arctic Water masses in Kongsfjorden have two cold spills during the Little Ice Age, both occurring after known West Spitsbergen glacial advances, possibly indicating enhanced glacial melting/calving. The Barents Sea record also indicates increased melt water supply through the last half of the LIA, as the Arctic Water becomes both cooler and fresher towards the present. The cooling and freshening coincides with increased AW inflow to both Barents Sea and Kongsfjorden, and we speculate that the increased AW inflow leads to enhanced glacial melting along western Spitsbergen. During a period of enhanced AW inflow around AD 1300, the Arctic Water response is opposite; it becomes warmer and saltier. This could result from increased AW mixing into the ArW, which is subsequently recirculated via the East Spitsbergen Current and the Bear Island Current, as is also seen today. AW influence increase steadily from ~AD 1750 on both sites. A rapid modern warming is observed from AD 1950 to present.

Paper IV

The aim of this paper was to reconstruct water mass distributions on the Svalbard Shelf and Slope during the Holocene, emphasizing on the influence of Atlantic Water, Arctic Water and melt water, and how this can be linked to climate change. The study is based on a sediment core retrieved from Outer Kongsfjorden, comprising the last 11700 years. Planktic foraminiferal distributions data is presented, as this gives implications on nutrient supply, productivity and temperature of the water masses; stable isotope data of both planktic and benthic foraminifera is presented as this monitors changes in physical and chemical properties of the water masses; IRD counts are presented as they give indications on glacial activity. Temperatures have been calculated from Transfer Functions (TF) and Oxygen Isotopes. The data are compared to several other Svalbard records in order to find consistency in the Holocene climatic evolution of the area. Until 9600 years BP a pycnocline was present in the waters west of Svalbard, at 100 meters depth on the shelf and 30 meters depth on the slope. The declining surface water thickness towards the slope is seen as an indication that it is largely driven by melt water supply. The upper portion of the stratified water column consisted of cold Arctic/Polar waters and melt water, while Atlantic Water prevailed underneath the pycnocline. After this a decreased influence of Arctic/Polar water and melt water followed, leading to a weaker stratification. Between 9000 and 6000 years BP AW dominated the entire water column. The AW dominance is linked to decreased melt water supply feeding the Arctic Water, hence allowing for AW inflow throughout the water column. Temperature maxima for the upper and lower water masses appear to be decoupled during the Holocene climatic optimum; in the lower water masses it occurred between 11 500 and 8200 yr BP; in the sub-surface water masses it occurred between 9000 and 6000. The delayed temperature maximum of the upper water masses is likely related to interplay between Arctic and Atlantic water masses. For the entire water column the temperatures decreased to a minimum between 5000 and 2000, while for the last 2000 years, unstable conditions transpire. Contributions to paper: The current writer contributed with benthic-foraminifera assemblages, and in general to the discussion of the paper.

5. Synthesis

The Polar Front area is an intriguing study site as it represents the meeting point of cold and fresh Arctic Water masses, which are highly affected by melt water from glaciers on Svalbard, and the warm saline Atlantic Water masses, originally advected from the Gulf of Mexico. The supply of warm Atlantic Water has a large impact on the climate in northern Europe, which is relatively mild for its latitude. The main aim of this thesis has been to enhance our understanding of oceanographic dynamics of Atlantic Water inflow to the Polar North Atlantic during the Holocene, with an emphasis on the latest and most unstable segment (~last 2k). It has aimed to understand how the AW inflow has varied during the Holocene interglacial period, and how the variation of inflow along the shelf affects the coastal areas (Paper I, III & IV). It has also aimed to enhance understanding of the interplay between a glaciated land mass and Arctic Water to the northbound, exotic Atlantic Water (Paper I & III). In addition to the reconstructions, a main objective has been to improve the Mg/Ca method for cold water environments, as this could allow for more plausible paleo-temperaure reconstructions in the Arctic and other cold water environments (Paper II and III).

5.1 Modern dataset and seasonality

The modern dataset was mainly based on samples from Kongsfjorden with a few exceptions retrieved from other Svalbard and northern Norwegian fjords. Of the five species of benthic foraminifera tested for Mg/Ca-temperature relationships, a temperature equation was developed for three of them; *I. helenae/norcrossi*, *B. frigida* and *N. labradorica* (Paper II). However, a correlation was not seen until the dataset was divided into sub-sets based on season. This implied that the different species held specific calcification seasons, and the local conditions during these calcifying seasons correlated well with known environmental preferences of the species; *I. helenae/norcrossi* appeared to calcify during July/August, concurrently with the sea ice diatom bloom in Kongsfjorden; *B. frigida* between July and November, which represents the period when AW is present in the fjord; and *N. labradorica* appeared to calcify in October/November which is the period of maximum Atlantic Water inflow to Kongsfjorden[1].

This result represented a possibility to reconstruct temperatures with a seasonal signature. However, the applied temperature reconstructions on the Late Holocene records from Barents Sea and Kongsfjorden indicated that it is not so straight-forward. Firstly, the term season can be misleading. The seasonality in Kongsfjorden is strongly linked to the presence of specific water masses, particularly AW. Two of the species studied show a correlation to AW, and were therefore believed to reconstruct the temperatures of AW. However, in Kongsfjorden, maximum AW inflow is seen in October/November, which is referred to as hydrological summer in Paper II. Conversely, in the Barents Sea, maximum AW inflow is, for most areas, seen during the winter months. Hence, it can be misleading to refer a specific species to a specific season, as this may vary between locations. This demonstrates the importance of knowing the modern conditions in the area studied for paleo-conditions. Secondly, what defines a season may not be consistent through time. Looking at Kongsfjorden today, the timing of AW inflow to the fjord is changing (Tverberg et al. 2007, Hegseth et al. 2009). This change also affects the timing of the spring bloom (Hegseth and Tverberg 2013), which could possibly have a domino-effect to other trophic levels, including benthic foraminifera. If a species is triggered by the spring phytoplanktic bloom, and a shift in oceanography simultaneously leads to AW domination (instead of Arctic water domination), this could potentially be interpreted as a rapid temperature change, when it in fact represents an oceanographic shift. Thirdly, benthic foraminifera are known to have strong environmental preferences. However, the several examples from the Late Holocene reconstructions indicated that the species were able to adapt and still reproduce/grow after conditions had changed (Paper III). For example, when AW influence disappeared in the Barents Sea record, *B. frigida* was still present, but it reflected temperatures of the Arctic Water instead. Such aspects need to be taken into account when reconstructing paleo-records, and is increasingly important in oceanographically dynamic areas. Hence, the seasonality aspect can likely provide a new and interesting perspective to paleo-reconstructions. However, great care must be taken when interpreting the data, and therefore not only a multi-proxy, but also a multi-species approach, is advised to achieve a best possible understanding of paleo-conditions.

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[1] Initially *N. labradorica* was interpreted to calcify during April/May and October/November. However, when applying the equation on a paleo-record it became obvious that the data had been misinterpreted by adding northern Norwegian data to the dataset. See Paper III for details.

5.2 Oceanic development of Polar North Atlantic

The full Holocene record from Kongsfjorden is based on benthic (Paper I) and planktic faunal assemblages, in addition to Oxygen Isotope and Transfer Function derived temperatures (Paper IV), as the Mg/Ca-ratio measurements were unsuccessful for this core. The long term environmental development in the western Barents Sea and western Svalbard margin are closely linked to the inflow of Atlantic Water. Atlantic Water advection towards the coast, represented by the fjord site, is mostly in phase with the Polar Front fluctuations registered further out on the continental shelf and slope. Also, the fluctuations in the WSC appear to be in phase with fluctuations of the NCaC. It therefore follows that the general climatic pattern described for the Holocene (e.g. an early Holocene climate optimum; a mid-Holocene transitional period of deteriorating climate; onset of glacial activity (referred to as the Neoglacial)) appears to be in phase with the insolation curve. The only distinct excursion from the general climate development are seen during the cold spell of the Pre Boreal Oscillation.

Reconstructions for the last 2 ka appear climatically unstable within the full Holocene record. Therefore high resolution temperature records were reconstructed for western Barents Sea and Kongsfjorden for the last ~1700 years. These were based on Mg/Ca-ratios (two for each site) and Oxygen Isotope-measurements (one for each site) (Paper III). All records indicated conflicting temperature developments. As discussed in section 5.1, the different temperature evolutions between the Mg/Ca-records were attributed to different timings of test growth between the different species. The offsets in Oxygen Isotope-derived records were attributed to the large potential impact of salinity changes along the Atlantic Water-Arctic Water boundary. In addition, salinity reconstructions were added to the dataset by pairing Mg/Ca and Oxygen Isotope records. This can provide information regarding which water mass were present in the record at a certain time. Looking at the Polar Front today, its position is known to fluctuate throughout a seasonal cycle, leading to the domination of distinctly different water masses over an annual cycle (AW and ArW) (Ingvaldsen et al. 2004). Kongsfjorden also has a seasonal cycle regarding water mass domination. This seasonal signal was captured by the Mg/Ca derived temperatures derived from different species, in the paleo-records of the present study and in particular from the Barents Sea record. This gave a good opportunity for ocean dynamics reconstructions.

In addition to the seasonal, or water mass, signals, changes within each record imply long term changes in Polar Front position. This is also seen in modern times, where a northward migration of the Polar Front implies increased AW inflow; a southward migration of the Polar Front implies lower AW inflow (Ingvaldsen 2005).

The trends of AW inflow during the late Holocene are decoupled from the insolation curve, and conditions appear unstable and changing, contrasting the mid and early Holocene. The Barents Sea record indicated several mayor shifts in Polar Front positions, inferred from changes in AW influence over the site. Before AD 1000 these changes are not present in the Kongsfjorden site, indicating that the WSC and NCaC are not in phase. After AD 1000 the AW influence to the sites can be correlated, indicating that the WSC and the NCaC are in phase.

Being able to reconstruct temperatures, and hence detect the presence of both the main water masses in the area, gave interesting results regarding oceanographic dynamics, particularly in the western

Barents Sea. The temperature recorded by the AW-preferring species gave an indication on whether it was "pure" AW or mixed AW present at the site. Comparing that to the ArW temperature gave an indication of the Front position at the time. When the temperatures were similar it was interpreted as a southward shift in the Polar Front position, leading to Arctic Water dominance throughout an annual cycle. When the discrepancy was large, it was interpreted as a northward shift. Two episodes of increased AW inflow and northward migration of Polar Front position in the Barents Sea during the Late Holocene have opposite effects on Arctic Water; a northward shift of the Polar Front occurring at ca. AD 1300 in the Barents Sea is followed by increased temperature and salinity in the Arctic Water. Conversely, increased AW inflow to the Barents Sea and Kongsfjorden ca. AD 1750 is followed by cooler and fresher Arctic Water. Possibly, the different effect on the ArW at this time is linked to the increased presence of Svalbard glaciers associated with the Little Ice Age, as they could have been a source for increased meltwater supply. A situation as seen around AD 1300 is also seen today during periods of increased AW inflow in WSC, where the AW mixed with ArW and recirculated southwards along the eastern side of Svalbard.

The Barents Sea site it situated in proximity to the present Polar Front, and reconstructs more distinct temperature signals, which appear to represent the regional development. Kongsfjorden, on the other hand, seems to reflect signals which have been diluted by water mass mixing processes and glacial activity, and is hence more difficult to interpret.

5.3 Proxies

At the Polar Front-proximal sites in the present study, there is an on-going interplay between Atlantic and Arctic water masses obvious in the records, with these oceanic shifts producing large impacts on environmental conditions in the area (Paper I, III & IV). This interplay also appears to have the capability to delay and mask the general climatic trend; excursions from the general climate development are seen during the cold spell of the Pre Boreal Oscillation (Paper I) and during some intervals in the Late Holocene, like the Little Ice Age (Paper III). The timing of the early Holocene climatic optimum indicated that oceanographic shifts are not always in phase throughout the water column, demonstrating the impact of meltwater delivery (Paper IV).

Improving the methodology regarding temperature reconstructions was a main objective of this thesis, and three new Mg/Ca-temperature equations were developed for cold water environments (Paper II). The reconstructions based on those gave interesting and reliable results. Comparing them to oxygen isotope- derived temperatures in the late Holocene records strengthened the assumption of a large salinity impact in the Polar front area, and the deviating oxygen isotope-derived temperatures were inferred to be corrupted by this.

For the full Holocene record temperatures were reconstructed using Transfer Functions (TFs) and oxygen isotopes (Paper IV). Mostly, the changes seen in the fauna correlated well, but during the mid-Holocene, for example, the temperatures increase slightly (Paper IV)while a distinct shift from warm to cold water mass is inferred from the faunal assemblages (Paper I). The TFs calculate a temperature based on the entire fauna. As discussed above, the species have various calcifying seasons. Hence the TFs represent an annual or sub-annual mean-average temperature. Periods with a large difference between summers and winters would not be apparent using TFs. This could explain the TF-based reconstruction from mid-Holocene. The distinct shift to an *E. excavatum* dominated fauna happens concurrently with an introduction of some species associated with a warmer climate.

Benthic foraminifera are known to have strong environmental preferences, but still their distributions and abundances can depend on many factors such as temperature, salinity, food supply, oxygen levels, and habitats. Hence using them as climatic and environmental proxies is not always straight-forward. Profound knowledge of their environmental and climatic preferences is important even when utilising their geochemistry for paleo-reconstructing purposes. In an oceanographically complex area like the Polar North Atlantic, the use of proxies is challenging, and a multi-proxy approach appears crucial in order to gain a complete understanding of past environmental and oceanographic change. The late Holocene record presented here also indicates that a multi-species approach can add further to this knowledge.

6. Future work

When the data for the modern Mg/Ca temperature-calibration curves were collected, samples were retrieved during several seasons and locations in order to achieve a wide temperature range. However, by grouping the data based on season, the number of samples in each species-specific calibration dataset was lowered dramatically. Hence, more data should be added to the dataset in order to make the temperature equations more robust, with indications on calcifying season presented in this thesis used as potential guidelines. Also, oxygen-isotope measurements of the modern samples, in order to recapture the temperatures of the ambient water masses during calcification, could possibly help making reliable temperature equations, as shown by (Kristjánsdóttir et al. 2007). However, great care must be taken when choosing a $\delta^{18}O_{water}$ in this process.

Making a second attempt on developing a Mg/Ca temperature equation based on *C. reniforme* and *E. excavatum* would be interesting, as these are such significant parts of Arctic and glacial faunas. These opportunistic species possibly have calcifying seasons deviating from other species, and could thus provide interesting paleo-records. In addition, it could provide new knowledge on their environmental preferences.

Once these equatinos are established, the next step would be to apply Mg/Ca temperature equations on longer time series, in order to get a better handle on temperature development throughout the Holocene and into the Late glacial, and how oceanographic dynamics have since changed.

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Paper I

Paper II

Paper III

Paper IV