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FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF GEOLOGY

Late Glacial – Holocene climate variability and sedimentary environments on northern continental shelves

Zonal and meridional Atlantic Water advection

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A dissertation for the degree of
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Stay Arctic!

2. Preface

The thesis was accomplished during a four-year PhD study financed by the Trainee School in Arctic Marine Geology and Geophysics (AMGG). The school is hosted by the University of Tromsø, Department of Geology, in collaboration with the Geological Survey of Norway, the Norwegian Polar Institute and the University Centre of Svalbard. Much of the work was carried out within the framework of the International Polar Year project "Arctic Natural Climate and Environmental Changes and Human Adaption: From Science to Public Awareness" (SciencePub) funded by the Research Council of Norway and University of Tromsø. During the PhD 25 % of the employment was allocated to work for University of Tromsø. This work included teaching and outreach activities. It also included assisting with preparations and the participation in six marine geological cruises on board the R/V Jan Mayen in addition to relevant micropaleontological analyses for various projects.

During the PhD study results were presented in eleven posters and seven talks at national and international workshops and conferences. The PhD study further included a three month research stay in autumn 2009 at the Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, USA.

3. Introduction

In recent decades the political establishment and the mass media have increased their focus on climatic changes. Climatic changes are observed globally including the Arctic and Antarctic regions (IPCC, 2007). The modern climatic changes are partly driven by burning of fossil fuels enriching the atmosphere with carbon dioxide (CO_2). Paradoxically, the prospect of exploiting new oil and gas reserves in previously inaccessible Arctic areas has fuelled a further need to study the Arctic climate system in more detail. Predictions of the future climate warming show that the worst case scenario involves a global 3°C temperature rise in the coming century. They further suggest that temperature increases might reach twice the global mean in the Arctic region (IPCC 2007). A range of immediate effects of global warming can be construed and include melting sea ice and land bound glaciers, eustatic sea level rise, more extreme weather and loss of biodiversity.

Standardized instrumental records of past oceanic temperatures reach back to around 1850 A.D. with uncertainties declining toward the present. Historical records reaching further back in time provide only sparse qualitative information (Brohan et al., 2006). In recent years application of remote sensing tools have generated vast amounts of data from the Arctic regions. These data have given information about influx of warm and saline Atlantic Water towards the Arctic, thickness and extent of Arctic sea ice and retreat rates of the Greenland ice sheet (e.g. Schauer et al., 2002; 2004; Sandven and Johannessen, 2006; Stroeve et al., 2007). However, all the modern environmental data sets are influenced both by natural and anthropogenic forcing. Thus, in order to identify the anthropogenic forcing on the (Arctic) climate system it is necessary to study the natural climate system variability on a longer timescale than covered by instrumental measurements.

Records of pre-industrial climate changes are stored as physical, chemical and biological proxies in the geological record through accumulation in sediments or ice. Paleo records may record variations both in external (e.g. solar and orbital) and internal forcing mechanisms (e.g. atmospheric, oceanic, cryogenic and volcanic).

The ocean has a large heat storage capacity and is a major component in the complex climate system responsible for redistributing large amounts of energy around the globe (Broeker, 1991). Previous studies have shown that especially during the Late Glacial the advection of Atlantic Water to high northern latitudes was highly variable. The rapid transition into the Younger Dryas cold event and equally rapid termination at the transition to the Holocene has been observed in records from the Nordic Seas (e.g. Klitgaard-Kristensen et al., 2001; Johnsen et al., 2001; Steffensen et al., 2008). The cooling has been ascribed to a freshening of the surface waters in the Nordic Seas. The freshening resulted in expanding sea ice cover and reduction in both the North Atlantic Deep Water (NADW) formation and the north-south exchange of water masses (e.g. Koç et al., 1993; Birgel and Hass, 2004; Jennings et al., 2006). The exchange of water masses in the North Atlantic and Nordic Seas is part of the global ocean conveyor belt system and is generally referred to as the Atlantic Meridional Overturning Circulation (AMOC). Several short lived cooling events forced by freshwater induced hampering of the AMOC have been identified during the early Holocene. These include the Preboreal Oscillation (e.g. Hald and Hagen, 1998), the 9.3 ka event (Rasmussen, S.O. et al., 2007) and 8.2 ka event (e.g. Klitgaard-Kristensen et al., 1998; Alley and Ágústsdóttir, 2005). Oppo et al. (2003) further showed that the NADW formation strength continued to vary throughout the early to late Holocene. Additional climatic and oceanographic fluctuations influencing the flux of Atlantic Water have been observed in the North Atlantic and the Nordic Seas through the Holocene. Bond et al. (1997; 2001) observed a ca. 1500 yr cycle of sea ice expansion linked to varying solar activity, reduced NADW formation and diminished meridional Atlantic Water advection. Variations in the North Atlantic wind patterns were deduced from glacier mass balances in maritime southern Norway reconstructing the North Atlantic Oscillation (NAO) index (Nesje et al., 2001). The NAO index is a measure of atmospheric pressure difference between Iceland and the Azores. Positive NAO indicates larger pressure difference resulting in stronger wintertime westerlies which increase the Atlantic Water influx to the Nordic Seas and generate warm/wet conditions over NW Europe. During negative NAO the pressure difference is smaller resulting in reduced Atlantic Water advection and cold/dry conditions over NW Europe (Hurrell, 1995). Finally, numerous studies from the Nordic Seas and adjacent landmasses depict an early to middle Holocene Thermal Maximum and subsequent temperature decline towards the end of the Holocene (e.g. Birks and Koç, 2002; Rasmussen, T. L. et al., 2007; Seppä et al., 2008). These changes have been linked to the declining insolation throughout the Holocene (Berger and Loutre, 1991).

The overall objective for this PhD-study was to increase the understanding of the oceanographic variability and development in the Nordic Seas during the Late Glacial and the Holocene. The study examines variations in meridional Atlantic Water transport via the North Atlantic Current into the Nordic Seas which is part of the AMOC. The focus is specifically on the poleward Atlantic Water advection along the continental margins of Norway, into the SW Barents Sea and further north past Spitsbergen (Fig 1). Marine sediment cores are good archives of past oceanic developments due to their often long time series of more or less uninterrupted sediment sequences that potentially store information about past climatic and oceanographic developments in physical, chemical and biological parameters.

This study aimed at achieving high resolution sediment cores at subcentennial to centennial scale. This was done in order to advance the understanding of the spatial and temporal variability of observed climatic and oceanographic changes and elucidate forcing mechanisms. The sediment cores were investigated using several paleoceanographic proxies (Fig 1, Table 1). These include planktic and benthic foraminiferal fauna distributions, transfer function SST reconstructions based on planktic foraminifer species counts and measurements of stable isotopes ($\delta^{18}O$, $\delta^{13}C$) in foraminiferal tests. Grain size analysis, IRD counts, clay mineral analysis and chemical analysis of bulk sediment carbon content were also used (Table 1). Additionally the relatively new paleothermometer, the Mg/Ca-ratio, was applied on planktic and benthic foraminifera to test and examine its applicability in Subarctic and Arctic environmental settings. The Mg/Ca-ratios were used to constrain reconstructions of sea surface and bottom temperatures. Furthermore, Mg/Ca-ratios combined with isotopic measurements performed on the same foraminiferal species were used for quantization of past oceanic salinity changes.

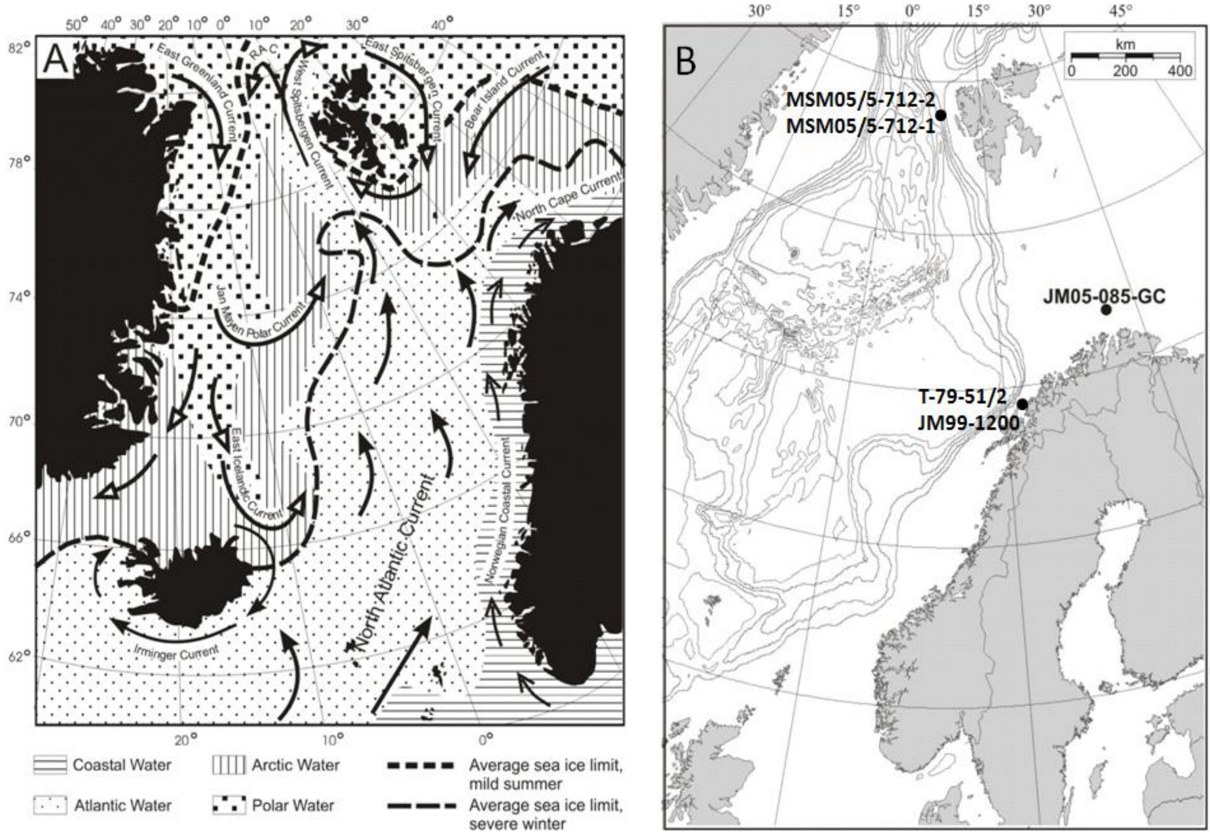

Figure 1. (A) Map of northern North Atlantic and adjoining seas showing major currents systems, oceanic fronts and sea ice limits modified from Mosby (1968), Hopkins (1991) and Marnela et al. (2008). (B) Core sites.

4. Study area and oceanographic setting

Warm and saline water masses of Atlantic origin enter the south eastern Nordic Seas primarily over the Iceland-Faroe ridge and through the Faroe-Shetland Channel (Hansen and Østerhus, 2000; Mauritzen et al., 2006). The water mass is topographically steered along the Norwegian shelf as the North Atlantic Current (NAC; T>2°C, S>35) (Swift, 1986) (Fig 1). The NAC bifurcates north of Norway into a zonal component and a meridional component. The zonal North Cape Current (NCaC; T > 3°C; S >34.9) flows eastward into the SW Barents Sea (Schauer et al., 2002). The meridional branch, the West Spitsbergen Current (WSC; T=3 to 7°C; S: 34.9 to 35.2), continues northward along the Barents Sea and west Spitsbergen slopes into the Arctic Ocean via the eastern part of the Fram Strait (Schauer et al., 2004) (Fig 1). The coastal regions of Norway are dominated by the Norwegian Coastal Current (NCC;

T=3 to 13°C, S=30 to 34) overlying the NAC in a westward, and the NCaC in a northward, thinning wedge with maximum thicknesses of 150 meters (Aure and Strand, 2001). In the western part of the Fram Strait the East Greenland Current carries cold and less saline waters southward (EGC; T: -1.7 to 0°C; S: 30 to 34) occupying the upper ca. 150 meters of the water column (Rudels et al. 2005). Landmasses adjacent to the meridional and zonal paths of the warm Atlantic Water (i.e. north western Europe and Scandinavia) generally experience a milder climate compared to landmasses at similar high latitudes elsewhere (i.e. Greenland). The topographically steered poleward transport of Atlantic Water is forced by a combination of different density gradients between water masses, wind stresses and tidal forces in the North Atlantic (Aagaard et al., 1985; Midttun, 1985; Broeker, 1991; Hurrell, 1995). In the Nordic Seas part of the advected Atlantic Water mass sinks because of the density increase caused by evaporation and cooling, and forms the NADW that is subsequently transported southward out of the Nordic Seas as a subsurface current overflowing the submarine sills between Greenland, Iceland and Great Britain (Broecker, 1991; Mauritzen et al., 2006).

5. Material and Methods

Three core sites, all situated under the axis of Atlantic Water inflow towards the Arctic, are investigated in the present thesis (Fig 1). Gravity-, piston-, box- and kastenlot corers were used to retrieve the sediment cores (Table 1). CTD (Conductivity, Temperature, and Depth) were measured before coring enabling comparisons to present day water masses.

5.1. Lithology

The kastenlot core MSM05/5-712-2 was lithologically described right after coring (Paper 3, 4). The gravity core JM05-085 was split longitudinally and lithological description was performed at the geological laboratory, University of Tromsø (Paper 1, 2). The split gravity core was x-rayed and x-radiographs were used to aid the lithological description by revealing internal structuring, bioturbation and clasts (Paper 1, 2). X-radiographs were furthermore used to identify grains >1mm which were considered IRD (Ice Rafted Debris) following Grobe (1987) (Paper 1, 2). The cores were sampled at different sample intervals from 1 to 10cm. The samples were freeze dried and wet sieved at >63µm, >100µm and >1mm fractions. The weight of the sediment samples were determined before and after freeze drying. Additionally all size fractions were weighed. The >1mm fraction was inferred as ice rafted debris (Vorren et al., 1983) (paper 3). The <63 µm fraction was analyzed on a

Micromeritics Sedigraph 5100 and relative silt (4-63 µm) and clay (<4 µm) fractions were determined (Paper 1, 2).

Table 1. Core location, geographical area, water depth, core length, proxies used in this study, investigated time intervals of the sediment cores. In addition references are made to previous studies of the cores.

Core id	Location	Latitude	Longitude	Water depth (m)	Core length (m)	New proxies used in this study	Studied time interval (Cal yr B.P)	Paper	Previous studies
JM99-1200	North Norwegian margin (Andfjorden)	69°15.95’ N	16°25.09’ E	476	11.12	Mg/Ca	11,600-14,000	4	(Ebbesen and Hald, 2004) (Knies et al., 2003)
T79-51/2	North Norwegian margin (Andfjorden)	69°18.00´ N	16°23.00´ E	505	3.45	Mg/Ca Isotopes	300-11,600	4	(Vorren et al., 1983) (Hagen, 1995) (Hald and Hagen, 1998)
JM05-085	SW Barents Sea	71°37.30’ N	22°55.05’ E	409	4.87	Fauna Isotopes TOC,TC Grain size/IRD Clay minerals	6,800-15,000 400-18,600	1 2	(Johannessen, 2006)
MSM05/5-712-2	West Spitsbergen slope	78°54.94’ N	06°46.03’ E	1487	9.5	Fauna Mg/Ca Isotopes TOC,TC Grain size/IRD	0-14,000 8,600-14,000	4 3	
MSM05/5-712-1	West Spitsbergen slope	78°54.94’ N	06°46.04’ E	1491	0.44	SIMMAX Mg/Ca	0-2000	5	

5.2. Chemical analysis

The weight percentages (wt.%) of total carbon (TC), total organic carbon (TOC) and calcium carbonate ($CaCO_3$) were determined at sample intervals from 1 to 6cm (Paper 1,3). TC and TOC were measured using a Leco CS 200 furnace. TC was measured on bulk sediment, while TOC was measured after the inorganic carbon was removed with HCl (10%) at room temperature (Espitalié et al., 1977). The $CaCO_3$ content was calculated using the equation: $CaCO_3 = (TC-TOC)*100/12$. Stable carbon isotope ratios of the organic matter ($\delta^{13}C_{org}$) were measured in decarbonated (10% HCl) bulk sediment samples (Paper 1). Subsequently the relative percentage of the marine vs. terrestrial organic carbon was determined using an end-member mixing model established for the Barents Sea (Knies and Martinez 2009) and northern Norwegian fjords (Knies et al., 2003).

5.3. Foraminiferal analysis

Faunal distribution and flux of planktic foraminifera is mainly controlled by environmental factors as water mass composition (i.e. temperature and salinity), food availability and sea ice coverage (e.g. Johannessen, et al., 1994; Carstens et al., 1997) (Paper 1, 3, 5). Foraminiferal analysis was conducted and relative species distribution was determined at sample intervals from 1 to 6 cm on material from the 100 µm to 1 mm size fraction (Meldgaard and Knudsen, 1979; Knudsen, 1998). Approximately 300 specimens were picked and identified per sample where possible and samples containing below 50 specimens were excluded. In paper 1 benthic foraminiferal fauna was qualitatively analyzed.

5.4. Stable isotope analysis ($\delta^{18}O$ and $\delta^{13}C$)

Stable oxygen and carbon isotopic ratios were measured on tests from planktic and benthic foraminiferal species from the >100 µm fraction (Paper 1, 3, 4). Oxygen isotope incorporation into foraminiferal tests is primarily governed by temperature and salinity of the ambient water mass (e.g. Spielhagen and Erlenkeuser, 1994). Incorporated carbon isotopes reflect the carbon isotopic ratio of the dissolved inorganic carbon (DIC) in the water mass which primarily is controlled by sources and sinks like ventilation and primary production (e.g. Katz et al., 2010). The isotope values of $\delta^{18}O$ and $\delta^{13}C$ were corrected for vital effects (e.g. Poole, 1994; Simstich et al., 1999; Jonkers et al., 2010). The $\delta^{18}O$ values were furthermore corrected for the ice volume effect accounting for low $\delta^{18}O$ ice stored mainly in terrestrial ice sheets (Fairbanks, 1989).

5.5. Trace element analysis

Trace element analysis was performed on planktic foraminiferal (*N. pachyderma*) (Paper 3, 4, 5) and benthic foraminiferal (*M. barleanus*) (Paper 4) tests. Pristine and clean specimens were picked from a narrow size range in order to minimize possible size-dependent bias, influence from post mortem dissolution and contamination (Brown and Elderfield, 1996; Elderfield et al., 2002; Barker et al., 2003). The planktic foraminifera were picked from the size fraction 150-212 µm (Paper 3, 4) and 100-150 µm (Paper 5), and the benthic foraminfera from 100-250 µm. Foraminiferal tests were crushed between glass plates exposing inner test chambers to the subsequent reductive (anhydrous hydrazine) and oxidative (H_2O_2) cleaning procedures (Boyle and Keigwin, 1985; Boyle and Rosenthal, 1996). Cleaned samples were analyzed by magnetic-sector singlecollector ICP-MS, on a Thermo-Finnigan Element2 at the Litmann Laboratory, University of Colorado. The trace element ratios Mg/Ca, Fe/Ca, Mn/Ca, Al/Ca, U/Ca, Zn/Ca, Sr/Ca, Cd/Ca, B/Ca and Li/Ca were simultaneously measured in the process. The Mg/Ca ratio in sea water is considered constant (Broecker and Peng, 1982). Temperature of the ambient sea water is considered to be the primary controlling factor on foraminiferal test Mg/Ca ratios (Lea et al., 1999). Studies have shown positive correlations between the Mg uptake and temperature (Elderfield and Ganssen, 2000; Kristjánsdóttir et al., 2007; Kozdon et al., 2009). Fe/Ca, Mn/Ca (Paper 3, 5) and Al/Ca (Paper 3, 4, 5) are used to identify post cleaning sample contamination (Barker et al., 2003).

5.6. Temperature and salinity reconstructions

Sea surface (SST) and bottom water temperatures (BWT) were reconstructed on the basis of Mg/Ca ratios in foraminiferal tests (Paper 3, 4, 5) using species specific temperature equations (Elderfield and Ganssen, 2000; Kozdon et al., 2009; Kristjánsdóttir et al., 2007). SST at 10 m water depth was also reconstructed using transfer functions (Pflaumann et al., 2003) (Paper 1, 3). Different statistical methods (Modern Analogue Technique (MAT), Weighted Average Partial Least Square (WAPLS) and the Maximum Likelihood Method (ML) were used when reconstructing the SST. The reconstruction was performed using the computer program C.2 version 1.3 (Juggins, 2002). In paper 5 the SIMMAX modern analog technique was applied on planktic foraminifer species counts (>150 µm size fraction) to calculate temperatures at 50 m water depth.

Tentative SST and BWT were calculated from stable oxygen isotopes ($\delta^{18}O$) values in foraminiferal tests (assuming constant $\delta^{18}O_{water}$) (Paper 1, 3) (Shackleton, 1974). Sea surface and bottom water stable oxygen isotope compositions (variable $\delta^{18}O_{water}$) were calculated on the basis of reconstructed temperatures and measured foraminiferal oxygen isotopes ($\delta^{18}O_{foram}$) utilizing the temperature equation of Shackleton (1974) (Paper 3, 4). After converting $\delta^{18}O_{water}$ from PDB to SMOW scale by adding 0.2‰, sea surface salinity (SSS) was reconstructed using mixing line equations that linearly relate $\delta^{18}O_{water}$ to salinity (e.g. Simstich et al., 2003) (Paper 3).

5.7. Chronology

Chronologies of sediment core records are based on accelerator mass spectrometry (AMS) radiocarbon date measurements. Test material from bivalves, benthic and planktic foraminifera was dated. Original and previously published AMS ^{14}C dates were converted to calibrated years using Calib version 6.0 (Reimer et al., 2005; Stuiver et al., 2005) and the marine calibration curve marine09 (Hughen et al., 2004; Reimer et al., 2009). In all calibrations a standard reservoir correction of 400 years was applied in addition to variable local corrections (ΔR; SW Barents Sea = 67±41; Eastern Fram Strait = 151 ± 51 (Magdalenafjorden); Andfjorden = 64±35). During Younger Dryas a reservoir age of total 600 ±50 years (ΔR=200±50) was applied to account for sea surface reservoir increases during this period (Bondevik et al., 2006). Age models were established by linear interpolation between the calibrated AMS ^{14}C dates using the mean of the 2σ interval of highest probability as tie points.

6. Summary of papers

Paper 1.

Aagaard-Sørensen, S., Husum, K., Hald, M. and Knies, J. (2010). Paleoceanographic development in the SW Barents Sea during the Late Weichselian-Early Holocene transition. *Quaternary Science Reviews*, 29**,** 3442-3456.

Atlantic Water transported into the SW Barents Sea via the North Cape Current has previously not been studied at high temporal resolution during the Late Weichselian - Early Holocene transition. Detailed temporal analysis has been hampered by scarcity of datable material in the Barents Sea region. However, the Ingøydjupet has acted as natural sediment trap leaving Late Glacial and Holocene sediments with well-preserved biological, geochemical, and physical paleoceanographic proxies also allowing carbon 14 dating of the core. The present study presents quantitative planktic and qualitative benthic foraminiferal assemblages, foraminiferal planktic and benthic $\delta^{13}C$ and $\delta^{18}O$ isotopes. Furthermore, grain size analysis and IRD counts were conducted and total carbon (TC), total organic carbon (TOC) and calcium carbonate ($CaCO_3$) were determined on the bulk sediment samples.

The Late Weichselian - Early Holocene variability of the North Atlantic Current has been studied with focus on the zonal component of this meridional transport during the transition from glacial to interglacial conditions. The investigated sediment core is from 409 m water depth in the SW Barents Sea. Eight Accelerator mass spectrometry (AMS) ^{14}C dates show that the core covers the last 20,000 cal yr B.P. with a centennial scale resolution during Late Weichselian – Early Holocene. Planktic foraminiferal assemblages were analyzed using the >100 µm size fraction and foraminiferal planktic and benthic $\delta^{13}C$ and $\delta^{18}O$ isotopes were measured. Furthermore, four time periods have been identified which represent the varying oceanographic conditions in Ingøydjupet, a glacial trough located off the north coast of Norway in the SW Barents Sea. 1) The late glacial (before ca.15,000 cal yr B.P.) influenced by the nearby ice sheets with high amounts of sea ice- or iceberg transported detritus. 2) The late Oldest Dryas stadial and the Bølling-Allerød interstadial (ca. 15,000 to 12,700 cal yr B.P.) with cold surface water conditions influenced by the collapse of the nearby ice sheets, high amounts of sea ice- or iceberg transported detritus and melt water and weak subsurface inflow of Atlantic Water. 3) The Younger Dryas cold stadial (12,700 to 11,650 cal yr B.P.) with low primary productivity and extensive sea ice cover and 4) The Preboreal and Early Holocene (11,650 to 6,800 cal yr B.P.) with strong influx of Atlantic Water into the area, near absence of ice rafted debris and generally ameliorated conditions in both surface and bottom water masses as seen from a high flux of foraminifera and increased marine primary production. After ca. 7,500 cal yr B.P. weaker influences of Atlantic water masses and north-eastward retreat of the Arctic Front, reflected by changes in the planktic foraminiferal distribution, signals the first step towards colder conditions in the SW Barents Sea.

Paper 2.

Junttila, J., Aagaard-Sørensen, S., Husum K. and Hald M., (2010)
Late glacial – Holocene clay minerals elucidating glacial history in the SW Barents Sea.
Marine Geology, 276**,** 71-85.

The overall goal of this paper is to advance knowledge on the onset of the deglaciation and subsequent advances/retreats of the ice streams in the Barents Sea during the deglaciation phase (cf. Andreassen et al., 2008). Three sediment cores located off the coast of northern Norway and in the Ingøydupet were investigated. All core sites were characterized by a relatively thick Late Glacial-Holocene sediment sequence. The sediments were studied in regards to relative clay mineral content (XRF), IRD content, magnetic susceptibility, density and grain-size distribution. The results show interaction and changes in the Fennoscandian – and Bjørnøyrenna ice sheets during the last deglaciation. High illite content and maximum kaolinite content (>18 700 cal yr B.P.) indicate glacial erosion from both Fennoscandian and Bjørnøyrenna ice sheets (LGM II). The occurrence of a *C. reniforme* dominated benthic foraminiferal assemblage (~18 700 cal yr B.P.) indicates that the northern most cores site in Ingøydjupet had already been deglaciated and was probably situated in a glacier distal environment. In addition, smectite content reaching its highest level concurrent with and the presence of *Neogloboquadrina pachyderma* (sin) dominated planktic foraminifera can be related to strengthening of the Atlantic Current and the inflow of the Atlantic Water maybe triggering the deglaciation for the Fennoscandian ice sheet (Bølling interstadial). A rapid increase in illite content reflecting strong melting of the Fennoscandian ice sheet (~15 000 cal yr B.P.) indicates the onset of deglaciation in core closer to the continent (Bølling). Decrease of illite and IRD contents together with the deposition of lamination in the sediments (15 000 to 14 000 cal yr B.P.) indicates colder conditions and formation of at least seasonal sea-ice (Older Dryas). Also, increased kaolinite content indicates increased glacial erosion of the Bjørnøyrenna Ice Stream. The highest values of the illite content and also increased IRD content (14 000 to 13 000 cal yr B.P.) can be related to strong melting of the Fennoscandian Ice Sheet (Allerød). Slight indication to the Younger Dryas cold spell is indicated by the decrease of illite and IRD contents. All clay contents are more stable during Holocene compared to LGM and the last deglaciation.

Contribution to paper 2:

The current writer carried out quantitative and qualitative analysis of planktic and benthic foraminifera for a selected interval of the sediment core (at ca. 380 to 360 cm core depth). The current writer also contributed to the development of the age models in addition to synthesizing the deglaciation and paleoceanographic evolution.

Paper 3.

Aagaard-Sørensen, S., Husum, K., Hald, M., Marchitto, T., Werner, K. and Spielhagen, R. in prep.: A Late glacial-early Holocene multiproxy record, Fram Strait, Polar North Atlantic.

Studies have shown that across the Late Glacial – Early Holocene transition (14,000 to 8,600 cal yr B.P.) large oceanographic changes occurred in the eastern Fram Strait. Quantification of Atlantic Water mass properties in high Arctic environments was done using traditional proxies alongside the relatively new proxy, the Mg/Ca-ratio paleo thermometer. This is the first time the Mg/Ca-ratio paleo thermometer has been tested in a high Arctic paleoceanographic setting. The combination of traditional proxies, including planktic foraminiferal assemblages (>100μm size fraction), foraminiferal planktic $\delta^{13}C$ and $\delta^{18}O$ stable isotopes (*Neogloboquadrina pachyderma*), grain size distribution and chemical analyses (TOC, TC, $CaCO_3$) show, that the proxy record correlates well to other previously published studies at the West Spitsbergen Slope. Therefore, the multiproxy record is considered a robust record for depicting paleoceanographic developments in the eastern Fram Strait. The Mg/Ca-ratios were measured on *N. pachyderma* and SSTs were subsequently reconstructed using the latest temperature equation from the Nordic Seas. The method provides new information on the variability of the sub surface temperature ($SST_{Mg/Ca}$) and in conjunction with stable oxygen isotope measurements also allows reconstruction of sub surface salinity (SSS) variability. The $SST_{Mg/Ca}$ and SSS reconstructions show values fluctuating between 1.9 to 5.5°C and 33.6 to 35.2, respectively. The results are used in combination with the other investigated well established proxies to interpret the paleoenvironmental development. From 14,000 to 10,300 cal yr B.P. cold polar sea surface conditions dominated and *N. pachyderma* dominated the planktic fauna. The period had extensive sea ice cover, iceberg transport and low surface temperatures resulting in low primary production. Atlantic Water inflow was reduced compared with the present day, but existed as a sub surface current. At ca. 10,500 cal yr B.P. Atlantic Water inflow increased and the Arctic Front retreated westward resulting in a large surface water temperature increase of ca. 5°C governed by the subpolar planktic foraminifer *Turborotalita quinqueloba* becoming dominant. Warm conditions prevailed in the uppermost water column until 8,600 cal yr B.P. The period had strong influence from Atlantic Water at the surface indicated by high sea surface temperatures, high foraminiferal fluxes, increased primary productivity and a near absence of ice rafted debris. Sub surface inflow of Atlantic Water continued with a modest average temperature rise of 0.5°C and salinity decrease of 0.4 compared to the previous periods.

Paper 4.

Aagaard-Sørensen, S., Husum, K., Hald, M., Marchitto, T. and Godtliebsen, F. in prep.: Atlantic Water influx in the Nordic Seas over the past 14.000 cal yr BP: Mg/Ca paleo temperature reconstructions.

The Mg/Ca paleothermometer has previously been used to reconstruct paleo temperatures for short time periods or at low temporal resolution in the Arctic and Subarctic settings. In the present study the temperatures of the Atlantic Water carried towards the Arctic by the North Atlantic Current and the West Spitsbergen Current over the past 14,000 cal yr B.P. have been reconstructed using Mg/Ca-ratios. SiZer analysis was used to identify periods of significant temperature change in the data sets at centennial to millennial time scale. The investigated sediment cores are located in outer Andfjorden, Northern Norway (69°18 N) and on the West Spitsbergen Slope, eastern Fram Strait (78˚54 N). The eastern Fram Strait Mg/Ca-ratios were measured on the planktic foraminiferal species *Neogloboquadrina pachyderma*. The Andfjorden Mg/Ca-ratios were measured on the benthic foraminiferal species *Melonis barleanus* and stable isotopes were measured on the benthic foraminiferal species *Cassidulina leavigata* in the Holocene part of the record. In the eastern Fram Strait no significant changes in sea surface temperatures ($SST_{Mg/Ca}$) are observed across the Late Glacial-Holocene boundary. A temperature decline initiating in the early Holocene culminated with lowest recorded averages at ~6,000 to 3,000 cal yr B.P. After 3,000 cal yr B.P. $SST_{Mg/Ca}$ gradually increased reaching the highest recorded values at the top of the record. In Andfjorden bottom water temperatures ($BWT_{Mg/Ca}$) at ~500 meters water depth showed strong influence from coastal waters during the deglaciation. Relatively high $BWT_{Mg/Ca}$ is recorded during the Bølling/Allerød followed by a decline in the Younger Dryas. $BWT_{Mg/Ca}$ and relative bottom water salinities (rel.BWS) increased markedly at 11,500 cal yr B.P. where Atlantic Water flushed the sea bed. $BWT_{Mg/Ca}$ and rel.BWS remained high and relatively stable throughout the rest of the Holocene with a small decrease identified at ca. 3,500 cal yr B.P.

Correlation to various proxy records representing forcing factors in the Arctic-Subarctic region reveal that the two records are governed by different mechanisms. The benthic record (Andfjorden) is influenced by late glacial ice sheet collapse and during Holocene show connection to the steadily declining insolation forcing. In contrast, no significant changes are observed in the planktic record (eastern Fram Strait) connected to the final deglaciation stages. However, throughout the Holocene the record indicates influence from and connection to the varying insolation and irradiation forcing while correlation to both varying NAO and NADW formation is observed.

Paper 5.

Spielhagen, R. F.,Werner, K., Aagaard-Sørensen, S., Zamelczyk, K., Kandiano,E., Budeus, G., Husum, K., Marchitto, T., and Hald, M. (2011): Enhanced Modern Heat Transfer to the Arctic by Warm Atlantic Water. *SCIENCE,* 331**,** 450-453.

The Arctic is responding more rapidly to global warming than most other areas on our planet. Northward-flowing Atlantic Water is the major means of heat advection toward the Arctic and strongly affects the sea ice distribution. Records of its natural variability are critical for the understanding of feedback mechanisms and the future of the Arctic climate system, but continuous historical records reach back only ~150 years. In this study a multidecadal-scale marine record covering the last 2000 years from West Svalbard was investigated. The site was strategically selected due to the position under the axis of Atlantic Water inflow to the Arctic Ocean. The temperature reconstruction of the Atlantic Water is based on two independent methods: (1) The SIMMAX modern analog technique applied on planktic foraminifer species counts yielding temperatures at 50 m water depth and (2) Mg/Ca measurements of the species *N. pachyderma* (sin). The investigation found that early 21st century temperatures of Atlantic Water entering the Arctic Ocean are unprecedented over the past 2000 years and are most probably linked to the Arctic amplification of global warming.

Contribution to paper 5:
The current writer carried out the full trace element analysis (Mg/Ca, Fe/Ca, Mn/Ca, Al/Ca) on the planktic foraminiferal species *N. pachyderma* (sin) and was responsible for the supplementary information concerning the trace metal analysis. Additionally, the current writer evaluated and interpreted the trace metal results and participated in the overall synthesis.

7.1. Synthesis

The present study used a multiproxy approach to elucidate paleoceanographic variability in the eastern and northern Nordic Seas and the Barents Sea during the Late Glacial – Holocene transition. Modern oceanography shows that Atlantic Water advection is the main transporter of salt and heat towards the north. The results from the present thesis indicate that Atlantic Water governed the foraminiferal fauna distribution in the past and exerted a large impact on the oceanographic environment. In order to improve the understanding of modern Arctic climate change it is necessary to understand the natural oceanographic system free of anthropogenic influences. Quantification of temperature and salinity of past water masses have been the aim for Arctic researches for decades. Therefore, the oceanic paleothermometer, Mg/Ca ratios measured on planktic and benthic foraminiferal shells, was applied to and tested on Subarctic and Arctic foraminiferal paleo fauna. Mg/Ca ratio analysis has not previously been conducted on long time series of foraminiferal fauna that lived in high northern latitudes.

The following main conclusions were reached on the basis of the presented results:

- Radiocarbon dating indicates an early deglaciation of Ingøydjupet, SW Barents Sea.

- Weak Atlantic Water influence was observed briefly at around 18,700 cal yr B.P. and after 15,000 cal yr B.P. in the SW Barents Sea (Paper 1 & 2). Influence from sub surface Atlantic inflow is observed from the beginning of the records at 14,000 cal yr B.P. in the eastern Fram Strait and in Andfjorden (Paper 3 & 4).

- The Atlantic Water influx was diminished during the Younger Dryas at all investigated core sites (Paper 1-4). Most pronounced hampering of Atlantic Water influx was observed in the SW Barents Sea where the sediments became barren of foraminifera and primary production was halted during the Younger Dryas.

- Planktic foraminiferal distributions indicate that strong inflow of Atlantic Water resulted in emergence at the surface during the glacial – interglacial transition. The emergence had a south-north time delay of ca. 1,000 years which probably can be ascribed to increasing influence from a lingering pool of sea-ice and melt water towards the north (Paper 1-4).

- Reconstructed temperatures of Atlantic Water entering the Arctic Ocean show a 2°C warming during the last ca. 100 years. This warming is unprecedented over the past 2000 years and is probably linked to the Arctic amplification of global warming (Paper 5).

- The Mg/Ca method proved its applicability in Arctic and Subarctic environments for both planktic and benthic foraminifera by generating realistic surface and bottom water temperatures, respectively (Paper 3, 4, 5). The Mg/Ca-ratio, representing an independent proxy for temperature was used in conjunction with stable oxygen isotopes measured in foraminiferal tests ($\delta^{18}O_c$), to reconstruct seawater oxygen isotope composition ($\delta^{18}O_w$). The combination of Mg/Ca ratios and oxygen isotopes was subsequently used to reconstruct past salinities of the ambient sea water. The applicability of the Mg/Ca method in cold environments was confirmed by realistic salinity estimates.

8. Evaluation of methods

Detailed analysis of sediment from three core sites under the influence of Atlantic Water were investigated in the present thesis. A range of biological, chemical and physical proxies were used to interpret the oceanographic development over the past ca. 14,000 years. Many of these proxies have frequently been utilized in studies of Subarctic and Arctic environments before. However, some of the proxies have inherent uncertainties attached that scientists relentlessly are trying to minimize.

Chronology

Dating of sediment cores is essential for paleo oceanographic studies in order to reconstruct the duration of past events and constrain the rates of change. Also, a robust chronology is vital when correlating different paleo records with each other. However, the marine reservoir age has changed through time and using a marine calibration curve prior to the Holocene has been questioned by the authors of the Marine09 calibration curve (Reimer et al., 2009). The authors emphasize that prior to the Holocene "tuning" to the Greenland ice cores and using tephra horizons and paleomagnetic tie-points may provide a more meaningful timescale than calibrated ^{14}C ages (Reimer et al., 2009). In a recent publication Jessen et al. (2009) show that characteristic patterns in magnetic susceptibility (MS) and lithology can be used for correlation on the western Svaldbard margin over the past 30,000 years. Expanding such work both spatially and temporally might provide a detailed and fast way to make a preliminary age model and subsequently via ^{14}C AMS dates further "tune" the results. In areas like the Barents Sea where datable material is scarce the method might prove especially useful.

Vital effect

Species specific vital effects applied to stable isotopes measured on foraminiferal tests are important when quantifying past water compositions. Studies have shown that the apparent vital effect may change between seasons (Jonkers et al., 2010) which might account for the inconsistent vital effect estimates published in the literature. Improving the vital effect estimates for both planktic and benthic foraminifera would greatly improve the capacity of using the stable isotopes for estimating past compositions of the water mass. Mixing lines are used to express the relation between $\delta^{18}O_w$ and salinity of specific water masses. Future development of specialized mixing lines representing narrower regions (i.e. the Fram Strait or SW Barents Sea) would improve the paleo salinity estimates. "Paleo" mixing lines tailored to represent deglacial conditions would also be an interesting addition in the paleo toolbox.

SST reconstruction: transfer function

Reconstruction of past sea surface temperatures can be achieved through relation of past planktic foraminiferal fauna distributions to modern distributions via a training set (Pflaumann et al., 2003). The training set used in the present thesis is based on planktic foraminiferal fauna compositions found in north Atlantic surface sediments with a sea surface temperature measured at 10 m water depth over the respective core sites (Pflaumann et al., 2003). However, planktic foraminifera live at ca. 10 to 300 meters below sea surface (e.g. Simstich et al., 2003). Therefore, geochemical analyses used for temperature reconstructions conducted on planktic foraminiferal test material (e.g. stable isotopes, trace metals) often record a temperature at deeper water depths creating an offset between reconstruction methods. Furthermore, the Pflaumann training set is based on fauna picked from the >150µm size fraction as opposed to the present faunal analysis conducted at the >100µm size fraction (Paper 1 & 3) (Pflaumann et al., 2003). Therefore the information stored in the smaller species that primarily (*T. quinqueloba*) or exclusively (*G. uvula*) are found in the <150 µm size fraction is missing in the Pflaumann training set which may bias the temperature reconstruction. Hald et al. (2007) found that the difference between size fractions in analysed samples (>100µm) and the training set (>150µm) might bias the result reconstructing temperatures that are ca. 1 to 2 °C too low for cold ocean temperatures (< 4°C).

Mg/Ca-ratios

Foraminifera incorporate Mg and Ca at varying relative ratios in their tests during their life cycle. The uptake ratio between Mg and Ca is primarily governed by the temperature of the ambient water mass (Elderfield and Ganssen, 2000; Kristjánsdóttir et al., 2007). In addition to temperature several other factors (e.g. salinity and pH) exert minor influence on the relative Mg/Ca ratio incorporated in foraminiferal calcite (Nürnberg et al., 1996; Lea et al., 1999). The thermodynamic control on the Mg uptake into foraminiferal calcite generates an exponential relation between temperature and Mg uptake. However, at narrow temperature ranges studies have shown that the relationship can be regarded as linear (Kristjánsdóttir et al., 2007; Kozdon et al., 2009). In paper 3 and 4 a linear relationship was assumed for *N. pachyderma* which lives in a narrow temperature range (Mg/Ca = 0.13 * T + 0.35; Kozdon et al., 2009). In paper 5 an exponential equation was used (Mg/Ca = 0.5 exp 0.10 T). The linear equation was developed from *N. pachyderma* found in Late Holocene sediment surface samples from the northern North Atlantic and the Nordic Seas (Kozdon et al., 2009). The exponential equation was developed from *N. pachyderma* found at high northern and southern latitudes (Nürnberg, 1995; Elderfield and Ganssen, 2000). For *M. barleaus* an exponential relationship was assumed suited for the species´ wider temperature acceptance (Mg/Ca = 0.658 ± 0.07 * exp(0.137 ± 0.020 * T) (Kristjánsdóttir et al., 2007) (Paper 4). This equation was developed on the basis of *M. barleanus* found in modern surface sediment samples from the west and north Iceland shelf and fjords (Kristjánsdóttir et al., 2007). Several equations relating Mg/Ca uptake to ambient water temperature in both *N. pachyderma* and *M. barleanus* were tested against the present data sets (e.g. Nürnberg, 1995; Elderfield and Ganssen, 2000; Lear et al., 2002; Elderfield et al., 2006; Kristjánsdóttir et al., 2007; Kozdon et al., 2009). The results were scrutinized and the most appropriate equations were utilized in the papers. The different areas where the faunas live, that formed the basis for the temperature equations, were also taken into account.

Further complications when using Mg/Ca ratios as paleothermometers are contamination and dissolution of the foraminiferal test material (Dekens et al., 2002; Barker et al., 2003). Contamination in samples, especially from high latitudes is a major concern when using the Mg/Ca method. This is because low foraminiferal Mg/Ca ratio values (because of low temperatures) increase the relative impact of contaminators on the measurements. Dissolution of foraminiferal tests after deposition has been found to lower the Mg/Ca ratios (Dekens et al., 2002). Therefore, when analysing Subarctic and Arctic foraminifera, care must be taken during the picking procedures to select pristine specimens unaffected by dissolution. Concurrently, specimens that are clearly contaminated with overgrowths or have chambers filled with foreign material should be avoided. Two different cleaning methods are commonly used when preparing foraminiferal test material for trace element analysis, the “Mg cleaning’’ (Elderfield and Ganssen, 2000) and the ‘‘Cd cleaning’’ (Boyle and Keigwin, 1985). The ‘‘Cd cleaning’’ is used in the present study since it utilizes an additional reductive step in the cleaning procedure aiming at removing Mn-Fe-oxide coating (Barker at al., 2003). However, the additional step lowers the overall Mg/Ca output by up to 10-15% which must be taken into account when analyzing the data (Barker et al., 2003).

9. Future work

The trace element analysis of benthic and planktic foraminifera over the past 14,000 years was focused on the paleo thermometer, the Mg/Ca–ratio, and the contaminant indicators (Fe/Ca, Mn/Ca and Al/Ca ratios) (Paper 3, 4, 5). Increasing the sample resolution of the Mg/Ca data sets would allow a more detailed analysis of the paleoceanographic changes. Increased sample resolution would also increase the possibility of detecting recurrent Holocene oceanographic variability via application of spectral analysis which is not possible at the present resolution (Paper 4). In addition, increased resolution of Mg/Ca ratios of cores JM99-1200 and MSM05/5-712-2 would permit better correlation to climate forcing factors and feedback mechanisms. The successful application of the Mg/Ca paleothermometer (Paper 3, 4, 5) holds a great potential for future investigations in Arctic and Subarctic environments, not least due to the small amount of material needed for trace metal analysis. Reliable results may be obtained on samples smaller than 10 µg $CaCO_3$ (postcleaning mass) (Marchitto, 2006). This is particularly helpful in areas like the Barents Sea where pre Holocene sediments hold limited amounts of foraminifera. Thus, application of the Mg/Ca analysis to foraminifera derived from sediments in proximity to the retreating Svalbard–Barents Sea ice sheet could be possible. If successful, the Mg/Ca method (alongside oxygen isotope measurements) could provide quantitative reconstruction of ocean temperature and salinity before, during and after collapse of a marine based ice sheet. The knowledge gathered from such analysis might improve the understanding of the processes governing collapse of marine based ice sheets and aid the prediction of future development in the Antarctic region. Although the Mg/Ca method has proven to be a robust proxy of temperature and salinity, it can still be improved. Preliminary investigations of the benthic foraminifera *Melonis barleanus* show that trace metal incorporation vary between three observed phenotypes (Slim, Transitional and Fat) (unpublished data, Jennings et al.). Additional work expectantly will confirm the division of *M. barleanus* into three phenotypes possibly with different stable isotope and trace metal incorporation capacities. Thereby use of this common species and its phenotypes will be improved in future Arctic/Subarctic paleo studies.

Mg/Ca and stable isotope analyses were performed on the planktic foraminiferal species *N. pachyderma* (sin) at different size fractions. In paper 1 and 3 stable isotopes were analyzed on specimens from the 100-1000 and 150-250 µm size fractions, respectively. In paper 3 and 4 the Mg/Ca ratios were measured on specimens from the 150-212 µm size fractions, and in paper 5 this analysis was carried on the 100-150 µm size fraction. Different test sizes might relate to different water depths, different levels of sea-ice cover, specific water densities, varying food availability and/or the season of calcification (e.g. Volkmann, 2000; Simstich et al., 2003; Schiebel et al., 2005; Jonkers et al., 2010). In order to better constrain the variability of the temporal, spatial and nutritional properties of the past water masses different foraminiferal test size fractions and several different species from each sample should be analyzed. This would also increase the robustness of the proxy.

During trace metal analysis a range of other trace element ratios, apart from Mg/Ca, Fe/Ca, Mn/Ca and Al/Ca, were measured synchronously: Li/Ca, B/Ca, Zn/Ca, Sr/Ca, Cd/Ca and U/Ca (Paper 3, 4, 5). Recent studies show the connection of these (and other) element ratios to different aspects of the ambient water mass including temperature, salinity, nutrition levels, pH, carbonate saturation state etc. Correlating between these additional trace element data and other proxy data obtained from the sediment cores might reveal new Arctic paleo proxies (Paper 3, 4, 5). Possible discoveries subsequently should be confirmed by core top studies and/or laboratory culture experiments.

It is also necessary to develop more correct and robust transfer functions for Subarctic and Arctic regions. Currently new transfer functions based on a new training set (>100µm size fraction) are being developed (Husum et al., in prep). This work will make interpretations of Arctic and Subarctic paleoceanographic changes and reconstruction of past (sub) sea surface temperature more accurate.

Analysis of the novel paleo proxies/biomarkers IP_{25} (produced by sea-ice-associated diatoms) and brassicasterol (open-water phytoplankton) (Belt et al., 2007; Müller et al., 2009) have been conducted on bulk sediment form core JM05-085-GC (Paper 1 & 2) (Massé, unpublished data). The preliminary results indicate that change in the biomarker concentrations can be correlated to other paleoproxies thereby strengthening the interpretation of ice-covered/ice-free periods during the Late Glacial/Holocene transition in the SW Barents Sea (Massé, unpublished data). IP_{25} and brassicasterol analysis conducted on the sediments from the West Spitsbergen Slope (Paper 3) would strengthen the interpretations of the observed changes and improve the applicability of the Mg/Ca method in Arctic environments.

One of the original tasks of the present thesis was to identify a possible seesaw effect between the two Atlantic Water end-member branches, North Cape Current vs. West Spitsbergen Current. This was however not accomplished. Assessing the variation of the relative current speeds through a methodical analysis of the sortable silt sediment fraction (Hass, 2002) in the Fram Strait and SW Barents Sea cores would improve the possibility for successful identification of the oceanic seesaw pattern.

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