Paleoceanography and paleoclimate in the Nordic Seas and the northern North Atlantic during the last 22 000 years

A study based on oxygen isotopes and Mg/Ca ratios in foraminifera

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Bergen, May 2006

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CONTENTS

OVERVIEW

Abstract

The paleoceanography of the Nordic Seas and the northern North Atlantic during glacial and deglacial times was studied, using oxygen isotopes and Mg/Ca of foraminifera. The specific objectives are listed below:

1) Sea surface temperatures (SST) during the Last Glacial Maximum (LGM, ~20 000 years ago) were reconstructed, using oxygen isotopes of the planktonic foraminifer *Neogloboquadrina pachyderma* (sinistral).

2) The LGM climate (air temperatures, precipitation/moisture, air pressure, wind systems) was simulated, using the SSTs produced under Objective 1 as boundary conditions.

3) Mg/Ca ratios of *N. pachyderma* (sin.) were tested to see if they could be used to make surface/subsurface temperature estimates in the Nordic Seas for previous times.

4) Water mass exchanges between the North Atlantic and the Nordic Seas through the period 22 000 - 6000 years ago were studied. This period covers the LGM, the last deglaciation and the recent interglacial (Holocene). Benthic oxygen isotopes were used as the main proxy, supported by benthic carbon isotopes and planktonic oxygen isotopes.

The results are presented in four papers. These papers form the main part of this thesis. Three papers represent the analytical work that I have had the main responsibility for. A fourth paper is included in which paleodata worked out in this thesis have been used as boundary conditions in an LGM modelling simulation. The papers are:

Paper 1: Meland MY, Jansen E, Elderfield H (2005) Constraints on SST estimates for the northern North Atlantic/Nordic Seas during the LGM. Quaternary Science Reviews 24: 835-852

Paper 2: Byrkjedal Ø, Kvamstø NG, Meland MY, Jansen E (2006) Sensitivity of last glacial maximum climate to sea ice conditions in the Nordic Seas. Climate Dynamics 26: 473-487

Paper 3: Meland MY, Jansen E, Elderfield H, Dokken TM, Olsen A, Bellerby RGJ (2006) Mg/Ca ratios in the planktonic foraminifer *Neogloboquadrina pachyderma* (sinistral) in the northern North Atlantic/Nordic Seas. Geochemistry Geophysics Geosystems 7: Q06P14, doi:10.1029/2005GC001078

Paper 4: Meland MY, Dokken TM, Jansen E, Hevrøy K (in prep) Water mass properties and exchange between the Nordic Seas and the northern North Atlantic during the period 22-6 ka: benthic oxygen isotope evidence. Manuscript in preparation

1. Introduction

The circulation regime in the Nordic Seas strongly influences the climate of the surrounding continents. The inflow of warm Atlantic upper water into the Nordic Seas, the open-ocean convection in the central Nordic Seas, and the returning overflow across the Greenland-Scotland Ridge, make up the northern parts of the Atlantic Meridional Overturning Circulation (AMOC) (Figure 1). In the Nordic Seas region this circulation provides winter air temperatures of 10-20˚C warmer than the global mean of locations at similar latitudes (Drange et al. 2005).

Past variations in this current system, reflected in the water mass properties, may have resulted in major short-term and long-term climate changes in the Northern Hemisphere at glacial and deglacial times (Broecker 1991; Rahmstorf 2002). To understand how the water mass properties, both in the Nordic Seas and the North Atlantic, have changed in the past, is therefore of significant importance. By using stable (oxygen and carbon) isotopes and Mg/Ca ratios of planktonic and benthic foraminifera, this thesis aims to increase the knowledge on how the oceanography of the Nordic Seas and the North Atlantic has varied through the last 22 000 years.

2. Motivation and background

This study is based on four papers. The motivation for writing these papers is summarised below.

Paper 1 focuses on SSTs during the LGM, using oxygen isotopes of the planktonic foraminifer *N. pachyderma* (sin.). The motivation was the SST reconstruction of CLIMAP (1981). The CLIMAP reconstruction concluded that the Nordic Seas were perennially sea-ice covered. These studies were based on planktonic foraminiferal transfer functions, carbonate minima and stable isotope stratigraphy. However, newer evidence indicates seasonally open water (Hebbeln et al. 1994; Wagner and Henrich 1994; Weinelt et al. 1996). Thus, there was a need for a new and updated reconstruction of the LGM SSTs for the Nordic Seas. In the years after CLIMAP (1981), several SST reconstructions were performed, but they all more or less fail in the colder, high latitude Nordic Seas. These proxies include planktonic foraminiferal transfer functions (Pflaumann et al. 1996), dinocysts (de Vernal et al. 2000) and alkenones (Rosell-Melé and Comes 1999).

Paper 2 is a climate modelling study, which aims to simulate the LGM climate (air temperatures, precipitation, air pressure, wind systems). The SSTs produced in Paper 1 are used as boundary conditions.

of sea-ice in the North Atlantic gives positive local responses in temperature, precipitation and a reduced sea level pressure. The responses are highest during the winter season. During summer, the amount of sea-ice seems to be of less importance. Intensified winter storm tracks in the LGM_N implies a potential for transporting moisture to the Fennoscandian and Barents Ice Sheet, giving ice growth as suggested by Boulton (1979), Elverhøi et al. (1995) and Mangerud et al. (2002). The growth clearly requires a strong source of precipitation and a component of meridional transport. Zonal circulation, which is the result obtained using the CLIMAP (1981) reconstruction as boundary conditions, seems to provide too little winter precipitation to feed rapid growth of ice sheets in the northern portion of the Nordic Seas.

The most important changes happen during the winter season. The winter-SST reconstruction in this work is only an approximation from the summer SST-reconstruction (Paper 1), assuming that the seasonal range of SSTs is the same for a given temperature as those at present in the area. They may, in fact, have been different during the LGM. The winter sea-ice edge, crucial for important climate dynamics, may thus have had a slightly different location. However, since the orbital configuration during the LGM was approximately the same as the modern, the LGM seasonal differences are unlikely to be very different from the modern ones.

Another issue is that the calcification of *N. pachyderma* (sin.) may have occurred slightly deeper than the surface. If this is correct, the SSTs for August were slightly warmer, possibly by 1-2˚C. Since a seasonal range of SSTs are used, this summer SST increase will automatically increase the winter-SSTs, bringing the sea-ice edge northwards and closer to the Fennoscandian and Barents Sea ice sheets. This may bring more moisture to these ice sheets, favouring rapid growth of glacial ice here. However, as discussed in Paper 1, if the upper water masses were of the Arctic Surface Water type (ASW), calcification probably occurred near the surface during the peak summer. We do not anticipate large changes compared to the winter-SST reconstruction used in this work.

Paper 3:
Meland MY, Jansen E, Elderfield H, Dokken TM, Olsen A, Bellerby RGJ (accepted) Mg/Ca ratios in the planktonic foraminifer Neogloboquadrina pachyderma (sinistral) in the northern North Atlantic/Nordic Seas. G-cubed: accepted for publication

This paper describes and interprets results from Mg/Ca core top calibration in the Nordic Seas, in addition to Mg/Ca results for the LGM and a low-resolution downcore study covering the Younger Dryas-Early Holocene transition, the LGM, and a period partly synchronous with the Greenland Interstadial 2. The core top Mg/Ca ratios do not reflect the modern oxygen isotope calcification temperature gradient from 2˚C in the northwest to 8˚C in the southeast. In ASW and Polar Water (PW) the Mg/Ca ratios are ~0.4 mmol/mol higher than expected from the calibrations of Nürnberg (1995) and Elderfield and Ganssen (2000). Also during the LGM the Mg/Ca ratios are elevated in this area compared to what is expected. In the Eastern Norwegian Sea and the northern North Atlantic the Mg/Ca based paleotemperatures for the LGM show similarities with the oxygen isotope based temperatures in Paper 1.

The elevated Mg/Ca ratios in the core tops and the LGM time slices are located in areas with low sedimentation rates (<~5 cm/kyr). Possible factors that may cause the unexpected high ratios may include bioturbation, Holocene variability in old core tops, dissolution, pore water chemistry, occurrence of volcanic ash, and other natural variability. In areas with high sedimentation in the Nordic Seas it looks like that the Mg/Ca ratios fall at or close to existing temperature equations (regarding data from this paper and unpublished data from Birgitte Nyland).

In the Faeroe-Shetland area, with high sedimentation rates, high Mg/Ca ratios are moderately correlated with low oxygen isotope values (core MD99-2284). During the cold Younger Dryas time interval, the low oxygen isotope values possibly contain a fresh water signal. This observation implies that fresh water may increase the Mg/Ca ratios, which suggests that Mg/Ca ratios may be indirectly influenced by salinity in a way similar to the foraminiferal oxygen isotopes. The elevated ratios in the core tops are also related to the presence of fresher and colder water masses (ASW and PW), combined with low seawater carbonate ion concentration (CO_3^{2-}), alkalinity and pH. These secondary factors may also influence the foraminiferal shell geochemistry.

Further, the paper explores different reasons for potentially disturbed Mg/Ca ratios, e.g. possible sediment contamination, Mg/Ca of the seawater and different degree of dissolution, and more or less excludes these factors. Based on the present knowledge, it is hard to define what factors influence the Mg/Ca ratios, with confidence.

Paper 4:
Meland MY, Dokken TM, Jansen E, Hevrøy K (in prep.) Water mass properties and exchange between the Nordic Seas and the northern North Atlantic during the period 22-6 ka: benthic oxygen isotope evidence. Manuscript in preparation

This paper aims to study the characteristics of the intermediate and deep waters in the Nordic Seas and the North Atlantic, and water mass exchanges between these oceans during the LGM, the last deglaciation and the first half of the Holocene.

Benthic foraminiferal oxygen isotope records from 21 cores were used to distinguish different water masses. Low benthic oxygen isotope values in the Nordic Seas were attributed to cold periods with brine-release and sinking of water during sea-ice freezing along the continental margins in the Nordic Seas.

During the LGM (22-19 ka), brine formation allowed dense water to sink to depths below 1500 m in the Nordic Seas. Above 1500-1800 m, the water mass consisted mainly of Glacial North Atlantic Intermediate Water (GNAIW), made by open-ocean convection in the Nordic Seas. This water mass possibly crossed the Greenland-Scotland Ridge, and entrained intermediate water in the North Atlantic, and probably also deepwater there to at least ~3700 m.

For the Early Deglaciation (ED, 19-15 ka), low benthic oxygen isotope values from cores located at intermediate water depths in the Nordic seas indicate intensive brine formation. This event was also partly seen in a low-amplitude fashion at deeper depths in the North Atlantic. The bottom waters formed by brine formation in the Nordic Seas were thus able to cross the Greenland-Scotland Ridge, penetrating the deeper water masses in the North Atlantic.

An event of brine formation also occurred during the Younger Dryas (YD, 13-11.5 ka), but not as intensively as during the Early Deglaciation. The overall high benthic carbon isotope values ($\delta^{13}C_b$) indicate at least some open-ocean convection and an ongoing AMOC. However, NADW with modern characteristics was apparently less present in the North Atlantic south of 40˚N than today, indicated by high $^{231}Pa/^{230}Th$ ratios (McManus et al. 2004; Gherardi et al. 2005), suggesting that open-ocean convection and meridional overturning was significantly weakened in the Nordic Seas. The high epibenthic $\delta^{13}C_b$ values may instead be caused by high $\delta^{13}C$ values in the sea surface, which is then transported to intermediate and deepwater masses through at least some sinking/convection. The high epibenthic $\delta^{13}C_b$ values during the YD may thus be due to some circulation, but not as strong as during warmer periods.

A finding of this study is that brine formation with corresponding intermediate and deep-water formation in the Nordic Seas may have contributed to and maintained an AMOC during cold periods like the ED and the YD, although weaker than today. This circulation may have maintained a net salinity flux to the north and was possibly an important mechanism enabling rapid shifts to warm conditions in the Bølling-Allerød (15-13 ka) and the Holocene. This is in agreement with Dokken and Jansen (1999), who suggested that a similar mechanism explained the rapid warmings from stadials to interstadials during the last glacial period.

During the Bølling-Allerød (15-13 ka) and the Early/Mid Holocene (11.5-6 ka) the benthic oxygen and carbon isotope values are high, indicating an AMOC with similar strength as today. During parts of the Mid Holocene (8-6 ka) the benthic oxygen isotope values in the Nordic Seas are even higher than for the last 5 ka, indicating a lower influence of brine than today. This reduced brine influence may be due to a warmer climate and less sea-ice formation in the Barents Sea compared to the Modern.

4. Discussion and topics for future work

In this thesis several aspects about the climate system in the Nordic Seas and the northern North Atlantic during periods of glacial and deglacial times are addressed, using oxygen isotopes and Mg/Ca ratios of foraminifera. The importance of an ocean free of sea-ice as a moisture source for rapid growth of huge ice sheets during the LGM is expounded (Paper 1 and 2). Paper 3 indicates that Mg/Ca in foraminiferal calcite is not mature as a reliable temperature proxy in the cold and low-sedimentation regimes of the Greenland and Iceland Seas. The Mg/Ca method should also be used with care in eastern and warmer parts of the Nordic Seas, since secondary factors cannot be ruled out. In Paper 4 it is shown that brine release induced by sea-ice formation probably was important for the formation of intermediate and deep water in the Nordic Seas during cold deglacial periods. These water masses probably overflowed the Greenland-Scotland Ridge. Thus, an active AMOC may have existed more or less continuously during glacial, deglacial and interglacial periods, although with variable strength. Sea-ice formation and brine-enrichment probably contributed to intermediate and deepwater formation during the LGM, ED and YD cold periods. Open-ocean convection was more vigorous during the Bølling-Allerød and Holocene warmer periods.

Several observations are only described briefly, and have the potential to be investigated further. An important challenge has been to find reliable proxies for upper ocean temperatures in the high-latitude Nordic Seas. I conclude that planktonic oxygen isotopes may currently be the best proxy for estimating/ constraining such temperatures in the Nordic Seas (Paper 1), even though foraminiferal oxygen isotopes are also influenced by salinity (Craig and Gordon 1965; Shackleton 1974). Mg/Ca ratios of *N. pachyderma* (sin.) do not seem to constrain the temperature signal as well as the oxygen isotopes, and cannot, therefore, be used as an independent temperature proxy for this species (Paper 1 and 3), at least not in colder waters of the region.

There are uncertainties related to a potential vital effect of oxygen isotopes in *N. pachyderma* (sin.), which are not yet sufficiently constrained. These uncertainties complicate the use of oxygen isotopes as a temperature proxy. In my calculations, I did not use any vital effect. If a vital effect of 0.6 is used for *N. pachyderma* (sin.), as suggested by Simstich et al. (2003) and Nyland et al. (in press), it implies that the oxygen isotope temperatures of Paper 1 should be 2-3˚C lower. However, this indicates calcification depths of *N. pachyderma* (sin.) of below 500 m northeast of Iceland, which we find unlikely In addition, the LGM oxygen isotopes may with a vital effect of 0.6 imply a more prevalent (permanent?) sea-ice cover, which we also find unlikely, based on studies in Paper 1. Even if we feel that a vital effect of 0.6 is too high, it is still important to better constrain the vital effect of *N. pachyderma* (sin.) and other species. Further, if the vital effect varies depending on the water mass, it will be very difficult to constrain calcification temperatures and calcification depths with recent knowledge. Laboratory culture experiments and more extensive sampling of live specimens by plankton tows may help to solve this issue.

Paper 2 shows that winter sea-ice conditions are crucial for climate modelling, implying that proxies for winter-SSTs and sea-ice conditions are important to constrain. In this paper we have reconstructed winter-SSTs from the summer-SSTs in Paper 1, based on an assumption that the seasonal differences between the summer and winter seasons during the LGM was approximately the same as today. Since the orbital configuration has not significantly changed between these periods, it may not have profound implications. However, one should keep in mind that the winter-SST shown in Paper 2 is only an approximation from the assumption that *N. pachyderma* (sin.) build their shells near the surface during summer.

Problems occur in using Mg/Ca in *N. pachyderma* (sin.) as a temperature proxy, especially in the colder and low-sedimentation areas of the Nordic Seas, composed of ASW and Polar Water (PW). In the warmer areas further east and south, with higher sedimentation rates, the Mg/Ca ratios seem to fall close to and below previously published Mg/Ca calibrations. An ongoing core top calibration in a high-sedimentation-rate transect north of the Faeroe Islands, indicates that the temperature signal is at least partly reflected in Mg/Ca ratios of *G. bulloides* and *N. pachyderma* (sinistral and dextral) (unpublished data from Birgitte Nyland). The temperature signal is here also reflected in the ASW. Consequently, sedimentation rates may, for some reasons, indirectly influence the foraminiferal Mg/Ca ratios, possibly through factors as pore water chemistry, diagenesis and bioturbation (Paper 3).

To get better confidence about the reliability of Mg/Ca as a temperature proxy in the upper ocean of the Nordic Seas, laboratory culture experiments of planktonic foraminifera, especially *N. pachyderma* (sinistral), should be performed, and tested against a range of temperatures, salinities, CO_3^{2-}, alkalinities, pH etc. Even though culture experiments are performed under artificial conditions, they have the advantage of giving an independent insight into how foraminiferal Mg/Ca ratios may vary against different factors under controlled conditions in a cold-water regime. Also, with culture experiments an eventual vital effect from the oxygen isotopes of *N. pachyderma* (sin.) may be better constrained. As long as the calcification depth and season of planktonic foraminifera are not well known, as well as the uncertainty of an oxygen isotope vital effect, it is difficult to make a core top Mg/Ca-temperature-calibration in this area (Paper 3).

Another issue is that the core top ages are not well known. In the core tops from areas with low sedimentation rates, there is a low percentage of rose bengal stained foraminifera, indicating that only few foraminifera represent modern conditions (Paper 3). Bioturbation is interpreted to be of significant importance where sedimentation rates are below ~15 cm/ka (Anderson 2001). This also has implications for the benthic oxygen isotopes in Paper 4. Since bioturbation may smooth signals, there is a possibility that, for instance, low benthic $\delta^{18}O$ values in some cores might be even lower. Bioturbation should, therefore, be kept in mind when studying cores from low-sedimentation regimes.

Reconstruction and synchronisation of climatic events from different ocean regimes requires a well-constrained age model. Potential errors in reservoir age through time and at different locations make difficulties constraining the age, even when the spatial coverage of AMS ^{14}C is high (Paper 4). Through parts of the deglaciation, it may occur that some of the age models are several hundreds of years "too old". This will also have implications for the deglaciation, where even small changes in the age model will influence the ice-volume correction of the oxygen isotopes. The Younger Dryas Chronozone is found to have an approximate reservoir age of 700 years, based on AMS ^{14}C-datings close to the well-dated Vedde Ash Layer (Austin et al. 1995). This increased age may be due to less ventilation. If this is true, an even higher reservoir age may have occurred in previous parts of the deglaciation, in accordance with e.g. Hagen (1999) and Waelbroeck et al. (2001). There is not yet any consistent data set available for the various regions and water depths for interpreting extended reservoir ages. Therefore, I consequently used the calculated global reservoir age in Calib 5.0 (Stuiver and Reimer 1993), averaging about 400 years. An exception is the Younger Dryas time interval, where a reservoir correction of 700 years was used. More studies on estimating the reservoir age through time and horizontal/vertical geographical location should be performed.

Another question is: do the extremely lowered $\delta^{18}O_{b\text{-}ivc}$ values during the ED and the YD partly represent a temperature increase of intermediate and deepwater masses? Other geochemical proxies, for instance benthic foraminiferal Mg/Ca ratios, may be able to produce temperature estimates in the range of -1 to +5°C. In this case, the temperature signals can be sorted out from the $\delta^{18}O_{b\text{-}ivc}$ values with larger confidence.

Other geochemical proxies, including $^{231}Pa/^{230}Th$ in the sediment and Cd/Ca of benthic foraminifera, may support the interpretation of the bottom water properties and the strength of meridional overturning in the Nordic Seas.

5. Authorship statement

Several persons have contributed with valuable and helpful information in the papers presented in this thesis. Except one paper, I have been responsible for the scientific approach and writing of the papers. A detailed authorship statement follows below:

Paper 1

All stable isotope data were produced previously by several people (see Table 1 in the paper for references). I produced the Mg/Ca data in Henry Elderfield´s laboratory at the University of Cambridge, UK. I wrote the paper, based on ideas that developed through discussions with Eystein Jansen. Henry Elderfield contributed with discussions about the Mg/Ca part of the study.

Paper 2

The modelling study and the writing of the paper was performed by Øyvind Byrkjedal. Nils Gunnar Kvamstø, Eystein Jansen and I contributed with planning and discussion of the paper. I contributed the SST data used as boundary conditions for modelling. The summer SSTs were also published in Paper 1. The winter-SSTs were made by me, using the approach described in Paper 2. Eystein Jansen and I also contributed with the background information and motivation, explained in Section 1 (Introduction) in this paper.

Paper 3

I produced all Mg/Ca data shown in this work, except some of the data in Figures 3b-c, which were published in Nürnberg (1995). The Mg/Ca data I produced in Henry Elderfield´s laboratory at the University of Cambridge, UK. Trond Dokken produced the oxygen isotope record of core MD99-2284, shown in Figure 5 in this paper. Are Olsen and Richard Bellerby contributed with data for the seawater carbonate chemistry. Through data analyses and discussions they also contributed with important information how this chemistry may potentially influence the foraminiferal Mg/Ca. I wrote the paper, with inputs and suggestions from Eystein Jansen, Henry Elderfield, Trond Dokken, Are Olsen and Richard Bellerby.

Paper 4

Most stable isotope data were produced previously by several people (see Table 1 in the paper for references). Trond Dokken and Kjersti Hevrøy produced the unpublished stable isotope data. I wrote the text. The paper improved through several discussions with Trond Dokken and Eystein Jansen.

References

Anand P, Elderfield H, Conte MH (2003) Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap series. Paleoceanography 18: doi:10.1029/2002PA000846

Anderson DM (2001) Attenuation of millennial-scale events by bioturbation in marine sediments. Paleoceanography 16: 352-357

Austin WEN, Bard E, Hunt JB, Kroon D, Peacock JD (1995) The ^{14}C age of the Icelandic Vedde Ash: Implications for Younger Dryas marine reservoir age corrections. Radiocarbon 37: 53-62

Boulton GS (1979) Glacial history of the Spitsbergen archipelago and the problem of a Barents Shelf ice sheet. Boreas 8: 31-57

Broecker WS (1991) The great conveyor belt. Oceanography 4: 79-89

CLIMAP (1981) Seasonal reconstruction of the Earth´s surface at the Last Glacial Maximum. Map Chart Series MC-36

Craig H, Gordon LI (1965) Deuterium and Oxygen 18 Variations in the Ocean and the Marine Atmosphere. In: Tongiorgi T (ed) Stable Isotope in Oceanographic Studies and Paleotemperatures. Cons. Nazional Rich. Lab. Geol. Nucl., Pisa, Italy, pp 9-130

de Vernal A, Hillaire-Marcel C, Turon J-L, Matthiessen J (2000) Reconstruction of sea-surface temperature, salinity, and sea-ice cover in the northern North Atlantic during the last glacial maximum based on dinocyst assemblages. Canadian Journal of Earth Sciences 37: 725-750

Dekens PS, Lea DW, Pak DK, Spero HJ (2002) Core top calibration of Mg/Ca in tropical foraminifera: Refining paleotemperature estimation. Geochemistry Geophysics Geosystems 3: 10.1029/2001GC000200

Dokken T, Jansen E (1999) Rapid changes in the mechanism of ocean convection during the last glacial period. Nature 401: 458-461

Drange H, Dokken T, Furevik T, Gerdes R, Berger W, Nesje A, Orvik KA, Skagseth Ø, Skjelvan I, Østerhus S (2005) The Nordic Seas: an overview. In: Drange H, Dokken T, Furevik T, Gerdes R, Berger W (eds) The Nordic Seas: An integrated perspective. AGU Monograph 158, American Geophysical Union, Washington DC, pp 1-10

Elderfield H, Ganssen GM (2000) Past temperature and $\delta^{18}O$ of surface ocean waters inferred from foraminiferal Mg/Ca ratios. Nature 405: 442-445

Elverhøi A, Andersen ES, Dokken T, Hebbeln D, Spielhagen RF, Svendsen JI, Sørflaten M, Rørnes A, Hald M, Forsberg CF (1995) The growth and decay of Late Weichselian ice sheet in Western Svalbard and adjacent areas based on provenance studies of marine sediments. Quaternary Research 44: 303-316

Gherardi J-M, Labeyrie L, McManus JF, Francois R, Skinner LC, Cortijo E (2005) Evidence from the Northeastern Atlantic basin for variability in the rate of the meridional overturning circulation through the last deglaciation. Earth and Planetary Science Letters 240: 710-723

Hagen S (1999) North Atlantic paleoceanography and climate history during the last 70 cal. ka. Dr.scient thesis, University of Bergen: 110pp.

Hebbeln D, Dokken T, Andersen ES, M. H, Elverhøi A (1994) Moisture supply for northern ice-sheet growth during the Last Glacial Maximum. Nature 370: 357-360

Mangerud J, Astakhov V, Svendsen JI (2002) The extent of the Barents-Kara ice sheet during the Last Glacial Maximum. Quaternary Science Reviews 21: 111-119

McManus JF, Francois R, Gherardi J-M, Keigwin LD, Brown-Leger S (2004) Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428: 834-837

Nürnberg D (1995) Magnesium in tests of *Neogloboquadrina pachyderma* sinistral from high northern and southern latitudes. Journal of Foraminiferal Research 25: 350-368

Nyland BF, Jansen E, Andersson C, Elderfield H (in press) *Neogloboquadrina pachyderma* (dextral and sinistral) Mg/Ca and $\delta^{18}O$ records from the Norwegian Sea. Geochemistry Geophysics Geosystems

Pflaumann U, Duprat J, Pujol C, Labeyrie L (1996) SIMMAX: A modern analog technique to deduce Atlantic Sea Surface Temperatures from planktonic foraminifera in deep-sea sediments. Paleoceanography 11: 15-35

Rahmstorf S (2002) Ocean circulation and climate during the past 120,000 years. Nature 419: 207-214

Rasmussen TL, Thomsen E (2004) The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations. Palaeogeography Palaeoclimatology Palaeoecology 210: 101-116

Rasmussen TL, Thomsen E, van Weering TCE, Labeyrie L (1996) Rapid changes in surface and deep water conditions at the Faeroe Margin during the last 58,000 years. Paleoceanography 11: 757-771

Rosell-Melé A, Comes P (1999) Evidence for a warm Last Glacial Maximum in the Nordic seas or an example of shortcomings in U^{K}_{37}' and U^{K}_{37} to estimate low sea surface temperature. Paleoceanography 14: 770-776

Shackleton NJ (1974) Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the Last Glacial. Colloques Internationaux du C.N.R.S. 219: 203-209

Simstich J, Sarnthein M, Erlenkeuser H (2003) Paired $\delta^{18}O$ signals of *Neogloboquadrina pachyderma* (s) and *Turborotalita quinqueloba* show thermal stratification structure in Nordic Seas. Marine Micropaleontology 48: 107-125

Stuiver M, Reimer PJ (1993) Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35: 215-230
Veum T, Jansen E, Arnold M, Beyer I, Duplessy J-C (1992) Water Mass Exchange between the North Atlantic and the Norwegian Sea during the last 28,000 years. Nature 356: 783-785
Vidal L, Labeyrie L, van Weering TCE (1998) Benthic $\delta^{18}O$ records in the North Atlantic over the last glacial period (60-10 kyr): Evidence for brine formation. Paleoceanography 13: 245-251
Waelbroeck C, Duplessy J-C, Michel E, Labeyrie L, Paillard D, Duprat J (2001) The timing of the last deglaciation in North Atlantic climate records. Nature 412: 724-727
Wagner T, Henrich R (1994) Organo- and lithofacies of TOC-lean glacial/interglacial deposits in the Norwegian-Greenland Sea: sedimentary and diagenetic responses to paleoceanographic and paleoclimatic changes. Marine Geology 120: 335-364
Weinelt M, Sarnthein M, Pflaumann U, Schulz H, Jung SJA, Erlenkeuser H (1996) Ice-free Nordic Seas during the Last Glacial Maximum? Potential sites of deepwater formation. Paleoclimates 1: 283-309

Figure captions

Figure 1. Present day surface and deep-water current pattern in the Nordic Seas.

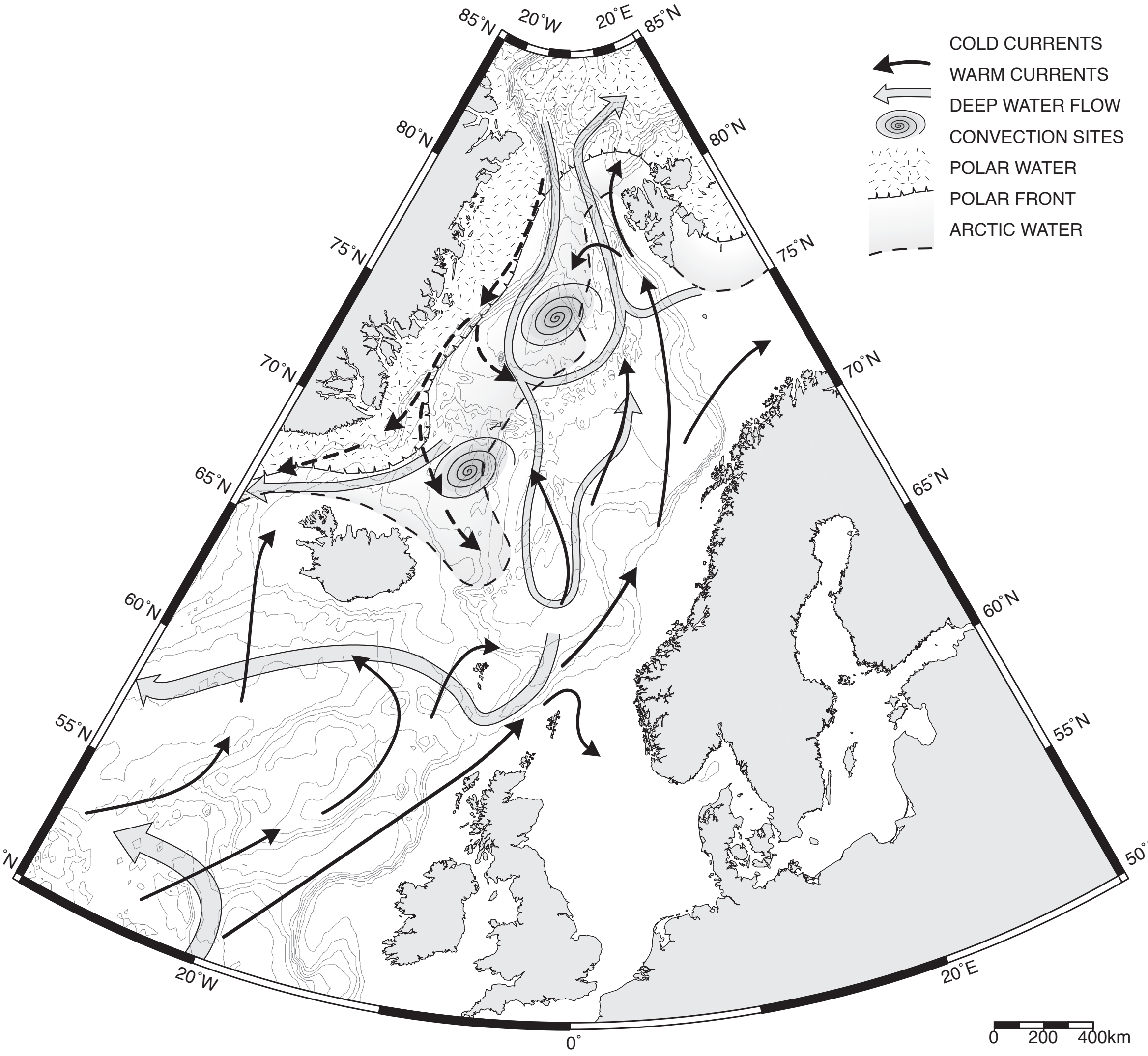
85°N
20°W
20°E
85°N
80°N
80°N
75°N
75°N
70°N
70°N
65°N
65°N
60°N
60°N
55°N
55°N
50°N
50°N
20°W
0°
20°E
COLD CURRENTS
WARM CURRENTS
DEEP WATER FLOW
CONVECTION SITES
POLAR WATER
POLAR FRONT
ARCTIC WATER
0 200 400km

Figure 1