On the Nordic Seas' role in the Atlantic Meridional Overturning Circulation

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Contents

Preface

An introduction and a collection of papers constitute my thesis presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy in physical oceanography at the Geophysical Institute, University of Bergen, Norway.

In the first part, an overview is given to motivate this thesis. A summary of the papers is presented.

The second part consists of the following papers submitted to international peer reviewed journals.

- **Paper I:** Iovino, D., and T. Eldevik, 2007: Fundamental aspects of the thermohaline gyre circulation in an idealized North Atlantic Ocean. Manuscript submitted to *Journal of Marine Research*.

- **Paper II:** Iovino, D., F. Straneo, and M. A. Spall, 2007: On the effect of a sill on dense water formation in a marginal sea. Manuscript submitted to *Journal of Marine Research.*

- **Paper III:** Eldevik, T., J. E. Ø. Nilsen, D. Iovino, K. A. Olsson and A. B. Sandø, 2007: The Greenland Sea does not control the overflows feeding the Atlantic conveyor. Manuscript to be submitted to *Nature*.

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Doroteaciro Iovino

Abstract

In the present climate, the North Atlantic thermohaline circulation (THC) plays a fundamental role in the global transport of heat at high latitudes. The response of the North Atlantic Ocean-Nordic Seas THC to surface forcing and basin geometries in an idealized one-hemisphere basin is analyzed to better understand the processes that are fundamental to the modeled circulation. Focusing on the dynamics of the Nordic Seas, analytical and numerical modeling highlight the relevance of a sill (Greenland-Scotland Ridge) in setting the properties of the water masses formed in and exported from a marginal sea. Finally, the influence of the convective activity in the Greenland Sea for the overflow, and thus the overturning, is assessed using hydrographic data (from 1950 to present), a regional ocean model, and a unique tracer release experiment. Greenland Sea Gyre water is estimated to contribute less than 1 Sv, and there is no evidence for causality between changes in the Greenland Sea and the overflow.

Chapter I

Introduction

Introduction

Evidence for abrupt climate changes on decadal-to-millennial timescales is readily identified in paleoclimatic reconstructions (e.g., Dansgaard et al. 1993). Dramatic shifts in the dynamics of the atmosphere and ocean, and their reflection on climate have been extensively analyzed and discussed in recent years (e.g., Alley et al. 2003). Many aspects of extreme events found in the paleo-data have been reproduced in numerical simulations, which provide indications for the possibility of such large and rapid changes also in scenarios applicable to the near future (Rahmstorf 2002). However, the roles of various components of the climate system, as well as their interactions, must be better understood in order to improve the estimates of probability and nature of future change in climate.

The Atlantic thermohaline circulation (THC), defined as the oceanic circulation driven by heat and salt fluxes at the surface (cf. subsection 1.1.1), has a major role in climate. Fluctuations in the strength, or even a collapse, of the THC in the North Atlantic Ocean have been a key factor for large climatic changes on regional-to-hemispheric scales over a course of a few centuries or even decades (Clark et al. 2002). The future evolution of the THC, the mechanisms that control its shape and strength, and its influence on climate are still the subject of much scientific debate and some controversy.

1.1 The role of the THC in the present climate

An assessment of the stability and variability of the large scale thermohaline circulation is, at present, one of the most relevant issues in studying many climatic phenomena and their changes. In a first order description, the present-day THC may be conceptualized by an “ocean conveyor belt” (figure 1), with no distinct start or end, spanning all oceans (Gordon 1986; Broecker 1987; 1991). Starting the loop in the North Atlantic, surface waters become dense, by e.g. wintertime cooling, sink to greater depth and flow southward toward the South Atlantic Ocean. Part of deep flow ultimately reaches the Indian and Pacific Oceans via the Antarctic Circumpolar Current. Underway, the deep waters mix with lighter ambient water; so that part of the deep flow rises to the upper ocean at a variety of locations, and eventually return to high latitude North Atlantic as a surface flow restricted to the upper few hundred meters.

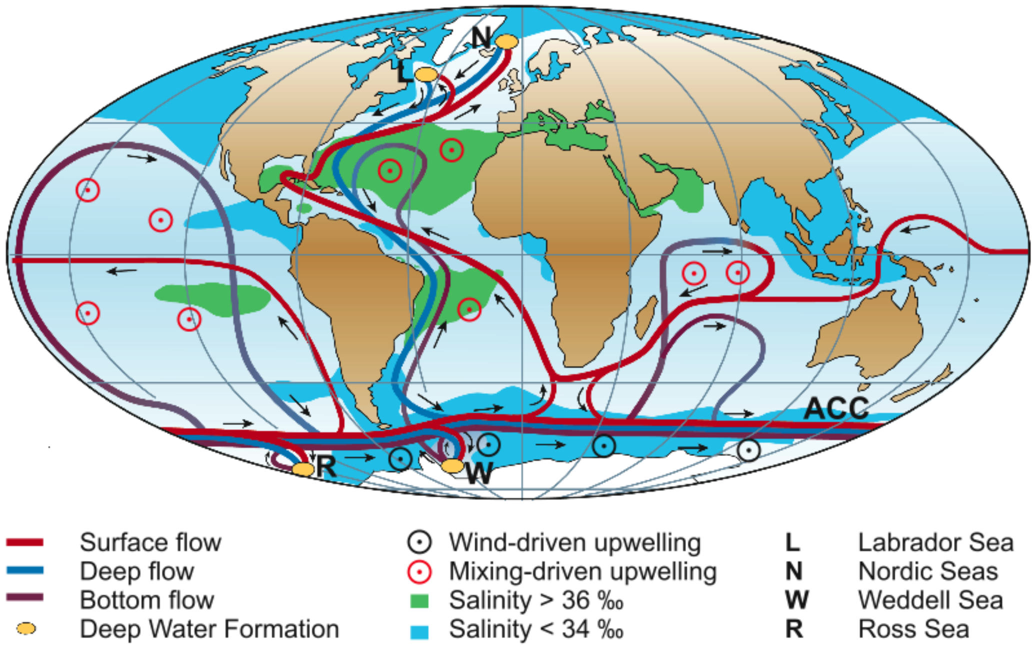

Figure 1. Simplified scheme of the global overturning circulation system (from Kuhlbrodt et al. 2007).

The ocean is an essential regulator of climate because of its ability to transport large amounts of heat. In the present climate, most of the northward transport of heat in the ocean is achieved by the Atlantic overturning circulation, which transports, at its maximum strength at about 24°N, more than 1 PW (Ganachaud and Wunsch 2003). This makes the THC a major player in the climate system, and its realistic representation an essential part of the climate modeling.

Future changes of the THC in response to global warming are likely. Modeling studies suggest that the strength of the THC may be reduced by about one third in the course of the century because of anthropogenic greenhouse gas emissions (Gregory et al. 2005; IPCC 2007). Global warming may lead to the weakening of the THC in (at least) two ways: by surface warming and surface freshening. Both would increase the vertical stability of the water column in the subpolar North Atlantic and the Nordic Seas, consequently reducing the density of high-latitude surface waters and thus restraining the deep water formation. Over the northern Atlantic sector, the cooling associated with this weakening offsets partly the expected greenhouse warming in this century. There is poor agreement between different models over how much the THC will weaken; even models that produce a similar weakening do so for different reasons. Further, not all models show a change in strength of the circulation in scenarios of global warming (Latif et al. 2000). Some more recent studies suggest that the THC would eventually recover, also from a near-collapse (Stouffer et al. 2006).

A major slow-down of the THC is likely to have considerable impacts e.g. on the El Niño-Southern Oscillation phenomenon (Timmermann et al. 2005), the position of the Intertropical Convergence Zone and the associated tropical rainfall belt (Vellinga and Wood 2002), the marine ecosystem in the Atlantic (Schmittner 2005), and the sea level in the North Atlantic (Levermann et al. 2005). All these aspects could have an unforeseen impact on the global climate (Stouffer et al. 2006).

1.1.1 On the driving mechanisms

The terms "thermohaline circulation" and "meridional overturning circulation" (MOC) are often used as synonyms, but they can have very different meanings. The term MOC does not refer to any particular driving mechanism. It is merely a description of the zonally integrated meridional, or net kinematic, flow as a function of depth (or potential density) and latitude. Hence, the MOC can be diagnosed from numerical models, and in principle measured in the ocean. The term THC is defined through the driving mechanism. It is regarded as the part of the large scale circulation driven by fluxes of heat and freshwater across the sea surface (there is also a rather small geothermal contribution at the ocean floor) and subsequent interior mixing of heat and salt (Rahmstorf 2003; Wunsch 2002). This circulation is distinct from wind-driven currents directly generated by frictional work of wind on the ocean surface. Surface buoyancy forcing cannot drive (in an energetic sense) the steady state circulation. The flow is rather mechanically sustained by wind and tides (Munk and Wunsch 1998; Wunsch and Ferrari 2004). However, the distribution of surface heat and freshwater fluxes is linked with the locations of sinking and dense water formation, as well as upwelling due to diapycnal mixing, and thus substantially influences the overturning. Because of the non-linearity of the real ocean system, the thermohaline and wind-driven circulations cannot be decoupled by oceanographic measurements: the wind-driven gyre circulation has a projection onto the THC and, conversely, large-scale horizontal circulations (e.g., the North Atlantic subpolar gyre) can be largely controlled by density gradients set up by the thermohaline properties. Nevertheless, different surface forcing fields can be prescribed in numerical models, helping us to understand which aspects of the circulation are linked to which individual forcing. The model studies presented in this thesis mostly focus on circulation driven by density gradients, the thermohaline circulation.

Which mechanical processes and locations ultimately drive the thermohaline circulation is not clearly established yet (e.g., Kuhlbrodt et al. 2007). The two major contenders as driving mechanisms are diapycnal mixing of heat and salt, and wind driven upwelling in the Southern Ocean. Diapycnal mixing (i.e., the turbulent mixing across layers of constant density) contributes most of the potential energy needed for the deep water masses formed in the North Atlantic to return back to the surface through upwelling at low latitudes. Diapycnal mixing of heat is mainly caused by small-scale motion induced by breaking of internal waves generated by wind and tidal forcing (Wunsch and Ferrari 2004). The availability of the energy required for diapycnal mixing might be a controlling factor in setting the shape and magnitude of the overturning circulation (e.g., Munk and Wunsch 1998). The gradients across which the mixing acts are however set by surface buoyancy fluxes.

The upwelling caused by diapycnal mixing cannot sustain the Atlantic overturning loop alone (Toggweiler and Samuels 1995). The other major contributor is the wind-driven deep upwelling in the Southern Ocean. There, westerly winds induce divergence and northward transport at the surface and convergence at depth (hence upwelling) that directly raise water towards the surface. Unlike in most of the ocean, where wind-driven upwelling is limited to the upper ocean, the upwelling here comes from deep waters. This wind driven process is facilitated by the unique Drake Passage latitudinal band: no east-west pressure gradient and hence no meridional flow outside frictional boundary layers can be maintained there due to the lack of topographic barriers. Therefore, the northward Ekman transport resulting from westerly winds can only be returned to the south at the depth of the Drake Passage where topographic features can support meridional flow.

The mechanical forcing does not fully determine the spatial extent and strength of the circulation. The amount of water that actually sinks and the location of this sinking in the North Atlantic are controlled by a variety of processes, including the horizontal gyre circulation, atmospheric cooling, precipitation, evaporation, deep convection, sea ice formation and melting, and brine release. These processes can drastically change the spatial pattern of the THC, and they can temporarily reduce or increase the amount of dense water formed, potentially with a strong impact on climate. The formation of dense water is generally regarded as a primary feature of the global overturning circulation. The structure and strength of the THC are sensitive to changes in dense water formation (Kuhlbrodt et al. 2007). The properties of the deep water masses are ultimately set by the surface buoyancy fluxes.

The North Atlantic is the region in the world with the most active deep water formation. Water formed there, North Atlantic Deep Water, retains its temperature-salinity signature fairly well as it flows away from the sites of formation. There are several processes that lead to dense water formation. Open-ocean deep convection, i.e. the mixing of a statically unstable water column, and other turbulent vertical mixing processes, e.g., the gradual densification of a buoyant boundary current, are associated with the actual heat loss to the atmosphere. The net downward motion of waters during a convective event is negligible (Send and Marshall 1995). Entrainment and sinking in boundary currents and overflows are associated with the actual downward motion. Mauritzen (1996a,b) found that the dense overflow from the Nordic Seas to the North Atlantic Ocean mainly derives from the gradual sinking of the Norwegian Atlantic Current (and not from convection in the central Greenland Sea, historically considered to be the main contributor to the overflow). Recent modeling studies (Spall 2004; Straneo 2006) also suggest that the sinking mainly occurs at the lateral boundaries in semi-enclosed marginal seas, such as the Labrador and Nordic Seas. Other studies suggest that there is an eddy-induced overturning with sinking in the convective region (Khatiwala et al. 2002).

1.2 North Atlantic-Nordic Seas system

At high latitudes, the Atlantic circulation is subject to a number of topographic constraints, particularly the Greenland-Scotland Ridge (GSR) across which warm and saline North Atlantic surface waters move into the Nordic Seas. Transports of mass and heat northward across the GSR (of about 8 Sv [1 Sv = 10^6 m^3 s^{-1}] and 300 TW, respectively; Østerhus et al. 2005) are essential for the water mass distributions and water mass transformations taking place in the Nordic Seas (Hansen and Østerhus 2000). The changes in the characteristics of inflowing Atlantic water and its participation in the dense water formation processes are of fundamental importance (Curry and Mauritzen 2005). The overflows across the GSR provide the densest water to the deep southward branch of the overturning circulation; hence, fluctuations in the overflow and changes in its hydrographic properties can strongly influence the overturning circulation (Hansen et al. 2001). The North Atlantic-Nordic Seas system is thus a region critical to the THC, and an important component of the global climate system.

1.2.1 The Nordic Seas

The Nordic Seas play an essential role in the regional and global dynamics of present and future climate (Drange et al. 2005). The Labrador Sea, which is the other major location of deep-water formation in the North Atlantic, is downstream of the exit from the Nordic Seas in the subpolar circulation of the North Atlantic, and is therefore influenced by processes acting within the Nordic Seas (Dickson et al. 2002). Furthermore, the Nordic Seas are the only deep connection between the Arctic Ocean and the global ocean. Also in numerical simulations, both the nature of the overturning circulation and its response to possible climate change is highly dependent on the deep water formation in the Nordic Seas and on the overflow to the North Atlantic (Stouffer et al. 2006). Nevertheless, a detailed understanding of the dynamics in this area, and their connection to the Atlantic and global circulation, is yet to be fully established.

The Nordic Seas are bounded to the north by the Fram Strait with a 2600 m deep sill that allows exchange with the Arctic Ocean, and to the northeast by the shallow Barents Sea. The southern border is the GSR that is relatively shallow, but provides gateways for the exchange of water masses with the Atlantic Ocean.

The major Atlantic inflow occurs with about equal amounts (3.8 Sv; Østerhus et al. 2005) through the Faroe Shetland Channel (sill depth about 600 m) and over the Iceland-Faroe Ridge (about 500 m). A minor inflow component of 0.8 Sv comes with the Irminger Current into the Denmark Strait (about 600 m). There are deep overflows to the Atlantic Ocean through all three openings, estimated at 3 Sv through the Denmark Strait and 3 Sv between Iceland and Scotland (Østerhus et al. 2001). The deepest of these is through the Faroe-Bank Channel, the 840 m deep continuation of the Faroe Shetland Channel south of the Faroes.

A detailed description of the Nordic Seas' topography and circulation (figure 2) is given by Blindheim and Østerhus (2005).

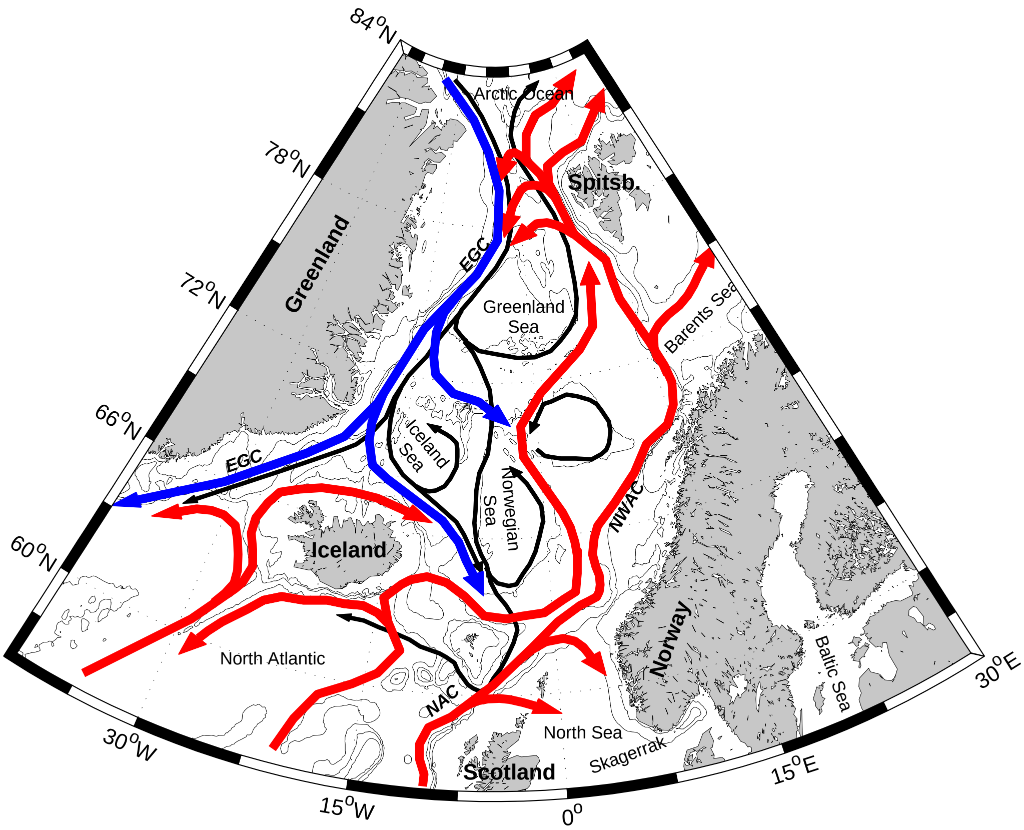

Figure 2. The main bathymetric features and a schematic of the circulation in the Nordic Seas. Red lines represent Atlantic water, and blue lines polar water. Black lines indicate intermediate and deep water (from Eldevik et al. 2005).

The dominant feature in the Nordic Seas is a cyclonic surface circulation. The Atlantic water enters into the basin across the GSR, and flows northward close to the Norwegian coast, losing heat to the atmosphere. Some of this water re-circulates in the Norwegian Sea; another branch enters the Barents Sea. Most of the inflow continues as the West Spitsbergen Current toward the Fram Strait where it either enters the Arctic Ocean or re-circulates to join the East Greenland Current along the continental slope of Greenland southward through the Nordic Seas. In addition, cold and fresh water enters into the Nordic Seas from the Arctic Ocean, and moves southwards branching off Polar Water into both the Greenland and Iceland Seas on its way along the

Greenland coast. Hence, waters flow southwards partly in the near-surface layers along the Greenland coast and partly at depth through the gaps in the ridge. The deep overflow of cold and dense water, after passing the ridge and the subsequent entrainment of ambient water, constitutes about two-thirds of the North Atlantic Deep Water (Dickson and Brown 1994).

Topography has an important control on the exchanges of deep water (Nøst and Isachsen 2003), and hence the fluxes of heat and salt between North Atlantic Ocean and Nordic Seas. The outflow is restricted by the topographical barriers, such as ridges or narrow passages, which place a limit on the maximum density of water that can escape the basins and feed the deep branch of the MOC. Any dense water mass circulating from the basin into the North Atlantic has to flow through one of the gates of the GSR. Hence, buoyancy loss causing dense water formation down to these depths is sufficient to create the overflow waters that are involved in the Atlantic overturning.

Changes in the thermohaline structure of the waters at different depths in the Nordic Seas can affect transport rates and properties of the overflowing water and thus water mass composition and circulation throughout most of the Atlantic (Hansen and Østerhus 2000). The overflow comprises different water masses with different formation and transport histories, classified by their origin. Along their path, the hydrography of the water masses in play is gradually changed by mixing with ambient water, and hence varies with depth in accordance with the dynamical activity (Rudels et al. 2005). This mixing increases the difficulty to determine the exact composition of the overflow and the fraction of the different water masses in it.

The hydrography of the overflow is highly variable even on short time scales, in response to variations in the circulation or atmospheric forcing that influences the formation and pathways of intermediate and deep water masses. Hydro-chemical analysis of the overflowing waters provides insight to the origin and formation of waters contributing to the overflow, and the physical mechanisms that control the exchanges over the GSR (e.g., Olsson et al. 2005; Tanhua et al. 2005).

1.3 Objectives

The general objective of this thesis is to provide insight into some of the issues under debate as presented in this introduction, and to contribute to the basic understanding of the thermohaline circulation in the North Atlantic - Nordic Seas system.

The specific objectives of the papers that constitute the thesis are:

- Paper I: to examine the response of the thermohaline circulation to modifications in the surface forcing and basin geometries in an idealized one-hemisphere basin in order to do better understand some of the key processes to the modeled Atlantic THC.

- Paper II: to analyze both analytically and numerically the properties of the water masses formed in a semi-enclosed basin subject to cooling and connected to the open ocean through a narrow strait with a sill (like the Nordic Seas), as function of sill configuration.

- Paper III: to test the common assumption that the convective activity in the Greenland Sea has a fundamental control over the Nordic Seas' overflows and the Atlantic conveyor, by combining a unique hydrographic database (1950-2005), a regional ocean model, and a tailor-made tracer release experiment.

1.4 Summary of the papers

1.4.1 Paper I: Fundamental aspects of the thermohaline gyre circulation in an idealized North Atlantic Ocean

A *z*-level general circulation model (MITgcm) has been used to perform a sensitivity study of the steady-state thermohaline circulation in an idealized North Atlantic Ocean. The response of the circulation to different combinations of surface forcing and basin geometries is examined. The presence of non-vertical lateral boundaries, such as a continental shelf, is instrumental in shaping a more realistic gyre circulation. The shelf supports a boundary-trapped cyclonic flow at high latitude, which tends to spread buoyant water horizontally. Consequently, location and strength of the overturning circulation and convective mixing change significantly. The "subpolar" gyre persists even in the absence of local surface forcing. Winds set an upper-layer Ekman circulation, but have a little impact on the deeper flow. The introduction of a zonal ridge (like the Greenland-Scotland Ridge) largely influences local and basin-wide dynamics, and, in conjunction with the shelf, is essential in modulating the exchange between the two basins.

1.4.2 Paper II: On the effect of a sill on dense water formation in a marginal sea

The influence of a sill on the properties of water masses formed in a semi-enclosed basin subject to surface cooling is analyzed both theoretically and numerically using the MITgcm. The marginal sea has a central flat bottom region and an outlying sloping topography; it is bound by the sill in a strait, the only connection to the open ocean. The introduction of the sill results in large changes in the circulation: waters in the interior and in the outflow become colder; the boundary current into the basin becomes narrower and shallower, limited by the sill depth over the open geostrophic contours (blocking effect). The magnitude of the influence of the sill is a function of its depth. Theoretical analysis provides further insight into the dynamics at play: the sill, modifying the vertical and horizontal structure of the inflow, makes it more unstable, and enhances the heat transport in the interior of the basin. This effect partly offsets the cooling due to the above mentioned blocking.

1.4.3 Paper III: The Greenland Sea does not control the overflows feeding the Atlantic conveyor

Open ocean convection in the Greenland Sea gyre is traditionally considered a primary component in the transformation of Atlantic inflow through the Nordic Seas, and hence to have a fundamental control of the overflows across the Greenland-Scotland Ridge that feeds the deep branch of the Atlantic overturning. The degree of causality between the hydrographic properties of the Greenland Sea and those of the overflows is tested by combining a unique set of hydrographic observations from 1950 to 2005, a unique tracer release experiment, and output from a regional ocean general circulation model. The analysis indicate that the Greenland Sea Water is estimated to constitute less than 1 Sv of the total overflow, and there is no evidence for causality between the variability of water mass properties in the Greenland Sea and that of the overflows.

References

Alley, R. B., J. Marotzke, W. D. Nordhaus, J. T. Overpeck, D. M. Peteet, R. A. Pielke Jr., R. T. Pierrehumbert, P. B. Rhines, T. F. Stocker, L. D. Talley, and J. M. Wallace, 2003: Abrupt climate change. *Science*, 299, 2005-2010.

Blindheim, J., S. Østerhus, 2005: The Nordic Seas, Main Oceanographic Features. In *The Nordic Seas: An integrated perspective*, H. Drange, T.M. Dokken, T. Furevik, R. Gerdes, and W. Berger, eds., American Geophysical Union, Washington DC, USA, 11-38, AGU Monograph 158.

Broecker, W. S., 1987: The biggest chill. *Natural History Magazine*, 97, 74-82.

Broecker, W. S., 1991: The great ocean conveyor. *Oceanography*, 4, 79-89.

Clark P.U., Pisias N.G., Stocker T.F., Weaver A.J., 2002: The role of the thermohaline circulation in abrupt climate change. *Nature*, 415-863.

Curry, R. and C. Mauritzen, 2005: Dilution of the northern North Atlantic in recent decades. *Science,* 308, 1772-1774.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J., and Bond, G., 1993: Evidence for general instability of past climate from a 250kyr ice-core record. *Nature*, 364, 218-220.

Dickson, R. R., and J. Brown, 1994: The production of North Atlantic Deep Water: Sources, rates and pathways. *Journal of Geophysical Research,* 99, 12319-12341.

Dickson, B., Yashayaev, I., Meincke, J., Turrell, B., Dye, S., and Holfort, J., 2002: Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, 416, 832-837.

Drange, H., T. Dokken, T. Furevik, R. Gerdes and W. Berger, A. Nesje, K. A. Orvik, Ø. Skagseth, I. Skjelvan, and S. Østerhus, 2005: The Nordic Seas: An introduction. In *The Nordic Seas: An Integrated Perspective*, H. Drange, T. Dokken, T. Furevik, R. Gerdes, and W. Berger, eds., American Geophysical Union, Washington DC, USA, 1-10, AGU Monograph 158.

Eldevik, T., F. Straneo, A.B. Sandø, and T. Furevik, 2005: Pathways and export of Greenland Sea Water. In *The Nordic Seas: An integrated perspective*, H. Drange, T.M. Dokken, T. Furevik, R. Gerdes, and W. Berger, eds., American Geophysical Union, Washington DC, USA, 89-103, AGU Monograph 158.

Ganachaud, A., and C. Wunsch, 2003: Large scale ocean heat and freshwater transports during the World Ocean Circulation Experiment. *Journal of Climate*, 16, 696-705.

Gordon, A. L., 1986: Interocean exchange of thermocline water. *Journal of Geophysical Research,* 91, 5037-5046.

Gregory, J. M., K. W. Dixon, R. J. Stouffer, A. J. Weaver, E. Driesschaert, M. Eby, T. Fichefet, H. Hasumi, A. Hu, J. H. Jungclaus, I. V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawratha, A. Oka, A. P. Sokolov, and R. B. Thorpe, 2005: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration. *Geophysical Research Letters*, 32, L12703.

Hansen, B. and Østerhus, S., 2000: North Atlantic-Nordic Seas exchanges. *Progress in Oceanography*, 45, 109-208.

Hansen, B., Turrell, W. R., & Østerhus, S., 2001: Decreasing overflow from the Nordic seas into the Atlantic Ocean through the Faroe Bank channel since 1950. *Nature,* 411, 927-930.

Hopkins. T. S., 1991: The GIN Sea - A synthesis of its physical oceanography and literature review 1972-1985. *Earth-Science Reviews*, 30,175-318.

IPCC, 2007: UN's Intergovernmental Panel on Climate Change. See http://ipcc-wg1.ucar.edu/wg1/wg1-report.html#foot-1

Khatiwala, S., P. Schlosser, and M. Visbeck, 2002: Rates and mechanisms of water mass transformation in the Labrador Sea inferred from tracer observations. *Journal of Physical Oceanography*, 32, 666- 686.

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf, 2007: On the driving processes of the Atlantic meridional overturning circulation. *Reviews of Geophysics*, 45, RG2001, doi:10.1029/2004RG000166.

Latif, M., E. Roeckner, U. Mikolajewicz, and R. Voss, 2000: Tropical stabilisation of the thermohaline circulation in a greenhouse warming simulation. *Journal of Climate*, 13, 1809-1813.

Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf, 2005: Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics*, 24, 347-354.

Mauritzen, C., 1996a: Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 1: Evidence for a revised circulation scheme. *Deep-Sea Research I*, 43, 769-806.

Mauritzen, C., 1996b: Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 2: An inverse model. *Deep-Sea Research I,* 43, 807-836.

Munk, W. and C. Wunsch, 1998: Abyssal recipes II: energetics of tidal and wind mixing. *Deep-Sea Research I*, 45, 1977-2010.

Nøst O. A. and P. E. Isachsen, 2003: The large-scale time-mean ocean circulation in the Nordic Seas and Arctic Ocean estimated from simplified dynamics. *Journal of Marine Research*, 61, 175-210.

Olsson, K.A., E. Jeansson, L.G. Anderson, B. Hansen, T. Eldevik, R. Kristiansen, M.-J. Messias, T. Johannessen, A.J. Watson, 2005: Intermediate water from the Greenland Sea in the Faroe Bank Channel: spreading of released sulphur hexafluoride. *Deep-Sea Research I,* 52(2), 279-294.

Østerhus, S., Turrell, W.R., Hansen, B., Lundberg, P. and E. Buch, 2001: Observed transport estimates between the North Atlantic and the Arctic Mediterranean in the Iceland-Scotland region. *Polar Research*, 20, 169-175.

Østerhus S., W. R. Turrell, S. Jonsson, and B. Hansen, 2005: Measured volume, heat, and salt fluxes from the Atlantic to the Arctic Mediterranean. Geophysical Research Letters, 32, L07603, doi:10.1029/2004GL022188.

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

Rahmstorf, S., 2003: Thermohaline circulation: The current climate. *Nature*, 421, 699.

Rudels, B., G. Bjork, J. Nilsson, P. Winsor, I. Lake, and C. Nohr, 2005: The interaction between waters from the Arctic Ocean and the Nordic Seas north of Fram Strait and along the East Greenland Current: results from the Arctic Ocean-02 Oden expedition. *Journal of Marine Systems*, 55, 1-30.

Send, U., and J. Marshall, 1995: Integral effects of deep convection. J. Phys. Oceanogr., 25, 855–872.

Smethie, W. M., Jr., and R. A. Fine, 2001: Rates of North Atlantic deep water formation calculated from chlorofluorocarbon inventories. *Dee-Sea Research I*, 48(1), 189-215.

Schmittner, A., 2005: Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. *Nature*, 434, 628-633.

Spall, M. A., 2004: Boundary currents and water mass transformation in marginal seas. *Journal of Physical Oceanography*, 34, 1197-1213.

Stouffer, R. J., J. Yin, J. M. Gregory, K.W. Dixon, M. J. Spelman,W. Hurlin, A. J. Weaver, M. Eby, G. M. Flato, H. Hasumi, A. Hu, J. H. Jungclaus, I. V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawrath, A. Oka, W. R. Peltier, D. Y. Robitaille, A. P. Sokolov, G. Vettoretti, and N. Weber, 2006: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *Journal of Climate*, 19, 1365-1387.

Straneo, F., 2006: On the connection between dense water formation, overturning, and poleward heat transport in a convective basin. *Journal of Physical Oceanography*, 36, 1822-1840.

Tanhua, T., K. A. Olsson, E. Jeansson, 2005: Formation of Denmark Strait overflow water and its hydro-chemical composition. *Journal of Marine Systems*, 57, 264-288.

Timmermann, A., S. An, U. Krebs, and H. Goosse, 2005: ENSO suppression due to weakening of the North Atlantic thermohaline circulation. *Journal of Climate*, 18, 2842-2859.

Toggweiler, J. R. and B. Samuels, 1995: Effect of Drake Passage on the global thermohaline circulation. *Deep-Sea Research*, 42, 477-500.

Vellinga, M. and R. A. Wood, 2002: Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, 54, 251-267.

Wunsch, C., 2002: What is the thermohaline circulation? *Science*, 298, 1179-1181.

Wunsch, C. and R. Ferrari, 2004: Vertical Mixing, Energy, and the General Circulation of the Oceans. *Annual Review of Fluid Mechanics*, 36, 281-314.