A Review of the North Atlantic Circulation, Marine Climate Change and its Impact on North European Climate

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A REVIEW OF THE NORTH ATLANTIC CIRCULATION, MARINE CLIMATE CHANGE AND ITS IMPACT ON NORTH EUROPEAN CLIMATE.

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INDHOLDSFORTEGNELSE

ABSTRACT

The circulation of the Atlantic Ocean differs significantly from the circulation of the other ocean basins by showing an intense overturning whereby warm water flows northward at the surface, cools and subducts at high latitudes returning southward as cold water at great depth. Associated with the overturning is a large transport of heat believed to be essential for the mild climate of northern Europe and Scandinavia. Possible changes in the Atlantic circulation could have severe regional as well as global climatic changes. Accordingly, the future changes in the Atlantic circulation have been subject to scientific investigations as well as intensive public debate. The present report gives an overview of the problem in a climate change perspective for the 21st century and reviews the latest research in an attempt to reach an up-to-date conclusion.

The response of the Atlantic ocean circulation to the global warming is most likely a gradual decline in the intensity of the overturning. This will be associated with a reduction in oceanic heat supply to the Arctic and sub-Arctic area which on its own acts to slow down the rate of global warming in the northern hemisphere. Nevertheless, almost all areas on Earth will experience an atmospheric warming by the end of the century.

We know that climate of the past has varied much more dramatically than the relatively slow warming trend that can be projected to result from human emissions of greenhouse gases. At glacial times, the climate of the northern hemisphere went through a series of abrupt changes. Within a few decades or possibly less, atmospheric temperatures changed with an amplitude comparable to half the full glacial to interglacial difference. The most often advocated explanation for such abrupt climate variability is changes in the circulation of the North Atlantic Ocean. The risk that global warming might lead to similar abrupt changes cannot be ruled out. Recent research, however, support the scientific view that abrupt climate change

within the 21st century is a highly unlikely response of the climate system to global warming. Furthermore, the impact on European climate of a possible collapse in the Atlantic ocean circulation and associated heat transport is likely quite different and weaker in the warmed climate of the future than in the colder climates of the past.

The risk of and implication of a complete shut-down of the thermohaline circulation is however not fully understood and hence further computations using coupled atmosphere-ocean models are recommended in order to improve the understanding of the problem.

SAMMENFATNING

Cirkulation i det Atlantiske ocean adskiller sig væsentligt fra cirkulationen i de andre ocean bassiner ved en kraftig vertikal udveksling af vandmasser hvorved varmt vand drives nordpå i overfladen, synker via afkøling ved høje breddegrader og returnerer sydover i stor dybde som en kold vandmasse. Denne cirkulation er forbundent med store varmetransporter og frigivelse af varme til atmosfæren under afkølingen, hvilket anses at være en essentiel komponent i opretholdelsen af Nordeuropas og Skandinaviens milde klima. Mulige ændringer i den Atlantiske cirkulation kan medføre alvorlige regionale samt globale klimaforandringer. Fremtidige ændringer i den Atlantiske cirkulation har derfor været et emne for både videnskabelige undersøgelser og intensiv offentlig debat. Nærværende rapport giver et overblik over problemstillingen set i relation til mulige klimaændringer i det 21. århundrede samt gennemgår den seneste forskning i et forsøg på at nå en opdateret konklusion.

Global opvarmning vil sandsynligvis medføre en gradvis reduktion i styrken af den Atlantiske oceane cirkulation. Hermed vil den oceane varmefrigivelse i Arktis og sub-Arktis ligeledes mindskes hvilket isoleret set medvirker til at begrænse den globale opvarmning over den nordlige halvkugle. Ved udgangen af århundredet vil temperaturen alligevel være steget over næsten alle områder på Jorden.

Vi ved, at fortidens klima har ændret sig langt mere dramatisk end den relative langsomme opvarmning som sandsynligvis vil resultere af menneskets udledning af drivhusgasser. Under sidste istid udviste klimaet over den nordlige halvkugle en række abrupte ændringer. Inden for få årtier, muligvis hurtigere, varierede temperaturen svarende til halvdelen af den glaciale til interglaciale ændring. Den oftest fremførte forklaring på disse abrupte ændringer bygger på ændringer i den Nordatlantiske oceane cirkulation. Risikoen for at den globale opvarmning kan medføre lignende abrupte ændringer kan ikke udelukkes. Ny forskning

underbygger imidlertid den videnskabelige opfattelse, at abrupte klimaforandringer i det 21. århundrede er en højst usandsynlig udvikling i klimasystemet som følge af global opvarmning. Ydermere, vil konsekvenserne for Europas klima af et eventuelt kollaps af den Atlantiske oceane cirkulation og tilhørende varmetransport sandsynligvis være betydeligt anderledes og svagere i det fremtidige opvarmede klima end under fortidens koldere klimatilstande.

Risikoen for og konsekvenserne af en fuldstændig kollaps af den oceane cirkulation er imidlertid ikke fuldt forstået, og det anbefales at der gennemføres beregninger med koblede atmosfære-ocean-modeller til at belyse problemet.

1 INTRODUCTION

Ocean-atmosphere interactions in the North Atlantic are responsible for heat transports that keep the Nordic region and northwestern Europe 5-10°C warmer than the average of the corresponding latitude belt (Fig. 1). This is to a large extent due to the characteristics of the Atlantic Ocean circulation.

The Atlantic Ocean plays a dominant role in the climate system of the earth, where formation of deep water at high latitudes is a key component of a global circulation pattern involving large pole-ward heat transports. Possible changes in the Atlantic circulation and its effect on future climate have been subject to scientific investigation (observations, modeling) as well as intensive debate in both the scientific literature as well as in the media for mainly two reasons:

- Paleoceanographic (paleo ~ past) investigations indicate that large, rapid climate changes are linked to changes in the Atlantic circulation.
- Global warming might possibly lead to a reduction or shut-down of the Atlantic deep water formation which subsequently could result in a rapid regional cooling of northern Europe.

The present report will give an overview of the problem and recent research progress. This include a historical perspective on our understanding of the Atlantic Ocean system in Sec. 1 below, a detailed description of the North Atlantic Ocean circulation and its climatic imprint, Sec. 2, and a review of our knowledge of the natural variability of the ocean circulation in Sec. 3. In Sec. 4, we focus on the response of the large scale circulation to anthropogenic forcing based on model studies. Model predictions showing both gradual- and abrupt changes in the ocean system are discussed in Sec. 4, while we return to the role of the ocean in abrupt climate change in the past in Sec. 5. A discussion of the recent trends in the North Atlantic is given in Sec. 6 along with concluding remarks and an outline of the ongoing European research in the area.

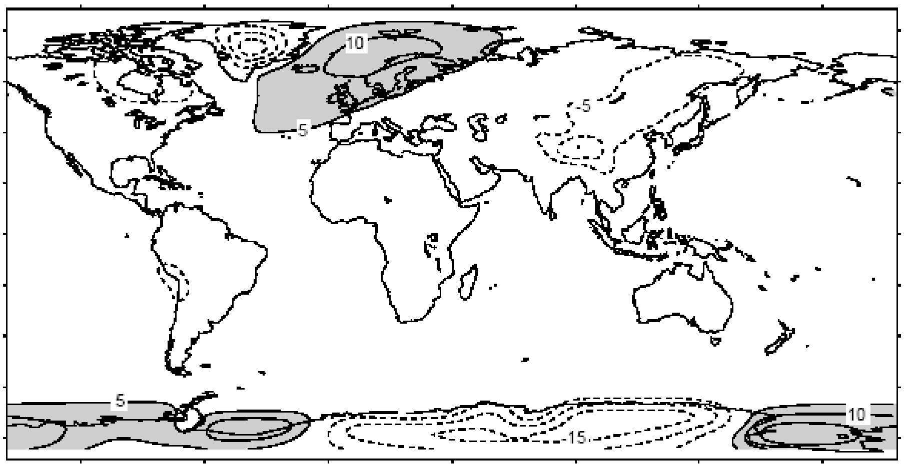

Figure 1. Departure from the zonal mean of annual mean surface temperature estimated from NCAR data (Rahmstorf and Ganopolski 1999). There is a 5-10°C warm anomaly over NW Europe and the Arctic Mediterranean.

1.1 System description, a historical perspective

To understand how ocean currents affect climate and to asses their role in the future enhanced greenhouse climate, we need to understand how they are caused. From the late 19th and into the early part of the 20th century, this debate was centered on two ideas; are ocean currents simply pushed along by winds or, are they a type of 'convection currents' driven by heating and cooling and by evaporation and precipitation at the surface. Though neither of these ideas have turned out to form a basis for an exhaustive theory, their formulation were urged by a - likely fragmented but - still valid picture of the major ocean features. This included knowledge of the stratified nature of the oceans, with warmer waters overlaying cold abyssal waters almost everywhere as well as the knowledge of basin wide wind-driven current systems like the subtropical gyre systems, the Gulf Stream and a persistent, warm pole-ward flow in the North Atlantic - the North Atlantic Current.

Into the early 20th century, the role of the oceans in the climate system received only little attention and the oceanographic investigations focused on describing the surface circulation. Hence, knowledge of the deep ocean, especially the abyssal circulation was then and is to some extent still quite limited. Amongst the first scientists to discuss the impact of ocean currents on climate were M.F. Maury (1855), James Croll (1886) and Edward Hull (1897). Maury described the importance of the eastward advection of warm, maritime air into the European continent for maintaining a climate much milder that of the eastern coast of North America. Croll and Hull further emphasized, that even small deflections in the path of the Gulf Stream could have large impact on the climate of the earth and they suggested mechanisms involving such deviations to explain climate changes on geological time scales.

From the stratified nature or the cold, deep ocean, it was however also straightforward to infer, that some renewal of the abyssal waters must take place with Arctic origin, water which had to sink and subsequently slowly spread into the low latitude regions. That the densest surface waters of the Atlantic ocean are found at the cold, high latitudes, not at the evaporative, warm and more saline low latitudes further supported the idea that deep convection at high latitude due to cooling by strong winds contributed to the work needed to drive the large scale ocean circulation. Continuity dictates that this water must return to the upper ocean by some process and form a closed meridional overturning circulation loop (MOC[1]) when replenishing the sinking water at high latitudes. The possible existence of such a circulation pattern brought some scientist to suggest that a reversal, whereby water would sink at low latitudes instead, could cause dramatic changes in the climate (Chamberlain 1906). The suggestion was based on the finding that the saline, low-latitude surface waters were only slightly lighter than the sinking, cold, high latitude waters and that subtle changes in the atmospheric pole-ward water transport maintaining the equator to pole salinity difference (haline forcing) could turn the balance. Thus, there existed a quite developed understanding of the part of the large scale ocean circulation driven by density differences later in time denoted the thermohaline circulation (THC) due to the counteracting effects of temperature and

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[1] The use of the term MOC is of fairly recent origin and is strictly defined as the zonal mean circulation of an ocean basin.

salinity on ocean density. This term is still used for the global scale ocean circulation patterns of which the Atlantic MOC is a central component. That the clearly wind-driven Gulf Stream and its eastward and pole-ward extension - the North Atlantic Current - seemed to act as the upper branch of the Atlantic MOC compromised the theory explaining the overturning as being driven by convective currents or by density differences within the ocean.

The foundation for the modern theoretical understanding of the ocean circulation were laid by a series of laboratory water tank experiments performed by Johan Sandström (1908) at the Bornö Oceanographic Station, located in Gulmarfjorden north of Gothenberg and still used for oceanographic teaching in Sweden and Denmark. Sandström used a tank filled with water of different densities from the adjacent fjord, with the light, warmer waters overlaying the cold, dense water. He blew air over the surface and heated/cooled the fluid at different levels at each end of the tank, thus elucidating the properties of the 'wind-driven' and 'thermal' circulation (Rahmstorf 2003). The most cited result of this work is known as Sandström's Theorem, stating, that thermal forcing can only give rise to a significant steady vertical circulation loop (overturning) if heating occurs at a greater depth than cooling. Although Sandström's theorem is not rigorous, it does appear to have a strong qualitative validity: The ocean is effectively forced by heating/cooling in the upper 100m and the theorem – formulated on the basis of a highly idealized experiment – apparently seem unable to explain any ocean circulation. Sandström recognized this puzzling problem and suggested that downward penetration of heat at low latitudes due to salinity driven convection could be a driving mechanism 'displacing' the heating source vertically and hence facilitating a meridional overturning circulation in the real ocean. It is only much more recent that we have come to understand the nature of this mixing, that it is the winds and tides, not salinity driven convection, that ultimately powers this turbulent downward mixing required for the dense abyssal waters to up-well across the stable stratification.

In his experiments, Sandström could also show that the depth of penetration of wind-driven circulation reaches the bottom in the unstratified tank, whereas it is effectively confined to the upper layer in the stratified case. The experiments therefore nicely illustrated the control exerted on the wind-driven current systems by the ocean density structure and consequently, on the density or thermohaline currents maintaining the stratification. The modern knowledge of the dependence of the thermohaline currents on the winds via turbulent mixing complicates further any conceptual division of the wind-driven and thermohaline currents in the ocean and despite being wind-driven, surface currents like the Gulf Stream are believed to be an integrated part of the MOC (e.g. Wunsch 2002). The conclusion we can draw is that any changes in the winds will change the thermohaline circulation and if the thermohaline forcing changes, the characteristics of the wind driven currents will be altered.

From a modeling perspective, the pioneering work of Stommel (1961) has been a cornerstone. Stommel showed, in experiments and theory, that the ocean overturning circulation can be associated with multiple equilibria and thresholds. He did so using a simple, two-zone model of the North Atlantic where he related the strength of the circulation to the density difference between the high and low latitude zone. Dependent of e.g. the freshwater forcing of the high latitudes, the model MOC are either in an intense, mainly thermal driven state or a weak, predominantly haline driven mode. A similar response is to some degree found in climate models of variable complexity today. Climate models of intermediate complexity (intermediate complex relative to General Circulation Models, GCM's, in the way that they are coarser in resolution and apply a wider range of parameterizations of unresolved physical process) are especially suitable for exploring the sensitivity of forcings for a broad range of values. Rahmstorf (1995) brought Stommel's picture into the modern era of climate modeling when showing the hysteresis structure of the North Atlantic Deep Water (NADW) flow (~MOC) in the CLIMBER model of intermediate complexity to closely follow the predictions by Stommel (see Fig. 2. for a schematic representation).

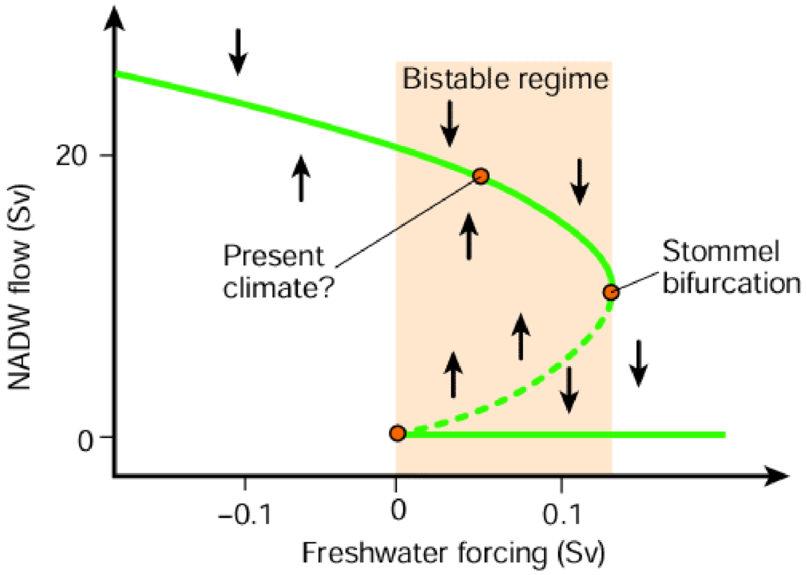

Figure 2. Schematic diagram showing the sensitivity of the North Atlantic Deep Water (NADW) flow in the CLIMBER model to high latitude fresh water forcing (1 Sverdrup (Sv) = 1 mill. cubic meters per second). The diagram closely follows the Stommel (1961) picture with a bistable regime where both a weak, haline and a strong thermal mode is possible and, a bifurcation point for relatively strong forcing beyond which only the weak haline mode exist (Figure from Rahmstorf 2002).

In a system exhibiting multiple stable states and bifurcation points, even weak linear forcing changes, internal or external noise can result in abrupt and irreversible changes as well as spontaneous 'flips' if the system is within the bistable regime and especially, if the initial state is close to the bifurcation point. Therefore, such understanding of the ocean system is of crucial importance when assessing the risk of future abrupt climate changes.

Recent ocean modeling results have given us some confidence in our understanding of the basic mechanisms controlling the strength of the Atlantic MOC. In Stommel's conceptual one-hemisphere picture, the flow strength is simply dependent on the density difference between the well mixed high and low latitudes. In the real, inter-hemispheric and three dimensional stratified ocean on our rotating planet, the picture needs some refinement. In both simple and advanced models, it has been shown that the strength of the MOC correlates much better with the inter-hemispheric gradient in steric height evaluated as the difference between the South Atlantic and high latitude North Atlantic (e.g. Rooth 1982, Thorpe et al. 2001), than with any equator to pole density difference or zonal gradient in density or steric height. The steric height is equivalent to the depth integrated density and reflects the sea-surface height at a given location if the ocean were to be motionless. Horizontal (meridional) gradients in steric height are predominantly maintained via surface forcing and this means, that pressure forces are acting within the water column to spin up ocean circulation. For an ocean atmosphere system in dynamical equilibrium, the gradient in steric height thus gives a measure of the strength of the forcing. Our model gained understanding allows us to loosely interpret this gradient in terms of the strength of the MOC. However, the theoretical basis for relating the strength of the MOC to the meridional gradient in steric height is quite unclear though suggestions can be found (e.g. Winton 1995). Numerical experiments as well as observational studies focusing on ocean vertical mixing have also recently resulted in a somewhat more complex view of the processes accounting for the upwelling of the abyssal water masses than simply low latitude mixing driven by winds and tides. The role of the Southern Ocean is highlighted in several studies, whereby wind driven upwelling caused by the prevailing westerlies account for returning a significant part of the cold branch of the MOC to the surface (e.g. Gnanadesikan 1999, Webb & Suginohara 2001). Thus, a number of processes other than formation of deepwater and turbulent mixing are likely candidates to exert a control on the strength of the Atlantic MOC.

2 THE OCEAN CIRCULATION OF THE NORTH ATLANTIC

The Atlantic MOC is an integral part of the complex circulation in the North Atlantic and the Arctic Mediterranean (Arctic Ocean, the Norwegian Sea, the Iceland Sea, and the Greenland Sea) which can be described as follows.

The warm North Atlantic Current, which is a continuation of the Gulf Stream, enters the north-eastern part of the North Atlantic in the surface from the southwest. The Atlantic Water flows into the Norwegian Sea through the Faroe-Shetland Channel, following the Scottish slope, and between the Faroes and Iceland, where modified North Atlantic Water feeds the Faroe Current, which flows eastward north of the Faroe Islands. East of the Faroes, the Faroe Current partly re-circulates into the Faroe-Shetland Channel, while some of its water continues towards north-east, as a western branch of the Norwegian Atlantic Current, (Blindheim et al., 2000). At around 70°N the current splits up into two components, one continuing along the west coast of Norway into the Barents Sea, and the other following the continental slope northwards to the Spitsbergen region, where it converges with the colder, less saline arctic surface water, sinks and continues as a subsurface current into the Arctic Ocean. Part of the North Atlantic Current branches off westwards, before entering the Arctic Ocean, into the East Greenland Current, where it underlies the Polar Water from 150 m to approximately 800 m. (Fig. 3).

Before entering the Iceland-Shetland opening, part of the North Atlantic Current turns westward as the Irminger Current, which occupies the ocean area south of Iceland. Part of this current follows the Icelandic coastline to the north through the Denmark Strait and continues along the north coast of Iceland, where it meets the cold, less saline East Icelandic Current. The other part of the Irminger Current turns towards Greenland south of the Denmark Strait, where it flows southward along the east coast of Greenland. Some of this water continues to Cape Farewell which it rounds, while a second portion remains within the Irminger Sea, where it recirculates in a cyclonical gyre. The part that rounds Cape Farewell into the Davis Strait and Labrador Sea contributes to the formation of Labrador Sea Water.

In its upper layers, the southward-flowing East Greenland Current carries cold, Polar Water of low salinity, including large amounts of sea ice, from the Arctic Ocean (Aagaard and Carmack, 1989). In its deeper strata (Fig. 4), there is also a transport of intermediate and deep water from the Arctic Ocean. A relatively warm intermediate layer with water of Atlantic origin returns from the West Spitsbergen Current and partly from the Arctic Ocean. Below, deep water formed in the Arctic Ocean primarily Eurasian Basin Deep Water (Swift and Kolterman, 1988) can be traced all the way to the Denmark Strait (Buch et al., 1996) and it constitutes an important contribution to the deep water in the Arctic Mediterranean. The main branches of the East Greenland Current are, firstly, the Jan Mayen Current, which brings all three water masses into the cyclonic circulation in the Greenland Sea Basin. Secondly further south, the East Icelandic Current, which carries a somewhat varying combination of the same water masses from the East Greenland Current into the Iceland and Norwegian Seas (Buch et al., 1996). The remaining part of the East Greenland Current leaves the Arctic Mediterranean through the Denmark Strait to supply fresh water to the sub-arctic gyre in the North Atlantic as well as dense overflow water, which contributes to the deep western boundary current in the North Atlantic.

The Arctic Front – the border zone between the domains of the Norwegian Atlantic Current and the waters of Arctic origin – is, north of Jan Mayen, topographically controlled by the mid-ocean ridge and shows only small fluctuations in position. Between Iceland and Jan Mayen, on the other hand, variations in the volume of waters masses carried by the East Icelandic Current may result in relatively large shifts in the position of the Arctic Front.

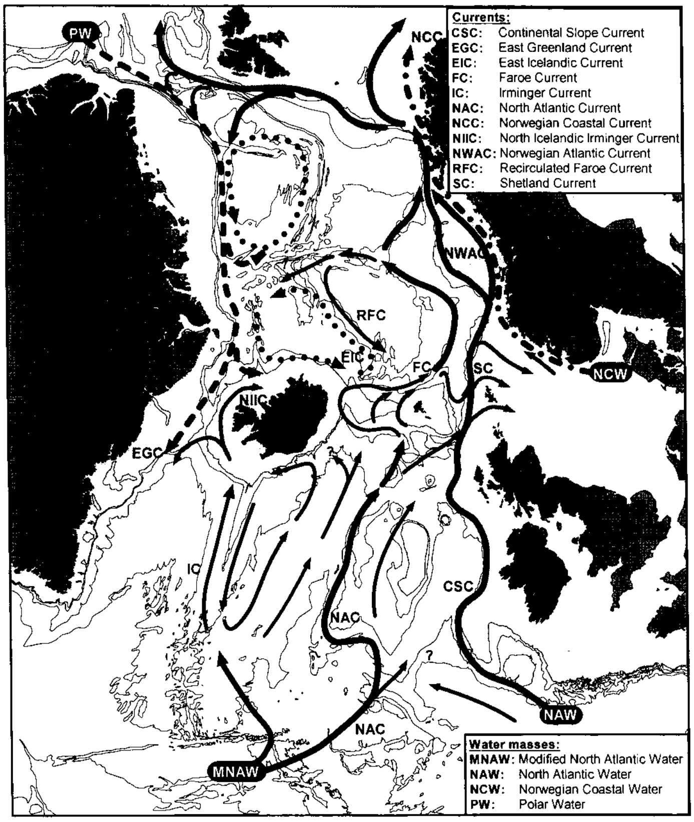

Figure 3. Main features of the near-surface circulation in the eastern North Atlantic and the Arctic Mediterranean. Continuous arrows show Atlantic water flow. Broken and dotted arrows indicate flow of other water masses. Water masses transported by the main current branches are indicated (after Hansen and Østerhus, 2000)

In the Arctic Mediterranean cooling and brine rejection during sea-ice formation increases the density of upper layer waters sufficiently so that they may descend to intermediate (500 – 1000 m) or deep levels. These “ventilated” waters leave the Arctic Mediterranean as deep “overflow” across the Greenland-Scotland Ridge into the North Atlantic. This comprises together with the surface flow of the East Greenland Current the total outflow from the area. Traditionally, the water that contributes to the overflow is divided into intermediate and deep water masses. There are four distinct mechanisms for creating deep water, (Aagaard et al., 1985, Blindheim and Aalandsvik 1995, Mauritzen 1996). One is the traditional scheme in which water in the Greenland Sea sinks from the near surface layers to large depths by open ocean deep convection. The second mechanism involves dense water being formed in the shallow shelf regions surrounding the Arctic Ocean. The two other mechanisms are sinking associated with fronts and deepening of boundary currents, respectively. Associated with the latter process is a gradual cooling and freshening of the Atlantic Water as it flows cyclonically through the Arctic Mediterranean.

Both deep water formation mechanisms require cooling of the upper water that has to have a sufficiently high salt content which may be acquired by advection of saline water from the surroundings i.e. North Atlantic Water or by brine rejection from sea ice formation.

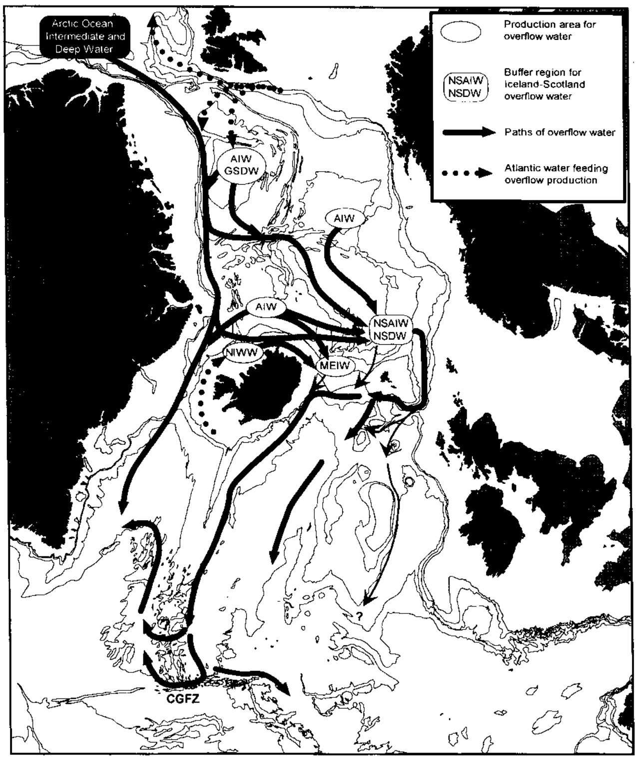

Figure 4. Main features of overflow water sources and paths towards the Greenland Scotland Ridge and paths of the overflow through the eastern North Atlantic and the Charlie Gibbs Fracture Zone. The thickness of the arrows crossing the ridge indicates magnitude and persistence of the overflow (after Hansen and Østerhus, 2000)

In the Arctic Ocean, the low salinity of the surface waters prevents deep convection, but not the formation of dense waters over the surrounding shelves (Aagaard et al., 1985). This water flows outwards over the shelf and descends the slope down to intermediate or deep levels, determined by its density, as modified by entrainment of surrounding water. Rudels et al. (1999) discuss in detail the contribution of Arctic Ocean waters to the overflow across the Greenland-Scotland Ridge. In contrast to older conjectures, they find that the outflow through the Denmark Strait contains intermediate water as well as some upper deep water from the Arctic Basin. The densest Arctic Ocean deep waters are too deep to overflow the Denmark Strait and are turned either at the Jan Mayen Fracture Zone or at the entrance to the Denmark Strait (Buch et al, 1996). As indicated in Fig. 4 these waters may, however, continue into the Norwegian Sea and there contribute to the formation of Norwegian Sea Deep Water (NSDW) (Rudels et al., 1999).

Intermediate water is, in the traditional view, produced in the open areas of the Iceland Sea and the Greenland Sea (Swift and Aagaard, 1981, Swift, 1986) from where it flows towards the Denmark Strait and into the Norwegian Sea (Blindheim, 1990). Sinking in frontal regions within the Norwegian Sea forms additional intermediate water and this water is clearly involved in the overflow between Iceland and Scotland (Blindheim and Aalandsvik, 1995).

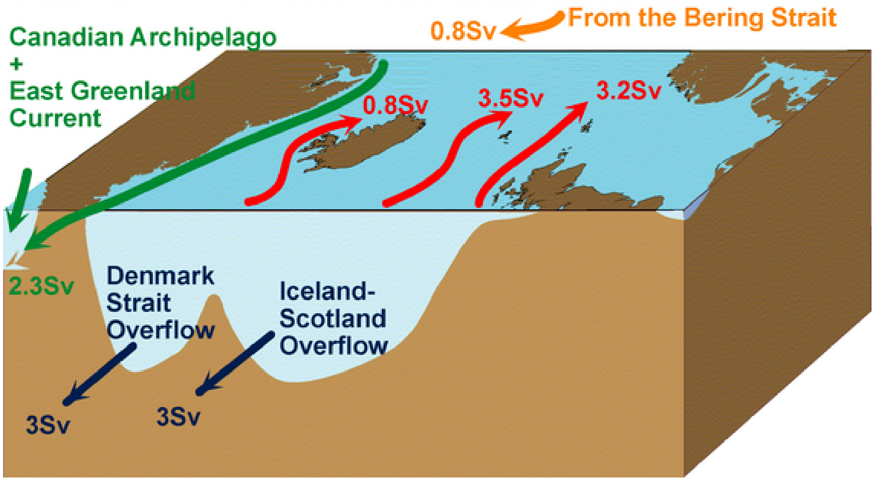

Figure 5. Volume balance of the Arctic Mediterranean ocean transports. Red arrows indicate Atlantic inflow (from Hansen et al. 2004).

The exchanges of water, heat, and salt between the North Atlantic and the Arctic Mediterranean, across the Greenland –Scotland ridge, are therefore critical for maintaining the global thermohaline circulation as well as the climatic conditions in the region. Estimates of this exchange of mass have over the years been reported by several scientists. Most of the estimates have, however, been based on indirect methods (e.g. geostrophic computations, budgets etc). With the launch of the inter-Nordic marine research program NORDIC WOCE in 1995 an observational system was initiated to monitor the exchanges through this gap and it has provided data that allow estimates of typical fluxes and their seasonal variations. Based on these measurements a water budget for the Arctic Mediterranean has been set up (Joensen and Briem, 2003, Turrell et al, 2003, Hansen et al, 2004), showing that the inflow consists of 7.5 Sv (1 Sverdrup (Sv) = 1 mill. cubic meters per second) of Atlantic Water plus 0.8 Sv from the Pacific Ocean through the Bering Strait, Fig. 5. The outflow shows that 6 Sv leaves the area as deep overflow water while 2.3 Sv leaves in the surface i.e. the East Greenland Current and through the Canadian Archipelago.

2.1 The climatic imprint of ocean transports

The warm and saline Atlantic water entering the Arctic Mediterranean and the outflow of deep overflow water is part of the global thermohaline circulation (THC) often presented schematically as a conveyor type circulation (Fig. 6).

Associated with the Atlantic MOC and the global THC, the inflow of Atlantic water to the Arctic Mediterranean is of crucial importance for several reasons:

- It transports heat northwards and thus modifies both the ocean and land climate in northern Europe.
- The relative high salinity of the Atlantic water is a crucial ingredient in the formation of the deep water masses which return as dense water from the Arctic Mediterranean into the North Atlantic where it again mixes and transforms into North Atlantic Deep Water.

- The deep water formation in the Arctic Mediterranean is important in a climate change perspective also due to the large storage capability of carbon in the deep ocean which is being renewed by deep water formation.

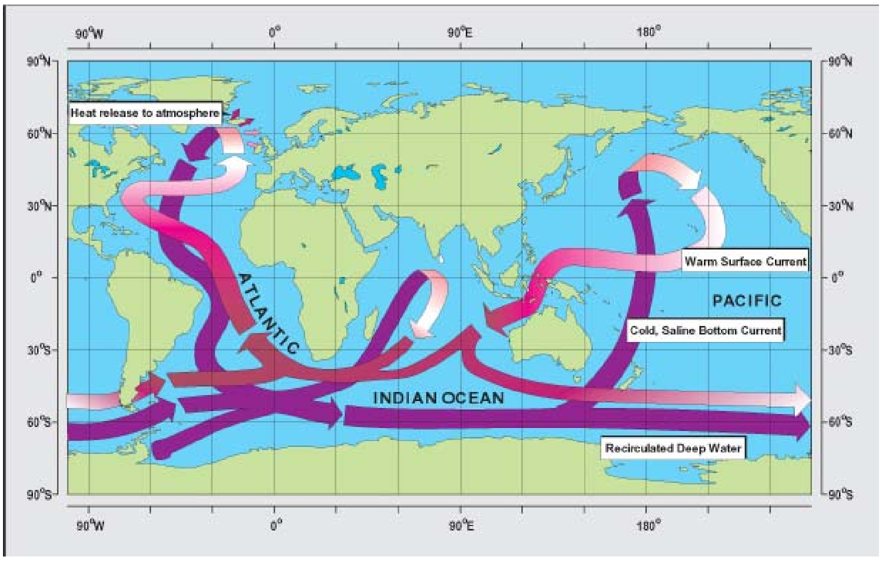

Figure 6. Schematic diagram of the global thermohaline circulation pathways (the Conveyor Belt, Broecker 1991)

The magnitude of the pole-ward ocean heat transports has recently been revised. Trenberth and Caron (2001) estimated the ocean transport relative to the atmospheric transport using a combination of satellite measurements of the total heat transport and direct (reanalysis) estimates of the atmospheric transport. This new estimate (Fig. 7) is in agreement with the sparse direct estimates of ocean heat transport based on hydrographic data but contrasts older estimates that had considerably higher ocean heat transport. From Fig. 7 it is apparent that the atmospheric heat transport dominates at most latitude belts except close to the equator where the two are of similar magnitude. Consequently, the new estimate leaves the ocean an apparently less prominent role in modifying the high latitude climate. This point is further stressed by studying the heat budget of the high latitude belt from 40° to 90°N. This region is heated about twice as much by absorbed shortwave radiation from the sun than results from the convergence of atmospheric transports (Trenberth and Caron 2001). The heating from the ocean transport is according to Fig. 7 a magnitude smaller.

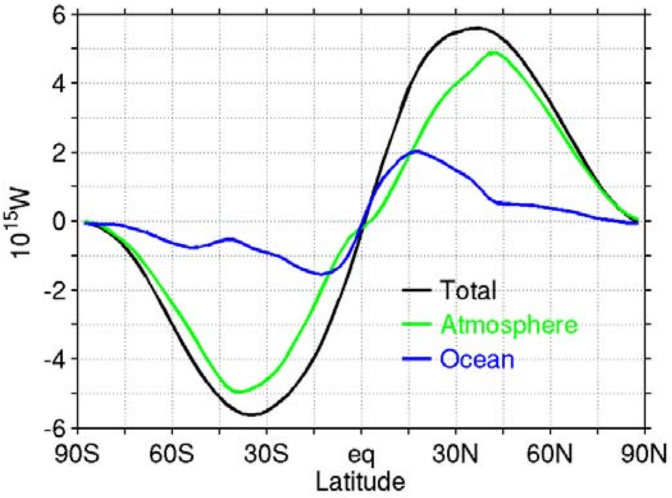

Figure 7. Northward atmospheric and oceanic heat transports from observations. The estimates are the average of ECMWF- and NCEP-based numbers from Trenberth and Caron (2001).

Despite the small relative contribution from the ocean to the total heat transport, it is still considered an important modifier of the high latitude climate. Mainly two features cause this modest transport to be of significance. Firstly, the transport is not equally distributed between the ocean basins (Fig. 8) due to localized deep water formation areas and the inter-hemispheric and inter-basin nature of the global thermohaline circulation (see Fig. 6). Consequently, the Atlantic Ocean heat transport is directed northward at all latitudes and, of utmost importance for the northern European climate, it maintains a relatively high level across mid latitudes.

A second feature of the oceanic circulation and associated heat transport is the potential for supplying its heat at the optimal time and place to effectively oppose sea ice expansion. This tendency involves wintertime convection near the ice-edge whereby heat stored in the deeper water masses is released to the upper ocean and atmosphere, limiting formation of sea ice. Due to its reflective characteristics, the sea ice cover (and snow cover) is a strong modifier of the global climate and especially the climate of the high latitudes. Further, by insulating the air from the sea, changes in sea-ice cover have a strong modifying effect on air temperatures over marine areas. Without ocean heat transports, the amount of heat available for release near the ice edge via ocean convection would be much reduced. In fact, during most of the winter and early spring (from early December), the North Atlantic heat release to the atmosphere relies solely on heat transported by ocean circulation. In comparison, locally stored heat during summer can only account for the release during autumn (Rhines and Häkkinen 2003). Model studies comparing climate model simulation with and without ocean heat transports clearly show these effects to be essential in counteracting the runaway ice-albedo feedback on climate (see Winton 2003 for a recent discussion). Consequently, the mechanism described imply that ocean heat transports have a disproportionate influence on high latitude climate which should be kept in mind when considering changes in ocean circulation as a consequence of global warming.

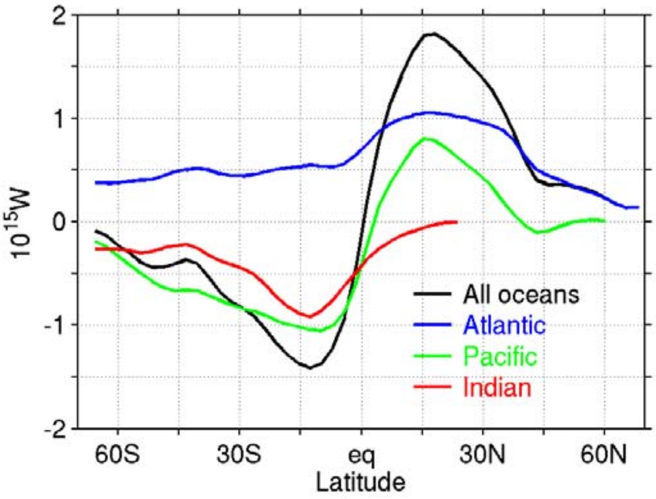

Figure 8. Northward oceanic heat transports from observations. The estimates are the average of ECMWF- and NCEP-based numbers from Trenberth and Caron (2001).

3 MARINE CLIMATE CHANGE AND VARIABILITY

Variations in the North Atlantic Current and thereby in the global thermohaline circulation has a great impact on the climate in Northern Europe, and a full understanding of the processes and their variability therefore attracts much attention in climate research. In the following we give an overview of the most important processes and their impact. We distinguish between climate change and climate variability. Climate change is related to human influence and climate variability relates to the natural variability of the climate system.

A substantial part of the climate variability in the North Atlantic/European region is associated with the North Atlantic Oscillation (NAO) , which is an natural mode of variability in the atmosphere.

3.1 The North Atlantic Oscillation

The NAO, which is associated with changes in the surface westerlies across the Atlantic onto Europe, refers to a meridional oscillation in the atmospheric mass with centers of action near the Iceland Low and the Azores High (van Loon and Rogers, 1978). Although it is evident throughout the year, it is most pronounced during winter and accounts for more than one-third of the total variance of the Sea Level Pressure (SLP) field over the North Atlantic. Because the signature of the NAO is strongly regional, a simple index of NAO was defined by Hurrell (1995) as the difference between the normalized mean winter (December-March) SLP anomalies at Lisbon, Portugal and Stykkisholmur, Iceland. The SLP anomalies at each station were normalized by dividing each seasonal pressure by the long-term mean (1964 - 1995) standard deviation. The variability of the NAO index since 1864 is shown in Fig. 9 where the heavy solid line represents the low pass filtered meridional pressure gradient. Positive values of the index indicate stronger than average westerlies over the middle latitudes associated with low-pressure anomalies over the region of the Icelandic Low and anomalous high pressures across the subtropical Atlantic.

In addition to a large amount of interannual variability, there have been several periods when the NAO index persisted in one phase over many winters (van Loon and Rogers, 1978, Barnett 1985, Hurrell and van Loon, 1997).

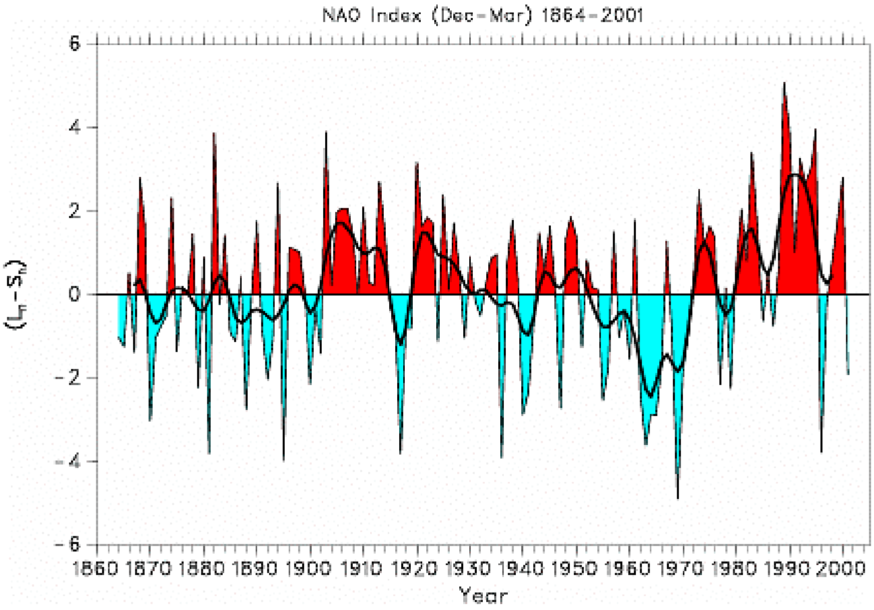

Figure 9. Time series of the winter (December - March) index of the NAO (as defined in the text) from 1864-1995. The heavy solid line represents the meridional pressure gradient smoothed with a low pass filter to remove fluctuations with periods less than 4 years. (Updated from Hurrell and van Loon, 1997).

Over the region of the Icelandic Low, seasonal pressures were anomalously low during winter from the turn of the century until about 1930 (with exception of the 1916-1919 winters), while pressures were higher than average at lower latitudes. Consequently, the wind onto Europe had a strong westerly component and the moderating influence of the ocean contributed to higher than normal temperatures over much of Europe (Parker and Folland, 1988). From the early 1940s until the early 1970s, the NAO index exhibited a downward trend and this period was marked by European wintertime temperatures that were frequently lower than normal (van Loon and Williams, 1976, Moses et al., 1987). A sharp reversal has occurred over the past 30 years and, since 1980, the NAO has remained in a highly positive phase with SLP anomalies of more than 3 mb in magnitude over both the sub-polar and the subtropical Atlantic. The 1983 and 1989-1995 winters were marked by some of the highest positive values of the NAO index recorded since 1864 (Fig. 9).

A detailed analysis by Hurrell (2000) shows, that the NAO exerts a dominant influence on wintertime temperatures across much of the Northern Hemisphere. Surface air temperature and sea surface temperature across wide regions of the North Atlantic Ocean, North America, the Arctic, Eurasia and the Mediterranean are significantly correlated with NAO variability. Such changes in surface temperature (and related changes in rainfall and storminess) can have significant impacts on a wide range of human activities as well as on marine and terrestrial ecosystems.

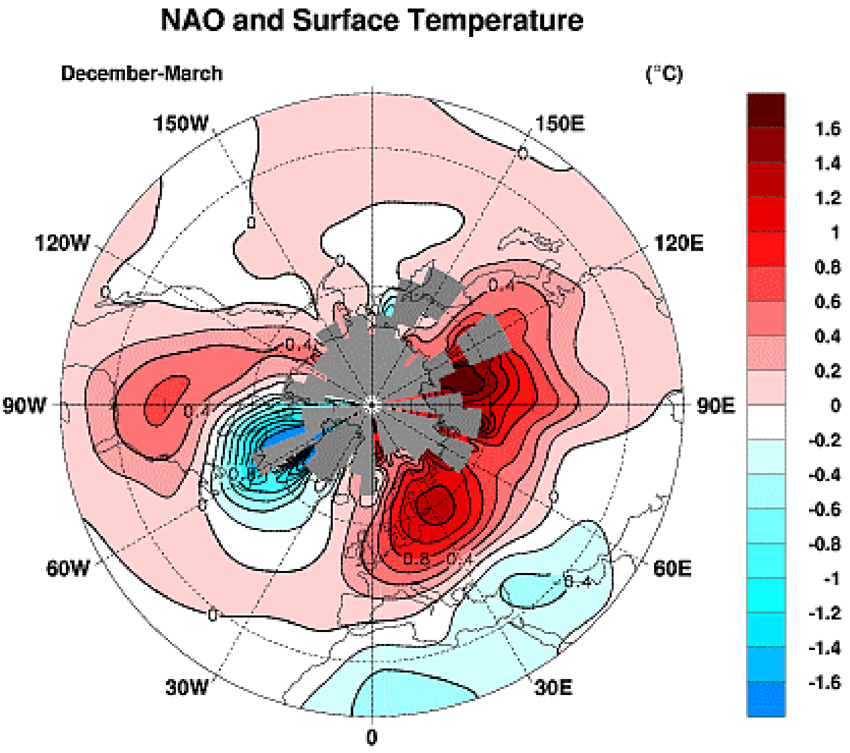

Figure 10. Changes in land surface and sea surface temperatures (°C) corresponding to a unit deviations of the NAO index for the winter months (December-March) from 1935-1999. The contour increment is 0.2°C. Regions of insufficient data are not contoured. (After Hurrell, 2000).

When the NAO index is positive, enhanced westerly flow across the North Atlantic during winter moves relatively warm (and moist) maritime air over much of Europe and far downstream across Asia, while stronger northerlies over Greenland and northeastern Canada carry cold air southward and decrease land temperatures and sea-surface temperatures (SST's) over the northwest Atlantic (Fig. 10).

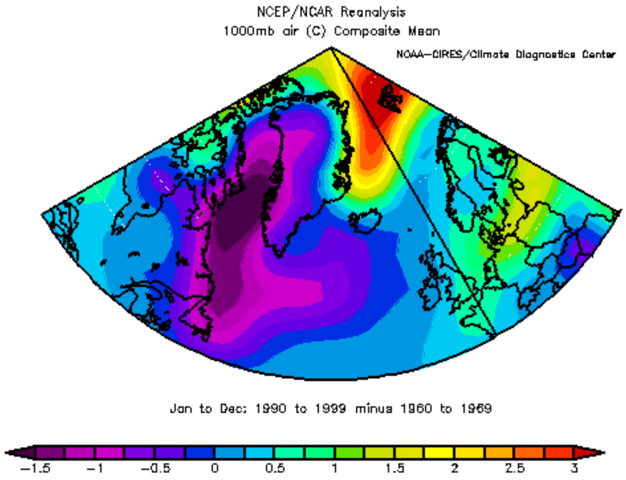

Figure 11. Difference in air temperatures at the 1000 mb level between 1990-99 and 1960-69. Calculated using the NCEP/NCAR reanalysis database.

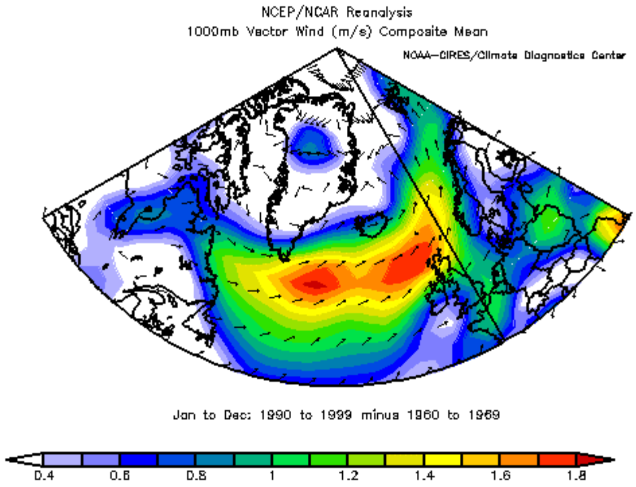

Figure 12. Changes in the 1000 mb winds between the 1990-99 and 1960-69. Calculated using the NCEP/NCAR reanalysis database.

This can be illustrated further by comparing the temperatures from a low NAO period (1960-69) to a high NAO period (1990-99), Figure (11). It is especially noticed that the Greenland Sea area was warmer in the 1990s than in the 1960s and that the Davis Strait-Labrador Sea was significantly colder, which has an direct effect on the deep convection in the two areas. Changes in the wind pattern in the North Atlantic area are illustrated in Fig. 12, showing the intensified westerlies.

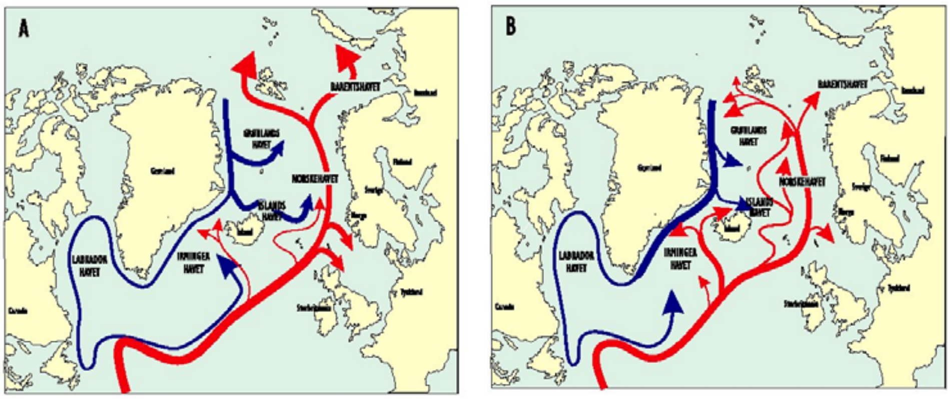

Figure 13. Ocean circulation under high (A) and low (B) NAO-index conditions (After Blindheim et al., 2001).

The influence of the changing NAO-index on the atmosphere naturally is reflected to the ocean and the ocean circulation. In Figure (13) the general ocean circulation of the North Atlantic is show under NAO$^+$ and NAO$^-$ - conditions.

Positive values of NAO result in an intensification of the North Atlantic Current, which is deflected towards the east having the result that the Irminger Current has low intensity, while the inflow to the North Sea and the Arctic Ocean are strong. This results in warm conditions in Europe and the Arctic region. The East Greenland Current has high intensity north of the Denmark's Strait but low south of the strait because water is flowing into the Greenland Sea and the Iceland Sea via the Jan Mayen- and the East Icelandic Currents.

During negative NAO conditions the intensity of the North Atlantic Ocean circulation is almost opposite. The intensity of the North Atlantic Current is weaker resulting in several side branches, strong Irminger Current, reduced inflow to the North Sea and the Arctic Ocean. The East Greenland Current has a high intensity all the way to Cape Farewell with weak inflows to the Greenland- and Iceland Seas.

The above given description of the NAO index clearly illustrates the strong correlation between the strength of the westerlies across the North Atlantic - the NAO index - and the climate in the North Atlantic regions. It also shows that the climate in Greenland and Europe are negatively correlated to each other, a phenomenon named Seesaw in the literature.

Dickson et al. (1996) discussed in detail the relation between NAO and the deep water formation in the Labrador Sea, the Greenland Sea and the Arctic Ocean and found:

- During the period of low NAO index from 1950 -1970 deep convection reaching depths of more than 3500m took place in the Greenland Sea. In the Labrador Sea, the deep convection was weak during this period, while some convection to intermediate depth was observed as far south as the Sargasso Sea.
- During the 1980s and 1990s - a period with extremely high values of NAO - the deep convection in the Greenland Sea has decreased drastically with a 80 % reduction in the Greenland Sea Deep Water formation and the convective exchange restricted to < 1000m in several winters. In the same period, the convection in the Labrador Sea has resumed and the convection in the Sargasso Sea disappeared.

The explanation to this coupling between the strength of the deep water formation at various localities is:

Low NAO index

- The strength of the west wind belt across the North Atlantic is weak having the effect that the Norwegian Atlantic Current is wide and branching off into the Greenland Sea.
- The local wind stress curl over the Greenland Sea is strong generating conditions favorable to convection, ie,. a strong cyclonic gyre with surface layer divergence through Ekman pumping and doming of isopycnals.
- A high-pressure system over Greenland builds up during wintertime. This results in a high frequency of northerly winds and record hard cooling over the Greenland Sea in the 1960s, which was favorable for the convection in the Greenland Sea through direct cooling as well as through brine rejection from the increased sea ice formation. The northerly winds increased the transport of low saline water from the Arctic Ocean to the Labrador Sea in the form of the Great Salinity Anomaly, which shut down the deep convection in this area. The Greenland High, together with a low pressure system over South eastern USA, caused a regime of cold winter air temperatures and extreme snow cover at the east coast of USA. This drew the center of maximum storm activity far to the south-west as compared to normal, thus reducing the storminess over the Labrador Sea and increasing it over the Sargasso Sea causing increased formation and ventilation of the so called 18-degree Water.

High NAO

- The strength of the west wind belt across the North Atlantic is enhanced which presses the Norwegian Atlantic Current closer to the Norwegian Coast (Fig. 14).
- The local wind stress curl in the Greenland Sea becomes weak resulting in weaker doming, a smaller scale gyre circulation and weak convection in the Greenland Sea.

- The winter High over Greenland weakens whereby the high frequency of strong northerly winds is decreased. This leads to reduced cooling of the Greenland Sea and sea ice formation. Additionally, the transport of low saline water to the Labrador Sea is reduced and the center of maximum storminess moved back to the Labrador Sea, whereby the conditions for deep convection again were favorable in the Labrador Sea but unfavorable in the Sargasso Sea.

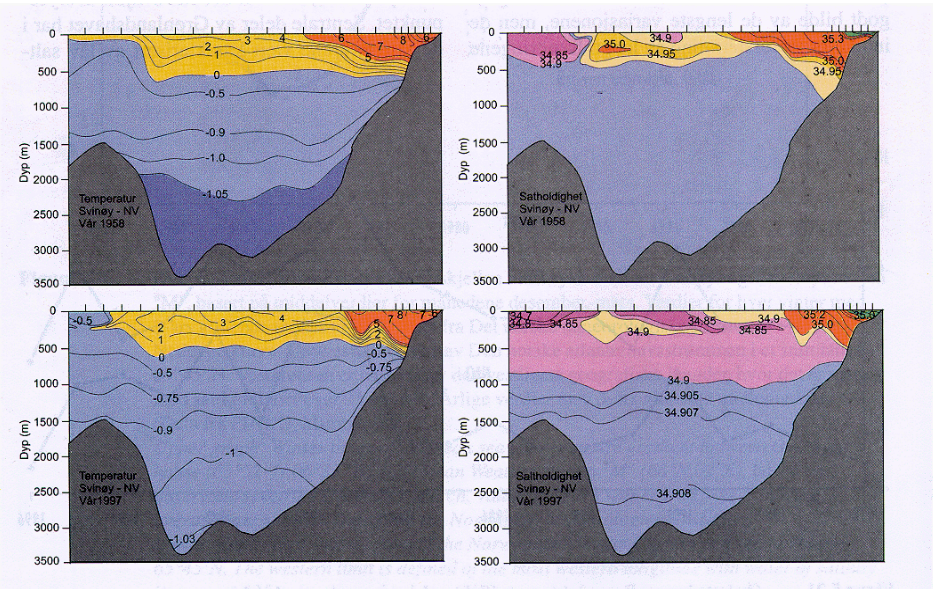

Figure 14. Potential temperature and salinity at the Svinøy section observed spring 1958 and spring 1997 (after Mork and Blindheim, 1999).

There is no documentation on the variability of the formation of Arctic Ocean deep water masses. However, the recent deepening of Eurasian Basin Deep Water layer in the Greenland Sea itself (Meincke et al., 1997) and its presence along the East Greenland Continental slope all the way to the Denmark Strait (Buch et al., 1996) indicates, that the deep water formation in the Arctic Ocean is presently taking place in a high rate.

4 THE ATLANTIC OCEAN CIRCULATION IN THE ENHANCED GREENHOUSE CLIMATE

Studies of the future behavior of the Atlantic meridional overturning circulation in response to anthropogenic forcing focus mainly on two questions:

- Is a gradual weakening the most likely response and can it be quantified?
- Is the ocean system associated with critical limits beyond which abrupt changes will occur or close to which the system becomes unpredictable?

The relevance of these quite specific questions is illustrated by three lines of research. First, it is widely expected that the hydrological cycle will be intensified in a warmer climate thus bringing more atmospheric freshwater to the high latitudes. Ultimately, this consensus is based on the fact that a warmer atmosphere holds relatively more moisture which again is available for meridional transports mechanisms within the atmosphere. Nearly all climate models exhibit this sensitivity. Second, our basic understanding of the thermohaline circulation tells us that increased freshwater forcing tends to slow down the thermally driven mode of the present day system and, that the thermally driven state is likely only one of (at least) two basic circulations states (Sec. 1). The third line of research that brings us to raise a question concerning the risk of abrupt climate change comes from the paleoarchive of climate data. Mainly ice core data have revealed that climate of the last ice-age was far from stable and contrasts the relative stability of the Holocene climate system up to date (see Sec. 5).

4.1 Gradual changes in the Atlantic MOC

A large number of numerical modeling studies, dedicated specifically to predicting the (near) future climate and the evolution of the Atlantic MOC, have been conducted within the IPCC 2001 framework (Cubasch et al. 2001). A robust feature of most projections is a gradual - meaning without abrupt transitions - reduction in the strength of the MOC (Fig. 15). This response to increased greenhouse gas concentrations and accordingly enhanced freshwater forcing of high latitudes gives a view of the ocean and climate system being well away from a critical threshold (Sec. 1). However, large uncertainties exist in the projections and are partly disguised in presentation made in Fig. (15). To aid comparison, the evolution of the MOC is presented as the deviation from the mean preindustrial value. However, the absolute strength of the overturning varies by more than a factor of 2 between the individual model results presented, ranging from 10 to 30 Sv.

The scientific status of coupled, numerical climate models has been developed in two key aspects during the recent years, partly also since the preparation of the IPCC third assessment report. Firstly, the necessity of using unphysical surface flux adjustments between the oceanic and atmospheric model components has – in some models – been eliminated due to a combination of enhanced resolution, better simulations of surface fluxes and meridional transports in the atmosphere. The use of flux corrections are known to distort the stability of the modeled MOC in a unrealistic way (e.g. Marotzke and Stone 1995). Second, coarse resolution ocean models tend to form deep water south of the Greenland-Scotland Ridge at odds with observations (Sec. 2). Enhanced resolution in ocean models has resulted in a prediction of separated deep water sources both north and south of the ridge. Both aspects lend confidence in model sensitivity though the spread in projections still need to be narrowed. However, the finer scales resolved in the models and hence the number of interacting mechanisms can result in a relatively complex sensitivity compared with coarser resolution models.

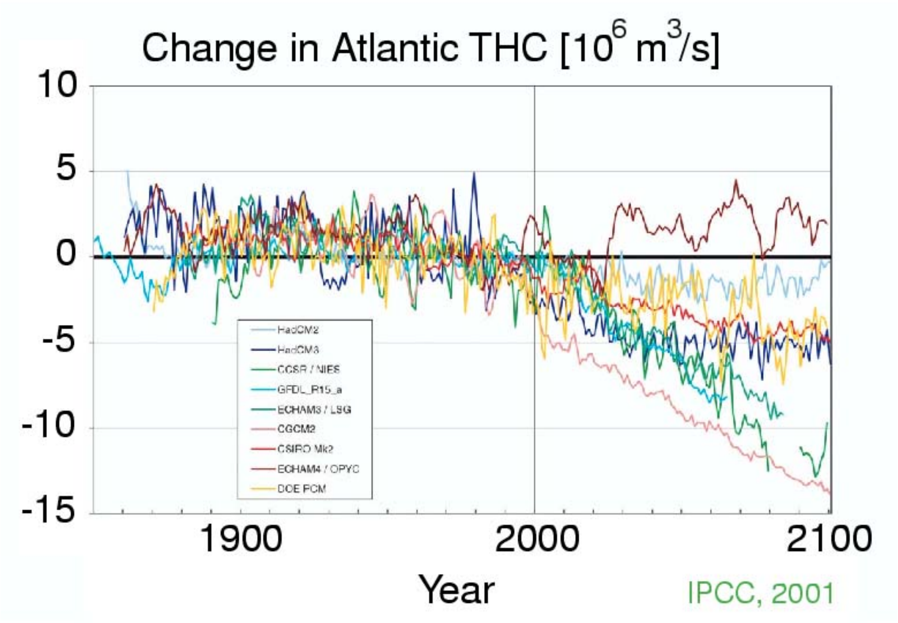

Figure 15. Predicted present variability and future changes of the Atlantic overturning predicted by the ensemble of coupled climate models applied in the IPCC assessment (Cubasch et al. 2001).

Neither of the projections performed as part of the IPCC 2001 assessment showed an abrupt response to enhanced greenhouse gas concentrations and results from a recent study by Wood et al. (2003) even questions the existence of a critical lower limit in the strength of the MOC beyond which a collapse will occur. They find the Atlantic MOC to be active, though highly reduced, even for CO2 forcing as high as 32 times pre-industrial levels. A similar conclusion was drawn by Thorpe et al. (2001), letting CO2 increase steadily to reach 20 times its initial level. At the end of this simulation the MOC had declined by 80% to only 5 Sv, without showing a complete collapse. In this large interval of response, their thorough analysis showed no indications of regime shifts in the stabilizing processes setting the strength of the circulation, a finding which yields confidence in a gradually changing future climate.

An independent study of Stouffer and Manabe (2003) are among the few fully coupled 3D-model studies showing a collapsed or inactive mode of the Atlantic MOC to exist as one of two equilibria for a given forcing. The second mode is the strong, thermally dominated circulation pattern resembling the Atlantic today. However, they find that both the active and inactive modes are very stable and, that it takes a very large forcing to make the MOC change between equilibria. In accordance with this separation of modes, they show the active mode of the Atlantic MOC to be rather insensitive to a doubling or a quadrupling of the atmospheric CO_2 concentration. In fact, they find a maximum strength in the MOC for a doubling of the CO_2 concentration, and further, that both for a doubling and quadrupling the MOC intensifies relative to the control climate (Fig. 16). However, in their model, the sensitivity of the MOC is found to be highly dependent on the climate forcing regime, with a much larger sensitivity for cold climates. This finding partly contrasts the results of Thorpe et al. (2001), though they did not explore the model response for the same forcing range.

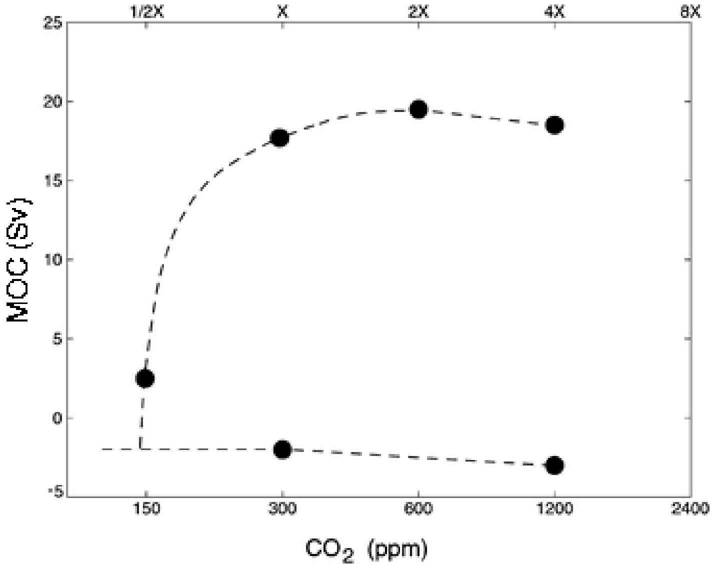

Figure 16. Intensity and multiple equilibria behavior of the Atlantic MOC obtained from half (1/2X), double (2X) and quadruple (4X) of preindustrial CO_2 concentration (X). The upper branch of points represents an active mode of the MOC resembling the present ocean state whereas the lower branch corresponds to a coexisting, inactive mode of the MOC. Figure modified from Stouffer and Manabe (2003).

The dominant processes acting to stabilize or destabilize the MOC have been shown to differ between models. Here, we will not attempt cover all suggested mechanisms or to order the strength of processes, instead we briefly go through the most robust mechanisms recently highlighted in relation to specific projections of future climate change scenarios (see e.g. Paul and Schulz (2002) for a recent discussion of the numerous ocean atmosphere feedbacks acting in the climate system).

The isolated effect of an enhanced hydrological cycle predicted by most climate models in response to increased greenhouse gas forcing is to weaken the MOC. At high latitudes this is related to a freshening of the ocean surface by two interrelated processes: direct freshening by increased precipitation and a partial suppression of open ocean convection. Hereby, the steric height difference decreases between the sinking and rising branches of the MOC and in turn, the MOC itself (Sec. 1). The same freshwater flux cause low latitudes to become more salty and acts to further reduce the meridional gradient in steric height, but likely more important, advection of anomalously saline water from low latitudes will oppose the freshening effect of the high latitudes and help maintain some deep water formation here (e.g. Latif et al. 2000). However, for the salt advection process to stabilize the MOC, upper ocean salinity advection has to be enhanced even though the MOC is reduced in strength. Such response would require that the salinity gradient is enhanced sufficiently relative to the decrease in the MOC, so that the two combined result in an enhanced salt transport in the upper, northward moving branch. Also, the meridional salinity transport within the wind driven ocean gyre circulation has been speculated to work more efficiently in the warm climate (Thorpe et al. 2001).

Two pathways of moisture transports are found important for the enhanced salinification of the low latitude Atlantic in the anthropogenically warmed climate. The dominant route is the meridional transport discussed above, but a significant change is also seen via an enhanced water vapor transport from the Atlantic to Pacific Ocean. This intensification is possibly associated with a change in the El Niño Southern Oscillation phenomenon (Latif et al 2000) or related to an increasingly strong trade wind regime in the tropical Atlantic (Thorpe et al 2001). Such net export of freshwater out of the low latitude Atlantic basin helps to maintain the salt water supply needed for deep-water formation in the Arctic Mediterranean without associated high latitude freshening. Consequently, this export acts to maintain an active Atlantic MOC. Large uncertainties in modeled precipitation and evaporation patterns make it an exceptionally difficult task to quantify the strength of these mechanisms.

A set of feedback mechanisms involving interconnected temperature and MOC changes have also been identified to work in the warming scenarios. An important factor in these is the temperature dependence of density. Near the freezing point, ocean density is high, but very insensitive to temperature changes, whereas there is a relatively strong sensitivity for less dense, warm water. If ocean temperature generally increases in the upper layer in response to increased greenhouse gas concentrations, the density contrast increases between the cold sinking and warm rising regions of the MOC. This dependence is part of the reason for the strong initial increase in the MOC seen in Fig. 16 for CO_2 going from half- to preindustrial values. Further, the strong nonlinearity also appears to be - at least partly - attributed to the inability of sea surface temperature to fall below the freezing point of sea water (-2°C). Especially in the colder climates (low CO_2) , this effect limits the temperature and thus density contrast between the sinking and rising regions of the MOC. Surface temperatures are, however, not expected to increase equally at high and low latitudes. Model surface air temperature response to increasing greenhouse gas concentration shows a concurrent picture of increasing sensitivity with increasing latitude. This common response of both atmosphere only- and coupled climate models is partly explained by the ice albedo feedbacks and by changes in cloud-cover affecting both the albedo and greenhouse characteristics of the atmosphere. The polar amplification tends to diminish the stabilizing effect of increased temperatures on the MOC.

The heat transport in the MOC itself is also identified as a stabilizing mechanism in some models (e.g. Thorpe et al. 2001). As the MOC weakens, less heat is transported northward and consequently water in the sinking region is colder and denser, but also the working of this mechanism is complicated by the fact that ocean density at high latitudes is fairly insensitive to temperature changes and that sea-ice acts as a thermostat on ocean temperatures.

A qualitative comparison between Fig. 2 and Fig. 16 is possible if we note that - among other changes - the freshwater flux increases with increasing CO_2. The apparent disagreement for low freshwater forcing can likely be attributed to the effects of the highly nonlinear, thermal feedbacks present in the CO_2 forced simulations but not in the experiment applying pure freshwater forcing. For enhanced forcing (higher CO_2 or freshwater flux) a similar (weak) decreasing tendency in the MOC is found in both models.

4.2 Abrupt changes in the ocean system

A number of coupled model studies have shown abrupt changes in the MOC either principally unforced, forced by gradual forcing changes or as response to often quite large artificial freshwater perturbations to the high latitude surface ocean. The latter type of studies are numerous whereas only a very limited number of studies have been reported, belonging to the former types and of interest in an assessment of the risk of future abrupt climate changes. Hall and Stouffer (2001) reported on what is to the knowledge of the authors the only fully coupled model study showing an abrupt climate event without external forcing, i.e. with fixed present day forcing. The abrupt - or extreme - event lasted 30-40 years in the 15.000-year simulation and was linked to a temporary shutdown of convection east of Greenland and subsequently rapid local cooling reaching 4°C on annual average at the peak of the event. Prior to and during the event, the North Atlantic atmosphere system was characterized by abnormally strong westerlies, associated with a positive mode of the model's NAO (see Section 2). In the model, the strong westerlies over the North Atlantic caused a positive anomaly of about 0.5°C in surface air temperatures over Europe and central Eurasia during the event.

Perhaps the most severe and abrupt change in the Atlantic MOC seen in simulations of the climate of the 21st century are found in a coupled climate model incorporating an interactive Greenland Ice Sheet (Fichefet et al 2003). In the model, the Greenland Ice Sheet responds to global warming by a net (time varying) freshwater flux to the high latitude Atlantic. The study therefore bear some resemblance to the studies applying an artificial freshwater perturbing of the North Atlantic ocean circulation, however, in the work of Fichefet et al., fluxes are modest and imposed as a dynamical response to global warming. The time series of the modeled MOC (Fig. 17) show a gradual reduction during most of the 21st century superimposed by decadal scale variability, in agreement with the IPCC projections (Fig. 15). At the very end of the century, a strong and abrupt decline in the Atlantic MOC is observed in the simulation incorporating a dynamical ice sheet. The decline is found to succeed a very large anomaly in the runoff from the ice-sheet. The drop in the MOC is preceded by a displacement of the main deep water formation site from east of the southern tip of Greenland to a region situated just south of Iceland. In some respects, similar displacements are also advocated to have played a role in abrupt climate variability during glacial climates (Ganopolski and Rahmstorf 2001, see Sec. 5) .

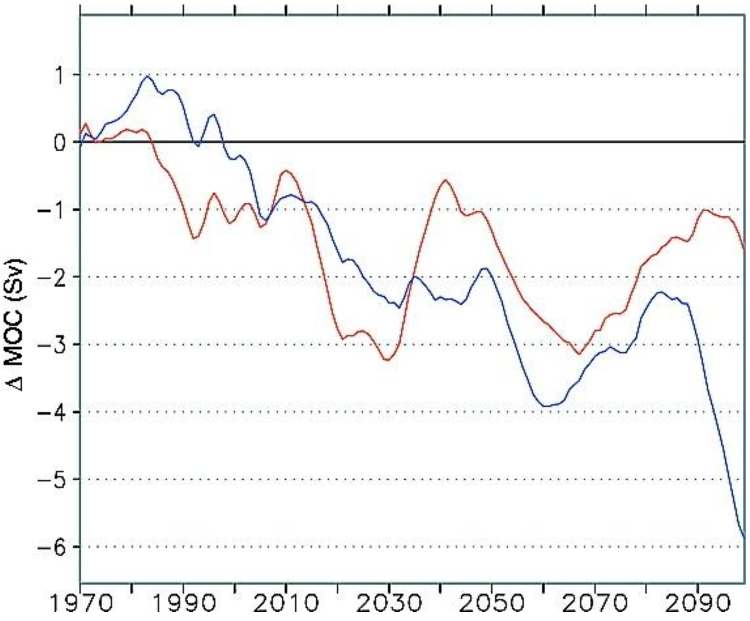

Figure 17. Anomaly of the North Atlantic MOC for a climate change projection into the 21st century. The anomaly is calculated as the difference between a control simulation without climate forcing and the projection. Simulations are shown for a model configuration with- (blue) and without (red) a dynamic Greenland Ice Sheet. (Modified from Fichefet et al. 2003).

The climatic impact of the abrupt decline in the MOC and associated heat transport is illustrated in Fig. (18) as the difference in temperature at the last five years of the 21st century between the model simulation with and without a dynamical ice sheet. Surface cooling in a range between 2 and 12°C are noticed over most of the northern North Atlantic and Arctic Ocean as well as the surrounding land areas including significant cooling over Scandinavia. The cooling is superimposed on the global warming pattern and, if seen relative to present day climate, all land areas except the eastern part of Greenland, will experience a warming, despite the abrupt decline in the MOC.

Both the study of Hall and Bryden (2001) and Fichefet et al. (2003) add to the knowledge of the behavior of the future climate, but they can be criticized in some key aspects relating to the model configuration and performance. In the study of Hall and Bryden, fixed flux corrections are applied to the model whereas Fichefet et al. experience a significant drift in their model without flux corrections. Also, the location of deep water formation areas is poorly represented in both models.

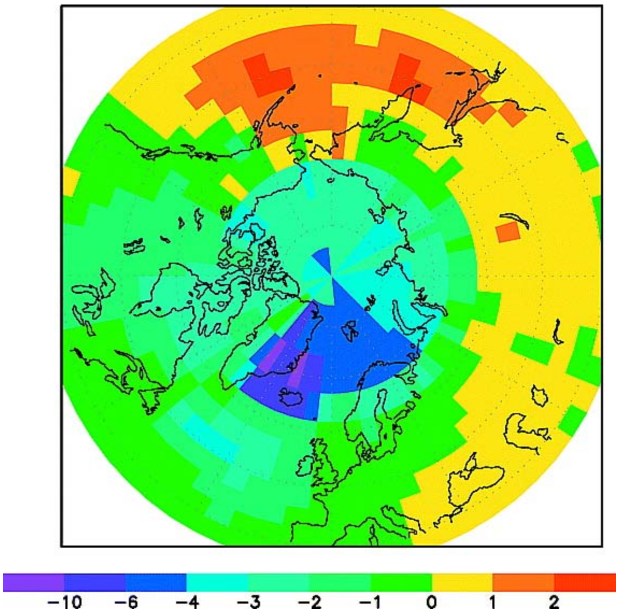

Figure 18. Impact on surface air temperatures from a strong decline in the North Atlantic MOC. From Fichefet et al. (2003).

A temporary shutdown of convection and a strong decline in the Atlantic MOC has also been noticed in a model without flux corrections, however, in response to an imposed doubling or a four fold increase in the carbon dioxide concentration (Stouffer and Manabe 2003). The period with a cease of convection differed between the two cases, lasting only for a few hundred years in the doubling experiment and for almost a millennium for the imposed quadrupling of CO2. In the latter case, a near extinction of the MOC was seen, but importantly, it did not collapse into the inactive, stable equilibrium shown to exist in the model. The resumption of the model convection and following spin-up of the MOC was aided by a gradual warming of the bottom waters as well as a slow increase in density contrast between the narrow sinking region near Greenland and the broad upwelling regions in low and southern latitudes. The increase in the density contrast was mainly due to an increase of temperatures at low- and southern latitudes.

5 THE ROLE OF THE OCEAN IN ABRUPT CLIMATE CHANGE

Public debate regarding climate change has focused on the climatic consequences of greenhouse gas emissions and their impacts on the planet, policy makers have given less attention to the possibility that large climate changes could occur quickly, either by natural causes or triggered by the human interferences in the climate system. However, a recent attempt to assess the geopolitical and socio-economic consequences of an envisaged, abrupt climate change events made by Schwartz and Randall (2003) received significant media attention. Such assessments are however rare though the scientific community has been aware of the risk and studied past climate variability intensively for several decades. A series of excellent reviews on this research have been published in the recent years (Clark et al. 2002, Rahmstorf 2002, Alley et al. 2003, Rahmstorf and Sirocko 2004). Here, we will introduce the evidence of abrupt climate variability during the Holocene warm period into the last glacial epoch, emphasizing the evidence pointing towards the oceans playing a dominant role. Finally, we will briefly discuss modeling results giving insight into the ocean reorganizations associated with glacial climate variability.

5.1 The Holocene

Our knowledge of abrupt climate change comes from various types of proxy records of past (paleo), e.g. temperature, storminess and precipitation patterns, with the most well known records stemming from analysis of the isotopic and chemical composition of ice cores retrieved from the Greenland ice sheet (Figure 19). During the deglaciation these records show that climate went through a series of abrupt shifts, with the Bølling-Allerød (BA) warm period and the Younger Dryas (YD) cold reversal being the most prominent. In comparison, Holocene climate changes have been less severe, with the 8.200-Year Event as an exception, the event upon which Schwartz and Randall (2003) based their assessment of the implications for society of abrupt climate change. The intensity of the event was about half of the YD cold reversal. Over Greenland, temperature dropped 6°C whereas the temperature depression over the Norwegian Sea adjacent to the northern Scandinavia is estimated to 2°C (Klitgaard-Kristensen et al. 1998). Most evidence support that, like the YD event, the 8.200-Year Event had a global impact (Alley et al. 1997) and that it was accompanied by a drastic reduction in precipitation in Northern Africa and Asia. The Little Ice Age (LIA) is the most recent in the long series of widespread millennial scale climate anomalies that punctuated the Holocene epoch (O'Brien et al. 1995), and the only event known from historical records and extending into the period of modern instrumental observations. The LIA covered the northern hemisphere and was associated with a modest cooling of about 1°C (e.g. Dahl-Jensen et al. 1998) though with significant impact on society mainly due to unusually harsh winters, increased sea ice coverage and poor crop yields (Denton and Karlén 1973, Grove, 1988).

Various approaches are used to establish possible connections between climate variability and ocean circulation changes. The more direct sources of evidence for an altered circulation stems from analysis of shells preserved through time in deep ocean sediments. Ocean floor sediments are composed of both biogenic and terrigenous material, whereby the biogenic component includes the remains of planktonic (near surface living) and benthic (near bottom dwelling) organisms. For paleoclimatic studies, preserved calcium carbonate rich shells of foraminifera (a form of zooplankton) constitute a valuable source of information. Records of hydrographic variability reconstructed from such shells have been studied extensively. Two types of analysis are commonly used: the isotopic composition of oxygen and carbon in the calcium carbonate and the relative abundance of warm and cold water species. Both techniques rest upon knowledge of the organisms in the present day ocean and to some extent, the present isotopic tracer characteristics of the dominant water masses. By analyzing both surface living and bottom dwelling organisms from sediment cores retrieved at various ocean depths, paleoceanographers can, in principle, establish both a vertical and horizontal view of the ocean through time.

Especially at low ocean depths shells are poorly preserved due to the acidity of the water and optimal core sites are usually found in the deep ocean parts.

Analysis of cores drilled in coral reefs have documented large melt water pulses likely originating from the Laurentide or Fennoscandian ice sheet during the termination of the BA warm period and onset of the YD cold period (see for example Fairbanks 1990). These pulses are believed to have occurred as outburst floods from ice-dammed lakes and with our knowledge of the ocean system, the Atlantic circulation would most likely be perturbed by these pulses. An explanation of the YD cold reversal as a perturbation or complete shutdown of the heat transport associated with the MOC and subsequently atmospheric cooling also finds support in the paleoceanographic record. Isotopic studies of the type discussed above has established that production of deep water in the North Atlantic was weak if not absent during the YD cold reversal (e.g. Boyle and Keigwin 1987, Bond et al. 1997). A series of modeling efforts partly support the interpretation by paleoceanographers (e.g. Manabe and Stouffer 1997,1999, Schiller et al 1997, Ganopolski and Rahmstorf 2001 and Vellinga and Wood 2002).

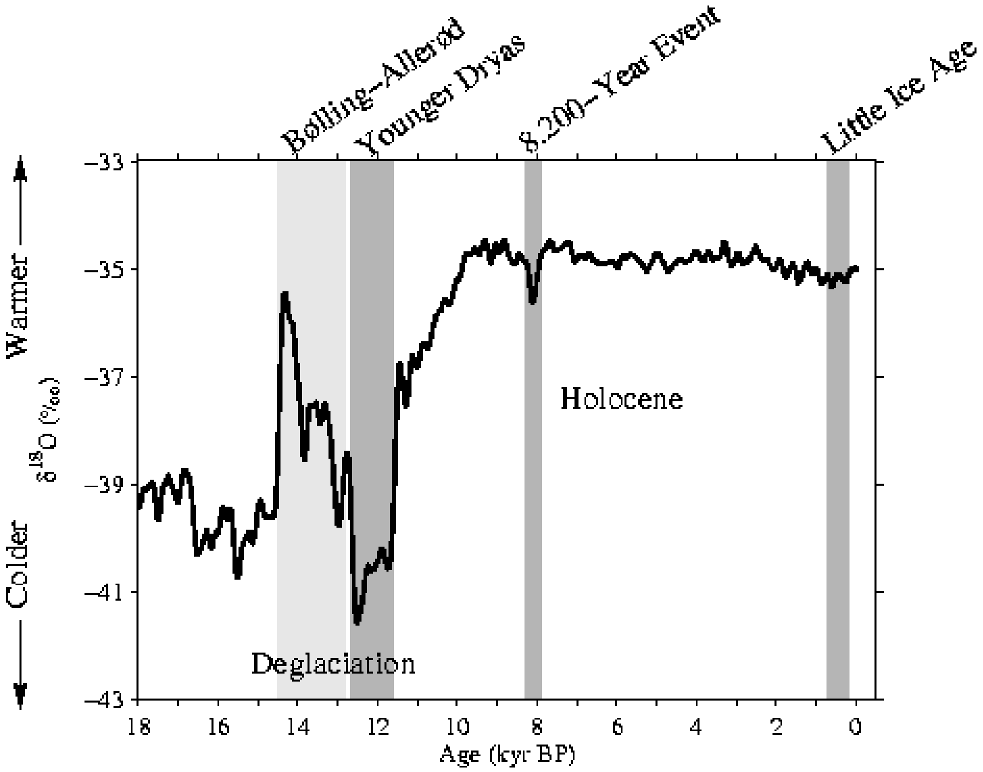

Figure 19. Climate variability through the deglaciation and Holocene warm period. The curve shows the oxygen isotopic composition of ice from the GRIP ice core Greenland (Dansgaard et al. 1993), a proxy variable for temperature. The absolute temperature jump from the warm Bølling-Allerød period into the Younger Dryas is estimated to be at least 15°C.

Of the various Holocene events, the 8.200-Year Event and the LIA are the only two candidates well enough known to search for associated MOC changes. Many indicators of climate change show a similar quantitative geographical response of the climate system between the 8.200-Year Event and the YD cold reversal, a fact which makes it likely that they might both be associated with a freshwater induced collapse of the MOC (e.g. Alley et al. 1997). Corroborative evidence exists indicating that a large melt water pulse from the Hudson Bay occurred nearly synchronous with the 8.200 Year Event (Barber 1999).

The published paleoceanographic literature on ocean variability during the Holocene has been reviewed by Keigwin and Boyle (2000). The authors state that it is premature to conclude that there actually was a change in the MOC associated with the LIA and further, that there are presently no paleochemical data that suggest the production of deep water in the Atlantic to actually being curtailed 8.200 years ago.

A part of the explanation for the inconclusive review by Keigwin and Boyle is found in the poor quality of the ocean sediment cores. Cores covering the Holocene usually have a low sedimentation rate relative to cores covering the glacial period. The low sedimentation rate complicates high-temporal sampling of the cores and subsequently dating and core to core comparisons. This is because when climate is warmer and sea level is higher, shallow water coastal regions trap sediments that in glacial climates would be exported out of the continental shelf to the abyss. However, more recent studies have overcome some of these issues and will be discussed below.

The quasi-periodic, millennial scale variability during the Holocene is hardly identifiable in the Greenland ice core oxygen composition (Fig. 19), where only the 8.200-Year Event and the LIA stands out. However, the concentration of impurities like the sea-salt Na in the ice, which is a good measure of the atmospheric storminess and hence climate, document such quasi-periodic variability (O'Brien et al. 1995, see also Fig. 20). Especially the LIA but also the 8.200-Year Event stands out in these glaciochemical data, with the LIA being the most abrupt off all events during the Holocene. Of the other events, the period from 5000 to 6100 years BP was especially winter like and characterized by an expanded polar vortex or intensified meridional flow in the atmosphere (O'Brien et al. 1995). Figure (20) reveals clear reductions in the amount of NADW production synchronous with the cold phases seen in the climatic records and with sea-ice advance. The NADW which in the present day ocean fills most of the subsurface North Atlantic are characterized by a $\delta^{13}C$ (an expression of the ratio between isotope ^{13}C versus ^{12}C in calcium-carbonate shells) value of about 1. The $\delta^{13}C$ reductions seen in the record are believed to correspond to periods of reduced ventilation i.e. production of NADW, with the most significant event between about 5 and 6 thousand years ago, coinciding with the most significant Holocene climate event.

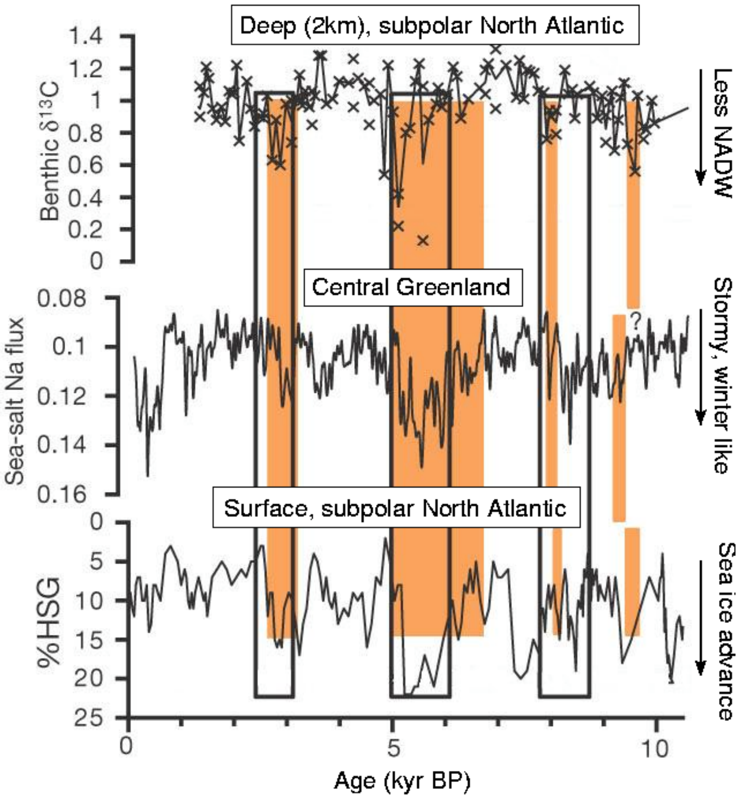

Figure 20. Holocene climate records revealing linked variability in the amount of deep water formation in the North Atlantic (top), winter like conditions in the atmosphere above Greenland (middle) and sea-ice advance in the sub-polar Atlantic (bottom). Shading highlight low NADW production events, i.e. low benthic δ^{13}C and rectangles extreme winter-like conditions deduces form Greenland ice core records, among these, the sea-salt Na flux (modified from Oppo 2003).

The δ^{13}C (~NADW production) record in Fig. (20) do not cover the LIA and though several other studies have attempted to constrain millennial scale NADW variability during the Holocene, results have been equivocal. Keigwin and Boyle (2000) noted that it is possible that reductions in the NADW formation occurred during some cold events. The more recent results by Oppo et al. (2003) shown here together with other dedicated studies of the (late) Holocene period (e.g. Marchitto and deMenocal 2003) reach a less ambiguous view of the correlation between Holocene climate change and NADW ventilation, including the LIA.

It is of key importance to note that - except perhaps the 8.200-Year Event - the Holocene reductions in NADW production occurred in the absence of forcing by large ice sheets and, hence, are not obviously linked to massive freshwater discharges likely explaining the YD cold reversal and possibly the 8.200-Year Event. The correlation between Holocene climate change and deep water ventilation either suggest a prominent control on climate by ocean circulation or, that the Atlantic MOC is quite sensitive to surface forcing (Oppo et al. 2003), but the question of cause and effect remains unsettled.

5.2 The last glacial period

In the northern hemisphere, the cold glacial climate was punctuated by abrupt warm periods of millennial time scale during which temperatures reached peak values nearly resembling the present day climate despite massive continental ice-cover (Fig. 21a). Transitions between cold and warm periods (Dansgaard-Oeschger (DO) Events) have been found to occur within a few decades. A remarkable feature of the glacial climate variability is the asynchrony between the two hemispheres: while the northern hemisphere had plunged into a cold phase, the southern hemisphere slowly warmed, and during the warm phase of the northern hemisphere DO Events, the southern hemisphere slowly cooled (compare Fig. 21 a & b). The asynchrony in warming suggests a change in the cross equatorial heat transport. We know that such transport mainly occurs via the ocean overturning and in the present day ocean, predominantly in the Atlantic associated with the Atlantic MOC (Fig 7 & 8, Sec. 2).

Ocean sediment cores from the Atlantic show layers with high concentration of ice-rafted debris (IRD) which have been interpreted as periods of increased iceberg calving from the continental glaciers. The most prominent of these events are known as Heinrich Events (H5-H2 indicated in Fig. 21) and are associated with global sea-level increase of up to ~10m (Lambeck and Chapell, 2001). These events occur at the culmination of long periods of Greenland cooling and, hence, precede abrupt warming. Layers with increased IRD are also found during the cold phase of the more frequent DO events (Bond and Lotti, 1995) and thus far more frequent than likely internal oscillations in the mass balance of the continental glaciers (MacAyeal 1993). These findings compromise the suggestion (Broecker et al. 1990, Kreveld et al., 2000) that glacier instabilities, massive iceberg calving and hence freshwater forcing of the high latitude may pace the millennial-scale cycle characterizing the glacial climate variability. Thus, it seems more likely that the occurrence of calving events reflect the operation of climate upon unstable ice sheets than vice versa (Bond and Lotti, 1995).

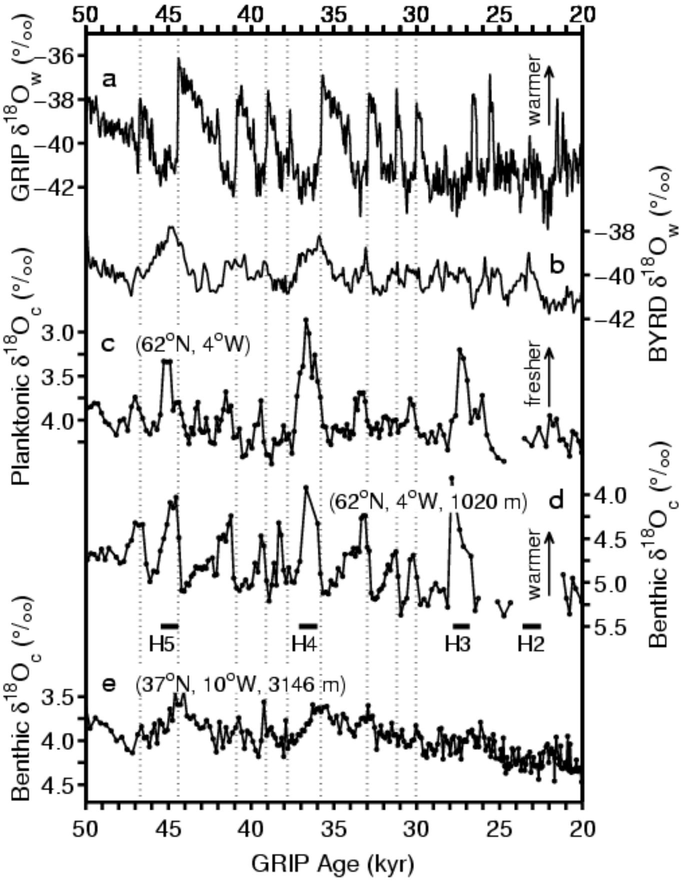

Figure 21. Abrupt northern hemisphere climate changes and inter-hemispheric asynchrony of climate variability during the last glacial period as seen in ice core record from GRIP, Greenland (a), Byrd, Antarctica (b) and Atlantic ocean sediment cores (c-e). The curves show the oxygen isotopic composition of ice, $\delta^{18}O_w$,(a,b), a proxy variable for temperature, and the isotopic composition of the oxygen in carbonate shells of planktonic and benthic organisms preserved in the sediments, $\delta^{18}O_c$. Likely hydrographic interpretations of the respective $\delta^{18}O_c$ records are indicated with arrows and text in the figure (from Olsen et al. 2004).

The oxygen isotopic record from ocean sediment cores (Fig. 21 c-d) gives some insight into the ocean reorganizations during the glacial period. The interpretation is however ambiguous: low or depleted values reflect a relatively fresh water-mass, warm water, or water formed by way of brine rejection. Following Olsen et al. (2004), the large decreases in the planktonic (near surface) $\delta^{18}O_c$ record (Fig. 21c) during the cold phase of both weaker and stronger DO events can be interpreted as a substantial freshening of the surface, high latitude Atlantic. At intermediate depths - about 1000m - (Fig. 21 d), the isotopic signal most likely reflect warming. The combination of surface freshening and high latitude interior warming during atmospheric cold phases suggest a simultaneous reduction in deep-water formation. An alternative explanation ascribes the variation in $\delta^{18}O_c$ to stem from changes between open-ocean deep-water formation in the warm phases – like seen in the Greenland Sea – and deep water formation by way of brine rejection during sea ice formation in the cold phase – as observed in the Arctic Mediterranean (e.g. Dokken and Jansen 1999).

While the $\delta^{18}O_c$ record at intermediate depths exhibit events with saw tooth shape, terminating with rapid increases tied to rapid Greenland warmings, slow benthic $\delta^{18}O_c$ variability at about 3000m (Fig. 21 e, off the coast of Portugal) tend to track the slow cooling and warming in Antarctica, most clearly seen for the stronger events (Shakleton et al. 2000). It is widely accepted that the variability in the deep North Atlantic is linked to invasion of cold Antarctic Bottom Water - depleted in $\delta^{18}O_c$ by brine rejection and ice shelf melting - during cold northern hemisphere phases and, a relative dominance of the North Atlantic Deep Water mass at this depth during the warm phases (e.g. Olsen et al. 2004). Independent evidence for such an alternation of water masses can also be seen in the North Atlantic benthic $\delta^{13}C$ record (Sarnthein et al. 2000). In combination, these hydrographic proxies suggest weak production of NADW during the cold phases give way for invasion of AABW connected with a shallowing of the NADW branch of the Atlantic MOC, whereas onset of NADW formation cause a spin-up of the MOC associated with deepening and subsequently retreat of AABW from the North Atlantic.

The leading, detailed understanding of the mechanisms behind the abrupt climate changes during glacial times accordingly involves changes in the strength of the MOC. The mechanism advocated most strongly involves shifts in the location of convection and subsequently changes in the MOC (e.g. Ganopolski and Rahmstorf 2001, Clark et al. 2002). With the “CLIMBER” model of intermediate complexity, Ganopolski and Rahmstorf were able to show that under glacial forcing, two bifurcation points and three modes of ocean operation existed in the model and further, that only weak periodic forcing was needed for the model to exhibit abrupt shift between ocean circulation states with convection north and south of the Greenland-Scotland Ridge, respectively. The resulting climate signal resembled well the variability seen in ice-core proxy data, including the abrupt saw-tooth shaped warming events and the inter-hemispheric asynchrony. Furthermore, in the Atlantic, alternating influence of NADW and AABW is found in their model in accordance with the proxy data. This behavior resulted from the model glacial climate state mapping close to one of the model bifurcation points, thus being prone to highly nonlinear behavior. Important for assessing future changes, their results did on the other hand also point out, that in the pre-industrial climate, the coupled model system show a much simpler hysteresis behavior to external forcing with only one bifurcation point (Stommel bifurcation, Fig. 2) and, that the pre-industrial climate state maps far from the critical threshold. The inter-hemispheric asynchrony in warming and cooling as well as the alternation of AABW and NADW in the North Atlantic are also found in more advanced models when the deep water formation in the North Atlantic is perturbed, but the sensitive behavior of the CLIMBER model as well as the shifts in convection sites have not been reproduced.

In summary, both modeling results and direct interpretations of the paleorecord shows that it is highly likely that changes in the oceanic circulation were responsible for the glacial, millennial scale sea-saw behavior between high- northern and -southern latitudes. Ice-age cycles, however, are associated with synchronous cooling and warming in both northern and southern hemispheres. This includes the most recent global glaciation which peaked approximately 22.000 years ago. In turn, the global or inter-hemispheric synchrony indicates that changes in ocean circulation are an unlikely triggering mechanism for global glaciation. Instead, the mechanism is believed to be linked to slow variations in the Earth's orbit with a timescale of about 100.000 years, i.e. corresponding to the periodicity of ice-ages. This variation has little impact on the total solar insolation received by the Earth, but the variation serves to redistribute the insolation in time and space. In particular, it appears that periods of weak northern hemisphere summer insolations are required for glaciation to initiate; The northern hemisphere is where the most ice forms and summer where melting dictates the limit of permanent snow or sea-ice coverage. Ocean circulation changes probably played a role, but most likely, changes in greenhouse gases in combination with the ice-albedo feedback on climate were primarily responsible for the amplification and globalization of the climatic changes induced by insolation (e.g. Archer 2000 and Alley 2003). Thus, our leading understanding of glacial cycles tell us that the present climate is not prone to such major transitions and will likely not be so for the next 5.000-50.000 years (Berger and Loutre 2002). Warm summer temperatures connected with the high concentrations of atmospheric CO_2 will effectively inhibit massive sea-ice and snow coverage on land and ocean and, ultimately, the build up of glaciers (see for example Weaver and Hillaire-Marcel and references herin).

Above understanding of the origin of the glacial climate state imply that cold climates are more sensitive to forcing changes. In fact, this is also what has been found in climate models (e.g. Spelman and Manabe 1984, Stouffer and Manabe 2003). Therefore, in the present climate, possible abrupt climate changes due to a collapse of the Atlantic MOC may well be quite different from abrupt climate change in the past. Further, independent of the results of Ganopolski and Rahmstorf (2001), it has been suggested by some researchers that abrupt variability in the Atlantic MOC is only possible during glacial periods, related to the dynamical impact on the ocean circulation by the closure of the Bering Strait connection between the North Atlantic and Pacific Oceans (Shaffer and Bendtsen 1994, de Boer and Nof 2004). The present depth of the Bering Strait is only 50m and lowered sea-level associated with large storage of water on land by continental glaciers caused it to dry out during most of the glacial period. Thus, in contrast to the present climate, the vulnerable climate of the cold glacial period was likely formed by an unstable Atlantic circulation in combination with an enhanced ice-albedo feedback. For completeness, it should be noted that cloud feedbacks on climate could complicate the simple relationship between climate sensitivity and climate state sketched above (e.g. Meehl et al. 2004).

6 DISCUSSION AND CONCLUSIONS

Indications of significant changes in the characteristics of the major Atlantic water masses since the middle of the last century are increasing. These changes may be early imprints of global warming. Alternatively, or in addition, the observed patterns of change could reflect a change in the strength of the Atlantic MOC. Most of the indications of ocean circulation changes are indirect, that is, inferred from changes in hydrography. However, some direct observational evidence of changes in the central components of the Atlantic MOC has also been reported:

- In the Greenland Sea, deep convection has been much reduced during the last three decades. This is implied by increasing bottom temperatures (Fig. 22) and salinities in the deep parts of the Greenland Sea. The lack of local production of deep water in the GIN seas has given way to an inflow of water from the Arctic Ocean (Meincke, et al., 1997).
- At the Faroe-Bank Channel branch of the dense overflow waters across the Greenland-Scotland ridge, a 20% reduction of the flux has been reported since 1950 (Hansen et al. 2001). To show this dramatic reduction of one of the fluxes feeding the Atlantic MOC, Hansen et al. coupled a long time series of hydrographic data from north of the Faroe-Iceland Ridge with a limited set of direct flux measurements in the Channel. A similar trend is not documented for the Denmark Strait branch of the overflow, however, there are no indications of a compensating enhancement in this branch either (Girton et al 2001, Dickson et al. 2002). Recently, it has been found that the Faroe-Bank Channel overflow has caught up in strength within the last two years (B. Hansen and D. Quadfasel, personal communication).
- Curry et al. (2003) published the most complete study up to date of recent changes giving some insight into the possible changes in the Atlantic MOC. By comparing observations on a north-south transect through the Atlantic from the 1950s against data from the past decade, they found a remarkable increase in salinities at the evaporative low latitude regions of

> the Atlantic as well as evidence of freshening over much of the water column at both northern and southern high latitude regions.

The high latitude freshening identified, among others, by Curry et al. (2003) has been attributed to some combination of enhanced wind-driven export of sea-ice or freshwater from Arctic, increased precipitation and elevated river discharges. Some of these changes can be associated with the exceptionally high NAO index (Fig. 9) of the nineties (Marshall et al. 2001, Peterson et al. 2002) but might also reflect and increase in the atmospheric hydrological cycle or slowdown of the Atlantic MOC.

Also, on the Atlantic scale, the pattern of hydrographic changes reported by Curry et al. (2003) is consistent with an increase in the hydrological cycle whereby fresh water has been lost from the low latitudes and added at high latitudes at a pace exceeding the ocean's circulations ability to compensate. Dickson et al. (2003) combined temperature and salinity measurements from the same transect through the Atlantic to derive a history of the steric height gradient between 32°S and 60°N. Their results suggest that there has been little sustained change in the gradient in recent decades and consequently, little evidence for changes in the strength of the Atlantic MOC.

The hydrographic explanation for the lack of change in the meridional gradient in steric height is mainly to be found in the Labrador Sea region, one of the two major deep water formation regions in the Atlantic. Contrary to the Greenland Sea where the occurrences of convection events since about 1970 has been few or only reaching shallow depths (increasing temperature in Fig. 22), the Labrador Sea has cooled significantly during the past decades due to resumed deep water formation. The resumption followed a period of low NAO index unfavorable for convection here (Sec. 2).

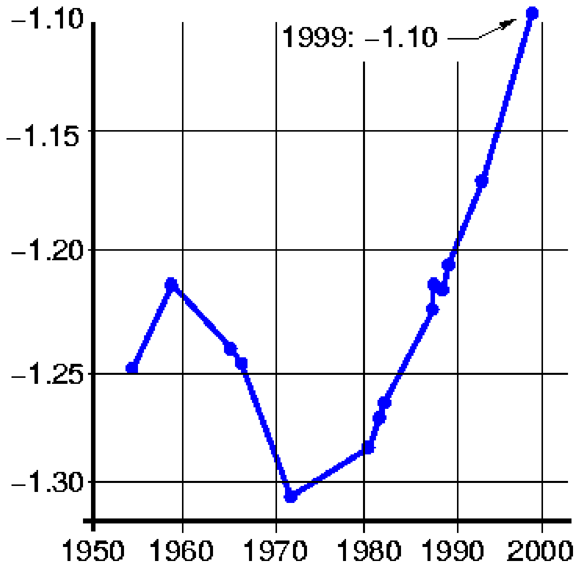

Figure 22. Mean temperature of the water below 3000 m in the central Greenland Sea (reproduced from Buch et al, 2001)

Coupled model simulations dedicated to reproducing the ocean variability during the last century have given some insight to the ocean processes involved in the observed changes in the Atlantic Ocean. A recent study by Wu et al. (2004) offers a rather controversial interpretation. From an ensemble of simulations using a state of the art climate model, they closely reproduce the observed pattern of changes in hydrography. But, accompanying the high latitude freshening trend, the Atlantic MOC shows an unexpected increase in strength since about 1960 rather than a decreasing trend which would be expected. However, a slow decline in the MOC starting in the 1990s is seen in their projections into the 21st century. The late 20th century upward trend in the MOC is diagnostically associated with an increased north-south, upper ocean density gradient between the sub-polar North Atlantic and the mid-low latitude which, however, is not identifiable in the observations. Wu et al. conclude that their model simulations do not support an interpretation of the observed freshening trend as an early signal of climate change due to human activities.

The variability in the volume exchanges between the North Atlantic and the Nordic Seas during the last 50 years has also been investigated in a number of synoptic forced, global ocean-sea ice models (e.g. Nilsen et al. 2003 and Zhang et al. 2004). These models generally resolve both the overflow pathways at the Greenland-Scotland Ridge as well as the location of convection sites. However, a rather different response is found between such models to the imposed atmospheric variability during the 20th century. Where Nilsen et al. find a decrease of the inflow of Atlantic Water to the Nordic Seas since the fifties Zhang et al. report the model inflow to increase with a steady rate. Interestingly, Zhang et al. simulate a decrease in the dense water outflow at the Faeroe Bank Channel in qualitative agreement with the observations by Hansen et al. (2001). In the model, the increased inflow is balanced by an increase in the Denmark Strait branch of the deep overflow, a feature yet to be documented by observations. Thus, these model results are equivocal concerning the present direction of change of the Atlantic MOC. Further, they imply that interpretations of isolated estimates of changes in overflow intensity in terms of changes in the Atlantic MOC are inherently ambiguous, at least until a robust correlation between the various branches of in- and outflows is established. To establish such correlations and to help us foresee future changes, it is of vital importance to keep monitoring the essential transports in the system and to analyze the changes with aid from modelers.

On the basis of model projections, the present consensus concerning the future of the Atlantic MOC is fairly similar to the conclusions drawn by the IPPC panel in 2001 namely, that the MOC will weaken over the next century in response to the increased greenhouse gas forcing. The more recent model studies falls within the range of previous predictions (Fichefet et al. 2003, Wood et al. 2003, Wu et al. 2004, Thorpe et al. 2004), supporting the conclusion. There is, however, little agreement between models on how much the MOC will weaken. Furthermore, models showing a similar tendency in the MOC for the same forcing have been documented to do so for different reasons. Both Dixon et al. (1999) and Wu et al. (2004) found the decrease in the modeled Atlantic MOC to rely mainly on changes in freshwater fluxes whereas changes in heat fluxes dominated the model MOC response in the study of Mikolajewicz and Voss (2000). Thorpe et al. (2001) and Stouffer et al. (2003) find that warming and freshening contribute roughly equally to the Atlantic density changes causing the MOC to decrease. These points tell us to exert great caution when attempting to synthesize the range of model predictions.

When seen in isolation, a reduced strength of the Atlantic MOC in the 21st century will according to all model projections have a general cooling effect on the northern, high latitude climate. However, it should be stressed, that for all models showing a gradual reduction in the strength of the Atlantic MOC, this cooling is found only to slow down the global warming trend (e.g. Wood et al. 2003, Fichefet et al. 2003). Thus, in the coupled ocean atmosphere model system simulated by GCM's, surface warming is predicted almost everywhere at the end of the century in response to IPCC forcing scenarios.

On a regional scale, model disagreement in the predictions of the future climate is substantial. However, on spatial scales corresponding to the scale of the NAO pattern in the Northern Hemisphere, a tendency is found of an enhanced positive NAO mode in a majority of the modeled scenarios (e.g. Gillett et al. 2003, Osborn, 2003, Sorteberg et al. 2004). This growing consensus amongst modelling groups has emerged since the publication of the IPCC Third Assessment Report. Here, it was concluded, that there was not yet a consistent picture of the ability of coupled models to reproduce the observed upward trend in the NAO index (Cubasch et al. 2001). It is further indicated from modeling studies that NAO like changes in pressure patterns over the Atlantic are linked to the slow variation in water temperatures, as the ocean currents rearrange the warm and cold ocean patterns that serve to guide the atmosphere in its preferred modes of oscillation (e.g. Czaja et al 2003, Gillet et al. 2003). An intimate link is thus suggested between the hydrography, ocean circulation and the dominant pattern of variability of the Northern Hemisphere atmosphere, the NAO. Such a link indicates that even relatively small changes in the ocean circulation can have a significant indirect influence on the regional climate via atmospheric reorganizations.

Advection by the atmospheric circulation is a requisite for bringing the warm maritime air from the North Atlantic into the coasts of Europe. Above we have argued for the role of the ocean in supplying part of the heat warming the atmosphere in winter and opposing sea-ice expansion. However, it has recently been argued that ocean heat transports contribute only little to the mild climate of Europe as opposed to the much harsher climate of the North American Continent at similar latitudes, Fig. 1, (Seager et al. 2002). The authors address the question using atmospheric circulation models coupled to a non-dynamic mixed-layer ocean model incorporating fairly simple descriptions of the sea-ice extent. In this type of models, a substitute for ocean heat transports can be artificially added or removed in the budget of the mixed layer. Such model configurations simulate the present atmospheric circulation well when applying oceanic heat fluxes derived from the present temperature distribution. However, they are inferior to coupled GCM's and are not suitable to describe climate states where the ocean circulation and the associated heat transport changes significantly from the present climate (see Rhines and Häkkinen 2003 for a discussion). Seager et al. suggested that ocean heat transports (mainly in the Atlantic) warms winter over land in a quite zonally uniform way and thus cannot account for relatively warmer climate of Europe. Even though this is likely not correct, the work is sometimes misquoted in terms of the role of the ocean in the climate system. Seager et al. find that removal of the ocean heat transport cause an average cooling of 6°C north of 35°N. If we note that the Little Ice Age was only about 1 to 2°C colder than average, this change is severe. Nevertheless, Seager et al. argue that ocean heat transports have “little impact”.

6.1 Conclusions

The two questions raised in the text concerning the future of the Atlantic Meridional Overturning Circulation in the anthropogenically warmed climate have partially been answered. Firstly, a steadily growing number of model simulations from gradually improved climate models support the prediction of a gradual decline in the strength of the Atlantic MOC. Secondly, abrupt climate change due to thresholds in the ocean system is a risk of high impact which cannot be ruled out. Recent research, however, support the scientific view that abrupt changes in the Atlantic MOC within the next century is a highly unlikely response of the climate system to global warming.

The rate at which the Atlantic overturning circulation is expected to decline is, however, associated with large uncertainties and hence also the climatic impact. On a regional scale or when considering the response of specific processes, the uncertainties in the predictions of the ocean system become even greater. Regardless the different rates of decline, most if not all model projections show an atmospheric surface warming almost everywhere at the end of the century in response to IPCC forcing scenarios. The same model projections reveal a tendency of the atmospheric circulation to rest in the high NAO mode as the climate warms. In northern Europe, high NAO conditions are associated with a relatively mild and wet winter climate. This tendency is possibly linked to changes in ocean temperatures or currents, but might also reflect a purely atmospheric response.

The estimated risk of abrupt climate change is based on the result that only a few relevant model simulations have shown abrupt changes in the MOC. However, it should be stressed that proxy data indicate occurrences of reduced North Atlantic Deep Water production in the later part of the Holocene. Concurrent with these episodes, the northern high-latitude experienced an anomalously winter like climate. The existence and details of these episodes are still debated and their cause unknown as they cannot obviously be linked to massive freshwater discharges from continental ice-caps which most likely explain earlier events.

6.2 Research initiatives

The ongoing European oceanographic research initiatives focusing on monitoring and modeling the North Atlantic circulation and Atlantic MOC are primarily gathered within the international research programs, ASOF (Arctic/Subarctic Flux Study), NOClim (Norwegian Ocean and Climate project) and Rapid-MOC (Projects for Monitoring the Atlantic Meridional Overturning Circulation). ASOF is a subprogram of inter-SEARCH (International Study of Environmental Arctic Change) and an endorsed project of CLIVAR (Climate Variability and Predictability Study) as part of the wider World Climate Research Programme. Rapid-MOC and NOClim have emerged from a bi-lateral UK-Norway initiative on Rapid Climate Change, Rapid-MOC being founded by the UK Natural Environment Research Council and the NOClim programme by the Norwegian Research Council.

MOEN (Meridional Overturning Exchange with the Nordic Seas) is one of three self-contained components of the European component of ASOF supported by the European Commission under the Fifth Framework Programme. MOEN is also the only of such projects with an active Danish participation - by the Danish Meteorological Institute.

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