Variability of the Thermohaline Circulation (THC)

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Abstract: Europe's relative warmth is maintained by the poleward surface branch of the Atlantic Ocean thermohaline circulation. There is paleoceanographic evidence for significant variability and even shifts between different modes of thermohaline circulation. Coupled ocean-atmosphere climate modelling allows first insight into the relative role of the various drivers of the Atlantic thermohaline circulation variability, i.e. the North Atlantic Oscillation, the tropical Atlantic variability, the ocean basin exchanges, small scale processes like high-latitude convection, overflows and mixing as well as effects of changes in the hydrological circle, the atmospheric CO_2-content and solar radiation. The strong need for continous model improvement requires concerted efforts in ocean time series observations and relevant process studies. New instrumentation and methods, both for *in situ* measurements and remote satellite sensing are becoming available to help on the way forward towards as improved understanding of North Atlantic climate varibility.

Rationale

About 90 % of the earth's population north of latitude 50 N live in Europe. This is a consequence of its climate which is 5 - 10 degrees warmer than the average for this latitude band, the largest such

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anomaly on earth (Fig. 1). A change or shift of our climate is thus likely to have a pronounced influence on human society. Europe's relative warmth is maintained by the poleward surface branch of the ocean thermohaline circulation (THC).

Most projections of greenhouse gas induced climate change anticipate a weakening of the THC in the North Atlantic in response to increased freshening and warming in the subpolar seas that lead to reduced convection (Rahmstorf and Ganapolski 1999; Manabe and Stouffer 1999). Since the overflow and descent of cold, dense waters across the Greenland-Scotland Ridge is a principal means by which the deep ocean is ventilated and renewed, the suggestion is that a reduction in upper-ocean density at high northern latitudes will weaken the THC (Doescher and Redler 1997; Rahmstorf 1996). However, the ocean fluxes at high northern latitudes are not the only constituents of this problem. Interocean fluxes of heat and salt in the southern hemisphere, wind-induced upwelling in the circum polar belt and atmospheric teleconnections also influence the strength and stability of the Atlantic overturning circulation (Latif 2000; Malanotte-Rizzoli et al. 2000).

Unfortunately, our models do not yet deal adequately with many of the mechanisms believed to control the THC, and our observations cannot yet supply many of the numbers they need. The problem lies in the wide range of spatial and temporal scales involved. Remote effects from other oceans and feedback loops via the atmosphere that affect the THC require a modelling on a global rather than a regional scale. Smaller scale processes such as exchanges through topographic gaps, eddy fluxes and turbulent mixing must either be resolved or properly parameterised. Our present instrumental observations are even insufficient to detect whether or not the THC is changing at all. Palaeoclimate records, however, show that massive and abrupt climate change has occurred in the northern hemisphere, especially during and just after the last ice age, with a THC change as the most plausible driver. Both paleo-climate records and models suggest that changes in the strength of the THC can occur very rapid, within a few decades (Rahmstorf 2002).

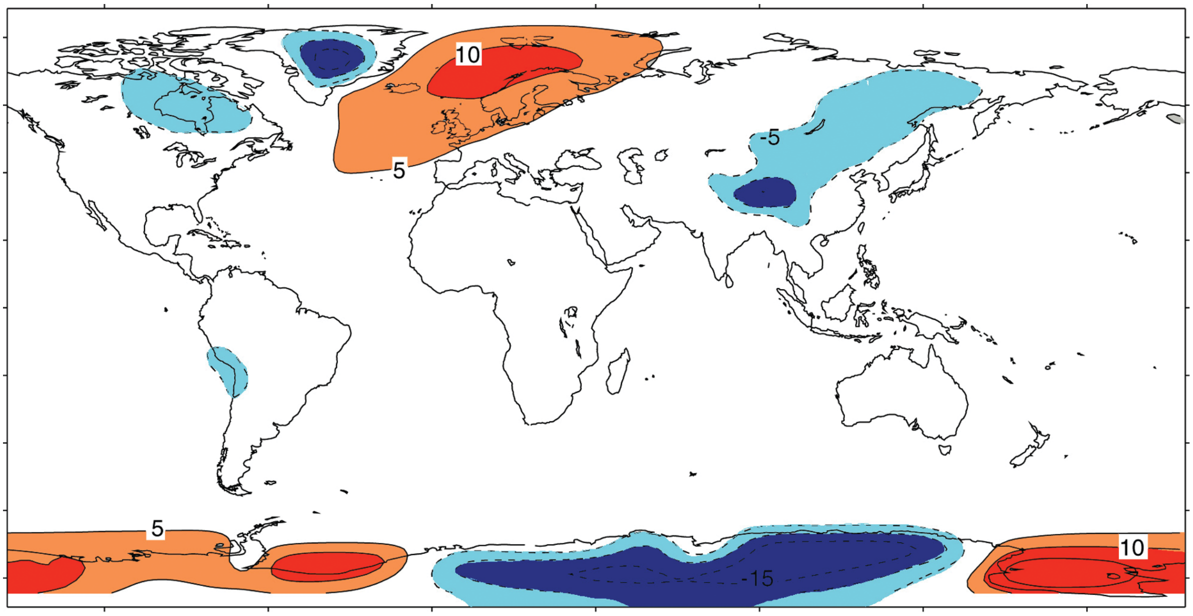
Data sets and model results allowing the recognition of long-term variability, including deep-ocean data, have only recently become available. The data base, however, is too incomplete to determine the underlying large-scale dispersal patterns adequately. An exception to this is the 'El Niño Southern Oscillation' phenomenon, which is fairly well understood with respect to the principal mechanisms involved (McPhaden et al. 1998). Because of the close atmosphere-ocean coupling, it can be predicted months in advance. For extra-tropical and higher latitude regions, this kind of prognosis is not yet possible. Significant research efforts are still required in this area. The northern Atlantic is of special importance in this connection, because of the direct effects of oceanic variations on the climate of Europe (Allen and Ingram 2002).

Science issues

Modes of variability and role of the ocean

Meridional overturning circulation

The earth receives most of its energy from the sun, in the form of short wave radiation. Some of this energy is reflected directly back into space, mainly by clouds, snow and ice, but about 70% is absorbed in the atmosphere, by the land surfaces and the oceans. Ultimately this energy is returned to space by the earth's long-wave temperature radiation. The earth is a sphere and its geometry leads to net gain of radiative energy near the equator and a net loss at high latitudes. The excess tropical heat is transported poleward by the atmosphere and the oceans. Each carries about half of this heat transport, the atmosphere by meso-scale eddy fluxes and the ocean by the overturning circulation as well as eddy fluxes. In the North Atlantic the Gulf Stream and the North Atlantic and Norwegian Currents transport warm water northward all the way to the Arctic Ocean. Along their path the currents continuously give their heat to the atmosphere and are so the main reason for the mild climate of Europe. The cooling of the water makes it so dense that it mixes to great depth and eventually returns as a deep and cold current flowing southward to the Atlantic. This a)



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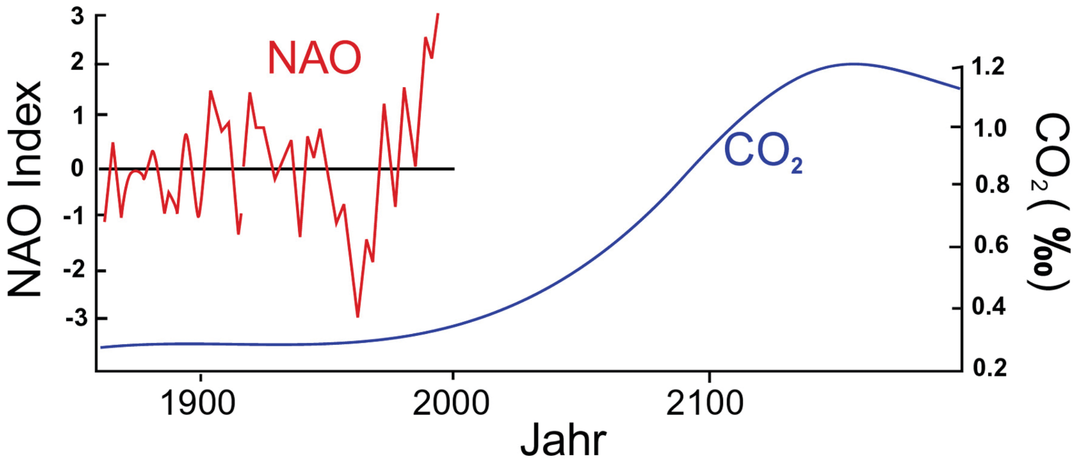


Fig. 1. a) Annual mean surface temperature anomalies form NCAR data, relative to zonal averages. There is a 5-10°C warm anomaly over NW Europe and the Nordic Seas, making this area highly sensitive to changes of the northward oceanic heat transport provided through the THC (Rahmstorf et al. 1999). **b)** Two examples for changes in atmospheric forcing: Observed changes of the NAO-index (3year running mean) and predicted increase of atmospheric CO_2 (after Rahmsdorf and Dickson pers. com.).

system is called "meridional overturning circulation" or "thermohaline circulation" which in this form is unique to the Atlantic Ocean (Schmitz and McCartney 1993) (Fig. 2).

The high northern latitudes and the ocean fluxes that connect them to adjacent seas provide the source of water masses for the deep branch of the THC. The circulation, however, is also driven by the sink terms of the deep water, i.e. the upwelling back into the upper layers of the ocean. This upwelling can either be directly driven by the winds, as in the case of the circumpolar belt, or induced by mixing across the base of the thermocline (Broecker 1991). The mixing is a complicated function of the circulation itself and its interaction with the topography and the stratification depends to a large extend on the local tidal and wind forcing (Munk and Wunsch 1998).

In addition, air-sea fluxes and interocean fluxes of heat and freshwater in the southern hemisphere are also controls on the strength and stability of the Atlantic overturning circulation. The characteristics of the northern sinking waters, in particular their salinity, is determined by the advective inflow into the southern Atlantic and by the integral surface buoyancy fluxes at the air-sea interface along its route to the Nordic Seas.

Long term variability and abrupt climate shifts

Ocean circulation models have shown that the thermohaline circulation can take on more than one stable equilibrium condition (Stommel 1961; Manabe and Stouffer 1988) (Fig.3). This results in the basic dynamic possibility of transitions between two conditions, or an abrupt breakdown of the thermohaline circulation within a period of only a few decades or even years. Model computations suggest that these processes have played a part in the observed rapid climate changes in the past (Marotzke 2000). The question whether such a breakdown can result from greenhouse warming

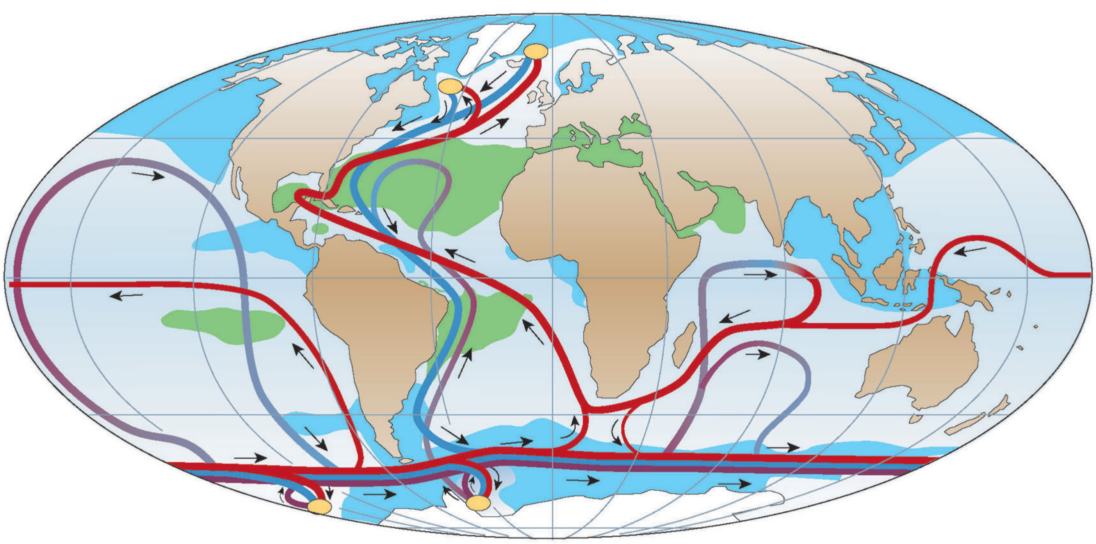


Fig. 2. Cartoon of the global thermohaline circulation (modified from Broecker (1987) by Rahmstorf 2002). Sinking of surface waters (red) in the yellow regions are the sources for deep currents (blue) and bottom currents (purple). Green shading indicates high surface salinities above 36/psu. Deep Water formation rates are estimated at 15+2 Sverdrup (1 Sverdrup= 10 ^{6} m^{3} s^{-1}) in the North Atlantic and 21+6Sv in the Southern Ocean. The northward heat transport in the surface circulation warms the northern North Atlantic air temperatures by up to 10°C over the ocean (from Rahmstorf 2002).

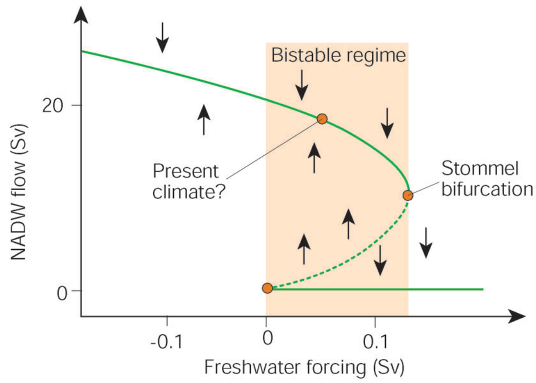


Fig. 3. The thermohaline circulation is nonlinear due to the combined effects of temperature and salinity on density. The plot illustrates the stability properties of the THC. Here the strength of the North Atlantic deep water transport is plotted against the freshwater input into the Atlantic (from Rahmstorf 2002).

is still not resolved and represents an important topic for further research.

In time series of paleoceanographic temperature estimates compiled from sediment cores in oceanographically sensitive regions of the North Atlantic, rapid climate changes have been demonstrated, especially in the form of changes in temperature-sensitive planktonic floral and faunal communities (Bianchi and McCave 1999; Sarntheim et al. 1994). The sporadic occurrences of sediment horizons with increased amounts of ice-rafted debris (Heinrich Events) provide the most convincing sedimentological evidence of such short-term climate swings during the past ice ages (Heinrich 1988) (Fig. 4). These can be attributed to periodically recurring instabilities, for example, of the Laurentide ice sheet in northern North America, causing intensified glacial break-off and increased ice berg drifts in the northern North Atlantic. These massive calving episodes occur at the ends of middle-term cooling phases that extend over periods of seven to ten thousand years. Temperatures in the North Atlantic region decreased steadily during these times while the land ice sheets underwent significant growth. Sediment cores taken from various sites in the North Atlantic at depths of one to four thousand meters indicate that carbon isotope values and carbonate content are clearly decreased during periods of increased ice-berg drift. This points to a restriction or even suspension of the thermohaline circulation in the North Atlantic, which presumably would have contributed to a further cooling of the North Atlantic region (Keigwin et al. 1994).

The existing data sets indicate a global cooling of about one degree Celsius during the "Little Ice Age", the most significant climate event of the past 1,000 years for the northern hemisphere. This phenomenon lasted from the 15th to the beginning of the 19th century (Bradley and Jones 1995). The subsequent period of natural global warming over-

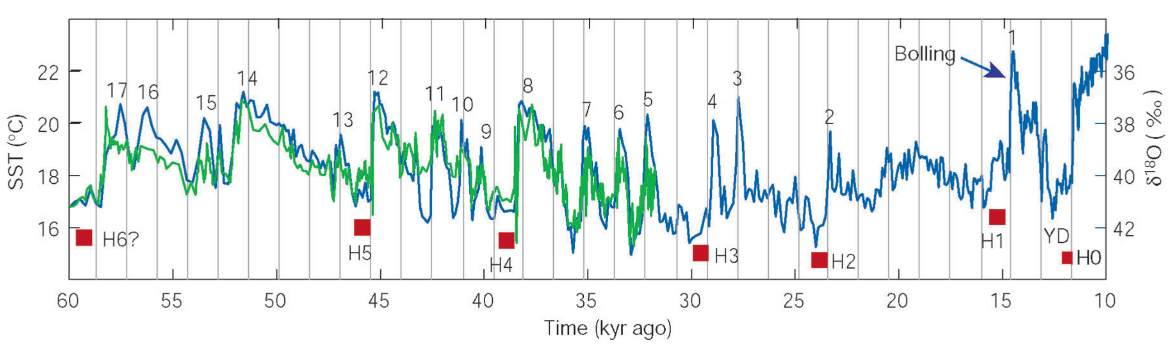


Fig. 4. Temperature reconstructions from subtropical Atlantic sediment cores (greenline, Sachs et al. 1999) and Greenland ices cores (blue-line, Grootes et al, 1993). Heinrich-events (H) are marked red, Dansgaard-Oeschger–events are numbered (from Rahmstorf 2002).

laps with the effects of increased industrial carbon dioxide emission and is used to study in detail the anthropogenic influence on the carbon cycle over the past 200 years. The natural and anthropogenic influences on the climate trend of the past 100 years are not easily distinguished. The "Little Ice Age" will be at the center of future Holocene climate research because it can be applied as a natural climate experiment, acting as a background upon which to interpret the anthropogenic influence on climate (Broecker 2000). Data profiles from 600-year-old sponge skeletons yield smaller temperature changes of less than one degree at the sea surface. From this it can be concluded that the post-Middle Ages cooling occurred primarily on the continents.

NAO/AO related variability

In mid-latitudes, the leading mode of atmospheric variability over the Atlantic region, the North Atlantic Oscillation (NAO), is profoundly linked to the leading mode of variability of the whole northern hemisphere circulation, the annular mode or Arctic Oscillation (AO) (Hurrell and v. Loon 1997; Deser 2000). This suggests that Atlantic effects are more far-reaching and significant than previously thought. The NAO exerts a dominant influence on temperatures, precipitation and storms, fisheries and ecosystems of the Atlantic sector and surrounding continents (see Hurrell 1995) (Fig. 5). It is the major factor controlling air-sea interaction over the Atlantic Ocean and modulates the site and intensity of the sinking branch of the ocean's overturning circulation. The NAO also seems to play a central role in real or perceived anthropogenic climate change. Understanding of the NAO and its time-dependence appear central to three of the main questions in the global change debate: has the climate warmed, and if so why and how? The THC in the North Atlantic accounts for most of the oceanic heat transport and is a major player in decreasing the pole-equator temperature gradient. The possibility of a significant weakening of the THC under global warming scenarios is a feature of coupled general circulation models (GCM) (Wood et al. 1999). This idea remains contentious. Yet, because of its large potential impact, the possibility

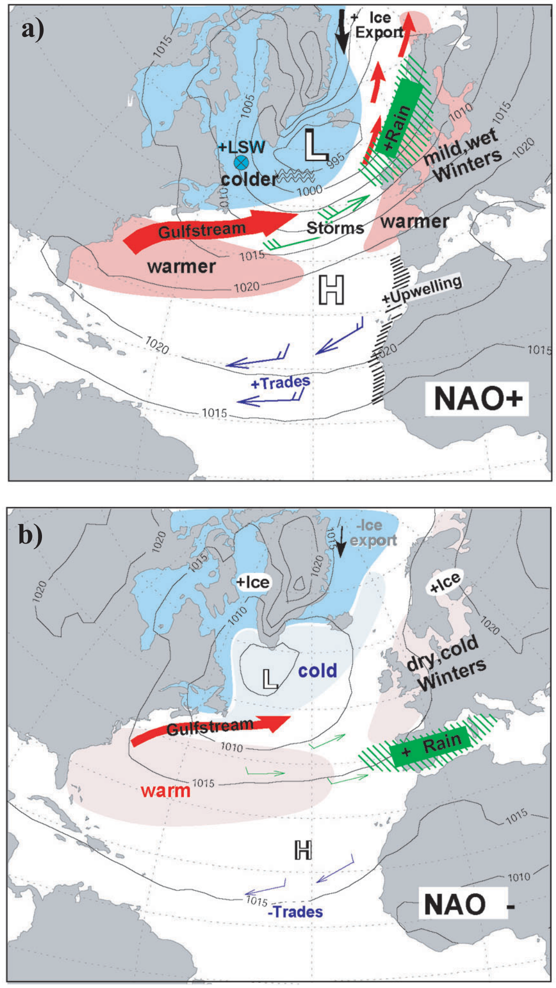


Fig. 5. a) Composite of effects of a NAO-extreme positive state. The enlarged pressure difference between the Azores High (H) and the Iceland Low (L) causes an intensified band of westerly winds stretching from southwest to northeast across the northern North Atlantic. Warm and humid air masses reach north western Europe and the Arctic, the North Atlantic Current and the ice flux from the Arctic are intensified. Massive outbreaks of cold arctic air affect the Labrador Sea and intensify convection. Enhanced trade winds cause strong upwelling off Northwest Africa. **b)** Composite of effects of a NAO-extreme negative state. A diminished pressure difference between the Azores High (H) and the Iceland Low (L) reduces the intensity of the band of westerly winds, which is more zonally oriented and reaches south eastern Europe. Northern Europe experiences dry and cold winters. The oceanic circulation is reduced, convection in the Labrador Sea is ceased.

that increased fresh-water input and atmospheric high-latitude temperature could suppress the THC must be taken seriously (Rahmstorf 2000).

Existing observations indicate indeed that decadal fluctuations of the northward water-mass and heat transport, as well as convection in the Labrador Sea, the European Nordic Seas, and the Arctic are dominated by the NAO. Phases of pronounced Azores highs and Iceland lows correspond with increased water-mass and heat transport of the North Atlantic Current and intensification of Labrador Sea convection. Interpretations of the still very incomplete data base indicate that less pronounced pressure differences weaken the North Atlantic Current and Labrador convection on the one hand and, on the other, strengthen convection in the Greenland Sea and over the Arctic shelf. Fluctuations in convection are synonymous with fluctuations in deep-water formation in the North Atlantic. This provides a significant mechanism for variations in the THC (Dickson et al. 2000).

The export of sea ice from the Arctic Ocean to the North Atlantic is also related to the oscillations observed there. The resulting meltwater fluctuations appear as salinity anomalies in the sub-polar gyre and can, as occurred during the so-called 'Great Salinity Anomaly' of the 70's, interrupt the primarily locally stimulated convection processes in the Labrador Sea and the Greenland Sea (Dickson et al. 1996). Initial investigations with an ocean-atmosphere model that also considers sea-ice processes has resulted in a process sequence: 'convection – intensity of the THC – intensity of the NAO – convection' that can be viewed as interdecadal variation in the North Atlantic (Morison et al. 2000). This result strongly suggests that low-frequency changes in the North Atlantic need to be considered with respect to a coupling concept, and that time series of relevant parameters can be expected to provide a certain degree of predictive potential.

This is interesting with respect to the correlation between decadal fluctuations of surface temperatures in the tropical Atlantic and deep-water production in the Labrador Sea, whereby the maximum temperature contrast is observed in the equatorial region about five years after the maximum convection depth in the Labrador Sea (Yang 2002). To determine whether these relationships are the result of THC fluctuations and transport of Labrador Sea water to the tropical Atlantic, or if atmospheric coupling is also involved, will require further intensive investigations.

Tropical Atlantic variability

The equatorial zone is considered to be another key region for the Atlantic meridional circulation. Recent investigations with modern current-measurement arrays and high-resolution numerical models have shown that the circulation structure in the equatorial region is very complex (Schott et al. 1998). For example the warm water flowing northward in the western Atlantic makes large detours to the east in the equatorial zone before it continues into the Caribbean and the Florida Current or the Gulf Stream. This is caused by several under- and counter currents. The southward flowing deep water from the North Atlantic, part of the THC's cold branch, also seems to be subject to such detours and transformations (Stramma and Rhein 2001).

Shallow meridional circulation cells coupling the tropics with the mid-latitudes have been detected in the Pacific (Gu and Philander 1997; Latif and Barnett 1996) and are believed to exist also in the Atlantic Ocean. These advect decadal temperature anomalies from the subduction regions of the eastern subtropics towards the equator where they rise to the surface by upwelling and trigger unstable thermodynamic interactions between the ocean and atmosphere. A further mechanism is postulated for the coupling of the tropics with mid-latitudes. ENSO events could initiate meridionally travelling Kelvin Waves that, in turn, could induce slow, westward moving Rossby waves in the mid-latitudes. These then lead to decadal-scale shifts of the western boundary currents causing changes in the ocean's northward heat transport.

Variability with periods of a few years has been observed in the tropical Atlantic, with strong effects on the regional climates, specifically precipitation (Folland et al. 1986; Enfield 1996; Latif 2000). It appears to be an atmopheric teleconnection originating from the Pacific El Niño -Southern Oscillation (ENSO). An open research question so far is how this variability affects the cross-equatorial exchange of the large-scale THC and if it has consequences reaching far beyond the equatorial zone. There is also an independent Atantic equatorial variability of quasi-biennial period. It is the equatorial Atlantic counterpart to the Pacific ENSO, with strongest SST anomalies in the eastern equatorial Atlantic. It influences strongly the precipitation over western Africa and eastern South America. Again, its role in modifying cross-equatorial exchanges is unknown.

Indian Ocean modulation of the THC

The overturning circulation of the Atlantic is controlled not only by the heat and fresh water fluxes at its surface but also by the exchanges with the neighbouring oceans. Deep waters from the North Atlantic exported to the Indian and Pacific Oceans via the Antarctic Circumpolar Current have an upper layer return transport that enters both via the Drake Passage and around South Africa. In the latter case warm and salty Indian Ocean waters are injected into the Southeast Atlantic and propagate northward with the overturning circulation (De Ruijter et al. 1999). Modelling studies indicate that the strength of the overturning circulation responds significantly to variations in this interocean transport by its direct impact on the large scale density gradient (Weijer et al. in press). Thus an enhanced input of saline Indian Ocean waters strengthens and stabilizes the overturning circulation. A reduction would lead to a decreasing strength of the overturning and could bring it closer to a state of reduced stability and enhanced variability. In that case the destabilizing impact of fresh water inputs via the Arctic connections would become more dominant.

Effect of small-scale water mass transformation on the large-scale THC and fluxes

Shelf and open ocean convection

Deep-reaching subduction processes within water masses, such as convection in the open ocean or on shelf slopes, are of critical importance for the large-scale, three-dimensional thermohaline circulation process (Marshall and Schott 1999; Backhaus et al. 1997; Marotzke and Scott 1999). Deep convection can occur in the open ocean when stability of the water column is so low that driving atmospheric forces are sufficient to cause instability. The Greenland, Labrador, and Weddell Seas are key regions for convection events. Convection on the shelf slope is controlled by the accumulation of dense water on the shelves. Slope convection occurs widely in the marginal areas of the Arctic Ocean. Its persistent occurrence in the western Weddell Sea has also been documented. The water masses formed by convection do not enter directly into the large-scale circulation, rather they are subject to further mixing and transformation processes. So far, the representation of convection in circulation models has not been satisfactorily resolved. This will require an intensive investigation of those processes that are responsible for decadal variations in the water mass composition in convection regions, both by model studies and *in situ* measurements.

Overflows and entrainment

There is evidence that the flow of water over submarine channel and ridge systems, so-called overflow, has a basin wide influence on the circulation process. An especially important example of this is the overflow of dense water masses formed in the European Nordic Seas through the cross channels in the Greenland-Iceland-Scotland Ridge (Dickson et al. 2002; Hansen et al. 2001; Dickson and Brown 1994; Doescher and Redler 1997; Käse et al. submitted; Davies et al. 2001) . Although this flow represents only about a one-third share of the deep-water formation in the North Atlantic, it is apparently of basic importance with respect to the water mass composition and the dynamics of basin-wide circulation, as indicated by model simulations. Various aspects of overflow problematics need to be addressed in a more detailed manner than previously to provide an improved understanding of the climate system in the northern Atlantic. Significant points include to what extent the flow-through rates of the channels are hydraulically controlled, which mechanisms determine the dynamics and mixing of the intense, near-bottom slope currents south of the ridge, and how the effect of overflow can be incorporated into large-scale model simulations.

Mixing in the interiour

While decadal fluctuations of the thermohaline circulation cells may be primarily controlled by processes in the deep-water source regions, effects at longer-term, secular time scales can only be explained by considering those small-scale mixing processes that are responsible for the gradual warming of deep waters in the world ocean. Recent investigations indicate that these mixing processes depend on the roughness of the bottom topography and their interaction with near bottom currents, such as caused by tides and meso-scale eddies (Kunze and Toole 1997). Mixing is then achieved through breaking internal waves. Presently almost all model simulations assume an even-shaped distribution of mixing intensities. A more realistic representation of the mixing is required in order to quantitatively determine its influence on long-term changes of the thermohaline circulation.

Relevant components of the hydrological cycle: E-P, river run-off, ice flux

The ocean contain 97% of the earth' fresh water, the atmosphere holds about 0.001% of the total. The ocean plays a dominant role in the global hydrological cycle. Present estimates indicate that 86 % of global evaporation and 78% of global precipitation occur over the oceans (Baumgartner and Reichel 1975). Small changes in the ocean evaporation and precipitation patterns can influence the global hydrological cycle to a large extent, including the terrestrial one, which is so important for many human activities and industries: agriculture, hydro-electrical power production, floods, water resources in general, etc.

Change in the water cycle can also affect the THC of the ocean. Deep water convection could be stopped if surface salinities decrease because of enhanced freshwater input (Bryan 1986; Broecker 1987; Manabe and Stouffer 1995). The main factors controlling the surface salinity are the distributions of evaporation, precipitation, ice and continental run-off, which makes it fundamental to know the hydrologic cycle in the ocean (Schmitt 1995).

In spite of the importance of the ocean in the global hydrological cycle its role is still not well known and understood. Little is known about its average state and its variability. Some of the main causes of this ignorance stem from the difficulties of measuring in-situ some of the variables that play a main role in the water cycle (i.e. precipitation, sea surface salinity), the scarcity of long-term records and the availability of global climatologies.

Atlantic CO_2-storage and –fluxes

Oceanic storage of carbon (Gruber 1998) on seasonal to centennial time scales is determined by an interplay between biologically mediated transport and transformation processes, and physical transport. In particular, the ventilation of deep intermediate water by thermohaline circulation plays a cruical role in removing carbon from the surface mixed layer to the abyss, while the associated large-scale upwelling brings "old water" to the surface. Variability of deep mixing, overflows, ventilation of intermediate water and the compensating large scale upwelling will affect decadal to centennial scale atmospheric CO_2 for given emission scenarios. The first global carbon cycle ocean circulation model scenario runs with reduced North Atlantic overturning circulation (Sarmiento and LeQuéré 1996) showed that not only the strength but also the way, in which this circulation is represented in the model significantly affects the future evolution of the ocean carbon sink.

Currently available data indicate that the strongest total ocean carbon sinks appear to be near convection regions in the North Atlantic –Nordic Seas and possibly in the Southern Ocean. Most models also indicate a large North Atlantic uptake (Wallace 2001) of anthropogenic CO_2 i.e. the perturbation of the air-sea fluxes by increased CO_2 levels in the atmosphere. However, observation based estimates of carbon transports (Holfort et al. 1998; Lundberg and Haugan 1996) indicate that the anthropogenic CO_2 stored in the northern parts of the North Atlantic is mainly advected in from the south. This would be consistent with expectations of maximum uptake of anthropogenic CO_2 over regions where old water is upwelled and equilibrates with the increasing atmospheric CO_2 content. The interplay between ocean carbon uptake across the sea surface and the transport of this carbon to deep sequestration is intimately linked to the thermohaline circulation.

Interannual and interdecadal anomalies in sea ice cover, surface heat loss and circulation strength are expected to affect the associated total and anthropogenic CO_2 uptake. One may hypothesize that NAO related variations e.g. in the distributions of Atlantic and Arctic water in the Norwegian-Greenland Seas and relative contributions of Labrador Seas vs. Greeenland Seas convection (Dickson et al. 1996) would affect carbon transports. Data for quantifiying such effects on the carbon system have been largely lacking so far (Skeljvan et al. 1999, for evidence of strong interannual variability of CO_2 fluxes in the Norwegian Greenland Seas). Coordinated carbon measurements from voluntary observing ships and time series stations are now technologically possible. By combining these data with physical fields, carbon uptake in different parts of the North Atlantic may be estimated as a function of time.

Observed interannual variability in growth rate of atmospheric CO_2 is large compared to annual emissions. This has most often been ascribed to terrestrial biology, but oceanic uptake variations may be of comparable strenght. By quantifiying variability of air-sea exchange in the North Atlantic we have the possibility to better constrain the atmospheric budgets, in particular the strength of terrestrial sinks in Eurasia and North America.

Radiative changes

It is becoming increasingly apparent that solar forcing of the earth's climate is not constant (Cubasch et al. 1997). Total solar radiative output has varied by 0.1% over the last two solar cycles; this is thought to be too small to significantly influence climate, although it may have been larger back in time. Solar output of UV has varied by 10-50% over the last solar cycle; this has possibly affected stratospheric ozone, and thus stratospheric temperatures, with the potential to influence the large-scale dynamics of the troposphere. Recently it has been shown that cloud properties and solar modulated galactic cosmic rays (GCR) are correlated (Svensmark 1998); this introduces a quite different solar influence through a chain involving the solar wind, GCR, and clouds. The suggestion here is that atmospheric ionisation produced by GCR affects cloud microphysical properties and hence their radiative impact on climate. Although these processes are still largely uncertain, historical evidence suggests that solar variability has played a role in past climate change.

How stable is the THC in a Greenhouse world?

Basic description of strength as function of time

Figure 6 from the IPCC report 2001 (IPCC Climate Change 2001) shows the results of nine climate models, for changes in the strength of the Atlantic THC for the period 1850 to 2100. Most models simulate a considerable weakening of the THC, but some models show no trend at all. It is presently not understood at all whether the THC will indeed undergo a drastic weakening in a greenhouse world. Moreover, it is unclear whether such a weakening would be reversible, or rather characterised by the irreversible crossing of a threshold value, followed by an abrupt transition to a qualitatively different circulation state.

The most basic requirements for future research are: A continuous observational record of the strength of the Atlantic THC. Present observations of the THC are insufficient to detect whether it is changing. Long-term observations of the forcing factors of the THC are needed, however for a number of them no single observational estimate exists to this date. The development of climate models that faithfully incorporate all the feedbacks that are important for the stability of the THC are of high priority.

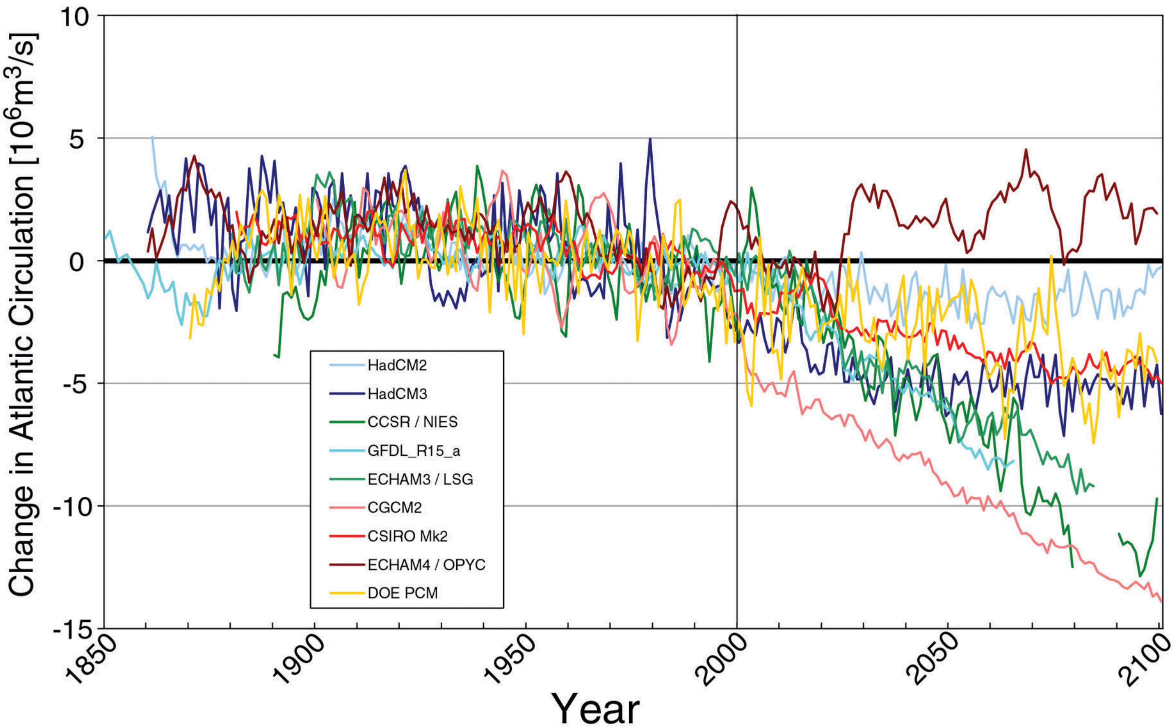


Fig. 6. Change of the volume transport of the Atlantic meridional overturning circulation, predicted from a variety of coupled ocean-atmosphere model. Atmospheric forcing according to the "business as usual scenario" with respect to atmospheric CO_2 -increase. (IPCC 2001)

Governing forcing and feedback mechanisms

The mechanisms believed to control the strength of the THC include: the northward flux of warm and salty Atlantic surface water; the freshwater flux out of the Arctic; the speed and density of the deep overflows crossing the Greenland-Scotland Ridge; open-ocean convection; mixing near the ocean margins, including the sea surface; ice-ocean and atmosphere-ocean interactions; freshwater input from the atmosphere and rivers. These processes and transports are poorly observed and understood, and are only crudely represented in the present generation of climate models. Many of the forcing factors listed above are strongly influenced by the dominant modes of atmospheric variability, in particular the North Atlantic Oscillation and related phenomena. In addition, there are a number of potentially crucial tele-connections, such as the influence of prolonged El Niño periods (Schmittner et al. 2000; Latif 2000), the interactions between deep waters of northern and southern origins (Wood et al. 1999; Doescher et al 1997), and the inflow of Indian Ocean waters into the South Atlantic (de Ruijter 1999).

There is apparently a close relationship between climate forcing and deep-water formation, or thermohaline circulation, in the North Atlantic. As a result of various feedback processes, the latter exhibits a strongly dynamic nonlinear behavior. With respect to this, model studies have identified an especially important mechanism called salt-advection feedback, by which the weakening of thermohaline circulation leads to decreased salt transport to the high latitudes. This leads to a further weakening of the circulation, resulting in a positive feedback that is reflected quite well in present models (Rahmstorf 1997). The critical point is that under similar external forcing conditions, fundamentally different equilibrium states can exist.

In addition to salt advection, further various feedback mechanisms have been found, which have been represented primarily only in idealized or low-resolution models, including some only locally operating feedbacks. These include those in which fresh water input at the surface could lead to an interruption of convection and thereby affect thermohaline circulation (Manabe and Stouffer 1997). Feedbacks between thermohaline circulation and sea ice are also viewed as significant factors in some model studies. These local events, however, are not well reproduced in present models. The quantitative role of the various oceanic mechanisms is poorly known and it can only be clarified by inclusion of atmospheric transport information.

The described feedback mechanisms are driven in the models by heat flow and fresh-water flow, which operate at the sea surface. Changes in the driving forces, particularly increased fresh-water input at high latitudes, can initiate a transition of the oceanic system to a different equilibrium state (Fig. 7). The rate of this transformation depends on the respective feedback processes. They generally take place within a few centuries. Based on circulation models, however, the deep circulation can also change fundamentally, up to a complete breakdown, in less than ten years. The causes for this are local processes at the sea surface. Once it is shut down, hysteresis effects can prevent the resumption of circulation, even after the triggering anomaly is no longer in effect. Results of model simulations indicate that climatic states associated with overall cooling in the Atlantic of up to 6 degrees may be possible even in the absence of strong thermohaline circulation (Rahmstorf 2002) (Fig. 8). The sensitivity of thermohaline circulation is not well known as opposed to changes in atmospheric forces and it is also strongly model dependent. Climate model computations for green-house scenarios estimate a significant reduction of Atlantic deep convection in the next century. This prognosis, however, is somewhat uncertain, especially because of the low resolution of the ocean model. It is therefore unclear whether the conditions leading to a breakdown of the North Atlantic Deep

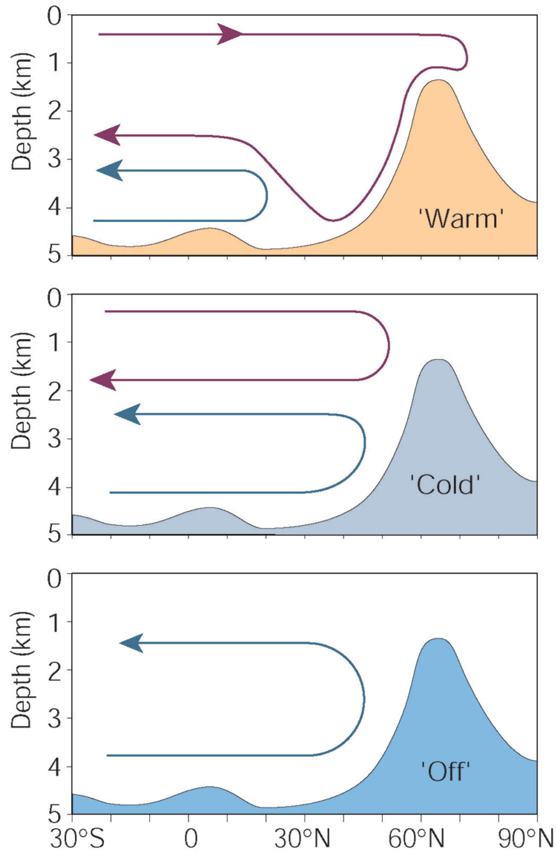


Fig. 7. Three different modes of Atlantic meridional circulation during the last glacial period. The ridge at 65°N symbolizes the Greenland-Scotland ridge. The red line represents the North Atlantic overturning circulation, the blue line represents Antarctic bottom water (from Rahmstorf 2002).

Water formation can be attained (Mikolajewicz and Voss 2000; Latif et al. 2000; Rahmstorf 2002; Stouffer and Manabe 1999) .

In principle, abrupt changes such as the breakdown or remobilization of the thermohaline circulation can also occur as a result of internal oceanic processes. In simplified ocean models, more-or-less regular swings of the deep-water circulation are observed, with alternating conditions of weaker and stronger circulation. Depending on the small-scale mixing of various water masses, a particular circulation pattern will remain stable for centuries or millennia, while transitions between the different states may last for only a few decades. However,

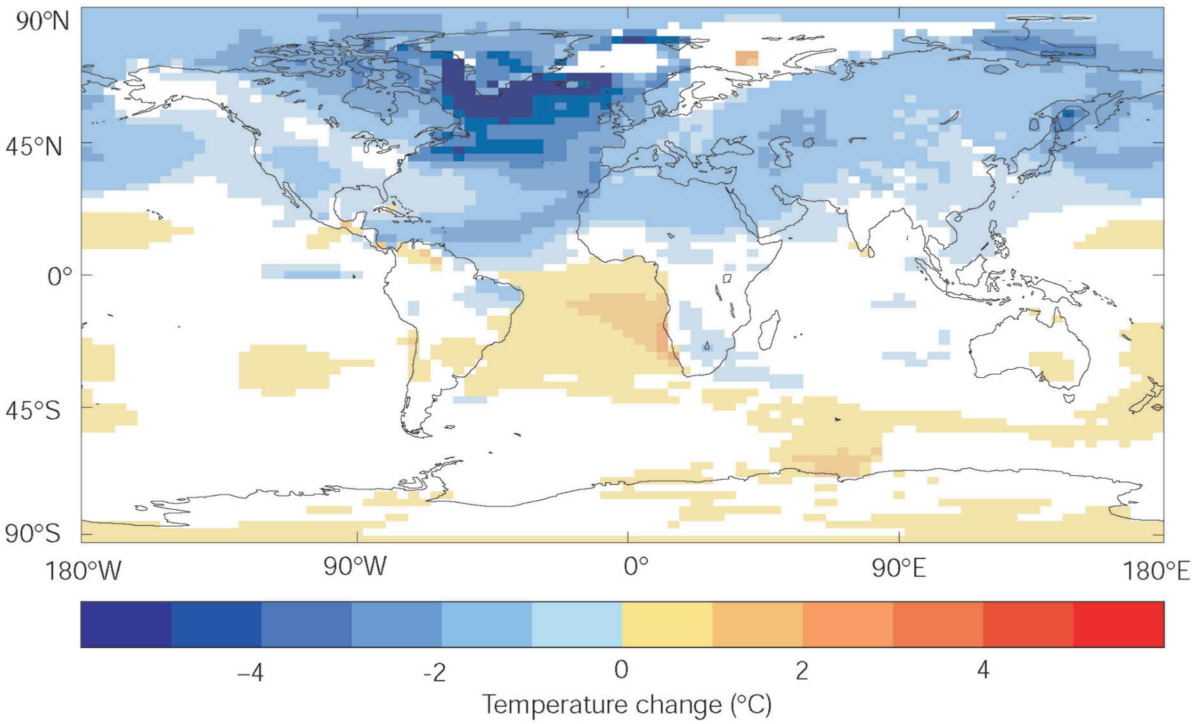


Fig. 8. Changes of surface air temperature caused by a shut down of the North Atlantic Deep Water formation in the coupled ocean-atmosphere circulation model of the UK-Hadley Center (Vellinga et al. 2002).

only a vague suggestion of such long-term fluctuations has been found so far in coupled models. It is not clear to what extent the signature of these swings agrees with the signals found in paleo data such as the Dansgaard-Oeschger Oscillations.

Implementation issues

Observing the THC variability

Long-term committment for ocean-observations

Several current initiatives will together provide the system of critical measurements that are needed to understand the role of the oceans in decadal to centennial climate variability in the North Atlantic realm. These initiatives are aimed at detecting THC-changes in the North Atlantic and understand them in the context of coupled variability to the Arctic-Subarctic system in the North and to the Tropical-Subtropical system in the South as well as to the processes internal to the North Atlantic system itself (Fig. 9).

Role of the Arctic and Subarctic seas-the ASOF Array: The basic intention of ASOF is to establish a long-term observational network that will investigate the role of Arctic and Subarctic seas in modulating the overturning circulation in the North Atlantic. The need for ASOF arises because present models do not deal adequately with many of the mechanisms believed to control the THC, and our observations cannot yet supply many of the numbers they need. E.g. we have only embryonic ideas as to the causes of long-term variability in the dense overflows which "drive" the THC, and no measurements of the freshwater flux between the Arctic Ocean and Atlantic by either of its two main pathways that are supposed to shut it down. Understandably then, we would take the view that these key mechanisms and processes are too crudely represented in the present generation of climate models, and it is the business of ASOF to provide them.

To meet that aim, ASOF would plan to establish a coordinated, circum-Arctic system of ocean flux measurements with decadal 'stamina' to cover all of the gateways that connect the Arctic Ocean with Subarctic seas (see Fig. 9). These time-space requirements are set by the decadal and pan-Arctic nature of the observed changes in the high latitude marine climate. The initiative includes a focus on the Labrador Sea as the site through which all the deep and bottom waters that "drive" the THC must pass.

The role of the tropical ocean – the PIRATA and western boundary arrays: The initiatives on time-series work in the tropical-subtropical Atlantic are aimed at linking the Atlantic upper oceanic and atmospheric tropical modes to the ENSO system of the tropical Pacific and to investigate the role that the equator has as a dynamical barrier for the cold and the warm limb of the THC, i.e.the southward flow of North Atlantic deep waters and the northward flow of subtropical/tropical surface waters of Indian Ocean and South Atlantic origin.The PIRATA-Array in the Tropical Atlantic (see Fig. 9 with PIRATA and western boundary arrays at 15N and 11S) is designed to serve as an equivalent of the Pacific TAO array for observing tropical Atlantic variability as well as identify any downstream effects of ENSO on the tropical Atlantic. It consists of Atlas buoys for meteorological observations, which carry T/S sensors for measuring upper-layer and thermocline stratification variability. Along the western boundary, near 11S off Brasil, the German CLIVAR group will maintain a boundary array to measure the variability of transports and water mass properties of the equatorward warm water transport that supplies the inflow into the equatorial zone and links up with the PIRATA observations. Likewise an array for measuring the fluxes of North Atlantic deep water into the equatorial zone will be kept in place near 15N off the Antilles.

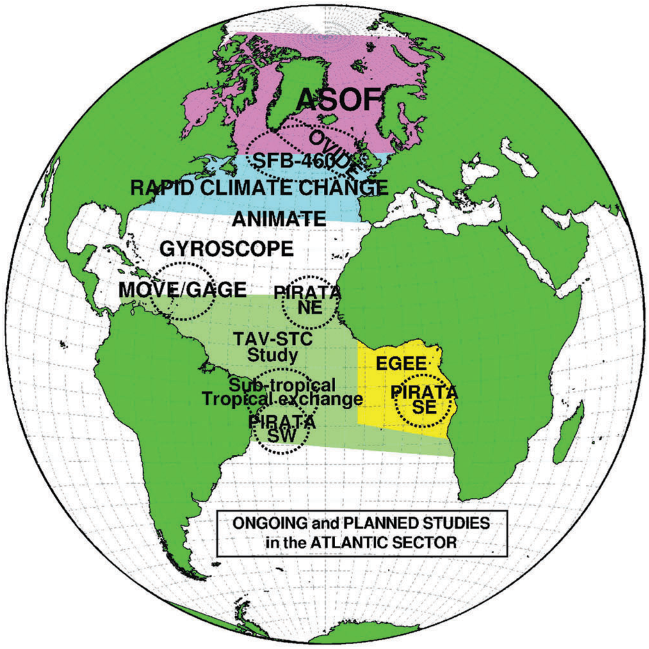
Processes internal to the North Atlantic: Processes driving the THC in the North Atlantic are the convective formation of deep and intermediate waters, the overflows of intermediate waters across the submarine ridges separating the Nordic Seas from the North Atlantic, and the export of waters from the convective regimes into deep boundary currents and the ocean's interior. Advection pattern and transformation of upper layer waters of polar and tropical origin are closely linked to the underlying processes mentioned before and so are the modes of atmospheric variability. Although the North Atlantic has a history of continued observational activities there is a scarce data base on decadal variability in the open ocean. Notable exceptions are the time series observations on convection in the Labrador Sea, on water mass variability near Bermuda and on the inflow of Atlantic water to the Nordic Seas. Data are lacking on processes like the export of water from the convective regimes into the boundary currents.

There are several initiatives aiming at longterm measurements of significance for decadal changes (see Fig. 9). They are planning for repeats of trans-Atlantic sections, for a network of timeseries-stations in the open ocean as well as the maintenance of current meter arrays at key locations for boundary currents. Acoustic tomography is being applied to determine integral properties on the basin scale, to monitor changes in convection activity and measure the changes in stratification and heat storage. Together with the continous employment of profiling drifters and satellite-altimetry it will become possible to estimate inventories and changes in fluxes, that will be related to the changes imposed from the Arctic and the Tropics.

The use of paleoclimate data

In order to extend the historical observations of decadal climate variability numerous high resolution paleoclimatic records are available. Potential paleoarchives for oceanic parameters include high resolution sediment records and biogenic skeletal growth chronologies e.g. from corals and molluscs.

Ideally, laminated sediments should be studied to achieve the highest temporal resolution possible in ocean sediments. Recent investigations from the tropical Atlantic (Cariaco basin) revealed many abrupt sub-decadal to century-scale oscillations that



ASOF: Arctic Subarctic Ocean Flux Array
RAPID CLIMATE CHANGE: (UK)
SFB-460: Subpolar North Atlantic Study (Germany)
OVIDE: Observation of the Interannual and Decadal Variability of the Subpolar gyre in the N. Atlantic (France)
ANIMATE: Atlantic Network of Interdisciplinary Moorings and time series for Europe (EU)
GYROSCOPE: ARGO funded by EU
MOVE: Meridional Overturning Variability Experiment (Germany)
GAGE: Guyana Abyssal Gyre Experiment (USA)
PIRATA Extensions: SE, SW, NE
EGEE: Study of the Oceanic Circulation and its Variability in the Gulf of Guinea (France)

Fig. 9. Map showing ongoing and planned oceanographic projects in the Atlantic Ocean for the decade around the year 2000 (Court. CLIVAR-IPO, Southampton).

are synchronous with climate changes at high latitudes in the North Atlantic (Hughen et al. 1996). Sediment grain-size data from the Iceland basin were used to reconstruct past changes in the speed of deep-water flow. The study site is under the influence of Iceland-Scotland Overflow Water, which is an important component making up the THC (Bianchi and McCave 1999).

The oxygen isotopic composition of benthic foraminifera can provide quantitative reconstructions of upper ocean flows at key locations (Lynch-Stieglitz et al. 1999). These archives reveal a seasonal resolution and comprise a variety of proxy records of environmental and climatic conditions. Long growth chronologies cover several centuries and possibly reach up a 1000 years. Comparison of coral records from the different ocean basins will help to reveal and confirm the different modes and climatic teleconnections between the climate subsystems. Recent coral based research has mainly concentrated on climate modes of the tropical Pacific as well as the Indian Ocean. Future research will exploit the potential of deep-sea corals, which provide one of the rare proxies to document past changes in North Atlantic intermediate and deep water masses (Adkins et al. 1998).

Modelling the THC variability

Climate modelling with improved resolution

Though a range of climate models suggests that greenhouse warming can lead to THC weakening, these models all have relatively crude spatial resolution in their oceanic components. It has never been demonstrated that the THC can undergo dramatic weakening in ocean climate models of the resolution and sophistication that we believe are needed to reproduce quantitatively observed features of ocean circulation, such as the narrowness of fronts and boundary currents. Coupled ocean-atmosphere models with eddy permitting ocean models (1/3 deg) are currently developed world-wide to address the question of the stability of the thermo-haline circulation in more detail.

The great spectrum of current fluctuations characteristic of the global circulation, clearly observed in all measurement programs, represents one of the central problems of computer simulation. Great progress in the modeling of ocean circulation has been achieved in the past decade because of improvements in the measurement database by the WOCE program and by improvements in the capabilities of high-performance computers. High-resolution circulation models driven by realistic atmospheric conditions can now reproduce the fundamental aspects of oceanic eddy activity as well as the principally wind-driven variability at synoptic seasonal and interannual time scales (Fig. 10). A fundamental challenge for future model development is improvement in the representation of some critical, very small-scale oceanographic processes that control the thermohaline circulation and thereby the reaction of the ocean-atmosphere system at decadal and longer time scales. Among them are the processes of convection, the export from convective regions into boundary currents, the overflows and mixing in the ocean's interior by the interaction of variable flows and topography.

Predictability

The requirements and starting point for any prediction include, first, a dynamic and model-oriented understanding of the relevant processes and, secondly, a quantitative determination of the physical condition of the ocean at a given time. Information from observations alone is not sufficient for either of these purposes, rather, a synthesis of observation data with models is necessary. Significant advances have been made in the development of methods for assimilating data into circulation models. The successful El Niño predictions, for example, would have been impossible without an operational system of data assimilation. Due to their spatial/temporal homogeneity, measurements from moored arrays and satellite observations are particularly well suited for assimilation. Because of the high variability of processes impacting climate and the chaotic nature of circulation caused by medium-scale variability, however, assimilation techniques applied to circulation in the middle and high latitudes are still in the developmental stages. The development of practicable methods for introducing various kinds of observation data into realistic models therefore presents a challenge for the coming years.

Predictions of processes in the high latitudes are not yet possible. It seems certain that decadal-scale oceanic variability in the middle and high latitudes are produced, to a considerable extent, by atmospheric fluctuations, particularly heat flow. These fluctuations, which have a bearing on the inherent nonlinearity of atmospheric circulation, are linked to large-scale patterns such as the North Atlantic Oscillation that are not predictable at present. Longer periods are reinforced by the great thermal capacity of the ocean yielding, in principle, the possibility of a certain degree of predictability for fluctuations in oceanic circulation.

Because of the short 'memory' of the atmosphere, processes in the global ocean-atmosphere

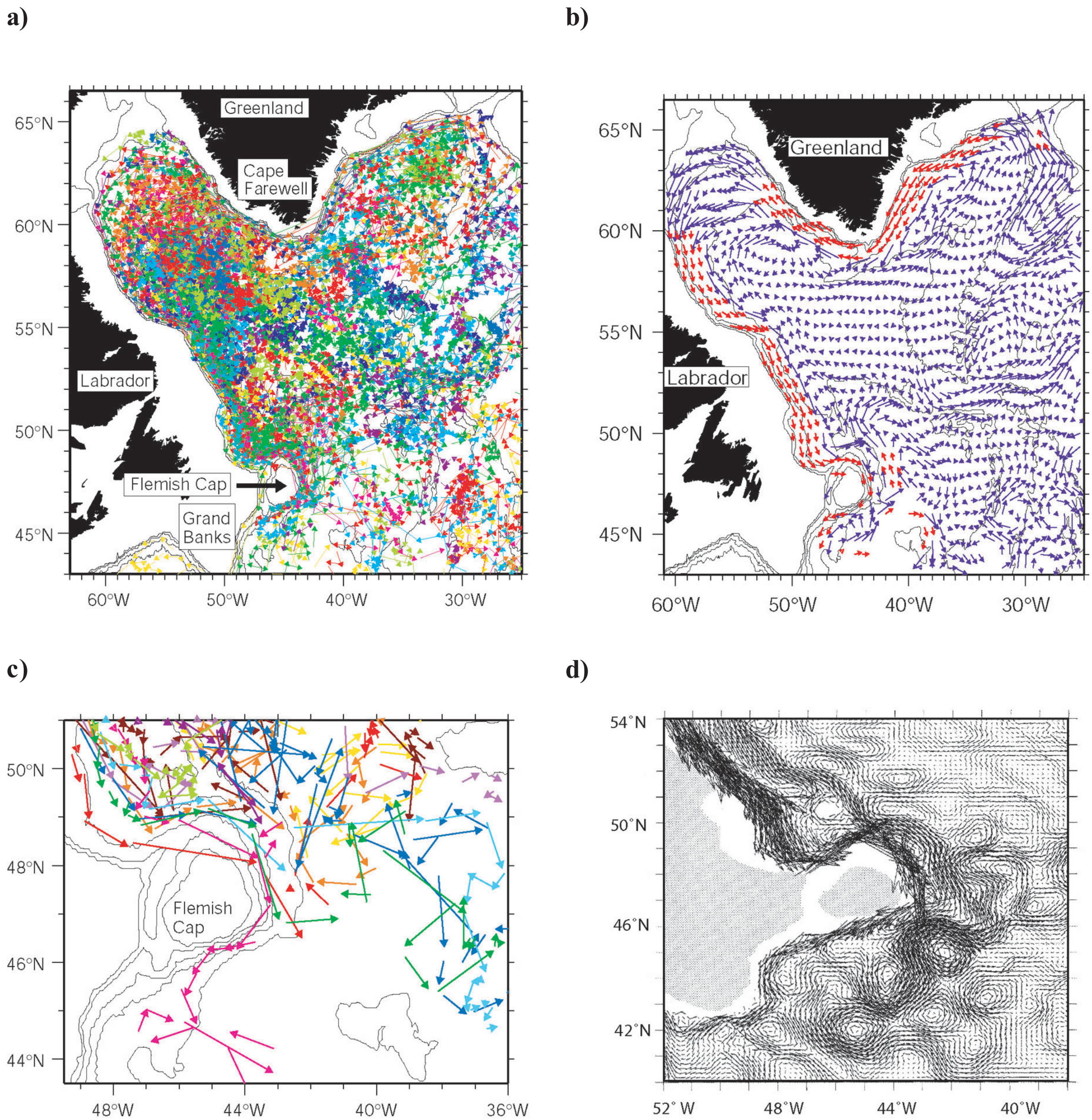


Fig. 10. a) Trajectories of floats in the Labrador and Irminger Seas at nominal depths of 400, 700 and 1500m. Each float is represented by one colour, data are from Nov. 1994 to April 1999 (from Lavender et al. 2000). **b)** Objectively mapped mean circulation at 700m depth. Blue arrows: Distances travelled over 30 days at speeds <5cm/s. Red arrows: Distances travelled over 8 days at speed >5cm/s. Note the narrow current filaments and their relation to the topography (from Lavender et al. 2000). **c)** Displacements of floats at 1500m depth at Flemish Cap. Note the incoherent southward flow along the boundary south of Flemish Cap (from Lavender et al. 2000). **d)** Result of a high-resolution (1/12 degr.) model run on the circulation at 1800m depth in the area of the Newfoundland Bank (C. Böning, pers. com).

system and thereby the climate can, in principle, only be predicted to the extent that atmospheric variability is induced or reinforced by the ocean. So far little is known about the strength of this reaction. Model computations, however, provide evidence of fluctuations of the coupled system that are produced by feedback from the ocean. They appear to be linked to the time lag of oceanic wave and transport processes whose periods vary between 10 and 60 years depending on the region. It seems to be possible, therefore, to predict at least some portion of the large-scale spatial variability of the Atlantic surface temperature, which is linked to fluctuations of European climate, on a decadal time scale. The extent and limits of predictability are significant research topics for the future.

Linking the shelf seas into the global system

Shelf and coastal seas are components of the global climate system. Their coupling to it is achieved via atmospheric fluxes (wind, heat, freshwater), advective exchanges with the open ocean, and runoff from the continent, including chemical and sedimentological components.. For the North Atlantic the shelf areas of NW-Europe and Canada are especially important since they include the large freshwater reservoirs of the Baltic Sea and the Hudson Bay. Implementation efforts are needed to develop the means for coupling of the global climate models with the shelf sea models of different complexity. Assimilating the numerous long time series observations from shelf stations into a coupled ocean-shelf climate model will allow to discriminate between natural and anthropogenic causes of the observed variability and will lead to identifying regional effects of global climate change.

The ocean's euphotic layer

It is the conditioning of the ocean's very upper layers that determines its primary productivity. Among the controlling parameters are the downward penetration of light, the rates of gas exchange with the atmosphere and the availability of kinetic and potential energy. The scales inherent to these parameters are small, both in the space and the time domain, thus causing the well known patchiness of the plankton distribution. Presently any quantitative modelling of oceanic productivity lacks appropriate data on the actual physical structure of the oceanic euphotic layer. Progress is expected from the combined use of satellite remote sensing of the surface and direct determinations of the TS-structure of the upper layers by the mass deployment of profiling drifters. With these data assimilated into high resolution ocean circulation models a new basis will be available for ocean ecosystem modelling.

Measurement technology

The results of physical oceanographic research at sea described above were also made possible by technical advances in measurement systems. These include Acoustic Doppler Current Profilers that can measure the depth distributions of currents for hundreds of meters, either from a cruising ship or a moored underwater station, employing the back scatter of sound waves from suspended particles (Fig. 11). Another system consists of profiling deep drifters. They drift with the current at pre-determined depths and then ascend to the surface at programmed time intervals to record a profile of the water mass parameters. These data and their positions are sent to a station on land via satellite before they descend again to continue their trip (Fig. 10). A future version of the deep drifters -the gliders- will be able to return to a deep target position after surfacing and transmitting its data, enabling it to provide successive profiles from the same area. This prevents the deep drifter from being carried out of the region of study by current motion and significantly enhances input of data into model simulations. The value of the profiling drifters can be greatly enhanced by adding sensors for biogeochemical parameters to their payload. However care has to be taken to keep the costs for a drifter in adequate balance with the requirement for mass deployment.

Generally, the technology for long-term measurements at moored stations has improved to the extent that maintenance-free placements can be carried out over periods of several years. Considerable efforts are presently put into achieving two-way communication between long term moored

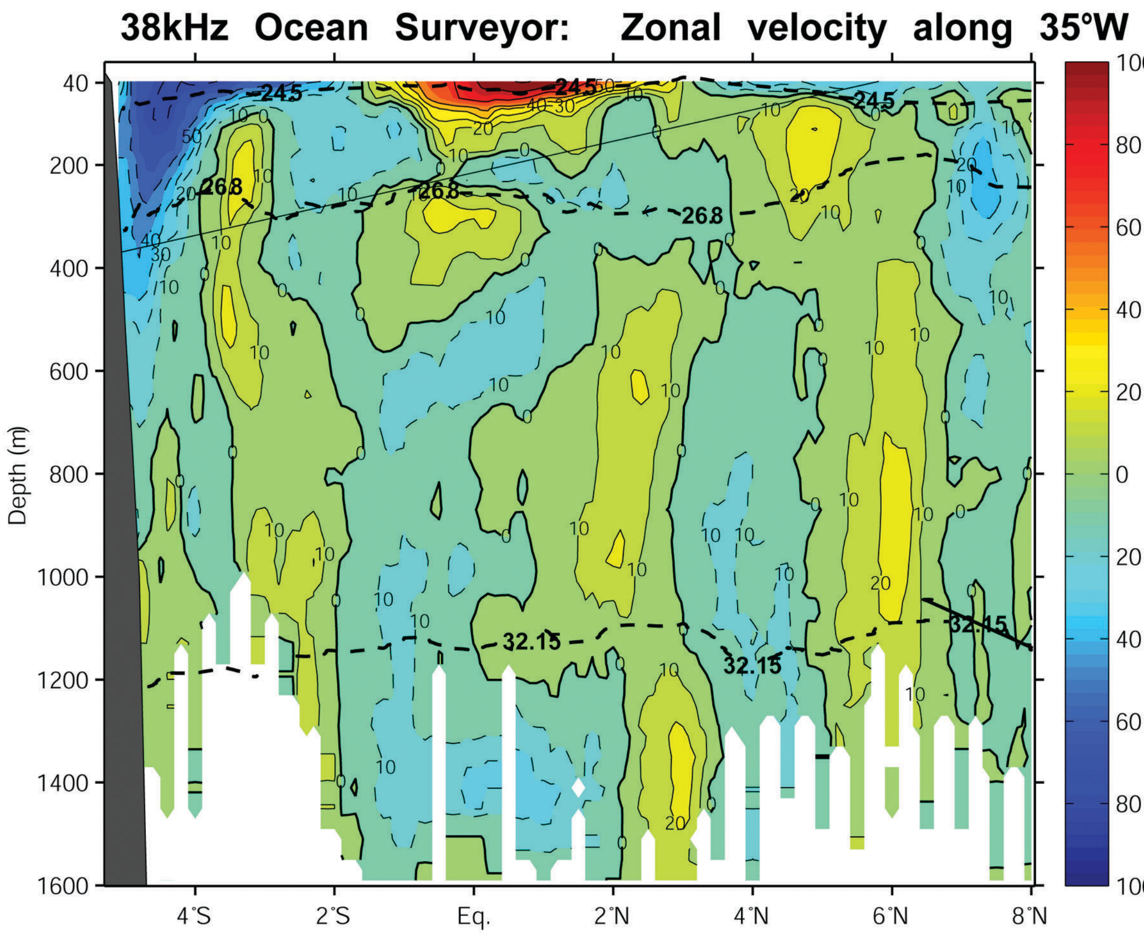


Fig. 11. Observation of zonal velocity in the equatorial region along 35°W. The data were aquired with a 38KHZ RDI-Ocean Surveyor during Meteor-cruise M53 in May 2002 (M. Dengler, F. Schott pers. com.). The figure demonstrates the most recent status in monitoring velocity profiles from underway-measurements.

sensor packages, which allows for data-transmission to shore and for the checking and re-programming of the sampling.

For future demands a measurement network of different autonomous systems needs to be planned that allows for the effective documentation of decadal oceanic variability for selected ocean areas. Present discussions include the installation of profiling CTD's and current meters in key-locations of ocean flux variability and moored measurement systems for acoustic tomography, by which the relatively small temperature changes of the climate signal can be determined on ocean basin scale. In addition, the mass-deployment of deep drifters is planned. This will yield watermass inventories for the ocean basins and together with the flux-arrays the detection of THC-changes will be possible.

Special effort will be needed to measure the freshwater export from the Arctic system. Whereas first time series of ice export are building up from combined *in situ* and remote sensing measurements, the methods of obtaining the liquid freshwater transport in ice-covered waters are presently still under development.

Considerable improvements in the speed and in the precision of anthropogenic transient tracer measurements can provide data fields, which allow to resolve for the major dynamical features of the circulation components for deep and intermediate waters, e.g. boundary currents and their recirculation cells etc. Thus transient tracers provide an important contribution to the set of ocean measurements, which will be needed in future activities of assimilating observations into higher resolution circulation models.

Satellite altimetry is an existing tool with proven success to map the oceanic eddy fields. Successive mapping yields information on eddy-related advection of heat and matter between ocean basins via the major retroflection zones (e.g. at the southern tip of Africa or the eastern tip of South America). Larger efforts are still necessary to obtain absolute sea level heights from altimetry, which would solve the classical problem of the reference level for absolute 3-dimensional current determinations from the measurements of mass distribution. These efforts are on the side of a more accurate geoid-information and on the side of the *in situ* observations of the oceanic mass field, which has to be compatible to the altimetric data both in time and space.

Measurement techniques should be further developed in the future for small-scale processes, and these should be applied toward quantification of the key processes that drive or modify the large-scale water mass distribution and circulation. These include in particular fine scale measurements of stratification and currentshear in overflows and boundary currents near significant topographic features to obtain direct estimates of entrainment and mixing. The goal is a more realistic parameterisation of the small-scale processes that are not resolved by models.

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