INTERNATIONAL COUNCIL FOR SCIENCE

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

WORLD METEOROLOGICAL ORGANIZATION

# WORLD CLIMATE RESEARCH PROGRAMME

# Report of the CLIVAR Workshop on North Atlantic Thermohaline Circulation Variability

13-16 September 2004
Steigenberger Hotel, Kiel Germany

May 2006

*ICPO Publication Series No.87*

**WCRP Informal Report No. 10/2006**

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meterorological Organisation, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO. The scientific planning and development of CLIVAR is under the guidance of the JSC Scientific Steering Group for CLIVAR assisted by the CLIVAR International Project Office. The Joint Scientific Committee (JSC) is the main body of WMO-ICSU-IOC formulating overall WCRP scientific concepts.

**Acknowledgments**

The workshop organizers would like to acknowledge financial support of the workshop and associated symposia by the following institutions:

- Deutsche Forschungsgemeinschaft, Bonn
- Leibniz-Institut für Meereswissenschaften (IfM-Geomar), Kiel
- World Climate Research Programme, Geneva

and sponsors:

- Nautilus Marine Service GmbH
- J. Bornhöft Industriegeräte GmbH
- LPL Lenkering Projects and Logistics GmbH
- A.W. Niemeyer GmbH

**Bibliographic Citation**

**INTERNATIONAL CLIVAR PROJECT OFFICE,** 2006: Report of the CLIVAR Workshop on North Atlantic Thermohaline Circulation Variability. April. International CLIVAR Project Office, CLIVAR Publication Series No. 87. (not peer reviewed).

**CONTENTS**


| | | |
|---|---|---|
| 1 | Introduction | 1 |
| 2 | Summary of outstanding issues and research questions | 2 |
| 3 | Session 1: THCV variability and climate | 3 |
| | 3.1 Atlantic THC variability: observations and indices | 3 |
| | 3.2 The Role of the Thermohaline Circulation in Climate Variability | 4 |
| 4 | Session 2: THC variability and the carbon cycle | 6 |
| | 4.1 Summary of plenary presentations | 6 |
| 5 | Session 3: Watermass transformation processes in the North Atlantic | 7 |
| | 5.1 Summary of plenary presentations | 7 |
| 6 | Session 4: Characteristics and mechanisms of MOC variability in the North Atlantic | 10 |
| | 6.1 Summary of plenary presentations | 10 |
| | 6.2 Variations in the North Atlantic Meridional Overturning Circulation: Forcings mechanisms, communication to low latitudes and implications for prediction | 10 |
| | 6.3 Forcing mechanisms of MOC variations and mechanisms of communication between polar latitudes of the Atlantic and its low latitudes: Southern Hemisphere | 11 |
| 7 | Session 5: The THC in a changing climate | 12 |
| | 7.1 Summary of Plenary presentations | 12 |
| | 7.2 AOGMM predictions of changes in Atlantic meridional overturning: the CMIP coordinated THC experiment | 12 |
| | 7.3 Do climate GCMs exhibit multiple THC equilibria/hysteresis? | 13 |
| | 7.4 Concepts and simplified models to quantify past and future climate change | 13 |
| | 7.5 Prospects for predicting the future of the THC in IPCC AR4 and beyond | 14 |
| 8 | Session 6: Future programs | 16 |
| 9 | Posters' abstracts | 18 |
| | Appendix I: Workshop Programme | 48 |
| | Appendix II: List of Participants | 51 |

## 1. Introduction

The Workshop on North Atlantic Thermohaline Circulation Variability took place at the Conference Center of Steigenberger Hotel, Kiel, Germany, from 13-16 September 2004. Under the auspices of the International CLIVAR project, it was organized jointly by the Atlantic Implementation Panel (chaired by Martin Visbeck), the Working Group on Ocean Model Development (chaired by Claus Böning), and the Special Research Programme on the "Dynamics of Thermohaline Circulation Variability" (SFB 460) at Kiel University. The Workshop, the agenda for which is at Appendix 1, was intended to bring together expertise from physical oceanographers, geochemists, and ocean and climate modellers, to discuss recent advances and outstanding problems in our understanding of the mechanisms of deep water formation in the subpolar North Atlantic, their relation to decadal variability of the meridional overturning circulation (MOC) and impact on the uptake of anthropogenic trace gases, and the future of the MOC under changing climate conditions. There were a total of more than 150 participants, from 49 different institutions and organizations of 16 countries. A list of participants is at Appendix 2.

The main goals of the workshop were:

- to take stock of our understanding and best estimates of the present and future state of the Atlantic Thermohaline Circulation
- to guide implementation plans by assessing the capabilities and future needs of THC observing and synthesis systems to detect and predict low-frequency changes or trends.

The workshop was comprised of a series of invited plenary presentations and poster sessions focused on a set of six themes. Five sessions during the first three days addressed the recent accomplishments and remaining challenges concerning main aspects of THC variability in the North Atlantic. The final, sixth session was devoted to a discussion of future research needs and scientific programs. The specific themes (chairpersons in parentheses) were:

- Session 1: THC variability and climate (J. Willebrand, C. Böning)
- Session 2: THC variability and the carbon cycle (D. Wallace)
- Session 3: Water mass transformation processes in the North Atlantic (C. Mauritzen)
- Session 4: Characteristics and mechanisms of THC variability in the North Atlantic (D. Stammer, A.-M. Treguier, W. Johns)
- Session 5: The THC in a changing climate (R. Wood, M. Latif)
- Session 6: Future programs (M. Visbeck, E. Chassignet)

Section 2 of this report provides an overview of the outstanding research issues and research questions which emerged from the meeting. In Sections 3-7 are summaries of plenary sessions 105, and/or presenters' short summaries (where available) of their individual presentations. Section 8 summarises the outputs from Working Groups and of the plenary discussion on "Future programmes". Finally, Section 9 collects together the workshop poster abstracts.

The workshop provided a special opportunity and international context for discussing the achievements of the SFB-program which represents an important long-term funding umbrella (1996-2006), provided by the Deutsche Forschungsgemeinschaft (DFG) for research activities at the newly formed Leibniz-Institut fuer Meereswissenschaften (IfM-Geomar) in Kiel. The SFB comprises a host of projects involving meteorologists, physical oceanographers, geochemists, and paleoceanographers, investigating the fluctuations of water mass transformation and transport processes in the subpolar North Atlantic, and the significance for the MOC and the uptake of anthropogenic carbon. The work program of the SFB combines model studies and extensive field work using shipboard measurements, floats and moorings focusing on the overflows, the Labrador Sea convection regime and boundary currents, thus transcending many aspects of the workshop's program.

A special part of the workshop, with a separate program, was a Symposium in honour of Prof. Fritz Schott on the occasion of his retirement. Public outreach activities included a very successful evening lecture by Prof. Mojib Latif (in German) on the future of the Gulf Stream and consequences for European climate, drawing an audience of more than 300; and a well-received invitation to a press conference, which led to a number of interviews on various issues of ocean climate variations.

## 2. Summary of outstanding issues and research questions

Recent findings indicate that in the North Atlantic the primary source of predictability on decadal time scales is the Atlantic meridional overturning circulation (MOC). This growing body of evidence from a variety of ocean-atmosphere model studies shows, that the MOC may have some predictability for lead times up to several decades. There is not consensus, however, on the extent to which these MOC variations lead to useful predictability of SSTs and the associated atmospheric response, although some encouraging evidence of useful predictability is beginning to emerge (PREDICATE Project, http://ugamp.nerc.ac.uk/predicate). There is need for a much more detailed understanding of which aspects of ocean conditions most constrain the future behaviour of the MOC and related aspects of climate. The roles of air-sea exchanges of buoyancy and momentum, convective mixing, overflows, boundary waves and advective processes in setting the time scale and predictability of changes in the MOC have to be clarified.

Changing external forcing, whether natural or anthropogenic, also influences climate on short and long time scales and is a further source of potential predictability. Many of the issues are global but there is a clear need to improve understanding of the factors that determine climate change at a regional scale. In the Atlantic Sector the interaction between initial conditions (notably in the MOC) and the effect of changing forcing is crucial. For predictions with lead times in the range of 1-30 years both factors are likely to be important.

The most relevant generic Atlantic MOC issues are:
- Understanding the limits of predictability of the MOC and the mechanisms that determine its predictability;
- Identifying which aspects of the oceanic initial conditions most constrain the future behaviour of the MOC;
- Understanding how initial conditions and changing external forcings combine to determine climate evolution on decadal time scales, and (relatedly) development of suitable ensemble techniques for sampling forecast uncertainty; and
- Understanding and quantifying the regional climate impacts of MOC change and the predictability of these impacts.

More specifically the following research questions emerged:

a) Basin scale and global modelling have become a major resource to study MOC variability and predictability. However, there is a continuing need to foster a dialogue and close collaboration between the modelling and observational communities to critique and advance the modelling capabilities. In particular:
- Models need to better represent the boundary processes (waves and advection) and communication with the interior (eddies) important in the generation and propagation of thermal and haline anomalies.
- How large a surface flux and/or temperature anomaly is significant for climate in different regions (and on different time scales)?
- How accurately can ocean state estimation (such as ECCO) constrain surface fluxes with a) presently available measurements and b) future planned measurements?
- How accurately can TOPEX combined with ARGO and other observing systems constrain the regional heat storage changes?
- Which observable ocean variables are the best predictors of future changes and associated climate impacts?
- What is the correlation and significance of local time series for the basin scale MOC system? Models might be able to provide such teleconnection relationships that can be used to extrapolate from regional observations.

b) Models, in particular with data assimilative capabilities are gaining traction with the general ocean research community. While several technical aspects are still under development, one needs to make a reasonable guess at the needs of a future sustained observing system. In particular:
- Which sustainable observations on decadal time scales can reduce the uncertainties in the initial conditions to the necessary level of useful predictability?
- How can we cost effectively observe MOC variability? And what is the expected uncertainty?

- How can MOC observing systems be best connected with the emerging operational oceanography under the banner of GEOSS (Global Environmental Observing System of Systems)?

c) While several models and a handful of observations have documented MOC variability, there are still a number of outstanding research issues that need to be addressed:

- Which local processes are how relevant for generating low-frequency variability in large-scale transports?
- What is the relationships between the deep water formation processes and MOC/heat transport variability at 25N?
- What is the role of boundary waves in the MOC adjustment process on decadal time scales?
- How significant are changes in the overflows compared to variability in the convective centres of the Labrador and Irminger Seas?

## 3. Session 1: THC variability and climate

### 3.1 Atlantic THC variability: observations and indices (*by Friedrich Schott*)

The focus of this overview presentation was on the evidence regarding the decadal changes of observed water mass distributions and potentially associated circulation changes, especially regarding the Meridional Overturning Circulation (MOC), and on the search for related observational indices. As regards the NAO as the main forcing index applied in North Atlantic variability studies, it needs to be considered that the Icelandic Low has shifted location at decadal time scales, yielding southward coast-parallel winds off East Greenland and high NAO - ice export correlations in recent decades when good observations were available. For the preceding decades the NAO was better correlated with the Baffin Bay ice export, contributing to the convoluted dependence of decadal Labrador convection variability on the different forcing ingredients. Drastic water mass changes occurred at the lower and middle NADW levels with the recent freshening of both, the DSOW and ISOW source waters. The origin of the freshening was in the Nordic seas, but there must also have been mixing along the way over the sills with shallower subpolar North Atlantic waters that were themselves freshening. The cause of this subpolar freshening was recently shown by Josey et al. (2004) to have been enhanced precipitation during the 80's over the northern subpolar gyre. DSOW anomalies were traced around the Labrador Sea by Stramma et al. (2004), typically exiting at the Tail of the Grand Banks near 43N about 2 years after passing by the Labrador Sea near 56N. The generation of the upper NADW or LSW has experienced large variations with maximum layer thickness of the classical LSW exported in the early 90s and propagating southward along the boundary, having been located off the Bahamas in 1996 and found at 8N in 2003.

What is the evidence as to whether these large source water changes of the lower, middle and upper NADW changed the boundary currents in the subpolar North Atlantic? On the one hand, Haekkinen and Rhines (2004) suggest a slowdown of the cyclonic subpolar gyre during 1994-2002, based on an EOF analysis of altimetry-derived geostrophic surface currents. On the other hand, current-meter time series obtained during 1996-2003 in the Labrador Current and DWBC at 53N and 56N (Fischer et al., 2004; and pers. comm., 2004) do not show any noticeable changes of the boundary current at the LSW level, particularly not a slowdown. Similarly, at the Tail of the Grand Banks, near 43N, DWBC transports from a Canadian WOCE array in 1993-95 and from repeat deployments during 1999-2001 by the Kiel SFB 460 yielded mean DWBC transports for both time periods that were very similar, at 11 Sv. Results from several model studies were analyzed but it is unclear at the present time whether the DWBC east of the Grand Banks can serve as an index for basinwide Deep Water export.

How about changes of the MOC? There is one WOCE line, A2, where repeat sections over the past decade have been carried out. It is located nominally at 48N, running from the Grand Banks to the English Channel, i.e. separating the subpolar from the subtropical North Atlantic. Lumpkin et al. (2004) evaluated the five sections along line A2 from the time period 1993-2000 by an inverse model analysis, constrained by air-sea fluxes to the north and by a boundary structure similar to the observed DWBC in the west. The inverse solutions yielded a small range of MOC changes, from 14.3-16.6 Sv, with no trend, and uncorrelated with the NAO. The corresponding range of heat transport changes from was also small, at 0.52-0.60 PW. This small range of MOC variability is in agreement with earlier inverse solutions from the 24N section, which concluded that the inferred values of MOC and heat transport from sections taken decades apart are very similar. It also agrees with model simulations that typically obtain r.m.s. MOC amplitudes of only 1-2 Sv at interannual to decadal time scales. It is hoped that from ongoing model sensitivity studies, in particular with coupled models, conclusions can be drawn for finding observational indices relating to such small MOC changes.

Regarding the subtropical gyre, NAO-related transport variability of the Florida Current and Gulf Stream was documented recently (Baringer and Larsen, 2003; Molinari, 2004). Further downstream, North Atlantic Current intensity was found to be the main source of eastern subtropical heat storage changes (Dong and Kelly, 2004), implying that horizontal gyre changes might play an important role in meridional heat transport variability.

What happens to the cold limb of the MOC when arriving at the equator? Regarding the mean circulation, a drastic transformation of about 10 Sv of lower NADW into middle and upper NADW classes occurs between the DWBC arriving at the equator and continuing across 5S. It involves zonal excursions far into the interior, including mixing processes through interaction with the mid-Atlantic Ridge the mechanisms of which are only poorly understood. South of the equator, near 8S, the DWBC breaks up into a series of anticyclonic eddies that then migrate southward from thereon (Dengler et al., 2004). The cause is dynamic instability of the DWBC, and model studies suggest that for weaker rates of the MOC the flow may continue as a laminar deep boundary current while for a more intense MOC it breaks up into deep eddies.
What is to be expected from northern source water changes? First, if the overflow densities do not change, only the T/S composition (as seems to be the case for the recent overflow salinity decrease), this is mere "spiciness" and is passively carried along at the advection speed of the DWBC. For a change of source water volume influx, model studies show that the initial response to a pulse-like change in deep water production in the North Atlantic consists of an equatorward-propagating baroclinic coastally trapped wave along the western boundary. Upon reaching the equator it is transmitted to the eastern boundary via an equatorial Kelvin wave and poleward in the basins by coastal Kelvin waves, and then westward into the ocean interior by long Rossby waves (Johnson and Marshall, 2002). Regarding the LSW production variability, observational evidence regarding its effects on the equatorial circulation has not yet been presented. The LSW pulse of the early 90's will arrive at the equator shortly and hopefully observations will be in place to study its propagation and potential effects.

### 3.2 The Role of the Thermohaline Circulation in Climate Variability (*by Rowan Sutton* )

The Thermohaline Circulation (THC) makes a major contribution to the O(1PW) northward transport of heat achieved by the North Atlantic Ocean. This heat is released to the atmosphere with significant impacts on climate. However, the THC and the associated heat transport, are not steady. Climate models suggest that, even in the absence of any external forcings, variations of up to 20% can occur on decadal timescales. These variations are partly a response to variations in climate. They are also a cause of climate variations. In this paper we review both the effects of climate variations on the THC and the effects of THC variations on climate. We focus on the North Atlantic and on decadal timescales, since higher frequency variations in the ocean heat transport are largely taken up by changes in heat storage (at least in the extratropics), and consequently have less effect on climate.

***Effects of climate variability on the THC***

Variations in the North Atlantic overturning circulation may be driven by winds or buoyancy fluxes and it is not possible to make a clean separation between wind forced and buoyancy forced circulations. However, model results suggest that whereas interannual variability in the overturning is largely driven by winds, variability on decadal and longer timescales is primarily driven by buoyancy fluxes. It is therefore reasonable to consider decadal and lower frequency variations in overturning as variations in the THC. Contributions to the buoyancy fluxes comprise fresh water forcing by precipitation, evaporation, runoff and sea ice melting or formation, and thermal forcing by turbulent fluxes (sensible and latent heat), radiative fluxes (short wave and long wave) and the latent heat of fusion associated with formation or melting of sea ice.

A considerable number of studies, both observational and model based, have indicated that variations in the North Atlantic Oscillation (NAO) are responsible for a large fraction of the decadal variance in North Atlantic overturning (e.g. Eden, C. and J. Willebrand, 2001, J. Climate, 14, 10, 2266-2280). The NAO is associated with variations in surface thermal and fresh water fluxes as well as variations in wind stress.

Several studies have suggested that variations in the heat fluxes dominate (e.g. Delworth, T. and R. Greatbach, 2000, J. Climate 13, 1481-1495; Eden, C. and T. Jung, J. Climate, 2001, 14, 5, 676-691). Changes in the overturning lag the NAO by 5-20 years, associated with baroclinic adjustment via Rossby waves (e.g. Eden, C. and T. Jung, J. Climate, 2001, 14, 5, 676-691). These results are important, but one should keep in mind that they mostly rely on relatively coarse resolution ocean models (O(1 degree)) with only simple representation of sea-ice processes. There is a need to explore their robustness with higher resolution, and more complete, models. There is also a need to understand in greater detail the processes and timescales of ocean adjustment to realistic variations in surface forcing, bridging the gap between idealised THC adjustment studies and the real system.

***Effects of THC variability on climate***

Observation-based reconstructions of sea surface temperatures for the North Atlantic region show variations on multidecadal timescales that have large amplitude by comparison with interannual variations. There was cool phase in early twentieth century (1900-1920), a warm phase in the mid century (1930-1960), a further cool phase in the 1970s and 1980s, and most recently another warming. The spatial patterns of sea surface temperature (SST) change are highly suggestive of changes in the Atlantic overturning circulation and associated heat transport. Furthermore, observations of surface air temperature (Johannessen, O. et al, 2004, Tellus, 56,4,328-241) indicate that the mid-century warm phase was associated with significantly warmer atmospheric conditions in high northern latitudes (poleward of 60N). These observations are the most direct evidence that variations in the THC can affect climate.

A limitation of the observations is that we lack direct measurements of variations in ocean heat transport. Climate models offer a means to relate directly variations in ocean heat transport with variations in SST and climate. In the HadCM3 model an index of decadal variations in Atlantic ocean northward heat transport accounts for up to 50% of the decadal variance in Atlantic SST and near surface air temperature. The largest regression coefficients are found in the high latitude North Atlantic, associated with changes in sea ice. Moreover, the pattern of temperature change in this region is in excellent agreement with the observed warming from 1920-30 reported by Johannessen et al (2004). This agreement strongly suggests that the observed warming is indeed attributable to changes in the THC.

The regression analysis on Atlantic Ocean heat transport also indicates a significant association with climate variations in the tropics. It is difficult in the coupled model to cleanly separate the oceanic influence on the atmosphere from the influence of the atmosphere on the ocean. To clarify cause and effect we performed additional experiments in which the atmosphere component of the HadCM3 is forced with prescribed SST anomalies in the Atlantic basin. The results from these experiments highlight the potential importance of changes in tropical Atlantic SST for understanding the climate impacts of variations in Atlantic Ocean heat transport. Tropical SST anomalies, even if small in magnitude, may have a large impact on climate because the atmosphere in the tropics is much more sensitive to SST than is the atmosphere at higher latitudes. Furthermore changes in the climate of the tropical Atlantic have the potential to rapidly influence other parts of the tropics via the atmospheric equatorial waveguide. Thus it is plausible that the tropical Atlantic may play a key role in communicating the effects of THC change to regions outside the Atlantic basin.

***Is THC variability a coupled ocean-atmosphere phenomenon?***

If climate variations both force and respond to variations in the THC it is natural to ask whether the THC may be considered a coupled phenomenon. Some model studies suggest not, arguing decadal variability in the THC is stochasticly forced by the (mid-to-high latitude) atmosphere (e.g. Delworth, T. and R. Greatbach, 2000, J. Climate 13, 1481-1495). However the engagement of the tropics suggests some potential coupled feedbacks. For example, THC induced changes in tropical SST might force a response in the NAO (Hoerling, M. et al, 2001, Science, 292, 90-92) which could feed back on the THC. They might also affect atmospheric freshwater transports (including inter-basin transports) and hence influence Atlantic salinity, with – again – potential feedbacks on the THC (Latif, M. et al, 2000, J. Climate, 13, 1809-1813; Vellinga, M. and P. Wu, 2004, J. Climate, in press). Understanding the nature and importance of tropical feedbacks on the THC, and the associated timescales, is undoubtedly a key area for future research.

## 4. Session 2: THC variability and the carbon cycle

**4.1 Summary of Plenary Presentations** (by D. Wallace and N. Gruber)

The session focused on the mechanisms and variability of the North Atlantic carbon sink. An overview of the present understanding and the outstanding questions was given in a keynote presentation by Nicolas Gruber. By taking up about 0.6 Pg C each year (equivalent to about 10% of global fossil fuel emissions), the North Atlantic is the strongest oceanic sink for atmospheric CO2 of the entire northern hemisphere. Based on the recent study by Sabine et al. [2004], the North Atlantic contains also the largest amount of anthropogenic CO2 per unit area, with a column inventory that is about 3-times larger than the global mean. The key questions arising from these two observations are (i) what maintains this large sink for atmospheric CO2, and (ii) how is this sink varying with time and how may it respond to anthropogenic climate change? These two questions were addressed on the basis of both observations and models.

Using a recently developed oceanic inversion method, it has been estimated that about half of the total uptake flux of the North Atlantic, i.e. about 0.3 Pg C yr-1, is driven by the uptake of anthropogenic CO2 [Mikaloff-Fletcher et al., 2005], and the other half is associated with the uptake of natural carbon [Mikaloff-Fletcher et al., in prep]. Thus, an important reason for the North Atlantic currently being such a strong sink region is that it is one of the few regions where natural and anthropogenic CO2 fluxes go in the same direction. The total uptake of 0.6+/-0.1 Pg C yr-1 from the atmosphere [Gruber et al., in prep], is in good agreement with estimates based on the air-sea difference of pCO2 (0.6 Pg C yr-1) [Takahashi et al., 2002] or the inversion of atmospheric CO2 (0.7 Pg C yr-1) [Gurney et al., 2002]. The mechanism underlying the anthropogenic CO2 uptake and the high observed storage is the formation of substantial amounts of intermediate and deep waters in this region, permitting anthropogenic CO2 to penetrate deeper into this basin than into any other basin. The mechanisms maintaining the large uptake of natural carbon are less well established, but are thought to be a consequence of the fact that this oceanic region can undergo cooling and deep convection without entraining high concentrations of remineralized inorganic carbon into the upper ocean, as evidenced by the low entrained concentrations of inorganic nutrients (see e.g. Broecker and Peng [1992]). This low entrainment can be traced back to the overturning circulation of the North Atlantic maintaining low nutrient concentrations in the thermocline and upper ocean by exporting nutrients into the other ocean basins.

Long-term observations from a timeseries site near Bermuda [Gruber et al., 2002; Bates et al., 2002] as well as atmospheric CO2 inversion studies suggest that the North Atlantic sink for atmospheric CO2 could be quite variable. Since the primary processes controlling the carbon balance and air-sea flux variability near Bermuda are convection and sea-surface temperature, and since anomalies in these two factors tend to occur congruently over large oceanic regions, the observations near Bermuda suggest air-sea flux anomalies up to 50% in the North Atlantic carbon sink, i.e. up to +/- 0.3 Pg C yr-1. This tentative extrapolation is supported by some atmospheric CO2 inversion studies, but not by ocean biogeochemical models, which show basin-scale variations of the air-sea CO2 flux of less than +/- 0.1 Pg C yr-1. However, the current generation of global biogeochemistry models tend to underestimate high-latitude variability in physical properties, so there exists the possibility that the basin-scale variations are larger than suggested by the current models. New analyses of existing data plus new long-term data from currently undersampled regions are required to resolve this discrepancy.

First results from the CO2/CLIVAR repeat hydrography program show very large changes in ocean interior carbon and oxygen distributions (e.g. Johnson and Gruber [2005]), suggesting that the higher sensitivity to climate variations hinted at by the few time-series observations may indeed be correct. If this was the case, we can expect the development of substantial positive feedbacks to the climate system from the ocean carbon cycle.

***References***


Bates, N., A. C. Pequignet, R. J. Johnson and N. Gruber (2002). A Variable Sink for Atmospheric CO2 in Subtropical Mode Water of the North Atlantic Ocean , Nature, 420, 489-493.

Broecker, W.S., and T.-H. Peng (1992). Interhemispheric transport of carbon dioxide by ocean circulation, Nature, 356, 587-589.

Gruber, N., N.Bates, and C.D. Keeling (2002). Interannual variability in the North Atlantic Ocean carbon sink,Science, 298, 2374-2378.

Mikaloff-Fletcher, S.E., N. Gruber, A. R. Jacobson, S. C. Doney, S. Dutkiewicz, M. Follows, K. Lindsay, D. Menemenlis, A. Mouchet, and J. L. Sarmiento (2005). Inverse estimates of anthropogenic carbon uptake, transport, and storage by the ocean, Global Biogeochemical Cycles, submitted.
Johnson, G. C. and N. Gruber (2005). Decadal water mass variations along 20W in the northeastern Atlantic Ocean, Progress in Oceanography, submitted.
Sabine. C.S., et al., The oceanic sink for anthropogenic CO2, Science, 305, 367-371, 2004.

## 5. Session 3. Watermass transformation Processes in the North Atlantic

### 5.1 Summary of Plenary Presentations (by C. Mauritzen)

The goal of the session was to assess the state of the art of the understanding of the various transformation processes believed to be of importance to the Thermohaline Circulation. The invited speakers, Detlef Quadfasel, Sonya Legg, Fiammetta Straneo and Monika Rhein, presented a broad geographic and mechanistic overview, starting in the Nordic Seas and ending near equator. This report is based on their presentations.

Watermass transformation in the Arctic Mediterranean is dominated by the formation of the overflow waters of the Greenland-Scotland Ridge. These are ultimately fed mainly by the Atlantic Water inflow, which is transformed through three main mechanisms: cooling and freshening (in the Norwegian and Barents Seas); interaction with shelf-slope convection (in the Asian Arctic); and interaction with convective gyres (in the Greenland and Iceland Seas). Large changes have occurred to this system through the last few decades: the hydrography of the Arctic Mediterranean has changed, and in particular the overflows have become fresher (Dickson et al., 2002); the air temperatures have warmed, the ice cover decreased and the river runoff has increased. Evidence that the exchange across the Greenland-Scotland Ridge has changed is weaker. It is noted that the northward flow of warm water across the ridge is balanced not only by dense returnflow (resulting in "*the overflows*"), but also by a shallow "*outflow*", an estuarine circulation of roughly half the strength of the overturning.

Watermass transformation in the subpolar North Atlantic is dominated by formation of Labrador Sea Water (LSW), occurring predominantly in the Labrador Sea's interior but also likely in the Irminger Sea (Pickart et al., 2003) and in the Labrador Sea's boundary current (Cuny et al., 2003; Brandt et al., 2004). Most of the transformation, 7 Sv on average (Rhein et al., 2002), is associated with the horizontal circulation in the Labrador Sea, with only approximately 1 Sv associated with an overturning in depth space (Pickart and Spall, 2004). Within the basin, the heat released to the atmosphere during LSW formation, is advected into the basin at a sub-surface level (Straneo, 2004) via eddies originating from the boundary current transporting warm, salty Irminger Water into the basin (Spall, 2004). The poleward heat transport associated with LSW formation is estimated to be 0.35PW (Talley, 2003).

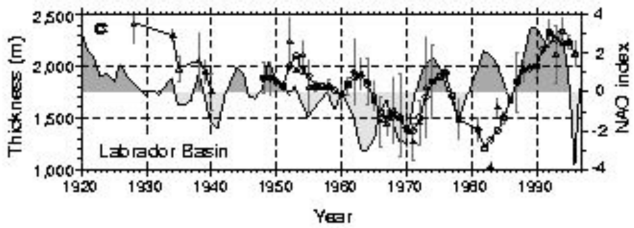


*Figure 1. LSW thickness variability in the Labrador Sea is correlated with the wintertime atmospheric forcing variability (here represented via the NAO Index) on decadal timescales. (Figure from Curry et al., 1998.)*

Data collected over the last 60 years, reveals considerable variability both in the amount of LSW formed (Figure 1) as well as in its properties (Yashayaev et al., 2004). Variable wintertime atmospheric forcing is thought to be the dominant cause of this variability, and the two are significantly correlated on decadal timescales (Figure 1; Curry et al., 1998). On shorter timescales, comparable to the basin's flushing time (order 4 years, e.g. Straneo et al., 2003) the Labrador Sea will tend to integrate the externally imposed variability.

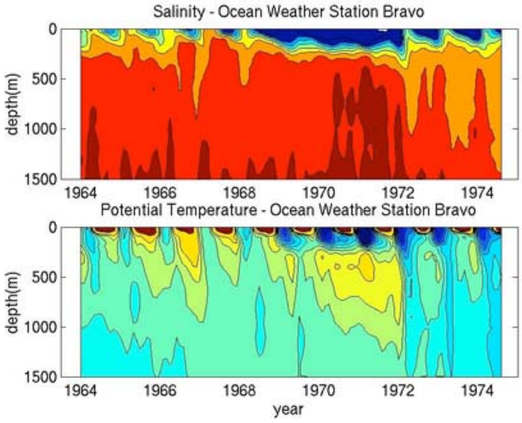


*Figure 2. Variations of properties within the Labrador Sea observed from Ocean Weather Station Bravo (Lazier, 1980). Note how the seasonal convection is arrested from 1969 to 1972, causing a net cooling of the surface layers and an accumulation of salt and heat in the sub-surface. (Figure from Straneo, 2004).*

Other causes for variability are due to changes in the oceanic circulation, connecting the Labrador Sea to the global ocean. For example, the shutdown of convection between 1969 and 1972 is, at least in part, attributed to a freshwater anomaly circulating the subpolar gyre (Lazier, 1980). During this period of time, the exchange between the interior and the boundary current persisted, resulting in a net sub-surface accumulation of heat (and salt), Figure 2. This is an example of how changes in the convective activity will affect both the export of LSW, the mean properties within the Labrador Sea and subpolar gyre (and hence the meridional density grandients), the poleward heat transport, and possibly lead to the radiation of topographic waves that may impact the larger oceanic circulation (Kawase 1987; Johnson and Marshall, 2002).

Changes in the CFC- inventories in the Labrador Sea Water of the subpolar North Atlantic can be used to infer changes in the formation rates of the various modes of LSW. Large scale CTD and CFC observations in 1997, 1999 , 2001 and 2003 showed that only lighter LSW varieties (the upper LSW) were formed in the last years, and that the total formation rate decreased. There are indications, that LSW might also be formed in the Irminger Sea in 1998/99. Export of newly ventilated LSW occurs most likely not only in the Deep Western Boundary Current but also along the Midatlantic Ridge. The spreading time of LSW from the source region to 43°N is 1-2 years and to the subtropical North Atlantic at 16°N about 12-14 years.

***Mechanisms***

The flow of dense water from a marginal sea into the deep ocean *("overflow")* involves several different physical processes. These include: *hydraulic control* processes at the topographic constriction; the *downslope descent* and acceleration of the dense water; *frictional processes* at the bottom boundary; *shear instability, entrainment and mixing* at the interface between dense water and overlying water; *detrainment* of dense water away from the topography and into the ocean interior; and *mesoscale eddy processes*. An ideal representation of overflows in a climate model would capture all of these processes, but does not yet exist. Much attention has recently been focused on the problems of accurately representing downslope descent in height-coordinate models: when horizontal resolution is insufficient downslope descent involves excessive mixing. Two solutions have been proposed to address this problem: crude ``plumbing'' models which connect grid-cells at the top and bottom of topographic slopes (e.g. Beckmann and Doscher 1997), and appended boundary layer models (e.g. Killworth and Edwards, 1999). While the ``plumbing'' models are easy to implement they do not allow any physically based parameterization of entrainment to be included, but nonetheless they improve large-scale model simulations significantly. The appended boundary layer models allow for entrainment, but are difficult to implement and have problems associated with attaching a sigma-coordinate region to a height-coordinate model. For this reason, no global model currently uses an appended boundary layer model.

The mixing of ambient fluid with the dense overflow has typically been characterized as an entrainment, and measurements from laboratory experiments and field observations have suggested an entrainment law as a function of bulk Froude number (Ellison and Turner, 1959). Streamtube models, such as the Price-Baringer model (1994) incorporate the Ellison-Turner entrainment parameterization, and are being implemented into the NCAR climate model to represent the overflows. This parameterization of entrainment has also been incorporated into isopycnal models as a diapycnal mixing coefficient dependent on local Richardson number (Hallberg, 2000), and shown to significantly improve simulations of overflows in this class of models (Papadakis et al, 2003). However, the implementation of a bulk entrainment model as a local closure requires some modifications, especially to represent mixing in the frictional bottom boundary layer (Legg, Hallberg and Girton, 2004). Additionally it is likely that mixing is under-represented in isopycnal models at very coarse resolution when shears are under-resolved.

Dense water formation through convection involves various stages of *preconditioning*. Preconditioning is the term used to describe the spatial localization of deep convection by the pre-existing ocean circulation on scales smaller than the atmospheric forcing. Preconditioned areas are typically associated with weaker stratification than the surroundings, or may force the water to be exposed to atmospheric cooling for a greater length of time. Preconditioning may occur on the large scale, associated with recirculating cyclonic gyres, which may trap the fluid in the vicinity of the cooling and have upwardly domed isopycnals with locally weaker stratification. Cyclonic recirculations have been identified in the Labrador Sea from PALACE floats by Lavendar et al (2000). The area of deepest convection in the Labrador Sea lies at the intersection of strong atmospheric cooling and a trough in the geostrophic pressure field. A mechanism for preconditioning in the Greenland Sea is the formation of ice (which increases density in surface waters through brine rejection) accompanied by wind-forced advection of ice to leave an ice-free region exposed to further surface cooling (Visbeck et al, 1995).

Preconditioning can also be small-scale, associated with eddies with dense cores and weaker stratification, seen in both Greenland Sea (Gascard et al, 2002) and Labrador Sea (Lilly et al, 2003). Such eddies are probably remnants of the previous year's convection.

In addition to providing locally weaker stratification, eddies may also influence convection by forcing mixing to be slant-wise rather than vertical, if mixing is along angular momentum surfaces (Straneo et al, 2002) or occurs predominantly through baroclinic instability (Legg et al, 1998). Convective mixing also modifies the pre-existing eddy field, forcing previously stable eddies to become unstable (Legg et al, 1998) and generating a vigorous barotropic eddy velocity field (Lilly et al, 1999).

In addition to dense core eddies, an additional class of anticyclonic eddies associated with surface enhanced stratification has been observed in the Labrador Sea (Lilly et al, 2003). These eddies are generated through instability of the Irminger current west of Greenland (Prater et al, 2002), and propagate into the center of the Labrador Sea. The enhanced surface stratification within these eddies locally suppresses convection, and indeed in the Northwestern Labrador Sea where most of these eddies are found, deep convection is not observed. These eddies play an important role in supplying warmer saltier water to the central Labrador Sea. The Labrador Sea has been observed to restratify rapidly following convection (Lilly et al, 1999) and some model studies (Katsman et al, 2004) suggest that boundary current eddies play an important role in this restratification (which occurs even while surface heat losses remain significant). However other model studies (Bernard Barnier, poster at this meeting) show that the eddies generated through instability of the deep convective region can carry out much of the restratifcation.

General circulation models generally include parameterizations of the fluxes due to mesoscale eddies (e.g. Gent and McWilliams, 1990) and so can capture the restratification processes associated with deep convection. However, the small-scale preconditioning effects of eddies are not captured, since they occur below the grid-scale, and so any modifications of convection due to the presence of mesoscale eddies (e.g. slantwise fluxes which penetrate deeper than the equivalent vertical fluxes) are not represented in today's climate models.

Numerical models still have outstanding problems regarding overflows. Therefore US CLIVAR has established a Climate Process Team on Gravity Current Entrainment (http://www.cpt-gce.org) to address problems that need to be solved in order to better represent overflows both in isopycnal and height-coordinate ocean models. The team includes members from several different academic institutions (WHOI, LDEO Columbia, Miami, Princeton) and representatives from modeling centers (GFDL, NCAR). By combining knowledge obtained from recent field programs and process studies with understanding of large-scale model development, the team aims to develop new parameterizations of overflows for use in climate models.

## 6. Session 4: Characteristics and mechanisms of MOC variability in the North Atlantic

### 6.1 Summary of Plenary Presentations (by *A.-M. Treguier, W. Johns and D. Stammer*)

This session was concerned with observational evidence about changes in the meridional overturing circulation and associated transport properties of the ocean, about forcing and adjustment mechanism of those changes and about ways to observe or estimate those changes using models and data in some combination. The session had several overview talks on those subjects. It started with a talk by Steward Cunningham on "What are the main characteristics of interannual-decadal variability in large scale transports?" followed by a review provided by Molly Behringer on "What is the potential of different types of observation systems for detecting/monitoring MOC changes."

Some emphasis was put on the review of forcing mechanism of MOC variations and mechanism of communication between polar latitudes of the Atlantic and its low-latitudes. Those talk were provided by Richard Greatbatch and Will DeRuiter who covered separately processes of the northern and southern hemispheres. Helge Drange added a discussion of the role of specifically the Arctic and GIN Sea in driving MOC variations. Those talks were followed by a review provided by Terry Joyce which originally had the title "Understanding the link between MOC variability and SST variability: What are the theoretical and observational basis of our knowledge about this?" A final talk was provided by Carl Wunsch ("Has oceanic state estimation matured sufficiently to be a required element of observing systems for the mass, heat, and other property fluxes? ") who described the way forward in observing and modeling changes in the ocean circulation, specifically those which are not likely to be observed by one single element of an observing system and the role of data assimilation dows and will play in ongoing and future climate research.
A brief summary of each individual talk and its conclusion will follow below.

### 6.2 Variations in the North Atlantic Meridional Overturning Circulation: Forcing mechanisms, communication to low latitudes, and implications for prediction *(by Richard J. Greatbatch)*

Indirect evidence from models was presented suggesting that the North Atlantic MOC does indeed vary on both interannual and interdecadal time scales. It was noted that variable wind stress forcing dominates on the interannual time scale, whereas variable buoyancy forcing (in particular, surface heat flux in the particular model shown) dominates on interdecadal time scales. It was noted that models show the importance of the North Atlantic Oscillation (NAO) for forcing the MOC on time scales of interannual to interdecadal, but indicate that forcing associated with the overflows is probably important on longer time scales (it was argued that the latter comment probably also applies to forcing from the southern hemisphere).

A simple coupled system was then described, in which a one parameter atmosphere (the NAO index) is coupled to a dynamical model of the North Atlantic Ocean, the whole system being driven by a white noise forcing in the atmospheric component. The coupled system was used to discuss the communication between high and low latitudes, and the harnessing of the dynamical adjustment of the MOC for prediction of the atmospheric and oceanic state on time scales out to decadal. The simple coupled system exhibits a damped decadal oscillation in which there is a positive feedback on interannual time scales from the wind stress forcing of the ocean model, while the decadal adjustment of the MOC to the buoyancy forcing provides a negative feedback. It was argued that when the decadal oscillation is excited, overshooting provides some potential for predicting both the atmospheric and oceanic states in the North Atlantic climate system on time scales out to decadal, but that the predictability of the atmosphere is likely to be weak. A novel diagnostic technique was used to show that in the model, the decadal time scale of the oscillation is set by advection of density anomalies in the subpolar North Atlantic, and also that anomalous geostrophic advection is important for maintaining the oscillation. Evidence was presented that wave processes probably play a role, in addition to advection, in carrying the signal to lower latitudes. It was noted that there is still uncertainty in the dynamics of how the MOC responds to changes in its forcing, and that this adjustment process depends on how a model handles both advective and wave processes along the western boundary of the North Atlantic.

**6.3 Forcing mechanisms of MOC variations and mechanisms of communication between polar latitudes of the Atlantic and its low latitudes: Southern Hemisphere** *(by Wilhelmus P.M. de Ruijter)*
The South Atlantic is the gateway by which the Atlantic meridional overturning circulation (MOC) communicates with the global ocean, exchanging properties and mass with the Indian and Pacific via the Southern Ocean and around South Africa. These inter-ocean links make possible the global reach of North Atlantic Deep Water (NADW) and of the compensating return flow within the ocean upper layers. The different latitudes of the passages connecting the South Atlantic to the Pacific and Indian Oceans as well as the sharply different nature of southeastern Pacific and southwestern Indian Ocean water masses allow South Atlantic access of very different water types.

Cool low salinity waters are introduced through the Drake Passage, warm and saline subtropical Indian Ocean waters enter at the Agulhas Retroflection. The resultant heat, freshwater and buoyancy budget of the South Atlantic is sensitive to the ratio of these two return flows. Which of the South Atlantic's neighbours dominates the inter-ocean exchange may to a large measure determine the meridional fluxes of the South Atlantic. Temporal variations in the ratio may be associated with climate variability as well as with variations in the Atlantic MOC (see, e.g., the review papers on inter-ocean exchanges by Gordon, 2001 and De Ruijter et al, 1999).

Modelling studies indicate that the so-called Agulhas leakage tends to stimulate and stabilize the northern sinking mode of the Atlantic overturning circulation (Weijer et al., 2001). Bering Strait (or other northern) fresh water fluxes oppose and destabilize it. At much reduced Agulhas leakage rapid switches may occur between different Atlantic overturning modes; gradual resumption of South Atlantic inter-basin exchange leads to an abrupt recovery of the northern overturning circulation (Weijer et al., 2002; Knorr and Lohmann, 2003). Proxy records from a sediment core in the Cape Basin indicate that Agulhas leakage was highly variable over the past 550,000 years: enhanced during present and past interglacials and largely reduced during glacial intervals (Peeters et al., 2004), supporting the model results of a Southern Ocean trigger of the transition into an interglacial northern sinking mode of the MOC.

In related GCM studies transitions were found between strong and weak MOC, with hysteresis effects, in response to changes in the strength or pattern of the surface fresh water forcing (Rahmstorff, 1995, Stocker, 2000, Gregory et al., 2003). Effects of continental asymmetry (asymmetric forcing due to the 'narrowness' of the North Atlantic) and the opening of Drake Passage (no pressure gradient possible against a continent to geostropically balance a meridional flow) were both shown to favour the northern overturning mode (Dijkstra et al., 2003).

A possible link was suggested (Toggweiler and Samuels, 1995) between the strength of the wind forcing over the latitudes of Drake Passage and the strength of the MOC. In a coarse resolution model, in the absence of sufficient diapycnal mixing to transfer surface to deep water, the equatorward Ekman drift across Drake Passage has to flow all the way to the deep-water formation region of the North Atlantic before it can return at depth along the deep topography in the Passage. However, later studies, using more complex models, have shown that balance is possible by local deep-water production just north of Drake Passage (Rahmstorff and England, 1997) or by poleward transport by mesoscale eddies (Speer et al., 2000). Nof (2000), applying the Island Rule on a global scale, derived an expression for the MOC as a function purely of the wind stress. However, due to the linearization involved in deriving the island rule the important inter-ocean exchanges by the boundary currents cutting through the integration contour around South America and Africa are ignored.

The wind pattern over the subtropical Indian Ocean exerts an important influence on the strength of the Indian to Atlantic fluxes (De Ruijter et al., 1999). There is also evidence for an oceanic teleconnection between the strength and variability of the equatorial climate modes over the Indian Ocean and the inter-ocean exchange around South Africa (Schouten et al., 2002). A monitoring programme for the South Atlantic should involve measurements of the varying inter-ocean exchanges, both around South America and Africa, as well as estimates of the mixing and water mass transformations in the two major blending regions: the Brazil-Malvinas confluence and the Cape Basin. To monitor the net effect of the varying inter-ocean exchanges and subsequent mixing and modifications on the vertical buoyancy characteristics of the South Atlantic and the basin-scale overturning fluxes a zonal section is proposed for sustained observations across the South Atlantic between 25°-30° S, i.e. north of the confluence region and the Agulhas Ring 'corridor'.

***References:***

De Ruijter, W.P.M., A. Biastoch, S.S. Drijfhout, J.R.E. Lutjeharms, R.P. Matano, T. Pichevin, P,J, van Leeuwen and W. Weijer - Indian-Atlantic inter-ocean exchange: dynamics, estimation and impact - *J. Geophys. Res.,* 104, 20885-20910 (1999).

Gordon, A.L., (2001) Interocean exchange. Ch. 4.7 in: *Ocean Circulation and Climate*, G. Siedler, J. Church, J. Gould (Eds.), Academic Press, 303-314.

Dijkstra, H.A., W. Weijer and J.D. Neelin, , Imperfections of the three-dimensional thermohaline circulation: hysteresis and unique-state regimes, *J. Phys. Oceanogr.,* 33, 2796-2814 (2003).

Gregory, J.M., O.A. Saenko and A.J. Weaver, The role of the Atlantic freshwater balance in the hysteresis of the meridional overturning circulation. *Climate Dynamics,* 21, 707-717, doi 10 1007/s00382-003-0359-8. (2003).

Knorr, G. and G. Lohmann,), Southern Ocean origin for the resumption of Atlantic thermohaline circulation during deglaciation, *Nature* 424, 532-536. (2003).

Peeters, F.C.J., G.J.A.Brummer, W.P.M. de Ruijter, G.M.Ganssen, R.R.Schneider, E.Ufkes and D.Kroon, Vigorous Exchange between Indian and Atlantic Ocean at the end of the last five glacial periods, *Nature,* 430, 661-665; doi: 10.1038/nature 02785, (2004).

Rahmstorf, S., and M.H. England, Influence of Southern Hemisphere winds on North Atlantic Deep Water flow. *J. Phys. Oceanogr.*, 27, 2040-2054. (1997).

Schouten, M. W., W.P.M. de Ruijter, P.J. van Leeuwen, H.A. Dijkstra - An oceanic teleconnection between the equatorial and southern Indian Ocean - *Geophysical Research Letters,* doi: 10.1029/2001GL014542 (2002) IM-02-11

Weijer, W., De Ruijter, W.P.M. and Dijkstra, H.A. - Stability of the Atlantic overturning circulation: competition between Bering Strait freshwater flux and Agulhas heat and salt sources - *Journal of Physical Oceanography,* 31, 2385-2402 (2001)

Weijer, W., W.P.M.de Ruijter, A.Sterl and S.S.Drijfhout - Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy, *Global and Planetary Change,* **34***,* 293-311. (2002).

## 7. Session 5: The THC in a changing climate

### 7.1 Summary of Plenary Presentations *(by R. Wood and M. Latif)*

The session discussed future THC scenarios based on the results of climate modelling. A particular question is to what degree model predictions depend on the representation of oceanic and atmospheric processes, and, based on this, the needs and prospects for improved THC simulations in the next generation of climate models.

### 7.2 AOGCM predictions of changes in Atlantic meridional overturning: the CMIP coordinated THC experiment *(by Jonathan Gregory)*

There is considerable modelling uncertainty over the response of the MOC to increasing greenhouse gases. Even given the same forcing scenario over the next century, a set of nine coupled atmosphere-ocean GCMs showed a response of the MOC ranging from a slight strengthening to a weakening of 15 Sv by 2100 (Cubasch et al. 2001, Fig. 9.21). Similarly, AOGCMs show a range of responses to surface freshwater input in the North Atlantic. In order to reduce the uncertainty in model MOC projections, it is necessary first to understand why the different models respond differently. This implies a detailed analysis of the processes operating in each model. Such an analysis has been performed for some models individually (e.g. Latif et al. 2000, Gent 2001, Thorpe et al. 2001), but no common picture has so far emerged: each analysis emphasises different processes. To encourage the development of a common understanding of model differences, a ‘coordinated THC experiment’ has been set up under the auspices of the Coupled Model Intercomparison Project (CMIP). The experiment defines a protocol for a set of common model runs, but at present each modelling group is responsible for its own analysis. So far 7 AOGCM groups and 4 EMIC groups are participating. Analysis is in progress and only preliminary findings from a subset of the models are presented here.

In the first set of experiments, the response to an idealised 1% per annum $CO_2$ increase is studied, up to four times the initial value. In addition, parallel ‘partially coupled’ runs are defined to separate the effects of radiative and fresh water changes on the MOC. In all models, the MOC weakens, by between 10 and 40 percent. In most cases, changes in surface heat flux are the dominant driver of the transient MOC change. The importance of the (secondary) contribution of fresh water flux changes varies between models. In no cases does the MOC shut down under this scenario, and in all cases the radiative warming swamps any cooling due to MOC weakening, so that Europe and North America warm.

In a second set of experiments ('water hosing') an extra fresh water flux of 0.1 Sv is added to a region of the subpolar North Atlantic for 100 years. The flux is then switched off and the model runs continued for another 100 years or more. The MOC weakens in all cases, producing a surface cooling around the North Atlantic. Once the perturbation is switched off, the MOC recovers. With a stronger water flux (1.0 Sv), some models show a weakening or shutdown of the MOC which does not recover after the perturbation is removed.

A more detailed analysis is required to obtain a full understanding of the different model responses. At this point it may be possible to define critical observational tests that will allow differentiation between models and so contribute to reducing the modelling uncertainty for the future of the MOC.

**7.3 Do climate GCMs exhibit multiple THC equilibria/hysteresis?** *(by Richard Wood)*
Since the pioneering work of Stommel (1962), it has been believed that the Atlantic MOC may have more than one stable equilibrium state, at least in certain parameter regimes. This opens up the possibility of thresholds and hysteresis in the MOC, and such behaviour has been seen in many models since Stommel's work, including several intermediate complexity climate models (EMICs). The possibility of such behaviour, including an alternative climate state with a weak or reversed Atlantic MOC, underlies much of our thinking on the future of the MOC, but to date multiple equilibria have only been seen in very few of the more complex atmosphere-ocean general circulation models (AOGCMs), which are the most comprehensive available models of the climate system. How robust is the hysteresis behaviour that is seen in the simpler models?

In most cases, modelling groups have attempted to locate the 'MOC off' state by applying a temporary fresh water flux to the North Atlantic sea surface, near the regions of deep water production. Typically the addition of O(50-100 Sv yr) of fresh water is sufficient to turn off the MOC. In at least two AOGCMs the 'MOC off' state persists even after the fresh water perturbation is stopped (Manabe and Stouffer 1999, Rind et al. 2001), suggesting a stable 'off' state. However, in other models the MOC recovers after the perturbation is removed. It should also be noted that the recovery of a model's MOC following a specific fresh water perturbation does not imply that the model does not have a stable 'MOC off' state, merely that if the off state does exist it is hard to get the model state onto its attractor. The reasons for the recovery have been analysed in a number of cases, with varying conclusions about the dominant timescales and processes responsible. Some important processes that have been identified in specific models are: large scale vertical mixing (Manabe & Stouffer 1999), mid- and high-latitude windstress feedbacks (Schiller et al. 1997), tropical (Vellinga et al. 2002) and high latitude (Schiller et al. 1997) fresh water feedbacks. Further factors which may be important and are not fully understood are the mean freshwater budget of the Atlantic (e.g. Rahmstorf 1996, Gregory et al. 2003), and the amount of internal variability (Monahan 2002).

It is likely that the key processes are present to some degree in most AOGCMs, but the overall stability of the MOC is likely to be a subtle balance between positive and negative feedbacks, each of which must be modelled quantitatively. A more quantitative and systematic analysis of a range of models (such as is planned under the CMIP coordinated experiment described in section 1 above) is required to understand fully the reasons for the range of model responses. This understanding would allow development of a set of observational tests that were focused on reducing uncertainty in MOC behaviour. Analyses to date suggest that the keys to MOC stability may lie in atmospheric, as well as oceanic processes.

**7.4 Concepts and simplified models to quantify past and future climate change** *(by Thomas Stocker)*
Rapid coolings and warmings punctuated the last ice age and the transition into the present interglacial. The latest results from the ice core from NorthGRIP indicate that there were 25 Dansgaard/Oeschger events, abrupt warmings of 8 to 16°C (NorthGRIP Members, 2004). Many paleoclimatic archives indicate that these changes were global in extent, albeit with differing amplitude and sign. Recent measurements of metallic tracers in marine sediments demonstrate that abrupt changes of the ocean's deep circulation are associated with the rapid changes in surface temperature (McManus et al. 2004). Simulations with a hierarchy of

climate models show that changes in the surface freshwater balance of the North Atlantic are able to disrupt the meridional overturning circualtion and hence induce a substantial cooling (Stocker et al., 2001). Associated with the cooling in the north is a warming in the south Atlantic and the Southern Ocean. This thermal bipolar seesaw can explain a large amount of variability in synchronised temperature estimates measured in ice cores from Greenland and Antarctica (Stocker and Johnsen, 2003). However, the damping time scale between northern and southern changes is about 1000 years, an order of magnitude longer than the longest adjustment times in the Southern Ocean. Simulations with a global ocean circulation model coupled to a dynamical atmospheric component suggest a revised concept of north-south connection (Knutti et al., 2004). The freshwater discharge to the North Atlantic generates anomalous geostrophic circulation in the northern and southern basins of the Atlantic and cause an additional heat transfer from the South Atlantic to the Southern Ocean. Therefore, even if the meridional overturning circulation in the Atlantic is already collapsed, additional freshwater discharge into the North Atlantic causes a climatic signal in the south. A comparison of this "thermal freshwater seesaw" explains about 70% of the variance in the Greenland and Antarctic ice cores, as well as in a high-resolution marine sediment core off Portugal. This strongly suggests that the abrupt changes were generated by freshwater discharges into the North Atlantic. A specific testable prediction of this simple concept is that all Dansgaard/Oeschger events in Greenland ice cores should have a counterpart in Antarctic ice cores. The same climate models respond with a weakening of the meridional overturning circulation when perturbed with increasing greenhouse gas concentrations, with the possibility of a complete shutdown in the 22$^{nd}$ century, if the forcing is strong enough.

**7.5 Prospects for predicting the future of the THC in IPCC AR4 and beyond** *(by Jochem Marotzke)*
*THC predictability:* We do not fully understand the fundamental limits on predictability of the THC over the next few centuries. If THC changes are dominated by a smooth response to changes in forcing (greenhouse gases etc.), then they may be predictable in principle despite the current level of modelling uncertainty. However if abrupt changes and threshold behaviour are possible, predictions may be much more uncertain (Wang et al. 1999, Knutti & Stocker 2002).

*Long-term MOC observation:* A number of observing systems are currently in place to monitor key elements of the MOC, although all are currently funded as research efforts with no guarantee of sustained support. Systems include the recent NERC/NSF funded array at 26N and up- and down-stream measurements along the western boundary and at key exchange points in the subpolar and subarctic regions. Continuous observation of the MOC will be required to detect and attribute MOC changes, and to initialise MOC forecasts (for ‘early warning’ of significant MOC change). If MOC changes are detected, the observing system must be capable of attribution of those changes, in two sesnses. Attribution of the first kind means providing a dynamically consistent picture of the changes on at least the basin scale. Attribution of the second kind (the traditional ‘IPCC’ sense) means separating anthropogenic trends from naturally forced or internal variability. There is scope here for use of the growing palaeoclimatic database (especially for the past 1000 years), to better define the level of internal variability.
A crucial issue in developing longer term funding for MOC observations will be to establish some kind of priority order for observations. This will be a contentious issue, but must be faced. The decision making process must involve experimental design studies using realistic models (e.g. Hirschi et al. 2003, Baehr et al. 2004), and must take into account the potential of broader observational programmes such as Argo and altimetry.

*What can we expect from future model developments?* A gradual move away from the use of flux adjustments is expected. While flux adjustments mask errors in surface climate and long term drifts, they do not necessarily remove underlying process errors which modify THC response (e.g. Marotzke & Stone 1995). Increases in atmospheric and oceanic model resolution are likely to have both stabilising and destabilising impacts on the THC, with the net effect hard to predict. Ensemble methods will be developed to understand or quantify uncertainty in model climate projections; this may include the establishment of a ‘traceable model spectrum,’ including EMICs which can be used to generate large ensembles but whose processes can be related to those present in AOGCMs. A particular challenge will be to understand better how to use both palaeo and instrumental observations to constrain model response.

*Regional impacts:* In coming years there will be an increasing emphasis on the regional impacts of climate change in general, and THC change in particular. Global model results must be downscaled to provide credible scenarios of climate impacts. A particular impact of changes in the THC is that on sea level. A weakening of the THC can be expected to result in sea level rise of a few tens of cm around the North Atlantic, even before taking into account the effect of increases in global ocean heat content. The net result could be enhanced sea level rise in this region in response to global warming. Since THC changes due to global warming will probably only result in net regional cooling if they are abrupt (see sectin 1 above), it may turn out that the most important impact of THC change is through sea level rather than surface temperature.

***References:***


Baehr, J., J. Hirschi, J.-O. Beismann and J. Marotzke ,2004: Monitoring the meridional overturning circulation in the North Atlantic: a model-based array design study. *J. Mar. Res.,* **62**, 283-312.

Cubasch, U., G.A. Meehl, G.J. Boer, R.J. Stouffer, M. Dix, A. Noda, C.A. Senior, S. Raper and K.S. Yap, 2001: Projections of future climate change. *In Climate Change 2001: the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate* (J.T. Houghton et al., editors), Cambridge University Press, 881pp.

Gent, P.R., 2001: Will the North Atlantic Ocean thermohaline circulation weaken during the 21st century*? Geophys. Res. Lett.*, **28**, 1023-1026.

Gregory, J.M., O. A. Saenko and A.J. Weaver, 2003: The role of the Atlantic freshwater balance in the hysteresis of the meridional overturning circulation. *Clim. Dyn.,* **21**, 707-717

Hirschi, J., J. Baehr, J. Marotzke, J. Stark, S. Cunningham and J.-O. Beismann, 2003: A monitoring design for the Atlantic meridional overturning circulation. *Geophys. Res. Lett.*, **30(7)**, 1413.

Knutti, R. and T.F. Stocker, 2002: Limited predictability of the future thermohaline circulation close to an instability threshold. *J. Climate* **15**, 179-186.

Knutti, R., et al., 2004: Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation, *Nature*, **430**, 851-856.

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

Manabe, S. and R.J. Stouffer, 1999b: Are two modes of thermohaline circu;ation stable? *Tellus*, **51A**, 400-411.

Marotzke, J. and P.H. Stone, 1995: Atmospheric transports, the thermohaline circulation, and flux adjustments in a simple coupled model. *J. Phys. Oceanogr.*, **25**, 1350-1364.

McManus, J.F., et al., 2004: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes, *Nature*, **428**, 834-837.

Monahan, A.H., 2002: Stabilisation of climate regimes by noise in a simple model of the thermohaline circulation. *J. Phys. Oceanogr.* **32**, 2072-2085.

NorthGRIP Members, 2004: High-resolution climate record of the northern hemisphere back into the last interglacial period, *Nature*, **431**, 147-151.

Rahmstorf, S., 1996: On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Clim. Dyn.* **12**, 799-811.

Rind, D., P. deMenocal, G. Russell, S. Sheth, D. Collins, G. Schmidt and J. Teller, 2001: Effects of glacial meltwater in the GISS coupled atmosphere-ocean model. Part 1. North Atlantic Deep Water response. *J. Geophys. Res.* **106**, 27335-27353.

Schiller, A., U. Mikolajewicz and R. Voss, 1997: The stability of the thermohaline circulation in a coupled ocean -atmosphere general circulation model. *Clim. Dyn.* **13**, 325-347

Stocker, T.F., and S.J. Johnsen, 2003: A minimum thermodynamic model for the bipolar seesaw, *Paleoceanogr.*, **18**, 1087.

Stocker, T.F., et al., 2004: The future of the thermohaline circulation - a perspective, in The Oceans and Rapid Climate Change: Past, Present, and Future, edited by D. Seidov, et al., pp. 277-293, American Geophysical Union, Washington, 2001.

Thorpe, R.B., J.M. Gregory, T.C. Johns, R.A. Wood and J.F.B. Mitchell, 2001: Mechanisms determining the Atlantic thermohaline circulation response to greenhouse gas forcing in a non-flux-adjusted coupled climate model. *J. Climate* **14**, 3102-3116.

Vellinga, M., R.A.Wood and J.M. Gregory, 2002: Processes governing the recovery of a perturbed thermohaline circulation in HadCM3. *J. Climate* **15**, 764-780.

Wang, X., P. H. Stone, and J. Marotzke, 1999: Global thermohaline circulation, Part I: Sensitivity to atmospheric moisture transport. *J. Climate*, **12**, 71-82.

## 8. Session 6: Future programs (summary provided by M. Visbeck and E. Chassignet)

During the workshop a number of smaller working groups got together to discuss issues related to future programs and especially the needed sustained observations. The working groups were first reminded of the two of most pertinent overall goals of the workshop:

- To take stock of our understanding and best estimates of the present and future state of the Atlantic Thermohaline Circulation.
- To guide implementation plans by assessing the capabilities and future needs of THC observing and synthesis systems to detect and predict low-frequency changes or trends.

and then challenged by the following questions:

- Do we want to built and sustain a global observing and synthesis system for the next 50 years? If so, how can this be done?
- What MOC related aspects are most important for climate?
- In which way can model experiments help to improve the design and interpretation of particular types of MOC related observing systems? And how efficient can these observations constrain MOC related ocean state estimates?
- Which observations need to be represented by the models in order to reduce the uncertainty of model based assessments and forecasts? To what degree?

With that in mind, five more specific themes were discussed:

a) To which degree depend future climate change model predictions on the representation of oceanic processes? (chair – R. Wood)
b) What MOC related aspects are most relevant to understand and potentially predict climate variability and change? (chair – R. Sutton)
c) What are the proposed mechanisms of MOC variability and what do we need to verify their existence and quantify their relevance? (chair – A. Treguier)
d) Which observations need to be simulated how well by ocean models used for interannual to decadal climate studies? (chair - B. Molinari)
e) How can models help to asses the relevance of particular MOC related observing systems? (chair – C. Mauritzen)

and results reported back to in plenary. Several groups came up with similar recommendations. In the following, a summary of the combined issues and recommendations for future investigation and research programs are given:

**What is the list of processes that must be understood and well represented in model in order to address variability questions? How realistic do the models have to be for us to trust the mechanisms they reveal?**

Ultimately, we would like the coupled models to simulate correctly today's climate before we start making predictions. So far, however, change assessments have shown diverging model behaviour with regards to the present and future evolution of the Atlantic MOC. This raises a question: How to achieve convergence in MOC simulation? The answer depends on the following points of view:

**Null hypothesis 1** - *Current climate models contain sufficient processes and resolution to model the future MOC – we just lack the right observations to sort out which ones to believe.*
If true, we could design a more or less objective approach to decide which observations are most crucial in order to discriminate between the observations that are needed for the evaluation of modelled processes and those that are needed to be sustained for ongoing MOC assessments.

**Null hypothesis 2** – *To predict the response of the MOC to current and future changes in forcing, it is neither necessary nor sufficient to model the mean state accurately.*
This leaves us with a broad range of processes that are potentially important in order to reduce uncertainty in model-based predictions of the Atlantic MOC. A suggested way forward to assess the relevance of a particular process is to combine high resolution or regional process modelling and/or observations with global scale analysis (global models) to convince climate model builders that they need to improve a

particular process. The analysis could include sensitivity analysis – ensembles of climate models (GCM/EMIC), adjoints, etc.

The working groups suggested a number of MOC relevant phenomena and processes that need to receive appropriate attention in ongoing and future programs. They include ocean transport and storage of mass, heat, fresh water, $CO_2$ with emphasis on:

- Overflows (most crucial for long term trends)
- Deep Western Boundary Currents from Greenland to South America
- Florida current transport
- Gulf Stream position as proxy for large scale circulation changes
- Number of North Brazil Current rings and deep eddies along S. American coats as proxy for MOC strength.
- Depth of winter convection in Greenland, Labrador, and Irminger Seas.
- Boundary signals (waves, anomalies) that could serve as a precursor to subsequent MOC changes.

Other key ocean/climate variables which may be sensitive to MOC changes:
- SST dipole signature between North and South Atlantic region
- heat storage as estimated from ARGO and satellite sea level.
- sea ice extent
- surface fluxes

In order to reduce uncertainty in model based MOC (and climate) predictions, two strategies were identified:
a) Use all available measurements in some optimal synthesis system (possibly state estimation by data-model assimilation). Then generate the best estimate of the current state of the MOC (ocean/climate). And from that perform dynamical ensemble forecasts. There is increasing evidence that the initial condition does matter up to decadal forecast time scales.
b) An alternative approach is to develop a reduced set of MOC (climate) predictors that when appropriately observed can be used for statistical forecasts.

Desirable features of MOC (Climate) predictors:
- High correlation with climate variables (Q, SST)
- Leading correlation needed for statistical predictions
- High signal to noise (e.g. decadal change vs interannual)
- "easy" to measure reliably

Candidate predictors:
- Heat transports
- Heat storage
- Boundary processes (waves, advection of anomalies)

Issues: accuracy/precision of measurements.

Approach a) is likely to be eventually the method of choice, however approach b) is valuable because it can help constrain the predictions made by approach a).

**In summary:**
- We know how to work with models, we know of the problems, and we know how to observe. The single most difficult issue is how to **sustain the observations**.
- We need to observe for decades to reduce the uncertainties to the necessary levels.
- Sampling issues can be addressed with models, but these exercises are very hard to fund.

## 9. Posters´abstracts

### A Moored Array to Monitor the North Atlantic Thermohaline Circulation at 26°N

by Stuart Cunningham[1], Joel Hirschi[1], Jochem Marotzke[2], William Johns[3], Molly Baringer[4] and Harry Bryden[1]
[1]Southampton Oceanography Centre, Southampton, UK, [2]Max Planck Institute for Meteorology, Hamburg, Germany, [3]RSMAS, University of Miami, Miami, USA, [4]NOAA/AOML, Miami, USA

During February-March 2004 on board RRS Discovery we deployed an array of moored instruments to measure temperature, salinity and velocity profiles at 22 locations across the Atlantic Ocean at 26°N. This is the beginning of a 4-year pilot monitoring effort to measure the strength and variability of the Atlantic meridional overturning circulation and heat flux across 26N under the "Rapid Climate Change" programme. Deployment of the array in two ocean circulation models (OCCAM and FLAME) has demonstrated that the planned array measurements can be used to accurately reproduce the variability in overturning circulation and heat transport within the models. Moorings are concentrated on the western side of the 26°N section to measure the deep western boundary currents, on the eastern side of the section to measure eastern boundary currents, and on either side of the Mid Atlantic Ridge to separate the contributions to the overturning circulation from the eastern and western basins. In particular, top-to-bottom profiles of temperature and salinity at the edges of the basin from 10 tall moorings will be used to measure the temporal variability in the basin-wide geostrophic velocity profile. The overall monitoring relies on ongoing measurements of the Gulf Stream transport through Florida Straits by submarine electromagnetic cable and on continuous estimates of surface Ekman transport derived from operational wind products. The array is due to be recovered and redeployed in Spring 2005.

### Meridional Heat Transport in the South Atlantic

by Silvia L. Garzoli[1] and Molly Baringer[1]
[1]Atlantic Oceanographic and Meteorological Laboratory, NOAA, USA

The South Atlantic Ocean is a major conduit for the warm upper layer water that flows northwards across the equator, compensating for the colder southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the South Atlantic. Previous estimates of the heat transport in the 30° to 35°S band varies from negative values to more that 1 PW. This variability may be a consequence of the different pathways and/or of the different methods used to calculate the heat transport, however natural variability in the heat transport, whether annual or interannual, cannot be ruled out using historical data. The upper branch of the MOC in the South Atlantic can be supplied by warm and salty water that enters the South Atlantic via the Agulhas leakage (the warm route, Gordon, 1986) or by cold and fresh intermediate water that enters the South Atlantic via the Drake Passage (the cold route, Rintoul, 1991). According to Gordon (1992) the AAIW derived from the Drake Passage returns saltier and warmer via the Agulhas leakage after a loop in the Indian Ocean. It is not clear which of these two routes is the most important or if there is seasonal or interannual variability that may lead to the large range of estimated heat transportvalues. What it is clear is that in order to better understand the global ocean thermohaline circulation and its impact on climate it is necessary to reduce the heat flux uncertainty in the South Atlantic. Beginning in 2002, and as part of the NOAA Global Ocean Observing System, a new XBT high-density line was started in the South Atlantic between Cape Town, South Africa and Buenos Aires, Argentina. The line was originally funded to be repeated twice a year but beginning in 2004, occupations will be quarterly. The line was conceived to close the upper layer mass budget in the Atlantic and to estimate the variability of the upper limb of the MOC transport. As of March/April 2004, a total of 5 transects have been conducted. In this poster, preliminary calculations of the mass and heat transport along AX18 are presented.

### Bermuda Speleothem Isotopic Analysis and Reconstruction of Early Holocene North Atlantic SST – Possible Implications for Gulf Stream Index Variability

by Steven E. Gaurin[1], Robert M. DeConto[2], Stephen J. Burns[2], and Meredith Gray[2]
[1]Smith College, Northampton, MA, USA, [2]University of Massachusetts, Amherst, USA

There is continuing debate over whether or not the Gulf Stream is responsible for keeping northern Europe's climate warm compared to other places at similar latitudes. Recent studies (e.g., Seager et al., 2003) suggest that atmospheric circulation patterns, as opposed to warm surface ocean currents, constitute the main

operative force behind this phenomenon. Stable isotope analysis of cave speleothems from Bermuda will hopefully shed light on this and other questions having to do with North Atlantic climate variability over the past several thousand years. d18O and d13C values from speleothem calcite can be used to reconstruct climate characteristics (rainfall patterns, temperature fluctuations) at sub-decadal time scales, with appropriate age models applied (e.g., Burns et al., 2003). This poster presents a proposed technique for reconstructing North Atlantic SST fields and determining a 'Gulf Stream Index' from such an analysis combined with inverse modelling of isotope tracers, as well as showing some preliminary isotopic results of a small speleothem from Bermuda, which will be used toward that end. This oceanic reconstruction will then be compared to climate data, including analysis of varved sediments from North America (e.g., Rittenhour et al., 2000) and from Europe, in an attempt to relate changes in Atlantic Ocean circulation to changes in continental climate, notably including the 8.2 ka cold event (see Ruddiman, 2003).

**A new ocean current feeding Denmark Strait Overflow Water from the Iceland Sea**

by Steingrímur Jónsson[1,2] and Héðinn Valdimarsson[1]
[1]Marine Research Institute, Skúlagata 4, P.O.BOX 1390, 121 Reykjavík, Iceland, [2]University of Akureyri, Glerárgata 36, P.O.BOX 224, 602 Akureyri, Iceland

This poster illustrates a previously unknown current that carries Denmark Strait Overflow Water (DSOW) from the Iceland Sea towards the sill in Denmark Strait. DSOW is one of the main components of the thermohaline circulation. There has been no consensus on where it is formed and by which way it is brought to the Denmark Strait. It is shown here that it is brought to the sill by a hitherto unknown current that is traced from the sill back into the Iceland Sea north of Iceland. The transport of this current is sufficient to account for a major part of the transport of DSOW as it has been measured at the sill if some entrainment of ambient water is assumed. This supports theories suggesting that the Iceland Sea is the main source for the DSOW and this has consequences for the way in which climate change affects the thermohaline circulation.

**Pathways and transports of southern hemispheric waters in the tropical/subtropical Western North Atlantic**

by Kerstin Kirchner[1], Monika Rhein[1] and Sabine Hüttl[2]
[1]Institut für Umweltphysik, Universität Bremen, Germany, [2]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Germany

The Atlantic ocean circulation is complex due to the presence of the Meridional Overturning Circulation (MOC), which connects the Northern Atlantic Ocean with the rest of the World Ocean. The MOC is estimated to be of some 14 Sv. To conserve mass the northward flow toward the high-latitude deep water formation regions must be of similar magnitude. Warm deep thermocline and intermediate waters enter the tropical Atlantic from the south and flow northward. This warm return flow interacts directly with the regional upper-ocean wind-driven circulation. The presence of the Subtropical/Tropical Cell and the small Tropical Cell make a description of the exact pathways of the MOC return flow in the equatorial current system rather difficult. The flow across the equator in the North Brazil Current is in the mean 35 Sv, containing parts of all the cells. Therefore, a large fraction of the NBC has to recirculate to close the STC and TC cells, while another part has to continue its way into the northern hemisphere. Pathways and transports of southern hemispheric water masses flowing northward from the NBC retroflection region are presented using different methods. Trajectories of real floats (ARGO-Programme) are compared with artificial float trajectories computed within the 1/12° FLAME-Model (IfM-GEOMAR Kiel). Investigations on the seasonal variability of the inflow regime into the Caribbean Sea are performed.

**Studying the variability of North Atlantic circulation by assimilation of sea surface height tendencies**

by Genady Kivman[1], Sergey Danilov[1], Lars Nerger[1] and Jens Schröter[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

The variability of the general circulation of the North Atlantic is studied with the finite element primitive equation model FEOM. Here we report on the impact of assimilating of sea surface height tendencies. Temporal sea surface height anomalies are much more accurately known than the difference between absolute sea surface height and the geoid. It is therefore common practice to subtract the mean altimetric surface from the measurements and replace it my some kind of 'synthetic' mean which may be an average model free surface elevation. This practice ensures that the ocean model will not drift away when the altimeter data are assimilated over periods of years.

The weak point in this strategy is that the mean model state cannot be improved. Here we assimilate tendencies, i.e. measured changes over time spans of 10 days or a month. The period of assimilation was chosen as 1993 to 2003. The impact of the assimilation is evaluated by comparison with a reference solution of the same model forced with atmospheric reanalysis data and SST observations. Comparisons with independent data show which aspects of the model performance become more realistic.

**Decadal Variability of Shallow Cells and Equatorial SST in a Numerical Model of the Atlantic**

by Jürgen Kröger[1], Tony Busalacchi[2], Joaquim Ballabrera[2], and Paola Malanotte-Rizzoli[3]
[1]the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, [2]ESSIC, University of Maryland, College Park, USA, [3]MIT, Cambridge, Massachusetts, USA

The relative role of extra-equatorial mechanisms modulating decadal SST anomalies in the equatorial Atlantic is investigated using an ocean general circulation model (OGCM) forced by observed wind stress and/or computed heat flux from the associated advective atmospheric mixed layer model.
Longterm variability of the shallow meridional overturning circulation, the Subtropical Cells (STCs), which conduit subducted water to lower latitudes, can lead to significant SST anomalies in the eastern tropics by either (1) equatorward advection of temperature anomalies formed by the subduction process in the subtropics or (2) by changes in the strength of the STCs themselves, varying the amount of cold water that is transported into the tropics.
A suite of sensitivity studies is applied to isolate each of the mechanisms at work and to estimate their particular impact on equatorial SST anomalies in the model.

**The North Atlantic heat budget studied by assimilation of satellite altimetry using the SEIK filter**

by Lars Nerger[1], Genady Kivman[1], Wolfgang Hiller[1], Sergey Danilov[1] and Jens Schröter[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

The heat budget of the North Atlantic is studied by many groups in several ways because of its major contribution to the global heat budget. Furthermore the stability of the North Atlantic circulation which depends on the thermal conditions is a prime candidate for investigations. In this context satellite altimetry is widely used.
Frequently sea surface height is taken as a proxy for the local temperature and/or heat content. Here we study to what extent this approximation holds and what depth intervals are involved in the annual cycle and interannual variations. To this end we assimilate satellite altimetry with the SEIK filter technique into the finite element primitive equation model FEOM. This filtering technique is from the class of Kalman filters with an efficient error subspace formulation.
We calculate heat fluxes and storage changes from the ocean model and relate them to storage changes implied by the adjustments due to data assimilation. Results are compared to the undisturbed model run which acts as a baseline for the analysis.

**Modeled exchanges across the Greenland-Scotland Ridge**

by Steffen M. Olsen[1] and Torben Schmith[1]
[1]Danish Meteorological Institute, Copenhagen, Denmark

It is expected that the Atlantic meridional overturning circulation (AMOC) will slow down as the concentration of greenhouse gases increases and the hydrological cycle of the atmosphere intensifies. Recent studies also show significant changes in the characteristics of the major Atlantic water masses since the middle of the last century, changes which may be early imprints of global warming. Alternatively, or in addition, the observed pattern of change could reflect a change in the AMOC. Here, we attempt to quantify the internal variability in the North Atlantic ocean system in relation to the observed trends in water mass characteristics. For this purpose, we have performed an ensemble, hindcast study of the period 1948-2001 with a global version of the MPI-OM1 ocean model, forced by NCEP reanalysis data and incorporating the effects of increased river discharge to the Arctic Ocean. The study focus on the strength and properties of the exchanges into the Nordic Seas across the Greenland-Scotland Ridge.

**Predictability of the North Atlantic Thermohaline Circulation in a Coupled AOGCM and Implications for European Climate**

by Holger Pohlmann[1], Frank Sienz[1], Michael Botzet[1], Mojib Latif[2], Andreas Roesch[3], Martin Wild[3] and Peter Tschuck[3]
[1]Max-Planck-Institut für Meteorologie, Hamburg, Germany, [2]Leibniz-Institut für Meereswissenschaften, Kiel, Germany, [3]Institut für Atmosphäre und Klima, Eidgenössische Technische Hochschule, Zürich, Switzerland

On seasonal timescales ENSO prediction has become feasible in an operational framework in the last years. On decadal to multidecadal timescales the variability of the oceanic circulation is assumed to provide a potential for climate prediction. To investigate the predictability of the coupled atmosphere-ocean general circulation model ECHAM5/MPI-OM a 500-year long control integration and 'perfect model' ensemble experiments are analyzed. The results show that the North Atlantic thermohaline circulation exhibit predictability on multidecadal timescales. The implications for North Atlantic and European climate are investigated.

**Towards a Continuous Record of Florida Current Temperature Transport**

by Deb R. Shoosmith[1], Molly O. Baringer[2] and William E. Johns[1]
[1]Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA, [2]Atlantic Oceanographic and Meteorological Laboratory, NOAA, USA

The oceans play a central role in regulating our climate due to their considerable capacity to store and transport heat and freshwater. The Florida Current contains the upper layer of the meridional thermohaline circulation and is thus a major contributor to North Atlantic circulation and heat transport. Early 2004 marked the beginning of a long-term continuous monitoring program to measure the strength and variability of the North Atlantic meridional overturning circulation and heat flux. Florida Current transport measurements are a vital part of this effort.

Since 1982, volume transports have been inferred from voltage measurements in submarine telephone cables across the Straits of Florida. Electromagnetic induction theory suggests that the cable voltage should actually give a more direct measure of conductivity weighted transport than pure volume transport. Due to the high dependence of conductivity on temperature, this would result in a direct and continuous estimate of the Florida Current temperature transport. This hypothesis is investigated using data from a large number (65) of temperature and velocity sections across the Florida Current at the cable location. Although the theory suggests that cable voltages should be more highly correlated with temperature transport than volume transport, the correlation with temperature transport does not show a dramatic improvement over that with volume transport, probably due to various sources of measurement error. Nevertheless, this work leads to a new calibration of the voltage signal for the temperature transport of the Florida Current, which is needed for transbasin heat flux estimates.

Regular cable calibration cruises are undertaken giving full-depth temperature profiles along with either full-depth or depth-averaged velocities. Depth-averaged velocities result in an accurate determination of net volume transport, but because there is no relationship between flow weighted temperature and transport, they do not give an accurate estimate of the temperature transport. In this study we quantify the errors associated with calculating Florida Current temperature transport in the absence of full water column measurements and investigate methods of reducing these errors such that every cruise can result in a calibration point for the cable temperature transport.

**Pentadal variability of the North Atlantic circulation determined from a sequence of inverse solutions**

by Dmitri Sidorenko[1], Genady Kivman[1], Sergey Danilov[1] and Jens Schröter[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

The hydrography of the North Atlantic ocean is known to change substantially over periods of pentads and longer. For each of the 5-year periods from 1950-1954 to 1990-1994 the corresponding steady state circulation is determined by an inverse ocean model. The model used here is the inverse of the primitive

equation finite element ocean model FEOM. A steady state velocity field is determined from the momentum equations where the advective-diffusive tracer balance acts as a soft constraint. We present and analyse the resulting sequence of current fields and meridional circulation patterns.

**Low-latitude freshwater influence on centennial variability of the Atlantic overturning circulation**

by Michael Vellinga[1] and Peili Wu[1]
[1]Met Office, Hadley Centre for Climate Prediction and Research, UK

Variability of the meridional overturning circulation (MOC) has been analysed in a long control simulation by the Hadley Centres coupled climate model HadCM3. It is shown that internal THC variability in the coupled climate system is concentrated at interannual and centennial timescales, with the centennial mode being dominant. Centennial oscillations of the MOC can impact on surface climate via an interhemispheric SST contrast, of 0.1 ºC in the tropics and more than 0.5ºC in mid and high latitudes. A mechanism is proposed which is based on large-scale air-sea interaction in the tropical Atlantic on multi-decadal timescales. Salinity anomalies that result from this propagate from the tropics to the sub-polar North Atlantic at time scales of 5-6 decades. The accumulated salinity anomaly changes upper ocean density, to which the MOC responds. The oscillation then enters the opposite phase. Northward propagation at these multi decadal time scales is seen in an idealised tracer experiment, where a tracer is released in the tropical North Atlantic.

**On the mass budget of the North Atlantic Ocean**

by Manfred Wenzel[1] and Jens Schröter[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

The mass budget of the North Atlantic Ocean is studied with a global ocean circulation model that conserves mass instead of volume. Fresh water (i.e. mass) is exchanged with the atmosphere via precipitation and evaporation and inflow by rivers is taken into account. Mass is redistributed by the ocean circulation. Additionally, volume changes by steric expansion with changing temperature and salinity. The model is constrained by assimilating satellite altimetry and hydrographic measurements using the 4DVAR technique. It is found that the strong seasonal cycle in the North Atlantic volume is produced mainly by local heating and cooling and to a smaller extent by mass exchange with other ocean basins. Interannual variability is much smaller than the seasonal cycle.
Recent volume changes are monitored successfully by altimetry. However, the corresponding mass changes – or bottom pressure variations - can be estimated only over large domains using secular changes in the geoid provided from the GRACE mission since 2003.
We compare modelled bottom pressure changes in the North Atlantic with those of other basins and with measurements.

**Assessing multidecadal variability in North Atlantic using ECHAM5/MPI-OM**

by Xiuhua Zhu[1] and Johann Junglaus[1]
[1]Max Planck for Meteorology, Hamburg, Germany

Variability on a time scale of 70-100 years is evident from reconstructed time series of North Atlantic SST and other Northern Hemisphere climate variables. The low frequency variability is associated with variations of the Atlantic Thermohaline Circulation. We study multidecadal variability of the THC in the coupled atmosphere ocean sea-ice model ECHAM5/MPI-OM. The variability is identified as damped oscillatory mode in the ocean that is excited by random atmospheric forcing. We investigate the dependences on the spatial structure of the forcing and the role of the exchange between subtropical and subpolar gyre and local oceanic processes, such as deep-water formation.

**North Atlantic MOC Observations and Links to Arctic: The Arctic – Subarctic Ocean Fluxes Study (ASOF)**

by Roberta Boscolo[1] and R. R. Dickson[2]
[1]IIM-CSIC, Vigo, Spain, [2]CEFAS, Lowestoft, UK

It has long been recognized that the Atlantic meridional overturning circulation (MOC) is potentially sensitive to greenhouse gas and other climatic forcing, and that changes in the MOC have the potential to cause abrupt and perhaps global climate change. Though the mechanisms remain poorly understood, the two-way exchanges of heat, mass and salt between the North Atlantic and the Arctic Ocean are known to be implicated, and their interplay and variability are becoming known from two main data sets: first, from standard hydrographic sections worked across the main gateways of exchange for periods of over a Century; second, from direct flux measurements conducted across each of the main choke-points by the multinational VEINS (1997-2000), ASOF (2000- present) and other programs.

ASOF is structured around six main regional tasks that identify the broad range of upstream influences that might impose change on the Deep Western Boundary Current (DWBC) of the North Atlantic. ASOF plans to cover simultaneously all the main ocean fluxes that connect the Arctic Ocean to North Atlantic. Further details on the ASOF program can be found at: http://asof.npolar,no/

From the gateway arrays supported by models it has been possible for the first time to quantify the main fluxes of freshwater passing south from the Arctic Ocean to the Atlantic either side of Greenland. The present records are rarely long enough yet to determine variability, however the available freshwater flux estimates seem self-consistent, with approx. 0.1 Sv (each) passing south through Davis Strait and Denmark Strait. A comparison of model-based and hydro-based estimates provides an initial indication that the freshwater gained by the watercolumn of the NW Atlantic since the 1960s is of a similar order to that lost from the Arctic Ocean.

The long-term salinity records of decade-to-century scale at a scatter of standard stations and sections throughout the northern seas show a recent rapid increase in the outflow of freshwater from the Arctic to the N Atlantic:

- A 40-year increase in the offshore density gradient in the upper ocean between the Labrador shelf and the central Labrador Sea suggests a 20% increase in the southgoing flux of the relatively fresh waters of the shelf and upper-slope around the margins of the Labrador Sea since the mid-1960s.
- Time series from OWS Mike in the Norwegian Sea and standard section data west of Norway provide evidence of a broadscale freshening of the upper 1-1.5 km of the Nordic Seas over the past 4-5 decades.
- Tapping-off the freshening upper layer of the Nordic Seas, the entire system of overflow and entrainment that ventilates the deep North Atlantic has undergone a remarkably rapid, persistent and uniform freshening by about 0.010 - 0.015 per decade over the past 4 decades.
- As the ‘receiving volume’ for these freshening inputs, the entire watercolumn of the Labrador Sea has undergone radical change over the past 3-4 decades; between 1966 and 1992, the overall freshening of the watercolumn of the Labrador Sea has been equivalent to mixing-in an extra 6m of fresh water at the sea surface
- Discharged into the Deep Western Boundary Current, this deep freshening had been tracked down the American seaboard to 8°N by 2000.

**Understanding and Predicting the Variability of the Atlantic THC: a Challenge for the CLIVAR Project**

by Roberta Boscolo[1] and The CLIVAR Atlantic Panel[2]
[1]International CLIVAR Project Office, [2]M. Visbeck (Chair), B. Bourles, W. Johns, J. Hurrell, N. Koc, K.-P. Koltermann, W. Hazelege, D. Marshall, C. Mauritzen, A. Piola, C. Reason, D. Stammer, R. Sutton, C. Zhang, I. Wainer and D. Wright

The implementation of CLIVAR in the Atlantic sector focuses on three phenomena: the North Atlantic Oscillation (NAO), the Tropical Atlantic Variability (TAV) and the changes in the ocean’s Meridional Overturning Circulation (MOC). The primary goal is to improve our description and understanding of those modes of variability and then explore to what degree they might be predictable on seasonal to decadal time scales. Further information on CLIVAR activities in the Atlantic sector can be found at: http://www.clivar.org/organization/atlantic/

Variations of the Thermohaline Circulation (THC) on decadal-to-centennial time scales lead to changes in SST and ocean heat transports. Furthermore, as the carbon uptake in the North Atlantic plays an important role in the global carbon budget, the THC variations may contribute to changes in the oceanic carbon transport and hence indirectly affect the atmospheric CO2 content.

There are evidences that climatic changes occurred in the geological past are associated with changes in the

THC. Some of these changes developed very rapidly. Indeed model studies suggest that THC is abruptly halted by an impulsive reduction in high-latitude salinity. A significant number of projections of greenhouse-gas induced climate change over the next century indicate a weakened MOC in the North Atlantic due to the freshening of the subpolar ocean. While observations reveal that consistent long-term changes are happening in the properties of the overflows and in convectively renewed water masses in the Labrador Sea.
The important role that the MOC plays in the global climate argues for improved understanding of the fundamental processes involved and their representation in the ocean component of climate models.

CLIVAR is promoting and coordinating several modelling and observational activities that aim at:

- to determine the space-time characteristics of past decadal-to-centannial variability that may be related to thermohaline circulation variations
- to determine the sensitivity of the thermohaline circulation to changes in the surface fluxes;
- to determine the conditions under which sudden transitions of the thermohaline circulation to another state may occur;
- to understand those oceanic processes which are critical for the dynamics of thermohaline circulation changes;
- to investigate the coupling mechanisms between the thermohaline circulation, the wind-driven gyres, and the atmosphere;
- to establish the degree of predictability arising from the influence of thermohaline circulation variations on atmospheric climate;
- to investigate the sensitivity to changes in interbasin exchanges.

**Temporal variability of the carbon transport in a North Atlantic section: the relevance of the Thermohaline Circulation.**

by Marta Álvarez[1], Fiz F. Pérez[1], Herle Mercier[2], Pascale Lherminier[2], Aida F. Ríos[1] and Pascal Morin[3]
[1]Instituto de Investigaciones Marinas, Vigo, Spain, [2]Laboratoire de Physique des Oceans, CNRS/IFREMER/UBO, France, [3]LCM Roscoff, IUEM UBO, France

Two nearby sections in the North Atlantic, from the Iberian Peninsula to Cape Farewell, were sampled in 1997 (WOCE A25 or 4x section) and 2002 (OVIDE02 section). Total inorganic and anthropogenic carbon estimates were performed along both sections. Additionally the absolute transports across both lines were estimated using inverse model, based on geostrophy, direct velocity measurements and mass conservation. Preliminary results show that the Meridional Overturning Circulation (MOC) was reduced by a factor of 2 in 2002. The southward TIC transport is halved in 2002 and the northward CANT transport increased 35%. With the aim of explaining this important variability the relevance of the barotropic, overturning and horizontal circulation in the transport of TIC and CANT accross both sections will be investigated.

**Oceanic Uptake of Anthropogenic Trace Gases – Effects of Mesoscale Processes in Ocean Models**

by Arne Biastoch[1], Christoph Völker[2] and Claus Böning[1]
[1]Leibniz Institut für Meereswissenschaften (IFM-GEOMAR), Kiel, Germany, [2]Alfred-Wegener Institut für Polar- und Meeresforschung, Bremerhaven, Germany

The ocean takes up a large fraction of the perturbation CO2 entering the atmosphere by human activity. A realistic representation of this uptake in numerical models is essential for future climate studies. Our main goal is to study the effect of mesoscale variability and interannual forcing fluctuations on the cumulative uptake of trace gases such as CO2 (and CFC) in a host of sensitivity experiments building on a hierarchy of Atlantic models.

Due to use of a basin-wide model it was possible to simulate anthropogenic trace gases over time ranges of 100 years in an eddy permitting ocean model of about 20 km horizontal resolution. Compared to a coarser resolution (about 80 km) version its tracer fields show a similar overall structure with less uptake in the subpolar regions associated with the more confined formation of deep water in the Labrador Sea. Surprisingly, the total amount of CO2 uptake is equal at both resolutions leading to the first result that horizontal resolution not matters for integral values. However, even more important is the structure of CO2 uptake, especially those in the subpolar North Atlantic, which is much finer in the eddy-permitting than in the coarse resolution configuration and due to the longer equilibration time is also contrasting to the CFC structure. It will be shown that the physical circulation strongly determines this uptake and distribution structures of $CO_2$.

**Deep circulation inferred from repeated measurements of CFCs in the Western North Atlantic Ocean**
By Rana Fine et al.

**High-precision oxygen measurements from profiling floats**
by Jens Schimanski[1], Arne Körtzinger[1] and Uwe Send[1]
[1]Leibniz Institut für Meereswissenschaften (IFM-GEOMAR), Kiel, Germany

The oceanic oxygen inventory is a sensitive indicator of global change driven trends in the physical and biological state of the ocean and is therefore currently receiving increased attention. An oxygen-based observation strategy for detecting large-scale oceanic changes will require a major measurement effort, which apart from the traditional research infrastructure needs to make use of modern oceanographic platforms for long-term observations such as floats. This potential is provided by state-of-the-art profiling floats which are equipped with novel optode-based oceanographic oxygen sensors. Two floats were simultaneously deployed in the central Labrador Sea Gyre on Sept. 7, 2003. They drift at a depth of 800 dbar and perform weekly profiles of temperature, salinity and oxygen in the upper 2000 m of the water column. The initial results from the first 8 months of operation are presented. Data are compared with a small hydrographic oxygen survey of the deployment site. They are further examined for measurement quality including precision, accuracy and drift aspects. The first 40 profiles obtained are of high quality and show no detectable sensor drift. The potential of such measurements is illustrated by an application which allows to independently estimate the wind speed dependence of the oxygen gas exchange coefficient from observed temporal oxygen inventory changes and NECP reanalysis winds.

**The influence of the NAO on the biogeochemistry of the Northwest-European shelf: results of a modelling study**
by Johannes Pätsch[1], Wilfried Kühn[1], Thomas Pohlmann[1] and Andreas Moll[1]
[1]Institute of Oceanography, University of Hamburg, Hamburg, Germany

The NAO influences not only the hydrodynamics and the biogeochemistry of the open North Atlantic Ocean, but also the physical and biogeochemical processes on the Northwest-European shelf. The changing meteorological conditions as well as the variation in the current system and in the water masses distribution have an impact e.g. on the efficiency of the so-called ‘shelf pump’, i.e. the carbon export from the shelf to the open ocean. This again might be of relevance for the carbon budget of the North Atlantic.

Using a coupled 3D hydrodynamic-biogeochemical model system for the Northwest-European shelf (48°-63°N, 15°W-12°E) we simulated the years 1994-96, which exhibit an extremely strong transition from a high-NAO to a low-NAO regime. The mean winterly current pattern on the shelf, which mirrors the different air pressure systems for these years, together with varying sea surface temperature and river loads of nutrients and organic material are responsible for the changes in nutrient and phytoplankton distributions and in the relevant biogeochemical fluxes (primary production, net community production, shelf import/export, air-sea-flux of $CO_2$). The (validated) results are discussed under the perspective of the biogeochemical interaction between shelf and deep ocean.

**The role of Mediterranean Water in the drawn-down of anthropogenic carbon**
by Fiz F. Pérez[1], Marta Álvarez[1], Deborah Shoosmith[2], Harry L. Bryden[3]
[1]Instituto de Investigaciones Marinas, Vigo, Spain, [2]Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA, [3]Southampton Oceanography Centre, United Kingdom

Combining portions of three WOCE sections sampled in 1998 we defined a three sided box in the Eastern North Atlantic, the Med Box, encompassing the Gibraltar Strait, so the formation region of Mediterranean Water (MW), known to have an important but still not well determined role in the global ocean thermohaline circulation. The aim of this work was to study the magnitude, mechanisms and pathways of the mass and CANT transport by water masses in the region with special emphasis on MW. In order to accomplish these objectives an estimation of the mass and CANT transport in the region obtained by an inverse model was coupled with a mixing analysis, an Extended Optimum Multiparameter (OMP), that provides the water masses contribution. The inverse method is set following the work in S&B (JGR, 2004, in revision), after having chosen the initial level of reference at s 3= 41.49 kg m -3 close to 3200 db, the mass, salinity anomaly and heat flux within defined layers is constrained, deep water formation is not allowed and the deep layer transport across the northern boundary in the Iberian Abyssal Plain is constrained northwards. The combination of the OMP analysis with the mass transport allowed us to estimate that 2.7 Sv of MW are produced within the Med Box, which come from the transformation of 2.4 Sv of Central Waters and 0.3 Sv of diluted AAIW. MW is mainly exported northwards near the Iberian margin. The main mechanism exporting MW at intermediate levels is the horizontal circulation within the area. Regarding CANT, the Med Box is accumulating CANT within the water column at a rate of 66 kmol s -1 , a 65% of this CANT is uptaken through the air-sea interface, the rest by advection. The region reveals as an important CANT sink relative to the surface area, with a mean CANT air-sea flux of 2.2 mmol C m -2 d-1 . The overturning circulation, responsible for the MW formation is introducing CANT at a rate of 69 kmol s -1 , whereas the horizontal circulation, mainly responsible for the MW export is also exporting CANT out of the region at a rate of -29 kmol s -1 . The amount of CANT draw-down to depth when MW is formed, about 135 kmol s -1 , and the amount of CANT exported with MW into the North Atlantic, -90 kmol s -1 . Remember that 2642 kmol s -1 equal 1 GtC y -1 .

**Response of the marine ecosystem to reorganisations in ocean circulation**

by Andreas Schmittner[1]
[1]Institut für Geowissenschaften, Kiel, Germany

Reorganisations of the Atlantic meridional overturning (AMO) circulation caused large and abrupt climatic changes in the North Atlantic region during the last glacial period. Projections with climate models suggest the possibility that similar reorganisations can also occur in the future due to anthropogenic global warming. Here I investigate the consequences of such disturbances to the marine ecosystem. Using simulations with a coupled climate model including a component of the upper ocean ecosystem I show that a disruption of the AMO leads to a decrease of globally integrated primary productivity by as much as 20%. In the North- and Southeast Atlantic plankton stocks rapidly collapse to one third and 40% of their initial biomass, respectively. As deep water formation remains absent subsurface nutrient concentrations in the North Atlantic slowly increase leading to a gradual recovery of biomass there. In the Pacific, Indian and Southern Oceans plankton stocks continue to decline due to decreased upwelling of nutrient rich deep waters. Resumption of the circulation leads to pulses of organic detritus flux to the sea floor in the North Atlantic caused by intense downward transport of organic matter. The model results are consistent with the paleo record and explain some apparent discrepancies between different productivity proxies.

**Eddy Induced Restratification in the Labrador Sea**

by Jérôme Chanut[1] ,Bernard Barnier[1], Laurent Debreu[2] and Eric Blayo[2]
[1]Laboratoire des Ecoulements Geophysiques et Industriels, Grenoble, France, [2]Laboratoire de Modélisation et de Calcul, Grenoble, France

The re-stratification phase after deep convection by mesoscale eddies in the Labrador sea is investigated from high resolution, realistic, numerical simulations. The numerical model is based on a grid refinement (3 to 4 km resolution) on the Labrador and Irminger basins embedded in an eddy permitting model of the North Atlantic and forced by climatological fluxes and winds. Two different sources of eddy variability that could contribute to the dispersal of newly convected water are identified. The first one is the well observed West Greenland Current (WGC) instability near Cape Desolation where warm, salty and very energetic eddies are shedded from the boundary current. The second one is linked to baroclinic instability around the convective front and produces significantly less intense eddies ("Labrador sea eddies") with a much shorter life. By comparing two sets of simulation where the WGC instability is resolved or not, "Labrador sea eddies" are found to be the main driver of the seasonal re-stratification of the interior Labrador Sea.

**Evolution and spreading of Labrador Sea Water in the subpolar North Atlantic over the last decade**

by Lars Böhme[1] and Tom Avsic[1]
[1]Leibniz-Institut für Meerswissenschaften (IFM-GEOMAR), Kiel, Germany

Labrador Sea Water (LSW) forms the upper part of the North Atlantic Deep Water which is part of the deep water flow of the meridional overturning circulation. During recent years dramatic changes in the source properties of LSW have been reported. Knowledge about the generation process, spreading and variability of water mass properties is therefor of particular interest. Nearly a decade of observations from moorings and CTDs in the central Labrador Sea are utilizied to investigate the change in the source characterisics of LSW. Recalibrated Argo float data (available since 2001) is used to trace the LSW and its layer thickness in the subpolar North Atlantic.

**Role of the eddy field for the export of newly formed Labrador Sea Water within the Labrador Current**

by P. Brandt[1], A. Funk[1], F. Schott[1], L. Czeschel[1], and C. Eden[1]
[1]IFM-GEOMAR, Leibniz-Institut für Meereswissenschaften, Kiel, Germany

The eddy field in the Labrador Sea during 1993 to 2002 was calculated from sea level anomalies measured by TOPEX/Poseidon and ERS-2 altimeters. The mean EKE as well as the mean seasonal cycle of EKE from altimetry is compared with the EKE from a yearlong simulation with the 1/12° FLAME model of the Subpolar North Atlantic. In general good agreement is found. The mean EKE field in the Labrador Sea comprises maxima within the main boundary currents, the West Greenland Current and the Labrador Current, and in the central Labrador Sea. The annual cycle is most pronounced in the West Greenland Current region, from where eddies are shed into the central Labrador Sea dominantly during winter, and in the Labrador Current. A comparison of the simulated velocity field at 53°N with moored observations shows good agreement in the strength of the south-eastward Labrador Current and of the north-westward recirculation. The export of newly formed Labrador Sea Water within the Labrador Current is studied using a Lagrangian trajectory analysis performed using daily and monthly mean model fields. Strong differences regarding the calculated backward trajectories are found for different temporal resolutions of the used model fields suggesting a large impact of the high-frequency variability within the Labrador Current. While for daily model fields about half of the Labrador Sea Water that during the model year was transported south-eastward at 53°N was part of the mixed layer during the same year, for monthly mean fields it was only one fifth. In the first case maximum transport rates of newly formed Labrador Sea Water are obtained for March to May and in the second case for June to July. The simulated high-frequency variability peaks in March consistent with altimetric and moored velocity observations. Float trajectories calculated from the daily model fields suggest that during this month a major fraction of the newly formed Labrador Sea Water leaves the mixed layer at the southern border of the convective patch and is transported within the Labrador Current away from the central Labrador Sea.

**On the role of eddy mixing in Labrador Sea convection variability**

by Lars Czeschel[1] and Claus Böning[1]
[1]IFM-GEOMAR, Leibniz-Institut für Meereswissenschaften, Kiel, Germany

Using a suite of model experiments (part of FLAME hierarchy) ranging from eddy-permitting (1/3°) to eddy-resolving (1/12°) resolution we investigate the role of eddies for the deep convection in the Labrador Sea and it's interannual variability.
In the eddy-resolving model two sources of eddy kinetic energy (EKE) can be identified. The first is a high generation of eddies seperated in the boundary currents (mainly in the WGC at Cape Desolation) . These eddies are well stratified and surpressing deep convection. The second is associated with deep convection (rim current eddies). Both sources are correlated to the NAO. In positive phases the generation of 'Cape Desolation-eddies' is increased in consequence of a stronger boundary current. The higher EKE results in a smaller deep convection area. On interannual timescales the boundary current variability is dominated by wind stress changes. So the deep water (LSW) formation is correlated to NAO heat flux changes and anti-correlated to wind stress changes. All experiments demonstrate that the mixing between the boundary currents and the interior Labrador Sea plays a crucial role for the temperature and salinity of newly formed Labrador Sea Water. In the eddy-permitting case a parameterization for the eddies is needed (Gent and McWilliams) to get the water mass properties in agreement with observational estimates.

In order to examine the mixing associated with the eddy field around the convective patch, we initialize a simple channel-model (1/12°) with an analytical temperature field corresponding to a section through the Labrador Sea after deep convection. A series of spin-down experiments (no suface forcing) show all plausible restratification timescales of ~3 months. We demonstrate that the transformation of available potential energy in EKE is highly dependent on the amount of diapycnical mixing. This leads to large discrepancies in the potential energy after the restratification process and thus to strong consequences for the deep convection next winter. An 1-dim mixed layer model show that these differences are O(100m). The results are confirmed by experiments with the realstic North Atlantic model differing in the diapycnical mixing.

**Pathways and export of Greenland Sea Water**

by Tor Eldevik[1,2], Fiammetta Straneo[3], Anne Britt Sandø[1,2] , and Tore Furevik[4,2]
[1]Nansen Environmental and Remote Sensing Center, Bergen, Norway, [2]Bjerknes Centre for Climate Research, Bergen, Norway, [3]Woods Hole Oceanographic Institute, Massachusetts, USA, [4]Geophysical Institute, University of Bergen, Norway

The dense water that overflows the Greenland-Scotland Ridge from the Nordic Seas is a major source for the deep waters of the North Atlantic. An advective-diffusive model of the Nordic Seas has been set up to address the spreading of Greenland Sea Water (GSW). The model currents are taken, in lack of in situ observations, from the data archive of a high resolution GCM. The variable spreading under different regimes and, in particular, distinct phases of the NAO, are presented. The variability between the different flow cases is striking, both in streamline patterns and in tracer distribution. It is found that the variability in tracer pathways and export reflects changes both in the pattern and the strength of the internal circulation of the Nordic Seas, and not in the fluxes of the overflows. The Jan Mayen Current plays a key role in the different spreading. A comparison of the model results with observations collected following the 1996 SF6 tracer release in the central Greenland Sea lends credibility both to the velocity field from the GCM as well as to the approach utilized.

**North Atlantic surface water mass transformation in the North Atlantic ocean general circulation models**

by Sergey Gulev[1], Bernard Barnier[2] and Jean-Marc Molines[2]
[1]P.P.Shirshov Institute of Oceanology, Russia, [2]Laboratoire des Ecoulements Geophysiques et Industriels, Grenoble, France

Ocean circulation is forced by buoyancy, representing the coupled effect of the surface fluxes of heat and fresh water, which provide surface transformation of water masses. We analyse several model experiments, forced by NWP fluxes in order to quantify the impact of the model performance on the characteristics of surface water mass transformation. Model experiments were performed with the North Atlantic SPEM model in a coarse resolution (1.2 degree) version and with CLIPPER model in both coarse (1 degree) and high (1/6 degree) resolutions. Surface heat and fresh water fluxes were expressed in terms of surface thermal and haline density inputs, diagnosed by the model. Variability in surface density fluxes, analysed in the T,S-plane and in terms of overturning stream function characteristics demonstrates differences with the original surface heat and fresh water fluxes. Leading modes of surface water mass transformation are considered in the T,S-plane. We obtained different responses of meridional circulation on surface water mass transformation in different models. Experiments with different resolutions, but with unique forcing formulation show that the higher resolution has a significant impact on the water mass transformation rate in the tropics, where it demonstrates lower negative density fluxes (less light water is formed), and in regions of high eddy kinetic energy. Impact is much less in the interior of calm gyres. The production of sub-tropical and sub-polar mode waters is increased by the higher resolution, but the LSW transformation rates are stronger in the coarse resolution model. The paper will attempt to quantify the contribution of the mesoscale eddies to these differences.

**Modelling Dense Water Overflow with a Finite Element Ocean Model (FEOM)**

by Sven Harig[1], Sergey Danilov[1] and Jens Schröter[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

Finite Elements allow for unstructured grids and provide large flexibility in horizontal and vertical resolution. This property is especially helpful with respect to overflow processes because it is possible to resolve ocean straits accurate whereas the resolution in the ocean interior may be rather coarse to save computational time.

The Finite Element Ocean Model (FEOM) was applied to an idealized overflow scenario that corresponds to Phase I of the DOME (Dynamics of Overflow Mixing and Entrainment) intercomparison study. It treats the flow of a dense water plume on a slope with prescribed geometry. The dense water enters the slope through a long embayment of several Rossby radii width.
We present results of experiments obtained for homogeneous and stratified water in the interior of the basin, and explore the resulting overflow rate, variability and path of the plume. For different stratifications in the embayment and Coriolis parameters the mean overflow rate varies in agreement with investigations of hydraulic control. In case of a homogeneous interior the overflow develops a variability time scale of several days and the plume disintegrates into patches of dense water. In experiments with a stratified interior the plume descends to the level of neutral buoyancy and moves along the slope at this level.

**On the structure of the Meridional Overturning Circulation for distinct cases of surface forcing and basin configuration**

by Dorotea Iovino[1]
[1]Nansen Environmental and Remote Sensing Center, Bergen, Norway

A level-coordinate ocean GCM (MITgcm) is used to examine what controls the positions and extents of the upwelling and downwelling regions in an idealized North Atlantic basin. Varying the atmospheric forcing and basin configuration, the model is set up for different cases of prescribed sea surface temperature, wind stress, or both.

The role of topography on the AMOC is also investigated, particularly by introducing an abyssal ridge across the basin (a "Greenland-Scotland Ridge").

**A practical indicator for the importance of heat and freshwater components on the total surface buoyancy flux**

by Johannes Karstensen[1]
[1]Leibniz-Institut für Meerswissenschaften (IFM-GEOMAR), Kiel, Germany

The interplay of heat and freshwater exchange at the ocean surface can either drive convection or stratify the water. Depending on the local atmospheric and oceanic state the individual contribution of the components could enhance of compensate for each other in terms of the total buoyancy. Here we propose to use an angle that is simply related to two buoyancy flux components and which allow to capture the relative importance of the two components as well as the direction of the total flux. The angle has the advantage over a simple flux ratio as the sign of the individual components is preserved and it is not ambiguous. The angle could be useful for e.g. climate studies where one is interested in detecting the shift in the buoyancy flux pattern. Atlantic and global distributions of the angle based on climatological data are presented and discussed.

**Pathways of Iceland Scotland Overflow Water in the Eastern Subpolar Gyre**

by Matthias Lankhorst[1], Rolf H. Käse[2,1], Andreas Macrander[1] and Walter Zenk[1]
[1]Leibniz-Institut für Meereswissenschaften an der Universität Kiel, Germany
[2]Zentrum für Meeres- und Klimaforschung, Universität Hamburg, Germany

Iceland Scotland Overflow Water (ISOW) is accounted a major constituent of the North Atlantic Deep Water. Consequently, it has a significant impact on the global thermohaline circulation. The overflow enters the subpolar gyre after passing the Faroe Bank Channel at the northern tip of the Iceland Basin. On the base of multi-year series of current observations supported by latest results from the high resolution ECCO ciculation model, pathways of ISOW are identified along the Reykjanes Ridge. While initially spreading as a contour current the ISOW entrains low-saline Labrador Sea Water in the depth range 1500-1700 meters. Moored current meter data and a hydrographic section repeated four times at ~23° W in the northeastern corner of the basin reveal scales of variability at a virtual source region where entrainment of prime ISOW has been abated. Trajectories of eddy-resolving RAFOS floats and cycling APEX floats allow insights into the nature of the intermediate and deep cyclonic circulation in the Iceland Basin. The Bight and Charlie-

Gibbs Fracture Zones (CGFZ) represent gateways for the export of ISOW towards the Irminger Basin. All observations are well reproduced in the numerical simulations. The strongly fluctuating inflow of Labrador Sea Water through the CGFZ encountering the westward outflow of diluted ISOW is documented in current meter time series and miscellaneous float trajectories. The remaining fraction of ISOW that has not escaped towards the Irminger Basin as CGFZ water forms the source for the continuing deep western boundary current along the Mid Atlantic Ridge, thus communicating with the northeastern edge of the subtropical gyre.

**Numerical simulations of entrainment in overflows**

by Sonya Legg[1] and Robert W Hallberg[2]
[1]Woods Hole Oceanographic Institution, USA, [2]NOAA/GFDL, USA

Dense overflows such as the Denmark Straits and Faroe Bank Channel overflows play an important role in transporting dense water from the marginal Greenland-Iceland-Norwegian seas into the North Atlantic. Small-scale mixing and entrainment modify the overflow tracers and transport, and ultimately determine the properties of the North Atlantic Deep Water.
Entrainment must be parameterized in coarse resolution models, but there is currently little understanding of the fidelity of present parameterizations of entrainment. This study evaluates the entrainment diagnosed from coarse resolution simulations of idealized dense overflows, using both the z-coordinate MITgcm (in which entrainment occurs through a combination of numerical diffusion and convective adjustment) and the isopycnal HIM (in which entrainment is parameterized by using a Richardson number dependent scheme), and comparing with high-resolution nonhydrostatic simulations, using the nonhydrostatic version of MITgcm.

A variety of scenarios with and without rotation and ambient stratification are considered. At horizontal resolutions of 10km (fine enough to resolve the gravity current, yet too coarse to resolve mixing) both z-coordinate and isopycnal formulations are found to underpredict entrainment and diapycnal mixing when compared with the high-resolution simulations. At coarser resolutions the z-coordinate model produces excessive mixing. This underprediction of mixing at intermediate resolutions suggests improvements could be made at these resolutions by modifying mixing parameterizations.

**Recent changes in Denmark Strait Overflow Transport**

By Macrander Andreas, R. Käse

**Freshwater fluxes from the Arctic Ocean into the North Atlantic: 1979-2002 model results**

by Wieslaw Maslowski[1], Catherine Williams[1], Jaclyn Clement[1], Jaromir Jakacki[1]
[1]Department of Oceanography, Naval Postgraduate School, Monterey, CA, USA

The Arctic Ocean has been warming since the 1990s. The warming appears to have accelerated during the last several years as observed by satellites and in situ measurements and as simulated by models. The main manifestation of this trend has been a decrease of the ice cover, which through positive ice-albedo feedback leads to further ice reductions and subsequent increases of freshwater export into the active convection regions in the North Atlantic.

To investigate the variability of sea ice cover and freshwater fluxes into the North Atlantic we use a high resolution coupled ice-ocean model of the Pan-Arctic region forced with realistic atmospheric data for 1979-2002. Model results suggest that the rate of decrease of sea ice thickness and volume might be larger than that of ice extent/concentration as modeled and observed from satellite data. The decrease of the total sea ice volume and the subsequent increase of freshwater content determined by the air-sea-ice interactions in the Arctic Ocean, translate into the increased total freshwater export into the North Atlantic. This trend, if continued, will introduce large amounts of ice-melt derived freshwater into the northern North Atlantic. Such changes will have major consequences on the ocean thermohaline circulation as well as on the long term ocean heat and salt transports.

**Atlantic freshwater transports in two coupled models**

by Anne Pardaens[1] and Malcolm Roberts[1]
[1]Met Office, Hadley Centre, Exeter, UK

Several model studies have shown ocean freshwater transports to be important for the behaviour of the Atlantic overturning circulation under greenhouse gas warming conditions and for thermohaline circulation variability. We have looked at the Atlantic Ocean freshwater transports in the control simulations of two ocean-atmosphere coupled climate models (HadCM3 and HadCEM), which have the same atmosphere model component, but ocean models which differ in resolution and some aspects of their physics. The timescales over which the Atlantic Ocean meridional freshwater transports come into balance with the surface freshwater fluxes are significantly different in these models, being close to 400 years for HadCM3 and near 150 years for HadCEM. We will present an analysis of the reasons for these differences in timescale and their relationship with the overturning circulations.

**Spatial structure of the West Spitsbergen Current and Atlantic Water transport estimation**

by Jan Piechura[1], Waldemar Walczowski[1] and Robert Osinski[1]
[1]Institute of Oceanology PAS, Sopot, Poland

CTD and ADCP measurements performed by Institute of Oceanology Polish Academy of Sciences during summer's expeditions of R/V 'Oceania' into the Nordic Seas are analysed. The special attention is paid to the Atlantic Domain of the Greenland Sea. Based on ship mounted ADCP and lowered ADCP measurements, volume, heat and salt transport in the region north of the Bear Islands were calculated. Vessel mounted and lowered ADCP results are also used for determination the barotropic component of the current as a reference to the baroclinic calculations. Measurements show considerable barotropic component of the flow over the Spitsbergen shelf slope and underwater ridges. This causes the high values of the total and Atlantic Water transport obtained from direct measurements and calculations. Meridional changes in the current structure, volume and heat transport are analysed. Latest measurements confirm our earlier findings that there are two northward flowing branches of Atlantic Water in the Greenland Sea. The main branch of the West Spitsbergen Current continues along the Barents Sea continental slope and Spitsbergen shelf break. The second, colder and less saline branch flows along the Mohns and Knipovich Ridges as jet streams of the Arctic Front. Bottom topography forces both branches of Atlantic Water to converge west of the central Spitsbergen. Farther to the north most of the Atlantic Water carried by the western branch recirculates westward as Return Atlantic Water. In contrary, the bigger part of Atlantic Water carried by the slope branch of the West Spitsbergen Current crosses the Fram Strait and enters the Arctic Ocean.

**Atlantic deep water circulation controlled by freshening in the Southern Ocean**

by Oleg A. Saenko[1], Andrew J. Weaver[2] and Andreas Schmittner[3]
[1]Canadian Centre for Climate Modelling and Analysis, Victoria, Canada, [2]University of Victoria, Victoria, Canada, [3]Institut für Geowissenschaften, Kiel, Germany

In the limit of weak diapycnal mixing in the ocean interior and away from rough bottom topography (order of 10-5 m2 s-1), the circulation of deep water in the North Atlantic is proportional to the buoyancy input to the Southern Ocean. This is illustrated using a coupled ocean-ice-atmosphere model. The buoyancy input to the Southern Ocean is supplied by transport of moisture from subtropical to subpolar regions in the Southern Hemishpere. It is shown that an increase in this moisture transport in the south increases deep water formation and ocean heat transport in the north. The input of buoyancy to the Southern Ocean requires an increase of the transformation of dense deep water into lighter intermediate water in the south, which at steady state is balanced by an enhanced transformation of light water into dense water in the North Atlantic. However, when the diapycnal mixing, and hence the associated mechanical energy available to support this mixing, increases beyond reasonable values, the formation of deep water and the heat transport in the Atlantic become mixing-controlled and are not sensitive to the buoyancy input in the south.

**The Role of Haline Stratification**

By Schmidt Sunke

**Variations in watermass transformation, dense water export and downwelling in a convecting semi-enclosed basin**

by Fiammetta Straneo[1]
[1]Woods Hole Oceanographic Institution, Woods Hole, USA

Variability in the meridional overturning circulation has been connected to changes in the convective activity of a few, high-latitude, convection regions. In these, the extent of convection is regulated by a number of parameters including past convective activity, atmospheric variability and variability in the oceanic circulation. The impact of each of these is investigated using a two-layer, idealized model of a convective region and the surrounding boundary current. Results show how the response is strongly modulated by the basin's memory (the timescale over which it can flush the dense water) and show the connection between changes in the convective activity with the dense water exported and downwelling that takes place within the basin. When adapted to the Labrador Sea parameters, and using realistic forcing, the model is able to reproduce much of observed interannual variability.

**Seasonal and interannual variability of the Subpolar Mode Waters in the North Atlantic**

by Virginie Thierry[1], Herlé Mercier[1], Carole Grit[1], Emmanuelle Autret[2] and Fabienne Gaillard[1]
[1]Laboratoire de Physique des Océans, CNRS/IFREMER/UBO, Brest, France
2Laboratoire des Sciences de l'Environnement Marin, CNRS/IUEM/UBO, Brest, France

Using ARGO float and hydrographic data, we describe the SubPolar Mode Waters (SPMW) properties and their seasonal and interannual variability. The floats display a substantial data set of high quality salinity and temperature measurements. The space-time sampling allows us to interpolate the data on pressure and potential density levels throughout the North Atlantic Ocean via an objective analysis. Comparison with previous studies shows the consistency of the interpolation method and the ability of the data set to observe the SPMW.

We confirm the presence of several varieties of SPMW in the North East Atlantic, quite unequally distributed and being set apart by the density ranges they occupy. They are distributed around the outer periphery of the North Atlantic Subpolar Gyre in extended patches north of the North Atlantic Current (NAC). South of the NAC density jumps are detected between the different varieties of SPMW. The analysis helps us distinguish recently ventilated SPMW from subducted SPMW. Those varieties can coexist in the same geographical area at different depth. A significant variability has been observed in regard to previous data sets.

**Vertical Mixing in the Subpolar North Atlantic**

by Maren Walter[1], Christian Mertens[1], Qiang Wang[1], and Monika Rhein[1]
[1]Institut für Umweltphysik, Universität Bremen, Germany

A large-scale hydrographic survey from 2003 (FS Meteor cruise M59/2) which covers large parts of the subpolar North Atlantic is used to map turbulent mixing in different depth layers and different hydrographic and bathymetric regimes/conditions. The mixing is studied by means of the spatial distribution and strength of eddy diffusivities. These are calculated from energy dissipation rates, which in turn are estimated with two complementary methods. Thorpe scales, which are determined from overturns in density profiles are linearly related to the Ozmidov scale, and therefore provide a direct estimate of the dissipation. The second method uses a spectral estimate of the variances of the vertical shear of the horizontal velocity and the strain of the density field as proxies for the energy content of the internal wave field, and the equlibrium energy dissipation rate. Results from the various analysis indicate generally small diffusivities below the LSW layer at mid depth in the open ocean. Higher values are found in the upper 1000 m (roughly corresponding to LSW layer), and near rough topography over the flanks of the Mid Atlantic Ridge. The strongest mixing occurs in the Deep Western Boundary Current off Flemish Cap.

**Reliability of the estimates of meriodinal heat transport in a high resolution ocean circulation model and from oceanic cross-sections**

by Alexey Arkhipkin[1], Sergey Gulev[1], Bernard Barnier[2] and Jean-Marc Molines[2]
[1]P.P.Shirshov Institute of Oceanology, Russia, [2]Laboratoire des Ecoulements Geophysiques et Industriels, Grenoble, France

Estimates of meridional heat transport (MHT) at oceanic cross-sections and in ocean general circulation models show a little comparability for both climate means and temporal variability characteristics. Direct comparisons of MHT estimates in the model experiments with those obtained at oceanic sections are influenced by several limitations. These limitations are associated with methods of MHT transport computations used in models and applied to hydrographic data, with the differences in temperature and salinity fields in the model simulations and in observational data and with the irregularity of sampling at the ocean cross-sections. For the direct comparisons of model and experimental estimates, there is no way of knowing which factor gives the largest contribution to the uncertainty. We used high resolution (1/6 degree) Atlantic Ocean general circulation model CLIPPER to simulate climate variability in the Atlantic Ocean for the period 1982-2000. Model estimates of MHT for selected years were compared with pre-WOCE and WOCE full-depth oceanic cross-sections at 48N. In order to achieve comparability we simulated ship-like sampling of model results for 9 actual cruises carried 48N A2 section. This allows for the estimation of sampling errors in MHT estimates and gives the possibility to quantify the impact of methods of MHT computations on the differences between the model and observed MHT. The role of sampling errors in MHT computations is normally smaller than the differences between the model and observational temperature and salinity fields, however it is not negligible and may particularly be responsible for the differences in MHT variability patterns in models and observations. The magnitude of the uncertainty of MHT computation associated with synoptic variability may amount to 40% of the mean MHT values, being comparable or higher than interannual variability.

**Monitoring the meridional overturning circulation in the North Atlantic: a model-based array design study**

by Johanna Baehr[1], Joël Hirschi[2], Jens-Olaf Beismann[3], Jochem Marotzke[1]
[1]Max Planck Institute for Meteorology, Hamburg, Germany, [2]Southampton Oceanography Centre, Southampton, UK, [3]Leibniz-Institut für Meereswissenschaften, IfM –GEOMAR, Germany

A monitoring system for the meridional overturning circulation (MOC) is deployed into an "eddy-permitting" numerical model (FLAME) at three different latitudes in the North Atlantic Ocean. The MOC is estimated by adding contributions related to Ekman transports to those associated with the zonally integrated vertical velocity shear. Ekman transports are inferred from surface wind stress, whereas the velocity shear is derived from continuous density "observations", principally near the eastern and western boundaries, employing thermal wind balance. The objective is to test the method and array setups for possible real observation in the ocean at the chosen latitudes and to guide similar tests at different latitudes.
Different "mooring placements" are tested, ranging from a minimal setup to the theoretical maximum number of "measurements". A relatively small number of vertical density profiles (about 10, the exact number depending on the latitude) can achieve a reconstruction of the MOC similar to one achieved by any larger number of profiles. However, the main characteristics of the MOC can only be reproduced at latitudes where bottom velocities are small, here at 26°N and 36°N. For high bottom velocities, in FLAME at 53°N, the array fails to reproduce the strength and variability of the MOC, because the depth-averaged flow cannot be reconstructed accurately. In FLAME, knowledge of the complete bottom velocity field could substitute for the knowledge of the depth-averaged velocity field.

**On the response of the thermohaline circulation (THC) to the North Atlantic Oscillation (NAO)**

by Manfred Bersch[1]
[1]Institute of Oceanography, University of Hamburg, Hamburg, Germany

Warm and saline subtropical water is carried northwards by the North Atlantic Current (NAC) in the upper limb of the THC. Due to heat loss to the atmosphere the water gets colder and denser and finally sinks to great depths, e.g. in the Labrador Sea, where it returns to the south in the lower limb of the THC. This process is strongly modified by the NAO, which is associated with a varying strength of the westerlies and changes of the heat and fresh water fluxes at the sea surface. Hydrographic measurements in the 1990s document the changes of the water masses involved in the THC and of the circulation in the northern North Atlantic.

During the first half of the 1990s strong and cold westerlies (high NAO index) caused a deep convection in the Labrador Sea, which reached more than 2000m depth in 1994. The very cold, fresh, and dense Labrador Sea Water (LSW) spread laterally and reached the Irminger Sea after about 2 years and the Iceland Basin after about 5 years, as is shown by the hydrographic data from WOCE/CLIVAR section A1E (Greenland-Ireland). After the drastic weakening of the westerlies in winter 1995/96 (low NAO index) there was a northward and westward shift of the Subarctic Front, associated with the NAC, north of 45 °N and thus a contraction of the subpolar gyre. Additionally, the supply of warm and saline water to the northeastern North Atlantic increased. The positive anomaly occurred on section A1E in August 1996 in the Iceland Basin and off the Rockall Plateau. After about 2 years it arrived in the Irminger Sea and was finally transported southwards in the East Greenland Current into the Labrador Sea in 1999 to 2001. On A1E the heat and salt contents increased by about 12 percent in the upper layer and stayed high during the second half of the 1990s, when the westerlies were relatively weak. Thus, in the 1990s the cooling and freshening of the deeper layers were followed by a warming and salinization of the upper layer, which reflects a pronounced decadal change of the THC.

**Interannual – Decadal Circulation Variability in the North Atlantic: Results from High-Resolution Modelling**

by Claus Böning[1], Julia Getzlaff[1], Arne Biastoch[1], and Joachim Dengg[1]
[1]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Germany

The mechanisms and characteristics of interannual to decadal variations are investigated using a suite of medium- (1/3°) to high-resolution (1/12°) models, forced by 40-year time series of atmospheric fluxes based on NCEP/NCAR data. The focus is on the role of different forcing mechanisms in the generation of large-scale transport variability, and on the manifestation of variations in the meridional overturning circulation (MOC) in the western boundary current (WBC) system of the subtropical North Atlantic.
The model experiments suggest that part of the variability can be related to MOC changes associated with buoyancy-driven variations in the formation of Labrador Sea Water, and a fast propagation of corresponding dynamical signals to subtropical latitudes. The thermohaline signal is, however, effectively masked by interannual variations in wind-driven transports: for all latitudes, the amplitude of wind-driven MOC anomalies exceeds that of thermohaline origin. In contrast to the long-term mean meridional flow, MOC anomalies on interannual time scales are not concentrated at the western boundary: the solutions reveal basin-wide recirculation patterns, associated with Rossby waves emanating from the eastern boundary and the Mid-Atlantic Ridge.

**The role of the Mediterranean Outflow Water in the decadal variability of the Atlantic Meridional Overturning Circulation**

by Sandro Calmanti[1], Vincenzo Artale[1], Daniele Iudicone[2]
[1]ENEA, Roma, Italy, [2]Stazione Zoologica, Napoli, Italy

We employed a simple (Stommel-like) box-model to investigate the role of intermediate depth anomalies, representing the spreading of Mediterranean Outflow Water (MOW) in the North Atlantic, on the dynamics of the decadal variability of the Meridional Overturning Circulation (MOC). Being a significant source of heat and salt for the North Atlantic intermediate layers, the MOW is a potential contributor to the dynamics of the advective feedback, which is a major large scale process affecting the stability and variability of the MOC in the North Atlantic.

We focused on the sensitivity of the linear stability of the equilibria to the presence of MOW, with two different scenarios concerning the spreading of MOW in the North Atlantic. In the first case the average circulation allows the intermediate depth anomaly to reach the mixed layer, where interactions with the atmosphere dump the heat anomaly while preserving the salinity anomaly. The advection of the resulting buoyancy anomaly acts as a destabilizing feedback for the MOC. In the other case, the intermediate depth anomaly mixes with the newly formed deep-waters and the MOC is stabilized. The relevance of these scenarios to the real ocean is addressed by means of lagrangian diagnostics of the spreading of MOW in the North Atlantic in a coupled ice-ocean GCM.

Eventually, implications on the decadal variability of the MOC are also addressed by studying the response of the box-model to stochastic perturbations of the freshwater forcing.

**Freshwater Transport Rates and Variability in the Labrador Sea**

by Nilgun Cetin[1] and Paul G. Myers[1]
[1]University of Alberta, Edmonton, Canada

The Labrador Sea is a particular basin in the North Atlantic as one of the few oceanic sites where surface waters are converted into mid-depth waters, forming Labrador Sea Water (LSW) through winter convection. One of the significant factors that affect the LSW formation is the amount of freshwater present in the central Labrador Sea. In the first part of this study, the Labrador Sea circulation is studied using two recently compiled climatologies based upon isopycnal and geopotential coordinates. The climatologies are then used in a diagnostic model to calculate transport rates, i.e. the freshwater leakage from the boundary currents into the Labrador Sea interior and the relative importance of the West Greenland Current (WGC) versus the Labrador Current (LC) as the source of freshwater. The second half of the study examines variability in the transport rates employing three-year running means and seasonal climatologies.

**Deep Boundary Current circulation and variability in the western subpolar North Atlantic**

by Jürgen Fischer[1] , Friedrich Schott[1], Marcus Dengler[1] and Lothar Stramma[1]
[1]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Germany

Observations of interannual to decadal variability in the western subpolar North Atlantic were carried out based on multiyear mooring arrays installed since 1996 in the Labrador Sea and the Newfoundland Basin, by repeat shipboard observations of currents and hydrography at key positions of the boundary current system, and by profiling floats.

In the Labrador Sea at 56°N and at 53°N, a well defined Deep Western Boundary Current (DWBC), the Deep Labrador Current (DLC), carries about 26 Sv of deep water comprising Labrador Sea Water, Gibbs Fracture Zone Water and Denmark Strait Overflow Water. Offshore of the DLC at both locations, weak top to bottom counterflows of about 8 Sv transport are present. Farther along the DWBC, at Flemish Cap, the section-average deep western boundary flow is somewhat distorted presumably due to energetic eddies and the location of the Northwest Corner of the North Atlantic Current. There the average DWBC transport is less than the transports determined for the northern sections. These mean transports are comparable to the net deep water outflow (boundary current minus recirculation) from several year long moorings at the western boundary, which was 18 Sv at about 53°N. At the transition from the subpolar to the subtropical regime near the tail of the Grand Banks at 44°N, the DWBC transport decreased to 12 Sv, and float trajectories suggest that other pathways, e.g., eastward and possibly along the MAR, have to be taken into account.

Throughout the observational period water masses changed markedly, showing not only a warming trend in the deep central Labrador Sea but also considerable warming of the LSW exported by the Deep Labrador Current. An important question now is, whether these changes are accompanied by significant longer term variability of the boundary circulation. This question will be addressed by analyzing composite time series of currents at 56°N and 53°N from the core of the DLC.

**Pathways of Deep Water from the Subpolar to the Subtropical Gyre in an eddy-resolving numerical model of the North Atlantic: Eulerian and Lagrangian Views**

by Klaus Getzlaff[1], Joachim Dengg[1] and Claus W. Böning[1]
[1]IFM-GEOMAR, Leibniz-Institut für Meereswissenschaften, Kiel, Germany

Eulerian measurements across the Deep Western Boundary Current at the Grand Banks of Newfoundland display an intense flow to the south along the shelf break with an apparent over-compensating deep northward transport offshore. From these observations, it is not clear to what extent this northward flow is a deep extension of the North Atlantic Current or a recirculating branch of the DWBC.
Combining the Lagrangian view of synthetic particles with Eulerian data from an eddy-resolving (1/12°) numerical model, two pathways of export of Deep Water out of the Subpolar into the Subtropical Gyre become apparent: The direct DWBC path around the Grand Banks along the continental slope and a second minor path through the interior of the basin along the western flank of the MAR turning westward to the

boundary at 36°N. We find preferred points in the mean circulation at which the southward flowing water masses are deflected from the DWBC. These locations are the consequence of the vigorous deep-reaching eddy field associated with the instability of the NAC in combination with topographic steering.
Simulated observational floats seem to have severe problems in reproducing these paths: Floats constrained to follow geopotential surfaces cannot follow the direct path due to the deepening of the DWBC along its southward path from 53°N to 43°N. Furthermore profiling floats show a strong dependence on the prescribed surfacing interval and duration, which affects the export behaviour drastically.
Both, the influence of the eddy field and the dependence on float characteristics may explain why float observations have mostly failed to depict a continuous pathway of the DWBC around the southern tip of the Grand Banks of Newfoundland.

**Temperature and salinity changes in the North Atlantic since 1920-s' as inferred from the comparison between historical and the WOCE period observations.**

by Viktor Gouretski[1]
[1]Max-Planck-Institut für Meteorologie, Hamburg, Germany

A composite quality checked historical dataset is used to infer temperature and salinity changes in the North Atlantic. We use both hydrographic and bathythermographic data and reconstruct salinities in the upper layers using typisation of the vertical temperature bathythermographic profiles.
Historical temperature and salinity profiles are compared with local high-quality profiles obtained during the WOCE period (1990-97) used as a reference period for our calculations.
The calculations reveal concerted changes in temperature and salinity in agreement with recent studies of long-term T,S-variations in the Global Ocean and in the North Atlantic (Levitus et al., 2000; Curry et al., 2003). Depending on the reference and historical data variability secular changes of temperature and salinity are investigated for a number of selected areas (shelf, deep ocean, seas).

**Interannual Variation of Gulf Stream Heat Transport in a High Resolution Model Forced by Reanalysis Data**

by Nicholas M. J. Hall[1], Bernard Barnier[1],Thierry Penduff[1], and Jean Marc Molines[1]
[1]Laboratoire des Ecoulements Geophysiques et Industriels, Grenoble, France

The variability present in a 1/6th degree Atlantic Ocean simulation forced by analysed wind stress and heat flux over a 20-year period is investigated by means of heat transport diagnostics. A section is defined which follows the Gulf Stream and its seaward extension, and transport of heat across this section is analysed to reveal the physical mechanisms responsible for 'intergyre' heat exchanges on a variety of time scales. Heat transport across another section that crosses the Gulf Stream is also diagnosed to reveal the temporal behaviour of the 'gyre' circulation. The Ekman response to wind stress variations accounts for the annual cycle and much of the interannual variability in both measures. For the gyre heat transports, cancellation by transient-mean flow terms leads to a very weak annual cycle. Transient eddies account for approximately half of the total intergyre transport of 0.7 Petawatts. They also account for a significant fraction of the interannual variability, but separate experiments with repeated-annual-cycle forcing indicate that the transient eddy component of the heat transport variability is internally generated. Links between the intergyre transport, the wind driven gyre circulation, the surface heat budget and the atmospheric 'North Atlantic Oscillation' are discussed.

**Origin of fresh water anomalies in the Arctic Ocean and Nordic Seas and their relation to the Arctic Oscillation**

by C. Herbaut[1], Marie-Noëlle Houssais[1] and J. Sirven[1]
[1]Laboratoire d'Océanographie Dynamique et de Climatologie, Paris, France

Numerical ice-ocean experiments are used to investigate the formation and evolution of the upper ocean salinity field in response to atmospheric forcing distributions representative of the Arctic Oscillation pattern over the period 1958-97. In particular, the anomalies of fresh water transport through Fram Strait and Denmark Strait are related to upwind changes in the sea ice and freshwater distributions in the Arctic Ocean and to their advection across the western Nordic Seas. Weak low frequency variability is found in the Fram Strait fresh water transport and the contribution of the liquid phase is smaller than that of sea ice. The relation between this transport and the fresh water transport through the Denmark is analysed in relation to processes occuring in the Nordic Seas. The latter are influenced by the local response to atmospheric forcing but also by anomalies of the salinity import through the Iceland Faroe Passage which appears to propagate remote signals originating in the subpolar gyre.

**Multi-decadal variability in the THC driven by the Arctic Ocean: Analysis of a long integration with the MPI-OM1**

by Philip K. Jakobsen[1] and Torben Schmith[1]
[1]Danish Meteorological Institute, Copenhagen, Denmark

In the picture of climate variability developed by Frankignoul and Hasselmann, atmospheric weather noise is integrated by the ocean and thereby yielding AR(1)-type spectra for the ocean. However, enhanced variability relative to the AR(1)-type ocean spectrum has previously been found in the 50-100 years band in the North Atlantic both in observations, proxy-data, and long integrations with coupled atmosphere-ocean models.
In the present work, we analyse a 2000 year long integration with the global ocean model MPI-OM1 forced with the atmospheric 'OMIP forcing', which is essential climatology with some typical weather noise added. The model is configured to have its rotated North Pole over Greenland, giving a rather good horizontal resolution in the sinking regions of the Nordic Seas. In this experiment enhanced variability with timescale 50-100 years is seen in the strength of the THC, in the density field of the North Atlantic, the Nordic Seas and the Arctic Ocean and in the Arctic Ocean sea ice volume. Applying POP analysis reveal a signal originating in the upper few hundred meters of the Arctic Ocean near the New Siberian Islands, from where it propagates across the Arctic Ocean and along the East Greenland by a mechanism still to be investigated. South of the Denmark Strait the density anomalies can be traced at depths 2-3000 meters along the east coast of North America and influences the strength of the North Atlantic meridional overturning circulation. Analysis of the experiment thus indicates that the North Atlantic multidecadal variability is maintained via a self-sustained mechanism in the Arctic Ocean.

**Variability of Upper Labrador Sea Water Formation since 1997**

by Dagmar Kieke[1], Monika Rhein[1], Lothar Stramma[2], William M. Smethie[3], Deborah A. LeBel[3] and Walter Zenk[2]
[1]Institut für Umweltphysik, Universität Bremen, Germany, [2]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Germany, [3]Lamont-Doherty Earth Observatory, Palisades, New York, USA

In the late 1990s, the shallow winter-time convection in the central Labrador Sea has favored the increased formation of Upper Labrador Sea Water (ULSW), a water mass that is found on top of 'classical' Labrador Sea Water (LSW). During 1997-2001, high-quality hydrographic and tracer data have been sampled in the subpolar North Atlantic which are used to estimate chlorofluorocarbon (component CFC-11) inventories of ULSW. From these, lower limits of the mean ULSW formation rates for the corresponding period have been inferred. In 1998 and 1999, the formation rate increased considerably to 6.6-9.2 Sv and weakened to 3.7-4.3 Sv in 2000- 2001. At least in 1998-1999, the convection area needed to form these amounts of ULSW exceeded the available area in the Labrador Sea. ULSW formation in 1998-1999 could not be confined to the Labrador Sea, but probably extended into the Irminger Sea.

**Anomalies of Meridional Overturning in the North Atlantic: Potential Mechanisms analysed with Optimal Observations**

by Armin Köhl[1]
[1]Scripps Institution of Oceanography, San Diego, now at Zentrum für Meeres- und Klimaforschung, Hamburg, Germany

Optimal observations are being used to investigate the overturning stream function in the North Atlantic at 30°N in 900 m depth. Those optimal observations are best suited to constrain the meridional overturning circulation (MOC) in numerical models and therefore establish the most efficient observation network for studying changes in the MOC. They are also ideally suited for studying the related physical mechanisms in a general circulation model. Optimal observations are evaluated here in the framework of a global 1° model over a 10 years period. Hydrographic observations useful to monitor the MOC are primarily located along the western boundary north of 30°N and along the eastern boundary south of 30°N. Additional locations are in the Labrador, Irminger, and the Iberian Sea.

On timescales of less than a year variations in MOC are mainly wind driven and are made up through changes in Ekman transport and coastal up- and down-welling. Only a small fraction is buoyancy driven and constitutes of a slow response, acting on time scales of a few years, to primarily winter time anomalies in the Labrador and Irminger Sea. Those anomalies are communicated southward along the westcoast by internal Kelvin waves at the depth level of the Labrador Sea Water. They primarily set the conditions at the northern edge of the MOC anomaly. The southern edge is mainly altered through Rossby waves of the advective type which originate from temperature and salinity anomalies off the west coast of Africa. Those anomalies are amplified on their way westward in the baroclinic unstable region of the southern edge of the subtropical gyre. The exact meridional location of the maximum MOC response is therefore set by the ratio of the strength of these two signals. Overall changes in the MOC are manifested through changes in the east-west density contrast in the upper 1000m.

**Monitoring Meridional Overturning Circulation in the Irminger Sea: Assimilation Twin Experiments**

by Daniel J. Lea[1], Thomas W. N. Haine[2], D. L. Porter[1], and R. F. Gasparovic[1]
[1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
[2]Earth & Planetary Sciences, Johns Hopkins University, Baltimore, MD, USA

We explore the prospects for monitoring the circulation and stratification of the Irminger Sea using variational data assimilation. Assimilation twin experiments are performed using simulated in-situ and satellite data, with realistic observing patterns, and a 10-km resolution regional general circulation model (the MITgcm). These experiments address the controllability and observability of the assimilation system with the existing in-situ and satellite observing network. That is, we ask: can the observations improve estimates of quantities that cannot be directly measured? Here, the focus is on the Irminger Sea stratification and meridional transport across key zonal sections.
Our results show that over periods of many months the model is not controllable. The adjoint sensitivities to initial conditions diverge exponentially, doubling every month, on average. We find that over 30 days the assimilation can fit the observations to the noise level, however, mainly by correcting the initial conditions. Only modest changes in the time-dependent surface forcing and open boundary values are needed. In this sense the model is controllable over 30 days. The system is able to accurately estimate sea surface height and sea surface temperature, correcting errors in the locations of surface fronts and eddies. The existing in-situ mooring observations downstream of the Denmark Strait are inadequate to accurately track the overflow variability at the Strait in our assimilation system. Improvement of the solution near the moorings is significant, however, and the benefit of these in-situ data propagate a few 100km upstream.

**Variability of the North Atlantic meridional overturning cell between 1997 and 2002**

by Herlé Mercier[1], Pascale Lherminier[1], Marta Álvarez[2], and the OVIDE Group
[1]Laboratoire de Physique des Océans, Plouzané, France, [2]Instituto de Investigaciones Marinas, Vigo, Spain

The OVIDE project aims at repeating a trans-oceanic hydrographic section from Greenland to Portugal every other year for ten years. The goal is to contribute to the monitoring of the inter-annual variability of the water masses as well as the variability of the mass, heat, and tracer transports in the northern North Atlantic Ocean. We present an analysis of the first Ovide hydrographic line that was carried out in June-July 2002 on R/V Thalassa. The absolute transports across the Ovide line are estimated using a box inverse model based on geostrophy, direct velocity measurements and mass conservation. The results on meridional overturning and heat transport estimates are provided. Using a similar computation on the 1997 WOCE hydrographic data collected roughly along the same section (Alvarez et al., 2004), we observe that the amplitude of the Meridional Overturning Cell was reduced by a factor of two in 2002 compared to 1997. Hypotheses about this variability are discussed.

**Estimates of North Atlantic low-frequency changes in volume and heat transports**

by Katja Lorbacher[1], Armin Köhl[1], and Detlef Stammer[1]
[1]Scripps Institution of Oceanography, San Diego, 1now at Zentrum für Meeres- und Klimaforschung, Hamburg, Germany

From a solution of the global ECCO state estimation we diagnose the low-frequency (seasonal-to-interannual) variability of meridional volume and heat transports between 20oN and 60oN in the North Atlantic Ocean. The model transports are compared with estimates across the nominal "48°N "-section

(WOCE/A2) -- reaching from the English Channel to the Grand Banks with a mean latitude of 45°N -- where a coherent hydrographic data set was obtained during seven cruises from 1993 and 2000.
The standard deviation of the monthly-mean anomalies of the simulated overturning rate at "48°N" amounts to 2 Sv and of the heat transport to 0.08 PW, respectively; the year-to-year variability is half of those numbers. In contrast to the model simulations, the observed amplitudes lie 50% above the model transport variations on interannual timescale.

The percentage of the different components contributing to the total heat transport in the model is consistent with the estimates from the observations: On the time-mean, the baroclinic component of the heat transport contributes 80% to the total integral and the Ekman component 10%. However, the latter explains almost 50% of the diagnosed low-frequency variability. For interannual variations of the heat transport infered from observations the baroclinic component is mainly responsible and thereby changes in the sign of the horizontal component appears to be dynamically relevant.
From the model output we compute error bars on the observed transport estimates to test their representativeness of low-frequency variability.

**Sensitivity of Atlantic Meridional Overturning Circulation to Surface Forcing Adjustments Obtained Through Data Assimilation**
by Youyu Lu[1] and Detlef Stammer[2]
[1]Bedford Institute of Oceanography, Dartmouth, Canada, [2]Institut für Meereskunde, Hamburg, Germany

The adjoint data assimilation approach obtains optimized initial condition and surface forcing fields for a coarse-resolution global ocean model as demonstrated by ECCO (Consortium for Estimation the Circulation and Climate of the Ocean). The meridional overturning circulation (MOC) and heat transport from the constrained run differ from the results of the unconstrained run. Three additional test runs are conducted to examine the sensitivity of the model solutions to the adjustments to initial condition and surface forcing. The test runs reveal that the difference in MOC between the constrained and unconstrained runs are set by differences in initial T-S fields, and are maintained by differences in surface forcing. The test runs also reconfirm the importance of including atmosphere-ocean feedback mechanisms in ocean-only simulations. Data assimilation adjusts surface forcing fields, hence acts to include feedback mechanisms implicitly. A crude explicit representation of feedback mechanisms is included in the unconstrained run through surface restoring. In the absence of the feedback mechanisms, the solution of ocean-only models may undergo abrupt changes as found in two of the test runs.

**Modelling Decadal Changes in the North Atlantic During 1949-2001**
by Youyu Lu[1] , Dan Wright[1] and Igor Yashayaev[1]
[1]Bedford Institute of Oceanography, Dartmouth, Canada

Changes in hydrography and circulation in the North Atlantic during 1949-2001 are simulated using the general ocean circulation model POP (The Parallel Ocean Program). The model uses a nominal 1 degree (longitude/latitude) horizontal resolution and 23 levels in the vertical. Meso-scale eddies are not resolved but are parameterized based on the Gent-McWilliams scheme. The model is driven by the monthly surface forcing obtained from the NCAR/NCEP re-analysis. The model's long-term mean temperature and salinity are nudged to the observed climatology, while time variations up to inter-decadal time scales are free to evolve according to the forcing and model dynamics. Analyses of the model solutions show that the model is able to reproduce much of the observed hydrographic variability in the Labrador Sea, such as the changes that occurred during the time of the Great Salinity Anomaly in the 1970s and early 1990s, and the recent re-stratification during the late 1990s. The decadal changes of hydrography in the sub-polar North Atlantic correlate reasonably well with the variability in the winter NAO (North Atlantic Oscillation) index. The model also simulates decadal variations in the meridional overturning circulation (MOC) and heat transport, as well as in the strength of the

**On the interannual to interdecadal variability of the Atlantic meridional overturning circulation in a coupled model**

by J. Mignot[1] and C. Frankignoul[2]
[1]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[2]LODYC, Université Pierre et Marie Curie, Paris, France

The link between the interannual to interdecadal variability of the Atlantic meridional overturning circulation (AMOC) and the atmospheric forcing is investigated using 200 years of a control simulation of the Bergen Climate Model, where the mean circulation cell is rather realistic, as well as the location of deep convection in the northern North Atlantic. The AMOC variability has a slightly red spectrum and is primarily forced by the atmosphere. In the model, the AMOC is primarily sensitive to the deep convection in the Irminger Sea, that it lags by about 5 years. The latter is mostly forced by a propagating, low-frequency atmospheric pattern that induces anomalous northerly winds over the area. The NAO influence on deep convection is realistic, but its influence on the AMOC is limited to the interannual timescale and primarily associated with direct wind forcing. At low frequency, the AMOC is influenced by the variability in the tropical Pacific with a time lag of about 40 years. Based on lagged correlations and the release of fictive lagrangian drifters, the mechanism of this interaction seems to be the following. El Niño induces positive sea surface salinity anomalies in the tropical Atlantic that are advected northward, circulate in the subtropical gyre and subduct. They are then in part advected along the North Atlantic current, eventually reaching the Irminger and Labrador Seas after about 35 years where they destabilize the water column and favour deep convection.

**Questions of Freshwater Transport and Variability in the Labrador Sea**

by Paul G. Myers[1], Brett Wheler[1], Ting On Chan[1] and Simon Josey[2]
[1]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton
[2]Southampton Oceanography Centre, Southampton

The climate of the North Atlantic and the Arctic are linked in a number of ways. Decadal variability in ocean properties, winds, precipitation, etc. have been linked to both the North Atlantic and Arctic oscillations and to each other through feedback loops. A key feature of all these loops is the role of freshwater. In this submission, issues of freshwater in the Labrador Sea are considered from modelling studies, atmospheric reanalyses and historic oceanic data.

The transport of freshwater is analyzed in an eddy-permitting regional model of the sub-polar North Atlantic, focusing on the export of freshwater (in liquid form) through Davis Strait.

The results show that, in these model simulations at least, convection in the Labrador Sea is not sensitive to enhanced export of freshwater from the Canadian Arctic Archipelago, as the enhanced freshwater does not escape from the Labrador Current into the gyre. Analysis of net precipitation minus evaporation over the Labrador Sea since 1950, from NCEP and ERA40 reanalyses are also considered. Results from both datasets are comparable (and consistent with satellite based measurements over the more recent part of the study period) and suggest a significant increase in precipitation over the Labrador Sea since the mid 1970's, mainly in spring and summer. Potential linkages between changes in the atmospheric precipitation and historical sea surface salinity changes, and the great salinity anomalies are considered. Finally, for the three most recent winters (2002-2004), additional data is provided from Argo floats operating in the Labrador Sea.

**Interannual variability of Atlantic Water hydrography in the West Spitsbergen Current in summer from 1991 to 2003**

by Pawel Schlichtholz[1] and Ilona Goszczko[1]
[1]Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland

The West Spitsbergen Current (WSC) participates actively in the North Atlantic/Arctic Ocean thermohaline circulation. It is the major source of heat and salt for the Arctic Ocean and the areas of deep convection in the Greenland Sea. The temperature and salinity of Atlantic Water (AW) carried by the WSC undergo considerable interannual variability. Some recent studies have tried to show a connection (or its lack) between variations of the AW hydrography in the area and variations of large-scale atmospheric patterns. The aim of the present paper is to study the interannual variability in the summer hydrography of the AW layer (50-500 m) in the WSC on the upper continental slope at 76.5 oN. To this end we have analyzed hydrographic measurements made from r/v Oceania in July every year since 1991. The data show two warm periods, 1994-1996 (W1) and 1999-2000 (W2), separated by a cold period 1997-1998 (C1) and year-to-year fluctuations before W1 and after W2. The peak-to-peak contrast in the averaged temperature from W1 to C1 exceeds 1 oC. A general feature of the averaged salinity variations is a decrease from 1991 to 1997 followed by an increase. The amplitude of both trends is nearly 0.1 psu. The temperature co-varies significantly with the North Atlantic Oscillation (NAO) winter index if both time series are smoothed. The correlation between salinity and the NAO index is poorer, owing to lack of coherence after 1999. Prior to that year, the correlation between the two series is very high, even higher than the correlation between temperature and the NAO index.

**Interannual variability of transports through Fram Strait estimated with a new inverse model based on the finite element method**

by Dmitry Sidorenko[1], Agnieszka Beszczynska-Möller[1], and Martin Losch[1]
[1]Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

Fram Strait is the only deep passage between the Arctic Ocean and Nordic Seas. The variability of oceanic fluxes through Fram Strait has been monitored by an array of moorings since 1997. Time series of temperature and velocity from moored instruments provide estimates of heat and volume fluxes with excellent temporal resolution but the spatial structure of the flow is underresolved. This is the main source of the error in the measured transport.

We present an inverse finite element model that combines both velocity and temperature data from moorings and temperature and salinity data from CTD surveys to estimate transports, thereby overcoming the poor spatial resolution of the moored instrument data by the high resolution of the CTD surveys. A novel aspect of the model is its use of the finite element method. Among many other advantages, this discretization method allows a flexible computational grid and thereby an accurate representation of the bottom topography, in particular the bottom wedges.

The instantaneous heat and volume fluxes obtained from the inverse model are based on the high resolution CTD data and referenced to the absolute velocities thus they also include the strong barotropic component that is dominant in Fram Strait. The results obtained with the finite element section model reveal that calculations from linear interpolation of mooring data alone tend to overestimate total transports.

**Rapid climate change and the N. Atlantic thermohaline circulation**

by Meric Srokosz[1] and Christine Gommenginger[1]
[1]Southampton Oceanography Centre, Southampton, UK

The possibility of rapid climate change (that is, significant change over a period of the order of a decade) is of interest both scientifically and to policy makers. Evidence from palaeo data (for example, Greenland ice cores and marine sediments) shows that over the last 11,000 years (the Holocene) the climate has been relatively stable. However, prior to that rapid changes in temperature of the order of 5-10 degrees have occurred in perhaps as short a time as 5-10 years. The palaeo data suggest that the oceanic thermohaline circulation (THC) is implicated in many of these changes. Computer models indicate that under a global warming scenario similar rapid changes might occur in the future, with a slowdown or shutdown of the N. Atlantic THC. Such rapid changes could have major climatic impacts particularly in NW Europe. The UK Natural Environment Research Council (NERC) has funded the Rapid Climate Change (RAPID) programme (£20M over 6 years), which aims to investigate and understand the causes of rapid climate change, with a main (but not exclusive) focus on the role of the Atlantic Ocean's THC. Using a combination of observations in the N. Atlantic, palaeo data and models, RAPID is working towards reducing uncertainties and improving predictions. Working in conjunction with NSF and NOAA, a major observational array has being deployed at 26.5°N across the N. Atlantic to measure changes in the meridional overturning circulation (of which the THC is the dominant component). In addition, arrays have been deployed further north to measure the deep western boundary current and study the propagation of signals along the Atlantic western boundary. The observations will better characterise the present state of the THC and lead to the definition of the operational MOC observing system that would be required to detect changes in the THC and act as an "early warning" system. Both present day observations and the palaeo data will be used to test, constrain and so help improve climate models. The ultimate goal of RAPID is to provide a better assessment of the possibility of future rapid climate change, and the role of the THC in such change. Here an overview is given of the work on the N. Atlantic THC already under way under the RAPID programme. Current and future activities within RAPID – in particular, the joint funding initiative between the research councils of Norway, The Netherlands and the UK – will be presented. More information on all aspects of RAPID can be found on the web at http://rapid.nerc.ac.uk.

**Spreading of North Atlantic Deep Water from the subpolar to the tropical Atlantic**

by Reiner Steinfeldt[1] and Monika Rhein[1]
[1]Institut für Umweltphysik, Bremen, Germany

CFC observations over the last decade reaching from the subpolar to the tropical Atlantic are used to investigate the spreading of North Atlantic Deep Water (NADW) within the deep western boundary current. The parameters of the age spectra are fitted to reproduce the observed CFC core concentrations for Upper Labrador Sea Water (ULSW), Labrador Sea Water (LSW) and Lower North Atlantic Deep Water (LNADW). From this adjustment procedure information about the velocity, dilution and isopycnal diffusion of the mean flow can be obtained. The observations at 55°N within the Labrador Sea are used to construct a CFC time history including the period in the mid 1990s with high CFC-concentrations due to intensified convection and LSW formation. First results indicate that age spectra with temporally constant parameters underestimate the CFC-concentration further downstream, which can be interpreted as an increase of LSW transport in the boundary current. The propagation of CFC anomalies arising in the Labrador Sea can be followed downstream towards the tropics, and the estimated propagation velocity of these anomalies is about 2 cm/s.

**Water mass variability and spreading in the deep western subpolar North Atlantic since the mid-1990's**

by Lothar Stramma[1], Jürgen Fischer[1], Friedrich Schott[1], Igor Yashayaev[2], Dagmar Kieke[3], Monika Rhein[3] and Klaus Peter Koltermann[4]
[1]Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), Germany, [2]Bedford Institute of Oceanography, Dartmouth, Canada, [3]Institut für Umweltphysik, Bremen, Germany, [4]Bundesamt für Seeschifffahrt und Hydrographie, Hamburg, Germany

Observations on deep water variability in the western subpolar North Atlantic since the mid-1990's were carried out based on repeat shipboard observations of currents and hydrography and on multiyear mooring arrays. Within the last decade, the Labrador Sea Water (LSW) in the isopycnal range sq=27.74-27.8 kgm-3 warmed significantly, became more saline and decreased in layer thickness. At the same time, the upper LSW (sq=27.68-27.74 kgm-3) was formed by convection and the layer thickness increased. The Gibbs Fracture Zone Water (GFZW) was getting colder and fresher between 1996 and 2001. The Denmark Strait Overflow Water (DSOW) showed two periods of cooling and freshening, separated by a rapid increase in temperature and salinity within a year. GFZW and DSOW temperature and salinity increased again since 2001, therefore the extrema in temperature and salinity can be used to follow the spreading of the signal within the subpolar North Atlantic. The arrival time of the extrema implies a DSOW spreading time of about 2 years from the western Labrador Sea at 56°N to the Grand Banks at 43°N. From a combination of our results with results in the literature, the spreading time from the Denmark Strait to the Grand Banks is estimated to be about 4 years. The ULSW and LSW formed by convection in the Labrador Sea spread mainly westward, are injected into the Deep Western Boundary Current (DWBC) and than are carried southward as part of the DWBC. While the hydrographic parameters showed longer period variability in the western subpolar North Atlantic, the current measurements at 53°N showed only weak longer period variability during 1997 to 1999.

**Variability of water mass transports between Greenland and Portugal in a 1/6° model of the Atlantic**

by Anne Marie Treguier[1], Herlé Mercier[1] ,Thierry Penduff[2] and Jean Marc Molines[2]
[1]Laboratoire de Physique des Océans, Plouzané, France, [2]Laboratoire des Ecoulements Geophysiques et Industriels, Grenoble, France

In collaboration with the OVIDE project (repeating section from Greenland to Portugal) we examine the variability along the OVIDE section in the 1/6° Atlantic 'CLIPPER' model. Over the years 1995 to 2002, the meridional overturning across the section varies from 8 to 16 Sv, but this is mainly a high frequency variability driven by the wind. The same model forced by a repeated seasonal cycle exhibits a lower variability (from 10 to 13 Sv). High frequency variability is mostly present in the East Greenland current transport. The variability of the North Atlantic current has a longer time scale. Although eddy activity is large in the model, eddy-induced transports across the OVIDE section are negligeable. Variability in water masses is not adequately represented in the model because of the boundary at 70°N, which excludes the Nordic Seas, and also because of the model drift.

**Timely detection of anthropogenic change in the Atlantic meridional overturning circulation**

by Michael Vellinga[1] and Richard A. Wood[1]
[1]Met Office, Hadley Centre for Climate Prediction and Research, UK

Detection of anthropogenic weakening of the Atlantic meridional overturning circulation ('MOC') may be improved by monitoring a limited number of key oceanic variables. We have identified a set of potentially useful ocean hydrographic observations in the climate general circulation model HadCM3. When the model is force d by an anthropogenic climate forcing scenario for the 21st century, a pattern is found that captures co-variability of these variables and strength of the MOC. Fingerprints of this pattern emerge clearly on time scales of 10 years from background noise caused by internal variability. If similar results are found in other climate models this will provide useful information for the design of an operational integrated MOC observing system.

**The spatial and temporal characteristics of the adjustment of the thermohaline circulation, in response to the removal of surface freshwater forcing in a coupled general circulation model**

by Paul D. Williams[1], Eric Guilyardi[1], Rowan Sutton[1], Jonathan Gregory[1] and Gurvan Madec[2]
[1]Centre for Global Atmospheric Modelling, University of Reading, UK
[2]Laboratoire d'Océanographie Dynamique et de Climatologie, Université Paris VI, France

The spatial distributions of precipitation and evaporation at the ocean surface are predicted to change, as the climate system adjusts in response to the increased radiative forcing provided by greenhouse gases. This could have a major impact on the thermohaline circulation (THC), due to the role played by the net freshwater flux in maintaining salinity structures and, in turn, the vertical stratification. The modified THC could further alter the climate system, giving the possibility of rapid climate changes, as seen in the past. Nevertheless, the relevant feedback mechanisms and adjustment timescales are poorly understood.
We present an investigation of the mechanisms which maintain the salinity field in a coupled atmosphere-ocean general circulation model. We compare two 100-year integrations, initiated from the same present-day thermohaline structure. A perturbed simulation, in which the net freshwater flux into the ocean is prescribed to be zero at each ocean gridpoint and each timestep, is compared with a control run which has interactive freshwater exchange. The radiative forcing is constant in both runs. The strength of the North Atlantic meridional overturning circulation in the perturbed simulation is greatly reduced by the end of the integration. We investigate the mechanisms associated with this THC slowdown, and assess the impacts on the dominant modes of interannual climate variability in the North Atlantic ocean.

**Response of the sub-polar North Atlantic Circulation to the NAO-related flux forcing in a regional eddy-permitting ocean model**

by Duo Yang[1] and Paul G. Myers[1]
[1]University of Alberta, Edmonton, Canada

A flux-forcing version of sub-polar North Atlantic eddy-permitting ocean model (SPOM) has been developed to examine the sensitivity of water mass formations and associated heat and freshwater transports to the NAO-related anomalous surface fluxes. During the 1st 40 years' integration, forced climatologically by buoyancy fluxes originating from the Southampton Oceanography Center (SOC) and wind stress from European Center for Medium-range Weather Forecast, the model remains stable and all major features of the sub-polar gyre are represented. Then the anomalous NAO-like fluxes, stemming from NCEP/NCAR, are added to SOC buoyancy forcing and run for additional 110 years (high NAO phase) and 60 years (low NAO phase), depending on the achievement of stability. Two modes of circulations are observed in low NAO-forcing experiment, associated with the local formation of deep sub-polar mode water due to strong heat loss in eastern basin during low NAO phase and subsequent adjustment in heat transport via the North Atlantic current (NAC). A potential multi-decadal oscillation in both circulation and heat transport is surprisingly revealed in our high NAO-forcing experiment, which might be brought about by the variability in heat transport through the NAC to balance the compensation to heat loss in Labrador Sea (intensive) and eastern basin (weaker than in low NAO phase). A further examination of the mechanism is still ongoing.

**Decadal Variability and Secular Trends in the Thermohaline Circulation and Ocean Ventilation in CCSM3 in Global Warming Scenarios**
by Gokhan Danabasoglu[1] ,Frank Bryan[1], Daisuke Tsumune[2], and Norikazu Nakashik[2]
[1]National Center for Atmospheric Research, Boulder, USA, [2]Central Research Institute of Electric Power Industry, Abiko, Japan

CCSM3 is the latest version of the NCAR Community Climate System Model. A series of multi-century control and global warming experiments have been conducted in two versions of the model that differ only in the resolution of the atmospheric component. The ocean model resolution is approximately 1°. There are important differences in the mean circulation of the North Atlantic and its decadal variability between the two versions. The version with a higher resolution (T85) atmosphere model has a stronger mean overturning and larger amplitude decadal timescale variability than the version with a lower resolution (T42) atmosphere. In both cases, there is a relatively small change (1 to 2 Sv) in the maximum North Atlantic overturning transport at the time of CO2 doubling, with a sharper decline between the time of doubling and quadrupling. In addition to the secular trend in the overturning, the amplitude of decadal timescale variability is suppressed under conditions of increasing CO2. An analysis of the mechanisms leading to these changes will be presented. In addition to documenting the changes in the mass transport of the overturning circulation, we will describe changes in the ventilation timescale of the ocean under global warming scenarios through analysis of an ideal age tracer included in the experiments.

**On the freshwater contributions determining the Atlantic thermohaline circulation in a model of intermediate complexity**
by Pedro de Vries[1] and Nanne Weber[1]
[1]KNMI, De Bilt, Netherlands

How freshwater transports into the Atlantic basin modify the strength and the stability of the thermohaline circulation (THC) is investigated. Depending on the large-scale salinity-advection feedbacks being either negative or positive, the THC may be in a monostable or bistable state. Which physical processes and variables effectively determine these stability properties is not yet fully understood. Employing a coupled model of intermediate complexity we show that atmospheric freshwater forcings and the resulting changes in the oceanic freshwater transports can be chosen such that both the strength as well as the stability of the THC can be established a priori.

**The thermohaline circulation in transient coupled ensemble climate simulations**
by Sybren Drijfhout[1], Wilco Hazeleger 1and Frank Selten[1]
[1]KNMI, De Bilt, Netherlands

Idealised models have documented stable and unstable equilibrium states for the thermohaline circulation. Transient changes in this circulation might be driven by transient changes in the atmospheric forcing, but they also might be due to the internal variability of the coupled ocean-atmosphere system. In order to study the probability of changes in the thermohaline circulation that are associated with climate change, it was decided to produce a large ensemble of transient climate simulations. To this end the NCAR CCSM1.4 model was integrated 62 times for the period 1940-2080. During the historical part of the simulation, GHG concentrations, sulphate aerosols, solar radiation and vulcanic aerosols were prescribed according to observational estimates. From 2000 onwards, the solar constant was held constant and sulphate aerosols were

kept fixed. Only the GHG concentrations varied according to a Business-as-Usual scenario. The ensemble members differ only in a small random perturbation in the initial temperature field of the atmosphere, enough to lead to entirely different atmospheric evolutions within the first couple of weeks of the integrations. The evolution of the thermohaline circulation in the 62 ensemble members is discussed, and the average change associated with the transient GHG forcing is separated from a part that is associated with the internal variability of the coupled ocean-atmosphere. In the latter we distinguish between THC variability that is associated with variations in the North Atlantic Oscillation and variability due to internal ocean dynamics.

**Sensitivity to the vertical diffusivity in a coupled general circulation model**

by Clotilde Dubois[1] Robin S. Smith[2] and Jochem Marotzke[2]
[1]Southampton Oceanography Centre, UK. [2]Max Planck Institute for Meteorology, Hamburg, Germany

The vertical diffusivity plays an important role in determining the ocean's circulation, since the vertical mixing of heat and salinity from the surface to the deep ocean drive the large-scale ocean circulation and the heat transport. The values of the diffusivity coefficients (Kv) in the current climate are quite uncertain. Scaling analysis and ocean GCM calculations suggest that for the North Atlantic the strength of the meridional overturning scales as Kv2/3, and the heat transport as Kv1/2.
Here, a fully coupled ocean-atmosphere CGM with realistic geometry, FORTE, is used to examine the sensitivity of the atmosphere-ocean circulation to the vertical diffusivity, with values ranging from Kv = 0.1 cm2/s to an unrealistic high value of 5 cm2/s over all ocean basins. At equilibrium, the strength of the meridional overturning follows the scaling argument in the South Atlantic and North Pacific basin, but the heat transport does not. The tropical Pacific shows a high sensitivity to Kv, and two vigorous tropical overturning cells are observed at high values. The atmospheric energy transport decreases with Kv in the tropical region, which can be associated with a swallower equator-pole sea surface temperature gradient and a change in the wind pattern in the tropical Pacific.

**Comparison of modelled THC and its variability in coupled GCMs with coarse-resolution and eddy-permitting ocean**

by Hiroyasu Hasumi[1], Tatsuo Suzuki[2], Takashi Sakamoto[2], Akira Oka[1] and Naosuke Okada[3]
[1]Center for Climate System Research, Tokyo, Japan, [2]Frontier Research System for Global Change, Yokohama, Japan, [3]National Institute for Environmental Studies, Tsukuba, Japan

Two coupled GCMs of different resolution are currently used by the CCSR/NIES/FRSGC research consortium for future climate change projection on the Earth Simulator. The lower resolution model incorporates a ~1° horizontal resolution ocean component, while the higher resolution model does an eddy-permitting ocean. The coupled models do not employ any flux adjustment, and the atmospheric component explicitly represents both direct and indirect aerosol effects. The coupled models are integrated under the fixed pre-industrial forcing (control case), under the historical forcing variations due to both natural (solar and volcanic activity) and anthropogenic (greenhouse gas, aerosol, and land-use) sources, under the 1%/yr atmospheric CO2 increase condition, and under the IPCC/SRES future emission scenarios (number of scenario runs and their duration for the higher resolution model are very limited due to the computational cost, though). Here we compare natural variability of the THC in control climates, its historical variations, and its changes in the course of global warming between the two models.

**Evolution of the THC under global warming conditions in the coupled AOGCM ECHAM5/MPI-OM**

by Johann Jungclaus[1] and Uwe Mikolajewicz[1]
[1]Max-Planck-Institute for Meteorology, Hamburg, Germany

Climate models give considerably different answers to the question how the strength of the meridional overturning will develop under global warming conditions. Here we analyze the results of the new Max-Planck- Institute coupled AOGCM ECHAM5/MPI-OM. The model is a coarse resolution version of the standard MPI climate models so that, in addition to ensemble integrations, a number of sensitivity studies can be carried out using different physical parameterizations and different CO2 increase rates.

The presentation discusses how the thermohaline circulation (THC) develops under global warming conditions, which processes are important for the THC stability and if irreversible mode switches occur. The sensitivity of the results to specific subgridscale parameterizations and the model resolution is investigated.

**Dynamic sea level changes following a shutdown of the thermohaline circulation**
by Anders Levermann[1], Alexa Griesel[1], Matthias Hofmann[1], Marisa Montoya[2] and Stefan Rahmstorf[1]
[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany, [2]Facultad de Ciencias Fisicas, Universidad Complutense de Madrid, Madrid, Spain

Using the coupled climate model CLIMBER-3a, we investigate changes in sea level due to a weakening of the thermohaline circulation (THC). In contrast to steric sea level rise following a melting of ice sheets or a warming of the deep sea, we focus on the dynamical effect resulting from a change in oceanic circulation. Such sea level changes follow quasi-instantaneously alterations in the ocean circulation. Since a THC shutdown can occur on a time scale of decades, the corresponding changes in sea level occur on the same time scale. The magnitude of this sea level rise can regionally reach up to 50 cm. This is comparable to changes in steric sea level due to a warming of the deep sea after an increase of atmospheric CO2 which occurs on much longer time scales. In contrast to deep sea warming or ice melting, the sea level changes discussed here vary strongly for different regions and average out globally, i.e. no mean global sea level rise is associated with the purely dynamical sea level changes. The emerging patterns are discussed with respect to the oceanic circulation changes. Most prominent is a South-North gradient along the Atlantic reflecting changes in the large-scale geostrophic surface currents. Comparison with recent measurements of sea level in the Atlantic and Pacific suggest that the THC has not reduced significantly in the last 40 years.

**Variations of the THC in the CCSR/NIES/FRSGC coupled GCM for 20 th century and future projection runs**
by Akira Oka[1], Naosuke Okada[2] and Hiroyasu Hasumi[1]
[1]Center for Climate System Research, Tokyo, Japan, [2]National Institute for Environmental Studies, Tsukuba, Japan

We present natural variability, historical variations, and projected future changes of the THC calculated by the CCSR/NIES/FRSGC coupled GCM. The model horizontal resolution is T42 for the atmosphere and ~1° for the ocean. The coupled model does not employ any flux adjustment, and the atmospheric model explicitly represents both direct and indirect aerosol effects. We run the model under the fixed pre-industrial forcing (control case), under the historical forcing variations due to both natural (solar and volcanic activity) and anthropogenic (greenhouse gas, aerosol, and land-use) sources since 1850, under the 1%/yr atmospheric CO2 increase condition, and under IPCC/SRES future emission scenarios. In the control climate, the sources of NADW are reasonably located in the Greenland and Labrador Seas, and the intensity of the meridional overturning circulation also falls within a reasonable range. In analysing the THC variations, focus is on changes in northern high-latitude and inter-basin scale sea surface freshwater budget, and the role of the atmospheric water vapour transport, which is on the background of the oceanic surface freshwater budget changes, is to be highlighted.

**South Atlantic Ocean Observing System for Climate**
by Silvia L. Garzoli[1], Mike Johnson[1], Alberto Piola[2], Christine Provost[3], and Gustavo Goni[1]
[1]National Oceanic and Atmospheric Administration, USA, [2]Servicio de Hidrografia Naval, Argentina
[4]Laboratoire d'Oceanographie Dynamique et de Climatologie, France

The importance of the role than the South Atlantic plays in the meridional overturning circulation (MOC) is indisputable. The South Atlantic Ocean connects the three major ocean basins: The Pacific Ocean, the Atlantic Ocean and the Indian Ocean. The meridional gaps between the continents of the Southern Hemisphere and Antarctica allow for a free exchange of water among the basins. The variability of the inter-ocean exchange has a direct implication on the thermohaline circulation and therefore should be closely monitored. An area that requires special attention because of its role in the thermohaline circulation, is the southern tip of South Africa where the Indian to Atlantic inter-ocean exchange takes place. One of the key questions when dealing with the thermohaline circulation in the South Atlantic is how much heat and salt is transferred from the Indian to the Atlantic Ocean. This inter-ocean exchange take place through the Benguela /Agulhas system, south of South Africa. There have been indications of recent warming which might be related to variability of deep convection and water mass transformation in the Weddell Sea. Hence, monitoring the various in- and outflows through the southern entrance of the South Atlantic as well as the interhemispheric exchanges is crucial for understanding MOC variability. Meridional heat flux in the ocean is a key element of the climate system because of the role that the ocean plays in determining the Earth's climate through its interaction with the atmosphere. Despite its small size, the Atlantic Ocean is responsible for over half of the heat transport carried by the global ocean. Sustained observations to monitor this heat flu shoul be a priority of the observing system. Another topic of relevance to climate is the distribution of sea surface temperature (SST). The knowledge of the distribution of SST anomalies in the South Atlantic is important at the global scale for modeling and prediction. The South Atlantic has been historically one of the less sampled basins. The spatial and temporal gaps in the observations result in poor climate forecasts. This poster presents a review of the role of the South Atlantic in climate and of the currently existing components of the international effort towards a South Atlantic Observing System. This includes sustained and long-term planned observations.

**Appendix I Workshop Programme**

**Monday 13 September**

| | | |
|---|---|---|
| 09:00 – 09:30 | **Opening, Welcome, Local arrangements** | |
| | Claus Böning (Speaker, SFB 460) | Opening |
| | Peter Herzig (Director, IFM-GEOMAR) | Welcome |
| | Martin Visbeck, Claus Böning (Co-Chairs) | Workshop objectives and scientific program |
| | Jürgen Willebrand, Lothar Stramma | Local organization |

**Session 1: THC variability and climate** *(Chairs: J. Willebrand, C. Böning)*
The introductory session highlights two issues: the observed ocean variability, and its role in climate.

| | | |
|---|---|---|
| 09:30 - 10:00 | ***Friedrich Schott*** | THC variability: Observations and indices |
| 10:00 - 10:30 | ***Rowan Sutton*** | Role of THC variability in climate |
| 10:30 - 11:00 | | Coffee |

**Session 2: THC variability and the carbon cycle** *(Chair: D. Wallace)*
This session explores the influence of THC variability on atmosphere-ocean transfers of "natural" and "anthropogenic" carbon that are associated with the solubility and biological carbon pumps.

| | | |
|---|---|---|
| 11:00 - 12:00 | ***Nicolas Gruber*** | Variability of North Atlantic carbon uptake: magnitude and causal factors |
| 12:00 - 12:30 | | Poster introductions for session 2 posters and Discussion |
| 12:30 - 14:00 | | Lunch |
| 14:00 – 14:30 | | Poster introductions: session 3 posters |
| 14:30 – 16:00 | | **Poster session**<br>Coffee, Refreshments |

**Session 3: Water mass transformation processes in the North Atlantic** *(Chairs: C. Mauritzen, U. Send)*
The session reviews our understanding of the integral effects of key processes governing THC variability, including convection, overflows and entrainment; it will assess their representation in large-scale models, and identify needs for improvements.

| | | |
|---|---|---|
| 16:00 – 16:30 | ***Detlef Qadfasel*** | Water mass transformation in the Arctic Mediterranean |
| 16:30 – 17:00 | ***Sonya Legg*** | *(1)* Modeling overflow and (2) preconditioning and eddies in deep convection |
| 17:00 – 17:30 | ***Fiammetta Straneo*** | Variability of Convection in the Subpolar North Atlantic: What we understand and what we don't |
| 17:30 – 18:00 | ***Monika Rhein*** | Formation rates and spreading of Labrador Sea Water |
| 18:00 – 20:00 | | Reception ("Icebreaker") aboard R/V Alkor |

**Tuesday 14 September**

**Session 4: Characteristics and mechanisms of MOC variability in the North Atlantic** *(Chairs: D. Stammer, A.-M. Treguier, W. Johns)*
The session reviews the main characteristics and our understanding of the causes and propagation of interannual-decadal variability signatures in water mass formation and large-scale transports, based on both observational and modeling results. A particular aim of the discussion will be to identify the potential of different types of observing systems for detecting THC changes, including transport arrays, hydrographic sections, and the role of data assimilation studies.

| | | |
|---|---|---|
| 09:00 – 09:45 | ***Stewart Cunningham*** | What are the main characteristics of interannual-decadal variability in large scale transports? |
| 09:45 – 10:30 | ***Molly Baringer*** | What is the potential of different types of observation systems for detecting/monitoring MOC changes? |
| 10:30 – 11:00 | | Coffee |
| 11:00 – 11:45 | ***Richard Greatbatch*** | Forcing mechanism of MOC variations and mechanism of communication between polar latitudes of the Atlantic and its lowlatitudes: *(A) Northern Hemisphere* |
| 11:45 – 12:30 | ***Will DeRuijter*** | Forcing mechanism of MOC variations and mechanism of communication between polar latitudes of the Atlantic and its lowlatitudes: *(B) Southern Hemisphere* |
| 12:30 – 14:00 | | Lunch |
| 14:00 – 14:30 | | Poster introductions: session 4 posters |
| 14:30 – 16:00 | | **Poster session**<br>Coffee, Refreshments |
| 16:00 –16:45 | ***Terrence Joyce*** | Understanding the link between MOC variability and SST variability: What are the theoretical and observational basis of our knowledge about this? |
| 16:45 – 17:30 | ***Helge Drange*** | Role of Artic and GIN Sea in driving MOC variations |
| 17:30 – 18:15 | ***Carl Wunsch*** | Has oceanic state estimation matured sufficiently to be a required element of observing systems for the mass, heat, and other property fluxes? |

**Public Lecture** (in German)

| | | |
|---|---|---|
| 20:00 | ***Mojib Latif*** | Versiegt der Golfstrom? Konsequenzen des globalen Klimawandels für Europa. |

**<u>Wednesday 15 September</u>**

**Session 5: The THC in a changing climate** *(Chairs: R.Wood, M.Latif)*

The session aims at a discussion of future THC scenarios based on the results of climate modeling. A particular question is to which degree model predictions depend on the representation of oceanic processes, and, based on this, the needs and prospects for improved THC simulations in the next generation of climate models.

| | | |
|---|---|---|
| 09:00 – 09:30 | ***Jonathan Gregory*** | *AOGCM predictions of changes in Atlantic meridional overturning: The CMIP coordinated THC experiment* |
| 09:30 – 09:50 | ***Richard Wood*** | Do climate GCMs exhibit multiple THC equilibria/hysteresis? |
| 09:50 – 10:15 | ***Thomas Stocker*** | *Concepts and simplified models to quantify past and future climate change* |
| 10:15 – 10:30 | | **Discussion** |
| 10:30 – 11:00 | | Coffee |
| 11:00 – 12:00 | | Poster Introductions: session 1, 5 and 6 posters |
| 12:00 – 12:30 | ***Jochem Marotzke*** | Prospects for predicting the future of the THC in IPCC AR4 and beyond |
| 12:30 – 14:00 | | Lunch |
| 14:00 – 15:00 | | **Poster session**<br>Coffee, Refreshments |

| | |
|---|---|
| 15:00 – 17:00 | **Working Groups** The aim of the working groups is to provide input to the discussion during session 6 on the following issues: How well can individual components of a sustained observing system contribute to a quantitative recording of MOC changes? What kinds of research do we need to improve the design and interpretation of these systems? What can we learn from models about present, past and future MOC changes? |

**Thursday 16 September**

| | |
|---|---|
| 08:30 – 10:00 | Working Groups (continued) |
| 10:00 – 10:30 | Coffee |

**Session 6: Future programs** *(Chairs: M. Visbeck, E. Chassignet)*
The final session aims to identify needs and requirements of future scientific programs that help in the

- design of observing systems for monitoring the THC
- improvement of model predictions of the fate of the THC

All other sessions and working groups are requested to contribute, i.e., will work towards providing input to this final discussion.

| | |
|---|---|
| 10:30 – 12:30 | Discussion of future developments and needs |
| 12:30 – 13:00 | Final remarks |
| | Adjourn |

**Appendix II List of Participants**

| | | |
|---|---|---|
| Affler Karine | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | kaffler@ifm-geomar.de |
| Alvarez Marta | Departamento de Oceanografia, Instituto Investigaciones Marinas (CSIC), SPAIN | malvarez@iim.csic.es |
| Avsic Tom | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | tavsic@ifm-geomar.de |
| Baehr Johanna | Max-Planck-Institut für Meteorologie, GERMANY | Johanna.Baehr@dkrz.de |
| Baringer Molly | NOAA-AOML/PHOD, USA | molly.baringer@noaa.gov |
| Barnier Bernard | Laboratoire des Ecoulements Geophysiques et Industriels, FRANCE | bernard.barnier@hmg.inpg.fr |
| Bersch Manfred | Institut für Meereskunde, Uni Hamburg, GERMANY | bersch@ifm.uni-hamburg.de |
| Biastoch Arne | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | abiastoch@ifm-geomar.de |
| Böning Claus | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | cboening@ifm-geomar.de |
| Boscolo Roberta | Departamento de Oceanografia, Instituto Investigaciones Marinas (CSIC), SPAIN | rbos@iim.csic.es |
| Brandt Peter | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | pbrandt@ifm-geomar.de |
| Bryan Frank O. | Climate and Global Dynamics Division National Center for Atmospheric Res., USA | bryan@ucar.edu |
| Calmanti Sandro | ENEA, Progetto Speciale Clima Globale, ITALY | sandro.calmanti@casaccia.enea.it |
| Cetin Nilgun | University of Alberta, Department of Earth and Atmospheric Sciences, CANADA | ncetin@ualberta.ca |

| | | |
|---|---|---|
| Chassignet Eric | University of Miami RSMAS/MPO, USA | echassignet@rsmas.miami.edu |
| Cunningham Stuart A. | Southampton Oceanography Centre, UK | s.cunningham@soc.soton.ac.uk |
| Czeschel Lars | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | lczeschel@ifm-geomar.de |
| Danilov Sergey | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | sdanilov@awi-bremerhaven.de |
| de Ruijter Will | Institute for Marine and Atmospheric research Utrecht (IMAU), THE NETHERLANDS | w.p.m.deruijter@phys.uu.nl |
| Dengg Joachim | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jdengg@ifm-geomar.de |
| Dengler Marcus | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mdengler@ifm-geomar.de |
| de Vries Pedro | Royal Netherlands Meteorological Institute (KNMI), Department of Climate Variability Research, THE NETHERLANDS | pvriesde@knmi.nl |
| Dietze Heiner | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | hdietze@ifm-geomar.de |
| Dommenget Dietmar | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | ddommenget@ifm-geomar.de |
| Drange Helge | Nansen Environmental and Remote Sensing Center, NORWAY | helge.drange@nersc.no |
| Drijfhout Sybren | Royal Netherlands Meteorological Institute (KNMI), Department of Oceanography, THE NETHERLANDS | drijfhou@knmi.nl |
| Dubois Clotilde | Max-Planck-Institut für Meteorologie, GERMANY | cdu@soc.soton.ac.uk |
| Eden Carsten | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | ceden@ifm-geomar.de |
| Eldevik Tor | Nansen Environmental and Remote Sensing Center, GERMANY | tor.eldevik@nersc.no |

| | | |
|---|---|---|
| Ernst Ute | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | uernst@ifm-geomar.de |
| Fine Rana | RSMAS, MAC, Univ. of Miami, USA | rfine@rsmas.miami.edu |
| Fischer Jürgen | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jfischer@ifm-geomar.de |
| Funk Andreas | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | afunk@ifm-geomar.de |
| Garzoli Silvia L. | Atlantic Oceanographic and Meteorological Laboratory NOAA, USA | silvia.garzoli@noaa.gov |
| Gaurin Steven | Smith College, Department of Geology, USA | sgaurin@email.smith.edu |
| Gerber Christian | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | cgerber@ifm-geomar.de |
| Gerdes Rüdiger | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | rgerdes@awi-bremerhaven.de |
| Gommengeiger Christine | | |
| Gouretski Victor | Max-Planck-Institut für Meteorologie, GERMANY | gouretsk@ifm.uni-hamburg.de |
| Greatbatch Richard | Dalhousie University, Dept. Oceanogr., CANADA | rgreat@phys.ocean.dal.ca |
| Gregory Jonathan | Centre for Global Atmospheric Modelling, Department of Meteorology, University of Reading, UK | j.m.gregory@reading.ac.uk |
| Gruber Nicolas | IGPP, University of Los Angeles, Center for Earth Systems Research, USA | ngruber@igpp.ucla.edu |
| Gulev Sergey | P.P.Shirshov Institute of Oceanology, RUSSIA | gul@sail.msk.ru |
| Haak Helmuth | Max-Planck-Institut für Meteorologie, GERMANY | haak@dkrz.de |

| | | |
|---|---|---|
| Haine Thomas | Earth & Planetary Sciences, Johns Hopkins University, USA | Thomas.Haine@jhu.edu |
| Hansen Bogi | Faroese Fisheries Laboratory, FAROES | bogihan@frs.fo |
| Hasumi Hiroyasu | Center for Climate System Research University of Tokyo, JAPAN | hasumi@ccsr.u-tokyo.ac.jp |
| Hazeleger Wilco | KNMI, Oceanographic Res. Dept., THE NETHERLANDS | hazelege@knmi.nl |
| Hetzinger Steffen | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | shetzinger@ifm-geomar.de |
| Hüttl Sabine | Leibniz-Institut für Meereswissenschaften Kiel. GERMANY | shuettl@ifm-geomar.de |
| Iovino Dorotea | G.C. Rieber Climate Institute Nansen Environmental and Remote Sensing Center, NORWAY | dorotea.iovino@nersc.no |
| Jakacki Jaromir | Naval Postgraduate , USA | jakacki@nps.edu |
| Johns William E. | Rosenstiel School of Marine and Atmospheric Science, USA | wjohns@rsmas.miami.edu |
| Joyce Terrence | Woods Hole Oceanographic Institution, USA | tjoyce@whoi.edu |
| Jungclaus Johann | Max-Planck-Institut für Meteorologie, GERMANY | jungclaus@dkrz.de |
| Kanzow Torsten | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | tkanzow@ifm-geomar.de |
| Karstensen Johannes | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jkarstensen@ifm-geomar.de |
| Käse Rolf | Institut für Meereskunde, Universität Hamburg, GERMANY | kaese@ifm.uni-hamburg.de |
| Keenlyside Noel | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | nkeenlyside@ifm-geomar.de |

| | | |
|---|---|---|
| Kieke Dagmar | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | dkieke@physik.uni-bremen.de |
| Kielmann Jürgen | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jkielmann@ifm-geomar.de |
| Kirchner Kerstin | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | kkirchner@uni-bremen.de |
| Kivman Gennady | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | gkivman@awi-bremerhaven.de |
| Köberle Cornelia | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | ckoeberl@awi-bremerhaven.de |
| Köhl Armin | Zentrum für Meeres- und Klimaforschung, Universität Hamburg, GERMANY | koehl@ifm.uni-hamburg.de |
| Körtzinger Arne | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | akoertzinger@ifm-geomar.de |
| Kösters Frank | Institut für Geowissenschaften, Universität Kiel, GERMANY | koesters@passagen.uni-kiel.de |
| Koltermann Klaus P. | BSH Hamburg, GERMANY | koltermann@bsh.de |
| Kröger Jürgen | The Abdus Salam International Centre for Theoretical Physics, Physics of Weather and Climate Section, ITALY | jkroeger@ictp.trieste.it |
| Kühn Wilfried | Institut für Meereskunde, Universität Hamburg, GERMANY | kuehn@ifm.uni-hamburg.de |
| Landerer Felix | Max-Planck-Institut für Meteorologie, GERMANY | landerer@dkrz.de |
| Lankhorst Matthias | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mlankhorst@ifm-geomar.de |
| Latif Mojib | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mlatif@ifm-geomar.de |
| Legg Sonya | Woods Hole Oceanographic Institution, USA | slegg@whoi.edu |

| | | |
|---|---|---|
| Levermann Anders | Potsdam Institute for Climate Impact Research, Climate Systems Department, GERMANY | anders.levermann@pik-potsdam.de |
| Löptien Ulrike | Max-Planck-Institut für Meteorologie, GERMANY | loeptien@dkrz.de |
| Losch Martin | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | mlosch@awi-bremerhaven.de |
| Lu Youyu | Ocean Sciences Division, Department of Fisheries and Oceans, Bedford Institute of Oceanography, CANADA | LuY@mar.dfo-mpo.gc.ca |
| Macke Andreas | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | amacke@ifm-geomar.de |
| Macrander Andreas | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | amacrander@ifm-geomar.de |
| Marotzke Jochem | Max-Planck-Institut für Meteorologie, GERMANY | marotzke@dkrz.de |
| Martin Thomas | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | tmartin@ifm-geomar.de |
| Marzeion Ben | Nansen Environmental and Remote Sensing Center, NORWAY | ben.marzeion@nersc.no |
| Maslowski Wieslaw | Department of Oceanography, Naval Postgraduate School, USA | maslowsk@nps.edu |
| Mauritzen Cecilie | Norwegian Meteorological Institute, NORWAY | C.Mauritzen@met.no |
| Meincke Jens | Institut für Meereskunde, Universität Hamburg, GERMANY | meincke@ifm.uni-hamburg.de |
| Mercier Herle | IFREMER, DRO/DOPS/Laboratoire de Physique des Océans, FRANCE | herle.mercier@ifremer.fr |
| Merkel Ute | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | umerkel@ifm-geomar.de |
| Mertens Christian | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | cmertens@physik.uni-bremen.de |

| | | |
|---|---|---|
| Mignot Juliette | Potsdam Institute for Climate Impact Research, Climate Systems Department, GERMANY | juliette.mignot@pik-potsdam.de |
| Möller Jens | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jmoeller@ifm-geomar.de |
| Molinari Robert | NOAA/AOML, USA | molinari@aoml.noaa.gov |
| Molines Jean-Marc | Laboratoire des Ecoulements Géophysiques et Industriels (LEGI /CNRS) FRANCE | Jean-Marc.Molines@hmg.inpg.fr |
| Moll Andreas | Institut für Meereskunde, Universität Hamburg, GERMANY | moll@ifm.uni-hamburg.de |
| Myers Paul G. | Department of Earth and Atmospheric Sciences, 1-26 ESB, University of Alberta, CANADA | pmyers@ualberta.ca |
| Nerger Lars | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | lnerger@awi-bremerhaven.de |
| Oka Akira | Center for Climate System Research, University of Tokyo, JAPAN | akira@ccsr.u-tokyo.ac.jp |
| Okada Naosuke | National Institute for Environmental Studies (NIES), JAPAN | okada.shuhei@nies.go.jp |
| Olsen Steffen M. | Danish Meteorological Institute, DENMARK | smo@dmi.dk |
| Østerhus Svein | Bjerknes Centre for Climate Research, NORWAY | nqtso@uib.no |
| Pätsch Johannes | Institut für Meereskunde, Universität Hamburg, GERMANY | paetsch@ifm.uni-hamburg.de |
| Pardaens Anne | Met Office, Hadley Centre for Climate Prediction and Research, UK | anne.pardaens@metoffice.com |
| Park Wonsun | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | wpark@ifm-geomar.de |
| Penduff Thierry | Laboratoire des Ecoulements Geophysiques et Industriels, FRANCE | thierry.penduff@hmg.inpg.fr |

| | | |
|---|---|---|
| Pfeiffer Miriam | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mpfeiffer@ifm-geomar.de |
| Pohlmann Holger | Max-Planck-Institut für Meteorologie, GERMANY | holger.pohlmann@dkrz.de |
| Quadfasel Detlef | Institut für Meereskunde, Universität Hamburg, GERMANY | quadfasel@ifm.uni-hamburg.de |
| Rabe Benjamin | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | brabe@ifm-geomar.de |
| Rhein Monika | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | mrhein@physik.uni-bremen.de |
| Ruprecht Eberhard | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | eruprecht@ifm-geomar.de |
| Saenko Oleg A. | Canadian Centre for Climate Modelling and Analysis University of Victoria CANADA | oleg.saenko@ec.gc.ca |
| Sakamoto Takashi | National Institute for Environmental Studies (NIES), JAPAN | sakamoto.shigeko@nies.go.jp |
| Scheinert Markus | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mscheinert@ifm-geomar.de |
| Schlichtholz Pawell | Institute of Oceanology, POLAND | schlicht@iopan.gda.pl |
| Schmidt Claudia | NOAA Office of Global Programs, USA | claudia.schmidt@noaa.gov |
| Schmidt Sunke | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | sschmidt@ifm-geomar.de |
| Schmith Torben | Danish Meteorological Institute, Climate Research Division, DENMARK | ts@dmi.dk |
| Schmittner Andreas | Institut für Geowissenschaften, Universität Kiel, GERMANY | andreas@passagen.uni-kiel.de |
| Schoenefeldt Rena | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | rschoenefeldt@ifm-geomar.de |

| | | |
|---|---|---|
| Schott Friedrich | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | fschott@ifm-geomar.de |
| Schröter Jens | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | jschroete@awi-bremerhaven.de |
| Schweckendiek Ulf | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | uschweckendiek@ifm-geomar.de |
| Semenov Vladimir | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | vsemenov@ifm-geomar.de |
| Serra Nuno | Institute of Oceanography, Faculty of Sciences of the University of Lisbon (FCUL), PORTUGAL | nserra@fc.ul.pt |
| Shoosmith Deb | Rosenstiel School of Marine and Atmospheric Science, USA | dshoosmith@rsmas.miami.edu |
| Siedler Gerold | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | gsiedler@ifm-geomar.de |
| Sidorenko Dmitry | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | dsidorenko@awi-bremerhaven.de |
| Sirven Jerome | LODYC (Laboratoire d`Oceanographie Dynamique et de Climatologie), Universite Pierre et Marie Curie, FRANCE | sirven@lodyc.jussieu.fr |
| Srokosz Meric | Southampton Oceanography Centre, UK | mas@soc.soton.ac.uk |
| Stammer Detlef | Institut für Meereskunde, Uni Hamburg, GERMANY | stammer@ifm.uni-hamburg.de |
| Stanitski Diane | Office of Climate Observation, NOAA Office of Global Programms USA | diane.stanitski@noaa.gov |
| Steinfeldt Reiner | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | rsteinf@physik.uni-bremen.de |
| Stocker Thomas | Climate and Environmental Physics, University of Bern, SWITZERLAND | stocker@climate.unibe.ch |
| Stramma Lothar | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | lstramma@ifm-geomar.de |

| | | |
|---|---|---|
| Straneo Fiamma | Woods Hole Oceanographic Institution, USA | fstraneo@whoi.edu |
| Sutton Rowan | Department of Meteorology, University of Reading, UK | rowan@met.reading.ac.uk |
| Tanhua Toste | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | ttanhua@ifm-geomar.de |
| Theetten Sébastien | IFREMER, DRO/DOPS/Laboratoire de Physique des Océans, FRANCE | theetten@ifremer.fr |
| Thierry Virginie | IFREMER, DRO/DOPS/Laboratoire de Physique des Océans, FRANCE | Virginie.Thierry@ifremer.fr |
| Thoma Inger | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | ithoma@ifm-geomar.de |
| Todd James F. | Office of Climate Observation, NOAA Office of Global Programms, USA | james.todd@noaa.gov |
| Treguier Anne-Marie | IFREMER, DRO/DOPS/Laboratoire de Physique des Océans, FRANCE | anne.marie.treguier@ifremer.fr |
| Vellinga Michael | Met Office, Hadley Centre for Climate Prediction and Research, UK | michael.vellinga@metoffice.gov.uk |
| Visbeck Martin | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | mvisbeck@ifm-geomar.de |
| Wallace Douglas | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | dwallace@ifm-geomar.de |
| Walter Maren | Institut für Umweltphysik, Abt. Ozeanographie, Universität Bremen, GERMANY | mwalter@physik.uni-bremen.de |
| Wenzel Manfred | Alfred-Wegener-Institut für Polar- und Meeresforschung, GERMANY | mwenzel@awi-bremerhaven.de |
| Wieczorek Gunda | BSH Hamburg, GERMANY | gunda.wieczorek@bsh.de |
| Willebrand Jürgen | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | jwillebrand@ifm-geomar.de |

| | | |
|---|---|---|
| Williams Paul D. | Centre for Global Atmospheric Modelling, Department of Meteorology, University of Reading, UK | p.d.williams@reading.ac.uk |
| Wood Richard | Met Office, Hadley Centre for Climate Prediction and Research, UK | richard.wood@metoffice.com |
| Wunsch Carl | MIT , Dept of Earth, Atm. & Plan Sciences, USA | cwunsch@mit.edu |
| Yang Duo | University of Alberta, Department of Earth and Atmospheric Sciences, CANADA | duo@ualberta.ca |
| Zantopp Rainer | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | rzantopp@ifm-geomar.de |
| Zenk Walter | Leibniz-Institut für Meereswissenschaften Kiel, GERMANY | wzenk@ifm-geomar.de |
| Zhu Xiuhua | Max-Planck-Institut für Meteorologie, GERMANY | xiuhua@dkrz.de |
| Zickfeldt Kirsten | Potsdam Institute for Climate Impact Research (PIK), GERMANY | Kirsten.Zickfeld@pik-potsdam.de |

**International CLIVAR Project Office**
**National Oceanography Centre**
**European Way**
**Empress Doc**
**Southampton, SO14 3ZH**
**United Kingdom**

**Tel: +44 (0) 2380 596 777**
**Fax: +44 (0) 2380 596 204**
**Email: icpo@noc.soton.ac.uk**