The Influence of Vertical Mixing on the Stability of the Atlantic Meridional Overturning Circulation

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Contents

Preface

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

In the first part, an introduction is given to the main questions addressed in this thesis. The papers are summarized and a synthesis of the conclusions is presented. This overview part ends with a discussion and an outlook on future work.

The second part consists of three papers submitted to, or published by, international peer reviewed journals. These papers are:

- **Paper I:** Marzeion, B., and H. Drange, 2006: Diapycnal Mixing in a Conceptual Model of the Atlantic Meridional Overturning Circulation, *Deep Sea Research Part II* 53, 226-238
- **Paper II:** Marzeion, B., A. Levermann, and J. Mignot, 2006: The Role of Stratification-dependent Mixing for the Stability of the Atlantic Overturning in a Global Climate Model, revised manuscript resubmitted to *Journal of Physical Oceanography*
- **Paper III:** Marzeion, B., A. Levermann, and J. Mignot, 2006: Stratification-dependent Mixing May Decrease Stability of Atlantic Overturning under Global Warming, manuscript submitted to *Geophysical Research Letters*

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Chapter 1

Overview

1.1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a vertical circulation loop that becomes evident when the meridional volume transports in the Atlantic Ocean are integrated zonally. It spans the entire Atlantic Ocean, connecting it through exchange of water masses with the Southern Ocean to the Indian and Pacific Oceans. At surface, warm waters flow northwards, whereas there is a return flow of cold and dense waters at depth. Regions of formation of dense water masses are found at the high northern latitudes. These newly formed water masses are fed by the northward transport of water at the surface, and constitute the deep, southward return flow. In low latitudes and in the Southern Ocean, the loop is closed by upwelling of deep water through the pycnocline. While the regions of downward motion are thought to be highly localized (Marshall and Schott 1999), the upward motion is generally considered to be more widely distributed over all ocean basins (Stommel and Aarons 1960), although it has been shown that the upwelling may be particularly strong close to the ocean margins and to rough topography (Moum et al. 2002; Garabato et al. 2004). In the following, a brief overview of the forcing mechanisms of the AMOC and its influence on the global climate system is given.

1.1.1 Influence of the AMOC on the State of the Climate System

Due to its astronomic setting, the earth receives most of the solar insulation in the low latitudes around the equator. Atmospheric and oceanic circulation cells transport part of the heat polewards, reducing the equator-to-pole temperature gradient. The AMOC constitutes an asymmetry of the meridional circulation of the Atlantic, leading to a cross-equatorial transport of heat of about 1 PW and a maximum transport of heat of about 1.3 PW around 25°N (Hall and Bryden 1982; Ganachaud and Wunsch 2000; Trenberth and Caron 2001). This asymmetry has several impacts on the Atlantic climate, such as a northward shift of the Intertropical Convergence Zone (ITCZ) over the Atlantic Ocean (Vellinga and Wood 2002). Further north, the oceanic heat transport has a strong impact on the climate of northwestern Europe: powered by relatively warm sea surface temperatures, winter low pressure systems bring moist and warm air into the northeast Atlantic, resulting in a European climate that is ∼15 K warmer than at comparable latitudes in North America (Drange et al. 2005; Pohlmann et al. 2006). Sutton and Hodson (2005) show that multidecadal variations of the AMOC strongly influence North American, European, and North African Climate.

By having a global effect on the thermocline depth, a weakening of the AMOC may surpress El Niño-Southern Oscillation (Timmermann et al. 2005). Zhang and Delworth (2005) on the other hand identify the southward shift of the ITCZ following a weakening of the AMOC to cause changes in the atmospheric circulation, resulting in an El Niño-like warming pattern in the eastern tropical Pacific. However, they do not discuss interannual variability. Furthermore, changes in the strength of the AMOC may have strong effects on the marine ecosystem of the Atlantic (Schmittner 2005), and on the North Atlantic sea level (Levermann et al. 2005).

The Role of the AMOC in Past Climate

Climate records from natural archives, such as ice cores (e.g. Petit et al. 1999; Johnsen et al. 2001; EPICA community members 2004) and ocean sediments (e.g. Bond et al. 1992; McManus et al. 2004), indicate that the climate system exhibited strong fluctuations during glacial times, known as Dansgaard/Oeschger (D/O) oscillations (millenial-scale climate fluctuations occurring during the last glacial maximum with the highest amplitude in the North Atlantic region) and Heinrich events, that were not present during interglacials. A number of mechanisms, often involving reorganisations of the AMOC, have been suggested to explain these abrupt climate changes.

For D/O oscillations, Weaver et al. (1998) suggested a mechanisms internal to the ocean to explain the observed variability. More recently, D/O oscillations were reproduced by coupled climate models using external, weak and noisy (Ganopolski and Rahmstorf 2002) or strong (Timmermann et al. 2003; Knutti et al. 2004) freshwater forcing. Gildor and Tziperman (2003) propose a switch-like behavior of sea-ice to cause changes in the AMOC, while van Kreveld et al. (2000) and Wang and Mysak (2001) suggest a mechanism of ocean-ice sheet interaction.

Heinrich events, characterized by a layer of ice-rafted debris in a belt of the North Atlantic ocean stretching from Labrador to the eastern Atlantic, coincide with particularly cold episodes in Greenland and warm anomalies in the southern hemisphere (Blunier et al. 1998; Stocker 1998). They are thought to be caused by partial collapses of the Laurentide ice shield, discharging a large amount of icebergs into the Labrador Sea. The associated release of melt water could have led to a strong reduction or even to a complete shut down of the formation of dense water in the North Atlantic (Elliot et al. 2002). Numerous model studies confirm that this would lead to a significantly reduced oceanic northward transport of heat and a warming of the southern hemisphere (Stocker and Wright 1991; Manabe and Stouffer 1995; Stouffer et al. 2006). Both internal ice sheet processes and external control mechanisms have been proposed as triggers of Heinrich events. Flückiger et al. (2006) suggest a feedback between sea level rise following a weakening of the AMOC and ice sheet instability, while Arbic et al. (2004) identify changes in the tidal amplitude as a possible reason for iceberg discharges into the North Atlantic.

Possible Implications for the Future Climate

Even though future climate simulations differ depending on the model and the greenhouse-gas emission scenario used, they have two robust features: a warming of the lower atmosphere, and a strengthening of the hydrological cycle (Cubasch et al. 2001). While the atmospheric and associated oceanic surface warming increases the stratification everywhere, the strengthening of the hydrological cycle reduces the stratification in low latitudes where evaporation exceeds precipitation, and increases it at the high latitudes, where precipitation exceeds evaporation. Further freshening of the high northern latitudes could be caused by melting of sea-ice, and potentially increased meltwater runoff from the continental ice sheet of Greenland (Fichefet et al. 2003; Peterson et al. 2006). The increasing stratification of the upper ocean has the potential to reduce the formation of dense water, leading to a reduction of the AMOC and a weakened oceanic northward heat transport. However, there is a strong disagreement between different models on how strong the reduction of the AMOC may be (in the range of 0 to 14 Sv in Cubasch et al. 2001). Recent results from idealized experiments (not taking into account increased meltwater input from continental ice) indicate that the increase of stratification from warming may play a stronger role in reducing the formation of dense water than the increased freshwater input that results from the spin-up of the hydrological cycle (Gregory et al. 2006). Furthermore, there are indications that a reduction of the AMOC will result in a reduction of the oceanic CO_2 uptake (Sarmiento and Le Quéré 1996).

1.1.2 Driving and Modulation Mechanisms

Two distinct processes, diapycnal mixing of heat and salt, and wind-driven upwelling in the Southern Ocean, are currently considered as driving mechanisms of the AMOC, while formation of dense water at high northern latitudes can be considered to modulate the strength and shape of the AMOC (Wunsch and Ferrari 2004; Kuhlbrodt et al. 2006). Below, these three processes will be discussed in more detail.

Diapycnal Mixing

Downward mixing of heat raises the center of mass in a stably stratified water column, and thus increases its potential energy, while convective mixing of an unstably stratified water column reduces the potential energy. At steady state, the downward mixing of heat is balanced by a broad upwelling motion, connecting the branches of shallow, northward flow of light surface waters, densification and sinking in high latitudes, and the deep southward return flow to form the overturning loop.

Following the advective-diffusive scaling, it is therefore the diapycnal diffusivity that sets the equilibrium rate of overturning in a stratified ocean (Bryan 1987). The energy required for diapycnal mixing is thought to be about equally provided by winds and tides (Munk and Wunsch 1998). Estimates of open ocean dissipation from altimetry data (Egbert and Ray 2000) match the energetic requirements for sustaining the observed overturning circulation (Wunsch and Ferrari 2004) reasonably well. However, direct measurements of open ocean diffusion (Oakey et al. 1994; Gregg et al. 2003) and estimates obtained from hydrographic sections (Talley et al. 2003) indicate that diapycnal diffusion may only account for part of the upwelling needed to close the overturning loop. Southern Ocean winds may contribute the remainder, as outlined below.

Southern Ocean Winds

Strong westerly circumpolar winds cause a northward Ekman flux of surface waters into the Atlantic Ocean. Because the periodic boundary conditions prevent geostrophically balanced meridional flow above the sill depth of ∼2000 m at the latitude of the Drake Passage, the southward return flow has to take place below the sill depth, and may contribute to the AMOC (Toggweiler and Samuels 1995). However, as pointed out by Rintoul et al. (2001) and Hallberg and Gnanadesikan (2006), a considerable fraction of the changes in the northward Ekman flux caused by fluctuations in the wind field may be returned locally by strong eddies formed in the Antarctic Circumpolar Current, which implies that the Ekman flux may not necessarily be connected with upwelling of water from depth. It may be difficult to conclude on the relative importance of Southern Ocean winds and low latitude diffusion for the AMOC from data, since the hydrographic structures of wind-driven and diffusion driven overturning circulations might be nearly indistinguishable (Samelson 2004).

Formation of Dense Water in the North Atlantic

From an energetic point of view, the formation of dense water, i. e. mixing of the water column following unstable stratification caused by buoyancy loss at the surface, does not contribute to maintaining the overturning circulation on long timescales. It does however play an important role in shaping and modulating the circulation system (Bentsen et al. 2004; Hansen et al. 2004). By setting the properties of the deep water below the pycnocline, dense water formation creates the density gradients across which diapycnal diffusion acts to power the overturning. Also, the location and rate of dense water formation has strong influence on the uptake and distribution of tracers like CO_2 (Doney et al. 2004). There are also numerous numerical studies showing that inhibiting dense water formation will have strong impact on the overturning circulation (e. g. Manabe and Stouffer 1993; Schmittner and Stocker 1999; Otterå et al. 2004; Stouffer et al. 2006).

Antarctic Bottom Water

In the southern hemisphere, dense water is formed on the shelfs surrounding the Antarctic continent. The dense waters enter then the deep Atlantic Ocean under the influence of strong entrainment, forming the Antarctic Bottom Water (AABW). The latter is, as a consequence of the thermobaric effect, found beneath the lower limb of the AMOC. Evidence from paleodata (Stocker 1998) and model studies (Fieg and Gerdes 2001) suggest that the

AABW cell is anticorrelated to the AMOC, forming a interhemispheric seesaw. Recent modeling studies however suggest a more complex behavior. Brix and Gerdes (2003) find the AMOC and AABW cells to respond in phase, albeit with different timescales, to changes in the wind forcing. Changes in the buoyancy forcing excited a seesaw-like behavior only when applied to the North Atlantic, and not when applied to the areas of AABW formation.

1.2 Objectives

While the importance of diapycnal mixing for the existence of a meridional overturning circulation and thus the density structure of the deep ocean have long been recognized (it can be derived e. g. from the findings by Sandström 1908), it was not until recently that the role of stratification for diapycnal diffusion has been recognized in ocean modeling. Gargett and Holloway (1984) and Gregg (1989) suggested that the rate of energy dissipation should scale with the local stratification. Based on this scaling, Nilsson and Walin (2001) discovered a potential feedback between mixing and stratification that could fundamentally alter the response of the overturning circulation to changes in the buoyancy forcing. While constant vertical mixing always leads to a weakening of the overturning in response to freshwater forcing, the associated weakening of the stratification may lead to increased mixing, and thus an increased overturning when stratification dependent mixing is employed.

The aim of this study is not to argue for the relative importance of Southern Ocean winds or diapycnal mixing as the drivers of the AMOC. Instead, the role of different parameterizations of diapycnal diffusion for the sensitivity of the AMOC is addressed, and the effect of Southern Ocean winds is included in all experiments for completeness of the system.

Specifically, the aims of this study are

- to further explore the mechanisms and the potential of the feedback suggested by Nilsson and Walin (2001) and Nilsson et al. (2003) in the idealized and conceptual context of a box model (paper I).
- to extend the study by employing stratification-dependent mixing in a general circulation model in an attempt to evaluate the validity of the assumptions and simplifications made in the previous idealized

studies, and adding the potential of additional effects of stratification-dependent mixing (paper II).

- to test the potential effects of stratification-dependent mixing in a warming future climate by employing it in a coupled climate model under increasing greenhouse-gas forcing (paper III).

The results of the study are summarized in the following section.

1.3 Summary of the Papers

1.3.1 Paper I: Diapycnal Mixing in a Conceptual Model of the Atlantic Meridional Overturning Circulation

Time-dependency is added to the 3-box model of Gnanadesikan (1999), and a bilinear equation of state is included. The diapycnal diffusivity $\varkappa$ between the shallow, warm and salty pycnocline box and the underlying deep, cold and fresh box representing the North Atlantic Deep Water is calculated as $\varkappa \sim N^{-\alpha}$. Here, N is the buoyancy frequency calculated using the pycnocline depth as the vertical scale, and α is a free parameter. In this setting, the two regimes of the overturning circulation identified by Nilsson and Walin (2001) are found to be separated by a critical value of $\alpha \approx 0.7$. Also the response of the northward heat transport is found do depend on the value of α, as is the change in temperature of the northern (and deep) box. In total, four regimes are identified, separated by critical values of α:

For small values of α, both the overturning, the northward heat transport, and the northern temperature decrease in response to an increased freshwater flux into the northern box. At slightly higher values of α, the response of the heat transport changes its sign, as it increases with increased freshwater forcing, while the AMOC is still decreasing. Then, the “freshwater-boosted” regime of Nilsson and Walin (2001) is reached. Finally, at high values of α, a change of sign occurs in the response of the temperature of the northern, deep box.

A study of the sensitivity of the results reveals their dependence on the forcing parameters of the model. This dependency is strongest for the critical values of α that separate the responses of the northern temperature and northward heat transport, which strongly indicates the need to employ a coupled General Circulation Model (GCM) to verify and possibly extend the obtained results.

1.3.2 Paper II: The Role of Stratification-dependent Mixing for the Stability of the Atlantic Overturning in a Global Climate Model

Stratification-dependent mixing is implemented into the model CLIMBER-3α (Montoya et al. 2005) by applying the parameterization as described above. The sensitivity of the model system is tested for different values of α by adding anomalous freshwater fluxes of 0.1 and 0.2 Sv into the North Atlantic. Opposed to the results from previous studies, the overturning is reduced by the enhanced freshwater flux for all values of α. The amplitude of the reduction is found to depend critically on α.

The lack of an equivalent of the freshwater-boosted regime in this model is explained by the presence of mixed boundary conditions at the surface: The box models of Nilsson and Walin (2001) and Marzeion and Drange (2006) include both temperature and salinity, but they assume a homogeneous distribution of these two tracers within the North Atlantic Deep Water box, as it is required to obtain the advective-diffusive scaling from which the model formulation was derived. It is argued that the assumption of a homogeneous distribution is invalid, because there is no direct coupling between surface salinity and freshwater fluxes. This is in contrast to the situation for temperature, where the warming of the ocean surface causes a decrease in the heat flux. The enhanced freshwater forcing at steady state sets up a salinity gradient between the surface water of the high northern latitudes of the Atlantic Ocean and the deep water at low latitudes, which could not be captured in the box models. Nilsson et al. (2003) on the other hand used an ocean GCM with a linear equation of state which depends on temperature only. This is in accordance with the assumption of homogeneity, and thus they found results that were in agreement with the box model.

The enhanced sensitivity of the AMOC to changes in the freshwater forcing for high values of α is explained by a feedback between stratification and mixing: The initial decrease of surface salinity causes stratification. This stratification decreases the vertical mixing, the amplitude of the decrease being stronger for higher values of α. This decrease in the vertical mixing causes the salinity anomaly to be confined to the surface for high values of α, up to a point where the salinity anomaly in the surface inhibits new formation of deep waters during winter. Once this regime occurs, the freshwater is not removed from the surface layers anymore, and it gets carried over into the next year. As a result, depending on α, dense water formation in the Nordic Seas is merely weakened or stopped by the freshwater forcing.

1.3.3 Paper III: Stratification-dependent Mixing May Decrease Stability of Atlantic Overturning under Global Warming

The same model system as in Marzeion et al. (2006a) is used to study the effect of stratification-dependent mixing on the stability on the AMOC under an idealized CO_2 increase scenario. Also here, the AMOC weakens for all values of α during the transient phase of CO_2 concentration increase. The two regions where dense water formation occurs in the model are influenced differently by the warming: In the Nordic Seas, the formation of dense water is initially weakened, but starts to recover as sea ice melts and a greater ocean surface is exposed to the atmospheric fluxes. The timescale of the recovery depends on α, because α influences the amount of buoyancy stored in the upper ocean layers during summer by controlling the diffusive exchange with the underlying water masses. In the Irminger Sea, the dense formation water is less influenced by changes in sea ice cover, and a similar mechanism as found in Marzeion et al. (2006a) is observed: This time, the surface warming is enhanced by high values of α limiting the diffusion to the deep ocean.

Two modes of the AMOC result at the equilibrium state under increased CO_2 levels: Low values of α yield increased rates of formation of dense water in the Nordic Seas and slightly weakened formation of dense water in the subpolar gyre, whereas high values of α imply increased rates of dense water formation in the Nordic Seas but nearly no dense water formation in the subpolar gyre.

1.4 Main Conclusions

The main conclusions of the papers constituting this study can be summarized as follows:

- Introducing stratification-dependent mixing into an ocean model has the potential to fundamentally alter the stability properties of the A-MOC to changes in heat and freshwater fluxes.

- The freshwater boosted regime caused by changes to the diffusivity across the pycnocline in box models and in idealized GCMs may not be found in realistic coupled climate models.
- In the areas where dense water is formed, a feedback between stratification and diffusion might have the potential to increase the sensitivity of the AMOC to perturbations in the forcing.

1.5 Discussion

1.5.1 A Cautionary Note on the Interpretation of Model Results

The Role of Model Complexity

Often, a realistic simulation of the climate system, and subsequently an accurate prediction of its future evolution, are seen as the ultimate aim in climate modeling. For this purpose, comprehensive climate models of great complexity are the common tool. However, a distinction has to be drawn between efforts trying to simulate the evolution of the climate system and efforts trying to understand its functioning. Obviously, there is a great need for comprehensive simulations and predictions of the future climate. Understanding of complex dynamical systems like the climate system is, however, often gained by relating them to systems of lesser complexity. Therefore, there is also a need for reduced complexity models, and for idealized experiments as the ones presented in this study (Held 2005).

In fact, understanding of the climate system can be greatly improved by discussing models that are unrealistic, or that even turn out to be incorrect. This implies that one has to be utterly careful with directly transferring results from these kind of experiments into the real world.

Equilibrium and Transient States

The results presented in Marzeion and Drange (2006) provide an example with potential for this fallacy: Only the equilibrium states of the model are thoroughly discussed. Doing so simplifies the discussion considerably, and is justified as a measure to comprehend the mechanisms governing the model on hand. For the real climate system, however, the discussion of equilibrium states may be of very limited use, since in nonlinear systems it is in general impossible to conclude on the transient behavior by looking at the equilibrium state. In this example, variations of the parameter α implied very different responses of the model system to changes in freshwater forcing in the equilibrium state, while the transient states initially developed in a very similar manner. The reason for this difference is that the equilibrium response hides processes acting and interacting on different timescales (in this case the advective and diffusive timescales). Ignoring the transient behavior could lead to fundamentally wrong conclusions about the meaning and implications of the modeling results.

Parameterizations in Climate Models

As we learn more about the climate system, the complexity of comprehensive ocean-atmosphere models grows: While increasing computational resources enable finer model resolution, which redundantizes parameterizations of subgridscale processes, the discovery of effects from other unrepresented processes causes the inclusion of appropriate parameterizations. Usually this is associated with an increase in the dimension of the parameter space (even though improved understanding of processes may eventually lead to the replacement of parameters with their physical representation). As a result, improvement in the numerical representation of the climate system does not necessarily cause a stronger concurrence of future climate predictions.

This may sometimes hide the progress that is being made in understanding the functioning of the climate system, but it ultimately only reveals the uncertainty that was concealed before.

1.5.2 Future Perspectives

The results presented in this study can only be a first step towards understanding the possible role of stratification-dependent mixing for the stability of the AMOC. They give a hint that models that do not take into account the effect of changes in stratification on diapycnal diffusion may miss an important mechanism of ocean variability, but leave many questions untouched.

One of the untouched questions is the role of ocean-atmosphere coupling.

While the studies in Marzeion et al. (2006a) and Marzeion et al. (2006b) are based on a coupled model system, the implications of the coupling have not been investigated. In Marzeion et al. (2006a), the reduction of the AMOC and the northward oceanic heat transport caused a warming in the shallow waters of the low latitude Atlantic Ocean. While freshwater anomalies at the surface were transported southward from the high latitudes by the subtropical gyre, there was no evidence of freshening in the region of the warm anomaly. This might be caused by enhanced evaporation, which compensates for the freshening in this region, possibly weakening the observed increase in stratification, and thus reducing the effect on diapycnal diffusion. Also, atmospheric coupling might enhance the warm anomaly that causes the halt in formation of dense water in the Irminger Sea (Marzeion et al. 2006b) by further reducing the ocean-atmosphere heat flux as a result of a decreased temperature difference between upper ocean and lower atmosphere.

Ocean microscale measurements of diffusion do not agree on a typical value of α (Sarmiento et al. 1976; Hoffert and Broecker 1978; Rehmann and Duda 2000; Fer et al. 2004). This reflects the deficiency of the parameterization used in this study to capture the full response of diffusion to changes in the ocean state, and it also illustrates that a typical value for α will likely have a spatial and temporal dependency. A large fraction of the diapycnal diffusion is powered by tidal dissipation (Munk and Wunsch 1998), which depends strongly on topography. This allows for speculation that the sensitivity of the AMOC to forcing perturbations may vary strongly over glacial cycles, which have a strong influence on ocean topography by altering the sea level by ∼150 m.

Also, it has to be shown whether the mechanisms observed in CLIMBER-3α are robust in a number of different model environments and different experimental designs.

References

Arbic, B. K., D. R. MacAyeal, J. X. Mitrovica, and G. A. Milne, 2004: Palaeoclimate: Ocean tides and Heinrich events. *Nature*, **432**, 460.

Bentsen, M., H. Drange, T. Furevik, and T. Zhou, 2004: Simulated variability of the Atlantic Meridional Overturning Circulation. *Climate Dynamics*, **22**, 701–720.

Blunier, T., J. Chappellaz, J. Schwander, A. Dällenbach, B. Stauffer, T. F. Stocker, D. Raynaud, J. Jouzel, H. B. Clausen, C. U. Hammer, and S. J. Johnson, 1998: Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature*, **394**, 739–743.

Bond, G., H. Heinrich, W. Broecker, L. Labeyrie, J. McManus, J. Andrews, S. Huonparallel, R. Jantschik, S. Clasen, C. Simet, K. Tedesco, M. Klas, G. Bonani, and S. Ivy, 1992: Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. *Nature*, **360**, 245–290.

Brix, H. and R. Gerdes, 2003: North Atlantic Deep Water and Antarctic Bottom Water: Their interaction and influence on the variability of the global ocean circulation. *Journal of Geophysical Research*, **108**, 3022, doi:10.1029/2002JC001335.

Bryan, F., 1987: Parameter Sensitivity of Primitive Equation Ocean General Circulation Models. *Journal of Physical Oceanography*, **17**, 970–986.

Cubasch, U., G. Meehl, G. Boer, R. Stoffer, M. Dix, A. Noda, C. Senior, S. Raper, and K. Yap: 2001, Projections of future climate change. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. Houghton, Y. Ding, D. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C. Johnson, eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 525–582.

Doney, S. C., K. Lindsay, K. Caldeira, J.-M. Campin, H. Drange, J.-C. Dutay, M. Follows, Y. Gao, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, G. Madec, E. Maier-Reimer, J. C. Marshall, R. J. Matear, P. Monfray, A. Mouchet, R. Najjar, J. C. Orr, G.-K. Plattner, J. Sarmiento, R. Schlitzer, R. Slater, I. J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2004: Evaluating global ocean carbon models: the importance of realistic physics. *Global Biogeochemical Cycles*, **18**, BG3017.

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

Egbert, G. and R. D. Ray, 2000: Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. *Nature*, **405**, 775–778.

Elliot, M., L. Labeyrieb, and J. C. Duplessy, 2002: Changes in North Atlantic deep-water formation associated with the Dansgaard-Oeschger temperature oscillations (60-10 ka). *Quaternary Science Reviews*, **21**, 1153–1165.

EPICA community members, 2004: Eight glacial cycles from an Antarctic ice core. *Nature*, **429**, 623–628.

Fer, I., R. Skogseth, and P. M. Haugan, 2004: Mixing of the Storfjorden overflow (Svalbard Archipelago) inferred from density overturns. *Journal of Geophysical Research*, **109**, doi:10.1029/2003JC001968.

Fichefet, T., C. Poncin, H. Goosse, P. Huybrechts, I. Janssens, and H. L. Treut, 2003: Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century. *Geophysical Research Letters*, **30**, 1911.

Fieg, K. and R. Gerdes, 2001: Sensitivity of the thermohaline circulation to modern and glacial surface boundary conditions. *Journal of Geophysical Research*, **106**, 6853Ű 6867.

Flückiger, J., R. Knutti, and J. White, 2006: Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events. *Paleoceanography*, **21**, A2014+.

Ganachaud, A. and C. Wunsch, 2000: Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, **408**, 453–456.

Ganopolski, A. and S. Rahmstorf, 2002: Abrupt glacial climate changes due to stochastic resonance. *Physical Review Letters*, **88**, 038501–1–4.

Garabato, A., K. L. Polzin, B. A. King, K. J. Heywood, and M. Visbeck, 2004: Widespread intense turbulent mixing in the Southern Ocean. *Science*, **303**, 210–213.

Gargett, A. E. and G. Holloway, 1984: Dissipation and diffusion by internal wave breaking. *Journal of Marine Research*, **42**, 15–27.

Gildor, H. and E. Tziperman, 2003: Sea-ice switches and abrupt climate change. *Philosophical Transactions of the Royal Society of London*, **361**, 1935–1940.

Gnanadesikan, A., 1999: A Simple Predictive Model for the Structure of the Oceanic Pycnocline. *Science*, **283**, 2077–2079.

Gregg, M., T. Sanford, and D. Winkel, 2003: Reduced mixing from the breaking of internal waves in equatorial waters. *Nature*, **422**, 513–515.

Gregg, M. C., 1989: Scaling turbulent dissipation in the thermocline. *Journal of Geophysical Research*, **94**, 9686–9698.

Gregory, J. M., K. W. Dixon, R. J. Stouffer, A. J. Weaver, E. Driesschaert, M. Eby, T. Fichefet, H. Hasumi, A. Hu, J. H. Jungclaus, I. V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawratha, A. Oka, A. P. Sokolov, and R. B. Thorpe, 2006: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration. *Geophysical Research Letters*, **32**, L12703.

Hall, M. and H. Bryden, 1982: Direct estimates and mechanisms of ocean heat transport. *Deep-Sea Research*, **29**, 339–359.

Hallberg, R. and A. Gnanadesikan: 2006, The role of eddies in determining the structure and response of the wind-driven southern hemisphere overturning: Results from the Modeling Eddies in the Southern Ocean Project, Journal of Physical Oceanography, in press.

Hansen, B., S. Østerhus, D. Quadfasel, and W. Turrell, 2004: Already the Day After Tomorrow? *Science*, **305**, 953–954.

Held, I. M., 2005: The gap between simulation and understanding in climate modeling. *Bulletin of the American Meteorolical Society*, **86**, 1609–1614.

Hoffert, M. I. and W. S. Broecker, 1978: Apparent vertical eddy diffusion rates in the pycnocline of the Norwegian Sea as determined from the vertical distributium of tritium. *Geophysical Research Letters*, **5**, 502–504.

Johnsen, S. J., D. Dahl-Jensen, N. Gundestrup, J. P. Steffensen, H. B. Clausen, H. Miller, V. Masson-Delmotte, A. E. Sveinbjörnsdottir, and

J. White, 2001: Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quarternary Science*, **16**, 299–307.

Knutti, R., J. Flückiger, T. F. Stocker, and A. Timmermann, 2004: Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation. *Nature*, **430**, 842–843.

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf: 2006, On the driving processes of the Atlantic meridional overturning circulation, Reviews of Geophysics, under revision.

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

Manabe, S. and R. Stouffer, 1995: Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature*, **378**, 165–167.

Manabe, S. and R. J. Stouffer, 1993: Century-scale effects of increased atmospheric CO2 on the ocean-atmosphere system. *Nature*, **364**, 215–218.

Marshall, J. and F. Schott, 1999: Open-Ocean Convection: Observations, Theory, and Models. *Reviews of Geophysics*, **37**, 1–64.

Marzeion, B. and H. Drange, 2006: Diapycnal Mixing in a Conceptual Model of the Atlantic Meridional Overturning Circulation. *Deep-Sea Research Part II*, **53**, 226–238.

Marzeion, B., A. Levermann, and J. Mignot: 2006a, The role of stratification-dependent mixing for the stability of the Atlantic overturning in a global climate model, *Journal of Physical Oceanography*, under revision.

— 2006b, Stratification-dependent mixing may decrease stability of Atlantic overturning under global warming, submitted to *Geophysical Research Letters*.

McManus, J. F., R. Francois, J. Gherardi, L. D. Keigwin, and S. Brown-Leger, 2004: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, **428**, 834–837.

Montoya, M., A. Griesel, A. Levermann, J. Mignot, M. Hoffmann, A. Ganopolski, and S. Rahmstorf, 2005: The earth system model of intermediate complexity CLIMBER-3α. Part I: description and performance for present day conditions. *Climate Dynamics*, **25**, 237–263.

Moum, J., D. Caldwell, J. Nash, and G. Gunderson, 2002: Observations of boundary mixing over the continental slope. *Journal of Physical Oceanography*, **32**, 2113–2130.

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

Nilsson, J., G. Broström, and G. Walin, 2003: The Thermohaline Circulation and Vertical Mixing: Does Weaker Density Stratification Give Stronger Overturning? *Journal of Physical Oceanography*, **33**, 2781–2795.

Nilsson, J. and G. Walin, 2001: Freshwater forcing as a booster of the thermohaline circulation. *Tellus A*, **53**, 629–641.

Oakey, N., B. Ruddick, D. Walsh, and J. Burke, 1994: Turbulence and microstructure measurements during NATRE. *EOS*, **75**, 130.

Otterå, O. H., H. Drange, M. Bentsen, N. G. Kvamstø, and D. Jiang, 2004: The transient response of the Atlantic Meridional Overturning Circulation to enhanced freshwater input to the Nordic Seas-Arctic Ocean in the Bergen Climate Model. *Tellus A*, **56**, 342–361.

Peterson, B. J., J. McClelland, R. Curry, R. M. Holmes, J. E. Walsh, and K. Aagaard, 2006: Trajectory shifts in the arctic and subarctic freshwater cycle. *Science*, **313**, 1061–1066.

Petit, J. R., J. Jouzel, D. Raynaud, J. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Y. Linpenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard, 1999: Climate and atmospheric history of the past 420,000 years from the Vostok icea core, Antarctica. *Nature*, **399**, 429–436.

Pohlmann, H., F. Sienz, and M. Latif: 2006, Influence of the multidecadal Atlantic meridional overturning circulation variability on European climate, Journal of Climate, in press.

Rehmann, C. R. and T. F. Duda, 2000: Diapycnal Diffusivity Inferred from Scalar Microstructure Measurements near the New England Shelf/Slope Front. *Journal of Physical Oceanography*, **30**, 1354–1371.

Rintoul, S. R., C. W. Hughes, and D. Olbers: 2001, The Antarctic Circumpolar Current System. *Ocean Circulation and Climate*, G. Siedler, ed., Academic Press, 271–301.

Samelson, R. M., 2004: Simple mechanistic model of middepth meridional overturning. *Journal of Physical Oceanography*, **34**, 2096–2103.

Sandström, J. W., 1908: Dynamische Versuche mit Meerwasser. *Annalen der Hydrographie und der Maritimen Meteorologie*, **36**, 6–23.

Sarmiento, J. L., H. W. Feely, W. S. Moore, A. E. Bainbridge, and W. S. Broecker, 1976: The Relationship Between Vertical Eddy Diffusion and Buoyancy Gradient in the Deep Sea. *Earth and Planetary Science Letters*, **32**, 357–370.

Sarmiento, J. L. and C. Le Quéré, 1996: Oceanic carbon dioxide uptake in a model of century-scale global warming. *Science*, **274**, 1346–1350.

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

Schmittner, A. and T. F. Stocker, 1999: The Stability of the Thermohaline Circulation in Global Warming Experiments. *Journal of Climate*, **12**, 1117–1133.

Stocker, T. F., 1998: The seesaw effect. *Science*, **282**, 61–62.

Stocker, T. F. and D. G. Wright, 1991: Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes. *Nature*, **351**, 729–732.

Stommel, H. and A. B. Aarons, 1960: On the abyssal circulation of the world ocean: I. Stationary flow patterns on a sphere. *Deep-Sea Research*, **6**, 140–154.

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

Sutton, R. T. and D. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. *Science*, **309**, 115–118.

Talley, L. D., J. L. Reid, and P. E. Robbins, 2003: Data-based meridional overturning streamfunctions for the global ocean. *Journal of Climate*, **16**, 3213–3226.

Timmermann, A., S. An, U. Krebs, and H. Goosse, 2005: ENSO surpression due to weakening of the north atlantic thermohaline circulation. *Journal of Climate*, **18**, 2842–2859.

Timmermann, A., H. Gildor, M. Schulz, and E. Tziperman, 2003: Coherent Resonant Millennial-Scale Climate Oscillations Triggered by Massive Meltwater Pulses. *Journal of Climate*, **16**, 2569–2585.

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

Trenberth, K. E. and J. M. Caron, 2001: Estimates of meridional atmosphere and ocean heat transports. *Journal of Climate*, **14**, 3433–3443.

van Kreveld, S. A., M. Sarnthein, H. Erlenkeuser, P. Grootes, S. Jung, M. J. Nadeau, U. Pflaumann, and A. Völker, 2000: Potential links between surging ice sheets, circulation changes and the Dansgaard-Oeschger cycles in the Irminger Sea, 60-18 kyr. *Paleoceanography*, **15**, 425–442.

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

Wang, Z. and L. A. Mysak, 2001: Ice sheet-thermohaline circulation interactions in a climate model of intermediate complexity. *Journal of Oceanography*, **57**, 481–494.

Weaver, A. J., M. Eby, A. F. Fanning, and E. C. Wiebe, 1998: Simulated influence of carbon dioxide, orbital forcing and ice sheets on the climate of the Last Glacial Maximum. *Nature*, **394**, 847–853.

Wunsch, C. and R. Ferrari, 2004: Vertical Mixing, Energy, and the General Circulation of the Oceans. *Annual Review of Fluid Mechanics*, **36**, 281–314, doi:10.1146/annurev.fluid.36.050802.122121.

Zhang, R. and T. L. Delworth, 2005: Simulated tropical response to a substantial weakening of the Atlantic Thermohaline Circulation. *Journal of Climate*, **18**, 1853–1860.