Ocean Mixing and the Stability of the Thermohaline Circulation

A collaboration proposal submitted to the *Research Council of Norway* and the *German Academic Exchange Service* under the *Mobility programme for research collaboration between Germany and Norway*
by

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Main Objective

To merge the existing 3-dimensional and conceptual climate modelling activities in Potsdam and Bergen in order to thoroughly address a delicate and long-standing problem in oceanography, with implications for understanding the past and predicting the future global climate: the stability of the thermohaline circulation.

Background

The thermohaline circulation (THC) is a large-scale circulation system spanning all oceans. In the Atlantic, it consists of warm surface water that flows northward to high latitudes, where it releases its heat to the colder atmosphere. The associated loss of buoyancy leads to sinking in the Nordic Seas and a conveyor-like circulation is formed, with a deep water branch returning the water southward. The THC transports about 1 PW (10^{15} W) of heat to the North Atlantic (Ganachaud and Wunsch 2002), thus having a major influence on atmospheric and oceanic temperatures in high latitudes (e. g. Manabe and Stouffer 1988; Wood et al. 1999).

In addition to these regional effects, the overturning circulation influences climate on a global scale (Winton 2003; Herweijer et al. 2005). Due to the associated heat transport, the thermal equator is shifted northward over the Atlantic and eastern Pacific. The Intertropical Convergence Zone follows this excursion, which leads to altered precipitation patterns compared to a climate state without overturning (Vellinga and Wood 2002; Stouffer et al. 2006). The dynamics of the inter-hemispheric overturning circulation cause the sea surface elevation to be some decimeters lower in the North Atlantic than in the North Pacific (Levermann et al. 2005), as well as a cooling of the southern hemisphere (Crowley 1992; Stocker 1998). The THC has strong implications for the marine biosphere (e. g. Schmittner 2005), and possibly links to the El Niño/Southern Oscillation (ENSO) phenomenon (Timmermann et al. 2005).

Combined evidence from ocean sediment data (e. g. McManus et al. 2004) and model simulations (e. g. Manabe and Stouffer 1997) suggests that large and abrupt changes in the THC have led to a number of major climatic shifts during the last glacial (for a detailed discussion see the reviews by Clark et al. 2002; Rahmstorf 2002). Past cessations of the Atlantic overturning have been associated with massive freshwater release from glaciers to the ocean (Bond et al. 1992), which freshened the ocean surface and made waters in the North Atlantic lighter, so that deep water formation was strongly reduced or completely stopped.

Recent observations of a continuous decrease of salinity in the North Atlantic and in the Nordic Seas led to speculations about the possible future fate of the THC (Curry et al. 2003; Curry and Mauritzen 2005). Current model simulations are unable to explain the observed freshening, and exhibit only a weak

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reduction in overturning circulation, even for strong global warming scenarios (Gregory et al. 2005).

A possibly significant deficiency of most current climate models is associated with the physical process that closes the loop of the overturning circulation. It is a long standing hypothesis that the upwelling of the waters that sank in the Nordic Seas can be explained as a motion balancing the vertical downward diffusion of buoyancy in low latitudes, closing part of the THC loop (Kuhlbrodt et al. 2006). The vast majority of current global climate models parameterize low latitudinal vertical mixing by applying a parameterization for diffusion (the so-called eddy-diffusivity $\varkappa$) that is constant in space and time. However, since more turbulent kinetic energy is required to displace water across a strong vertical density gradient, vertical diffusion is strongly influenced by the stratification of the ocean (Gargett and Holloway 1984). The stratification itself is set by the distribution of temperature and salinity, which again depend on the ocean circulation.

State of the Art

One approach is to write the diffusivity as $\varkappa \sim N^{-\alpha}$, where N is the local buoyancy frequency, a measure for the stratification. Here, α is a parameter that determines the influence that changes in stratification have on vertical mixing. Values for α between 0 and 3 have been suggested from a variety of measurements for different parts of the ocean (Sarmiento et al. 1976; Hoffert and Broecker 1978; Broecker and Peng 1982; Rehmann and Duda 2000).

Nilsson and Walin (2001) used a two layer model of the North Atlantic to investigate the cases $\alpha = 0, 1$, and 2. They identified two regimes of THC stability: For the standard case of constant diffusivity ($\alpha = 0$) the THC was reduced in response to anomalous freshwater forcing to the Atlantic surface. For $\alpha = 1$ and 2 however, they found an inverse behavior: The freshwater flux increased vertical mixing through reduced stratification, and thereby enhanced the THC. Idealized simulations with a three-dimensional ocean model, supported these hypothesis (Nilsson et al. 2003). Marzeion and Drange (2006) extended this study using a conceptual oceanic model based on the model proposed by Gnanadesikan (1999), and identified a critical value $\alpha_c = 0.75$ for the transition from a freshwater-impeded to a freshwater-boosted regime.

Through an email collaboration, we recently performed the first simulations with varying values for α in a coupled climate model with realistic topography and three dimensional ocean component. The model results are in strong contradiction to the findings by Nilsson and Walin (2001), in that we did not observe an increase in overturning for any value of α. Instead, our simulations revealed a strongly non-linear behavior of the THC: We find a much stronger reduction of the THC compared to the standard case of constant diffusivity ($\alpha = 0$), if α was above a critical value $\alpha_c \approx 0.75$

We proposed a general feedback explaining this threshold behaviour: If α is large, both positive and negative perturbations of stratification are amplified by associated changes in diffusivity. This enhances the initial positive stratification anomaly in northern high latitudes which is created by the anomalous freshwater flux. As a result, convection is strongly reduced, and the overturning is significantly weakened (Marzeion et al. 2006). However, this analysis was based on a small number of model experiments. For a exhaustive stability analysis, carefully designed so-called hysteresis experiments are necessary.

If our findings can be confirmed, they will have fundamental implications for projections of future climate, for understanding the climate records of the past, and for ocean model design.

Work Plan

The analysis of the previous model simulations was done practically via email contact between the co-authors. Systematically addressing this problem, e.g. with a full hysteresis experiment in which the anomalous freshwater forcing in the Atlantic is varied continuously over thousands of years, requires both more careful design and much deeper analysis.

Workpackage 1: Design model experiments to systematically address the question how stratification-dependent mixing changes the stability properties of the thermohaline circulation under a wide range of forcing conditions.

Workpackage 2: Implement and run the experiments, using the Earth System Model of Intermediate Complexity CLIMBER-3α. (Experiments will run for ∼4 months, CPU resources will be provided by the Potsdam Institute for Climate Impact Research.)

Workpackage 3: Evaluate the experiments, and adjust the experimental design based on the preliminary results.

Workpackage 4: Analyse the experiments, and publish the results.

Time Plan

	2007/1	2007/2	2007/3	2007/4	2008/1	2008/2	2008/3	2008/4
WP1	░	▓ ●						
WP2		░	▓ ■	░	░			
WP3					▓ ●	░	░	
WP4							▓ ■	▓

Light gray shading indicates the duration of the activity, dark gray indicates the period of main activity; ● indicates a German visit to Norway, ■ indicates a Norwegian visit to Germany.

Expertise of the Partners

With the Earth System Model of Intermediate Complexity CLIMBER-3α, the Potsdam group has the appropriate tool and knowledge to carry out the numerical simulations. CLIMBER-3α has a three-dimensional oceanic component, and does therefore capture the most relevant features of the ocean circulation in the Atlantic. Due to its reduced-complexity atmospheric component, it is computationally efficient enough to be used on long timescale simulations as needed in this project. Anders Levermann was involved in all published research that was carried out with CLIMBER-3α so far and has a profound knowledge of the model. His main research activity focuses on the stability properties of the THC.

As one of the founding members of the Bjerknes Centre for Climate Research (Bergen, Norway), the Nansen Center is part of a close collaboration involving measurements of ocean turbulence, as well as full complexity ocean-atmosphere modelling activities. Ben Marzeion has been studying the effect of small scale mixing on large scale ocean dynamics during the past three years as part of his PhD work.

This project will build a brigde between conceptual studies of ocean mixing and climate, intermediate complexity earth system modelling, and full complexity climate system modelling, to address systematically a fundamental problem in physical oceanography.

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