

[4] Glacial Ocean Mixing (GLOMIX): Investigating the role of diapycnal ocean mixing for glacial climate stability and sensitivity

a project proposal submitted to the Theme 4 (Young Scientist) of the
NORKLIMA program by

Ben Marzeion

Nansen Environmental and Remote Sensing Center (NERSC), Bergen, Norway

Main objective

To provide an integrated perspective on how glacial climate boundary conditions may have contributed to a less stable Atlantic climate through changes in the diapycnal mixing in the ocean interior.

Specific objectives

1. To implement an energetically consistent mixing scheme driven by realistic tidal dissipation and wind forcing in a intermediate complexity earth system model
2. To use this model system to quantify changes in the sensitivity of the Atlantic Ocean circulation to atmospheric forcing, melt water runoff, sea level change, and changes in the background state of the ocean at the Last Glacial Maximum

Summary

Diapycnal mixing is a source of potential energy in the ocean and is therefore believed to limit the rate of overturning on centennial and longer timescales. For the present-day ocean, winds and dissipation of tidal energy drive the diapycnal mixing with approximately similar contributions. Both components are thought to be considerably different in a glacial climate: A stronger meridional temperature gradient in the atmosphere implies intensified winds, whereas the distribution and strength of tidal dissipation is very sensitive to the ocean topography. The latter was changed significantly by the lower sea level during glacial times.

A coupled earth system model of intermediate complexity with a realistic tidal model and the best available paleo-data sources will be used to provide an integrated perspective on whether the stability of the glacial ocean state was generally changed due to a different state of the background diffusivity field. Furthermore, the relative and combined contributions of an increased freshwater flux and the associated sea level change will be assessed for different freshwater impeded overturning regimes.

Rationale

Climate records from natural archives, such as ice cores (e. g. Dansgaard et al., 1993), ocean sediments (e. g. Bond et al., 1992) and terrestrial records (Grimm et al., 1993), indicate that the climate system exhibited strong fluctuations during glacial times – known as Dansgaard/Oeschger and Heinrich events – that were not present during interglacials. A number of mechanisms have been suggested to explain these abrupt climate changes, usually involving reorganisations of the Atlantic Ocean circulation.

For Dansgaard/Oeschger events, models suggest that a shift in the location of dense water formation could explain the typical characteristics seen in sediment records (Ganopolski and Rahmstorf, 2001). Broecker et al. (1991) suggested changes in the volume transport, driven by a build-up and discharge of salinity anomalies at low latitudes, as a mechanism. Also, the bistability of the overturning circulation found in Stommel's (1961) box model has been used to explain Dansgaard/Oeschger events as the Atlantic Ocean switching between two widely different circulation modes (Broecker et al., 1985). Finally, Clement and Cane (1999) proposed the idea that reorganisations of the atmospheric flow field could trigger rapid and strong shifts in the North Atlantic temperatures.

Heinrich events, characterized by a layer of ice-rafted debris in a belt of the North Atlantic ocean stretching from Labrador to west of Europe, coincide with particularly cold episodes in Greenland and warm anomalies in the southern hemisphere (Blunier 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 lead to a strong reduction or even to a complete shut down of dense water formation (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 (e. g. Stocker and Wright, 1995; Manabe and Stouffer, 1995). Both internal ice sheet processes (MacAyeal, 1993) and external control mechanisms (e.g. van Kreveld et al., 2000) have been proposed as triggers of Heinrich events. Flückiger et al. (2006) suggest a feedback between sea level rise following a weakening of the Atlantic Overturning 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.

However, none of the suggested mechanisms explicitly involves effects of diapycnal diffusivity, even though it has been shown theoretically (Huang, 1999) and in numerous model studies (e.g. Park and Bryan, 2000; Scott and Marotzke, 2002; Dalan et al. 2005) that, on multicentennial and millennial timescales, vertical diffusivity is limiting the rate of overturning. Energy budget calculations (Wunsch and Ferrari, 2004) and remote sensing data (Egbert and Ray, 2000) suggest that, at present, the energy necessary for sustaining the deep ocean stratification is contributed in about equal parts from winds and tidal dissipation. Furthermore, tidal model simulations taking into account sea level variations indicate that the tidal dissipation in the deep ocean was up to three times larger during the LGM than it is in present day conditions (Egbert et al., 2004).

Using a highly idealized loop current model, Wunsch (2005) speculated that the sea level increase during the deglaciation might have caused changes in the vertical diffusivity leading to the Younger Dryas. Similar mechanisms may have contributed to the rapidity of other observed climate fluctuations during the past.

State of the art

Simmons et al. (2004) were the first to implement a realistic tidal mixing into an Ocean General Circulation Model, and got very favourable results when comparing with observational data. They used a tidal model developed by Jayne and St. Laurent (2001) to calculate tidal dissipation rates that are used in their ocean model to drive vertical diffusion.

Egbert et al. (2004) used the model developed by Egbert et al. (2002) to estimate the rate of tidal dissipation during the LGM. While they have to rely on present day stratification to estimate the internal tide drag, sensitivity experiments indicate that their results of a strongly increased tidal dissipation in the deep ocean during the LGM is robust.

Nilsson and Walin (2001) used a two-layer model of the northern hemisphere Atlantic Ocean to investigate the effect of stratification dependent mixing on the sensitivity of the Meridional Overturning Circulation to freshwater hosing, and found two distinct regimes: the well-known ‘freshwater-impeded’ regime near the limit of constant vertical mixing, and a ‘freshwater-boosted’ regime for stratification dependent vertical mixing. Their findings were confirmed in a box-model study (Marzeion and Drange, 2006), but recent results from a coupled climate system model (Marzeion et al., 2006) indicate that the ‘freshwater-boosted’ regime may be a result of oversimplification in the theoretical considerations and the model setup.

In Marzeion et al. (2006), the magnitude of the decrease of the Atlantic Meridional Overturning Circulation was found to depend critically on the choice of parameterisation of the diapycnal diffusivity. While experiments using a parameterization that provided a weak coupling between stratification and diffusivity (i.e., in the limit of constant vertical mixing) exhibited a linear response to freshwater hosing, stronger coupling resulted in a strongly nonlinear response of the overturning. The latter was caused by a feedback amplifying the initial perturbations of the stratification at the high northern latitudes, causing the deep convection to cease at comparatively low rates of freshwater forcing.

Work Plan

Tidal Modelling: To estimate the present day sensitivity of the overturning circulation, the tidal model by Egbert and Erofeeva (2002) will be adopted to provide tidal mixing in the ocean component of the earth system model of intermediate complexity developed at MIT (MITemic, Dutkiewicz et al. 2006). The performance of the model will be evaluated, and sensitivity experiments will be conducted to determine the present day effect of tidally driven mixing, as opposed to constant mixing, for the stability of the AMOC to freshwater hosing.

Glacial Tides: Sea level and topography reconstructions will be used to estimate tidal dissipation rates during different stages of the last glaciation. An ocean state estimate for the LGM currently being prepared at the Bjerknes Centre for Climate Research (BCCR) in collaboration with MIT will be used to calculate the difference of the internal tide drag caused by changes in the stratification compared to present day.

LGM Sensitivity: The combination of the LGM tidal dissipation rates and the MITemic will be used to estimate the effect that an increased freshwater flux, the associated sea level and topographic change, and their combination, might have had on the glacial overturning

circulation. The results will be compared with the findings from the experiments for the present day state to address the main objective of this project.

Work Packages

WP1: setup of tidal model for present day

Adopt the tidal model driver of the TPXO tide model (Egbert and Erofeeva, 2002) to provide tidal currents suitable for following the Simmons et al. (2004) approach to include tidal mixing in the MITemic.

Duration: months 1 - 8

WP2: implementation of tidal mixing in the MITemic

Make the output of the tidal model usable in the MITemic. This includes implementing a parameterization for calculation of internal tide drag, and test runs to check for possible improvements or degradations in model performance.

Duration: months 1 - 12

WP3: sensitivity studies for present day

Perform freshwater hosing experiments to check for changes of the systems sensitivity under present day climate conditions. The output of these experiments will form the basis for a refereed publication.

Duration: months 8 – 16

WP4: tidal simulations for LGM

Use ice sheet and sea level reconstructions and set up the tidal model to run under glacial topography at different time slices of the last glaciation. Perform test runs with MITemic using the corresponding topography.

Duration: months 8 - 20

WP5: use LGM state estimate for IT drag

Use the output of the LGM state estimate currently being performed at BCCR and MIT to calculate internal tide drag coefficients based on glacial stratification instead of present day stratification. Compare differences in the spatial mixing distribution, and test the response of the ocean circulation. This will result in a peer-reviewed publication in the beginning of year 2009.

Duration: months 12 - 28

WP6: sensitivity studies for LGM conditions

The complete model system will be used to estimate the climate sensitivity using LGM topography, internal tide drag coefficients, and freshwater hosing strength reconstructed from sea level change. The results will be compared with the present day simulations performed under WP3. Two publications will result until end the of 2009.

Duration: months 20 - 36

Time Plan

Time-plan for the activities. Grey shading indicate duration of the activity; black cells indicate time of main activity, crosses indicate publications in international refereed journals.

Activity	2007			2008			2009		
WP1 – setup of tidal model for present day	■	■							
WP2 – implementation of tidal mixing in MITemic	■	■	■						
WP3 – sensitivity studies for present day			■	■					
WP4 – tidal simulations for LGM			■	■	■				
WP5 – use of LGM state estimate for IT drag				■	■	■	■		
WP6 – sensitivity studies for LGM conditions						■	■	■	■

Expected results

The project will – for the first time – systematically address and give first answers to a number of fundamental questions :

- what is the importance of realistic spatial distribution of vertical mixing for the sensitivity of the present day climate system to perturbations in the freshwater forcing?
- how sensitive is the climate state to changes in the internal tide drag caused by changes in the stratification?
- was the climate system during the LGM less stable then today because of a different spatial distribution and amplitude of vertical mixing?
- how did changes in the vertical mixing associated with sea level change contribute to climate fluctuations in the past?

Connections to other projects/international links

During the second stage of the project, results from a state estimate for the glacial ocean that is currently being developed at BCCR in collaboration with MIT will be used to perform tidal simulation under glacial boundary conditions. For this purpose, Ben Marzeion will visit MIT during the second year of the project. Close collaboration is foreseen with researchers from MIT (Jeffrey Scott) and BCCR (Kerim Nisancioglu and Trond Dokken) during the duration of the project.

Budget

The over-all budget is 696 kNOK for 2007 and 2009, and 822 kNOK for the year 2008, supporting one PostDoc at NERSC from 2007 to 2009, including funding for a one-year stay at MIT during 2008.

For a detailed outline of the budget and justifications of cost, see the application form.

Computational resources needed are estimated to 20000 allocation units per year.

About the proposer

Ben Marzeion (born 1977 in Germany) finished his Master Thesis at the Institut für Meereskunde, Kiel, Germany, in 2003. The work on bio-physical climate feedbacks in the tropical Pacific was partially performed at the School of Ocean and Earth Sciences and Technology, University of Hawai'i, USA, with support of the German Academic Exchange Service. It was published in *Journal of Climate* in 2005.

Since 2003, Marzeion has been working as a PhD student at the Nansen Center and the Bjerknes Centre for Climate Research. The work on the role of diapycnal mixing for the stability of the Atlantic Meridional Overturning Circulation has so far resulted in one published and one submitted paper.

Since 2002 Marzeion has been continuously awarded with fellowships by e-fellows.net, a German organization funded by private companies to support future leader personalities.

Marzeion will defend his PhD thesis in November 2006. In total, Marzeion has 2 papers published, 1 submitted, and 1 in progress.

References

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

Blunier, T., 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. Huon, R. Jantschik, S. Clasen, C. Simet, K. Tedesco, M. Klas, G. Bonani, and S. Ivy, 1992: *Evidence for massive iceberg discharges into the North Atlantic Ocean during the last glacial period*, *Nature* **360**:245-249

Broecker, W. S. , D. M. Peteet, and D. Rind, 1985: *Does the ocean-atmosphere system have more than one stable mode of operation?*, *Nature* **315**:21-26

Broecker, W. S., G. Bond, M. Klas, G. Bonani, and W. Wolfi, 1990: *A salt oscillator in the glacial North Atlantic?, 1. The concept* , *Paleoceanography* **5**:469:477

Clement, A. C. and M. A. Cane, 1999: in *Mechanisms of Global Climate Change at Millennial Time Scales* (eds. P. U. Clark, R. S. Webb, and L. D. Keigwin) 363–371, American Geophysical Union, Washington DC.

Dalan, F., P. H. Stone, I. V. Kamenkovich, and J. R. Scott, 2005: *Sensitivity of the Ocean's Climate to Diapycnal Diffusivity in an EMIC. Part I: Equilibrium State*, *Journal of Climate* **18**:2460-2481

Dansgaard, W., S. J. Johnsen, H. B. Clausen, D. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C. S. Hvidberg, J. P. Steffensen, A. E. Sveinbjornsdottir, J. Jouzel, and G. Bond, 1993: *Evidence for general instability of the past climate from a 250-kyr ice core record*, *Nature* **364**:218-220

Dutkiewicz, S., A. P. Sokolov, J. R. Scott, and P. H. Stone, 2006: *A Three-Dimensional Ocean-Seice-Carbon Cycle Model and its Coupling to a Two-Dimensional Atmospheric Model: Uses in Climate*

Change Studies, Report No. **122** of the MIT Joint Program on the Science and Policy of Global Change

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

Egbert, G. D., R. D. Ray, and B. G. Bills, 2004: *Numerical modelling of the global semidiurnal tide in the present day and in the last glacial maximum*, *Journal of Geophysical Research* **109**:C03003

Egbert, G. D., and S. Y. Erofeeva, 2002: *Efficient Inverse Modelling of Barotropic Ocean Tides*, *Journal of Atmospheric and Oceanic Technology* **19**:183-204

Flückiger, J., R. Knutti, and J. W. C. White, 2006: *Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events*, *Paleoceanography* **21**, doi:10.1029/2005PA001204

Ganopolski, A. and S. Rahmstorf, 2001: *Rapid changes of glacial climate simulated in a coupled climate model*, *Nature* **409**:153-158

Grimm, E. C., G. L. Jacobsen Jr., W. A. Watts, B. C. S. Hanson, K. A. Maasch, 1993: *A 50,000-year record of climate oscillations from Florida and its temporal correlation with the Heinrich events*, *Science* **261**:198-200

Huang, R. X., 1999: *Mixing and energetics of the oceanic thermohaline circulation*, *Journal of Physical Oceanography* **29**:727-746

Jayne, S. R., and L. C. St. Laurent, 2001: *Parameterizing tidal dissipation over rough topography*, *Geophysical Research Letters* **28**:811-814

MacAyeal, D. R. 1993: *A low-order model of the Heinrich event cycle*, *Paleoceanography* **8**:767-773

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

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*, submitted to *Journal of Physical Oceanography*

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

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

Park, Y.-G., and K. Bryan, 2000: *Comparison of thermally driven circulations from a depth-coordinate model and an isopycnal-layer model. Part I: Scaling law sensitivity to vertical diffusivity*, *Journal of Physical Oceanography*, **30**:590-605

Scott, J. R., and J. Marotzke, 2002: *The location of diapycnal mixing and the meridional overturning circulation*, *Journal of Physical Oceanography*, **32**:3578-3595

Simmons, H. L., S. R. Jayne, L. C. St. Laurent, and A. J. Weaver, 2004: *Tidally driven mixing in a numerical model of the ocean general circulation*, *Ocean Modelling* **6**:245-263

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

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

Stommel, H., 1961: *Thermohaline convection with two stable regimes of flow*, *Tellus* **13**:224:230

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

Wunsch, C. and R. Ferrari, 2004: *Vertical mixing, energy, and the general circulation of the oceans*, *Annual Review of Fluid Mechanics*, **36**:281-314