Antarctic basal ice shelf melting may enhance Southern Ocean heat uptake under global warming through subpolar gyre acceleration

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Employing a simple parameterization for basal ice shelf melting around Antarctica, a time-varying freshwater flux is applied to the subsurface in a global coupled climate model. Melting rates produced by the model in equilibrium under pre-industrial boundary conditions compare well with higher resolution regional models. Under global warming basal melting increases significantly. The resulting subsurface freshwater flux strengthens the gyre circulation in Weddell and Ross Sea through enhancing the density difference between the gyre's center and the freshening coast. Thereby near surface northward transport of cold water masses is increased and oceanic heat uptake is enhanced.

1. Introduction

The increase in global mean surface air temperature has enhanced oceanic heat uptake during the past century [*Levitus et al.*, 2000]. Under future global warming oceanic heat uptake plays a key role for rate of atmospheric warming [*Hansen et al.*, 2005] and steric sea level rise [*Church and White*, 2006]. The main oceanic heat uptake occurs in the deep water formation sites of the North Atlantic and in the Southern Ocean (SO) [*Huang et al.*, 2003]. From the ocean side, the uptake distribution is determined by vertical heat transport away from the surface to the deep ocean and by horizontal circulation between different latitudes. The main relevant processes are vertical mixing in the upper layers and advection through the large scale ocean circulation. While vertical mixing shows a strong spatial heteorogenity, changes in near surface circulation are similarly hard to predict (e.g. [*Fyfe and Saenko*, 2006]). They play a significant role, since they redistribute heat most efficiently between latitudes of very different air temperature.

Surface freshwater fluxes in the SO influence the large-scale circulation only for relatively large fluxes because strong surface currents strongly dilute the signal [*Seidov et al.*, 2005]. While it is not clear if changes of surface fluxes of the required magnitude may occur under future warming, basal ice shelf melting (ISM) yields subsurface fluxes and is likely to be enhanced in a warming world [*Rignot and Jacobs*, 2002]. Here we introduce subsurface meltwater and corresponding heat fluxes through a simple parameterization of basal ISM [*Beckmann and Goosse*, 2003; *Holland et al.*, 2008] into the global coupled climate model CLIM*BER*-3α in order to investigate its influence on the SO circulation, in particular the SO subpolar gyres (SPGs) in the Weddell and Ross Seas. We present a baroclinic mechansim by which enhanced SPG transport can increase SO heat uptake.

0094-8276/09/$5.00

2. Model and experiments

The global coupled climate model CLIM*BER*-3α, described in detail by *Montoya et al.* [2005], combines a three-dimensional ocean general circulation model based on the GFDL MOM-3 code with a statistical-dynamical atmosphere and a dynamic and thermodynamic sea-ice component. We use an improved version of the model, comprising a deeper Indonesian throughflow among other changes [*Levermann et al.*, 2007] and apply a background value of vertical diffusivity of $0.3 \cdot 10^{-4}$ m^{2}s^{-1}. Thus the mixing induced upwelling in both the Atlantic and Pacific ocean is small [*Mignot et al.*, 2006] and the global meridional overturning circulation is mainly driven by SO wind stress [*Schewe and Levermann*, 2009]. In order to focus on baroclinec effects due to meltwater, wind stress onto the ocean is prescribed to present-day climatology [*Trenberth et al.*, 1989].

Following *Beckmann and Goosse* [2003] with a generalization by *Holland et al.* [2008] heat loss and corresponding fresh water flux due to ISM are introduced along the six major Antacrtic shelf ice regions in CLIM*BER*-3α (fig. S1). The net heat flux

$$H = \rho_w c_p \gamma L \int \mathrm{dl} \cdot \Delta \mathrm{T_{equ}} \left(\left(\mathrm{T_o} - \mathrm{T_f} \right) / \Delta \mathrm{T_{equ}} \right)^{\alpha}. \quad (1)$$

is computed as the along shore integral of a power $\alpha \in [1, 2]$ of the mean temperature difference between the ocean outside the ice shelf cavity between 200m and 600m depth (T_o) and the pressure melting point at 200m, T_m. It is proportional to an effective cross-shelf penetration length $L = 10$km. A thermal exchange velocity $\gamma = 10^{-4}$ ms^{-1} describes heat diffusion through an oceanic boundary layer at the shelf-ocean interface [*Holland and Jenkins*, 1999]. $\rho_w = 1000$ kg/m^3 is density and $c_p = 4000$ J/kg/K specific heat of water. By use of latent heat $L_i = 3.34 \cdot 10^5$ J/kg and density of ice $\rho_i = 920$ kg/m^3, the heat flux is converted into an oceanic freshwater flux $F = H/(\rho_i L_i)$. $\Delta T_{equ} = (T_o - T_f)_{equ}$ is the temperature difference for the pre-industrial equillibrium simulation. Simulations presented here start from a multi milennia integration (approx. 15000 years) with pre-industrial boundary conditions of 280 ppm CO_2 equivalent greenhouse gas concentration. In addition to this equilibrium without ISM, we compute an equilibrium with melting parametrization and $\alpha = 1$, in which case ΔT_{equ} drops out and the equilibrium reference temperature can be determined and used for $\alpha > 1$. Melting rates in equilibrium for each of the ice shelves compare well to higher resolution simulations [*Hellmer*, 2004; *Hattermann and Levermann*, 2009].

Starting from equilibrium CO_2 is increased by 1% per year for 140 years. Subsequently concentration are kept constant at 4x280 ppm = 1120 ppm for a number of centuries. In addition to an experiment without ISM (NoISM), we apply ISM heat and fresh water fluxes with different exponents $\alpha = 1, 1.2, 1.4, 1.6, 1.8$ and 2.0. In order to investigate their respective influence, two supplementary experiments with fixed heat (fixH) and freshwater flux (fixF) (prescribed to their pre-industrial equilibrium fields) were carried out. For a detailed description of the experiments and the performance of the model with ISM compare [*Hattermann and Levermann*, 2009].

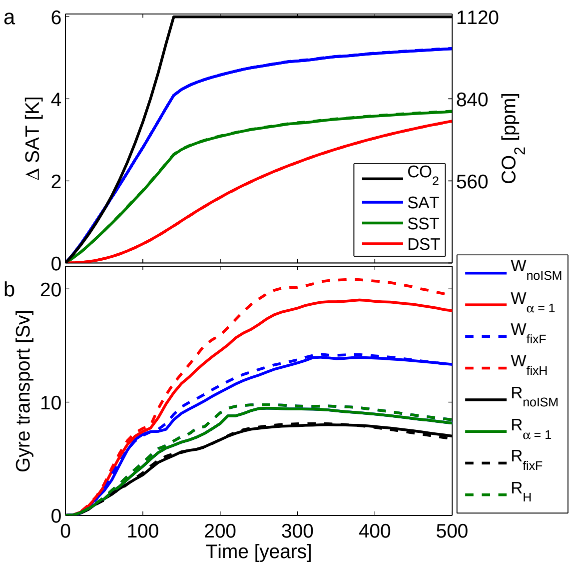

Figure 1. Time evolution of the simulations. Panel a: atmospheric CO_2 concentration (right axis) and anomalies of global mean surface air temperature (SAT), sea surface temperature (SST) and deep ocean temperature from 500m to 2000m depth (DST) for the NoISM run (left axis) Panel b: Anomaly of maximum zonal transport through a meridional cross section south of the SPG center between 10°W and 30°W in the Weddell (W) sea and 150°W and 180°W in the Ross (R) sea down to 2000 m depth. The latitude of the center moves southward during the warming scenario and varies between 64°S and 66°S for the Ross and between 60°S and 62°S for the Weddell gyre. Initial values are 29 Sv for the Ross and 46 Sv Weddell gyre. Experiments with freshwater fluxes (fixFW) and heat fluxes (fixH) fixed to the fields of the control simulation reveal that freshwater fluxes constitute the main influence of ISM on the SPG.

3. Enhanced gyre through global warming

First consider the control simulation without ISM but with global warming (NoISM). In response to rising atmospheric temperature the SO north of the Antarctic Circumpolar Current (ACC) is warming more rapidely than near the Antarctic coast (fig. 2a). This is a common feature observed in warming experiments within coupled climate models of varying complexity [*Raper et al.*, 2002]. The emerging temperature gradient influences the horizontal circulation. Similar to the North Atlantic SPG [*Myers et al.*, 1996; *Levermann and Born*, 2007] the horizontal SO circulation has a wind-driven and a baroclinic component [*Wang and Meredith*, 2008]. The density difference between the denser center and the lighter rim of the gyre induces a geostrophic flow which enhances the circulation. Depth integration of the momentum balance equations reveals that this baroclinic contribution is proportional to the difference in potential energy $\Delta\chi \equiv g \int dz \cdot z\Delta\rho$ between the center and the exterior of the SPG (e.g. [*Born et al.*, 2009; *Hattermann and Levermann*, 2009]. Consequently the gyre strength correlates with the difference in potential energy rather than density which can be verified in our simulations (fig. 2c); i.e. enhanced warming north of the ACC strengthens the SPGs (fig. 1b). Please note that this means that the significance of density differences for the circulation thus increases with depth, which is important with respect to the subsurface meltwater inflow compared to surface perturbations.

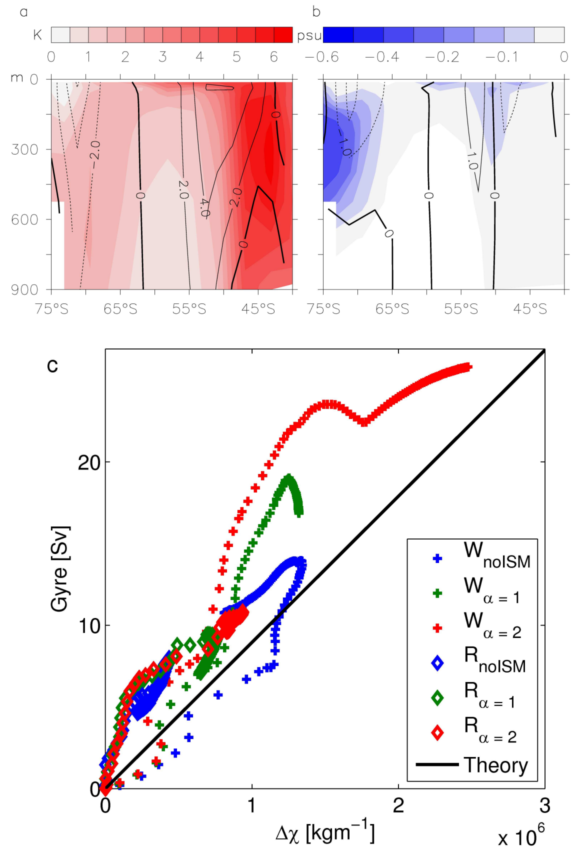

Figure 2. Enhanced baroclinic contribution to SO SPGs. panel a: temperature increase more strongly north of the gyre under global warming (NoISM year 200 minus year 1). panel b: salinity decrease south of the gyre due to ISM. Both effect decrease density in the outer SPG rim and enhance its transport.

4. Enhanced gyre and heat uptake through ice shelf melting

Under global warming melting rates increase drastically with some time-delay to the SAT (fig. S2) which is determined mainly by the downward advection of the positive temperature anomaly to the base of the ice shelf [*Hattermann and Levermann*, 2009]. In response to this, ISM yields a small local oceanic cooling in the ice shelf regions which limits further melting and constitutes a negative feedback stabilizing ISM at a slightly lower level compared to melting rates that would be diagnosed in an uncoupled simulation [*Hattermann and Levermann*, 2009]. In our model this effect is limited by local oceanic transport processes, mainly mixing, and its relevance reduces under global warming. With respect to gyre strength, simulations with freshwater fluxes and heat fluxes fixed to the time-dependent field of the control run reveal that ISM-related heat flux does have nearly no influence (fig. 1). To the contrary ISM-meltwater fluxes strongly strengthen the SO SPGs due to associated freshening. The effect is enhanced for higher exponents α due to the related ISM enhancement (figure S3).

Dynamically ISM has a similar effect as the warming north of the ACC by enhancing the density difference between SPG center and exterior (fig. 2c). Here, however, the subsurface meltwater injection (200m-600m) lightens the southern edge of the SO SPGs (fig. 2b). Note that it is crucial that the density is reduced at depth since the baroclinic contribution is proportional to the difference in potential energy not merely to the density difference.

In agreement with *Hellmer* [2004] and *Wang and Beckmann* [2007] our simulations show that ISM locally stabilizes the water column and thereby reduces oceanic heat loss to the atmosphere around the Antarctic coast (red coastal areas in figure 3). This is at some places enhanced through stronger sea ice cover which further reduces heat loss. The main increase in oceanic heat uptake, however, occurs in the latitudinal band between $54°$S and $40°$S (fig. 4b). The enhanced SPG advects colder near surface water masses towards lower latitudes where it increases the temperature difference between the cold oceanic surface and the warmer atmosphere and thereby increases oceanic heat uptake (fig. 3).

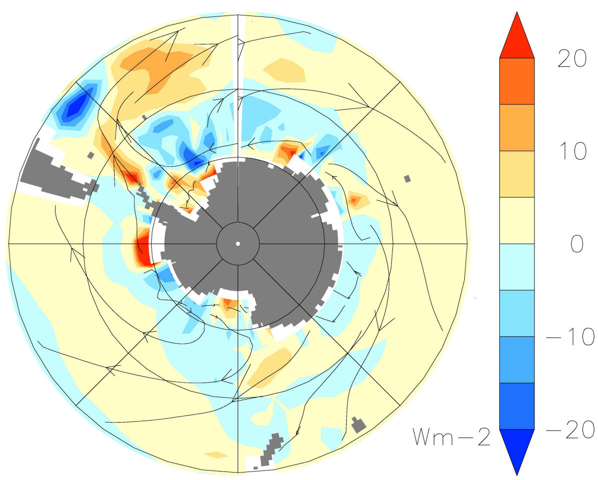

Figure 3. Surface heat flux difference after 200 years ($\alpha = 2$ minus NoISM experiment) and NoISM surface velocities.

5. Discussion and conclusion

In a global coupled climate model comprising a coarse resolution oceanic general circulation model we find that SO heat uptake is enhanced under global warming due to an increase in SO SPGs strength. The reason is an enhanced density difference between the denser core and the lighter outer rim of the gyres which is caused by two effects. First the region north of the ACC warms more strongly then southern regions which is a common feature of model simulations of varying complexity. The second cause is related to ISM which freshens the Antarctic coast and thereby lightens the southern SPG rim.

The aim of this study is to propose the qualitative mechanism described which depends mainly on the geostrophic balance between the center and the outer rim of the SPGs. While the mechanism is likely to be robust in a qualitative manner, we can not claim that the effect is properly represented in a quantitative way. A number of important aspect may influences the amplitude of heat uptake in a comprehensive future projection.

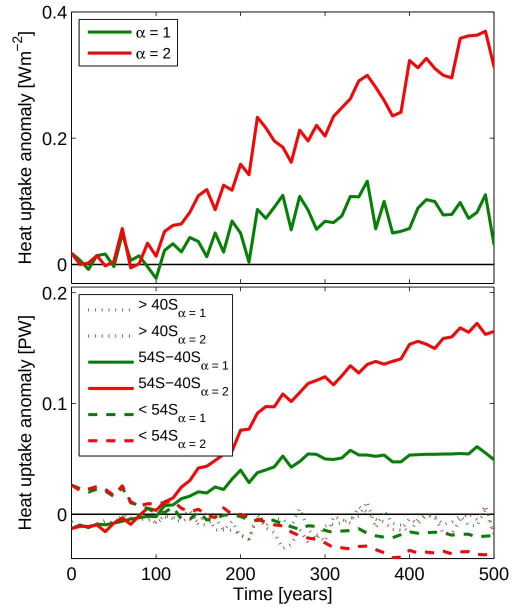

Figure 4. panel a: timeseries of global mean ocean heat uptake in ISM experiments compared to the NoISM experiment. panel b: spatialy integrated components of oceanic heat uptake at different latitudes in basal melting experiments compared to NoISM experiment. The global integral is split up into the area north of the ACC ($> 40°$S), the regime north of the Drake Passage ($40° - 54°$S) and the sea surface adjecent to the Antarctic continent ($< 54°$S).

First of all we purposefully have not taken any changes in wind stress and related circulation changes into account in order to capture the baroclinic response to ISM. Wind changes might dominate variability, especially on sub-decadal time scales. Secondly, since we do not model the oceanic circulation below the shelf, our results need to be interpreted within the framework of the applicability of the melting parameterizations of [*Beckmann and Goosse*, 2003; *Holland et al.*, 2008] which might have their limitations. Thirdly, the coarseness of the representation of the ocean currents has a number of implications. One question is how quickly the fresh meltwater is rising to the upper ocean layers where it is less efficient in altering the SPG circulation. Simulations with higher resolution models [*Hellmer*, 2004; *Losch*, 2008] suggest that the fresh signal rises rather quickly within the outer SPG rim which would weaken the mechanism proposed here. The results will furthermore depend quantitatively on how far north surface water masses are transported within the gyres. While in our simulations the SO SPGs generally reach further north than observed which might increase the effect compared to the real ocean, they are also generally weaker than observed which argues for an enhanced effect in the real ocean compared to this study.

Generally coarse resolution models, as applied here, tend to blurr density gradients which is, for example, the reason for our relatively weak initial SPG and ACC strength. In the more pronounced observed density structure the meltwater may have a stronger influence on the circulation than simulated here which would strengthen the effect. Furthermore, in our simulations, the export of the negative heat anomaly produced by the ISM away from the shelves is achieve mainly by mixing. Small scale advective processes as observed in the real ocean would be more efficient than mixing and reduces this negative feedback enhancing ISM. These mechanisms may have led to an underestimation of the described mechanism in this study.

While we observe the same qualitative behavior of both SPGs, the influence of ISM on the Ross Gyre is much weaker because the amount of meltwater there is much smaller. However, this is not taking into account the fast flowing outlet glaciers in the Amudsen and Belinghausen Sea which were proposed to contribute most of Antarctic mass loss by basal melting [*Rignot et al.*, 2008]. The freshening from these areas, which are not represented within our model are probably influencing the water mass distribution in the continental shelf areas, also reaching into the Ross basin. This would increase the response of the Ross gyre to ISM compared to our findings.

While our observation of reduced atmospheric warming due to enhanced melting around Antarctica is in general agreement with *Swingedouw et al.* [2008], the associated mechanism is radically different. In the previous study a similar meltwater flux was applied at the surface along the Antarctic coast which strongly stratified the ocean near the surface, shoaling the oceanic pycnocline and reducing vertical heat transport. This lead to a strong increase in sea ice cover even under global warming and thereby to a regional atmospheric cooling through the higher sea ice albedo and a reduction of global SAT increase of about 10%. Our simulations in which a similar meltwater flux is applied at depth show only slight increase in sea ice cover which suggests in *Swingedouw et al.* [2008] and *Swingedouw et al.* [2009] the surface application of the freshwater is crucial for the effect. In contrast to our study, the surface flux originates from the loss of grounded ice. Thus under global warming, both effects will play a role.

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