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Antarctic ice-sheet melting provides negative feedbacks on future climate warming

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[1] We show by using a three-dimensional climate model, which includes a comprehensive representation of polar ice sheets, that on centennial to millennial time scales Antarctic Ice Sheet (AIS) can melt and moderate warming in the Southern Hemisphere, by up to 10°C regionally, in a 4 × CO_2 scenario. This behaviour stems from the formation of a cold halocline in the Southern Ocean, which limits sea-ice cover retreat under global warming and increases surface albedo, reducing local surface warming. Furthermore, we show that AIS melting, by decreasing Antarctic Bottom Water formation, restrains the weakening of the Atlantic meridional overturning circulation, which is a new illustration of the effect of the bi-polar oceanic seesaw. Consequently, it appears that AIS melting strongly interacts with climate and ocean circulation globally. It is therefore necessary to account for this coupling in future climate and sea-level rise scenarios. **Citation:** Swingedouw, D., T. Fichefet, P. Huybrechts, H. Goosse, E. Driesschaert, and M.-F. Loutre (2008), Antarctic ice-sheet melting provides negative feedbacks on future climate warming, *Geophys. Res. Lett.*, *35*, L17705, doi:10.1029/2008GL034410.

1. Introduction

[2] Current anthropogenic greenhouse gas emissions are likely to affect climate for millennia, notably due to the large thermal inertia of the oceans and the long memory of the ice sheets [*Meehl et al.*, 2007; *Hasselmann et al.*, 2003]. Archives of the past suggest noticeable Antarctic Ice-Sheet (AIS) melting contributions to sea-level changes during the last deglaciation [*Clark et al.*, 2002; *Philippon et al.*, 2006] and glaciation [*Kanfoush et al.*, 2000; *Rohling et al.*, 2004], illustrating the possibility of massive freshwater input into the Southern Ocean, which could have influenced the climate [*Weaver et al.*, 2003]. Recent observations report an accelerated melting of the West Antarctic Ice Sheet [*Rignot and Thomas*, 2002; *Cook et al.*, 2005; *Velicogna and Wahr*, 2006; *Shepherd and Wingham*, 2007]. This ice melting may partly explain the freshening of the Ross Sea observed during the past four decades [*Jacobs et al.*, 2002]. Freshening also appears in the Antarctic Bottom Water (AABW) [*Rintoul*, 2007] and could limit this deep-water formation in the future and affect climate. While none of the coupled climate models participating to the IPCC Fourth Assessment Report [*Meehl et al.*, 2007] take into account the ice sheets melting for projections going up to the year 2100, it is necessary to evaluate the potential effect of this melting for longer projections.

[3] Potential irreversible changes both in the ice sheets and ocean could actually lead to dangerous effects for the environment, society and economy [*Rahmstorf and Ganopolski*, 1999; *Oppenheimer and Alley*, 2004]. It is therefore urgent to account correctly for ice-sheet-climate interactions in climate projections. Ice-sheet retreat can regionally enhance climate warming through changes in topography and albedo. Furthermore, ice-sheet melting releases freshwater into the ocean that can modify the ocean circulation and sea ice cover [*Weaver et al.*, 2003; *Fichefet et al.*, 2003; *Swingedouw et al.*, 2006], and thus the climate. The Greenland and Antarctic ice sheets are rather different from each other since the total melting of the former would represent around 7 m of sea-level rise, while the latter would correspond to about 61 m [*Huybrechts*, 2002]. Moreover, contrary to the Greenland Ice Sheet (GIS), the AIS has massive ice shelves, bordering the Ross and Weddell Seas, where the bulk of AABW is formed. The impact of GIS melting on climate and ocean circulation has been evaluated in several studies [*Fichefet et al.*, 2003; *Ridley et al.*, 2005; *Swingedouw et al.*, 2006; *Driesschaert et al.*, 2007], contrary to its southern counterpart, the AIS. In this study, we quantify the interactions of future AIS melting with climate, using the climate model LOVECLIM.

2. Experimental Design

[4] To capture the respective roles of the AIS and GIS impact under global warming, we performed 5 different experiments (Table 1) using LOVECLIM, a three-dimensional Earth system model of intermediate complexity (EMIC) that includes representations of the polar ice sheets (see methods section in the auxiliary materials).[1] The first experiment is a control simulation (CTRL) under pre-industrial conditions that satisfactorily reproduces the climate mean state [*Driesschaert et al.*, 2007]. In the other simulations, the atmospheric CO_2 concentration is increased by 1% per year (compounded) until it reaches four times its initial value, where it remains unchanged for 3000 years. These are idealized experiments (called scenarios hereafter) designed to capture the relevant ice-sheet-climate interactions in a warming world at the millennial timescale. The first scenario (iAiG) has fully interactive ice sheets over Antarctica and Greenland, while in the second one (fAfG), climate compo-

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Table 1. Description of the 3000-Year Numerical Experiments Performed With LOVECLIM

Name	Description
CTRL	Control simulation with a constant forcing corresponding to pre-industrial conditions, notably with the CO_2 concentration in the atmosphere set to 277.6 ppm.
fAfG	Scenario simulation in which the CO_2 concentration increases from the pre-industrial level by 1% per year and is maintained constant after 140 years of integration when it reaches a value equal to four times the pre-industrial level (4 × CO_2 scenario). The climate components experience constant Antarctic and Greenland ice-sheet areas and elevations, fixed at their preindustrial estimate. The potential melting of the ice sheets due to warming is however calculated "off line", but the corresponding freshwater fluxes are not released to the ocean.
iAiG	Same as fAfG but with fully interactive Antarctic and Greenland ice sheets. Freshwater fluxes associated with melting are released to the ocean. Ice-sheet area and elevation are free to evolve and to influence the climate.
fAiG	Same as fAfG but with fully interactive Greenland ice sheet.
iAfG	Same as fAfG but with fully interactive Antarctic ice sheet.

nents are forced with a fixed ice-sheet configuration. In this experiment, we still force the ice sheets "off line" with the simulated warming, but without the potential feedback of melting on climate. The ice sheets in this experiment are therefore only "one-way" coupled. Two complementary experiments have been conducted to isolate the individual role of the AIS and GIS. Experiment iAfG (fAiG) has interactive (fixed) AIS and fixed (interactive) GIS.

3. Results

[5] The AIS begins to loose mass after a few centuries in iAfG and iAiG. This is in contrast with previous studies [*Meehl et al.*, 2007; *Mikolajewicz et al.*, 2007] and is related to a large warming over the AIS in this model, which leads to a larger increase in ablation than accumulation for the grounded AIS (see Figure S1 and Text S1 in the auxiliary material). The melting of the AIS reduces the increase in surface air temperature by 10% (0.3°C) on a global average after 500 years and beyond in iAfG and iAiG compared to fAfG and fAiG (Figure 1a). The relative cooling between iAiG and fAfG occurs mostly in the southern high latitudes (Figure 1b) and reaches 10°C in the Weddell Sea sector (Figure 1c). This is associated with a smaller decrease in sea-ice cover in the Southern Ocean in iAiG compared to fAfG (Figure 1d). A slightly larger warming appears north of 60°N in iAiG compared to fAfG, mostly after 2000 years. At that time, 70% of the GIS has melted (Figure S2), which explains this larger warming north of 60°N when GIS is interactive, and is due to a reduction in elevation and albedo over Greenland [*Driesschaert et al.*, 2007]. In the Northern Hemisphere, the annual mean sea-ice extent decreases approximately at the same rate in the different scenarios and evolves from 15 × 10^{12} km^2 to 6 × 10^{12} km^2 after 3000 years. The annual mean sea-ice extent in the Southern Hemisphere decreases from 10 × 10^{12} km^2 to 3 × 10^{12} km^2 in iAiG and to 0.9 × 10^{12} km^2 in fAfG after 3000 years. Contrary to the melting of the GIS, the climatic impact of AIS melting is therefore mainly due to interactions with the ocean and sea ice. After 3000 years, there is an additional freshwater input into the Southern Ocean of up to 0.14 Sv in iAiG as compared to fAfG. This freshwater decreases the surface density of the Ross and Weddell Seas leading to the formation of a shallow halocline. Consequently, the weakening of the deep convection and hence the reduction in vertical heat exchange in the ocean enhance the sea-ice extent, which cools the climate through the higher sea-ice albedo [*Stouffer et al.*, 2007].

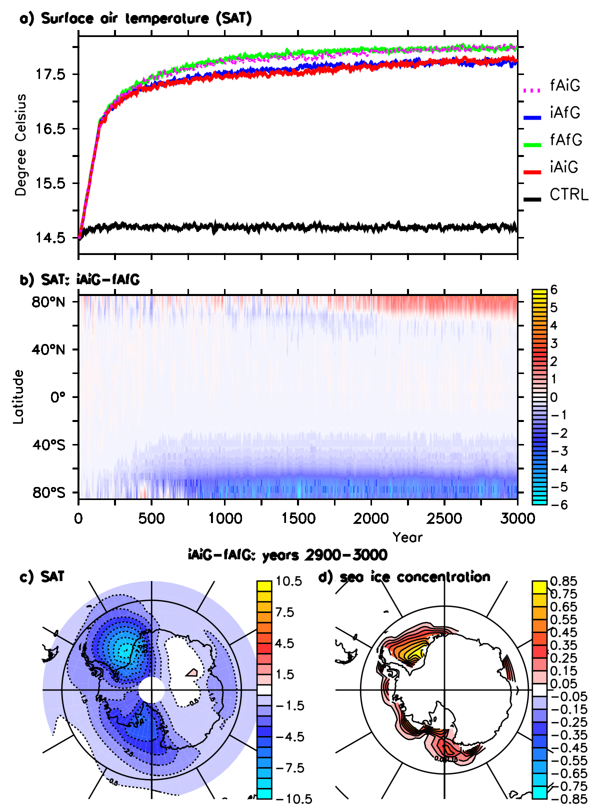

Figure 1. Time series of the annual mean surface air temperature (SAT in °C): (a) globally averaged from CTRL (black), iAiG (red), fAfG (green), iAfG (blue) and fAiG (purple dotted line) and (b) zonally averaged: difference between iAiG and fAfG. A 10-year running mean has been applied to all time series. (c) SAT difference between iAiG and fAfG averaged over years 2900 to 3000 expressed in °C and (d) same difference but for sea-ice concentration for each grid (ratio between 0 and 1), which is an index of sea-ice cover.

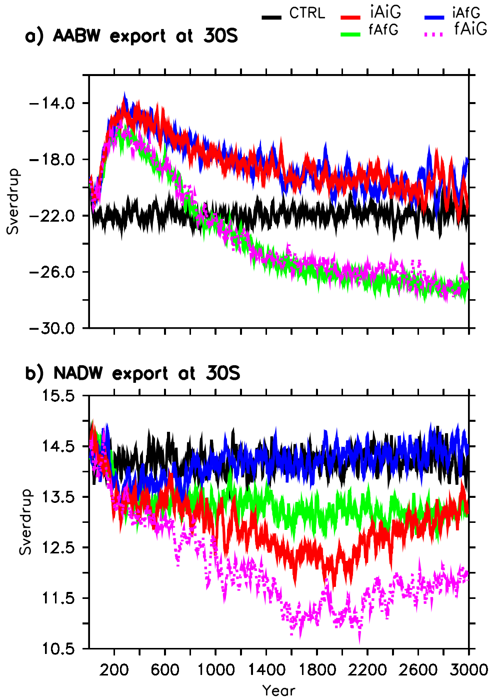

Figure 2. Time series of the annual mean value of (a) the minimum of the oceanic global meridional overturning streamfunction at 30°S (in Sv, 1 Sv = 10^6 m^3/s), representing the export of Antarctic and Circumpolar Deep Water (AABW and CDW) at 30°S, and (b) the maximum of the Atlantic meridional overturning streamfunction at 30°S, representing the export of North Atlantic Deep Water (NADW) at 30°S. CTRL is in black, iAiG in red, fAfG in green, iAfG in blue and fAiG in purple dotted line. A 21-year running mean has been applied to all time series.

[6] Furthermore, the freshwater input associated with AIS melting influences the ocean circulation in the scenarios. Without AIS melting, the annual mean AABW export at 30°S (which is an index of the strength of the AABW cell) weakens during the first 300 years and then recovers (in agreement with studies from *Bi et al.* [2001] and *Bates et al.* [2005]), and is even enhanced compared to CTRL after 1000 years (Figure 2a). This is caused by changes in the sea-ice freshwater forcing related to the retreat of the sea-ice cover (Figure S3). Indeed, the net annual mean sea-ice melting in the Weddell and Ross Seas is lower in fAfG compared to CTRL. This increases the surface salinity and density, and counteracts the density loss stemming from the temperature increase, leading to an increase in AABW formation in these seas in fAfG compared to CTRL after 3000 years.

[7] The AABW export is 35% smaller in iAiG than in fAfG, due to a decrease in surface density around Antarctica and a reduction in AABW formation, associated with AIS melting. Interestingly, the AIS melting also affects the North Atlantic Deep Water (NADW) export (which is an index of the strength of the NADW cell). At 30°S, this export diminishes in all the scenarios (Figure 2b), but recovers after 1000 years in iAfG contrary to fAfG, illustrating the stabilizing effect of AIS melting on the NADW cell weakening. When GIS melting is accounted for, the NADW cell further weakens. This melting notably leads to a peak difference of 3.3 Sv (23% of NADW export at 30°S in CTRL) in fAiG compared to fAfG after 2000 years. The AIS melting once more reduces the NADW cell weakening by 1.2 Sv in iAiG compared to fAiG. This stabilization effect of the AIS melting on the NADW cell can be explained by the so-called bi-polar ocean seesaw [*Stocker et al.*, 1992; *Seidov et al.*, 2001; *Brix and Gerdes*, 2003], which emphasizes that a reduction in AABW density allows the NADW to penetrate deeper and further south in the Atlantic, enhancing the associated cell (see Text S1).

[8] Another important impact of ice-sheet melting concerns the sea-level rise. Here, we evaluate how interactions between climate and ice-sheet melting can feed back on this melting and influence sea-level rise in the various scenarios (Table S1). According to its relative warming effect, the GIS melting yields a positive feedback: in line with earlier finding using LOVECLIM [*Driesschaert et al.*, 2007], the whole ice sheet has melted in fAiG and iAiG after 3000 years, while 60% remains in fAfG and iAfG. This positive feedback is due to the reduction in albedo and altitude of the ice sheet, which accelerates the melting. On the contrary, according to its relative cooling effect, the AIS melting produces a negative feedback, quantified by the comparison of the Antarctic contributions to global sea-level rise in iAiG (3.2 m) and in fAfG (10.0 m, calculated but not released to the ocean) after 3000 years. Moreover, the AIS melting tends to increase the oceanic heat content (Figure 3) and leads to a larger thermal expansion in iAiG compared to fAfG. This effect increases the sea-level rise by 1.4 m in iAiG compared to fAfG and corresponds to a warming at depth, while the surface, particularly in the Southern Ocean, experiences cooling. This is due to the capping of the ocean surface by freshwater coming from the AIS melting, which inhibits the vertical mixing of heat in high latitudes and warms the ocean interior. On the whole, after 3000 years, the sea-level rise is 13.8 m in iAiG, or 0.8 m less than the 14.6 m calculated in fAfG, illustrating the compensation, in terms of sea-level rise, between the GIS positive feedback and the AIS negative feedback.

4. Conclusions

[9] A number of factors should however be borne in mind when interpreting our results. The model used is an

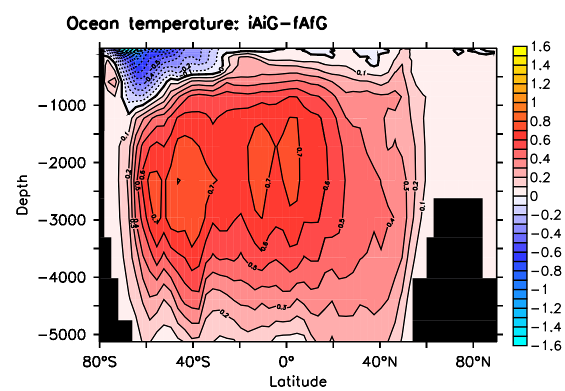

Figure 3. Latitude-depth distribution of the annually averaged temperature difference (in °C), years 2900 to 3000, of iAiG minus fAfG in the global ocean. Blue (red) shading indicates values where the water is colder (warmer) in iAiG than in fAfG. The contour interval is 0.2°C.

EMIC and has therefore a rather coarse resolution. This could affect deep water formation and the interaction between the ocean and the ice-shelves [*Nicholls*, 1997] but this is presently unavoidable to simulate the long-term evolution of climate. Nonetheless, LOVECLIM has reached sufficient realism concerning ice-sheet-climate interactions to correctly capture the underlying mechanisms we have illustrated here. The present study should not be seen as a forecast but gives insight on the potential feedbacks between climate and ice sheets melting for a given warming scenario. Regarding the ice-sheet model, some of the potentially fast processes (basal lubrication from penetrating surface melt water, ice-flow acceleration induced by ice-shelf disintegration) by which warming may contribute to the ice-sheet mass loss are not fully represented [*Alley et al.*, 2005] so that a faster decay could potentially happen. Note that ice sheet melting might also be more rapid if processes responsible for the widespread glacier acceleration currently observed in Antarctica [e.g., *Rignot et al.*, 2008] were taken into account in the model. We therefore argue that ongoing efforts in ice-sheet modelling should continue and that AIS models should be incorporated interactively in current ocean-atmosphere general circulation models for centennial and millennial projections of the climate system.

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