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

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Background and motivations

- 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.
- Archives of the past suggest noticeable Antarctic Ice-Sheet (AIS) melting contributions to sea-level changes during the last deglaciation, illustrating the possibility of massive freshwater input into the Southern Ocean, which could have influenced the climate [1].
- Recent observations report an accelerated melting of the West Antarctic Ice Sheet. This ice melting may partly explain the observed freshening of the Ross Sea observed during the past four decades. Freshening also appears in the Antarctic Bottom Water (AABW) and could limit this deep-water formation in the future and affect climate.
- None of the coupled climate models participating to the IPCC Fourth Assessment Report take into account the AIS melting, it is necessary to evaluate the potential effect of this melting on projected long-term global warming.

Can the AIS melt and impact on climate, ocean circulation and sea-level rise projections?

Surface temperature changes

- 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.
- After 3000 years, the whole Greenland has melted (peak of freshwater flux of 0.1 Sv [2])).
- The AIS melting **reduces the climate sensitivity by 10%**.
- The Greenland Ice Sheet (GIS) melting does not have such a global climatic impact.
- The relative cooling between iAiG and fAfG occurs mostly in the southern high latitudes and reaches 10°C in the Weddell Sea sector.
- This is associated with a smaller decrease in sea-ice cover in the Southern Ocean.
- 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.

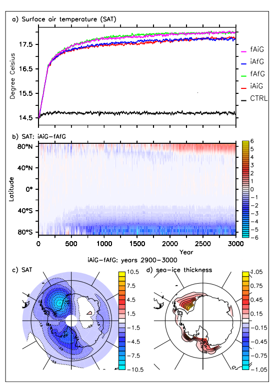

FIGURE 2: Time series of surface air temperature (SAT in °C): a) globally averaged for the different experiments; b) zonally averaged: difference between iAiG and fAfG. c) SAT difference between iAiG and fAfG averaged over years 2900 to 3000 and d) sea-ice thickness difference in m.

Sea-level rise changes

Quantification of the feedbacks between climate and ice-sheet melting after 3000 years:

- The **AIS melting produces a negative feedback of 6.8 m**.
- The GIS melting yields a positive feedback of 4.6 m.
- The AIS melting also leads to a larger thermal expansion of -1.4m.
- 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.
- This illustrates the compensation, in terms of sea-level rise, between the GIS positive feedback and the AIS negative feedback, in this model.

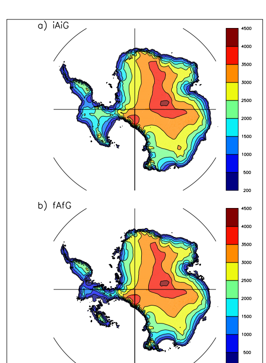

FIGURE 5: Ice-sheet surface elevation in Antarctica (in m) averaged over years 2900 to 3000. a) iAiG experiment. b) fAfG experiment.

Components of sea-level rise in the experiments (in m):

	Antarctica	Greenland	Thermal expansion	Total
iAiG	3.2	8.0	2.6	13.8
fAfG	*10.0*	*3.4*	1.2	14.6
iAfG	3.2	*3.6*	2.3	9.1
fAiG	*9.8*	7.9	1.5	19.2

The figures in *italic* stand for the fact that they have been calculated, but the associated melting has not been released to the ocean and has therefore no impact on ocean circulation.

Experimental design

Tool: LOVECLIM, a climate model of intermediate complexity [2]:

- ECBilt: Quasi-geostrophic atmospheric model (prescribed cloudiness; T21, L3).
- CLIO: Ocean general circulation model coupled to a thermodynamic-dynamic sea ice model (3°×3°, L20).
- VECODE: Reduced-form model of the vegetation dynamics and of the terrestrial carbon cycle (same resolution as ECBilt).
- LOCH: Comprehensive oceanic carbon cycle model (same resolution as CLIO).
- AGISM: Thermomechanical model of the ice sheet flow + visco-elastic bedrock model + model of the mass balance at the ice-atmosphere and ice-ocean interfaces (10km×10km, L31).

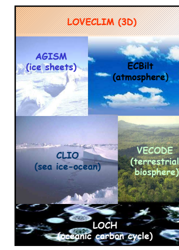

FIGURE 1: Components of LOVECLIM

Numerical experiments of 3000 years performed [3]:

CTRL	Control simulation with a constant forcing corresponding to pre-industrial conditions, notably with the CO2 concentration in the atmosphere set to 277.6 ppm.
fAfG	Scenario simulation in which the CO2 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.
iAfG	Same as fAfG but with only fully interactive Antarctic ice sheet.
fAiG	Same as fAfG but with only fully interactive Greenland ice sheet.

Oceanic circulation and heat content changes

- The AABW export is 35% smaller with to AIS melting after 3000 years.
- The AIS melting enhances the North Atlantic Deep Water (NADW) cell.
- This **stabilization effect of the AIS melting on the NADW cell** is due to the bi-polar ocean seesaw [4].
- The Southern Ocean surface is capped by freshwater coming from the AIS melting, which inhibits vertical mixing and warms the ocean interior.

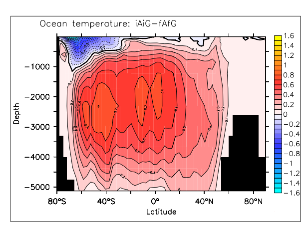

FIGURE 3: Latitude-depth distribution of the temperature difference (in °C), years 2900 to 3000, of iAiG minus fAfG in the global ocean.

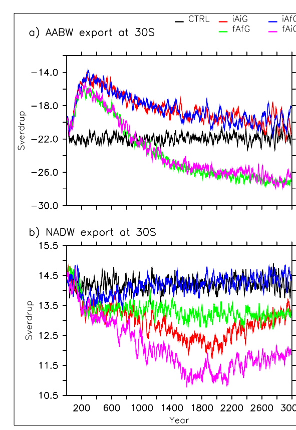

FIGURE 4: Time series of: a) the minimum of the oceanic global meridional overturning streamfunction at 30°S (in Sv, 1 Sv=10^6 m^3/s); b) the maximum of the Atlantic meridional overturning streamfunction at 30°S.

Conclusions

- The AIS melting moderates warming in the Southern Hemisphere, by up to 10°C regionally, in a 4×CO_2 scenario of 3000 years.
- The AIS melting, by decreasing AABW formation, restrains the weakening of the Atlantic meridional overturning circulation through the bipolar oceanic seesaw [4].
- The AIS melting feedback strongly impacts on sea-level rise projections.
- Some potentially fast processes (basal lubrication from penetrating surface melt water, ice-flow acceleration induced by ice-shelf disintegration) by which ice-sheet loose mass are not fully represented.
- Such an effect will lead the coupled feedbacks here illustrated to happen earlier.

AIS models should be incorporated in ocean-atmosphere models for centennial climate projections

References

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[2] Driesschaert E, Fichefet T, Goosse H, Huybrechts P, Janssens I, Mouchet A, Munhoven G, Brovkin V, and Weber SL. Modelling the influence of Greenland ice sheet melting on the Atlantic meridional overturning circulation during the next millennia. *Geophys. Res. Lett.*, 34:L1070, 2007.

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