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ScienceDirect
Earth and Planetary Science Letters 248 (2006) 750–758
EPSL
www.elsevier.com/locate/epsl

Evolution of the Antarctic ice sheet throughout the last deglaciation: A study with a new coupled climate—north and south hemisphere ice sheet model

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Received 20 December 2005; received in revised form 5 May 2006; accepted 9 June 2006
Available online 24 July 2006
Editor: M.L. Delaney

Abstract

The aim of this paper is to assess, through the understanding of deglaciation processes, the contribution of the Antarctic ice sheet to sea-level rise during the last deglaciation. To achieve this goal, we use an Earth System model in which the interactions between the atmosphere, the ocean, the vegetation and the northern and Antarctic ice sheets are represented. This new tool allows the simulation of the evolution of the Antarctic ice volume, which starts to decrease at around 15 ka. At the end of deglaciation, the melting of the Antarctic ice sheet contributes to an ice-equivalent sea-level rise of 9.5 m in the standard experiment and 17.5 m in a more realistic sensitivity experiment accounting for a different bathymetry in the Weddell Sea which succeeds in producing both major ice shelves (Ross and Ronne-Filchner). In both experiments, the melting of all ice sheets contributes to 121.5 m and 129.5 m, respectively, which is very consistent with data. The new coupled model provides a timing and amplitude of the Antarctic deglaciation different from those previously obtained by prescribing the temperature record from the Vostok Antarctic ice core (78°27′S 106°52′E) as a uniform temperature forcing. Sensitivity experiments have also been performed to analyse the impact of the parameters at the origin of the deglaciation process: insolation changes, atmospheric CO_2 variation, basal melting and sea-level rise. All those parameters have an influence on the timing of the deglaciation. The prescribed global sea level rise is shown to be a major forcing factor for the evolution of the Antarctic ice volume during the last deglaciation. We quantify the direct effect of the sea-level rise due to the northern hemisphere ice sheet melting on the grounding line retreat which, in turn, favours enhancement of grounded ice flow by lowering the buttressing effect of ice shelves.

Keywords: Last deglaciation; Sea-level; Ice sheets; Climate-ice sheets interactions

1. Introduction

During the last decade, ice sheet models have often been forced by ice core records to simulate the

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doi:10.1016/j.epsl.2006.06.017

evolution of past ice sheets during the last glacial–interglacial cycles [1–8]. An alternative approach consists of using (by forcing or coupling) climate model outputs to derive the surface mass balance of the northern hemisphere ice sheets (NHIS) [9,10]. Most of these studies concern the NHIS which produced the largest contribution to the sea-level rise when melting. Very few modelling studies have been devoted to the evolution of the Antarctic ice sheet (AIS). Among those, DeConto and Pollard [11] succeeded in simulating the onset of glaciation of Antarctica ~34 m.y. ago, with a 3-D ice sheet model. However, to achieve this goal, they did not account for the dynamics of the grounding line, which splits the grounded ice from the floating ice shelves. Only two 3-D AIS models include a representation of a dynamical behaviour of both the Ross and Ronne-Filchner ice shelves and of the grounding line [6,8,12]. All the numerical experiments using these models have been carried out prescribing a climate forcing computed from the data from the Vostok Antarctic ice core (78°27′S 106°52′E). Assuming that the past temperature evolution over the entire AIS was parallel to the one derived from Vostok remains a large approximation. Moreover, in such experiments, the feedbacks between climate and massive ice complexes are not represented. On the other hand, a few modelling studies based on climate models of intermediate complexity coupled either with a 2-D vertically integrated ice sheet models [1–3,13,14] or with a 3-D thermomechanical coupled ice sheet models [15–18] have been designed to explore the interactions between ice sheets and climate. However, these studies only focussed on the history of the northern hemisphere ice sheets during past ages.

The aim of this study is to assess the contribution of the AIS to the sea-level rise during the last deglaciation through a detailed analysis of the different processes occurring during this large climatic transition. To achieve this goal, we have developed a numerical tool that is able to simulate the main mechanisms responsible for the evolution of this ice sheet. We have therefore developed a coupling procedure between a 3-D AIS model and a climate model previously coupled with a northern hemisphere ice sheet model [16,17]. To our knowledge, this new tool is the only one which offers a representation of the entire atmosphere–ocean–vegetation system coupled to all major ice sheets and can be run for durations greater than 10,000 yr. In the present study, we first examine whether a reasonable deglaciation scenario can be obtained with this new tool only forced by insolation and CO_2 variations and starting from an LGM reconstruction. We also investigate, through a series of sensitivity experiments, the role of the different processes responsible for deglaciation.

2. Models and coupling strategy

2.1. The climate model: CLIMBER

The CLIMBER model (CLIMate-BiosphERe) used in this study is a climate model of intermediate complexity [19,20]. This model is based on simplified representations of the atmosphere, the vegetation, the ocean and the sea-ice, and describes the interactions between these components. In our study, all CLIMBER components are used. This includes interactive atmosphere, ocean and dynamic vegetation. The atmospheric module has a resolution of 51° in longitude and 10° in latitude and it includes a full description of the hydrological cycle. The oceanic model is composed of three 2-D (latitude-depth) basins for the Atlantic, Indian and Pacific oceans. The resolution in each basin is 2.5° in latitude × 20 vertical levels. These three basins are connected around Antarctica.

2.2. The ice sheet models: GRISLI and GREMLINS

The Antarctic ice sheet model, GRISLI [8] (GRenoble model for Ice Shelves and Land Ice) is a 3-D ice sheet model (40 km × 40 km). It predicts the evolution of the geometry of the AIS and accounts for thermomechanical coupling between velocity and temperature fields. It deals with inland ice and includes a representation of the ice flow through the ice shelves. The position of the grounding line is also dynamically computed. The northern hemisphere ice sheet model GREMLINS (GRenoble Model for Land Ice in the Northern hemiSphere, 45 km × 45 km) is developed in the same way than GRISLI, except that it only deals with inland ice [7].

In the present state of the art, these models do not reproduce sub-grid scale processes, such as the flow from glaciers, which has recently been shown to be a major process for the acceleration of the Greenland ice melting [21,22]. However, they include a representation of the main mechanisms responsible for slower processes and can be reasonably used for the simulation of the last deglaciation.

2.3. The coupling strategy

The coupling strategy between GREMLINS and CLIMBER is described in Charbit et al. [16] and Kageyama et al. [17]. The coupling method between the atmosphere of CLIMBER and the AIS surface is based on the same procedure: the annual and summer surface air temperatures and annual snowfall are given to the ice sheet model for the calculation of the surface mass balance.

The specificity of the Antarctic model lies in the representation of the dynamics of the ice shelves. In our model, the basal melting under the ice shelves is derived from the parameterization described in Beckmann and Goosse [23] and used by Dumas [24]. Observations [25] show that the basal melting is maximal near the grounding line and above the continental shelf. On the contrary, in our model, a basal freezing is produced under the centre of the major Ronne-Filchner and Ross ice shelves. Therefore, the basal melting is an exponential function of both the distance to the continental shelf and the CLIMBER oceanic temperatures at 61°S and 550 m depth. When GRISLI is not coupled to CLIMBER, the basal melting parameterization uses a climatic index derived form the Vostok temperature record, which varies with time, instead of the CLIMBER oceanic temperature.

In turn, the altitude and the nature of each ice sheet model grid point is returned to CLIMBER (land-ice or ice shelf, ice-free land and oceanic area). The fresh water due to the melting of the ice sheets is also released to the ocean, and if the ice sheet grows, the equivalent liquid water is subtracted from the runoff to the ocean. Fields are exchanged every 20 yr between CLIMBER and GREMLINS and CLIMBER and GRISLI.

2.4. Initial conditions

For the Antarctic ice sheet, a simulation (with GRISLI) is necessary by using the climatic fields derived from the Vostok ice core from 430 ka to the LGM [26]. This procedure gives an initial state at LGM reaching the geologic data (ice thickness, topography and bedrock elevation) and also includes a reasonable temperature profile in the ice.

This procedure differs from the one chosen for the northern hemisphere. This is justified because in the northern hemisphere surface characteristics are more rapidly propagated towards the base of the ice sheet due to higher accumulation rates, and hence, the ice temperature equilibrium is obtained more rapidly.

For the northern hemisphere, the initial topography is given by the ICE-5G LGM reconstruction [27]. This reconstruction gives the ice thickness, the topography and the bedrock elevation at the Last Glacial Maximum (LGM).

The last step is to perform a 10 kyr LGM (21 ka) equilibrium simulation using the CLIMBER model only, forced by the LGM ice sheets reconstructions. For this simulation, the CO_2 is fixed at 190 ppm and we use the 21 ka insolation [28].

3. Description of the standard and sensitivity experiments

The external forcing factors used for the CLIMBER-GREMLINS-GRISLI simulations are the variations of insolation [28] and atmospheric CO_2 obtained from the Vostok ice core [29]. In addition, the ice sheet models (ISM) are forced by the global sea-level reconstruction derived from the SPECMAP benthic $\delta^{18}O$ [30].

In a first step, we prescribe the sea-level rise using SPECMAP. In the future, we plan to prescribe the sea-level rise directly from ice sheet melting. We did not do it in this study because of uncertainties on location of the large amount of freshwater input from melting ice sheets.

Table 1 summarizes the experimental setup for the baseline experiment (STD) and the following sensitivity experiments, which in all cases simulate the deglaciation. Simulation SLW is similar to STD except that the ice sheet models are forced by the Waelbroeck et al. [31] sea-level reconstruction. The Antarctic ice sheet model is consistently initialised using the 21 ka state obtained after a four climatic cycle (GRISLI only experiment) forced by the sea-level [31]. In experiment RONNY, the seafloor in the Weddell Sea in GRISLI is lowered by 200 m, which remains within the error bars of the bathymetry in this region.

SL21 experiment has been obtained with a constant sea-level fixed at −127.5 m; the INSO21 and the CARB21 experiments respectively correspond to a constant LGM insolation and to a constant atmospheric CO_2 fixed at 200 ppm. Finally, the FUS21 experiment is obtained by assuming that no basal melting occurs under the ice shelves.

Table 1
Overview of model deglaciation experiments

Experiment	Description
STD	Standard experiment CLIMBER-GREMLINS-GRISLI
SLW	Same as STD, but with the Waelbroeck [31] sea-level forcing
RONNY	Same as STD, but with −200 m in the Weddell Sea
SL21	Same as STD, but with fixed sea level at −127.51 m
INSO21	Same as STD, but with LGM insolation
CARB21	Same as STD, but with CO_2 fixed at 200 ppm
FUS21	Same as STD, but with no basal melting under the ice shelves
GRISLI_ALONE	GRISLI forced by Vostok climatic fields (in STD configuration for the bathymetry)
PERTURB	Same as STD, but with a climatic perturbative method

GRISLI_ALONE simulation is performed with the GRISLI model only, forced by the Vostok climatic fields [8,24]. The temperature in each point above Antarctica is reconstructed as a function of the Vostok temperature, topography and latitude. The accumulation is a function of the calculated temperature. The initial conditions imposed to the ice sheet model are the same than in STD experiment.

PERTURB experiment consists of using the anomaly fields for temperature and precipitation (defined respectively as a difference for temperature between past and present and as a ratio for precipitation) instead of the temperature and precipitation directly obtained by CLIMBER.

4. Simulation of deglaciation: standard experiment

4.1. Ice volume variation

In the standard experiment (STD), the melting of the northern hemisphere ice sheets provides a contribution to sea-level rise of 85 m (Laurentide, LIS) and 25 m (Fennoscandia, FIS), which are close to the results from Peltier [27]. The total grounded Antarctic ice volume starts to decrease after 15 ka (Fig. 1a), which is consistent with geomorphologic evidence from Anderson et al. [32], who reported the triggering of the deglaciation between 15 ka and 12 ka in Antarctica. Anderson [32] addresses the onset of contribution to sea-level rise due to Antarctica. In our simulation, the East AIS (EAIS) retreats after 15 ka and the West AIS (WAIS) after 13 ka (not shown). At the end of the simulation, the grounded ice volume is $30.6\times10^{+15}$ m^3 ($24.0\times10^{+15}$ m^3 for EAIS and $6.6\times10^{+15}$ m^3 for WAIS). The East Antarctic ice volume is very similar to the observed one ($24.6\times10^{+15}$ m^3) [33]. However, the West Antarctic ice volume is overestimated compared to the observations ($4.8\times10^{+15}$ m^3) [33]. The final ice volume, after 21 kyr of simulation, is quite satisfactory since it is only 4% greater than the observed one. This is due to the major contribution of the EAIS to the overall mass balance. In our simulation, the grounding line has retreated in the Ross Sea at the present-day period and, therefore, creates the Ross ice shelf (Fig. 2a). However, the Ronne-Filchner region remains covered by grounded ice, contrary to observations (Fig. 2c) [33]. This is at the origin of the overestimation of the ice volume in the WAIS.

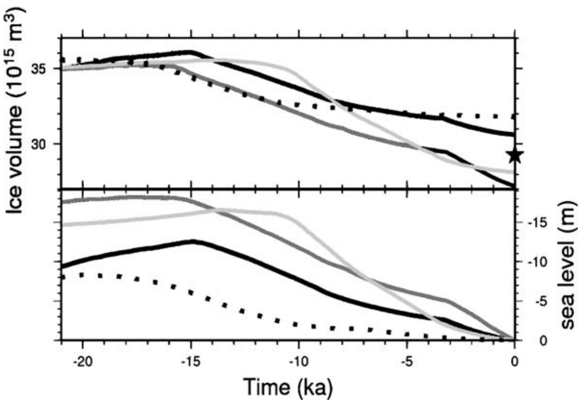

Fig. 1. (a) Evolution of the Antarctic total grounded volume throughout the deglaciation for the STD experiment (black curve), for the RONNY experiment (dark grey curve), for the GRISLI_ALONE experiment (light grey curve) and for the SLW experiment (dot black curve). The star corresponds to the present-day grounded ice volume [33]. (b) Evolution of the Antarctic contribution to sea-level rise for the same experiments.

4.2. Sea-level rise

Since the variations of the oceanic area from the LGM to the present-day period are small, the oceanic area is assumed to be constant for this calculation. The sea-level rise is thus estimated by dividing the Antarctic ice volume variation (grounded plus floating ice) by the present-day oceanic surface ($3.64\times10^{+14}$ m^2 [27]). Our STD simulation (Fig. 1b) leads to an Antarctic contribution to the sea-level rise since the LGM of 9.5 m (3.0 m from EAIS and 6.5 m from WAIS). In this simulation, the coupled model simulates a deglaciation of ice sheets which corresponds to a global sea level of 121.5 m (AIS + LIS + FIS + Greenland IS = 9.5 + 85.0 + 25.0 + 2.0). This global estimate is consistent with the values provided by the sea-level reconstructions from coral dating [34–38].

4.3. Why does the ice melt?

In the STD run, at around 15 ka, the oceanic temperature (61°S, 550 m depth) increases by more than 1.5 °C (Fig. 3). This appears to be related, in the ocean model, to an enhancement of the North Atlantic Deep Water formation leading to a global change in oceanic circulation and temperature, and to a southward shift of the isotherms across the 61 °S latitude. As a consequence, the basal melting under the ice shelves is more active. Secondly, the basal melting tends to thin the ice shelf, which acts in favour of a decrease of the buttressing effect, and thus, destabilizes the upstream grounded ice. Therefore, the ice thinning accelerates the ice flow, and the grounding line retreats across the Ross Sea. This grounding line retreat is also associated with a decreasing of grounded ice volume [8]. Then, the ice grounded surface collapses (Fig. 3) and acts in favour of an increase of the melting of the AIS (Fig. 1a).

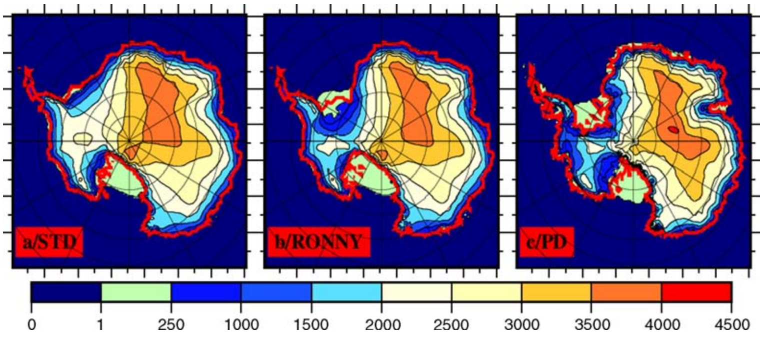

Fig. 2. (a) Simulated altitude (in meters) of the ice sheet for the present-day period in the STD experiment. The red line represents the grounding line; the light green areas correspond to the ice-shelves. (b) Simulated altitude of the ice sheet for the present-day period in the RONNY experiment. (c) Observed ice sheet elevation from Huybrechts [33].

4.4. Sensitivity to the external sea-level forcing

To evaluate the link between the Antarctic ice sheet deglaciation and the sea-level forcing, we performed the SLW sensitivity experiment, forced by the Waelbroeck et al. [31] sea level instead of the SPECMAP one used in the STD experiment. In SLW, the Antarctic grounded ice volume starts decreasing at 18 ka, that is 3 kyr earlier than in the STD case (Fig. 1a). This can be explained by the fact the sea-level signal provided by Waelbroeck et al. [31] starts to increase 2 kyr earlier than the SPECMAP signal. The total present-day grounded ice volume obtained at the end of the run is $31.8\times10^{+15}$ m^3. This value is 8% greater than the observed ice volume. As in the STD simulation (Fig. 2a), the grounding line has retreated in the Ross Sea at present-day period and creates the Ross ice shelf but not in the Weddell Sea (not shown). The contribution of Antarctica to sea-level rise is ~8 m (Fig. 1b), similar to the STD simulation. Therefore, the use of different sea-level signals to force the ISM has an impact on the timing of the deglaciation. However, the impact on the diagnosed sea-level contribution coming the Antarctic ice sheet is fully negligible.

5. Impact of the bathymetry: RONNY experiment

5.1. Ice volume and sea-level variations

One of the boundary conditions which is underconstrained in our STD experiment and may explain why the Ronne-Filchner ice shelf is still grounded in our final simulated state (i.e., at present-day) is the bathymetry in the Weddell Sea. To account for the uncertainty in this region [39], we perform the RONNY sensitivity experiment, in which the seafloor in the Weddell Sea is lowered by 200 m, resulting on a deeper Weddell Sea. In this experiment, the evolution of the northern hemisphere ice volume does not differ from the STD one, but the Antarctic grounding line retreats both in the Ross and in the Ronne-Filchner regions (Fig. 2b), leading to a significant decrease of the grounded ice volume (Fig. 1a).

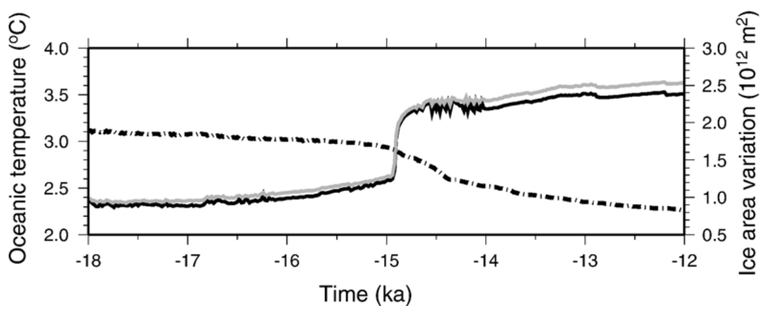

Fig. 3. Evolution of Atlantic (black curve, left axis) and Pacific (grey curve) oceanic temperature in °C (61°S and 550 m depth) used for the basal melting under the ice shelves for the STD experiment. Evolution of the ice grounded surface variation in 10^{12} m^2 between the time of simulation and the present-day simulated surface (dashed dot curve, right axis).

For the Ross ice shelf, the same mechanisms as the ones previously described in the STD experiment are observed, but the increase of the oceanic temperature occurs 1 kyr earlier (16 ka) than in the STD case. As a consequence, the total grounded ice volume starts decreasing at 16 ka (Fig. 1a). At 3.5 ka, the Atlantic oceanic temperature (61 °S, 550 m depth) increases by 2.5 °C (not shown). The consequence of a deeper seafloor in the Weddell Sea is that a part of the ice which was previously grounded is transformed in floating ice. This enhances the basal melting under the ice shelf and acts in favour of the melting the Ronne-Filchner grounded ice, leading thus the Ronne-Filchner ice shelf to be created. Consequently the grounding line retreats and the ice volume decreases (see Section 4.3). At the end of the run, the simulated ice volume obtained in this simulation is $27.6\times10^{+15}$ m^3 ($24.5\times10^{+15}$ m^3 for EAIS and $3.1\times10^{+15}$ m^3 for WAIS).

This experiment shows that the migration of the grouning line in the Weddell Sea in our model is clearly sensitive to the bathymetry. The resulting ice-equivalent sea-level rise is 17.5 m (6.0 m from EAIS and 11.5 m from WAIS) instead of 9.5 m in STD. Although the Ronne-Filchner ice shelf is not completely deglaciated, this new simulation estimate of the ice-equivalent sea-level rise is more realistic because the final step simulated by our model the present day is more consistent with the observations and with a deglaciated Ronne-Filchner ice shelf.

5.2. Comparison of our Antarctic contribution to sea-level rise since LGM in the literature

Although our experiments still present some discrepancies with observations, our values for the contribution of the AIS to sea-level rise are consistent with the large spectrum of values (from 7.0 to 19.2 m) found in the literature (Denton and Hughes [40], glacial and marine geologic data, 14 m; Ritz et al. [8] and Huybrechts [6], glaciological model, 7 m and 14–18 m, respectively; Bentley [41], onshore and offshore glacial geology, 6.1–13.1 m; Peltier [42], constrained by corals and by geologic data, 16.8 m). However, our results clearly disagree with the contribution to sea-level rise found by Colhoun et al. [43] (reconstruction of the LGM extent based on raised beaches in the Ross Bay and in AIS; 0.5–2.5 m), Nakada and Lambeck [44] (rheological model constrained by observed relative sea level near the sites of the former northern ice sheets; 37 m), Budd and Smith [45] (glaciological model but overestimated present-day ice extent; 38 m), Oerlemans [46] (glaciological model; 27.5 m) and CLIMAP [47] (ice margins, equations of flow lines; 24.7 m) which are below or above our results. Since we account for large uncertainties on a weakly constrained parameter (i.e., bathymetry of Weddell Sea), we consider that our estimates in the STD and the RONNY experiments cover the spectrum of realistic values we may reach with this modelling approach.

6. Impact of different parameters on the Antarctic ice sheet deglaciation

To examine the relative importance of each parameter at the origin of the deglaciation process, we have performed sensitivity experiments. Previous sensitivity experiments devoted to the northern hemisphere [16] have shown that the insolation is a key parameter for the melting of the ice sheets (especially for Fennoscandia). In our work, climate experiments have been run using the same methodology, taking the STD experiment as a basis. In each of them, one forcing factor is kept constant during the simulation (see Table 1 and Section 3 for the definition of the experiments). The comparison of these sensitivity experiments (Fig. 4) shows that in CARB21, FUS21 and INSO21, the beginning of the deglaciation lags that of the STD experiment by 2 kyr. Moreover, the CARB21 and FUS21 present-day simulated ice volumes are, respectively, 5% and 4% higher than their STD counterpart (1% lower in INSO21). The present-day

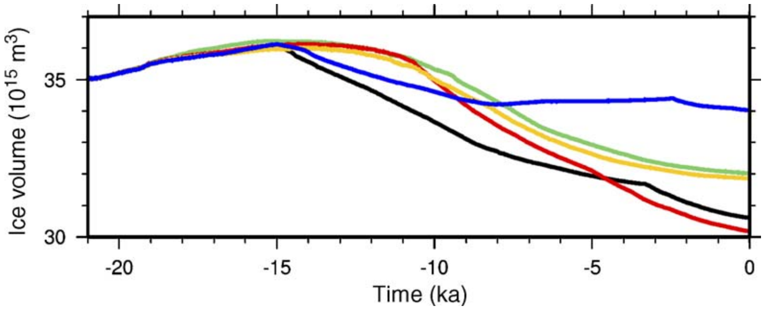

Fig. 4. Evolution of the Antarctic total grounded volume throughout the deglaciation for the STD experiment (black curve), for the SL21 experiment (blue curve), for the INSO21 experiment (red curve), for the FUS21 experiment (yellow) and for the CARB21 experiment (green curve).

simulated ice volume in SL21 is 11% greater than in the STD case.

These results clearly demonstrate that insolation, atmospheric CO_2 and basal melting all have an influence on the triggering of the deglaciation process. Moreover, basal melting and atmospheric CO_2 also have an impact on the overall surface mass balance. However, the greatest influence is observed in the SL21 experiment, showing that sea level is a crucial parameter for the deglaciation through its impacts on the formation of the ice-shelves (simulation SL21 forms more than one third Ross ice shelf compared to the STD one) and consequently on the inland grounded ice. This confirms the conclusions previously reached by Huybrechts et al. [4] and Ritz et al. [8].

7. Comparison with a simulation forced by the Vostok data

In previous sections we showed that the RONNY simulation succeeds in producing a realistic deglaciation of all ice sheets and a realistic present-day Antarctic topography. To investigate the impact of the coupling between ice sheets and climate, we compare the STD and RONNY experiments with GRISLI_ALONE (see definition in Table 1 and Section 3).

7.1. GRISLI_ALONE results

The beginning of the deglaciation in GRISLI_ALONE occurs at around 13.5 ka, 1.5 kyr later than in STD (Fig. 1a). In the STD simulation, the ice volume starts to decrease at around 15 ka due to basal melting, and after 13 ka in the GRISLI_ALONE experiment. The activation of the basal melting tends to retreat the grounding line, and therefore, the ice volume decreases. Compared to GRISLI_ALONE, the STD experiment tends to accumulate ice over the Ronne-Filchner ice shelf and to slightly melt grounded ice in the Pacific part of the EAIS. These differences are mainly due to locally higher CLIMBER precipitation in the Weddell Sea and to a lower basal melting.

In the Weddell Sea, the grounding line retreats in the GRISLI_ALONE simulation only, whereas it retreats in the Ross Sea in both GRISLI_ALONE and STD experiments. Because the grounded ice flows in both Weddell and Ross Seas, the present-day GRISLI_ALONE grounded ice is lower than the STD one and the contribution to sea-level rise is higher in the GRISLI_ALONE simulation. The ice-equivalent sea-level rise obtained in GRISLI_ALONE is 15.0 m for the AIS (i.e., 13.0 m for WAIS and 2.0 m for EAIS), a higher value compared to that provided by the STD experiment.

7.2. Antarctic inversion temperature

The largest difference between the STD and GRISLI_ALONE simulations resides in the surface temperature forcing of ice sheet. To compare these temperatures, we focus on ice cores on the Antarctic plateau, especially above domes because at these locations the accumulation is low and the sliding is limited. At Vostok, our STD coupled model simulates a 4.8 °C decrease of annual ice surface temperature warming between 20 ka and the present-day period (5.4 °C variation for RONNY experiment). Petit et al. [29] infer a 7.8 °C warming from the ice core.

Therefore, our model yields a temperature variation between the LGM and the present-day period which only catches 61% (STD) and 69% (RONNY) of the ice core signal. However, the simulated present-day annual surface temperature for STD is largely underestimated, −33.5 °C at Vostok instead of the observed −57.1 °C at this site [29]. This large discrepancy of ice surface simulated temperature when compared to the present-day reconstruction is explained by a lack of representation of the temperature inversion over the Antarctic plateau in CLIMBER [48,49] and therefore is especially overestimated in winter. To account for the mismatch, we performed a last experiment which accounts for more realistic surface temperature representation. A sensitivity experiment (PERTURB) based on a perturbative method [9] was carried out. The timing of the Antarctic deglaciation is delayed by more than 1 kyr and results in a present-day grounded ice volume very similar to observations ($24.6 \times 10^{+15}$ m^3 for EAIS and $5.9 \times 10^{+15}$ m^3 for WAIS). The contribution of Antarctica to sea-level rise is very similar to that obtained in the standard experiment (not shown). Therefore, the more realistic temperature over the EAIS does not change the contribution to sea-level rise. Owing to the fact that the inversion temperature profile is not simulated, CLIMBER overestimates temperature over Antarctica. On the other hand, because the temperature simulated remains very cold (~−30 °C), the evolution of Antarctica through the deglaciation is not drastically affected in terms of contribution to sea-level rise. The major change is the timing of deglaciation which starts at 14 ka.

8. Conclusion

We have developed a model simulating the interactions between the atmosphere, the ocean, the vegetation, the northern and Antarctic ice sheets (CLIMBER-GREMLINS-GRISLI). This model has been used to study the last deglaciation period with an emphasis on the evolution of Antarctica.

The standard experiment shows that the total grounded Antarctic ice volume starts to decrease at 15 ka, due to an increase of oceanic temperature, which leads to the retreat of the grounding line and the decrease of the ice grounded surface and ice volume. During the deglaciation process, the grounding line retreats in the Ross Sea and therefore creates the Ross ice shelf, whose final state is in very good agreement with observations [33], whereas the Ronne-Filchner region is still covered by grounded ice. This is related, in terms of ice-equivalent sea-level rise, to an Antarctic contribution of 9.5 m for the deglaciation, which is certainly an underestimation due to the fact that we are not able to create the Ronne-Filchner ice shelf in the STD experiment. Nevertheless, from a global point of view, the melting of all ice sheets gives a global simulated sea-level contribution of 121.5 m which is very consistent with data [34–38]. In order to give a better estimate of the contribution from Antarctica, and because the bathymetry of the Weddell Sea is poorly constrained, a second experiment has been performed with a lowered bathymetry in the Weddell Sea. In this simulation, the Antarctic grounding line retreats both in the Ross and in the Ronne-Filchner regions. The corresponding ice-equivalent sea-level rise is 17.5 m and the global sea-level rise is 129.5 m. The Antarctic sea-level contributions (9.5–17.5 m) are in agreement with Denton and Hughes [40], Ritz et al. [8], Huybrechts [6], Bentley [41], Peltier [42], but are not consistent with Colhoun et al. [43], Nakada and Lambeck [44], Budd and Smith [45], Oerlemans [46] and CLIMAP [47].

Sensitivity experiments have been performed to identify which parameters trigger the decrease of the ice volume. These results clearly demonstrate that insolation, atmospheric CO_2 and basal melting have an influence on the triggering of the deglaciation process. Basal melting and atmospheric CO_2 also impact the overall surface mass balance. However, the greatest influence is that of the sea-level rise due to the NHIS melting, which is a crucial parameter for the deglaciation of Antarctica through its impacts on the destabilization of the ice shelves and, consequently, on the inland grounded ice. To test the impact of simulating the climate throughout the deglaciation period rather than prescribing it from the Vostok reconstruction, we compared the fully coupled experiment to a GRISLI only one forced by the Vostok data series. We showed that the difference in sea-level rises (9.5 m for the former and 15.0 m for the latter) is mostly due to the underestimating the surface temperature over the ice sheet. Therefore, we performed a last sensitivity experiment where we used a perturbative method to produce more realistic temperatures over the ice sheet. This last simulation yields a similar sea-level rise, but different deglaciation timing.

Since we obtained a realistic deglaciation scenario, we were able to show that the sea level is a crucial parameter for the melting of Antarctica. The sea level produced by the melting of ice sheets in our model will be prescribed to CLIMBER in future work instead of using SPECMAP sea-level rise curve.

In this work we do not account for high-frequency variability occurring during the deglaciation (Heinrich events, Younger Dryas, Bølling-Allerød). A future step is to investigate the impact of such events during the deglaciation process. In particular the impact of Heinrich Event 1 in terms of freshwater perturbation may be addressed to infer whether it may change the timing of deglaciation of our standard experiment.

Acknowledgments

We thank Andrey Ganopolski and the CLIMBER team for providing their model, Valérie Masson-Delmotte and Didier Paillard for helpful advice and Claire Carvallo. The authors appreciate the constructive comments of M.L. Delaney and anonymous reviewers. This work has been supported by PNEDC French National Programs IMPAIRS. Computing was carried out at LSCE, supported by CEA.

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