Coupling an AGCM with an ISM to investigate the ice sheets mass balance at the Last Glacial Maximum

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Abstract.
The aim of this paper is to investigate the consistency between the ice sheets reconstruction at the LGM and the climate simulated by AGCM. In particular, to investigate whether the laurentian and the fennoscandian ice sheets have an equilibrated mass balance, we use two complementary approaches. First we analyze the changes of snow and water budgets over the ice sheets, only using the model results of LGM runs. Second, we use a thermomechanical ice sheet model [*Ritz et al.*, 1997] forced with the AGCM simulated climate, to perform long term runs at finer spatial resolution. Analyzing the results obtained with both approaches, we show that the ice sheet mass balance computed directly from AGCM results may be biaised. Moreover we show, using two versions of the LMD AGCM, that the ice sheet mass balance computed by the ISM is drastically sensitive to the summer surface temperatures simulated by the AGCM.

1. Introduction

The impact of the ice sheet on glacial climates has already been investigated [*Manabe and Broccoli*, 1985, *Kutzbach and Wright*, 1985]. The storm track evolution has also been intensively studied for Northern Hemisphere [*Hall et al*, 1997, *Rind*, 1986, *Kutzbach and Guetter*, 1986]. A step towards coupling Atmospheric Global Circulation Models (AGCM) and Ice Sheets Models (ISM) has also been done [*Verbitsky*, 1995], and also for past periods (Eemian, 115 kyears BP, *Schlesinger*, 1996). Here we want to investigate the capability of AGCM alone and AGCM one way coupled with ISM to maintain the ice sheets during LGM. In previous papers [*Ramstein et al*, 1997, *Fabre et al*, 1997], we have shown that the results obtained using different versions of LMD AGCM simulations of the LGM, with a direct and a one way coupling approaches, were model-dependent. The term "one way coupling" will be employed to refer to the use of AGCM results as input to the ISM. It is not a real coupling, because results of the ISM are not feedbacked to the AGCM.

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2. Description of the models and design of the experiments

2.1. Description of the AGCM

The numerical experiments described below have been performed using the LMD AGCM. A detailed description of this model and the version used can be found in *Ramstein et al* [1997]. All the AGCM simulations have been performed in the framework of Paleoclimate Modeling Intercomparison Project (PMIP) [*Joussaume*, 1995]. The ice sheets reconstruction which has been chosen as a common boundary for all the models performing LGM simulations, is *Peltier* [1994]'s reconstruction. A first experiment is performed with LMD4.3 (prescribed sea surface temperatures); we analyze results of both the direct and one way coupled approaches (EXP 1). Then three experiments are performed using LMD4.3 with computed sea surface temperatures (EXP 2), LMD5.3 with the 64x50 resolution (EXP 3) and LMD5.3 with the 96x72 resolution (EXP 4). In these three experiments, we only analyze the results of the coupled approach (i.e. the ice sheets characteristics).

2.2. Description of the ice sheet model (ISM)

We use a three dimensional ISM. It has been used to simulate the present and LGM states in the northern hemisphere [*Fabre et al*, 1997, *Ramstein et al*, 1997]. The evolution of the ice sheet surface and geometry is a function of surface mass balance, velocity and temperature fields, and bedrock position. We will not present here the equations of the model, but a comprehensive description has been done in *Ritz et al* [1997]. However we will devote a few words to the surface mass balance calculation. The surface mass balance is the sum of several terms calculated separately: accumulation, ablation and calving. The accumulation term is computed from interpolated AGCM temperatures and precipitation. We consider accumulation as the solid part of precipitation, which is obtained by taking into account the precipitation of the fraction of the year with mean daily temperature less than 2°C. The ablation term is computed using the "positive degree-day method" [*Reeh*, 1991], which uses the number of days with a positive mean temperature in an empirically derived function. The mean daily temperature is computed from the mean annual and the mean summer temperatures, assuming the annual temperature cycle can be represented by a sinusoidal cycle. As the surface temperature is dependent upon altitude, it is computed each time the altitude has a new value, using a temperature versus altitude gradient of 8°/km, as is observed in polar regions [*Reeh*, 1991]. Ice shelves are not treated in the model. The ice lost by calving at the margin is computed by setting the ice thickness to zero on a "coast line" determined by sea level, which is set to zero for present state simulations, and to −105 metres for LGM state simulations, following *Peltier* [1994]. The initial condition for each ISM experiment is *Peltier* [1994]'s LGM ice sheets reconstruction. We analyze the results after 10 000 years of integration under the same climatic conditions, assuming that steady state is obtained when the main characteristics of the ice sheets do not evolve anymore.

2.3. Coupling strategy between the AGCM and the ISM in the one way coupled approach

In the direct approach, we analyze the outputs of the AGCM, without any correction. In the one way coupled approach, we use three data sets from the AGCM simulations as input to the ISM: mean JJA (June-July-August) surface temperature, mean annual surface temperature and mean annual precipitation. The first two are used to compute ablation at the ice sheet surface and the last two to compute accumulation. The AGCM fields are not directly used in the ISM. They are first converted from the AGCM geographical grid to our cartesian system by the Lorgna projection (Lambert azimuthal equi-areal projection), and interpolated on the ISM grid (50 km x 50 km). The initial ice sheet topography for the LGM simulations comes from *Peltier* [1994], with a resolution of 1°by 1°. When used in AGCM simulations, the topography is interpolated on the AGCM grid and the elevation is smoothed because of the coarse grid boxes. From the AGCM simulations of present-day and LGM climates, we deduce the "anomaly" of temperature and precipitation, which represents the difference between simulated LGM and present-day climates. To be used as an input to the ISM, we reconstruct the LGM surface temperature (T_{LGM_rec}) as follows:

$$T_{LGM\_rec} = T_{clim} + (T_{LGM\_AGCM} - T_{ctrl\_AGCM}) \quad (1)$$

where $T_{LGM\_AGCM} - T_{ctrl\_AGCM}$ is the anomaly computed by the AGCM between LGM and present-day runs and T_{clim} the present-day surface temperature given by the climatology. These values are then corrected for the elevation difference between the AGCM grid and the ISM grid, to account for the finer resolution of the ISM, with the same lapse rate as in the ISM, 8°/km. LGM precipitation is reconstructed using a ratio of precipitation rather than a difference to define the AGCM anomaly between LGM and control [*Fabre et al*, 1997]. The LGM "reconstructed" precipitation (P_{LGM_rec}) is given by:

$$P_{LGM\_rec} = P_{clim} \frac{P_{LGM\_AGCM}}{P_{ctrl\_AGCM}} \quad (2)$$

where notations are the same as in equation 1.

3. Discussion

The results of the direct and coupled approaches are analyzed together. The outputs of the AGCM simulations are directly analyzed, in terms of mass balance at the surface of the ice sheets; these outputs are then used as input to the ISM, following the coupling methodology presented above, and the results of the ISM are analyzed, in terms of ice sheet extension and thickness.

3.1. Comparing LMD4.3 results for both approaches

A first LGM simulation has been performed using the LMD4.3 version of the AGCM. LMD4.3 has a low resolution, with 48 points in longitude and 36 points in sine of latitude (lower resolution at the high latitudes). The results of the direct approach show a nearly equilibrated mass balance above the fennoscandian and the laurentian ice sheet, respectively 0.16 and 0.25 mm/day (cf table 1), considering mass balance as precipitation minus evaporation and runoff (all these terms are computed from the AGCM, without any correction). In the one way coupled approach (fig. 1), the results show that the ice sheets cannot be maintained: both the fennoscandian and the laurentian ice sheets nearly collapse, with the strongest effect on the Laurentide. In this approach, the initial LGM ice sheets (Peltier's reconstruction) are clearly not in equilibrium with the prescribed LGM climate, because of a negative mass balance. The comparison of the results of both direct and coupled approaches shows a major disagreement [*Ramstein et al*, 1997]. In a first step, we shall investigate the reasons for such differences.

Comparing AGCM precipitation for present-day run and climatology, we observe an overestimation of the AGCM over the continents of the northern hemisphere by a factor 1.5 to 3. This leads to a very different precipitation between direct results of the AGCM (P_{LGM_AGCM}) and inputs of the ISM (P_{LGM_rec}) when correction is done. The ISM precipitation for LGM is drastically reduced. Considering the reconstructed precipitation deduced from the Greenland ice core [*Dahl-*

Table 1. LGM mean annual, summer and winter net snow accumulation S, surface temperature T_s, precipitation P, evaporation E, and runoff R, as simulated by LMD4.3. $P-E-R$ represents the ice sheet mass balance.

Ice sheet	Period	S (cm)	T_s (°C)	P (mm/day)	E (mm/day)	R (mm/day)	$P-E-R$ (mm/day)
Fenno-	annual	30.99	-16.77	1.33	0.73	0.44	0.16
scandia	DJF		-38.70	0.72	0.05	0.00	0.67
	JJA		1.66	1.81	1.44	0.63	-0.26
Lauren-	annual	34.92	-9.55	2.12	0.89	0.98	0.25
tide	DJF		-22.7	1.62	0.24	0.28	1.10
	JJA		1.43	2.62	1.41	1.82	-0.61

Figure 1. Map of the steady state obtained with the ISM for the LGM climate, with temperatures and precipitations reconstructed from LMD4.3 (prescribed SST). Ice elevation is in kilometres.

Jensen et al, 1993] and comparing it with simulated LGM values, there is also an overestimation of precipitation in the LMD AGCM: the corrected values used in the ISM seem then more realistic. Therefore in the direct approach, the accumulation is overestimated due to heavy precipitation, and the mass balance of the ice sheet is obtained because there is an equilibrium between important accumulation and ablation. The ablation reaches also high values because the summer temperatures for LMD4.3 are positive, leading to melting (cf table 1). On the other hand, in the coupled method, the ablation is similar but the accumulation is strongly reduced, which leads to a collapse of both ice sheets. However, these results must be taken with caution, because they may depend on the way ablation is parameterized in the ISM (empirical parameterization on present day values for the snow and ice melting coefficients). The lapse rate coefficient used to correct surface temperatures (8°/km) is empirical too. The sensitivity to the lapse rate values may slightly modify the results. In conclusion, the one way coupled method is more adequate to evaluate LGM ice sheets equilibrium. In other experiments, we will therefore focus only on the results of the coupled appproach.

3.2. Impact of the Sea Surface Temperatures

In this first experiment (EXP1), the sea suface temperatures (SST) were prescribed by the *CLIMAP* [1981] data base. This is a very strong constrain on the simulated hydrological cycle. To avoid this constrain we couple the LMD4.3 AGCM with a slab ocean (mixed layer 50 meters, constant depth), which accounts for the oceanic thermal response (EXP2). The results (not shown here) are similar to those of the fixed SST experiment (EXP1): Laurentide and Fennoscandia still collapse. Moreover, ice caps are created in Alaska and Siberia, where geological evidences do not show ice at the LGM. Computing SST therefore does not play an important role in the maintenance of the ice sheets for this version of the model. The important factor is the high summer temperatures simulated in both runs (fixed or computed SSTs), which lead to high ablation values and the collapse of the ice sheets.

3.3. Results with a new version of the AGCM

A new simulation has been performed with a more recent version of the AGCM, LMD5.3. Both the resolution and the physics of the model have improved in this version: its resolution is 64 points in longitude and 50 points in sinus of latitude. The internal physics has improved mainly on three domains: first, this version includes a sub-grid representation of fractional sea ice cover; second, the vegetation cover is taken into account; the last improvement concerns surface albedo: it is computed from the snow depth, cover and age, and the vegetation cover. This snow albedo modification is indeed the most important for our concern because it tends to increase albedo over the ice sheets and decrease temperatures which are too warm in the previous version. Results of the experiment (EXP3) are shown on figure 2. This experiment clearly gives better results than the previous ones (EXP1 and EXP2): the laurentian and fennoscandian ice sheets are very close to their initial configuration, which proves that the ice sheets are in equilibrium with the AGCM simulated LGM climate. When comparing the precipitation and surface temperature fields from LMD4.3 and LMD5.3 (table 1), it appears that precipitation fields are close, but that mean summer surface temperatures over snow are much

Figure 2. Map of the steady state obtained with the ISM for the LGM climate, with temperatures and precipitations reconstructed from LMD5.3 (resolution 64 × 50).

colder in LMD5.3 than in LMD4.3 (respectively -2.20°C and 1.66°C on the fennoscandian ice sheet, and -3.45°C and 1.43°C on the laurentian ice sheet). Consequently, mean ablation is lowered, which leads to a mean mass balance near zero. We thus conclude that the most important improvement from LMD4.3 to LMD5.3 for our results concerns the snow albedo calculation.

Another important improvement between EXP3 and EXP1 and 2 is the finer resolution. This may have participated to the better results we obtain in EXP3. Using outputs with a finer resolution leads to a smaller correction when we interpolate the AGCM outputs on the 50 km × 50 km ISM grid. To test the impact of the resolution, we have performed a last experiment (EXP4) using LMD5.3, and an even finer resolution: 96 points in longitude, 72 points in sine of latitude. The results (not shown here) are still satisfactory, but they have not been improved compared to the last experiment (EXP3, fig.2).

4. Conclusions

Using two parallel approaches in evaluating LGM ice sheets equilibrium through mass balance, we have shown that AGCM results, in terms of mass balance, had to be analyzed carefully. The accumulation term is strongly overestimated in both versions of the LMD AGCM and biaises the ice sheet mass balance. In the one way coupled approach, the precipitation is corrected and the reconstructed precipitation leads to more realistic values for the accumulation term. This approach is then more appropriate to compute the ice sheet mass balance. For the LMD4.3 simulation we have demonstrated that whatever the SST were prescribed or computed using a slab ocean, both ice sheets Fennoscandia and Laurentide collapsed. The main reason for this collapse is the strong ablation due to the positive summer temperatures computed by the LMD4.3 version at LGM over both ice sheets. With the more recent LMD5.3 version, the ice sheet albedo is more accurately computed and leads to higher values which decrease temperatures over the ice sheets. We get very satisfactory results with this version: the initial Peltier's ice sheets are in equilibrium with the simulated LGM climate. Moreover, we show that there are not important improvements when we increase the resolution from 64 × 50 to 96 × 72. Next step will be to use the one way coupled approach to diagnose the ice sheet mass balance with other european AGCM involved in PMIP. As we have shown that the ISM was very sensitive to the AGCM inputs, such a coupling should be a very interesting tool to intercompare model results over the ice sheets. It would also be interesting to evaluate the sensitivity of results to different ISM, in order to know to what extent the results presented here are dependent on our ice-sheet model.

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