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Climate of the Past Discussions

Interactive comment on “Numerical reconstructions of the Northern Hemisphere ice sheets through the last glacial-interglacial cycle” *by* S. Charbit et al.

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Responses to Lev Tarasov :

1) Pbs with d18O and initial boundary condition should be more clearly spelled out in the introduction and the conclusions :

a) Due to their high computational cost the GCMs cannot provide a transient evolution of climate over glacial-interglacial cycles. Using GCMs, the only way to derive a time-dependent climatology to force an ice-sheet model over such a long time period is to use climate snapshots and to interpolate the climate fields through time. The rapid climate variability which occurred during the last glacial period has likely played a major role in the ice sheets evolution. To account for this variability, a climatic index inferred from the temperature signal of the GRIP ice core seems to be one of the best choices to interpolate through time climate snapshots. However, we agree with Lev Tarasov on the fact that the d18O climate index presents some shortcomings. The climate recorded at the GRIP site results from the external forcings (i.e. insolation, greenhouse gases, aerosols, and so on) added to all internal climate feedbacks that may have occurred, but at the GRIP location only. Therefore, if some feedbacks are only activated at the GRIP site they can produce artifacts in other regions. We have also tested other climatic indices, such as that based on the atmospheric CO2 record at Vostok, tested for the last deglaciation period (not published), which provided results close to those obtained with the d18O index. Another way consists in using the insolation signal to derive a climatic index. However, this method cannot account for any internal climate feedbacks. As recommended by Lev Tarasov, this point will be more clearly spelled out in the revised manuscript.

b) This works also identifies the importance of having an accurate ice sheet boundary condition for paleo-intercomparison of GCMs :

The deviations of our simulations from geological data are partly due to an overestimation of the albedo effect in the climate simulations due to shortcomings in the ICE-4G reconstruction. As an example, the glaciation of the Siberian region results from cold temperatures simulated by the climate models in response to the erroneous amount of ice provided by the LGM ICE-4G reconstruction. Another artifact induced by the initial GCM boundary condition is the too large eastward expansion of the Eurasian ice sheet around the Middle Wechselian period; this latter shortcoming also results from the fact that our approach is unable to produce a reduction of precipitation in the Eastern part due to the growth of ice over the Scandinavian region. This is stated in the manuscript but will be better emphasized in the corrected version.

2) Fast flow :

Lev Tarasov would like to see addressed the question of fast flow representation (due to till deformation) in the ice-sheet model and raises the question of this fast flow would improve the comparison between our LGM simulated ice volumes. It is clear that accounting for the fast flow due to basal till deformation would probably improve our LGM results in terms of simulated ice volume-sea level data comparisons; Moreover, as outlined by Lev Tarasov in his review of the present paper, fast flow is required to obtain a reasonable multi-domed ice-surface topography that fits relative sea-level constraints (Tarasov and Peltier, 2004). The last point is that accounting for sediment deformation could also improve the timing of our simulated deglaciations. However, the GREMLINS model does not include any representation (or parameterization) of the ice streams and therefore no representation of fast flow due to basal water. Therefore, we think that it would be of poor physical meaning to include a representation of fast flow due to basal till deformation without accounting for streaming (or at least for the impact of longitudinal stresses). However, we agree that the suggestions of Lev Tarasov are of great interest in ice sheet modeling, and the fast flow due to sediment deformation will be implemented in the near future in the GRISLI-North model. This model was first developed for the Antarctic and has been recently applied to the Northern Hemisphere. It accounts for flow through ice shelves, computes dynamically the grounding line migration, and detects the ice stream zones where the ice flow is considerably accelerated. Using this latter model, Peyaud (2006a) performed simulations of ice sheets over the last glacial-interglacial cycle. The forcing climate relies on a pertubative method of the present-day climate, and the anomalies of climatic fields between glacial and interglacial periods and used to force GRISLI are interpolated through time using the GRIP-based d18O index. These anomalies are not computed by GCMs but are deduced from an inverse method and are constrained by ice margin limits consistent with geological data. Sensitivity experiments to parameters which control the water drainage efficiency have been carried out. The difference of LGM ice volumes between the baseline experiment (which is equivalent to a grounded ice-only experiment in which no streaming occurs, and thus fully consistent with a GREMLINS experiment) and the most dynamic experiment is about 8.0x1015 m3. This comparison allows the

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impact of ice stream flow to be evaluated. As an example the highest LGM ice volumes are obtained in the present study with the UGAMP and CCSR1 models (73.6x1015m3 and 71.5x1015 m3 respectively). Accounting for streaming could lower these values to 65.6x1015m3 and 63.5x1015 m3 respectively. Moreover, in the Eurasian sector, the discrepancies between simulated ice sheets and geological data could also come from the absence of the ice-shelf dynamics in GREMLINS (Peyaud, 2006a,b) and from shortcomings in the ICE-4G reconstruction, as mentioned above (see response 1b). If the amount of Eastern Siberian ice is removed (geological data show that this region has never been ice-covered), the UGAMP and CCSR1 ice volumes are respectively 61.8x1015m3 and 60.1x1015m3, well above the value of 56.1x1015m3 corresponding to the sea-level converted into ice volume. This computation has been performed for all the GCMs used in the present study. The results will be presented in the revised manuscript. The use of the LMD5 model provides the most compatible value with the ICE-4G LGM value. The ECHAM3 model leads to a value close to the sea-level equivalent ice volume value. UGAMP and CCSR1 lead to too high volumes, even after corrections for strong sliding and Siberian ice volume, whereas, GENESIS2 and MRI2 ice volumes are significantly too small. However, these volume corrections partly rely on the correction of streaming (and set to its maximum value of 8.0x1015m3). To go thoroughly we need to account for the deformation of sediments which is responsible for a great part of the ice streams flow. This question will be addressed in a future paper devoted to same kind of study but with the PMIP2 AO-GCMs, run with the updated ICE-5G reconstruction at the LGM. These new runs will force the new GRISLI-North model

3) Glacio-hydro-isostasy models :

We fully agree with Lev Tarasov, and his comment will be added in the revised manuscript.

4) Third alternative approach :

Although the areal extents of the North American and Eurasian ice sheets are quite well constrained during the last deglaciation and the late quaternary periods respectively, great uncertainties remain about the shape and the ice volumes of these major complexes. In the introduction of this paper we mentioned two different approaches to reconstruct the past 3D history of both ice sheets. The first one is based on glacio-hydro-isostasy models and the second one on 3D-thermomechanical modeling. However, we omitted to precise that a third alternative approach proposed by Tarasov and Peltier (2004), consists in taking advantage of both methods: they performed a set of simulations where the model parameters were varied in order to cover the deglacial phase space. Moreover the ice sheet margin chronology was imposed, and the model is constrained by relative sea-level data, the space geodetic observation of the present-day uplift rate at Yellowknife and a transect of absolute gravity measurements going from the West coast of the Hudson Bay to South Iowa. This will be added in the revised manuscript.

5) Description of the calving treatment :

Although the ice-calving is not explicitly computed in the model, it is parameterized in the following way: the ice lost by calving is setting to 0 when ice begins to float. This cut-off condition is not imposed at each time step so that ice is allowed to advance over the continental shelf. Consequently, if the sea-level drops, but there is still water in a given location, the ice sheet can expands over the sea. This will be added in the revised manuscript.

6) Lapse rates :

It is worth noting that lapse rates values used in this study rather resemble moist adiabatic free-atmosphere lapse rates rather than near-surface temperature lapse rates. Marshall et al. (2006) reported near-surface values around 4°C/km for the Ellesmere Island region and for a period spanning from May 2001 to April 2003. They also presented evidence for a strong dependence with seasons and atmospheric condi-

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tions: steep lapse rates (˜ 6 to 7°C/km), close to our summer value (˜ 6.5°C/km) are more common in summer and associated with an enhanced cyclonic activity, whereas weaker values (˜ 2°C/km) occur when anticyclonic flow prevail. Although these findings are not warranted to be suited other regions, since lapse rate values are expected to spatially vary, we must keep in mind that an overestimation of the vertical temperature gradient will lead to an underestimation of snow and ice melt in ice-sheet mass balance modeling studies. This comment will be added in the discussion section.

7) Multi-domed ice-sheet :

The comment of Lev Tarasov will be accounted for in the revised manuscript;

9) Section 3.2 :

We will include in the revised manuscript a table including the main results mentioned in section 3.2.

8) A few precisions about the timing of the last deglaciation :

At the end of the simulation (see Fig. 7), small ice caps have not completely retreated in the Arctic Ocean, while the simulated deglaciation of the Laurentide ice sheet is achieved. At around 6 ka BP (not shown in the manuscript), the ice-sheet spatial distribution exhibits ice over the Canadian Archipelago for all models. At around 4 ka BP, this ice complex is still present in the simulations forced by UGAMP, CCR1, and to a lesser extent, by ECHAM3, while it is completely melted in runs forced by LMD5, MRI2 and GENESIS2 models. Therefore, it is clear that the simulated deglaciation is a little delayed compared to geological data that show that at 6 ka BP the deglaciation was achieved. Several reasons may be at the origin of this lag:

a) The first one is linked to the huge LGM ice volumes obtained with UGAMP, CCSR1 and ECHAM3;

b) The second one may be due to the fact that the ice-sheet model is forced by the sea-level reconstruction provide by Bassinot et al. (1994), and in this reconstruction the sea-level does not return to its present-day level before 4 ka BP;

c) The Antarctic contribution to sea-level rise is accounted for in the “sea-level reference curve” (dashed line in Fig. 8a). This contribution has been deduced from the modeling study of Ritz et al. (2001). In their simulation, the grounded ice volume undergoes a monotonic decrease from the 14 ka BP (corresponding to the maximum Antarctic ice volume) until present. In the same way, using a coupled climate-ice-sheet model Philippon et al. (2006) presented the same kind of behaviour for the deglaciation of Antarctica.

Responses to the anonymous reviewer

1) Rewiever 2 notes that the content of the manuscript lacks sufficient depth into investigation and only examines the temporal ice volume and extent and the spatial distributions of the simulated ice sheets. We fully agree with this statement and we could have examined in more details other parameters such as the temporal evolution of the ice flow velocities, the impact of isostasy. We could also have added an ad-hoc correction to account for the albedo effect by increasing/decreasing temperature when ice appears/disappears. Moreover, the impact of “ground/ocean” effect has not been examined. This effect is due to a strong temperature contrast between continents and adjacent oceans. With the relative method used to force the ice-sheet model this effect is poorly represented and may induce additional artifacts in our simulations. However, our aim was to investigate the ability of GCMs to simulate a climate consistent with past ice sheet geological reconstructions. We were faced with a great variability within the results, and this is why we have not studied other processes, which are of second order compared to the huge differences highlighted in our analysis of the results.

2) Figures 5 and 6 :

The ice-sheet model is forced by the sea-level, but the sea-level is not interactively computed. Therefore, what is highlighted in the figures is the isostatic effect, and not the ice equivalent sea level: if there is a large amount of ice over Beringia or adjacent regions, the bedrock will deeply be depressed, and as a consequence, the Bering Strait will remain opened.

3) All the technical corrections and the suggested references will be added in the revised manuscript.

References :

Peyaud, V., Rôle de la dynamique des calottes glaciaires dans les grands changements climatiques des périodes glaciaires-interglaciaires, PhD thesis, Joseph Fourier University, 2006a.

Peyaud, V., Ritz , C., Krinner, G., Modelling the Early Wechselian Eurasian Ice Sheets: role of ice-shelves and influence of ice-dammed lakes, submitted to CClimate of the Past, 2006b.

Interactive comment on Clim. Past Discuss., 2, 879, 2006.