Earth Syst. Dynam. Discuss., 6, C675–C681, 2015
www.earth-syst-dynam-discuss.net/6/C675/2015/

Earth System Dynamics Discussions

Interactive comment on "An ice sheet model of reduced complexity for paleoclimate studies" *by* B. Neff et al.

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Received and published: 12 October 2015

Revision Memo to Anonymous Referee #2 (3 October 2015)

We thank reviewer #2 for the review and the important comments. Since the comments concern the basic aim of our manuscript we will answer them in full here. We are aware that our manuscript is at the interface of several journals but we decided in favor of ESD for reasons detailed below. The reviewer's comments are very useful for us to revise our work toward a better fit with this journal. However, as we will point out below, we consider them to be straightforward to address, for which we suggest specific amendments.

Reviewer:
This paper aims at presenting a new ice sheet model which can be used for paleoclimate studies. If focus was only on the model, then Geoscientific Model Development (GMD) would have a much better venue than Earth System Dynamics (ESD). But the authors also want to show that interesting results can be obtained with this model, in particular the hysteresis of the northern hemispheric ice sheet distribution versus global temperature offset (section 4).
On both aspects, however, the paper is not sufficiently developed to recommend publication and a major revision is needed. Below suggestions are given to improve the paper; only major issues are mentioned.

Response:
We agree that GMD would have been an almost equally well suited journal for our work. However, in our opinion this would have put too much emphasis on the model development aspect of the manuscript. Ice sheet models of similar complexity as ours have been presented before, but at that time the focus on numerical efficiency was motivated by the lack of computational power. The novelty of our approach is the deliberate choice to trade detail in the ice dynamics for the possibility to run very long simulations and large ensembles. Thus, it is very important to acknowledge that our model does not compete with current state-of-the-art ice sheet models. Our model rather fills a gap in the hierarchy of ice sheet models between more simplified and often unphysical models and comprehensive, but computationally heavy ice sheet models. Ice age cycles and their frequency and the stability of ice sheets can now be studied with a physically based model. It is this broader aim that motivated our decision to submit this work to ESD instead of the more specialized GMD or 'The Cryosphere'. We trust that the editorial decision to accept the paper for pre-publication in ESDD took the scope of the manuscript into consideration.

Reviewer:

1. In section 2, many essential details of the model are not given. For example, it is unclear how the surface mass balance (please use M instead of SMB in (1)) is precisely computed from the temperature and precipitation. The model uses a C-grid but, as only h and B appear to form the state vector, how are the variables staggered? What is the time step and is this accurate enough over long integration periods?

Response:
From the comments of both reviewers we understand that certain details of the model description were not sufficiently clarified. We made the effort to eliminate non-essential technical information from the manuscript for publication in ESD but apparently misjudged the importance of certain details. We apologize for the resulting confusion. The full technical description is available in the thesis of the first author, and the essence will be included in the manuscript, including a figure to clarify the staggered numerical grid (see figure 1 at the end of this document).
The discretization is as follows: The ice diffusivity D, equation (2), is calculated on the regular model grid, for which the gradient in surface elevation dZ/dx is calculated from centered differences. In the next step, the flow of ice is calculated on staggered grid points (FN, FS, FW, FE in figure 1). The diffusivity D is interpolated on these points. Lastly, the four ice fluxes surrounding one regular grid box are used to determine the ice thickness on the regular grid for the next time step of one year. We also performed simulations on an Arakawa A-grid (only regular grid points) which did not yield stable results. We are prepared to include all of this information in the manuscript, including a revised version of figure 1.
As already summarized in our reply to reviewer Bas de Boer, the surface mass balance is calculated from daily data. The time step for the ice dynamics is one year, which is common in models of this complexity. This information is indeed included in the present manuscript, but apparently not clear enough.

Reviewer:

2. What is important to show in section 2 is that an integral mass balance (over the model domain) is satisfied in the model. As boundary conditions at the ice interface are dealt with in a rather sloppy way, such an integral balance may be easily violated with possibly large consequences for the solutions. If there is no integral balance of mass, the paper cannot be published.

Response:
We agree that the positive degree day (PDD) method is not ideal for modern ice sheet models because it lacks a physical justification. Notwithstanding, it is still widely used and was found to describe the surface mass balance satisfactorily in a number of applications (e.g., Quiquet et al., 2013).
Regarding the integral mass balance, we argue that this important quantity is implicitly, but thoroughly, tested by the EISMINT simulations in section 3. Here, a prescribed surface mass balance is applied as defined from idealized evaluation experiments. The ice thickness at the center of the simulated ice sheet in our results agrees with the reference results to within less than a meter in both experiments. The shape of the ice sheets is virtually indistinguishable from the reference. This strongly suggests that the integrated ice balance is satisfied in the model. In other words, it does not contain spurious sources or sinks of ice. In addition, we implemented safeguards that prevent imbalances in the mass balance even in the unlikely case that the Courant-Friedrichs-Lewy condition is temporarily not met. This information will be included in the revised manuscript.
The simulations in the Northern Hemisphere domain calculate the surface mass balance differently, which has known shortcomings that we discuss, but since the ice dynamics code is the same as in the idealized EISMINT simulations, it conserves mass to an integral of zero in equilibrium also here. There is a possibility for an imbalance in the implementation of the PDD and the accumulation which has not been tested yet. This analysis is straightforward to carry out without major modifications to the model. We will specifically test and document this in a revised version of the

manuscript.

Reviewer:
3. The most interesting results are presented in section 4.3 but these are only described, without any further analysis on the mechanisms of the hysteresis behavior. For a paper in ESD, it is important that further analysis should be done. So what feedbacks (mass balance-height, marine ice-sheet instability, ..) determine the transition from a solution on one branch in Fig. 8 to the other?

Response:
The experiments in section 4.3 illustrate one of the main strengths of the new model and we are heartened to see this being recognized. We will gladly expand this section. As mentioned above, the aim of these experiments was to test the stability of the Northern Hemisphere ice sheets as a function of their volume, which is fundamental to explaining the nonlinear response of ice sheets to orbital forcing and the resulting frequency of Pleistocene glaciations. As an example for how to expand the analysis, we propose to investigate one fundamental but untested assumption underlying the ice age model by Paillard (1998), that ice sheets of intermediate size are inherently more stable to increasing insolation (warming) than fully developed glacial maximum ice sheets (their figure 1). In the revised manuscript, we will extend our analysis to systematically test the impact of temperature increases on ice sheets of different size. This opens the possibility to discuss physical mechanisms in more detail as suggested by reviewer #2.

References:
D. Paillard (1998), The timing of Pleistocene glaciations from a simple multi-state climate model, Nature 391, 378-381, doi:10.1038/34891
A. Quiquet et al. (2013), Greenland ice sheet contribution to sea level rise during the last interglacial period: a modelling study driven and constrained by ice core data,

Climate of the Past 9, 353-366, doi: 10.5194/cp-9-353-2013

Interactive comment on Earth Syst. Dynam. Discuss., 6, 1395, 2015.

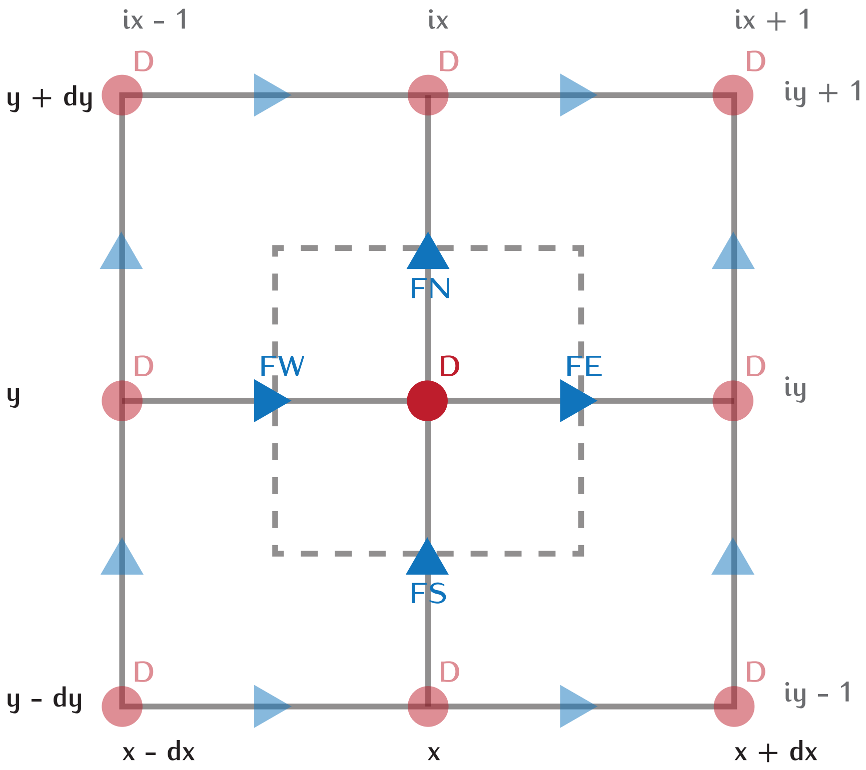

Fig. 1.