Interactive comment on "Glacial cycles simulation of the Antarctic Ice Sheet with PISM – Part 1: Boundary conditions and climatic forcing" by Torsten Albrecht et al.

Response to Referee Johannes Sutter (johannes.sutter@awi.de)

(Received and published: 4 July 2019)

We thank Johannes Sutter for his excellent suggestions and thoughtful comments. Find in **blue** the referee's comments in in **black** the author's response.

The study by Albrecht et al. is an impressive compendium of Antarctic Ice Sheet ensemble simulations covering the response of the ice sheet to different forcing settings and ice sheet model parameterizations. This manuscript is poised to become standard literature for people starting to use the Parallel Ice Sheet Model (PISM) as well as for scientist which already use PISM. The scope of the manuscript fits well into the topics covered by The Cryosphere and I think it is a nice entry into the ice sheet modelling literature.

That being said, the manuscript needs some additional work to improve the readability and to clarify the main "take-aways" for the reader. Due to its holistic scope and length it is sometimes difficult to follow the line of thought. Also typos and the german-style syntax sometimes hampers the reader to fully grasp the content of the manuscript. In isolation these points are very minor but clustered throughout the manuscript they make it difficult to enjoy the overall high quality of this work.

I will provide some general remarks which I deem necessary to be addressed followed by minor comments. Please also find comments and corrections to the manuscript in the annotated attached pdf.

Once again, we would like to thank the reviewer for his very constructive assessment and suggestions for improvement, they really improve the readability of manuscript considerably. We are glad that he considers the study worthy for publication in The Cryosphere (TC).

1. The manuscript truly has an epic length and discusses the impact of different model parameterisations, forcing approaches as well as specific research questions regarding e.g. Termination I. In theory the manuscript could be actually split into two publications, one covering the uncertainties intrinsic to the choice of model parameterisations and climate forcings, and one investigating specifically the response of the AIS to the latter in glacials and Terminations, specifically Termination I. I assume the authors would like to abstain from splitting the manuscript in two, so I suggest reordering the discussion of the results into a part covering the effect of different parameterisations and forcings (e.g. individual forcings versus combined forcings) and a part specifically addressing the intricacies of glacial termination and the impact of model parameterisations and forcings during that period.

We very much understand the reviewer's impression, but as this study consists already of two parts (sensitivity experiments in part 1 and ensemble analysis in part 2), we preferred to reorganize the manuscript with focus on the model description and on the model parameter selection for the ensemble study in the companion paper (Albrecht et al., 2019b). The selection is mainly based on two criteria, the reproduction of the present-day state within an uncertainty range and the LGM ice volume sensitivity to parameter change, while the paramter choice also covers the four uncertainty classes and both Antarctic parts. We totally agree, that in particular the last deglaciation is of particular interest for the community, such that we would like to discuss this aspect in more detail in a separate study.

2. Model results are almost exclusively illustrated as integrated variables (ice volume or SLE ice volume). It would be nice to see some illustrations of ice sheet geometry as modelled for the LIG, LGM and present day, either within the manuscript or as e.g. supplementary videos.

We understand that so much more can be learned about the model's sensitivity to the choice of parameters and boundary conditions with a more detailed look to certain Antarctic regions. Yet, this is boyond the scope of this study, which focusses on a first estimate of relative parameter sensitivity, as selection criterion for the ensemble analysis in the companion paper (Albrecht et al., 2019b).
In fact, there is already a movie of the reference simulation available in the assets of this manuscript submission covering LIG, LGM and PD (see https://doi.org/10.5446/41779). As the reference simulation corresponds to the best fit simulation in the companion paper (Albrecht et al., 2019b) there are also some more plots in the corresponding Sect. 3.3 covering LGM, last deglaciation and present-day. We have already mentioned this in the introduction section:
„The sensitivity of the modeled ice volume above flotation to different choices of parameters and boundary conditions is evaluated as the difference to a baseline simulation (Movie: Albrecht, 2019) that is consistent with the model configuration of the best fit ensemble simulation presented in the companion paper (Albrecht et al., 2019, ***see plots in Sect. 3.3****).“*

3. Currently, there is a study in TCD by Tigchelaar et al. (https://doi.org/10.5194/tc-2019-83) addressing the effect of isolated forcings versus combined forcings on late Quaternary (ca. last 400 kyr) ice sheet evolution. A similar discussion can be found in condensed form in Section 4.5 of this manuscript. It would be nice to include a comparison to the findings in Tigchelaar et al. as to put the results presented here in perspective.

Yes, we noticed the study by Tigchelaar et al. (2019), published in TCD just one week after our submission. We have added a short paragraph to Sect. 4.5:

„Another recent study using the PSU-ISM ice sheet model also finds a dominance of atmospheric and sea-level forcing on the Antarctic ice volume, over the last four glacial cycles (Tigchelaar et al., 2019), which together drive glacial-interglacial ice volume changes of 12–14 m SLE, while ocean temperature forcing is almost negligible, also during interglacials. Here, we do not want to go into the details of this study, which uses a comparably coarse output of an Earth System Model of intermediate complexity for the atmospheric and ocean forcing instead of a scaling with ice core temperature reconstructions. As a key result, Tigchelaar and colleagues find much smaller individual ice volume changes, which amount to less than half of the full ice volume response. In our simulations, however, the individual response to sea-level forcing (and surface temperature forcing) as well as the sum of all individual forcings exceed the combined response. This is partly due to the fact, that precipitation forcing (up to 50% less during

glacial climate) provides a strong negative effect on the ice volume in full forcing case, which seems to be weaker in the "atm" forcing in Tigchelaar et al. (2019, ca. 15% in Fig. 8). If we consider the LGM and present-day state as rather stable states, a certain perturbation threshold need to be hit to initiate the (non-linear) transition (Termination I) into the other state. In our simulations this threshold can be reached with individual forcings, while in the other study the combined superposition is required.“

Minor comments:
In general, throughout the manuscript you often omit articles ("e.g. the") which makes some sentences hard to read. I marked the spots which where most obvious to me (attached annotated pdf) but maybe I missed a couple.

Thanks, we revised and rephrased the manuscript accordingly.

It would be helpful to know which "baseline" parameter set was used in the parameter sensitivity experiment shown in the various volume line-plots. Is it the one highlighted (in brackets) in Table 1? I guess you put this Table almost to the end of the manuscript as to provide the reason for your parameter selection in the preceeding sections. I would prefer to see such a Table at the very beginning of the paper as to get a quick overview of which parameters have been investigated and which are the optimal combination for paleo-studies with PISM. Some readers might not get to page 38 and miss the table altogether.

We appreciate the reviewer's perspective. Yes, the parentheses are the reference values. We have shifted the table to the PISM introduction and added this (baseline) information to the caption. We have also added a second Table to the end of the results section summarizing the sensitivity stastistic for all varied parameters and boundary conditions.

Check your use of past tense, you almost never use it, I tried to mark all instances in the annotated pdf.

Thanks, we changed this in the manuscript.

You mostly discuss glaciation timescales, glacial maximum ice volume and glacial termination while only shortly touching on the effects of different parameterisations and forcings on interglacial ice volume and extent. Is there a specific reason for this? Also, in your simulations MIS5e ice volume seems to be very similar to your simulated present day ice volume. I think it would be worth discussing this briefly in the manuscript.

LIG is indeed an interesting time period covered by the two-glacial-cycle (2GC) simulations. We found that WAIS collapse at LIG, as the most likely candidate for additional ice mass loss in comparison to PD (as in Sutter et al., 2016), is prohibited in all our simulations. However, discussing the required conditions for WAIS collapse at LIG would fill a separate study.
We find relatively low sensitivity to (warmer than present) ocean forcing as we do not interpolate melt rates over the grounding line. Additionally, the used precipitation scaling with temperature forcing seems to compensate for the mass losses by sub-shelf melting (Fig. 25, light and dark blue). There is also another feedback at play (precipitation scaling with surface elevation change), which seems to stabilize grounding line retreat (we have appended a corresponding simulation to Fig. 25, light orange). Till water availability and till

friction angle seem to play an important role as well. The optimized till friction angles yields intermediate values of up to 20° in the inner WAIS, while the parameterization with respect to bed-topography suggest minimal till friction angles in this deep marine region (e.g. 5°) which increases the risk for collapse (as in Fig. 13).
We have discussed parts of it in the companion study, and have added a paragraph to the revised ocean forcing section *and to the basal paramter section*:

„Ocean forcing likely plays a key role in warmer than present-climates. However, we do not see this effect in our simulations during the Last Interglacial. Although ocean and surface temperatures rise by 1-2 K above present we find similar ice volumes as for present-day, in all our simulations. Precipitation scaling and the till properties seem to play an important role in stabilizing WAIS and preventing from collapse. However, a thorough investigation of necessary model settings for WAIS collapse during LIG would fill a separate study.“
„Till friction angle is an important uncertain parameter for possible WAIS collapse. As no (partial) WAIS collapse is induced in the simulations, we find very similar ice volumes for last interglacial and present day.“

p8, l214-216 Doesn't your study from last year (Kingslake et al. 2018) show sensitivity specifically of the Ross Sea grounding line to the Eigencalving parameterization (Extended Data Figure 7)? I guess it is a question of the ice sheet state and memory effects whether the calving parameterization can play a role or not.

The effect of the eigencalving constant K in both this study and in the previous study (Kingslake, Scherer, Albrecht et al., 2018) is quite similar. For the reference value $K=1\times10^{17}$ m s and larger we do not see much influence on the grounding line and ice volume history, as the eigencalving rate is mainly limited by the minor eigenvalue of the strain rate tensor. For smaller values (e.g. $K=1\times10^{16}$ m s) we find generally smaller calving rates and the ice shelf front can advanced up to the edge of the continental shelf (where an additional calving condition applies), rather independent of climate conditions. This adds some more buttressing and hence causes slightly higher interglacial ice volumes. In fact, a lower K value seems to initiate earlier deglaciation in both studies, which may be a result of existing ice shelves in the LGM state, which become unstable in response to rising sea-level and ocean temperatures. We added some more discussion on this issue and linked to the previous study.

*„For a smaller value of 1×10^{16} m s**, in contrast,** estimated calving rates tend to be smaller than terminal ice shelf flow and thus calving front expands up to the edge of the continental shelf**. The additional buttressing supports a slightly larger present-day ice volume, while in turn the more extended LGM ice shelves can respond effectively to increasing sea level and ocean temperatures, leading to slightly earlier deglaciation (Kingslake, Scherer, Albrecht et al., 2018) .**“*

Naturally for such an extensive manuscript, the discussion sections is covering a lot of ground which makes it difficult to structure. Maybe one or two sentences at the beginning of the discussion preparing the reader with respect to the structure would be helpful (e.g. in the following we summarize the main findings of our study with regard to the impact of different parameterisation and climate forcing choices on the evolution of the Antarctic Ice Sheet during the last glacial cycles analysed above.).

We now provide an overview over the manuscript structure and contents at the end of the introduction. And we rephrased the beginning of the conclusions: „*In this study we have run PISM simulations of the Antarctic Ice Sheet over the last two glacial cycles ~~and investigated the sensitivity of ice volume history to variations in~~. **In the following we summarize the main findings of our analysis with regard to the impact of different** model parameter settings, boundary conditions and climate forcing **choices on the evolution of the Antarctic Ice Sheet.**“*

We also added a transition sentence just before the first results section 2: *„In the following sections we will discuss different choices of model parameterizations, boundary conditions and climatic forcings on the sea-level relevant Antarctic Ice Sheet history over the last two glacial cycles.“*

References

Albrecht, T., Winkelmann, R., and Levermann, A.: Glacial cycles simulation of the Antarctic Ice Sheet with PISM – Part 2: Parameter ensemble analysis, The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-70, in review, 2019b.

Kingslake, J., R. P. Scherer, T. Albrecht, J. Coenen, R. D. Powell, R. Reese, N. D. Stansell, S. Tulaczyk, M. G. Wearing, and P. L. Whitehouse. "Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene." *Nature*558, no. 7710 (2018): 430.

Sutter, J., Gierz, P., Grosfeld, K., Thoma, M., & Lohmann, G. (2016). Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse. *Geophysical Research Letters*, *43*(6), 2675-2682.

Tigchelaar, Michelle, Axel Timmermann, Tobias Friedrich, Malte Heinemann, and David Pollard. "Nonlinear response of the Antarctic ice sheet to Quaternary sea level and climate forcing." The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-83, in review, 2019.