Reply to comments by Reviewer 3: The influence of present-day regional surface mass balance uncertainties on the future evolution of the Antarctic Ice Sheet (egusphere-2023-2233)

Summary of Changes

We are grateful to the reviewers for evaluating our work, and the valuable and constructive comments that help improve the manuscript. In response, we now

- Perform individual thermal spinups for PD-equilibrium simulations.
- Perform additional pre-industrial control simulations.
- Calculate the maximum sea level contribution difference taking into account the control simulations.

Below, we respond to the reviewer's individual comments in detail and describe the actions we took to address them.

Detailed response

(Original report cited in italics)

This paper explores the projections of sea-level rise (SLR) from the Antarctic Ice Sheet using the Parallel Ice Sheet Model (PISM), driven by Surface Mass Balance (SMB) forcing derived from four distinct Regional Climate Models (RCMs). Specifically, the study assesses the impact of these RCMs on SLR projections under the global Climate Model HadGEM2-ES. The research reveals that the choice of RCM reference forcing introduces uncertainties in future sea-level rise predictions, comparable to influential factors like ice sheet model parameterization and global climate model choices. Notably, the study emphasizes that the selection of the RCM can influence the timing of the West Antarctic Ice Sheet (WAIS) grounding line retreat under RCP8.5. A parallel investigation examines the present-day forcing from ERA 5 on the 30ka long-term stability for the four different RCMs.

For clarification, we do not employ ERA5 forcing to drive our model. We employ Regional Climate Models which are driven by ERA-Interim boundary conditions.

While the paper holds promise for publication, there is room for improvement in synthesizing the results, particularly regarding the equilibrium experiments. Further clarification is sought for the 2100 and 2300 experiments, with a specific focus on the rationale behind the SLR projection calculations and whether the numbers are subtracted by control runs.

Equilibriums runs:

While the same parameters tuned to RACMO yield different results for the other RCMs, I understand that it might be computationally prohibitive to conduct a spin-up for every RCM and parameterization. However, my concern lies in whether the obtained results convey physical insights. Typically, a glacial spin-up is undertaken to mitigate model shock, ensuring that projections are grounded in physical processes rather than numerical artifacts. Given this, I find it surprising that RACMO still exhibits considerable model shock.

For our PD equilibrium simulations, we performed an initial thermal spinup using the RACMO forcing. In this thermal spinup we keep the ice sheet geometry fixed while letting the ice-temperature profile adjust. As discussed in our replies to Reviewer 1 and 2, this carries the risk that the thermal state is primed towards the RACMO model. Therefore, we will perform individual thermal-spinups for every RCM forcing individually.

After the thermal spinup, we simulated 30 kyrs of ice sheet evolution starting from the Bedmachine (Morlighem et al., 2020) geometry. Since we employ a wide range of parameters, we assume that not all parameter configurations will be in immediate equilibrium with the initial ice sheet geometry. Therefore, we let the ice sheet simulation evolve for 30 krys such that the simulations approach equilibrium.

We are not sure if the Reviewer addresses our equilibrium simulations in the second half of the paragraph or if the Reviewer addresses already our model projections. To us it is unclear what the Reviewer means with “glacial spin-up". If the reviewer refers to a glacial thermal spinup in which the ice geometry is kept constant, but a transient glacial thermal forcing is applied to the ice sheet, we agree that this might be another option to thermally initialize the ice sheet but it is not necessarily the typical standard option as can be seen in the variety of thermal spinup methods in ISMIP6 (Seroussi et al., 2020). The same also applies if the reviewer refers to a full glacial spinup which additionally allows the ice sheet to freely evolve over one or multiple glacial cycles. Nevertheless, this method would not be useful to just find an equilibrium state of the AIS under present day conditions. For future projection like simulations, it is an approach used by some studies but not the typical one, as also can be seen in the ISMIP6 model methodology.

Our revised spinup approach, suggested by the reviewers' comments, better reflects what has been done in previous studies including ISMIP6 reasonably well. As one of our main goals is to illustrate the impact of RCM-uncertainties in such model setups we are confident that this approach is suitable for the question at hand.

Could you clarify whether there was a change in resolution from the glacial spin-up to the equilibrium run? If not, kindly include the 16km resolution in your experimental design details. Additionally, I am curious about the parameters utilized for the glacial spin-up.

The thermal spinup was performed at 16 km resolution. The equilibrium simulations were also performed at 16 km resolution. The parameter configuration for the thermal spinup was [-pseudo_plastic_q 0.75 -topg_to_phi 8,30,-700,0 , sia_e=ssa_e=1].

I am grappling with the interpretation of the results, uncertain about their physical significance versus numerical artifacts. It would be immensely helpful if you could articulate your key take-home messages from the equilibrium experiments for the reader's clarity. Notably, you mentioned that differences between RCM forcings are four times smaller than the overall model bias. In your opinion, can uncertainty be adequately captured by selecting just one RCM with an ensemble of ice sheet model parameters? The similarities between COSMO, RACMO, and HIRHAM raise questions about whether a recommendation for the future could be to choose MAR and one of the three RCMs to encompass uncertainty. Additionally, would you advocate for a separate glacial spin-up for MAR? These considerations could potentially enhance the abstract of your study.

The PISM-specific model bias occurs in all simulations regardless of the applied forcing. To isolate the signal imposed by the individual forcings from this we calculated the ice thickness differences from the common mean Δh given in equation 3.
Our equilibrium simulations show two main findings. The different RCM forcings lead to different quasi-equilibrium states with over 2m of sea level equivalent ice mass difference, for the same parameter sets. Second, under the same parameters one RCM forcing might lead to strong non-linear responses, while another RCM forcing only exhibits minor changes, which is illustrated in Figure 5. We aim to mention this as well in the abstract of a revised version of the manuscript.

With regard to this finding, we would not generally agree that it is sufficient to look at a model with an overall high SMB (e.g., MAR) and another model with a lower SMB, since the distribution of the SMB plays a key role for regional ice sheet evolution, especially when it comes to nonlinear responses of the ice sheet. Figure 5 can be misleading in this case, since it gives the impression that there is only a difference between simulations forced by MAR and simulations forced by one of the other RCMs. Additional simulations shown in Figure C1 clearly show that there is not only a difference between MAR and the other models.
We now also performed simulations in which we performed a thermal spinup with every RCM forcing individually. Results are illustrated in Figure R3 and will be incorporated into a revised version. We still observe parameter combinations in which one forcing might trigger a strong nonlinear response while other forcings don't.

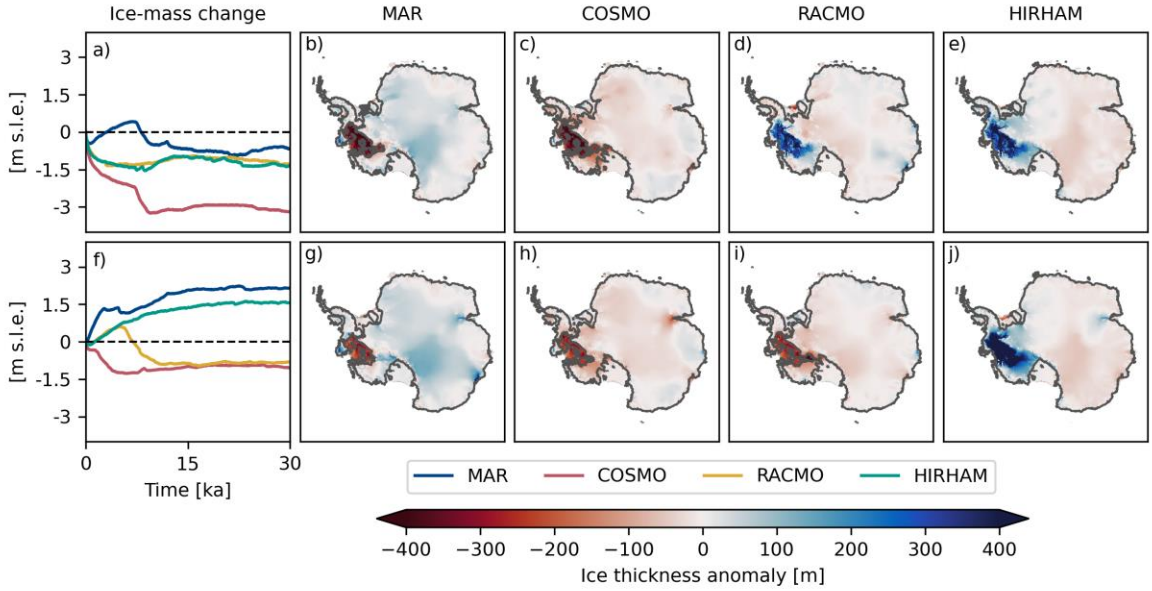

Figure R3

In Figure 4 I cannot see the purple line.

Thank you for spotting this, we removed the purple line to enhance readability. We will adjust the caption accordingly.

Centennial Projections:

Regarding Figure 6: Could you confirm whether all Sea-Level Rise (SLR) contributions are subtracted by the control run? I might have overlooked this detail, and it would be helpful if you could explicitly state whether such subtraction has been performed. Notably, Seroussi et al. subtracted all the runs by control runs. Additionally, consider showcasing only the HadGEM2-ES results from Seroussi's work or, alternatively, emphasize the PISM run(s) for comparison.

Here we do not subtract the control run from the simulation. We discussed our reasoning for this in the reply to Reviewer 1. In summary, we primarily investigate simulation differences due to the RCM forcing. Subtracting by a control run which is driven with the same RCM forcing would subtract some of the RCM signal we want to investigate. To avoid confusion, we will clarify this in the methods of a revised version.

Nevertheless, as also discussed in our reply to Reviewer 1, it is valuable to additionally calculate the mean maximum sea level contribution difference of simulations from which the control run has been subtracted. Therefore, we will present both numbers in the revised version.

As we stated in the manuscript, our main goal is not to provide robust projections of Antarctic SLR contributions, but rather to assess the uncertainties due to the choice of different RCM reference forcings in such simulations. Therefore, we are more interested in the spread between simulations driven by different underlying RCM forcings, than the difference to the present-day ice sheet configuration. Nevertheless, we agree on the necessity of reasonable model-projections and the potential interest of the reader in absolute SLR as well as the model drift. Therefore, we propose the revised simulation setup, described in the reply to Reviewer 1 and Figure R2. In this new setup, we achieve minimal model drift compared to the current setup by performing a 300-year model relaxation under constant PI forcing. Additionally, we will also perform control runs under pre-industrial forcing, for every individual RCM forcing as well as for a mean of all forcings.

On page 12, line 321, you mention calculating the maximum SLR contribution in a specific manner. I am curious about the choice of not subtracting the control run in this calculation. Considering that the glacial spin-up involved a single RACMO forcing, and parameter set, wouldn't it be necessary to subtract the control run for each member individually? Especially after the results obtained from the equilibrium runs show so different behaviour for each RCM. This consideration becomes especially relevant when examining projected SLR uncertainties. Could you conduct this subtraction and provide insights into how it influences the projected uncertainties? Based on Figure D1, it appears that the control runs might not align with the values from 2005, particularly noticeable in the year 2300. Further clarification on this aspect would be appreciated.

We assume the reviewer refers to equation 4 on page 12, (line 232).
As we state in the manuscript, we calculate for every given parameter set the maximum difference in sea level contribution. Since there are four simulations for every parameter set, one for every RCM, the maximum sea level contribution difference is the difference between the simulations with the highest and lowest sea level contribution. Since, we have many different parameter configurations, we then calculate a mean as well as a min and max value over our ensemble. We interpret this number as an estimate of the maximum impact of the choice of an RCM forcing for SLR projections.

As stated above we recognize the interest of the reviewers in the control corrected ice mass change, which is why we will provide additional pre-industrial control runs.

The control runs in Figure D1 show the evolution of Antartica under constant 2005 climate, to contrast the significant changes due to further warming in the RCP scenarios. We do not necessarily expect our simulations to be in equilibrium with the 2005 climate. Consequently, we do not expect the control runs to stay at 2005 levels for the next 295 simulation years.

Figure 7,9: which Year are you showing? I cannot see a purple line either.

We show the year 2300. We will clarify this in the caption.

Figure 9: Is there maybe a number to quantify this change? Mean thickness deviation for each RCM or something similar. This way we can see more easily if these difference arise more for the RCPs or RCMs.

We thank the reviewer for this suggestion. We will calculate the mean thickness difference for each RCM. However, Figure 9 illustrates the thickness deviation from the common mean and not present-day observations. Nevertheless, calculating one scalar number would help to quantify the change of RCM influence for different RCP scenarios.

References:

Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J. S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., Karlsson, N. B., Lee, W. S., Matsuoka, K., Millan, R., Mouginot, J., Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel, A., Seroussi, H., Smith, E. C., Steinhage, D., Sun, B., Broeke, M. R. v. d., Ommen, T. D. v., Wessem, M. v., and Young, D. A.: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, Nature Geoscience, 13, 132–137, https://doi.org/10.1038/s41561-019-0510-8, number: 2 Publisher: Nature Publishing Group, 2020.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multimodel ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, 14, 3033–3070, https://doi.org/10.5194/tc-14- 3033-2020, publisher: Copernicus GmbH, 2020.