Author response for egusphere-2024-4061

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Review 2

In this paper, the authors use the EC-Earth climate model to test the impacts of reduced albedo under Late Pliocene ice sheet configurations to the climate system. Experiments also include the impacts of elevated greenhouse gas levels. While the topic is of great interest, I have several big-picture concerns, specifically about the internal consistency of the experiments presented here.

First, it is unclear what boundary conditions the authors are using for these experiments. In Section 2.2 (Experiment setup), the authors state they are using the PlioMIP 4F Tier 2 experiments (Line 78). PlioMIP uses Pliocene boundary conditions of the ice sheets, including modified ice sheet extent and orography and other changes associated with a reduced ice sheet and warm period, such as changes to vegetation and GHGs etc. However, the previous paragraph (L75) the authors state that they exclude orographic changes and freshwater input associated with the ice sheet extent. If indeed orographic and freshwater changes are not included in these experiments, it remains unclear to me how these changes were implemented in the model. What albedo was chosen in places where West Antarctica or Greenland are longer "ice"? How are these grid cells treated, presumably as land? What albedo is used in these locations? More clarification and explanation is required. Thereafter throughout the manuscript, the authors often refer to using a Pliocene ice sheet configuration, and that such a configuration serves as an analogue of future configurations. The term 'configuration' implies that all relevant elements of that configuration have changed, including orography (e.g. L196). Better explanation and justification is needed on experiment design, and care must be taken when using terms like 'configuration' and 'reduced ice sheet extent' throughout, especially if this is not what the experiment is actually doing.

#Response#: We appreciate the questions raised by the reviewer and understand that we needed to provide a more concise and accurate description of our experiment design and motivation for our study. Firstly, we have included in the methodology section, more detailed information of how the model boundary conditions were changed in order to perform our sensitivity experiments:

"The aim of these sensitivity experiments is to unveil the isolated impact of shrinking of the AIS and GrIS to the climate of the polar Southern Hemisphere. Therefore, Ei simulations involve changing only ice sheet extent for the Greenland and Antarctic Ice Sheets (Haywood et al., 2016; Chandan and Peltier, 2018). LP

AIS was originally developed using the high-resolution British Antarctic Survey Ice Sheet Model, integrated with climatologies from the Hadley Centre Global Climate Model (Hill et al., 2007; Hill, 2009), utilising PRISM2 boundary conditions (Dowsett et al., 1999). Figure 1 provides a visual comparison of the modern and LP ice sheet extent. LP GrIS reconstruction is provided for PlioMIP2 Haywood et al. (2016) and based on 30 modelling results from the PLISMIP project Dolan et al. (2012).

The PRISM2 ice sheet mask was interpolated onto the grid of EC-Earth's atmospheric component, IFS, and substituted into the snow depth variable of the initial condition file. IFS does not have a specific variable for ice sheets, therefore, altering the snow depth provides only a change in the ice sheet extent, being ice sheets the regions where snow depth exceeds 10 metres. To solely focus on climatic feedbacks resulting from change of AIS and GrIS; albedo values were not modified, modification of ice sheet orography was excluded and accompanying freshwater hosing experiments to account for meltwater from ice sheet change were not performed. With these exclusions, we aim to create idealised sensitivity experiments."

#Response#: Following your suggestion, we have replaced the term "configuration" with "extent", as this is the specific variable we modify in our experiments.

#Response#: Regarding the potential for analogy that we have drawn in several sections of our manuscript, we have included sentences that highlight the fact that our findings reveal that the albedo change resulted from reducing AIS and GrIS has an opposite impact as what is found in literature for the LP orography and freshwater input from ice sheet melting. With our experiment design, we were able to disentangle the contribution of this aspect of ice sheet dynamic from other climatic feedbacks. Further research under the umbrella of the PlioMIP project phases has only been performing experiments where the orography and ice sheet extent were modified in parallel. Therefore, with our experiment, we are able to acknowledge the amplified importance of reduced ice sheet height and increased meltwater input to the Southern Ocean in the context of current and future climate change. Our findings reveal that the albedo change as a result of our Ei400 experiment, isolated, acts in the opposite direction as freshwater forcing from ice sheet melting and orography change that are analogous to the Late Pliocene conditions. We derive such conclusions with literature from studies that target the Late Pliocene, current and future climate change. Without performing such an experiment, we would not be able to disentangle these forcings and understand their contributions to climate change.

#Response#: We also acknowledge in our conclusions that future research could aid in directly attributing the role of CO_2 forcing, LP ice sheet orography, meltwater forcing and boundary condition modifications onto not only LP but also future climate change:

"This study underscores the critical sensitivity of the Southern Ocean to increased atmospheric warming. Current conditions do not yet reflect the full extent of AIS reduction or collapse, as projected in future climate experiments Roach et al. (2023); Armstrong McKay et al. (2022); Naughten et al. (2023); Steig et al. (2015). However, our results suggest that even under present trends, the ability of the Southern Ocean to ventilate the deep ocean is at significant risk. Furthermore, while we isolate the albedo effect in this study to reduce uncertainties, the exclusion of other climate feedbacks may underestimate the potential catastrophic outcomes of AIS collapse.

This raises potential research questions for future investigation. We believe that an extended set of sensitivity experiments would provide valuable insights into future climate change and even reduce model biases. Experiments would include:"

1. Freshwater hosing equivalent to the ice sheet volume that is reduced in LP relative to PI;
2. Application of reconstructed LP paleogeography (topography and bathymetry);
3. Increased greenhouse gas forcing;
4. Interactive ice sheets.

If I understand correctly, only albedo is being modified in these experiments. I am struggling with the rationale and relevance for such an experiment. Keeping a modern AIS/GrIS topography, but reducing albedo to match Pliocene ice extent results in inconsistent boundary conditions. You cannot collapse WAIS as in Figure 1 but maintain modern topography. If WAIS is ice-free this implies it is collapsed. Therefore, not only is the orography fundamentally different, but also ocean pathways between the Ross, Amundsen and Weddell Seas open up, leading to different ocean circulation, sea ice regimes and atmospheric circulation (e.g. Steig et al (2015), Pauling et al (2023)). Therefore, much of the analyses presented here (changes in sea ice regime, SAM index, albedo, surface air temperatures and precipitation) is limited by the presence of land above sea level in West Antarctica, and drawing conclusions about those elements of the climate system would be inaccurate.

#Response#: We acknowledge this limitation and address it directly throughout the paper. We now emphasize that:

- This is a highly idealized experiment designed to isolate the effect of albedo change;
- Other PlioMIP studies change both orography and extent in parallel, making it hard to separate individual effects;
- Our design provides novel insights by disentangling these often conflicting forcings

#Response#: Future work is proposed to explore experiments that combine albedo, orography, and freshwater forcing in a systematic sensitivity framework.

#Response#: We have also clarified in the text manuscript that we do not change the underlying land/sea mask or surface albedo values in the model. Therefore, although the snow depth is reduced below 10 m (removing the ice sheet), the model retains the pre-industrial albedo values in those grid cells. This simplification helps us isolate the indirect feedbacks (e.g., cloud, temperature) from the direct albedo effect. This has been explained in detail in the methodology section.

If the goal of the study is to ask how the Southern Ocean and AIS climate responds to reduced ice sheets (as in the manuscript title), this experimental design cannot answer that question. Instead, it seems to me that the authors are asking what the impact would be if WAIS was suddenly painted black (or whatever low ocean/land albedo is being used here). If that is the question, please justify. To isolate the effect of albedo a better tool might be a simple global energy balance model. This would also resolve the authors' technical issues with modifying

the atmospheric component of the model when modifying orography (though I will note this is technically possible and not uncommon (see PlioMIP experiments)). Another option would be to use the current experiments, but rather than comparing to a PI control run, also compare this simulation to a run where the full configuration of the ice sheets is changed (including orography). This would allow the authors to better detangle the role of albedo-only changes, by comparing to cases with and without orography change.

#Response#: We appreciate the reviewers suggestions and ideas. We considered an energy balance model as they can help isolate radiative effects, but they lack interactive ocean-atmosphere dynamics. Using an Earth System Model enables us therefore to trace feedbacks affecting winds, SAM, stratification and deep-water formation, which are critical aspects of polar climate. We have strengthened our justification for using EC-Earth3 in this context, and drawn more light to the uniqueness of our study as a fully PlioMIP-conform study with the same model has been published in de Nooijer et al. 2020.

Once these big picture issues are taken care of, there are a number of other issues throughout the paper that I recommend addressing. For example: As mentioned above, the title does not accurately represent this work – you are not actually reducing ice sheet extents in these experiments

#Response#: The title has now been changed to more accurately represent our main objectives: " Late Pliocene Ice Sheets as an Analogue for Future Climate: A Sensitivity Study of the Polar Southern Hemisphere".

The abstract needs work to make connections clearer and providing appropriate motivation for the experiment.

#Response#: We have re-written the abstract considering your recommendation. The abstract has been revised to better articulate the motivation and clarify that this is an idealised sensitivity experiment focusing on surface reflectivity change, not full PlioMIP-like boundary forcing.

As mentioned above, the experiment design (Section 2) should include a more comprehensive description of the experiments and implementation.

#Response#: We have now included a table with full experiment design (see below) and an in-depth methodology of the changed boundary conditions, as clarified in early comments.

"To investigate the impacts of varying ice sheet extent and CO_2 concentrations in the polar Southern Hemisphere, we performed a series of sensitivity experiments, displayed in the below table. These experiments employed modern ice-sheet extent (labeled E) and Late Pliocene ice-sheets (labeled Ei) under two atmospheric CO_2 levels: pre-industrial (280 ppmv) and intermediate (400 ppmv)."

The protocol for our pre-industrial (PI) simulation follows Eyring et al., 2016. Ice sheets, land geography, topography and vegetation are all unmodified from the model. GHG concentrations for CO_2, CH_4 and N_2O are 284.3 ppmv, 808.2 ppbv, and 273.0 ppbv, respectively. For orbital parameters; eccentricity set at

Table 1: The four Core and Tier 2 Pliocene for Future protocol experiments conducted. PI refers to pre-industrial conditions, LP for Late Pliocene. Name terminology is from Haywood et al., 2016.

Experiment ID	Ice sheet extent	LSM	Topography	Vegetation	CO_2 (ppm)	Orbit
E280	PI	PI	PI	PI	280	PI
E400	PI	PI	PI	PI	400	PI
Ei280	LP	PI	PI	PI	280	PI
Ei400	LP	PI	PI	PI	400	PI

0.016764, obliquity 23.549 and perihelion - 180 is 100.33.

Figures need to be better labeled. For example, Figure 1 should have labels, and the caption should explain more. Consider also including a cross section of the orography for the two ice sheets.

#Response#: We have worked carefully in labelling our figures in a clearer manner. We have chosen, however, to not include a cross-section of the orography of the two ice sheets as orography is not modified in this study.

Figure 2 it is unclear why albedo is spatially variable in the Ei experiment. This is confusing.

#Response#: While the prescribed snow depth change is fixed, model feedbacks (e.g., clouds, moisture) alter the effective albedo. This is now clarified in the text accompanying the figure:

"In Ei400, albedo changes are not confined to regions affected by ice sheet change and there is an overall albedo decline of 20% across the Antarctic interior, with decreasing severity toward the eastern coastline. There is a small hotspot showing pronounced loss of 30-40% on the east coast (60°–70°E, 75°S). Additionally, albedo decreases of up to 30% are observed along the coastline at 0°–10°E and 140°–160°E. These widespread albedo reductions are a result of the interplay of climate feedbacks, with changes in cloud cover, atmospheric temperature and moisture transport influencing the radiation balance and surface reflectivity."

There are some claims throughout, such as the stability of ice sheets being increasingly at risk, please provide appropriate citations for these.

#Response#: Appropriate references have been added to support such statements, including recent work on AIS vulnerability and Pliocene analogues.

Usually Greenland Ice Sheet is abbreviated as GrIS rather than GIS.

#Response#: This has been corrected throughout.

Include references when discussing EC-Earth's proven capabilities.

#Response#: We have now included, per your recommendation, the references: Hang et al 2021, Chen et al 2022, Han et al 2024 and de Nooijer et al 2020, to prove EC-Earths capabilities over different paleo time periods.

The discussion requires more work, more context, and some of the concluding claims are not well-supported. For example, it is not clear how this experiment will help identify early signals of ice sheet retreat and possibly ice sheet instabilities because this study does not include a dynamical ice sheet.

#Response#: Following the new analysis, improved understanding of atmospheric and ocean processes and properly highlighting the uniqueness of our study, the discussion section has now been rewritten. It now links together our results, the interplay between them and compares the results and mechanisms with other studies, including paleo Antarctic work (Weiffenbach et al., 2024, Hutchinson et al., 2024, Yeung et al., 2024), and literature focusing on current and future polar southern hemisphere change (Silvano et al., 2023, Sidorenko et al., 2021, Kidston et al., 2011, Kusahara et al., 2017). We have fully delved into the limitations of the experimental setup and avoid unsupported conclusions. We now clarify that this experiment isolates the albedo effect, and future studies should include meltwater and orography to understand ice sheet instabilities. This is reflected in the proposed set of follow-up experiments.