Response to Anonymous Referee #2

REVIEW OF 'HYSTERESIS AND ORBITAL PACING OF THE EARLY CENOZOIC ANTARCTIC ICE SHEET' BY VAN BREEDAM ET AL.

Van Breedam et al. quantify the CO2-thresholds for glaciation and deglaciation of the Early Cenozoic Antarctic ice sheet using an ice sheet model coupled to a climate model through a process emulator. They investigate the influence of the choice of bedrock topography, glacial isostatic adjustment, and orbital parameters (eccentricity and obliquity) on these thresholds. Their main findings are: 1) the choice of bedrock topography significantly affects both thresholds, but not the difference between them (hysteresis); 2) excluding glacial isostatic adjustment raises the CO2 level of glaciation but does not change the deglaciation threshold value; 3) the long eccentricity cycle has a significant impact on the timing of glaciation.

The topic of the study is interesting and timely, the methodology is sound, and the results are robust. My only concern is that the implications of the study are mostly left for the reader to deduce. In principle, the study achieves its stated aim of identifying the forcing needed to initiate and end a continental-scale glaciation, under various assumptions on bedrock topography, GIA and CO2. But what do the results actually mean for ephemeral glaciations prior to the EOT? What is the consequence of the hysteresis and orbital variations for the stability of the transiently evolving ice sheet? It could be worthwhile to include a (brief) discussion of proxy CO2 or ice volume data in this respect. The discussion section could be further improved for instance through a comparison, either present-day to Early Cenozoic Antarctica, or Antarctica to other ice sheets (the comparison to Greenland in the discussion section that is there, is a bit half-hearted). With some more discussion in this direction, the manuscript would in my opinion reach a wider audience.

Author's response: We thank the reviewer for the overall positive appraisal of the manuscript and for the suggestions to improve the significance. Also the discussion and the conclusions are rewritten to better grasp the implications of the research.

More specifically, we added a paragraph in the discussion on the implications of this study for ephemeral glaciations during the late Eocene. We also compared the early Cenozoic Antarctic ice sheet with a present-day forcing with the early Cenozoic Antarctic ice sheet, to assess the different climatic setting.

Furthermore, I have some recommendations to the authors for minor revisions to clarify the text and figures.

SPECIFIC COMMENTS PER SECTION:

§1 Introduction

L22-24:

The recent publication by Li et al. (2023) is also relevant here:

Li, Q., Marshall, J., Rye, C. D., Romanou, A., Rind, D., & Kelley, M. (2023). Global Climate Impacts of Greenland and Antarctic Meltwater: A Comparative Study. *Jounrla of Climate*, 1-40.

Author's response: We added the reference Li et al. (2023) that found a similar 50% decrease in AMOC, albeit for a different freshwater forcing.

L27, L32: 'favourable' and 'optimal'

The environmental conditions do not necessarily have to be favourable, and certainly not optimal, for glaciation to occur. They just have to be sufficient.

Author's response: Thanks for the remark. We changed 'favourable' to 'satisfactory' and 'optimal' to 'sufficient' in the revised manuscript.

L55-64:

Also worthy to mention that Pollard and DeConto (2005) did not use early Cenozoic Antarctic bedrock topography.

Author's response: We added this information and removed the information from the idealized orbital parameters, which is less crucial.

L58-60:Pollard and Deconto (2005) determined the hysteresis of the early Antarctic ice sheet at the Eocene-Oligocene transition using an isostatically rebounded present-day bedrock topography and a matrix method where a limited number of climate model runs were performed based on end members in the forcing.

L68:

Recent paleo-bedrock elevation reconstructions

Author's response: We made the change from 'bedrock elevation reconstruction' to 'paleo-bedrock elevation reconstruction'

§2 Model description and experimental set-up

§2.1:

Is ice-ocean interaction not important at all (i.e., no ice shelves)? How is the basal mass balance underneath the ice shelves calculated? And calving? Are sea level variations taken into account, if yes, how?

Author's response: The ice ocean interaction is taken into account, but is strongly simplified given the large unknowns about the ocean temperature and the translation of these temperatures and salinities into shelf melt rates. We opted for using a mean basal melt rate of 10 m per year. Calving physics are not explicitly included and the ice shelf breaks off when the ice thickness decreases below 120 m.

Which sliding law is used, and what about the grounding line physics? These are important factors, especially for deglaciation.

Author's response: We clarified the basal sliding and grounding line treatment as follows:

L151-154:

The basal sliding velocity in AISMPALEO follows a Weertman relation and is proportional to the third power of the basal shear stress and inversely proportional to the height above buoyancy. The basal sliding coefficient is a constant multiplication factor for the basal sliding and equals 1.8 x 10^{-10} $N^{-3}yr^{-1}m^{8}$.

L158-159:

The grounding line is a one grid cell wide transition zone between the grounded and floating ice where all the stress components contribute in the effective stress in the flow law.

L90-91:

Influx of snow (from the atmosphere) and ice (from upstream), I think?

Author's response: Yes, we added this information.

L92:

So the input consists of daily temperatures and precipitation rates?

Author's response: Not completely, the PDD model uses the yearly sum of the mean daily temperatures above 0˚C to determine the melt potential, but monthly time steps are taken. Inputs are therefore monthly mean temperatures and precipitation rates. This information is added to the manuscript.

L168-169:

In practice monthly time steps are sufficient to calculate the total amount of PDD's.

L97-100:

Please mention the specifics of the GIA model.

Author's response: We add the following explanation for the GIA model, which is indeed an important component to describe in light of the isostasy sensitivity runs.

L177-185:

The isostatic model consists of an elastic lithosphere with a flexural rigidity D of 10^{25} Nm (which is a measure of the strength of the lithosphere) on top of a viscous asthenosphere, to allow the crust to deform far beyond the local ice loading (Huybrechts, 2002). The vertical deflection of the lithosphere w is given by a fourth order differential equation (Eq. 2) Here, q is the ice load, ρ_m is the mantle densitiy (3300 kg m^{-3}) and g the gravitational acceleration. This equation is solved using a Green's function. The viscous asthenosphere responds to the ice load with a relaxation time τ of 3000 years (Le Meur and Huybrechts, 1996).

$$D\nabla^4 = q - \rho_m g\, w \qquad (2)$$

L113-114:

The Wilson topographies are also used in the ISM, in higher resolution, I guess?

Author's response: That is indeed true. We explicitly mentioned it in the description and explained in more detail how we created the higher resolution topographies:

L98-103:

The bedrock topography used in the climate model is the Wilson maximum bedrock topography and is representative for the Eocene-Oligocene transition (EOT) at 34 Ma (Figure 2). The minimum and maximum bedrock topographies are applied as a boundary condition in the ice sheet model at a 40 km resolution. In order to grasp the entire uncertainty, each ice sheet model grid cell takes on the lowest and highest value for respectively the minimum and maximum bedrock topography from the original higher resolution Wilson et al. (2012) dataset within each ice sheet grid cell.

Figure 2:

It could be a valuable addition to show the difference between the two reconstructions.

Author's response: Thanks for the suggestion. We added a difference plot between the maximum and minimum bedrock topography reconstruction in Figure 2.

L121-122:

What vegetation is used for ice-free land, tundra (L500 seems to suggest this) or bare bedrock, and what is the albedo?

Author's response: The albedo varies between the 0.8 for ice/snow covered land and 0.2 for tundra. We added this as follows:

L117-118:

The albedo varies between the discrete values of 0.8 for ice/snow and 0.2 for tundra.

L127-128:

Worthy to mention Herrington and Poulsen (2011) here:

Herrington, A. R., & Poulsen, C. J. (2011). Terminating the Last Interglacial: The role of ice sheet–climate feedbacks in a GCM asynchronously coupled to an ice sheet model, Journal of Climate 25(6), 1871-1882.

Author's response: We added the reference Herrington and Poulsen (2011) as they found a similar coupling time step of 500 years, sufficient to capture climate-ice sheet feedbacks in a coupled ice sheet-climate model.

L137-139:

Winter precipitation may be lower, but judging from the temperatures summer precipitation will be almost all rain.

Author's response: We added this observation as follows:

L140-141:

In winter, most precipitation falls as snow, while snowfall is limited to the highest elevated regions such as the Gamburtsev Mountains and Dronning Maud Land in summer.

L147-149:

Mention that these CO2 bounds apply to this particular model set-up. You could add that these values are roughly in line with proxy data (see also my comment to L495-496).

Author's response: We added that these values are specific for our model set-up.

Figure 4:

Please make the black lines bracketing 34.2 and 31.8 Ma a little thicker, or preferably highlight this period in some other manner.

Author's response: We thank the reviewer for this suggestion. We added a grey shaded region to highlight the period between 34.2 and 31.8 Ma.

§3 Ice sheet hysteresis

L189-190:

It would be interesting to see what the difference in maximum ice thickness is between the two simulations (Wilson min and max), could you include a (supplemental) figure showing maps? And is the ice sheet in fact still land-terminating in this case (L198-199)?

Author's response: The ice sheets are mostly land terminating, expect for small regions along the West Antarctic ice sheet. The Wilson et al. (2012) bedrock topographies are significantly higher than a rebounded present-day bedrock topography because the bulk of the erosion has been taking place during the Miocene when the ice sheet is thought to have been very dynamic. A supplementary figure (Figure S1) showing the difference in ice sheet thickness between the simulations using the Wilson minimum and Wilson maximum dataset has been added.

Figure 6:

Why do you show this at 550 ppm CO2? I don't get that.

Author's response: Because the maximum ice sheet extent is reached at 550 ppmv.

Figure 7:

To aid comparison, it would be beneficial to have the same y-axis scales in both panels.

Author's response: Figure 7 has been adapted to have the same y-axis in both panels.

Figure 8:

Here as well, maps of maximum ice thickness (and maybe surface height) would be nice. I would think excluding GIA will lead to higher surface elevations, but only slightly because precipitation is depleted when the surface is raised. On the other hand, the ice will be less deep, because the bedrock topo remains higher.

Author's response: A supplementary figure (Figure S2) showing the difference in ice sheet thickness between the simulations including isostasy and excluding isostasy has been added.

L283-284:

I am not sure why the ice area is larger at the start of the no-GIA experiment.

Author's response: The ice area is larger shortly after the start of the experiments when a small ice sheet has been formed that has not depressed the bedrock, allowing for a larger accumulation area and hence a larger ice area. We rephrased this sentence:

L324-326:

As it occurs, the initial temperature difference of about 0.5˚C between both experiments with CO_2 concentrations between 1000 and 1150 ppmv is due to the larger ice sheet area in the experiment that excludes isostasy.

§4 Threshold dependency on orbital forcing

§4.1

This paragraph is not so clear to me. Which experiments do you discuss here? Judging from the text you keep the CO2 constant but vary all the orbital parameters. If that is the case, why are these experiments not described in §2?

Author's response: This is indeed what we do, the CO_2 is kept constant and the orbital parameters vary. These experiments are described in Table 2 of the experimental design (section 2.4).

L308: 'exceeding 0.03'

You mean below 0.03?

Author's response: We rephrased these sentences:

L358-363:

The extreme eccentricity value of 0.064 that occurs after 2 Myr is not sufficient to melt the ice sheet once it has grown to a continental scale for a CO_2 forcing between 810 and 890 ppmv. This shows again the hysteresis effect of the Antarctic ice sheet: an eccentricity below 0.032 is enough to initiate continental-scale ice sheet growth for a CO_2 forcing up to 890 ppmv, while an eccentricity of >0.06 is not sufficient to make the ice sheet melt entirely after this. The extreme eccentricity of 0.064 influences the ice sheet volume for all simulations forced with a constant CO_2 concentration between 800 and 890 ppmv, but the peak insolation forced by the precessional cycle is too short-lived to melt the entire ice sheet (Figure S3).

L298-299 (L317-318, L325)

Why has the ice sheet size changed after a few precessional cycles, is there a trend towards larger ice volume? Even at constant high CO2-levels?

Author's response: Indeed! The initial conditions (ice volume) have changed after a few precessional cycles, even for constant (high) CO_2 levels.

Figure 10:

The duration of the experiment is the time passed since 34.2 Ma, and it affects the background ice sheet size, right? The main text explains it well, but I must say the figure remains hard to interpret: I cannot see a clear pattern, particularly not for the glaciation threshold.

Author's response: I do agree that the figure is not that easy to read, but together with the text you understood it right. The overall pattern for the glaciation threshold is the following: the higher the CO_2 forcing, the longer it takes to achieve the threshold to full glaciation. So there is a clear pattern in the timing or the duration before the glaciation occurs, owing to the different initial state after a few precessional cycles. To initiate glaciation, a low eccentricity is beneficial because then the influence of the precession is attenuated. So, overall, you expect that the eccentricity threshold can be larger for lower CO_2 values and the eccentricity threshold should be lower for higher CO_2 values. We tried to increase the clarity of the figure by making these interpretations on the figure and added the following text to the figure caption:

The blue and green arrows indicate the decrease in eccentricity threshold for increasing CO_2 values to initiate glaciations and the orange arrows indicate the increase in the eccentricity threshold for decreasing CO_2 values to end glaciations.

L346-347:

The difference in timescale between glaciation and deglaciation mentioned later on (L375-376) is relevant here already, I believe.

Author's response: We agree with the reviewer and refer to Figure 12 already here.

Table 3:

You could add present-day values for comparison.

Author's response: We added the present-day austral summer insolation at 65˚S in Table 3 and the following text:

L396-398:

For comparison, the present-day austral summer insolation (mean daily for DJF at 65˚S) is 439 Wm^{-2}. The eccentricity and the obliquity values resemble the cold orbital configuration, but the Earth is in perihelion during the austral summer today.

L363-365, L366-367

Add 'not shown'.

Author's response: Done.

Figure 12:

And here again, showing maps (e.g., like Fig. 15 does) would be nice.

Author's response: We added maps showing the geometry right before the tipping point is reached at 900 ppmv for ice sheet growth (cold orbital configuration) and at 950 ppmv for ice sheet decline (warm orbital configuration) and added this information to the figure description.

L382-383:

So there is a double importance of ice area: the area itself (larger accumulation area), and the higher accumulation rate at the margins of the area. Moreover, the CO2 level affects the precipitation rates as well I think (warmer = more precip)?

Author's response: Not completely. Initially the accumulation is also larger inland in the Gamburtsev Mountains and decreases as the ice sheet develops. So there is no linear increase in the accumulation rate per unit area.

L387-389:

One could also think of an ice-volume-CO2 feedback loop: initial ice volume increase leads to lower CO2, which stimulates further glaciation.

Author's response: This feedback has been proposed to explain CO_2 variations during the Quaternary ice ages, possibly caused by changes in the ocean deepwater circulation or the Asian monsoon (Ruddiman, 2006). We do acknowledge that such a feedback mechanism could exist during the early stages of Antarctic glaciation, but the mechanisms behind it might be very different. Here we investigate the response of the ice sheet for prescribed CO_2 values.

Ruddiman, W. F.: Ice-driven CO_2 feedback on ice volume, Clim. Past, 2, 43-55, 2006.

Figure 14:

Could you add a color scale?

Author's response: The color scale is a measure of the ice thickness, but the ice thickness can also be read on the z-axis. Therefore, we believe it is not necessary to include a color scale to improve the figures quality.

§5 Discussion

L453-455:

Is colder ice flowing slower in fact a positive feedback? On the one hand, indeed, more ice will remain within the net accumulation zone. But on the other hand, expansion of the net accumulation zone due to surface uplift by inflowing ice is impeded.

Author's response: This is a good point since changes in the ice viscosity influences different processes and we did not attempt to disentangle the effect of ice temperature on the internal deformation and the ice sheet evolution. We decided to leave out this statement from the manuscript.

L460-470:

Hysteresis behaviour of the AIS is also quantified (albeit for the Miocene) in the appendix of Gasson et al. (2016):

Gasson, E., DeConto, R. M., Pollard, D., & Levy, R. H. (2016). Dynamic Antarctic ice sheet during the early to mid-Miocene. *PNAS 113(*13), 3459-3464.

Author's response: In this paragraph we discuss the effect of a certain change in ice sheet area on the glaciation and deglaciation. These ice-albedo effects have not really been quantified in the study from Gasson et al. (2016).

L471-480:

You could also compare to Abe-Ouchi et al. (2013), who found that instantaneous isostatic rebound obstructs deglaciation, in experiments of the Pleistocene Northern Hemisphere ice sheets.

Abe-Ouchi, A., Saito, F., Kawamura, K., Raymo, M. E., Okuno, J. I., Takahashi, K., & Blatter, H. (2013). Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. Nature 500(7461), 190-193.

Author's response: Isostatic rebound is not instantaneous but delayed, and as such Abe-Ouchi et al. (2013) states that during deglaciation, the isostatic rebound cannot prevent deglaciation. We also found that for deglaciation, the difference in ice volume response between the simulations including isostasy and excluding isostasy is negligible. We added the following text to the discussion:

L545-548:

During deglaciation, our simulations have indicated no significant impact of isostasy on the threshold to deglaciation. Isostatic rebound has the potential to obstruct ice sheet melt, but the delayed response of the lithosphere to changes in ice loading is too slow to counteract the increasing snowline (Abe-Ouchi et al., 2013).

§6 Conclusions

L495-496:

It should be noted that these values are very model-dependent, see Gasson et al. (2014). Maybe you could include a (brief) comparison to proxy data from around the EOT?

Gasson, E., Lunt, D. J., DeConto, R., Goldner, A., Heinemann, M., Huber, M., ... & Valdes, P. J. (2014). Uncertainties in the modelled CO2 threshold for Antarctic glaciation. Climate of the Past 10(2), 451-466.

Author's response: We thank the reviewer for the suggestion and added a brief comparison in the discussion.

L508-511:

These CO_2 thresholds to initiate glaciations are 650 ppmv (minimum bedrock topography datset) and 870 ppmv (maximum bedrock topography dataset). Aside from the bedrock dataset dependence, the thresholds also depend on the climate model used. As shown in Gasson et al. (2014), the thresholds may vary between 560 and 920 ppmv when additionally climate model uncertainty is included.

§ Code and data availability

Thank you for sharing the code of the emulator. I realize it is not required by the journal, but on a personal note I'd like to ask: Has the code of AISMPALEO also been made publicly available? If not, please do so. This facilitates transparency and reproducibility.

Author's response: The code of AISMPALEO is not publicly available, but people who are willing to use the code are welcome to contact us.