Dear Prof. Phipps,

We are submitting our revised manuscript entitled "How changing the height of the Antarctic ice sheet affects global climate: A mid-Pliocene case study" by *Huang et al.* to you for consideration for publication in *Climate of the Past*.

We are very grateful to the reviewers for the thoughtful suggestions, which have been incorporated into the revised paper (track changes). They are detailed below.

Comments of Reviewer 1:

General comments

Huang et al. presented an interesting analysis of the global-scale effects of changes in ice sheet volume. It is useful to see the local, regional, and global changes in climate variables caused by reductions in the height of the east Antarctic Ice Sheet. The results were clearly and systematically presented. The methodological limitations of the model were nicely discussed and addressed.

However, it is unclear to me whether this is intended as an idealized study, or whether it seeks to replicate the effects of actual past and future changes in ice sheets. If the former, that should be made clear. If the latter, then there needs to be a much more robust discussion of the relevant past and/or future scenarios that are meant to be reproduced here. If these experiments are meant to investigate possible future changes in climate, then it would also be useful to see comparisons between the Pliocene control simulation and pre-industrial control, given that the Pliocene control simulation is run with PRISM4 boundary conditions that include significantly reduced ice sheet volume (specifically over West Antarctica and Greenland) as compared to the present-day. In general, it would be useful to see a more detailed discussion of how the sensitivity experiments presented here correspond to past/future scenarios that have been studied in the scientific literature.

Yes, our simulations are intended as idealized studies. As HadCM3 is a 'rigid lid' model, the water contained in Antarctica did not get redistributed over the ocean when we reduced the EAIS height, which means the sea-level is essentially fixed.

Therefore, the effect of changes in the surface albedo, sea level, and continental margins, which would undoubtedly occur with such orographic variations, have not been explicitly taken into account in our simulations (see section 4.3 Modelling methodological limitations; lines 254-259). We add some words to make the expression clear (line 66).

Specific comments

1) Paragraph starting on line 50: You discuss using the mid-Pliocene warm period as an analog for end-of-century climate. The time-scales for changes in different parts of the Earth system differ; as you discuss, although present-day CO_2 concentrations are similar to the Pliocene, it will take time for Earth's global mean temperature to rise to Pliocene levels. It will also take time for vegetation to adjust to the Pliocene climate, and—importantly—for ice sheet loss comparable to Pliocene conditions to occur. I think this section needs to include some discussion of the existing scientific understanding of future changes in the volume of the East Antarctic Ice sheet, including the possible time-scales of ice sheet loss. How far into the future might we expect to see a mid-Pliocene-like East Antarctic Ice sheet volume?

   Done (lines 64-65). Thanks for the suggestion.

2) Line 105, "our experiments focus on changing the East Antarctic Ice Sheet height": this makes it sound like you are changing the East Antarctic Ice Sheet height against its modern or pre-industrial value, but you are changing the East Antarctic Ice Sheet height against its reconstructed Pliocene value.

   Thanks. We have revised the sentence to make it clear (see line 110).

3) Paragraph starting at line 108: I'd like to see more justification for this experimental design. Are the 0%EAIS, 25%EAIS, 50%EAIS, and 75%EAIS experiments intended to represent analogs for possible future scenarios, and if so under what conditions and over what time-scales could these scenarios arise?

These sensitivity experiments are hypothetical scenarios. We add more justification for the experimental design (lines 123-127).

4) Line 112: Are changes in the ice sheet dynamically resolved in the model, or are you manipulating the height of the ice sheet for each sensitivity simulation? This is unclear here.

In our study, we manipulate the height of the ice sheet for each sensitivity simulation. We have improved the sentence to make it clear (lines 115-117).

5) Lines 112-118: Does the mid-Pliocene control experiment already have reduced EAIS volume, as specified in the PRISM4 boundary conditions? If so, it would be helpful to describe in more detail the differences between PRISM4 EAIS configuration and its present-day volume/extent.

In the mid-Pliocene control experiment, the EAIS volume was as specified in the PRISM4 boundary conditions (lines 128-130). The differences in EAIS volume between the mid-Pliocene and present-day have been added (lines 130-132). Thanks for the suggestion.

6) Lines 188-191: The winds bringing moisture over the continent are different from the katabatic winds mentioned; it would be helpful to be more explicit here about the causal relationships between weakened katabatic flow and elevated moisture transport.

Done (lines 202-206). Thanks for the suggestion.

7) Lines 203-205: This is too vague.

Thanks for this comment. As our sensitivity experiments are hypothetical scenarios, it’s hard to be more specific there based on the preliminary results.

8) Line 208: In section 4.4, you present a nice analysis of the energy balance, and find that “heat transport by winds from the Southern Ocean to Antarctica is the

primary factor influencing the temperature changes over Antarctica." Line 208 makes it sound like the atmospheric temperature lapse rate is the primary factor for warming over East Antarctica, which seems to contradict your findings in section 4.4.

Based on the analysis of the energy balance (Figure 10 in the manuscript), we found that the primary factor is actually heat transport. However, the topography (which represents the lapse rate) is also important (turquoise line in Figure 10). We did not say that the atmospheric temperature lapse rate is the 'primary' factor on line 208. We are sorry for the misleading sentence, which have been rewritten (lines 226-227). Moreover, we add some words to make the expression more clear (line 296).

9) Line 230: was EAIS height reduced below the PRISM4 reconstructed height during the mid-Pliocene warm period? PRISM4 focused on a specific interglacial period, so the height of ice sheets would have fluctuated during the mid-Pliocene. But is there evidence to suggest that the EAIS would have disappeared completely? Or are these hypothetical scenarios? Again, the justification for the experimental design needs to be more clear.

This is the same question posed in specific comment 3. See the responses above.

10) Line 245: would this have effects on ocean gateways such as the Bering Strait, and what impact might this have on ocean dynamics? Would these effects be significant?

Yes, that is correct. Reducing the height of the land could open up some gateways that are closed in our experiments. However, this experiment was designed to remove the unrealistic surface air pressure anomaly over the land (Figure 9a), and see how this affected the surface air temperature anomalies. Therefore, we add some sentences to make the experiment design more clear (lines 265-269)

11) Section 4.4: Please add more detail about how you conducted this energy balance analysis.

Done (lines 286-287).

12) Line 273: Which of these sensitivity experiments are applicable to which future and/or past climate scenarios? Please be more specific here.

Thank you for the suggestion. Our sensitivity experiments are hypothetical scenarios. It's hard to specify which future and/or past climate scenarios based on the preliminary results. To avoid misunderstanding, we rewrite the sentences (lines 301-303).

13) Line 278: similar to previous comments—is there evidence for these changes in EAIS height actually occurring during the mid-Pliocene warm period? Or are these hypothetical scenarios?

These are hypothetical scenarios. This is the same question posed in specific comment 3. See the responses above.

Technical corrections

1) Line 59: would make more sense to write: "due to the large thermal inertia of the oceans, the global mean temperature is not projected to reach the level of the Pliocene until the 2040s."

   Done (line 61). Thanks for the suggestion.

2) Line 85: this is the spatial resolution of, not over, the ocean—correct?

   Done (line 89).

3) Line 194: Typo, MPComtrol to MPControl

   Many thanks. We are sorry for this mistake and have revised it (line 213).

4) Line 209: could change to "which can be explained by the lapse rate"

   We have rewritten this sentence (lines 226-228).

5) Line 219: rewrite as "leading to higher air pressure over Antarctica and lower air pressure over extra-Antarctic regions."

   Done (line 239).

6) Line 220: perhaps it would make more sense to replace "translate to" by "correspond with."

Done (lines 240-241). Thanks for the suggestion.

7) Line 232: "costal" to "coastal"

Done (line 252).

8) Line 269: there is no Section 4.4.4

Many thanks. We are sorry for this mistake and have revised it (line 296).

9) Line 284-285: should be "the surface air temperature and the sea surface temperature both decrease…. The surface air pressure increases over East Antarctica, while decreasing elsewhere"

Done (line 313). Thanks for the suggestion.

10) Line 286: awkward sentence. Could rewrite as: "Energy balance analyses show that the temperature changes over Antarctica are mainly caused by topographic changes in the EAIS."

Done (lines 314-315). Thanks for the suggestion.

Comments of Reviewer 2:

General comments:

1) Terminology regarding EAIS is a bit confusing; '0% EAIS' for the largest anomaly is not very intuitive. Consider adjusting to e.g. -25/-50/-75/-100%, and 0% or 'original' for the default configuration.

We have changed the names of the sensitivity experiments following the suggestion (lines 121-122), except for the "0% or original" for the default configuration. This is because the "0% or original" is a control experiment. Thus we prefer to name it as "MPControl", following conventional use.

2) Does the inclusion of dynamic vegetation have any significant impact compared to the original configuration?

In this study, all the boundary conditions (including the vegetation) are the same except for the height of the East Antarctic Ice Sheet. Therefore, it is difficult to discuss the effect of the dynamic vegetation just based on our sensitivity experiments.

3) Overall, figures of different experiments are rather repetitive. It could be more informative to show e.g. anomalies normalized by the 0% EAIS anomaly, to check whether the other experiments result mostly in a linear response of the strongest signal.

Our study has already analyzed the anomalies normalized by the MPControl experiment (100%EAIS instead of 0%EAIS). The results show a linear response of temperature and precipitation to the EAIS height changes, i.e. a warming of 5 °C per kilometer of EAIS height lost and a precipitation enhancement of ~5% per °C (lines 146-148, 172-174). We believe that the two approaches (100%EAIS and 0%EAIS) answer the same question.

4) The paper is quite descriptive, I am missing a more mechanical insight into the responses shown. Many of the claims or explanations are not supported by what figures show, or not shown at all, making it hard to follow the discussion of the results.

We have improved the Figures 6 and 10 following the suggestions of reviewer #2 (see Figures 6, 10 in the manuscript). In addition, a new Figure (Figure 1 in the manuscript) has been added in our paper and some sentences have been added to make the claims or explanations more clear (lines 169-170, 202-206).

5) Subsections 4.1 and 4.2 seem to be mostly results and should therefore at least partly move to section 3?

Thanks for the suggestions. Subsections 4.1 and 4.2 aim to explain the changes in Antarctic precipitation and global temperature, respectively. Therefore, we would rather keep them in the Discussion section. To make the expression more clear, we have replaced the titles of Subsection 4.1 and Subsection 4.2 with “Cause of Antarctic precipitation changes” (lines 194-195) and “Cause of global temperature changes” (line 225), respectively.

6) Structure can be improved; many of the analyses implemented are presented 'on the go', rather than in the methods section up front along with their motivation. This would make the overall storyline clearer.

Done. We have added some sentences in the methods section to make it clearer (lines 123-127).

Specific remarks:

1) L19: surely there are studies? e.g. work of DeConto et al, Gasson et al.

DeConto et al. (2016) investigated the contribution of Antarctic ice sheets to past and future sea-level rise, and Gasson et al. (2016a, b) evaluated the climate effect of Antarctic ice sheet changes in the Miocene. Our sensitivity experiments are hypothetical scenarios, which focus on the EAIS height changes and their climate effect during the mid-Pliocene. We have added some words to make the expression more clear (line 20).

2) L25: temperature changes as a result of pressure changes: how are these linked?

As shown in Figure 8 in the manuscript, the surface air pressure increases over Antarctica and decreases elsewhere, which is similar to the spatial pattern of the air temperature changes (Figure 3 in the manuscript). With the reduction of the EAIS height, the air mass increases over Antarctica at the expense of those over the rest of the globe, leading to higher air pressure over Antarctica and lower air pressure over extra-Antarctic regions (Figure 8 in the manuscript). According to the ideal gas law (Clapeyron, 1834), lower air pressures correspond with lower air temperatures, which well explains the temperature contrast between Antarctica and extra-Antarctic regions (lines 240-242).

3) L136: 5C/km is much lower compared to free tropospheric lapse rate (usually ~7K/km, often ~8C/km over ice sheets), is there an explanation for this?

A previous study has shown that the lapse rate over the Greenland ice sheet depends strongly on background climate (Erokhina et al., 2017). Specifically, the lapse rates for the early Holocene, preindustrial and observational periods are within the range of ∼5.5 and 9.5°C km^{-1}, while the LGM lapse rates are up to 4°C km^{-1} higher than the interglacial values. Therefore, we believe that the low lapse rate obtained in our study (5°C/km) may result from the warm conditions in the mid-Pliocene, which is consistent with the finding of Erokhina et al. (2017).

4) L167: Some decrease in precipitation can indeed be expected at lower temperatures, but can you also estimate how much? Does that explain the changes seen? Apart from the global precipitation reduction outside of Antarctica, I hardly see any correlation between the temperature and precipitation anomaly patterns, so clearly other processes are at play to explain the regional responses.

Our results show that annual precipitation decreases consistently over most areas on the globe in all the sensitivity experiments compared to the MPControl experiments. This is consistent with the decreased air temperatures, which reduce moisture carrying capacity of the air and lead to less precipitation (lines 180-182). However, precipitation varies from region to region, it is hard to estimate how much it has been decreased.

It's true that, except the global pattern, the correlation between the temperature and precipitation anomaly patterns is hard to see. Our results show that he largest precipitation anomaly is found in the tropics that are dominated by the intertropical convergence zone (ITCZ). In general, for most areas except the Southern Ocean, the simulations that display the largest SAT sensitivity to the prescription of EAIS height changes also exhibit the largest precipitation anomaly (lines 188-191). The temperature changes may lead to the southward shift of the ITCZ, which contribute to the regional precipitation changes.

5) L175: The precipitation response seems to occur mostly in the South Pacific ITCZ and SPCZ, can you explain why?

The ITCZ is a zone of convergence at the thermal equator where the trade winds meet. It is a narrow band of intense precipitation and migrates with the changing position of the thermal equator. Based on our results, the temperature increases over Antarctica with the successive reduction of the EAIS height, which may lead to the southward shift of the ITCZ. This reasonably explains why the precipitation response occurs mostly in the South Pacific ITCZ and SPCZ.

6) L188: It would be very helpful here to make a simple budget analysis of the zonally averaged southward moisture transport at different atmospheric levels. The strongest precipitation responses extend quite far over the ocean, suggesting that reduced baroclinicity may play an important role as well.

Thanks for the suggestion. As shown in Figure 7 in the manuscript, the weakened katabatic flow, due to the successive topographic reduction, leads to an elevated moisture transport into the continent, which well explains the increased precipitation over EAIS (Figure 5 in the manuscript; lines 202-206). Anyway, it is worthy of further study on the moisture transport at different atmospheric levels, as well as on the changes in baroclinicity, which will definitely be included in our future work.

7) L198: again, it would be nice to know whether the responses of the different experiments are linearly related to the EAIS reduction factor and if not how they can be explained.

Yes, the responses of the different experiments are linearly related to the EAIS reduction factor (see answers to the general question 3).

8) L220: I doubt whether this seemingly very simple reasoning explains what is going on; besides the global pattern the temperature and pressure responses do not seem

to be that well correlated either. What about circulation changes, heat transports, radiative effects?

In our study, we focus on the temperature and pressure contrast between Antarctica and extra-Antarctic regions. The results show that the temperature and pressure both increase over Antarctica and decrease over extra-Antarctic regions. We analyzed the energy balance (Figure 10 in the munascript) which represents a combined result of heat transport, topography, GHG, cloud, and albedo. We found that heat transport is the primary factor influencing temperature, and the topography (which represents the ideal gas law) and GHG play a secondary role (turquoise line in Figure 10). As for the discrepancies in temperature and pressure responses over relatively small scales, the internal feedback should be important, which requires further study.

9) If it is purely the effect of pressure, you should use the ideal gas law and estimate the temperature response from the pressure response and compare it to the actual temperature change found.

Based on the analysis of the energy balance (Figure 10 in the manuscript), we found that the primary factor is actually heat transport. However, the topography is also important (turquoise line in Figure 10). We did not say that the temperature changes are purely the effect of pressure changes. We are sorry for the misleading sentence, which have been rewritten (lines 226-227). Moreover, we add some words to make the expression more clear (line 296).

10) L234: Your abstract suggests that such studies do not yet exist?

Sorry for the misleading expression. Tewari et al., (2021) addressed future climate changes, while we focus on the studies of Pliocene warm period.

11) L238: Can you support this statement?

I think this statement is a reasonable inference. To support this statement, we performed a new experiment in which the EAIS height has been reduced 100% but the land topography (away from Antarctica) is reduced by 60m, to artificially raise the sea level (lines 265-269). The results show that the cooling away from Antarctica is robust, and would occur even if sea level changes were accounted for.

12) L260: This EBM approach was also used for the Eocene by Lunt et al 2021 and for the Pliocene by Baatsen et al 2022.

The references have been added (line 286).

13) L262: The heat transport component indeed seems to be quite important over Antarctica. I do not follow how a cooler Southern Ocean is linked to higher Antarctic temperatures here? Also, it would be very useful to separate the temperature gradient and circulation components of the meridional heat transport.

Based on the energy balance analysis (Figure 10 in the manuscript), the heat transport component is the primary factor influencing the temperature changes over Southern Ocean. The heat transport increases significantly over Antarctica, while it decreases over the rest of the globe. We think the heat transport from the rest of the globe, especially from the Southern Ocean, to Antarctica is the primary factor influencing the temperature changes over Antarctica (Figures 10). This may result from the proximity of the Southern Ocean to Antarctica. We have rewritten the sentence to make the expression more clear (lines 288-289).

Thanks for the suggestion on separating the temperature gradient and circulation components of the meridional heat transport. We would conduct such analysis in our future work.

14) L281: I do not find this number anywhere in the results, how was it determined? Same for the 5% precipitation increase per degree C.

Both the temperature and precipitation numbers are shown in the results section (lines 146-148, 172-174).

15) L286: Yet, you show that the heat transport is more important in the EBM analysis?

Yes, based on the analysis of the energy balance (Figure 10 in the manuscript), we found that the heat transport is the primary factor influencing the temperature changes, which ultimately result from the topography changes of Antarctica. To make the expression more clear, we have rewritten this sentence (lines 314-315).

16) L287: This seems to be more of a motivation, rather than a conclusion from the results.

Thanks. We have deleted the sentence (lines 316-317).

Figures:

1) Missing a figure showing the heights and/or height anomalies applied in the experiments.

Done. The figure has been added (Figure 1 in the manuscript).

2) Figure 2: it would be helpful to remove the idealised lapse rate effect due to elevation changes, to distinguish with other dynamical/feedback effects.

The lapse rate is actually obtained from Figure 1 (Figure 2 in the manuscript) rather than Figure 2 (Figure 3 in the manuscript). We would like to keep it just for reference.

3) Figure 3: SST responses are almost identical to SAT responses, so I'm not sure what this figure adds besides using a more practical colour scale. Maybe showing the full-depth or upper x meter average temperature response would reveal some more fundamental circulation-related impacts. In fact, I am missing any ocean circulation responses in the figures shown.

Yes, the SST responses are almost identical to SAT responses. I think this means that the height reduction of the EAIS has similar effect on SAT and SST. We have tried our best to adjust the colour scales of Figure 3 and 4. As the SST is an efficient indicator for ocean temperature and is widely used for analyzing patterns of climate variability.

We think that the SAT parameter is sufficient to address the effect of EAIS height changes, and would keep the suggestion in mind in our future investigations.

4) Figure 4: again this figure is rather repetitive between the experiments. While this is useful to know, it does not give any explanation of the patterns seen. Are these the direct result of elevation changes, or rather e.g. the related temperature/circulation changes? What are the seasonal responses?

Figure 4 (Figure 5 in the manuscript) shows the spatial distribution of the annual mean precipitation anomalies over Southern Hemisphere between each sensitivity experiment and MPControl experiment. The explanation of the patterns is given in Subsection 4.1 (lines 200-206), because it is not appropriate to discuss it in the results section. Our experiments were deigned to investigate the effect of EAIS height changes, and we believe the precipitation patterns are the result of elevation-induced changes. As all figures show annual results, we thus present the precipitation annually instead of seasonally to be consistent and facilitate comparison.

5) Figure 5: precipitation anomaly plots are always challenging to interpret, as there is already substantial variability in the reference, without which it is tough to see what is relevant.

Done. We have added the reference plot into Figure 5 (Figure 6e in the manuscript).

6) Figure 6: This is a very useful figure, but hard to read. Why show the entire Southern Hemisphere, rather than e.g. 30S-90S? The projection used seems to be cylindrical, which contracts Antarctica at the expense of lower latitudes. Using a polar stereographic projection seems to be a more logical and practical choice here. Interpreting anomaly quiver plots is pretty challenging. I think it would help to add colour shading showing whether the anomaly induces a weakening (e.g. blue) or strengthening (e.g.) red of the flow in the MPcontrol.

The temperature and precipitation changes both show the entire Southern Hemisphere and use the cylindrical projection. To be consistent, here we also show the entire Southern Hemisphere rather than 30S-90S and keep the cylindrical projection.

7) Figure 8: global sea level is adjusted by lowering the land by 60m, but coastlines seem unaffected? This figure also shows that besides the EAIS, temperature and pressure anomaly patterns do not correlate well.

This experiment was designed to remove the unrealistic surface air pressure anomaly over the land (Figure 9a in the manuscript), and see how this affected the surface air temperature anomalies. Therefore, locations where the land was below 60 m are set to 0 m to maintain the mid-Pliocene land sea mask. We have added some sentences to make the experiment design more clear (lines 265-269).

8) Figure 9; it is hard to see what is going on besides Antarctica and for the largest terms. Consider changing the scaling or separating some of the components. The different components do not show actual warming/cooling, but their estimated (linear) temperature contribution from the EBM.

Done (see Figure 10 in the munascript).

Typos/small errors:

1) L134: increases?

Yes, it should be "increases" (line 145). We have corrected this mistake.

2) L194: MPcomtrol

Done. We are sorry for this mistake and have revised it (lines 212-213).

3) L195: the Antarctic continent?

Our MPControl experiment uses the PRISM4 boundary conditions without any changes. As the West Antarctic Ice Sheet has been melted in the PRISM4 boundary conditions, here we use the East Antarctic continent.

4) L209: explained by lapse rate: something is missing here

To make the expression more clear, we have rewritten this sentence (lines 226-227).

5) L268: height sheet

Done. We have revised it (line 295).

6) L284: decrease

Done. We have replaced "decreases" with "decrease" (line 312).

References

Clapeyron, É.: Mémoire sur la puissance motrice de la chaleur. Journal de l'École polytechnique, 14, 153–190, 1834.

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Erokhina, O., Rogozhina, I., Prange, M., Bakker, P., Bernales, J., Paul, A., and Schulz, M.: Dependence of slope lapse rate over the Greenland ice sheet on background climate, J. Glaciol., 63(239), 568–572, 2017.

Gasson, E., DeConto, R. M., Pollard, D., and Levy, R. H.: Dynamic Antarctic ice sheet during the early to mid-Miocene, P. Natl. Acad. Sci. USA, 113(13), 3459–3464, 2016a.

Gasson, E., DeConto, R. M., and Pollard, D.: Modeling the oxygen isotope composition of the Antarctic ice sheet and its significance to Pliocene sea level, Geology, 44(10), 827–830, 2016b.

Tewari, K., Mishra, S. K., Dewan, A., Dogra, G., and Ozawa, H.: Influence of the height of Antarctic ice sheet on its climate, Polar Sci., 28, 100642, doi:10.1016/j.polar.2021.100642, 2021.

Comments of community:

Unfortunately I do not have time to write a formal review of this paper (wish I did, but I'm busy over in Paleoceanographyh and Paleoclimatology). You may want to consider discussing these results in light of the following papers:

Frigola et al. 2021: https://www.sciencedirect.com/science/article/pii/S003101822100376X

Goldner et al. 2014 https://www.nature.com/articles/nature13597

Knorr et al 2014 https://www.nature.com/articles/ngeo2119

Kennedy et al 2015 https://royalsocietypublishing.org/doi/full/10.1098/rsta.2014.0419

Done. References have been added (lines 42, 231).