Review of Delhasse, Kittel, and Beckmann: "Exploring the Greenland Ice Sheet's response to future warming-threshold scenarios over 200 years"

Dear Authors and dear Editor:

For transparency: I reviewed an earlier version of this manuscript submitted to a different journal. Since then, the manuscript has improved considerably and the current version addresses many of my previous comments.

Before I can recommend publication, I would like to ask the authors to address my comments below, most of which revolve around the writing quality and clarity.

Best,

Andy Aschwanden

University of Alaska Fairbanks

Dear Reviewer,

We would like to thank you for your comprehensive comments and suggestions, again on this version of the manuscript. We have incorporated your comments, which have significantly improved our paper.

Best,
Alison Delhasse, Christoph Kittel and Johanna Beckmann

(PS: you will find in red the suggested modification in our manuscript)

General Comments:

I recommend using acronyms sparingly as they make a manuscript less readable. In almost all cases, I find spelling it out improves the flow. Acronyms do have their place like for models like MAR or PISM or commonly used acronyms where the acronyms is better known that what it stands for (GPS, NASA, etc).

We retain the acronyms MAR, PISM, SLR, GrIS, SMB, and CESM2, while removing EBM PDD, ESM, CMIP6, and RCM as they are never used.

SMB and GrIS are commonly used in The Cryosphere. If the Reviewers and Editor think we should avoid using them, we will also remove it from our manuscript.

L 3: We explore responses to global atmospheric temperature increases from +0.6C to +5.8C since pre-industrial and…

Changed accordingly, thanks for the suggestion.

L 5: "Our study then only..." First, I'm not sure what the "only" refers to (what are you not evaluating?) and second, "then" is commonly used in constructs like "First, we did this, second, we did that, then we..." Please clarify.

We removed the “then” and rewrote the sentence.

Our study focuses exclusively on evaluating the effect of atmospheric changes on the Greenland Ice Sheet, without considering oceanic warming.

L 15: ...such as the Greenland Ice Sheet, are having…

Corrected.

L 18: "fourfold increase in ice loss" can you clarify whether or not this refers to rates of ice sheet mass change? Is it taken from table 2 in Otosaka 2023?

We weren't sure where this exact number came from, following Otosaka et al 2023 or Morlinghem et al., 2019, this should be more around sevenfold if we compare numbers from Table 2 in Otosaka 2023 (-35 Gt/yr in 1992-1996 vs -257 Gt/yr in 2017-2020) or -41 Gr/yr in 1990-2000 to -286 Gt/yr in 2010-2018 in Morlinghem et al., 2019. We

Melting of large land ice areas, such as the Greenland Ice Sheet (GrIS), is significantly impacting sea levels. Recent higher temperatures—amplified by Arctic amplification \citep{fettweis2017reconstructions,bevis2019accelerating}—along with reduced cloud cover \citep{hofer2017decreasing} and persistent atmospheric blocking events \citep{seo2015accelerated,hanna2018recent,tedesco2020unprecedented,hahn2020importance}, have led to an around sevenfold increase in GrIS mass loss when comparing rates from the 1980s to those observed between 2010 and 2020 \citep{mouginot2019forty,otosaka2023mass}.

L 19: "Mass loss projection for the end of the 21st century..."

Thanks for your suggestion. We’ll make changes accordingly.

L 24: "causing the ice sheet to retreat". Please clarify. The ice sheet is already retreating, I assuming you mean that the Greenland Ice Sheet could disappear?

“In the longer term, and under scenarios of even higher temperatures, ice losses could become irreversible or cause the ice sheet's disappearance.”

L 35-45 Paragraph requires some clarifications and disentanglement. Here is a suggestion based on what I think you are trying to say, modify and elaborate accordingly:

"All the previous studies overlook key processes..." I would change this to something like "Previous studies have a variety of shortcomings. Some studies employ standalone ice sheet models, ignoring, i.e., temperature and precipitation feedbacks between the ice sheet and the ice atmosphere (cite studies). Other studies use Earth System Models with interactive ice sheets (citations, e.g. Vizcaino 2015); while these models capture crucial feedbacks, their resolution of the atmosphere is often to coarse to resolve katabatic winds that impact surface melt, or their surface models can be biased because ...(elaborate). Polar-oriented regional climate models, by contrast, employ much higher resolutions than..., allowing for... However they lack the capability to simulate ice sheets, a limitation...

We tried to improve this paragraph with your suggestion keeping important informations about RCMs.

Previous studies have a variety of shortcomings. Some studies (Zeitz et al., 2022, Bochow et al., 2023) employ standalone ice sheet models, ignoring, i.e., temperature and precipitation feedbacks between the ice sheet and the ice atmosphere (Le et al., 2019). Other studies use Earth System Models with interactive ice sheets (e.g. Vizcaino et al., 2015, Muntjewerf et al., 2020); while these models capture crucial feedbacks, their resolution of the atmosphere is often to coarse to accurately resolve precipitation patterns associated with complex high-elevation topography (Fettweis et al., 2020). Polar-oriented regional climate models, by contrast, employ much higher resolutions than Earth System Models, allowing for a more accurate representation of the ice sheet slope and its influence on precipitation or winds influencing surface melt (Delhasse et al., 2024). They also incorporate advanced surface schemes that simulate snow and ice evolution more precisely, resulting in improved simulation of surface properties (Lenaerts et al., 2019, Fettweis et al., 2020). However, they lack the capability to simulate ice sheet dynamics, a limitation that can be addressed when coupled with an ice sheet model.

L 47: We also investigate the ice sheet's response to an idealized reversion to the current…

Corrected

L 54: ...coupled with the Parallel Ice Sheet Model (PISM, …)

Done.

L 55: "Using MAR instead of a simpler energy balance model..." Rephrase, maybe something like

"Using MAR to downscale coarse atmospheric forcing, combined with MAR's sophisticated surface energy balance model comes at a high(er?) computation cost, but results in a more realistic reproduction of surface mass balance (cite a study showing that).

Thanks, we will cite Fettweis et al., 2020 that compare different models to reproduce SMB over the Greenland Ice Sheet.

L 59: PSIM -> PISM

Thanks

L 61: "the ice sheet model has a monthly time step". PISM uses an adaptive time step by default. Did you enforce a 1 month time step?

Thank you for pointing this out. We indeed did not impose a fixed monthly time step in the simulations, and it appears that no specific limit for the maximum time step (`max_dt`) was set. We will revise the manuscript to clarify this.

“The ice sheet model used an adaptive time step to ensure numerical stability.”

L 93-100. This is quite interesting and possibly worth a figure to visualize the non-linearity. How about plotting the sea level contribution (y axis) as a function of the per-degree increase in temperature (x axis)?

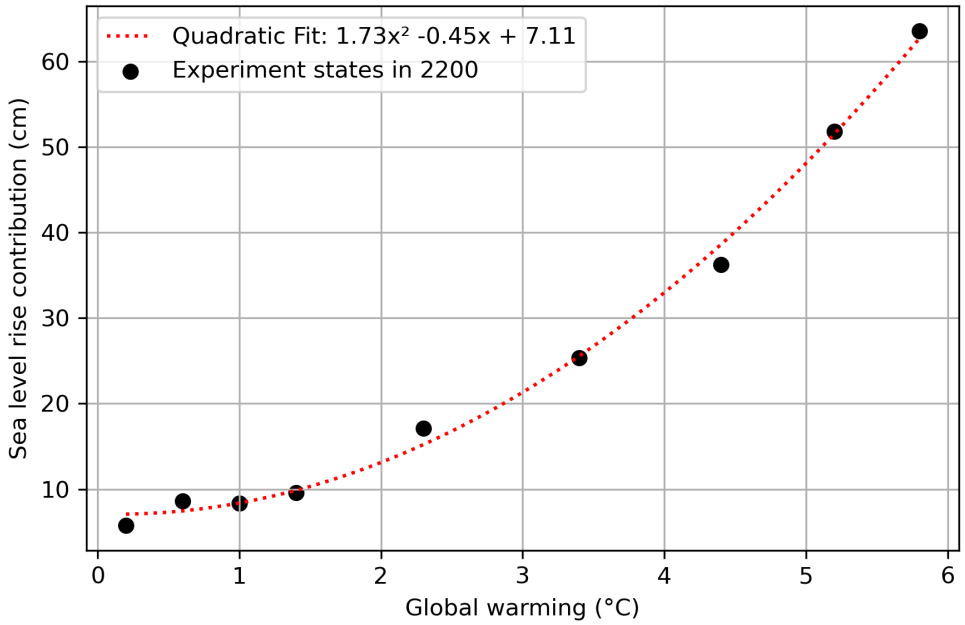

Figure 1. Global atmospheric warming (°C) reached in each of the warming experiments in 2200 in function of the contribution to sea level rise (cm) of these experiments (black dots). In dotted red is the quadratic fit of this relation.

The plot of this relationship illustrates pretty well our words, thanks for the comment. However, as we can already guess that’s not a linear relationship in Figure 2A, we prefer to add this one in the Supplement for a seek of space and to not have multiple times the same information. However, if the editors or one of the reviewers think this figure should appear directly in the main manuscript, we remain open to include it.

L 109-10: "the mass balance increasingly depends on surface mass balance, with a progressively smaller contribution from ice discharge through the grounding line."

Changed accordingly.

L 128: clarify "over the same horizon"

We propose this new sentences.

A temperature increase above +2.3°C leads to a greater increase in runoff, further reducing the surface mass balance (SMB) and resulting in significantly smaller ice geometries by 2200 compared to those projected under a +1.4°C warming scenario.

L 132: "continuous" Do you mean "irreversible"

We're not sure irreversible is the right word (nor is continuous). We propose to change to "mass loss intensifies" as our reverse experiment shows that the melt can decrease in an idealized reversion to the current climate long after having exceeded the threshold.

L 134: What do you mean with "long term dynamics"?

We can remove *long-term* as these experiments do not account for ice dynamics at all. We also change the remaining part of the sentence:

However, these studies do not account for ice sheet dynamics or surface feedbacks such as the melt–elevation feedback.

L 142: "...remain relatively weak for global temperature increases below 1.4degC."

Thanks for the suggestion, we have changed accordingly.

L 165: "In our experiment" -> "In our experiments"

Changed accordingly.

L 179: "Ice discharge stabilizes around 2120 at about -230Gt/yr, causing the lag between SMB and mass balance turning positive.

Thanks for the suggestion, we have changed accordingly.

L 199: "Even if the reverse experiment has a larger mass loss in 2200 than the +2.3 and +3.4degC experiments, its SMB in 2200 is higher, suggesting a lower SLC on time scales longer than considered here."

Again thanks for this suggestion and you did before.

L 209: "The Greenland Ice Sheet's mass balance almost turns positive in 2200, despite the SMB being lower (231Gt/yr) compared to 2000--2010 (453Gt/yr)".

Changed.

L 210-15: Can you elaborate on this: "leading to rapid ice loss at the end of the experiment, when the SMB and mass balance rapidly decline again". I don't see this rapid decline in Figure 2 or S1. It appears to decline a bit, but to me this looks more like inter-annual variability. "Ice discharge has decreased by 417Gt/yr favored by the GrIS thinning, compensating the lower surface accumulation ". Do you mean "lower surface mass balance" instead of "surface accumulation"? Also "favored by ... thinning" sounds odd to me. Can you rephrase? "This suggests...could be more stable..." I'm afraid I'm not following here. The Greenland Ice Sheet is currently not in an equilibrium state. Could you clarify what you mean?

Thank you for the insightful comment. You're absolutely right—"rapid ice loss" as a sustained trend is misleading in this context. The drop in SMB and mass balance toward the end of the experiment primarily reflects interannual variability rather than a systematic decline. However, when comparing the beginning and end of the simulation, we observe increased sensitivity of the surface mass balance to warm years. This is due to long-term changes in surface snow and firn properties (e.g., reduced albedo, saturated firn limiting meltwater refreezing, and a lower ice surface elevation), which lead to enhanced runoff production even under similar atmospheric conditions.

Regarding the phrase "lower surface accumulation," you're correct—it should read "lower surface mass balance." As for "favored by the GrIS thinning," we agree the wording was unclear. We've revised it to better reflect the role of ice sheet thinning in reducing discharge.

Lastly, in saying the future GrIS "could be more stable," we meant that under the same atmospheric conditions, the Greenland Ice Sheet in the reverse experiment approaches a quasi-equilibrium state. This occurs because the reduced ice discharge resulting from long-term thinning compensates for the increased runoff, unlike the present-day GrIS, which is still adjusting and losing mass under current climate conditions.

Despite a lower SMB, the GrIS reaches an almost balanced state in the reverse experiment. Over the final decade of the simulation, the mean SMB is 231 Gt/yr, compared to 453 Gt/yr during 2000–2010. While the SMB appears variable near the end of the reverse experiment, this reflects interannual variability rather than a sustained decline. However, changes in firn and surface snow properties—such as reduced refreezing capacity due to firn saturation, lower albedo, and decreased surface elevation—lead to increased runoff potential during warm years, even under the present atmospheric conditions. Ice discharge has decreased by 417 Gt/yr compared to the present-day value, due to the long-term thinning of the ice sheet. This compensation between reduced ice discharge and enhanced runoff suggests that, under identical atmospheric conditions, the future GrIS in the reverse experiment may approach a quasi-equilibrium state, whereas the present-day GrIS is losing mass under the same forcing.

L 266: "With a cautious..." I don't understand this sentence. Could you please rephrase it?

We suggest to remove the first part of the sentence and rewrite as following

Determining a warming threshold for the disappearance of the GrIS based solely on the point at which SMB becomes zero is insufficient, as our results show that a positive SMB under +2.3 °C warming can later turn negative leading to a sharp rise in sea level and the potential long-term loss of the Greenland Ice Sheet.

L 285: fix citation types from \citep to \cite.

Done thanks.