Response to the comments of reviewer 1 for the manuscript "Stabilizing feedbacks allow for multiple states of the Greenland Ice Sheet in a fully coupled Earth System Model"

by M. Andernach, M.-L. Kapsch and U. Mikolajewicz

November 2025

We would like to thank the reviewer for his valuable comments and specifically for his suggestion to highlight the feedbacks that maintain the steady states. We have carefully considered the feedback provided and will revise our manuscript accordingly.
We provide a detailed point-by-point reply to all comments below. The reviewers' comments are presented in regular font, the authors' replies in turquoise font, and changes to the text in *italic green* font.
All authors have read and approved the suggested changes. We appreciate the opportunity to enhance our manuscript and are looking forward to your feedback.

Kind regards,

Malena Andernach, Marie-Luise Kapsch and Uwe Mikolajewicz

Response to reviewer 1

This manuscript investigates the potential multi-stability of the Greenland Ice Sheet (GrIS) using a fully coupled climate–ice sheet model under pre-industrial climate conditions. The existence of multiple steady states of the GrIS is not new, but this study provides a fresh and valuable contribution by employing a fully coupled model configuration and identifying four distinct equilibrium states at approximately 100%, 48%, 28%, and 19% of the pre-industrial ice volume.
The paper is well written, clearly structured, and scientifically solid. It is thoroughly embedded in the existing literature and successfully highlights both the consistency with, and the departures from, earlier work. The study thus adds important nuance to our understanding of Greenland Ice Sheet stability and the role of climate–ice sheet feedbacks.
I recommend acceptance with minor revisions. The manuscript is already strong, and the suggestions below are primarily aimed at clarification, readability, and strengthening the framing around stabilizing feedbacks.

We are grateful for the overall positive feedback of our analysis of the impact of a disintegrated Greenland Ice Sheet (GrIS) on the atmosphere and ocean. We thank the reviewer for taking the time to review our manuscript.

Focus on stabilizing feedbacks and suggested summary table: The title emphasizes stabilizing feedbacks as key mechanisms allowing for multiple steady states. Given this framing, the paper would benefit from a clearer and more systematic presentation of which feedbacks dominate and how they differ among the identified equilibria.
I suggest including a summary table (e.g. in Section 4) listing the four steady states and the corresponding stabilizing feedbacks that maintain each. If the same mechanisms apply across all states, this could be explicitly stated. Such a synthesis would align the manuscript with its title and improve clarity for readers.

Thank you for this excellent idea. We will perform additional sensitivity experiments that allow us to better quantify the individual contribution of each feedback to maintain the steady states. We will add a table of their contributions to the results section.

L7–8: "These steady states are stabilized through several feedback processes, such as the melt-elevation and melt-albedo feedback."
Please clarify whether the melt–elevation and melt–albedo feedbacks are indeed stabilizing. These processes are usually considered positive feedbacks (destabilizing). Are they stabilizing only in certain states, depending on basin of attraction? A brief explanation of when and how their sign changes would be useful.

Thanks for pointing this out. The way we phrased it could be misleading as they are typically destabilizing feedbacks. Therefore, we will slightly modify the sentence: *"These steady states are stable through several feedback processes, such as the melt-elevation and melt-albedo feedback, which prevent an expansion of the ice sheet towards ice-free areas."*

L12: "highlight the importance of climate–ice sheet feedbacks"
Consider adding "fully coupled", as this aspect is a major strength of the study.

Thanks. We will change this accordingly: *"highlight the importance of fully coupled climate–ice sheet feedbacks"*

L61–69: You mention stabilizing feedbacks via isostatic adjustment and freshwater release into the North Atlantic. Could you clarify whether these are active in your simulations and, if so, whether they appear among the feedbacks constraining your steady states? If they are not significant here, a short note acknowledging that would be helpful.

Yes, isostatic adjustment and freshwater release from the melting ice sheets is included in the model and they also contribute to the emergence of the four steady states. We find that the bedrock elevation of Greenland rises locally by several hundred meters after the partial to complete disappearance of the GrIS. This effect slightly counteracts the melt-elevation effect, by raising the surface bedrock by several hundred meters. However, the raise it not strong enough to allow for a regrowth after disintegration. We will add the contribution of the glacial isostatic adjustment feedback to the mentioned table, add a figure of the isostatic adjustment (Fig. 1) and also an explanation to the text. Freshwater release from the melting GrIS could impact the SST and salinity of the North Atlantic, the stability of the water mass and therefore the AMOC. The impact of SST and AMOC on the steady states is analyzed in the present manuscript in l.220-231 and discussed in l.359-362 and l.377-380. We further pointed out the importance of the AMOC and SST changes on the state transition of M* (l.246-251) and in the sensitivity experiments with a constant PI AIS (Section 3.3.2).

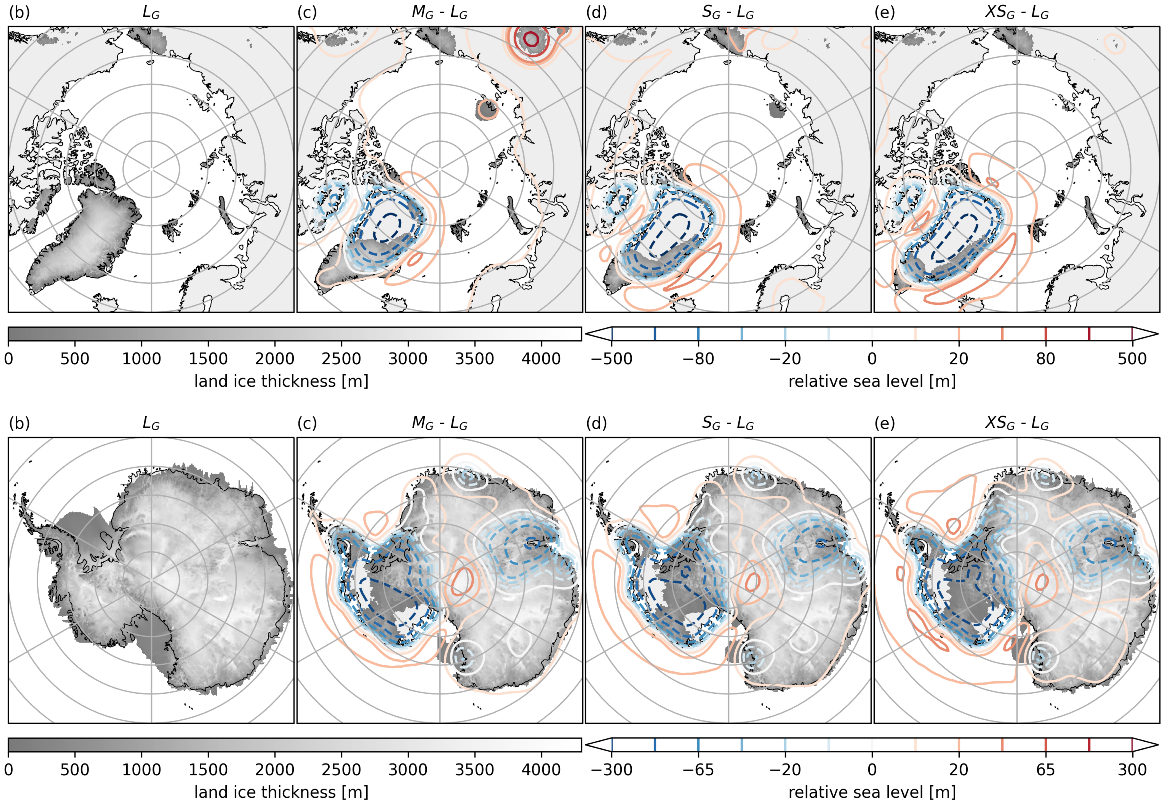

Figure 1: Effect of isostatic adjustment, shown as the relative sea level, and ice sheet thickness for each steady state. The left column displays the absolute values of L_G. The remaining columns show the difference in relative sea level of each state compared to L_G, depicted as colored contour lines, ranging from lower sea levels (blue) to higher sea levels (red).

L85–86: You talk of previous studies neglecting interactions with components such as the AMOC, vegetation, and isostatic adjustment. Since these interactions were previously neglected, it would strengthen the discussion (in Section 4 and perhaps already here) to comment briefly on whether they are important in your results—e.g., does the AMOC play a stabilizing or destabilizing role for any of the steady states?

We agree with your comment. In our manuscript, we explain that the AMOC contributes to the stabilization of the southern part of the XS GrIS (l.220-223). We have analyzed the variability of the AMOC and the SMB in XS_G and find a linear relationship with an increase of the SMB by 45.8 mm WE per 1 Sv decrease of the AMOC strength (Fig. 2). We will add the following sentence to highlight the contribution of the AMOC: "A weaker AMOC strength at 30° N in XS_G (*14.6* Sv) compared to L_G (17.3 Sv) further reduces the northward heat transport, contributing to the colder upper ocean temperatures in the Nordic Seas. As the colder air is advected onto the GrIS by southeasterly near-surface winds (Fig. 4d), this cold ocean anomaly likely contributes to preserving the southern part of the very small ice sheet in XS_G. *Analyzing the variability of the AMOC and the SMB in XS_G, we find a linear relationship with an increase of the SMB by 45.8 mm WE per 1 Sv decrease of the AMOC strength.*" We also find that the destabilization of M_G* coincides with a stronger AMOC (see our response to your previous comment).

As outlined in our response to your previous comment, we will add a short analysis of the GIA feedback to the results section. We will also mention the contribution of regrowing vegetation more explicitly in the results section: "Another contribution arises from the smaller glacier mask and the absence of a snow cover in summer, which changes surface parameters to those of a non-glaciated surface. *The latter enables the dynamic growth of grass and shrubs in ice-free areas. These surface changes reduce the summer albedo by about 0.6, leading to a strongly positive melt-albedo feedback. They also allow surface temperatures to exceed the melting point in XS_G. .*"

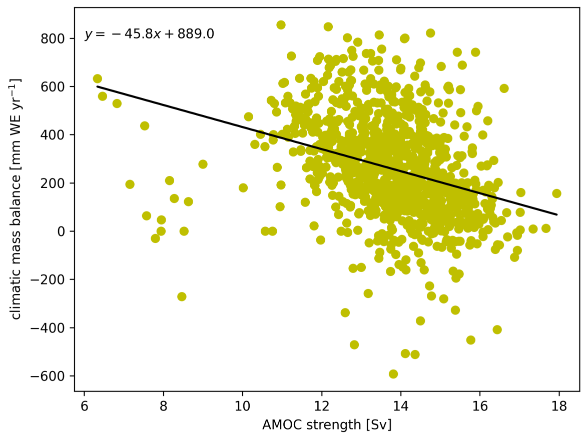

Figure 2: Regression between the climate mass balance and the AMOC strength in XS_G.

L95–96: "we identify which feedbacks or combination of feedbacks constrain each steady state of the GrIS." This is central to your paper's theme but remains somewhat implicit. A concise table summarizing which feedbacks constrain which state would help make this claim more concrete.

As mentioned in earlier comments, we will add summarizing table to the results.

L127: "the asynchronous coupling method has no impact on the results." This phrasing feels too strong. Consider softening it to something like "We find no significant impact on the results or conclusions from the asynchronous coupling method."

Thanks. We will add: *"Focusing on the equilibrated steady states, we do not find a significant impact on the results or conclusions from the asynchronous coupling method."*

L129–150 This paragraph is long and dense. Consider splitting it into smaller paragraphs to improve readability.

This is true. We will split the paragraph into three separate paragraphs.

L130 "five simulations starting from different GrIS volumes (0%, 21%, 43%, 70%, and 100% of the PI value; Tab. 1)." The list of initial conditions does not match Table 1 (which lists 0%, 33%, 70%, 100%). This creates confusion. Either align the lists or move the table reference to where the consistent set appears.

Thanks for pointing this out. The values in the table refer to the simulations analyzed in the results section, which have been obtained from the combination of the baseline and threshold experiments. To not confuse the reader, we will remove the first reference to the table and add a sentence in which we refer to the table after describing the experiments: "*The final steady state simulations and the sensitivity experiments are summarized in Table 1.*"

L200–201: "the dynamic growth of grass and shrubs in the unglaciated areas, which leads to strongly positive melt-albedo feedback." Please clarify whether vegetation expansion is itself what you refer to as the melt-albedo feedback. Typically, the melt-albedo feedback refers to darkening of snow/ice by melt rather than vegetation. If the vegetation effect is distinct, please rephrase accordingly.

We will rephrase this part accordingly: "Another contribution arises from the smaller glacier mask and the absence of a snow cover in summer, which changes surface parameters to those of a non-glaciated surface. *The latter enables the dynamic growth of grass and shrubs in ice-free areas. These surface changes reduce the summer albedo by about 0.6, leading to a strongly positive melt-albedo feedback. They also allow surface temperatures to exceed the melting point in* XS_G."

L242–243: When describing how the SG state becomes unstable and transitions to the MG state (paraphrasing: Above a certain threshold it becomes unstable), consider mentioning which physical processes cause this instability.

This is a good idea. We will add: "[...] *into M_G, due to a weakening of the southerly winds, weaker Föhn winds, a less strongly redistributed precipitation and more ice flowing into the central areas.*"

L290: You mention "the inertia of the ice sheet." Please clarify what is meant by "inertia." In a physical sense, ice sheets have relatively slow response times but limited true dynamical inertia; a short explanation would avoid confusion.

We will revise this part accordingly: "[...] arises from the *slow response time* of the ice sheet due to which the AIS needs several [...]."

L342: "Below 70–68%, even further parts of the GrIS are lost". It is unclear where these threshold numbers (70 – 68%) come from. Please specify.

Unfortunately, an error occurred in this threshold. The correct threshold should be 43-33% based on Figure 2. We will correct the percentages accordingly.

L193: Suggest to revise to: "Only in the mountains are temperatures cold enough..."

We will revise the sentence accordingly.

L263–264: Revise to: "does an ice cover in the northwest become stable"

Thanks, we will revise the sentence.

L273: "disintegrates" (add final s)

Thanks for spotting this. We will correct the grammar.