Author Response to Reviewer 2

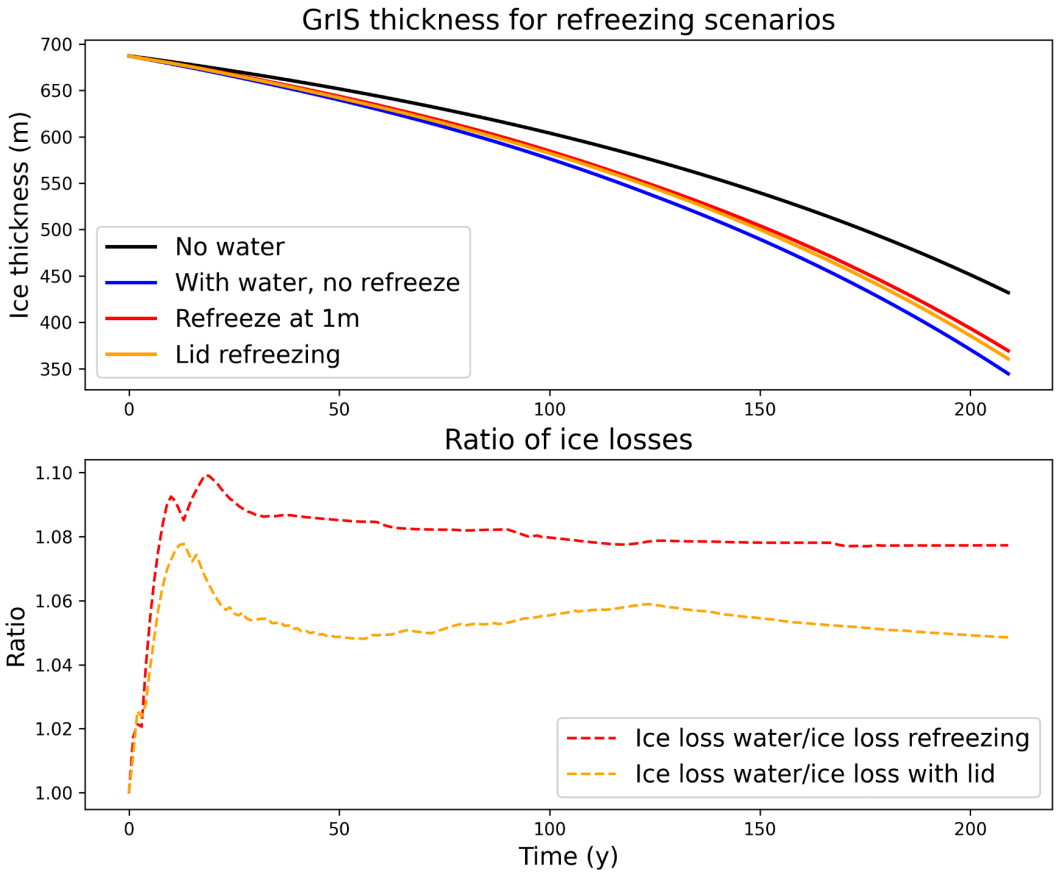
We thank the reviewer for their constructive and insightful comments. In response, we have substantially revised the manuscript to improve clarity and readability, and to more clearly articulate the central aim of our study. Specifically, our focus is not on achieving a fully realistic representation, but rather on elucidating the conceptual mechanism underlying large-scale water removal in the model. Our work should be understood as an extension of the melt-elevation feedback described in Levermann and Winkelmann (2016); Accordingly, the primary objective is to investigate the implications of this mechanism within an idealized framework, rather than to provide quantitatively realistic simulations. We have revised the manuscript to make this perspective explicit throughout and provide detailed responses to the reviewer's specific comments below.

In this manuscript, the authors describe a simple model to investigate the impact of ponded surface meltwater on Greenland ice sheet surface topography and elevation change. In general, such an exercise is interesting and does have important implications for the inclusion of ponded meltwater in Global Climate Models, which largely neglect meltwater processes. However, I have several major and minor concerns with the modelling approach, all of which impact the robustness and applicability of the results.

Major Concern #1 – I understand the justification of having a simple model for these exercises. However, some model simplifications here deviate too far from reality. For instance, not considering refreezing is a huge limitation. In reality, many surface lakes refreeze or become buried (20-60% depending on location and year; Dunmire et al., 2025). It is therefore hugely unrealistic to assume that all meltwater produced is transported off the ice sheet via seepage. Lake refreezing limits the processes of lake-bed deepening and elevation lowering. The impact of ponded meltwater on these processes (e.g., L262-265) is a key result of this manuscript; however, without considering refreezing, I fear this result is unrealistic and a bit meaningless.

Answer: We thank the reviewer for stressing the importance of refreezing. According to that, we have considered scenarios where a small portion of lakes refreezes or stores water with the formation of a lid. Within the simplified framework of our model the results show that these refreezing processes can slow down ice melting, but are not very relevant in with respect to the onset of the feedbacks we consider. This is detailed in the new panels of the old Figure 8 in the paper and in the updated discussion concerning refreezing. Additionally, here we show that the ice thickness in the scenarios with lakes and refreezing is comparable in our model. The plot below (not included in the paper) shows in detail that the ice evolution is comparable and that ice refreezing does not change the feedback effects. Additionally, if we consider the ratio between the ice loss in the models without refreezing and with the two refreezing scenarios, this is more relevant at the beginning of the simulation, when the lake basins are filled through the

refreezing processes. Additionally, we have also clarified the role of seepage within our manuscript.



In addition to the neglection of refreezing, the accumulation rate is far too low (~33% regional climate model estimates), which I believe further amplifies elevation changes in perhaps an unrealistic manor.

Answer: We stress in the text that we want to amplify the elevation change to show how the feedback works.

Another consideration that is neglected is the impact of a diurnal cycle. The decision to not include diurnal temperature dynamics should be discussed.

Answer: The diurnal cycle is not explicitly included in our model due to its conceptual design, which focuses on longer-term (seasonal to interannual) temperature and melt dynamics rather than sub-daily variability. We acknowledge that this is a simplification and may affect short-term melt variability; however, its impact on the longer-term evolution considered here is expected to

be limited. We now mention this limitation in a dedicated section: “Simplifications and comparison with other models”, together with other model assumptions and potential extensions to more complex frameworks.

In general, many model details are either missing or discussed in illogical places. For instance, what is the timestep over which the model is run? Many variables and parameters in the equations are either not defined or are defined much later in tables. For ease of reading, it would be helpful to define parameters as they appear in the text, instead of listing the values in a table which is not referenced until much later.

Answer: We have revised the manuscript in such a way that all parameters are explained, including their values, in the text, when they occur for the first time. In addition, we kept the table with all parameters to provide an overview, which we hope makes it easier for the reader to get a comprehensive view on the model parameters.

My last major comment is that, in general, many of the sentences are difficult to read. There are numerous long, convoluted sentences that I had to read multiple times to understand. I would suggest shortening and simplifying sentences where possible.

Answer: We have rephrased and shortened many sentences throughout the manuscript, which now are easier to read.

Minor Comments
L8: “Only the lowest emission scenarios prevent…” This sentence is quite extreme and I’m not sure that it is substantiated by the results of this manuscript, considering that this model is very simplified and missing key processes.

Answer: We agree that the original wording was too strong given the simplified nature of the model. We have revised the sentence to more clearly reflect the idealized character of our model.

L17: “Assuming that ice ablation occurs at a rate…” Is there a simpler way to write this sentence? It is very convoluted and I had to read several times to understand what it was saying.

Answer: We have rephrased the sentence and split into more subsentences to improve its clarity

L30 – What is meant by “Mechanical processes”

Answer: We use "water transport" instead.

L30 – “In this study…” Perhaps this would be best at the end of the introduction. It feels a bit abrupt to go from background information (L13-30), to what was done in this study (L30-35), then back to background information (L35-60). I would recommend consolidating the background information.

Answer: Many thanks, this is a good suggestion. We have moved the sentence towards the introduction; additionally, we have rephrased several sentences to consolidate the background information.

L34 – “and all Greenland more than global means” Not sure what is meant by this.

Answer: We rephrased our sentence, explicitly mentioning Arctic amplification.

L40 – “Eventually supraglacial lakes typically drain through moulins and fractures in the ice sheet”. This is not necessarily true. In fact, a large portion of the water (20-60%) refreezes or remains buried in buried lakes depending on the year and ice sheet region. While many lakes drain, literature does not suggest that this is the most “typical” fate of supraglacial lakes.

Answer: We understand the reviewer's point. We have rephrased this sentence in the revised version.

L45 – the mention of sea ice here is very abrupt. Either remove the comparison to meltwater on sea ice, or I suggest finding a better transition here.

Answer: We rephrased the introduction to this paragraph

L49-51- This concept of the positive melt-albedo feedback has been explained several times in the introduction section. I recommend consolidating these explanations and then later referring to this process as the “melt-albedo feedback”, as it is commonly referred to.

Answer: We have removed the redundancies and modified the text accordingly

L70 – “We assume that these are the main variables that need to be taken into account”. I would re-frame this to something like “We assume that these are the main state variables…”. Originally, I was very concerned to not see precipitation considered here, but then I found it was included later on. I would consider rephrasing here to avoid similar confusion.

Answer: We rephrased the sentence as the reviewer suggests.

Figure 2 confuses me. Why is the water level below the snow? Personally, I don’t take a whole lot away from this figure.

Answer: We understand that the representation of snow on liquid water is misleading. This was also mentioned by Reviewer 1. We have rephrased the text to better clarify the scope of the figure and we have added a new figure in the revised version.

Could there be a figure depicting some of the equations? For instance, you could show how the melt rate (Eq. 2), or albedo (Eq.3) vary as a function of water depth (W). This would be more helpful than either Figure 1 or 2.

Answer: While a plot illustrating the dependence of albedo on water depth is already available in (Luthje et at., 2006), and we therefore considered it unnecessary to reproduce it here, we agree that additional visual clarification of the model is beneficial. Accordingly, we have added a new panel to Figure 2 that better illustrates the processes represented in our model. In addition, we now explicitly refer readers in the manuscript to the albedo plot presented in (Luthje et at., 2006).

It seems from Equation 4, that as soon as the temperature drops below freezing, seepage begins to occur? Is this true?

Answer: Seepage occurs throughout the entire year and is not restricted to periods when temperature is below freezing. This is clarified in the manuscript, where the representation of seepage is now described more detail.

Equation 5 – what is x? What is theta?

Answer: We have clarified the use of variables. We also exchanged x by z to avoid potential confusion with the horizontal domain variable x.

L154 – “basin by basin” is confusing, because you are not considering the GrIS drainage basins. Maybe rephrase to “lake basin”? Also, it should be mentioned earlier that only a 40km cross-section of the Greenland ice sheet is considered here.

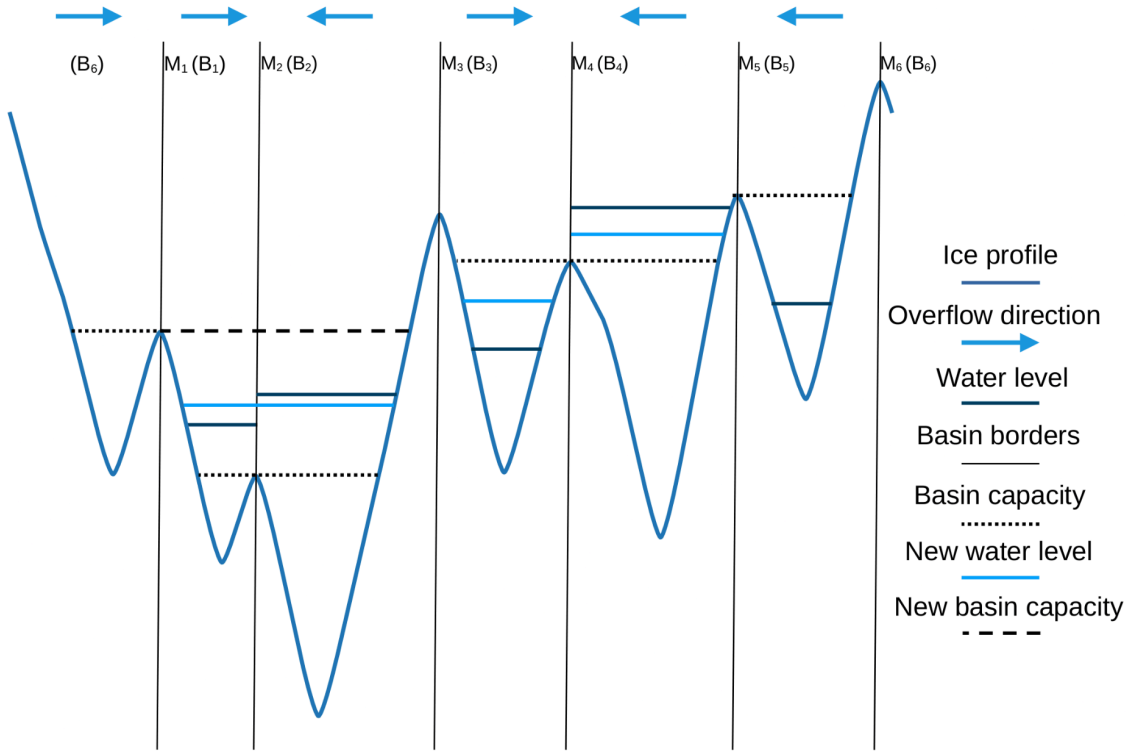
Answer: We have replaced all occurrences of “basin” with “lake basin” to avoid confusion with Greenland Ice Sheet drainage basins. In addition, we now clarify earlier in the manuscript that the model represents a 40 km cross-section of the Greenland Ice Sheet, which is intended to improve readability and context.

Algorithm 1 – maybe move this to the appendix? It’s not easy to read and not intuitive to figure out what happens here. Another suggestion would be to make a graphical schematic for water flow in your model.

Answer: We moved the algorithm to the appendix, further adding a graphical schematic for the steps of the algorithm.

L159 – “specifically the one located immediately to its right.” It is unclear to me what is meant by this, and I have a hard time visualizing. As suggested above, a schematic could be helpful.

Answer: In the text we further refer to the new figure to illustrate this process. The figure is attached below and its caption details the steps in the algorithm.



L205 – Is just the ice thickness considered in the linear relationship between elevation and temperature? Not the ice+snow elevation?

Answer: We also added the snow elevation to the old equations 8, 9, 14 and 15. However, its effect on the computations is negligible because the initial snow thickness is set to zero and therefore does not affect the temperature evolution.

L207 – 8 °C drop in temperature per kilometer – please motivate this value in the manuscript.

Answer: This value is taken from the literature, namely (Reeh, 1989). We added the corresponding citation.

L217 – How long is the spin-up period?

Answer: We have specified in the revised version that the spin-up is 10 years.

L220 – I'm confused about the decision to initialize with no snow. Likely, you now have a situation with a too-shallow snow layer (especially considering the low accumulation rate), which leads to the snow melting out too early, contributing to increased ponding, and an amplified, potentially unrealistic feedback.

Answer: The choice to initialize the model with zero snow was intentional and serves to create an idealized setup in which the feedback mechanisms associated with supraglacial lake formation can be isolated. We acknowledge that this assumption may lead to a relatively shallow snow layer early in the simulation, which can accelerate melting and ponding and thereby enhance the associated feedback strength. This limitation has been clarified in the manuscript in Section 2.3, where we explicitly state and justify the chosen initialization.

L241 – "We integrate the model described above over 200 years with an additional 10-year spin-up" What is meant by this? You run the model for 200 years?

Answer: We specified that we integrate the equations with a spin-up of 10 years and then we integrate the model for 200 years. We now say this explicitly in the text.

Table 1 – It would be good to integrate some of these values within the text as well.

Answer: We integrated the values of the table in the text.

Figure 3 – Change the legend to "Ponded water" and "no ponded water. (same for Figure 4). The second simulation has melt water, it just cannot pond, correct? Also, the tick labels are very small in this figure and difficult to read.

Answer: We thank the reviewer for this comment. We clarify that in the second simulation meltwater is still generated, but it does not accumulate or form ponds, as it is immediately removed from the model domain and therefore does not contribute to surface water storage or lake formation. This distinction has been clarified in the text for better understanding. Regarding Figure 3 (and 4), we acknowledge the reviewer's suggestion about the legend wording and the readability of tick labels. Additionally, we have modified the tick labels in the figure.

Section 4 – Sensitivity analysis of the model: The sensitivity analysis should first be introduced in the methods section.

Answer: We thank the reviewer for this suggestion. We agree that the sensitivity analysis should be clearly introduced earlier in the manuscript. We have therefore clarified its role in the model

evaluation and ensured it is explicitly described in the section where the model setup and evaluation procedures are presented, improving its visibility and logical flow.

L270 – “Each parameter” – which parameters?

Answer: We clarify that “each parameter” refers to the set of model parameters introduced in Section 4. The text has been revised accordingly to remove ambiguity.

Figure 4 – Since panels A) and C) depict the same experiment with ponded water, they should probably be placed next to each other.

Answer: We exchanged the panel order.

Figure 6 – It is interesting here that with the accumulation rate doubled, you essentially prevent any elevation change. It is especially interesting considering the accumulation rate used is already less than half regional climate model estimates.

Answer: Yes, we agree, it is a really interesting finding.

L307 – Do you bias correct the GCMs for the historical period? Both CESM2 and NorESM have temperature biases compared with ERA5 for the historical period and these biases should be considered.

Answer: We specify that old Equations 14 and 15 are not affected by offset bias in the models, we also briefly discuss other kind of bias in the models and their effects in the revised manuscript.

In the introduction, a large motivation for this work is to help in the parameterization of supraglacial lakes in global climate models. However, this is not brought up again in the discussion or the conclusions. From this study, do the authors have suggestions as to how to adapt GCMs to include supraglacial lakes?

Answer: We have added a paragraph in the Discussion section highlighting the implications of our results for the parameterization of supraglacial lakes in global climate models. In particular, we suggest that GCMs could incorporate simplified parameterizations of supraglacial lakes that represent meltwater storage and drainage dynamics, and their effect on the surface energy balance through changes in albedo and enhanced melt due to ponded water. Our results indicate that lake–ice feedbacks can amplify melt locally, and this could be represented in large-scale models through an effective parameterization linking surface melt rates to transient water storage. We also note that differences in spatial and temporal scales between our model and GCMs limit direct implementation, but our findings provide guidance for developing improved sub-grid-scale representations of supraglacial hydrology.

The way that equations are referenced is not consistent. For example, “second

equation in Eq. 1” (L96) and “first Eq. of Eqs. 4” (L125).

Answer: We have uniformed the equation referencing.

Technical corrections
L35 – remove possible
L57 – “adapted from a climate model” à “adapted for a climate model”
L69 – Remove “According to our aim”
L246 – Replace “circa” with “approximately”

Answer: We have implemented all technical corrections suggested by the reviewer.