Response reviews

We would like to thank the editor and reviewers for the additional comments we received. The comments clarified the previous reviews and are implemented in the revised manuscript. We combined the answer to both reviews into a single file. The reviewer's comments are displayed in black and our response is in blue. We refer to the track changes file for line numbers mentioned in this response. The line numbers refer to the attached track changes file. In addition to addressing the reviewer's comments, we made several textual improvements.

Ice layer definition (reviewer 1)

Thank you for addressing the review comments. I support the proposed revisions described in the response document and feel the paper will be a solid contribution to the literature. However, the revised manuscript could still benefit from better treatment of one of the review comments: the discussion of ice-layer formation in IMAU-FDM and its potential relevance to the study results.

The current response simply states that ice layers form by refreezing, creating a layer with density of 917 kg m^{-3}, the density of pure ice. While this defines an ice layer, it does not explain the model processes that lead to full saturation of firn and ice layer formation, nor does it clarify under what circumstances ice layers develop, where they occur within the firn column, and how frequently they form.

I think the paper could benefit from some additional explanation because how the model handles ice layers is not common knowledge, and the treatment of ice layers could be quite relevant to the interpretation of the results.

Specifically, the reader should be informed as to the mechanisms by which a firn layer reaches ice density in the model. To achieve a density of 917 kg m^{-3}, the pore space must effectively be eliminated through saturation and refreezing. How does this occur in IMAU-FDM? Does the model permit ice layers to form at any depth within the firn column, or only under specific conditions in the top-most or bottom layers? What determines where and when an ice layer forms?

My understanding is that water storage in a layer should be limited by the model's treatment of liquid-water retention, after which excess water is passed downward. If so, it is not obvious how a single melt event could completely fill and refreeze the pore space of a firn layer. Instead, one possible interpretation is that ice layers only form through many repeated episodes of wetting and refreezing, with each event incrementally reducing pore space until the layer eventually reaches ice density. If this is correct, the manuscript should state this explicitly and discuss where, when, and how frequently this process occurs within the model. If other pathways exist, these should also be described.

Related to this, a simple cold-content estimate suggests that a firn layer at approximately 20 degree celcius could freeze only on the order of 10-15% of its own mass before warming to the melting point. If my understanding is correct, this would imply that complete pore-space elimination is generally not achievable during a single event and instead requires multiple melt-refreeze cycles. If that reasoning is incorrect in the context of IMAU-FDM, the authors should explain why.

In summary, I am not asking for a definition of an ice layer, but rather for a description of the model conditions that generate one, and where/when these circumstances tend to occur. Clarifying whether ice layers form only through cumulative multi-event densification, whether they can form at depth as well as near the surface, and what conditions control their formation would make interpretation of the the manuscript and its findings considerably clearer.

The reviewers understanding of ice layer formation is correct: ice layers form through many repeated episodes of wetting and refreezing. We added the following description of ice layer formation in line 97: 'Water refreezes when in a firn layer cold content is available, reducing the pore space of the firn. In IMAU-FDM, ice layers form through subsequent events of wetting and refreezing, whereby the density is increased and pore space is reduced until the ice density of 917 kg m^{-3} is reached. Ice layers primarily form near the surface where sufficient meltwater and cold content allow for repeated cycles of filling pore space and refreezing. Therefore, in the current model setup, a single melt event cannot completely fill and refreeze the pore space of a firn layer. '

To stress that a single melt event does not completely fill and refreeze the pore space in a firn layer, we also made the following changes:

- In line 15 we replaced 'ice' by 'higher density firn'.
- In lines 203-204, 209, and 311-312 we stressed that only the meltwater that can be retained as irreducible water in the pore space refreezes.

Firn changes in a steady climate and during spin-up (reviewer 2)

While the manuscript has been improved in terms of acknowledging that a portion (and in some cases most) of the firn change is due to model spinup, I am myself interested to see maps of where the spinup makes the most difference. This would be highly informative for the firn modeling community. The new figure (Fig. 11) is very nice, and a helpful illustration of height change at the chosen locations over time. And Figure 9b does clearly show that differences are driven by spinup. However, the results shown are isolated to specific chosen locations. I recommend that the authors add a figure with a map of the difference in FAC at the beginning of the historical simulation (i.e. after spinup) to most simply illustrate spinup differences. Of course, any type of spatial representation of differences that the authors think would work better could suffice, as long as it gives the reader a way to spatially distinguish what areas are affected by spinup vs. the historical simulation. Section 3.1 should then reference the new figure, so that the spinup impact is mentioned along with the discussion of Figure 3. As is, I find Figure 3 misleading to non-firn modelers (and, actually, to me at first until I got much farther into the manuscript), so I think it needs better context for those who don't know what they are looking at when it is introduce in the manuscript. Of course, even a figure in a supplement would be helpful, and it could still be easily referenced in Section 3.1.

We respectfully disagree that Fig. 3 is misleading: it is the FAC difference one would get for various dt_{force} when running a firn model in the usual way, i.e. with a spinup period (for an approximate steady state climate) followed by an unconstrained run over the full period for which climate forcing is available. The mechanisms described in section 3.2 operate at every time step in the simulation, also the during spin-up. The spin-up and subsequent simulation have the same dt_{force}.

However, we agree with the reviewer that it is interesting to distinguish between the effect of dt_{force} under the steady state climate during spinup and a changing climate after that. Therefore, we added Section 4.3: "Implications for steady state and changing climates". The Antarctic Peninsula Ice Sheet (APIS) is in a steady state for most of the simulation period (1979 - 2020) except for the last three years. That is why the spin-up period is chosen from 1979 to 2020 and the ΔFAC for the APIS is mainly established during the spin-up. For the southern Greenland Ice Sheet, the steady state climate and thus spin-up period is chosen from 1939 until 1970, after which the climate starts to change. Therefore, the final ΔFAC is established both during and after the spin-up period. We discuss these effects in Section 4.3 and illustrate them in Fig. A1.

Data availability The forcing products used for this study are referenced in lines 105-108. Since these references are for older releases of the products (i.e. from 2018), it is not clear in the manuscript where these specific products (through 2023) can be downloaded from in the Code and data availability section. Are they part of the "datasets" that are planned to be published on zenodo? Please specify explicitly in the text.

Unfortunately, the forcing files are too large to upload to Zenodo. The files contain 3-hour, 6-hour, 1-day or 1-month data over the simulation period for the whole Greenland and Antarctic domains. In the code and data availability we added the following: "The RACMO2.3p2 forcing data is extended from the simulations of Van Wessem et al. (2018) and Noël et al. (2018). The forcing data are available upon request due to the size of the files."