Response to reviewer 1

We would like to thank the reviewer for the comments we received. Based on the feedback, we suggest several changes that will improve this manuscript. The reviewer's comments are displayed in black and our response is in blue.

Major comments

1. Table 1 in the Introduction

Table 1 does not add much in its current form. The list of papers and their time steps does not appear to be exhaustive, which makes the table potentially misleading. Simply referencing some examples in the text may be sufficient. Alternatively, the introduction could include a more informative table or figure that explicitly links model time-step choices to processes, firn model classes, or data availability constraints, etc.

We do agree with this comment and this comment aligns with the feedback from reviewer 2. Therefore, we propose here a solution for Table 1 that addresses several reviewer comments.

We propose to remove the table, and instead refer to examples in the text. More specifically, we propose the following textual changes:

- We will stress in line 36 that IMAU-FDM is forced with surface mass balance components at its upper boundary, to present the scope of this study
- We will extend the discussion section 5 by distinguishing between general conclusions and those specific to IMAU-FDM, to provide better context and reduce potential misinterpretation. For example, IMAU-FDM is forced at the surface, and we found that a climate forcing time step greater than a day allows for a non-physical coexistence of snowmelt and sub-zero surface temperatures, leading to immediate shallow refreezing of meltwater. This finding is relevant to other models that prescribe surface temperature and snowmelt, such as The Community Firn Model (Medley et al., 2022). Firn models with surface energy balance schemes that explicitly compute melt fluxes might be less sensitive to this finding, as long as the model does not allow coexistence of sub-zero temperatures and snowmelt under 1-day or larger forcing time steps.

2. Conceptual Overview (Figure 4)

While a conceptual overview figure is a valuable addition to the paper, Figure 4 requires substantial revision. In its current form, the schematic is difficult to interpret and appears inconsistent with the physical processes described in the text (to be blunt, it looks like something generated by AI). A few examples of shortcomings: In Process 1, the depiction of large refreezing grains at depth versus smaller refreezing grains near the surface does not appear physically meaningful and is inconsistent with the description in the text; In Process 2, the distinction between the left and right panels is unclear, and the intended contrast is not adequately explained in either the caption or the manuscript; In Process 3, it is not clear how the illustrated elements relate to time stepping at all. Given the importance of this figure for synthesizing the paper's key ideas, a clearer and more physically grounded conceptual diagram is needed.

We propose to substantially revise this figure, see Fig. 1 in this response. We suggest the following changes:

- We give each process a descriptive title that highlights the main finding, e.g. "1. Melt and refreezing remove more FAC with greater forcing time steps", instead of "Process 1: melt".
- In process 1, we illustrate melt with water droplets instead of the blue grains.
- In process 1, refrozen grains have a similar grain size and are shown in gray. The red shading indicates heat release.

- In process 2, we separate the two time step related processes that influence densification. One relates to the amount of firn, for which we increased the contrast between the dt_{3h}^{force} and dt_{1d}^{force} panel. The other process is related to heat release.
- In process 3, we relate the process to the time stepping.
- The figure is not made by AI and we made it more visually attractive.

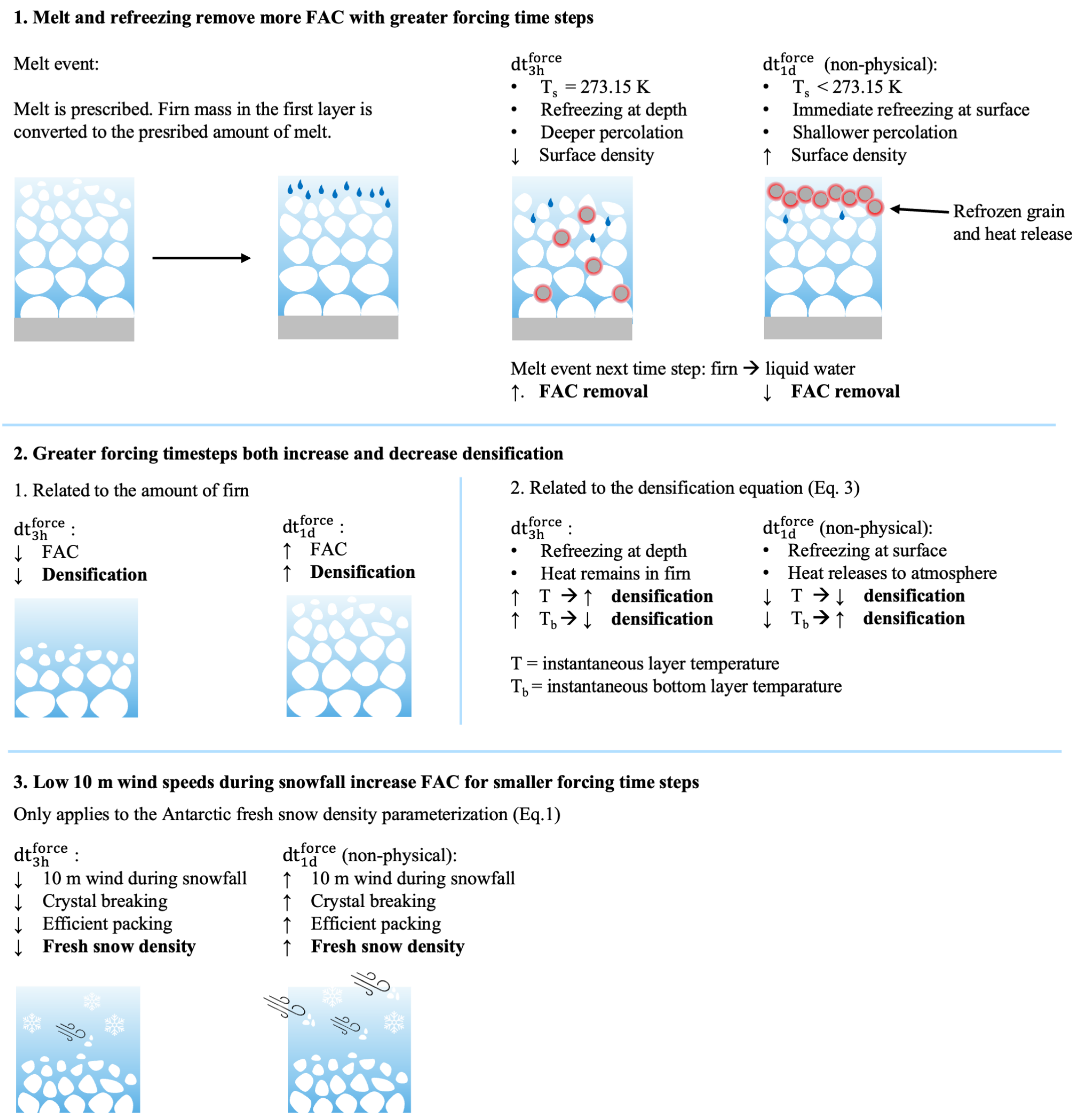

Figure 1: Processes that control (Δ) FAC.

3. Formation of Ice Layers in the Model

The model description needs to explicitly explain how ice layers are formed in IMAU-FDM. This information is essential for interpreting the results. For example, it is unclear whether daily forcing could artificially promote near-surface ice slab formation due to the way meltwater refreezing and layer formation are implemented.

Without a clear description of how refreezing transitions into discrete ice layers, whether those layers are permeable or impermeable, and how they evolve over time, the reader cannot fully evaluate the paper's conclusions regarding the impacts of model time step on firn structure and pore-space evolution.

In line 90 we will add a description of ice layer formation. In short: Ice layers have a density of 917 kg m^{-3} and form through refreezing of liquid water. The bucket scheme does not allow standing water over ice layers. Instead, water percolates downward to the next layer when no pore space is available.

4. Snowfall

The language surrounding “Snowfall” and Process 3 is confusing and needs revision. The term *snowfall* typically refers to a precipitation rate or mass flux, whereas this section is primarily concerned with the initial (fresh) snow density parameterization. Referring to this process as “Snowfall” is therefore confusing because the effect arises from how fresh snow density is prescribed as a function of meteorological variables that depend on time step. This distinction is important because elsewhere in the manuscript (e.g., in comparisons between Greenland and Antarctica), *snowfall* clearly refers to accumulation magnitude. Clarifying this terminology, or renaming this section, would substantially improve readability and reduce potential confusion. In fact, I am not confident that I have correctly deciphered the sections concerning snowfall.

We thank the reviewer for pointing out the inconsistent use of the term snowfall. We now clarify that accumulation represents the sum of snowfall, sublimation and drifting snow processes (deposition/erosion). The newly accumulated snow, if any, is assigned the fresh snow density. We will consistently use this terminology throughout, by implementing the following changes. In section 2.5 we will add the definition of accumulation. In line 120 we replace snowfall by accumulation. In the revised Fig. 1 in this response, we explain that low 10 m wind speeds during snowfall increase fresh snow density. We rename section 3.2.3 'Process 3: snowfall' to 'Process 3: fresh snow density on the APIS'. The remainder of section 3.2.3 consistently uses the terms snowfall and fresh snow density. In this section, we will add the process described in the revised figure (Fig. 1): with dt_{1d}^{force}, higher wind speeds during snowfall lead to more crystal breaking, and therefore more efficient packing at the surface, increasing the fresh snow density. In line 277 we replace snowfall by fresh snow density parameterization.

5. Organization

Section 3.1 (delta-FAC) is difficult to interpret when it is presented before the relevant physical context. At this stage in the manuscript, the reader does not yet understand the mechanisms responsible for the reported differences and so has little ability to absorb or evaluate the overall findings presented in this section. The manuscript would be more accessible if Section 3.2, describing the processes affected by time stepping, were presented first, followed by the resulting FAC differences. This structure would allow readers to interpret delta-FAC patterns in light of the governing processes.

Although we understand the reviewer on this point, we propose to stick to the order of sections. Instead, we plan to explain the structure to guide the reader through the text more easily. Our motivation for the current section structure is that we first present the magnitude and pattern of ΔFAC to give the reader a feeling for FAC in both regions and the differences that a climate forcing time step cause. Section 3.1 provides relevance for further investigating the mechanisms behind ΔFAC. Moreover, we want to show the reader in what areas the dt^{force} has largest impacts. The idea behind this structure is to stress the motivation before diving into the mechanisms behind ΔFAC.

Minor Line-by-Line Comments

Somewhere in the introduction it may be useful to note that, while time step is often constrained by spatial resolution and numerical stability in atmospheric or ice-sheet models, this is generally not the case for purely one-dimensional firn models. Clarifying this distinction would help contextualize the choice of forcing time steps.

We do not fully understand the reviewer's comment. In our study we did not investigate numerical stability or sensitivity to the model time step. The model time step is 15 minutes in all simulations. The forcing time steps are 3-hours, 6-hours, 1-day, and 1-month and those forcings were linearly interpolated to the 15 minute model time step. As our analysis focuses on the effect of the forcing time step rather than the model timestep, we did not discuss the constrains for spatial resolution and numerical stability. We are also not confident that large model time steps can be used in firn models in general. In section 2.4, we will stress that we focus on forcing time step instead of model time step.

Line 17. The term *aliasing* would be appropriate when referring to distortion or loss of the diurnal signal.

We agree with the reviewer that the term *aliasing* describes the processes discussed. However, as the manuscript is already quite technical, we prefer to not introduce an additional term.

Line 90. Does this statement assume that the entire firn column is at the melting point? How are ice layers handled in this context? This again highlights the need for a clearer description of ice-layer formation in the model.

Please, see our response to major comment 3 for the description of ice layer formulation and the proposed adjustments. During runoff events, all firn layers with densities below ice density contain liquid water and are at the melting point. The temperature of ice layers is determined through heat conduction.

We would like to thank the reviewer for the comments below. We will incorporate them all.

Line 4. "In literature ..." is awkward phrasing. Consider "In the literature" or "Prior studies ...".

Line 41. "We want to ..." is awkward and redundant; the intent is already clear and "want" can be removed.

Figure 5. The two dashed line styles are nearly indistinguishable; these should be revised.

Figure 7. Adding a 1 m depth marker to the top panels would help the reader interpret the figure.

References

Medley, B., Neumann, T. A., Zwally, H. J., Smith, B. E., & Stevens, C. M. (2022). Simulations of firn processes over the greenland and antarctic ice sheets: 1980–2021. *The Cryosphere*, *16*(10), 3971–4011. https://doi.org/10.5194/tc-16-3971-2022