ANONYMOUS REFEREE #1

1 Overview
==========

This is a modeling study to investigate the response of firn to changes in air temperature. The investigators run a simple step-forcing experiment to determine the spatial and temporal responses of a simulated firn column over Greenland, to step changes of 1 degree C in both warming and cooling. The experiment and procedures are well-described and the paper is generally well written. Many interesting insights are illustrated in the paper, and it looks to be an interesting contribution to the literature on firn in a warming world. While the main conclusions may be unsurprising to those who think about firn a great deal, the conclusions are well-founded and are well worth publishing. I have mainly a few relatively minor issues with the existing study and they should be straightforward to address.

We thank the referee for reviewing the manuscript and providing constructive suggestions and feedback. In particular, we are grateful for the suggestions that have made the manuscript clearer and more digestible to the reader. We have made modifications to the text and figures and believe the overall manuscript has been improved following the referee's feedback. Please find below our responses to comments in blue text, and specific changes made to the text in ***blue, bold, italic font.*** Line numbers refer to the original manuscript.

2 Minor issues
==============

- Timescale of the experiment: As the authors note (lines 151-152 and 165), the model in the perturbed state (both warming and cooling) comes _close_ to equilibrium (as shown in figures 2 and 7 for example) but doesn't quite get there. It would definitely be a more satisfying experiment to run these models to equilibrium. That would also allow an additional result- the quantification of the total change in FAC for the changes, and the total response time to equilibrium (bringing home the point the authors make about the dependence of response time on mean state climate- in lines 165-167).

We agree about the utility of experiments that run to equilibrium. We note that this has previously been done in Kuipers Munneke et al. (2015). As such, our study focuses on features of the firn that emerge even though the experiments don't quite reach equilibrium. Based on the results of this previous paper, we do not see evidence that running our experiments out longer will change our main results. For the ice-sheet-integrated response to reach equilibrium, each individual grid cell would have to reach an equilibrium as well. As shown in the original Figure 7, the time required to reach equilibrium varies in each example. This means that the timing for the ice-sheet-integrated response could be controlled by only a few grid cells. As such, investigating why certain cases reach an equilibrium faster than others would be more informative for understanding timescales. This has been done in Kuipers Munneke et al. (2015), so we have chosen not to repeat a similar set of experiments.

- Additional experiments: It seems that once the forcing framework is in place and the perturbations are set for 1 degree, it would not be difficult to 'turn the crank' on other perturbation experiments; most simple would be doubling the warming or cooling, but another more interesting question would be what is the magnitude of cooling required to match the change in FAC from the 1 degree warming experiment? There's an extent to which the answer to the existing experiment is self-evident to folks who study firn...additional experiments like this might make this a more widely-cited paper.

The primary goal of this paper is to compare warming and cooling responses using a highly idealized experimental set-up. While a key finding is that the warming effect on firn air content is greater than the cooling effect, the exact values of we report for firn air content change correspond to this ideal framework. While the exact values can change slightly, the main results do not depend on starting climate. Our main results are interesting, and also make physical sense. Thus, we focus on presenting this relative difference in firn air content change rather than the exact values or running experiments to answer questions like the reviewer raises here (i.e., "what is the magnitude of cooling required to match the change in FAC from the 1 degree warming experiment?"). While additional experiments would no doubt be interesting, we do not see evidence that they would change our primary science findings. On a practical note - the computational expense and storage requirements for running additional experiments are substantial given our resources so it is not so easy to 'turn the crank' as the reviewer suggests. While we agree that these subsequent ideas are interesting, they are substantial enough ideas that they could be left for additional studies.

- Appropriateness of title, given Figure 9c: at and near line 250, the authors state that the majority (1282/1724 = 74%) of the grid cells fall into the category labelled "Equal response" in figure 9. This is graphically shown in figure 9c. Given this statement, does the title (claiming unequal response) make sense? I certainly concede the point made in lines 252 and 262 that within this 5% bound the warming is usually greater (pinkish tint in Figure 9d). Figure 2c makes the point (of the title) well but then it's a bit undermined by the later discussion of figure 9c. Maybe instead of "Greenland's firn" in the title you might insert "Greenland's marginal firn"? Or change some of your binning here in this paragraph to make the point in the title more clearly made? Perhaps this is pedantic but seemed worth discussing.

As it is, the title conveys our most important result: both in the Greenland Ice Sheet interior and closer to the margins, the response to warming is greater. More importantly, we're communicating that when integrated across the full ice sheet, the warming response is greater. With that in mind, we have chosen to keep the title the same.

However, we appreciate the reviewer's point here about the title and the use of "equal response" within the paper. Even in the cases we originally labeled as "equal", the response to warming is slightly greater, but only by a small amount. To avoid using the word "equal" when the response magnitudes are not actually equal, we have instead changed how we describe these "small difference" relationships. We have changed the classification in the original Figure 9 (Figure 8 in the updated manuscript) to call this category "small difference (<5 %)" responses. We have also made changes to the text in Section 3.3 that describes this figure. Below are our modifications for sentences in lines 249 and 260, respectively.

In a small difference response relationship, the difference in magnitudes of firn air content change due to cooling and warming is <5 %. Most grid cells fall into this category with 1282 of the 1724 grid cells having a similar gain of firn air content due to cooling as the loss due to warming (Fig. 8c). It is worth noting that even in these cases where the responses to warming and cooling differ by a small amount, the response to warming is slightly but persistently greater in magnitude (Fig. 8b, d).

For the most part, the typically dry ice sheet interior has a response relationship with small differences (<5 %) between warming and cooling. Although these locations are defined by a similar-magnitude response, the vast majority of these grid cells have a slightly greater response to warming than to cooling when comparing absolute magnitudes of the responses (Fig. 8d).

The updated figure (originally Figure 9 but relabeled as Figure 8 in the revised manuscript) is shown below.

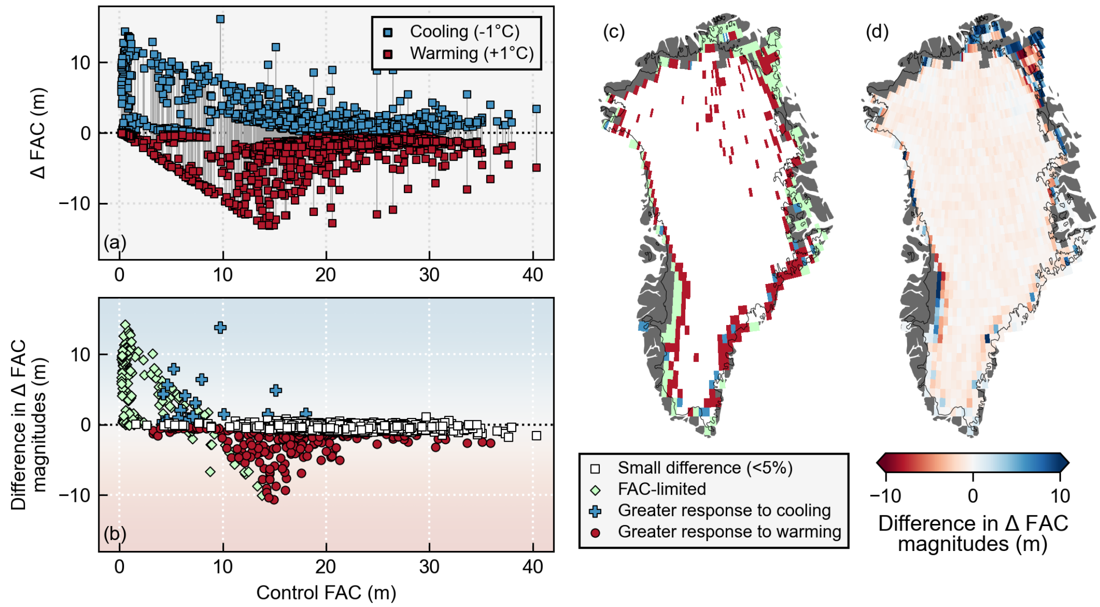


Figure 8: Types of firn air content (FAC) response relationships across the ice sheet. (a) The change in firn air content (FAC) for each grid cell calculated as the final value minus the control mean as a function of the control mean firn air content. Blue markers indicate the effect of cooling and red indicate the effect of warming; gray vertical lines connect the warming and cooling responses from each grid cell. (b) The difference in the magnitudes of firn air content changes due to warming and cooling. The difference is calculated as the magnitude of the cooling change minus the magnitude of the warming change, such that positive values indicate a greater response to cooling (blue background shading) and negative values indicate a greater response to warming (red background shading). The different marker shapes and colors differentiate the four types of responses shown in the legend to the right. (c) Locations of the different response types across the ice sheet. (d) The difference in magnitudes of firn air content change due to cooling and warming shown in map view. The thin black line in (c) and (d) represents the ice sheet outline.

3 Mainly small issues, line-by-line
=================================

- Line 32: I would argue that firn air content and density are not really separate properties in this context; just different ways of describing the same property. Since air content is the key term used in the title and throughout, I'd either suggest a sentence relating the two, or leaving density out of it entirely.

This is a great point that another reviewer also brought up (see response to Referee #2, line 137). We have made the following changes to this paragraph:

"such as air content and density" → ***like air content***
"Changes in firn air content and firn density" → ***Changes in firn air content***

We kept one distinction between density and firn air content because we refer to specific papers that looked at one or the other variable.

- Line 33 Not sure MacFerrin et al 2022 is the right reference for the concept of compaction (they didn't come up with it!). Not clear a reference is needed here, but if so, please go back further in the literature- MacFerrin et al 2022 cite many other studies like Herron and Langway 1980, Morris and Wingham 2014, among others. If you want to stick with references already existing in the manuscript I'd suggest Herron and Langway 1980 and Arthern and Wingham 1998.

Thank you for pointing this out. Following your suggestion and those of another reviewer, we have removed “(MacFerrin et al., 2022)”.

- Line 80: non-modelers might not know what a "bucket scheme" is; suggest a short description.

We have added the following brief description to the end of that sentence:

in which liquid water is moved downward when a layer’s water holding capacity is exceeded.

- Line 122: By "modern Greenland Ice Sheet" I think you mean 'holocene', right? It should really reflect something like the 1991 Greenland Ice Sheet, which is definitely changed in the past three decades (thus "modern" does not mean 2023).

This is a great point. We have removed this sentence since we feel it is imprecise and adds very little to this section. In response to this comment and another referee’s we have specifically mentioned that we mean the 1991 climate. Please see our response to Referee #2, line 84 for additional explanation.

- Line 139: presumably the reason the big changes are slightly inland from the edge is that at the edge FAC is zero to begin with (ablation zone)? If so, this sentence may either not be needed or could include this point...

This sentence has been changed to reflect suggestions from another referee. Please see our response to Referee #2, line 150 for additional explanation.

- Figure 4: It took me a while to understand the observations made in lines 181-182, because there's a lot going on in this figure. Perhaps in lines 181-182 refer to the colorbar for 4c,d to remind readers that the initial FAC in the control is indeed shown in those panels...

Thank you for pointing this out. We have added a reference to Figure 4c, d in the text.

- Figure 6: if the editors want to save space, this would be a good figure to cut, as it illustrates essentially a null result which was expected.

We appreciate this suggestion and have moved this figure to the appendix. Figure numbers have been updated to reflect this change and the main text now includes only 9 figures while the appendix has 2.

- Line 224 and Figure 7f: Also a more general comment about this figure- the annual/seasonal cycles of changes in FAC are apparent particularly in 7f but the differences from the max in 7f and a min in 7e are pretty stark; this is worth discussing at least a little bit.

The first-order seasonality in the firn air content records is primarily a result of two surface mass balance components: snowfall and melt. Since we are not modifying the precipitation variable at all, the seasonality here is largely just a reflection of the melt, and therefore the air temperature. There are of course other processes like firn temperature changes modifying the compaction rate, which have a higher relative importance in the dry firn zones compared to in the wet firn zones. In an effort to not distract the reader from our main points, we have chosen to leave out a discussion on the seasonality.

- Line 239: If we are genuinely in the ablation zone, the snowfall cannot "almost completely" melt away in summer, it must completely melt away (and thus there would be by definition 0 FAC). Call this "here near the equilibrium line" instead of "here in the ablation zone".

This is an excellent point and we appreciate this feedback. We have made the suggested change.

- Line 250: The fact that the large majority of grid cells fall into the "almost equal" category sort of implies that the title of the paper might be an overgeneralization. See my 'minor point' above on this.

Thanks for the specific line reference here. We have addressed this comment above (see line 76 of this document).

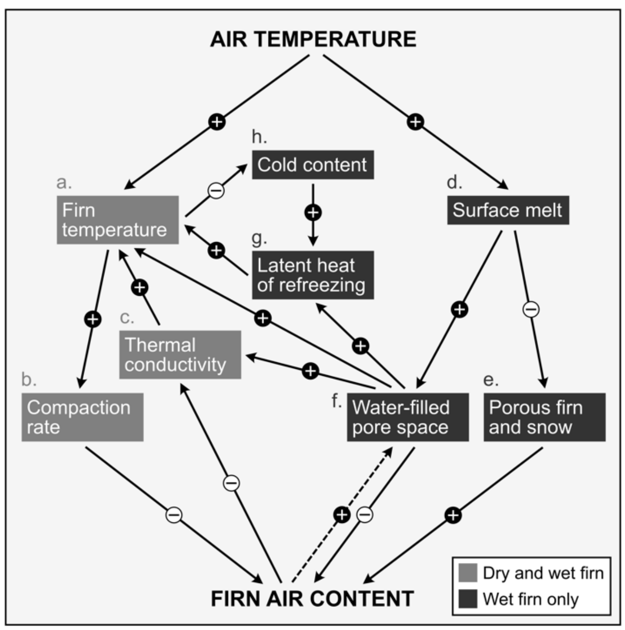
- Line 272: instead of the equivocal "impacts the bulk thermal conductivity", state the generalized relationship (ie increasing air content reduces conductivity)- it may be obvious to some readers but not all; it's implied in lines 272-3 but could be made more clear to the reader.

We appreciate this suggestion and have changed the sentence to:

Additionally, increasing air content reduces the bulk thermal conductivity, allowing faster heat transport to deeper layers in the case of warming, and slower transport due to cooling.

- Figure 10: This is a pretty complicated figure, which may be the point, but it's challenging to follow the description in the text along with the figure. One option would be to have letters or numerals on each box, so that instead of referencing 'Figure 10' in the text, you can refer to a specific box or set of boxes in the figure.

We agree that this is a complex figure, and we have made the suggested changes so it is more easily understood. There are now letters labeling each box on the figure, and we have added references to the specific boxes throughout the text in Section 4.1. The modified figure is shown below.



- All of section 3.4: It's not clear that these are actually results, and they read like discussion. Consider putting them in section 4.

We have moved this section to the discussion and split the new discussion section into three subsections.

- Line 299: here you state "most regions" have a greater change in FAC from warming than from cooling- this needs to be reconciled with the statements around Line 250 and in figure 9 where most of the area of the ice sheet falls into the "equal response" category. Also see my 'minor point' about the title of the paper above.

We thank the referee for noting this. We have removed “in most regions” so the sentence is better supported by our findings.

- Line 345: "While a lot can be learned" a but colloquial. Suggest changing to "much can be learned".

Done.

- Line 547: reference to Kuipers Munneke et al 2015: Van den Brooke's name is broken up in an incorrect way, it should be Van den Brooke, M. R. (note I didn't check all of these references I just noticed this one, suggest double-checking the typesetting- probably a simple BiBTeX issue).

Thank you for finding this error. The reference manager software incorrectly split up some of the last names. We have fixed the noted issue and checked the other citations as well.

References used in this response

Kuipers Munneke, P., Ligtenberg, S. R. M., Suder, E. A., and Van den Broeke, M. R.: A model study of the response of dry and wet firn to climate change, Ann. Glaciol., 56, 1–8, https://doi.org/10.3189/2015AoG70A994, 2015.