Response to Reviewer Comments

RC1:
Remarks:
1) Improve description of modeling methods
2) Improve presentation of model results

--- Accommodate these general remarks via explicit treatment of specific comments ---

Specific Comments:
1. line 13: There are many missing hyphens between words, such as 'one dimensional'should be 'one-dimensional'.
Fixed.

2. line 14: I suggest 'compaction' instead of 'burial'.
Changed.

3. line 38: I think that it is worth stating that these percentages are area and not volume.
Done.

4. line 68: the two-dimensional extension deserves much more explanation!
We have expanded the paper methods to include a more robust description of our horizontal ice flow implementation.

5. line 71: I suggest adding a paragraph describing the road map for the paper.
The final paragraph on the introduction, starting line 66, has been expanded to provide a clear statement of purpose and objectives.

6. line 77: could add 'as well as compaction and advection', given that this is the topic of the paper and these clearly influence the density and thermal structure. This would strengthen the topic sentence.
We have rewritten the first two sentences of this section. However, we have kept the advection discussion in the second sentence because we see this as a modifier on the primary physics of densification.

7. line 84: 'rather' would be a good addition after the comma.
This section has been rewritten.

8. line 91: It makes sense that the one-dimension advection does a good job approximating the two-dimensional solution because the downstream gradients are small (viz. Hewitt and Schoof, 2017). The important issue, however, is that the one-dimensional advection does not include downstream transport of moisture, which is likely to be very important and is not included in the two-dimensional implementation described in the supplement, correct?

This is true. This manuscript is focused exclusively on the role of horizontal ice flow, impacts the full percolation zone. Horizontal routing of meltwater is an outstanding topic of research for the field and is beyond the scope of this work.

9. line 97: this paragraph is confusing as it makes it sound like the authors implementedeverything in FEniCS — is this true?
Yes, the model physics are simulated within the finite element package FEniCS.

10. line 120: why wasn't the Community Firn Model (Stevens, 2018) used? It contains several implementations of meltwater percolation through firn and is open source(https://github.com/UWGlaciology/CommunityFirnModel).
The model of Stevens (2018) does not include horizontal advection of the firn column. We therefore developed our own code to include horizontal transport from ice flow. As described in the text, we tested our model against other models based on the FirnMICE experiments and found favorable agreement.

11. section 2.3: I think it would be very valuable to write to out the equations in a general way, so that it is clear (1) what advance the authors have made and (2) how the advance is implemented operationally. In other words, I suggest writing the density ρ evolution equation as $d\rho dt=f(\rho,T,...)$, (1)where the right-hand side is given by Reeh et al. (2005) etc. is a function of the temperature T. Then, the authors could state that they will add downstream ice advection u as $\partial\rho\partial t+u\partial\rho\partial x=f(\rho,T,...)$,(2)and state that this advection process occurs explicitly (my assumption), where the upstream density is advected downstream at each time step.
In our expansion of the paper's methods, we have included general equations for the densification rate of change and heat transport. These are foundational to our model implementation, which we now describe in more detail in section 2.14.

12. section 2.3.1: I suggest including some of the figures from the supplement in the main text to demonstrate how the models work.
We have moved much of the supplemental text to the manuscript body to better communicate the model mechanics. Regarding the results of the synthetic experiments, we have edited Figure 2 to show the influence of advection on simulated air content because this illustrates the primary process with which the papers is concerned. Including plots from all sensitivity tests in the manuscript body would also oblige us to describe the results from each in detail, with negative consequences for the clarity of the manuscript. We therefore have distilled these results to their most important points in the text, and leave figures of all sensitivity tests in the supplemental for interested readers.

13. line 276: 'for much another reason' should be 'for another reason'.
Fixed.

14. line 282: typo as there should be parentheses around the figure reference, i.e. '(Figure5b)'.
Fixed.

15. line 302: ‘x’ should be ‘x’.
Fixed.

16. line 335: simulations produce data. How do I access the simulations? Also, I suggest putting Leone in parentheses to match the other funding acknowledgments.
This section has been edited and expanded to address these issues.

17. line 378: error in title
Fixed.

18. figure 1: is this figure useful/insightful?
We believe that is important to demonstrate to the reader the regions of the ice sheet which have relevance to the findings of this paper: this figure shows where high melt in the accumulation zone is coincident with relatively high horizontal displacement. In addition, this figure shows the locations of our study transects.

19. figure 2: I suggest addressing the dot, solid, and dot-dash lines within the caption. Also, an additional figure showing the two-dimensional results for the different models shown in figure 2 could be very useful (i.e. figure 3 but for the figure 2 simulations).
We have addressed the dot, solid, and dot-dash lines in the figure caption. A two-dimensional example from a sensitivity test would be useful only inasmuch as it would clarify how the sensitivity tests are performed (the results are best summarized in the figures that are already included). We have therefore improved description of the sensitivity testing in the revised manuscript methods.

20. figure 3: it would be helpful to label the subfigures on the actual figure. For example, the transect name could be put next to the letter, i.e. ’(a) EGIG line’ and topography, pore close-off depth, and differences could be labeled on the respective panels.
We have edited the figure panel labeling following these suggestions.

21. figure 4: I suggest converting this plot to either 3 panels, one for each model, or 4panels, one for each transect. Currently, it is impossible to decipher.
We have broken the figure in to four panels (one for each transect) to better facilitate comparison of the different infiltration schemes.

Response to Reviewer Comments

RC2:
Major Comments:
1. Scope: upscale model results across the ice sheet via simple 'rules'

2. Presentation of results: make results more 'quantitative' (ie. metric-based) to facilitate upscaling via major comment #1.
We address these two comments together since they are related. The purpose of this single manuscript is to demonstrate to the community that horizontal advection is an important process in determining firn structure and heat content which should not necessarily be overlooked when considering the percolation zone. At present, there is little guidance from existing literature as to whether or not this is an important process in Greenland's percolation zone.

We agree with the reviewer that analyses should be upscaled where such an exercise can be performed relatively easily while maintaining fidelity. Indeed, this is the case when considering the influence of advection on MFP, and so we have presented the methods to do so (see Discussion section 4.2). We have chosen to present methodology, rather than a quantitative map of advection-influenced MFP over the ice sheet, because presenting the methods allows interested readers to apply the methods with their own data and assumptions (e.g. averaging timescale of climate conditions) as they see fit. We view this as a much more flexible approach to upscaling for the community.

Regarding the generation of simple metrics for upscaling advection impacts on density and temperature, we believe that attempting such an exercise would be flawed for several reasons: 1) the results are sensitive functions of heat transport and densification processes which cannot simply be transformed to a common metric, 2) as we show in the manuscript, results are heavily impacted by choice of meltwater infiltration scheme which remains an outstanding challenge to the field, and 3) the results are subject to ice flow and climate variables that are prone to change in time. For these reasons, we believe that any proposed metric to simply quantify the role of advection would have limited fidelity. Without full upscale to the ice sheet, we maintain that the paper has merit because as far as we know, no existing literature has addressed this issue.

3. Modify manuscript structure: a) bring supplemental model description in to the methods, b) restrict results section to results only -- no intercomparison of results.
Our intent in the original submission was to treat the modeling methods at a high level because the objective of the paper is not to present a 'new firn model' to the community, but rather focus on the process of advection as it impacts firn structure. However, we recognize that as presented, the modeling methods may have lacked clarity for the reader without consulting the supplemental information, with negative consequences for the manuscript readability. We have therefore moved much of the supplemental model description to the methods section of the

revised manuscript, to more completely describe our numerical implementation of horizontal ice flow.

With regards to the intercomparison of results in the results section, while we understand this reasoning, the results of our methods are the comparison between two modeling scenarios. In other words, the paper is about investigating whether horizontal advection matters or not in the percolation zone, since all prior work has neglected this process. Thus, we compare 1D to 2D simulation output. We discuss the implications of the results, and with respect to prior work, in the discussion section.

Specific Comments:

Line 13: Although I know now what the paper is about, there is nothing in these two sentences that explicitly define what "horizontal transport", "burial" or "advection" apply to. It would read the same if it applied on temperature advection, water vapour advection or mass advection. Consider rephrasing. Consider adding a sentence framing the study, giving its relevance on a larger scale.

We have rephrased the abstract's introductory sentence to clarify that horizontal advection acts on the entire firn column. This opening sentence places the subject in a broad context which we feel is suitable for the abstract. The introduction expands on the broader relevance of the percolation zone.

Line 17: See my general comments. These qualitative assessment are rather weak conclusions. The model, however, allows for the first time to quantify this phenomenon. So please be quantitative in the description of the impacts of advection.

Please see response to general comments above.

Line 24: I do not see the specific part in the study that support this conlcusion.

This is a discussion point; not an explicit result of the study.

Line 41: Please be more specific about how the percolation zone is related to the accumulation zone. How do you define the percolation zone?

The percolation zone was originally defined by Benson (1960); our use here is consistent with that and we do not believe repeating this information here is an efficient use of journal space. However, a related issue may be the limits we set for our modeling domains. This is more appropriately described later in the paper and is clearly illustrated in Figure 1 and its caption.

Line 52: unclear what they are

We recognize that this phrasing implies a distinction between 'evolutionary' processes and those that are not evolutionary, which is confusing. We have rephrased this sentence to eliminate this confusion.

Line 53: unclear what is the framework of the firn column

We have edited this sentence and now state explicitly that we are referring to the firn column density and ice structure.

Line 56: Please quantify.
--- this will change depending on where you are, as the paper illustrates. so quantifying is of little value and
Compared to ice divides, the percolation zone is a region of the accumulation area with high horizontal motion compared to submergence rate. --- Velocities in the perc zone can range from 20 m/yr to upwards of 1000 m/yr in areas of SE GrIS, where the accumulation zone extends nearly to the ice sheet margin.---

Line 57: Please define submergence rate
Accumulation areas of glaciers have submergent (downward) flow, whereas ablation zones have emergent (upward) flow. These are common glaciological terms (e.g., see Paterson, *Physics of Glaciers*, or Hooke, *Principals of Glacier Mechanics*).

Line 57: This is your definition of advection. Please make it clear. The word "advection" in many ways (e.g. vertical advection to describe the burial of firn under new snow).
Changed to 'horizontal advection' throughout to be more precise.

Line 62: Consider just "firn column"
Sentence reworded.

Line 63: Deep pore space do not absorb heat. Please rephrase.
We have clarified that the meltwater stored in deep pore space is a potential source of latent heat.

Line 73: Since I read the Supplementary Material after the main manuscript, I realized quite late that many crucial information were located there. Even more worrying, there are part of the model design that I completely misunderstood while reading the main text. Please bring all the model description currently in the supplement into the main text to avoid that. I leave my comments below to show which info I was looking for and which misunderstanding were created.
We have restructured and expanded the Methods in response to reviewer comments. The model physics and experiments are now more fully explained in the manuscript.

Line 75: This explanation would be very useful in the introduction.
Fair point, but we believe this is a better place so that (a) the introduction stays focused on the bigger picture, and (b) our methods have better context.

Line 83: Repeating the introduction. Consider removing. No need to describe what you do not do.
We have removed this repetitive statement from the revised manuscript.

Line 87: model?
This statement has been removed in the revised methods.

Line 94: Please move this part to the end of your model description. The reader has not seen yet what the model is about that the limitations of the model are presented. This is confusing.
We have restructured and expanded the methods section in response to the reviewer's comments. The description of model testing against the explicit 2D framework now follows the description of the physics upon which the model is based.

Line 98: please give the values/equations you use for firn thermal conductivity, heat capacity
We present the equation used for thermal conductivity and include the heat capacity value used in the revised manuscript.

Line 100: Are you tuning parameters in that schemes? If yes how? If not, which values are you using for the constants in Herron and Langway's scheme?
The Herron and Langway scheme is now presented in the Methods, clarifying the lack of tunable parameters necessary.

Line 103: give link to description
We have provided reference to the FEniCS platform in the revised methods.

Line 103: give reference
Galerkin's method is a standard solution method when using finite elements and, in our opinion, does not necessitate referencing.

Line 104: Please describe how you relate vertical velocity to accumulation rate. Which density do you use for fresh snow accumulating at the surface? Where do you get accumulation rates from? On which time scale is your model run?
These comments have been addressed in the revised methods.

Line 108: Please move to the discussion as a potential development/limitation to the study. Methods are about what was done, not what was not done.
We have opted to keep this statement in the revised methods because the outstanding challenges associated with modeling meltwater infiltration motivate our experimentation with 3 different melt schemes.

Line 112: Independently from the temperature and available pore space within the annual layer?
Yes. Reeh's method assumes the annual layer is made up of a firn fraction and ice fraction from melt without consideration of pore space or temperature.

Line 113: Although used in the cited works, the words "tipping bucket" are not appropriate to describe the model being used: In the "bucket type" water routing scheme, each layer has a storage capacity (or "bucket") defined as a fraction of the pore space (the irreducible water content); when the "bucket" is filled, the excess water goes to the next layer but the "bucket" remains "full" and holds the water it contains; the "bucket" does not tip (which would mean empty itself in the following layer).

This model design originates from the historical concept of bucket type reservoir in hydrology. The word "tipping" was introduced by confusion with the "tipping bucket" rain gauges.

Consider removing "tipping" in the whole manuscript.

We have simplified ‘tipping bucket’ to simply the bucket scheme throughout the manuscript.

Line 115: please give the irreducible water content being used.
We have included the irreducible water content in the revised methods.

Line 116: larger?
We have adjusted the language to state that water percolates until the available water fails to exceed the irreducible water content.

Line 130: What is the dimension of your model domain?
We have moved this relevant information from the Supplemental to the Methods.

Line 133: Please give these ranges in a table.
We now include the ranges of values in the manuscript text.

Line 135: Please point at the relevant section of the supplementary material.
We have made this edit in the revised manuscript.

Line 136: Please give the investigated gradients.
We now list these gradients in the methods.

Line 144: How do you deal with along-transect velocity variations and mass conservation? Do you take into account material accumulating in areas of slow-down and dynamic thinning in areas of increasing velocity?
The reviewer brings up an insightful point regarding along-flow velocity variations which may influence the densification and burial rates. In short, we do not account for along-transect velocity changes in our modeling. In reality, along-flow velocity changes may influence densification rates in two ways: 1) Velocity variations may result in longitudinal deviatoric stresses that increase the effective stress, and therefore strain and densification rates within the firn profile; 2) Horizontal strain from velocity variations change the rate at which mass is added to the firn column.

Regarding mechanism 1, this effect has been found to be substantial in the special case of Antarctic ice streams (Alley, 1988), but we expect this enhanced softening to be negligibly important in Greenland’s percolation zone for two reasons: 1) firn temperatures in the percolation zone are relatively warm (cf. Antarctica) as a result of meltwater infiltration and refreezing. The warmer temperatures will decrease the firn viscosity, thereby limiting longitudinal deviatoric stresses. 2) Longitudinal deviatoric stresses go as the 2nd derivative of the velocity. Over the vast majority of Greenland's percolation zone, small velocity variations result in 2nd derivatives that are essentially negligible. As one example, Meierbachtol et al. (2016) found longitudinal resistive stresses to be very small above the long term ELA around the K-Transect.

Regarding mechanism 2, the Herron and Langway assumptions upon which our model is based, assume that the densification rate is a function of the current density, and the rate at which mass (overburden) is added (this is the accumulation rate). This is given as: $\frac{d\rho}{dt} = C(\rho_i - \rho)b\rho_i$ (note that in Herron and Langway the constant C absorbs ice density so the eqn becomes $\frac{d\rho}{dt} = k(\rho_i - \rho)$, eg. Reeh (2005)). The addition or removal of mass from ice flow effectively acts to modify the mass addition from accumulation. This magnitude of the of this mass gain/loss depends on the depth in the firn column. Deeper in the column, the mass gain/loss is amplified because the horizontal straining is acting over a larger firn thickness. The addition of a strain thinning/thickening term can be included in the equation for densification rate as: $\frac{d\rho}{dt} = C(\rho_i - \rho)\left(b\rho_i - \dot{\varepsilon}_{xx}\int_{sfc}^{z}\rho(z)dz\right)$. For clarity, we simplify the integral so that the equation reads: $\frac{d\rho}{dt} = C(\rho_i - \rho)\left(b\rho_i - \dot{\varepsilon}_{xx} z\overline{\rho(z)}\right)$. The horizontal strain is positive in stretching, and the variable z refers to the depth below the surface.

The above equation provides a convenient way to think about the influence of velocity variations on densification. Over the vast majority of the ice sheet, accumulation rates are on the order 10^{-1}-10^{0} m a^{-1} (ice equivalent). In contrast, strain rates over the vast majority of the GrIS percolation zone slowly increase towards the ice margin. Horizontal strain rates are on the order 10^{-3} - 10^{-4} a^{-1} (for instance, EGIG and K-transect flowlines show velocities which increase by <50 m a^{-1} over the *lowest* 50 km; a strain rate of $<10^{-3}$). So when integrated over 10s of m of firn, the thinning rates are unlikely to exceed ~10^{-2} m a^{-1}: a small fraction of accumulation.

While the above argument holds for the vast majority of the ice sheet, there are rare regions where large speed-ups along the flowline result in substantial longitudinal stretching rates. The Jakobshavn transect is one such location. Horizontal strain rates are on the order ~10^{-2} in the lowest reaches of the transect. For a firn thickness of ~30 m (Figure 3) with average density ~600 m kg^{-3}, the resulting mass loss from thinning offset as much as ~40% of accumulation. However, in these rare locations, crevassing is likely to take up the majority of the strain, minimizing the continuous mass loss from strain thinning. This is indeed the case along Jakobshavn and even EGIG, where extensive crevassing has occurred in recent years, limiting the mobility of field parties (including ours).

We have included a sentence in the methods acknowledging this limitation of the model, and have added the above analysis to the supplemental information discussing the consequences of omitting along-flow velocity fluctuations on densification rates.

Line 146: why roughly?
Word removed.

Line 148: How do you define the number of 1D runs? Could you replace this range by a unique number of 1D run per km of transect?
We have clarified the language in the methods to state more clearly that the 1D runs were performed at annual displacements, based on the surface velocity.

Line 149: along each profile?
We have removed this confusing language.

Line 149: on?
See comment above (Line 148).

Line 150: how do you calculate the spacing from displacement?
See comment above (Line 149).

Line 157: give coordinates, average temperature, accumulation and melt rate.
We have included site location information and melt history from satellite.

Line 158: This is trivial. Consider removing. Please justify why taking this specific site as the upper limit of the percolation zone?

I understand that you need to define your transects and that it sometimes can be arbitrary. A possibility would be to state that, to limit model domain and computation time you limit your transects at the locations where melt goes below X or accumulation is above Y, which correspond to Crawford Point.

Crawford Point should however not be presented as the upper limit of percolation zone.

We have included a sentence justifying the choice of Crawford Point as a test site for investigating the role of ice flow on melt feature interpretation. It is selected because a deep core has been collected here (one of the few in Greenland's percolation zone); not exclusively because we believe Crawford Point is the upper limit of the percolation zone.

Regarding our transect modeling, we recognize that definition of the percolation zone inland extent is quite subjective, and potentially prone to large fluctuation over time. The reviewer provides no argument as to why Crawford Point should not be selected as the inland boundary. Our definition is grounded in physical process and measurement.

Line 162: By "leading to" I understand "from higher elevation down to Crawford Point"? Is it the case or is this one of the transects mentioned above? Why not presenting it a fifth transect?

What is the upper reach of this transect?
Because the objectives of this modeling exercise are unique, compared to the other 4 transects, we have opted to keep this section, rather than include this model experiment as a fifth transect. We have edited language to more explicitly state the model domain.

Line 164: what do you convert from space to time?
We have removed this statement for clarity.

Line 164: mean values over which period?
We have addressed this in revisions.

Line 166: Does that mean that you make a 100-year long run? Or do that mean that you get the spatial gradient from the 100-year average (give start/end years) temperature, melt and accumulation in RACMO for each transect?

I recommend to calculate the spatial gradient the following way for each transect: For each year, calculate the annual spatial gradient, then calculate the 100-year mean of that gradient. This should give you the same value as when calculating the spatial gradient from 100-year average forcing fields. However, with the recommended method you will be able to calculate the standard deviation that applies on the 100-years spatial gradient. It will illustrate how variable this spatial gradient was around its long-term mean value and whether the assumption of constant gradient is valid.
We have clarified that the century time scale is based on the required simulation time.

The proposed method for calculating spatial gradients essentially quantifies the interannual variability in climate gradients over the transect, whereas our interest is in long term averages. With this in mind, we have retained our existing method.

Line 167: This should be discussed properly in the Discussion section. It is important to have an idea about whether the spatial patterns in temperature, melt and accumulation are consistent enough so that firn advection would have the same effect every year.

Line 171: Please detail this, how observational studies "employed" shallow infiltration?
We have clarified that past MFP studies assume melt does not bypass the annual layer.

Line 189: Please replace by "meltwater routing scheme"
Done.

Line 202: Please give a graph of the surface altitude and climatic forcing for each transect. The reader needs to understand that the climatic gradient is not homogeneously distributed but more pronounced at lower elevation due to steeper topography.
We have included a reference to this figure, which is in the Supplemental Information.

Line 214: Please be specific: how local slope changes or even reverts the impacts of advection?

We have expanded this point with specific examples of how changes in surface slope enhance and mute the impacts of horizontal advection along the EGIG and Jakobshavn transects.

Line 221: give in %
We have quantified the reduction in surface speed relative to the Jakobshavn and EGIG transects.

Line 224: increased? decreased? be specific
Done.

Line 226: Please find a more explicit section name. Maybe "role of advection in the observed stratigraphy at Crawford Point" (also in the Methods section)
Done.

Line 227: Please be specific: which information in Figure 5 indicate the following?
We have restructured the beginning sentences of this paragraph to closely follow the figure panels in order to more explicitly walk the reader through these results.

Line 227: In this section (and in Figure 5) I find the association of depth and time not clearly defined and rather confusing. In the presence of advection, it is natural to see a gradient of MFP through depth. But it does not mean that, at that location, there was any temporal change of melt.
I recommend only discussing the MFP gradient through depth: remind that in constant climate, a 1D model gives constant MFP through depth, your model with advection gives a certain MFP gradient through depth and the observations give a third value of MFP gradient through depth.

You can then conclude that advection alone cannot explain the observed MFP gradient, confirming that the recent increase of surface melt is responsible for it.
We recognize that switching between depth- and time-gradients in MFP is somewhat non-intuitive and can generate confusion. We edited this section to more clearly explain the results in terms of changes versus depth. However, MFP has historically been used as a metric to determine time changes in climate from dated firn cores, so we also feel it is important that we present our results with respect to time. We have edited language to clearly state this conversion in the results.

Line 237: Please discuss the numerical diffusion caused by the horizontal and vertical shift of material through a fixed grid.

I am also missing a discussion point comparing the EGIG and Jakobshavn transects: they are located in the same region but, due to their differing topography, advection does not have the same impact.

Please also discuss the fact that densfication schemes have been tuned to match observed density profiles while neglecting advection. So these scheme might implicitly include the impact of advection when used by a 1D model. The following questions can then be investigated: Which sites have been used to tune the densification scheme? Were they subject to advection?

1) Our modeling scheme is lagrangian in the horizontal dimension, eliminating the introduction of horizontal diffusion where velocities are highest. Vertical velocities are low, on the order of 1 m a^{-1}, minimizing the potential for numerical diffusion (as exemplified by the number of existing firn densification models in the literature which do not treat numerical diffusion).

2) We have added a section to the Discussion focused on spatial variability of firn structure that is introduced by changing ice flow. We discuss the 'local' differences between EGIG and Jakobshavn simulations, as well as the regional differences between our simulated transects.

3) Regarding the densification schemes, Herron and Langway's empirical parameterizations were determined based on a number of cores drilled at sites in Greenland and Antarctica's dry snow zone, out of the percolation zone and in a region of the ice sheet where surface speeds are small. As one example, the 'Milcent' site presented used by Herron and Langway (1980) is located ~115km inland of Crawford Point. We acknowledge that the densification parameters we employ are for dry snow zone densification in the manuscript Methods, but we view focusing discussion on the influence of advection at these dry snow sites as a non-sequitor.

Line 251: what does "it" refer to here?
Reworded.

Line 264: It is rather late in the manuscript to introduce the core. This should be moved to the methods.
Our rational for including this information in the discussion is that we are interpreting our results with respect to the findings of prior literature. Further, details about the Crawford core is not appropriate for our methods section because we did not do the work, but instead appear here with appropriate referencing.

Line 271: Do you have a reference for that?
Do you mean at Crawford Point or at the locations where the 100-year-old firn in the core was deposited?
This sentence is a natural continuation of the previous, which references Higgins (2012). Referencing Higgins again would be redundant and unnecessary.

Line 276: Please rephrase
Done.

Line 280: Is that a result from Higgins and Porter? Please be specific: how much increase over which period and with which level of significance?
We have included reference to Higgins in this sentence. The melt increase over the 1900-2007 period is reported in the previous paragraph and would therefore be redundant to repeat.

Line 281: Here it is one of your main result: be specific, how much?
We interpret this comment to largely be a matter of personal writing style. In our view, reporting a specific fraction does not enhance the impact of the result. Our point is that ice flow can generate an MFP signal that is significant and should be considered when researchers interpret MFP measured in firn cores. Whether the specific value in our example is 31% or 34% has little relevance.

Line 286: Please point at the specific section/plot where thius result has been presented.
We have edited the text to directly refer to the inland portion of the EGIG transect.

Line 292: Consider using percentage point when describing the increase of a value given in %. https://en.wikipedia.org/wiki/Percentage_point

Be specific: what fraction?
Fixed.

Line 293: This is one of the main limitation of the paper: you need to provide an estimation of where these might happen on the ice sheet.
See response to Major comments 1 and 2 above.

Line 302: Please remove "package".
Changed to parcel, because it is important to clarify flow within a 2D firn domain.

Line 302: Please reformulate this equation and distinguish x_0 the location where the firn is generated and x(t) the location where the firn is located at time t.
The purpose of this section is to provide readers with a framework for estimating the influence of horizontal advection on MFP measured in a percolation zone core. Thus, the reference location x_0 must be the core site, not the location where the firn was generated. This way, with a dated core, a user could use equation 1 to determine the location where each dated firn parcel was deposited, and compute the MFP at that location from equation 2. We have therefore kept our formulation.

Line 304: This equation is somehow already part of the model: it determines how is calculated the new position of firn from a given velocity map. This should be introduced properly in the methods: how do you shift mass in adjacent cells based on the velocity map.
The model calculates firn conditions in a time-forward sense, but here we are interested in working backwards from a core site location (not forwards from the surface to generate core conditions with depth).

The reviewer has criticized the paper for a lack of upscaling the results to the broader GrIS-scale. Yet this section is precisely where we provide this upscaling. Not every researcher has access to or interest in modeling the 2D firn conditions leading to core sites. So long as the core is dated, full modeling of the coupled densification and heat transport is not necessary. We provide a framework for any interested researcher to calculate this themselves at any point of interest. It is quite simple to apply, which we view as an attractive feature, rather than a repetitive rephrasing of our model as the reviewer states below. Further, it is more appropriate than providing a map of advection-controlled MFP at all depths and locations across GrIS' percolation zone because it allows researchers themselves the flexibility to apply the method in ways they deem appropriate for their site/application.

We therefore have kept this section in Discussion as it is a key outcome of the paper.

Line 304: This is the definition of MFP. Needs to be in the methods.
See response above.

Line 306: In your figure 5, you already show that a 2D model including firn advection, forced with constant climate could give a depth gradient in MFP that could be misinterpreted as a temporal trend when it is in fact only the signature of spatial gradients in surface melt and advection. This paragraph and Eq.1&2 just give a mathematical rephrasing of that phenomenon and seem repetitive. Also Eq.1 and 2 are not used for anything. Consider removing the whole paragraph.
See response above.

Line 314: Please be specific: give the results for each transect.
Our objective in the conclusions is to provide a summary of results, rather than explicitly repeat the details of the results findings. With this in mind, and considering that the purpose of the manuscript is to demonstrate the process of advection (as opposed to a specific site study), we have decided to leave this statement.

Line 315: These qualitative conclusions could be made from a conceptual understanding of firn advection. With your 2D model you have the unprecedented opportunity to put numbers on these impacts. So please give numbers.
These qualitative conclusions are fundamental to understanding how advection influences firn structure. As with all models, our simulations are simplifications of the full and complex suite of processes interacting to set the firn structure across the GrIS. We therefore view the strict quantification of impacts to firn structure from advection as a fruitless exercise, and one which detracts from the main points of the manuscript. Our discussion regarding the uncertainty due to infiltration processes exemplifies why such an exercise cannot be carried out with confidence.

Line 319: I understood that the largest impacts of advection were located in over steeper regions of the percolation area. Do you expect these regions to migrate?
How the geometry of the ice sheet will evolve in the future is a very interesting question, but discussion and speculation on this topic is beyond the scope of this paper.

Line 474: red?
Fixed

Line 476: gray?
Fixed

Line 478: Am I supposed to see E, K and H letters in the figure ?
We have included letters for each transect in the revised figure.

Figure 3: add "in firn density" in the label
We referenced density in the subplot panel following suggestions from Reviewer 1.

Figure 3: add "in firn temperature" to the axis label
See above.

Figure 4: This figure is very hard to read. Please use separate panels for each transect.
Fixed

Figure 5: Although nothing is wrong in this figure, it took me a long time to understand it. Consider presenting Depth and year as y axis with 0 at the top and MFP as x axis. This will highlight that you are looking at the MFP distribution through depth at a fixed location and for a constant climate.
The intent of the figure is to communicate the influence of ice flow on interpretations of climate history using MFP, the existing literature of which has plotted time (and/or depth) on the x-axis (e.g. Graeter et al, 2018, Trusel et al., 2018, Higgins, 2012). We therefore have kept the figure as it is, which also facilitates the presentation of statistics in the manuscript in units of percentage points per year.

Line 582: Add "at Crawford Point"
Fixed

Supplemental

S1.3: This is not at all what I understood from the main text: you mention "we do this [running the model] over a 2D domain accounting for advective displacement" which I understand as "over a grid resolving depth and horizontal distance along a flowline". This is very different from taking a 1D model and apply a temporal gradient in surface forcing to mimic the transport of the firn column to lower elevation.
We have clarified our methods and moved corresponding supplemental material to the main manuscript body.

S1.4: Please update this equation to differentiate z_0, the depth to which air content is calculated and z, the variable "depth" in the integral and of which rho is a function.
This equation is accurate in its general form. The depth to which air content is calculated is a function of density of that integrated depth.

S1.4: In S6, C is presented as cumulative air content. then what is the total capacity? Maye just add the division by rho_ice in S6 and remove the discussion of water vs. ice density.
We've add division by ice density to the equation.

S1.5: This is the only section that fits in the supplement. Please move all the rest of the supplement to the main text.
See response to general comments. Much of the supplemental is now in the manuscript body.

S2.1: Is there more processes than just ice motion? If yes, which ones? If not, just use "...the impact of ice motion on model results".
This statement is no longer in the supplemental.

S2.1: Here you mention two dimensional runs again. Is it over a grid that resolves explicitly depth and horizontal distance or is it the 1D column forced by a changing surface condition?
We have clarified this in the revised manuscript.

Figure S2: This figure should be either properly used and discussed or removed.
The figure is referenced in the manuscript text and distilled to its most important points in the presentation of the model results. For clarity, we leave the full presentation of synthetic testing in the supplemental for the most interested readers.

~~Advection~~Horizontal Ice Flow Impacts the Firn Structure of Greenland's Percolation Zone

Rosemary Leone[1], Joel Harper[1], Toby Meierbachtol[1], and Neil Humphrey[2]

[1]Department of Geosciences, University of Montana, Missoula MT 59812

[2]Geology and Geophysics, University of Wyoming, Laramie WY 82071

ABSTRACT. One-dimensional simulations of firn evolution neglect horizontal ~~transport during burial.~~advection from ice flow, which transports the firn column across climate gradients as it is buried by accumulation. Using a suite of model runs, we demonstrate the impacts of horizontal advection on the development of firn density, temperature, and the stratigraphy of melt features through the Greenland ice sheet percolation zone. The simulations isolate processes in synthetic runs, and investigate four specific transects and an ice core site. ~~The~~Relative to one-dimensional simulations, the horizontal advection process tends to increase the pore close-off depth, reduce the heat content, and decrease the frequency of melt features with depth by emplacing firn sourced from higher locations under increasingly warm and melt-affected surface conditions. Horizontal ice flow interacts with topography, climate gradients, and meltwater infiltration to influence the evolution of the firn column structure; the interaction between these variables modulates the impact of horizontal advection on firn at locations around Greenland. Pore close-off and firn temperature are mainly impacted in the lowermost 20 km of the percolation zone, which may be relevant to migration of the lower percolation zone. Relatively high in the percolation zone, however, the stratigraphy of melt features can have an advection derived component that should not be conflated with changing climate.

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1. INTRODUCTION

Summer melting of bare ice, epitomized by stream networks and moulins, represents a relatively small portion of the Greenland Ice Sheet (GrIS) periphery since about 90% of the ice sheet's area is perennially snow covered accumulation zone (e.g., Ettema et al., 2009). A large fraction of the snow covered region also experiences melt (Figure 1): between 50-80% of the area melted during summers of the period 1958-2009 (Fettweis et al., 2011), for example. Further, the inland extent and duration of melting have demonstrated increasing trends and have frequently established new records (Mote, 2007; Tedesco, 2007; Tedesco et al., 2013). Melting of the accumulation zone (i.e., the percolation zone) is therefore an increasingly important aspect of the ice sheet, and so too are the glaciological processes governing the snow/firn interactions with surface climate.

Meltwater from the lower accumulation zone may run off from its point of origin (e.g., Machguth et al., 2016), while at higher elevations the water may simply infiltrate into cold snow and firn to fill underlying pore space, forming ice when it refreezes (e.g., Braithwaite et al., 1994; Harper et al., 2012) or remaining liquid if it does not (e.g., Forster et al., 2014; Humphrey et al., 2012). The capacity of the firn column to accommodate meltwater is dependent on its thermal state, its density, and structure of ice layers. However, many aspects of the processes governing firn's structural and thermal evolution, and whether meltwater is retained, remain unclear. While current model fidelity prevents confident constraint on the amount of melt retained in the percolation zone, existing estimates are that 40-50% of the meltwater generated never escapes (van Angelen et al., 2013; Janssens & Huybrechts, 2000; Reijmer et al., 2012). ~~However, the evolutionary processes governing many aspects of the framework of the firn column, and thus its ability to accommodate meltwater, are still unclear.~~

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The percolation zone is a region with relatively high horizontal motion compared to submergence rate (*cf.* divide regions) (Figure 1). Ice sheet flow displaces the firn column to lower elevation, where it is buried by subsequent winter layers experiencing higher

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intensity summer melt. Thus, the deep firn column's structural makeup and thermal state results from a climate that varies in both time *and* space. ~~The impact of this effect is undocumented, and likely varies substantially around the ice sheet.~~ Ice motion potentially impacts the ~~structural framework~~structure of the firn column~~,~~, including the amount of deep pore space that could absorb meltwater and ~~heat, and~~act as a source of associated latent heat. Further, it may have implications for the interpretation of melt feature stratigraphy within ice cores collected from these regions.

Here we investigate the role that horizontal motion plays in driving the structural evolution of the ~~deep~~ firn layer~~.~~ in Greenland's percolation zone. We utilize previous approaches for modeling firn densification and meltwater infiltration, but ~~extended the~~we extend our analysis to ~~two dimensions to~~ include horizontal advection of the domain due to ice flow. Climate and ice flow are highly variable around the ice sheet, but sparse observational data, computational limitations, and questions of fidelity surrounding models for meltwater infiltration in firn, prevent us from simulating the entire ice sheet with a high level of confidence. Our purpose here is therefore to test for the importance of ice flow to firn structure in Greenland's percolation zone, because ice flow has largely been overlooked and is not currently included in regional climate model simulations of firn evolution. To explore this process, we focus our investigation ~~is focused~~ on synthetic modeling of isolated processes, four differing transects of the GrIS percolation zone, and partitioning the signal of climate change from an advection signal within an ice ~~cores~~core from the percolation zone.

2. METHODS

2.1 Model Description

~~The density and thermal structure of firn within the percolation zone is a function of temperature, accumulation rate, and melt/refreezing processes (Herron and Langway, 1980; Reeh et al., 2005). The spatial gradients in these parameters, coupled with the speed at which the ice moves through the gradients, determines the influence of ice flow on deep firn structure. We simulate these processes in a thermo-mechanically coupled framework for firn densification and heat transfer that includes meltwater penetration and refreezing.~~

We employ the most common approach to simulating firn densification, adopt standard physics for heat transfer, incorporate three different approaches to meltwater infiltration, and we do this over a 2D domain accounting for advective displacement. We do not introduce a new suite of physics to the firn modeling community, we explore the impact that advection can have under various conditions on development of a firn column.

Our modeling incorporates changing surface conditions while ice flow transports the firn column down-glacier by translating time-varying boundary conditions based on surface speed. This approach captures the processes of burial, infiltration, and vertical heat transport, and is advantageous in that it easily accommodates a range of meltwater infiltration schemes (detailed below). It does, however, lack horizontal heat diffusion, but testing against an explicit 2D model for densification and heat transport including horizontal diffusion yielded negligibly different results (Supplementary information; Figure S1). Omission of this process therefore streamlines computational efficiency with little impact on results.

Firn temperature is modeled by solving the standard one-dimensional time-dependent heat-transfer equation with latent heat from the refreezing of meltwater (Cuffey and Paterson, 2010). We implement the time dependent model for densification from Herron and Langway Air temperature, accumulation rate, and melt/refreezing processes drive the evolution of the density and thermal structure of the percolation zone's firn column (e.g., Herron and Langway, 1980; Reeh et al., 2005). The spatial gradients in these parameters, coupled with the speed at which the ice moves through the gradients, also impacts evolution of the firn column. We simulate these processes in a thermo-mechanically coupled framework for firn densification and heat transfer, including meltwater penetration and refreezing, that also incorporates horizontal displacement of the firn column due to ice motion.

2.1.1 Firn Densification

The rate of change of firn densification is described by it's material derivative:

$$\frac{D\rho}{Dt} = \frac{\partial\rho}{\partial t} + \mathbf{u} \cdot \nabla\rho \qquad (1)$$

where ρ is firn density and **u** is the velocity vector. Many existing densification models are based on the empirical assumption that the proportional density change is linearly related to the change in overlying load (Robin, 1958), and ours is no different. As rate parameters, we use the empirical constants developed by Herron and Langway (1980), for dry snow densification, based upon it'sthe relatively simplistic formulation with few tuning parameters and favorable comparison with other densification schemes (Lundin et al., 2017). Temperature,The total densification rate is therefore:

$$\frac{D\rho}{Dt} = \begin{cases} c_0(\rho_i - \rho) & \text{if} \quad \rho \le \rho_c \\ c_1(\rho_i - \rho) & \text{if} \quad \rho_c < \rho \end{cases} \qquad (2)$$

where the critical density, $\rho_c = 550\ \mathrm{kg\ m^{-3}}$, and vertical velocity were coupled together and solved using the finite element library FeniCS with Galerkin's method. Dirichlet boundaries for state variables temperature, density, and vertical velocity (based on and accumulation rate)-dependent constants c_0 and c_1 are imposed atdefined as:

$$\begin{cases} c_0 = 11\left(\frac{\rho_i}{\rho_w}\right) b \cdot \exp\left(\frac{-10160}{RT}\right) & \text{if} \quad \rho \le \rho_c \\ c_1 = 575\left(\frac{\rho_i}{\rho_w} b\right)^{0.5} \cdot \exp\left(\frac{-21400}{RT}\right) & \text{if} \quad \rho_c < \rho. \end{cases} \qquad (3)$$

In Equation 3, *R* is the model surfacegas constant (8.314 J K^{-1} mol^{-1}), accumulation rate *b* is in ice equivalent units, and vertical gradients in these variables are set to 0 atT is the model baseabsolute temperature.

2.1.2 Temperature Evolution

Firn temperature is simulated using the standard heat transfer equation, including latent heat additions from meltwater refreezing (see Section 2.1.3):

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) + \rho c \mathbf{u} \cdot \nabla T + S \qquad (4)$$

where c is the specific heat capacity of ice, taken to be 2100 J kg^{-1} K^{-1}, and S reflects latent heat release from refreezing. In Equation 4, K is the thermal conductivity, which we prescribe to be density-dependent following Arthern and Wingham (1998) ($K=2.1(\rho/\rho_i)^2$).

2.1.3 Melt Infiltration Schemes

Modeling complex and heterogeneous meltwater infiltration in firn with high fidelity remains an outstanding problem of critical importance ~~that solving~~and is beyond the scope of this project. Our approach is to implement three existing infiltration schemes which vary in complexity and reflect a range of approximations. The first model considers only shallow infiltration, assuming that all meltwater refreezes in the top annual layer (Reeh et al., 2005). The second implements a standard~~ tipping~~ bucket method ~~(Kuipers Munneke et al., 2014; Ligtenberg et al., 2018)~~(Kuipers Munneke et al., 2014; Ligtenberg et al., 2018), allowing meltwater infiltration as far as permitted by thresholds for cold content and irreducible water content~~. Meltwater percolates until reaching a firn layer with a smaller irreducible water content than the available liquid water or the pore close off density is reached; any remaining meltwater runs off instantaneously.~~ (the latter of which is defined following Coléou and Lesaffre (1998)). Meltwater percolates until reaching either a firn layer in which the available liquid water fails to exceed the layer's irreducible water content or the pore close off density; any remaining meltwater runs off instantaneously. The third infiltration model implements a continuum approach (Meyer and Hewitt, 2017), simulating the physics of water flow based on Darcy's Law, and treating both saturated and unsaturated conditions.

2.1.4 Numerical Methods

We implement horizontal advection in modeling exercises using a Lagrangian approach. One-dimensional firn profiles are initiated with conditions characteristic of the dry snow zone, and are transported through the percolation zone along a flowline following a prescribed horizontal velocity. Because porous firn is confined to relatively shallow depths (cf. to the ice sheet thickness), vertical shear is negligible and the horizontal velocity can be assumed to be equivalent to the surface value. Horizontal motion is therefore simulated by translating spatially varying surface conditions (temperature and accumulation rate) to time-varying boundary conditions following the prescribed velocity, and Equations 1 and 4 remain restricted to the vertical dimension.

This approach implicitly captures the horizontal advection terms in Equations 1 and 4, but neglects any influence of along-flow velocity variations on firn structure. Firn densification rates may be influenced by mass changes arising from strain thinning/thickening, as well as stress enhancement induced by horizontal deviatoric stresses (Alley and Bentley, 1988), but are likely to be negligible around the GrIS percolation zone (Supplemental Material 1.1).

In addition, our modeling approach neglects horizontal heat diffusion. To assess the consequences of this, we tested our Lagrangian approach against an explicit 2D model for densification and heat transport including horizontal diffusion in an Eulerian framework. Results from these tests yielded negligibly different results (Supplemental Material S1.2; Figure S1). We therefore continue with our Lagrangian approach, which streamlines computational efficiency and permits flexible implementation of various melt infiltration schemes.

Changes in temperature, and density were coupled together along with vertical velocity and solved using the finite element library FeniCS (Logg et al., 2012) with Galerkin's method. Dirichlet boundaries for state variables temperature, density (ρ_0=360 kg m^{-3}), and vertical velocity (following the accumulation rate as $w_{sfc} = -b \cdot \frac{\rho_i}{\rho_0}$) are imposed at the model surface, and vertical gradients in these variables are set to 0 at the model base. The model domain in all experiments is 80 m in the vertical; mass added to the model surface from accumulation is balanced by mass exiting the domain at the model base. We use a time step of one year in all simulations.

2.3 Model Experiments

The influence of horizontal advection on firn structure at depth is dependent on ice flow speed and spatial gradients in climate forcings (temperature, melt, and accumulation). We conducted an initial test of model sensitivity to each of these variables to understand, in isolation, the influence of changes in these processes on firn structure. We then applied the model to four flowline transects across GrIS' percolation zone representing a spectrum of ice sheet and climate conditions. Finally, we performed a model test at a site in the upper percolation zone to investigate the influence of horizontal advection on melt feature interpretation.

2.3.1 Sensitivity Analysis

~~Synthetic sensitivity tests were performed around a base scenario with horizontal velocity of 100 m/yr and an accumulation rate of 0.5 m/yr ice equivalent, approximately matching conditions along the EGIG transect. Horizontal velocities, accumulation rate, and total melt were then varied across ranges of values spanning the conditions that may occur in the GrIS percolation zone (Supplementary information). Additionally, we imposed three different surface temperature gradients in each simulation to determine model sensitivity to a spatially varying surface temperature boundary.~~

Synthetic sensitivity tests were performed over an 80 km model domain with spatially invariant surface slope, horizontal velocity, and accumulation rate. Melt rates were assumed to increase linearly from 0 at the inland boundary, to a specified fraction of accumulation at the lower model boundary. Horizontal velocity, accumulation rate, and melt rate were varied around a base scenario of 100 m a^{-1}, 0.5 m a^{-1} ice equivalent, and 85% of accumulation respectively. Baseline conditions were chosen to approximately match conditions along the EGIG transect. Horizontal velocities, accumulation rate, and total melt were then varied across ranges of values spanning the conditions that may occur in the GrIS percolation zone: velocity was varied from 0 - 500 m a^{-1}, accumulation from 0.1 - 1.0 m a^{-1} ice equivalent, and melt from 0-85% of the accumulation rate. For each combination of horizontal velocity, accumulation rate, and melt forcing, we also imposed three different surface temperature gradients based on surface slopes of 0.3°, 0.6°, and 0.8° with a temperature lapse rate of -7.4 °C/km (Fausto et al., 2009). Sensitivity test results were compared against 1D results at the end of the 80 km model domain. Further details of the metric of comparison are presented in the Supplemental Material (section S2).

2.3.2 Greenland Transects

Our ~~2D~~ modeling approach was implemented at four test transects ~~spanning~~(Figure 1) around the GrIS ~~(Figure 1):~~percolation zone: 1) the well-studied EGIG transect in western GrIS, 2) a transect feeding Jakobshavn Isbrae, 3) the K-transect in southwest GrIS, and 4) a transect extending into Helheim Glacier. These four study profiles were selected to capture a wide variety of ice sheet conditions (Table 1). The inland extent of the percolation zone was selected to correspond with the location where melt, as a fraction of accumulation rate, is equal to the value at Crawford Point (Figure 1); a choice based on temperature measurements indicating melt infiltration at Crawford Point is insufficient to warm the firn above the annual average temperature (Humphrey et al., 2012).

Surface velocities along study transects were defined from satellite velocity data (Joughin et al., 2010), and RACMO2.3p2 (Noël et al., 2018) was used to select 1980-2016 average climate variables (Figure ~~S4~~S3). This time period ~~roughly~~ captures the increase in GrIS melt since the late 20th century (Fettweis et al., 2011). In addition to the ~~2D~~transect simulations ~~of the transects,~~incorporating horizontal ice flow, in each transect we also completed 1D simulations at 600-1700 locations ~~in each transect, variably~~ spaced ~~between profiles based~~ at annual displacements~~.~~ (calculated from surface velocities) along the flowline. The latter were used for baseline comparisons of the effects of including or ~~not including~~neglecting horizontal advection of the firn column.

2.3.3 Impact on Core Stratigraphy ~~Example~~

~~A commonly used metric for quantifying changing climate conditions from firn cores is the annual increment of surface melt, or Melt Feature Percent (MFP) (Graeter et al., 2018; Kameda et al., 1995; Koerner, 1977; Trusel et al., 2018). To investigate the role that advection can play in MFP records, we simulated the specific conditions at Crawford Point located along the EGIG line. This site is relatively high elevation in the percolation zone with far less surface melt than the lower percolation zone. In recent decades the average~~

~~summer at this site experiences about 15 days of melt~~ A commonly used metric for quantifying changing climate conditions from firn cores is the annual increment of surface melt, or Melt Feature Percent (MFP) (Graeter et al., 2018; Kameda et al., 1995; Koerner, 1977; Trusel et al., 2018). To investigate the role that horizontal advection can play in MFP records from the percolation zone, we simulated the conditions leading to Crawford Point (69.877°N, 47.0102°W, 1997 m elev), located along the EGIG line. This site is relatively high in the percolation zone; in recent decades the average summer at this site experiences about 15 days of melt (Mote, 2007)~~.~~

. Multiple shallow cores have been collected for density and temperature measurements (Harper et al., 2012; Humphrey et al., 2012), and in 2007 and a deep core was collected and interpreted within the context of GrIS melt history (Higgins, 2012). The site therefore offers an opportunity to assess the role of horizontal advection on interpretation of melt history in a core profiling the full firn column of the percolation zone.

We modeled the 2D firn evolution ~~on~~along a flow line ~~leading to~~beginning 22 km inland, and ending at Crawford Point using datasets for the modern state. This transect extent is chosen to ensure that the simulated conditions at Crawford Point contain no remnants of the initial condition. Ice surface geometry (Morlighem et al., 2017) and ~~velocity (Joughin et al., 2010) datasets were used for converting from space to time; and, mean~~, mean (1980-2016) melt and snowfall values from RACMO2.3p2 (Noël et al., 2018) were used to determine spatial climate gradients. ~~We assume the spatial gradients in these datasets have not changed over a century time scale. The validity of this assumption is unknown and perhaps tenuous; our intention, however, is a demonstration of the advection process constrained by ice sheet conditions. Furthermore, if there are in fact large time changes in gradients, this only increases complexity to advection signal. Finally, we~~As with the other Greenland transects (Section 2.3.2), horizontal advection during burial is represented by present-day velocity datasets (Joughin et al., 2010). We employ the (Reeh et al., 2005) model for infiltration to be consistent with ~~the assumption of shallow infiltration employed by MFP observational studies.~~past MFP observational studies which assume all annual melt is confined to the corresponding annual layer (e.g., Graeter et al., 2018; Kameda et al., 1995;

Trusel et al., 2018). We assume the spatial gradients in input datasets have not changed over the century time scale required to simulate firn conditions at the bottom of the firn column. The validity of this assumption is unknown and perhaps tenuous; our intention, however, is a demonstration of the horizontal advection process constrained by ice sheet conditions. Furthermore, if there are in fact large time changes in gradients, this only increases complexity to horizontal advection signal.

3. RESULTS

3.1 Sensitivity Tests

Including 2D horizontal advection in simulations of the percolation zone yields greater air content in the firn column and ~~therefore~~ increased depth to pore close off ~~than~~compared to 1D results (Figure 2; Figure S2). ~~Greater~~Surface speeds approaching the upper limit of what may be expected in GrIS' percolation zone generate a firn column with air content that can differ from 1D simulations by 80%. Yet, while greater ice flow speed clearly influences horizontal advection~~-~~-based results,~~ but~~ the impacts are strongly modulated by the magnitudes and gradients in other variables. For example, the impact of horizontal advection is also a function of accumulation, with smaller accumulations causing a 25-35% increase in the depth to pore close off and total air content in 2D simulations relative to the 1D model runs. This stems from reduced densification rate under smaller annual increments of overburden, and thus longer preservation of cold and porous firn that becomes deeply buried firn further down-glacier. Adding melt gradients to the scenarios exacerbates the effect, with wet surface conditions overprinting dryer conditions at depth.

Adding horizontal advection to simulations also decreases the firn temperature; the temperature profile and temperature at pore close off reflect advected firn from higher, colder conditions. Heat content is strongly influenced by the choice of ~~melt~~meltwater routing scheme: for example, under very high accumulation and melt, the ~~tipping~~ bucket method yields deep penetration of water and warmer firn temperature at depth (cf. the 1D case) (Figure S2)). Steeper topography yields larger along-flow gradients ~~between~~in melt, temperature, and accumulation, causing greater disparities between 2D-~~avection~~advection and 1D-profile simulations. The ice flow speed has potential to ~~strongly~~ impact simulations with 2D-advection, but importantly, the ~~impact of speed~~magnitude is strongly modulated by the values and gradients in other variables. ~~In~~ Interestingly, while the presence of any meltwater infiltration amplifies density differences, meltwater refreezing reduces the thermal disparity between 1D simulations ~~of high horizontal gradients in climate (i.e., steep topography),~~ and ~~limited melt penetration (i.e., infiltration following Reeh et al. (2005)), model results~~those including ice flow ~~differ from 1D by up to four-fold at highest speeds.~~(Figure S2).

3.2 Transects

The most significant differences between the 1D and 2D model simulations are along the lowermost 10-15 km of our four sample transects. ~~Here, surface speed and slope (a proxy for climate gradients) both increase substantially relative to the upper percolation zone, and the surface experiences heavy melt.~~ By including ice flow in these firn simulations, the density differs by >50 kg m^{-3} for the EGIG, Jakobshavn, and Helheim transects (Figure 3; Figure S4; Figure S5), resulting in increases to pore close off depth of up to 8 m, 13 m, and 19 m, respectively. The commensurate impacts on total air content in the firn column can also be large: for example, along the EGIG transect it changes by ~50% in the lower 10 km, and by 5%-15% along the next 10-20 km.

The different melt infiltration schemes yield variable impacts. The largest impact is with the Reeh et al. (2005) scheme, under which the inclusion of horizontal advection in simulations increases the firn column air content by up to several meters from a 1D simulation (Figure 4). Local changes in surface slope along the transects both enhance and diminish the impacts of horizontal advection on the underlying firn structure, complicating the 2D ~~firn~~ geometry of the firn layer within the percolation zone. ~~The~~This is exemplified in both EGIG and Jakobshavn transects (Figure 3). A flattening of the surface profile near 20 km in both transects means that snow accumulates under similar climate conditions over many km. This generates a deep firn density structure that is more similar to 1D profiles as the firn is buried and horizontally advected through the transect. Conversely, these flat regions terminate abruptly with a sharp increase in slope, and therefore climate gradients as well. This results in deep firn with densities that are reduced by 20-30 kg m^{-3} compared to 1D simulations. In contrast to the EGIG and Jakobshavn transects, the changes to density structure throughout the K-transect are comparatively small~~ because the topography and ~~. Surface speeds are ~~so much lower than most places on the ice sheet~~consistently ~18 - 50% of the values along EGIG and Jakobshavn counterparts (Table 1~~),~~); such slow velocity all but ~~eliminating~~eliminates the impact of ice flow (Figure 3d).

The process of horizontal advection generates colder firn temperature profiles. Along the EGIG transect, horizontal advection decreases firn temperatures at the depth to pore close off by 1.0°-1.5° C in the lower 15 km, and by 0.8°-1.0° C in the next 15 km. With the high speeds, steep topography, and heavy melt of the lowermost reaches of Jakobshavn and Helheim transects, firn temperatures were ~~altered~~reduced by as much as 3° C by including horizontal advection.

3.3. Impact on Core Stratigraphy~~ Example~~

~~Our modeling indicates that at ~~At Crawford Point, ~~the depth (time) change in MFP that is attributable to advection alone is inconsequential in firn generated in recent decades (i.e., <60m depth). The shallower firn was~~firn deposited along the first ~5km above Crawford Point~~,~~ reflects a region with very low slope and essentially no ~~horizontal ~~climate gradient caused by elevation~~.~~ (Figure 5A). Consequently, MFP values are relatively constant in the upper ~60m of the firn column, indicating that horizontal advection is inconsequential to firn structure over depths that are equivalent to recent decades at this site (Figure 5B).

Below ~~this~~~60m depth, however, there is an abrupt inflection to continuously decreasing MFP to the bottom of the core (Figure 5). ~~At depths >60 m, the change in MFP due to advection amounts to about 0.04% per year.~~Horizontal advection generates a decline in MFP of approximately 7 percentage points from 60 m depth to the end of the core. Presented in terms of simulated age (rather than depth), this amounts to an apparent reduction in melting of 0.04 percentage points per year that arises from horizontal ice flow and not time changes in climate. As discussed below, this is a non-trivial magnitude when scaled against the annual change arising from warming climate and increased melt.

4. DISCUSSION

4.1. Uncertainty due to Infiltration

The choice of meltwater infiltration scheme has a large effect on the simulated impacts of ~~firn~~horizontal advection of firn in the percolation zone and is a key uncertainty in the fidelity of model results. In reality, water moves vertically as a wetting front propagating downward from the surface (Colbeck, 1975), but also by complex and unpredictable inhomogeneous infiltration processes (Marsh and Woo, 1984; Pfeffer and Humphrey, 1996), and it can be routed horizontally along impermeable ice layers (e.g., Machguth et al., 2016). ~~With so little known about deep infiltration, none of our schemes are likely to be entirely accurate: the (Reeh et al., 2005) scheme~~With so little known about deep infiltration, none of our schemes are likely to be entirely accurate: the Reeh et al. (2005) scheme only allows melt penetration within the annual snow increment which is known to be incorrect, especially low in the percolation zone where melt rates are high (e.g., Humphrey et al., 2012); the continuum model (Meyer and Hewitt, 2017) uses the most complex physics, but has large uncertainties for coefficients of permeability and grain sizes; and, the ~~tipping bucket model (Kuipers Munneke et al., 2014; Ligtenberg et al., 2018)~~bucket model (Kuipers Munneke et al., 2014; Ligtenberg et al., 2018) disregards the complex physics governing flow of water through ~~it's own solid~~the firn matrix, simplifying the problem to just density and cold content and assuming the flow of meltwater is instantaneous.

With ~~firn~~horizontal advection of firn tending to move open pore space underneath an increasingly melting surface, the depth/quantity of infiltration is key: the deeper melt penetrates, the more the pore space is 'overprinted' by surface melt and the advected deep pore space is not preserved. Alternatively, infiltration that is limited to shallow depths enhances the disparity between deep firn and that nearer to the surface. Our suite of model runs show that, in the lower percolation zone, the choice of infiltration scheme has nearly equivalent impact on the total air content as the incorporation of ice flow.

~~4.2.~~4.2 Spatial Variability of Firn Structure

Simulation results demonstrate the changing influence of horizontal advection on firn structure in response to changing climate gradients and ice speed as the firn package traverses the percolation zone. Transect modeling indicates that along any given flowline the influence of advection tends to increase towards the lower percolation zone; an intuitive result considering that surface speed and slope (a proxy for climate gradients) both increase substantially relative to the upper percolation zone, and the surface experiences heavy melt (Supplemental Figure S3). Sensitivity testing showed that each of these factors amplifies differences between 2D and 1D representations of deep firn structure.

Transect modeling also reveals that ice flow introduces variability in firn structure around the ice sheet, not just along individual flow lines. Surface speeds within the GrIS' percolation zone shown in Figure 1 vary from nearly 0 to more than 1000 m a^{-1}. The K-Transect, EGIG, and Jakobshavn transects demonstrate the differences in firn structure that can develop regionally across Western Greenland as a result of ice flow patterns (Figure 3). However, the EGIG and Jakobshavn simulations show that advection can also influence firn structure at a more local scale. Despite being separated by ~40 km, differences in surface speeds between the two transects develop in the lower 15-20 km as speeds in the Jakobshavn transect accelerate towards the margin (Figure S3). This results in a simulated firn column that is 5-10 m thicker compared to the nearby EGIG profile at the same elevation. While the local gradients in ice speed are perhaps greater here than nearly anywhere else on the ice sheet, the local and regional differences in our simulated transects illustrate that differences in deep firn structure are likely to exist in regions of the GrIS percolation zone with otherwise similar climate conditions, purely as a result of differences in ice flow patterns and topography that dictate spatial gradients in climate.

4.3. Melt Feature Stratigraphy

A 152 m long ice core collected at Crawford Point in 2007 (Higgins, 2012; Porter and Mosley-Thompson, 2014) offers the opportunity to compare measured data against our modeled depth change in MFP stemming from horizontal advection. The core age extends back to the year 1765 based on seasonal isotope variations, and the modeled flow field shows the bottom of the core originated ~260 years prior and about ~22 km up the flow line (Figure 5a). Thus, the flow model age estimate at the core-bottom is within 7% of the age determined by isotope methods. Higgins (2012) measured an overall trend of increasing MFP from 1765-2007 of 0.08~~%~~ percentage points per year. However, melt events prior to 1900 were minor and infrequent; the more recent trend from 1900-2007 therefore ~~increases~~increased to 0.11~~%~~ percentage points per year.

The horizontal advection signal we calculate is also highly dependent on the defined time period, but for ~~a much~~ another reason: different time periods sample different spatial gradients in climate as firn moves through the percolation zone. The MFP signal in firn from recent decades is not influenced by horizontal advection because this firn has formed along a locally flat spot in the topography extending about 5 km up flow from Crawford Point (Figure 5a). However, over the ~100 years during which Higgins (2012) measured significant melt increases ~~are observed~~ in the core, our modeling suggests that approximately one~~-~~-third of the MPF change is attributable to the process of horizontal advection ~~process~~ (Figure 5b). Thus, the stratigraphy of melt features along an ice core from the percolation zone can have a spatial component that must be evaluated to properly interpret temporal change.

~~That~~Simulated profiles of firn density and temperature high along the EGIG transect are barely impacted by horizontal advection (Figure 3) yet the MFP record at Crawford Point, ~~yet the MFP record~~ which lies at the inland boundary of the transect, is strongly influenced by horizontal advection~~,~~. This result may seem counterintuitive. However, these are different entities: the former firn properties evolve over a time-space continuum, whereas the MFP record represents a time-trend in the occurrence of discrete events. Furthermore, the magnitude of trends sets the importance of horizontal advection in a MFP record. In the Crawford case, the multi-decadal trend in MFP due to changing melt is a fraction of a ~~percent~~percentage point per year, an important indicator of changing climate, but not large enough to completely mask horizontal advection. Where the horizontal advection signal is strong it may be ~~likely~~plausible that it is equivalent to the climate trend.

Certainly some locations in the percolation zone may yield ice cores with MFP trends that are not significantly impacted by ice flow. But considering the potential for ice flow to obscure climate trends, a simple procedure for quantifying this effect has utility. If the present ice sheet state (speed, accumulation, and melt rates) is assumed to be constant in time, an apparent climate signal at any core site can be quantified from spatially extensive datasets of the above variables. At a dated core depth corresponding to a time t years before present ~~(t),~~, the firn ~~package~~parcel originated at a location (x~~)~~(t)) upglacier from the core location, where $x(t)$ is the integral of the spatially varying velocity (v) along the flowline over t years:

$$x(t) = -\int_0^t v(x)\,dt.$$
(~~1~~5)

The MFP at time (t) can therefore be determined from the accumulation and melt conditions at this upglacier location:

$$MFP(x) = \frac{m(x)}{b(x)}.$$
(~~2~~6)

Equations ~~1~~5 and ~~2~~6 can thus be combined to generate a time series of MFP at a core site that is a record of spatially varying climate advected by ice flow; the component that should not be incorrectly interpreted as time-changing climate.

5. CONCLUSIONS

Elevated horizontal ice flow in the percolation zone compared to ice divides results in a firn column that is not always well represented by 1D models for time-evolving density and temperature. The impacts of horizontal advection are highly variable around the ice sheet, but accounting for horizontal advection in simulations can change the firn's air content by 10s of percent and the temperature can differ by several degrees. Lower accumulation, higher velocity, higher melt, and steeper topography (which drives climate gradients) all increase the mismatch between surface and deep conditions (and the failure of a 1D simulation). The horizontal advection process thus has greatest influence on firn evolution in the lower accumulation zone (e.g., 10-15 km); a nexus of conditions that are likely migrating upward as climate warms, but are also subject to the greatest uncertainty regarding melt infiltration processes.

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The 2D evolution of firn in the percolation zone is influenced by topography: horizontally invariant firn is generated in flat regions, whereas local hills/swales enhance the 2D influences from horizontal advection. The deeper meltwater penetrates, the more pore space is filled by surface melt and the advected deep pore space and cold content is not preserved. The stratigraphy of melt features along an ice core from the percolation zone can have a strong spatially derived component. Melt feature stratigraphy can be impacted by horizontal advection high in the percolation zone, where firn density and temperature are relatively unaffected by ice flow. This effect must be evaluated to properly interpret temporal changes in ice cores related to climate, especially over decadal and longer time scales.

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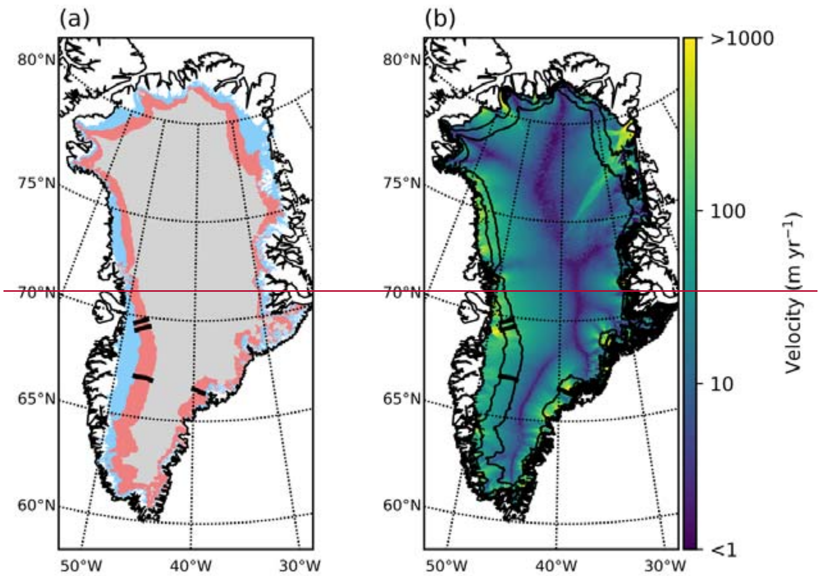
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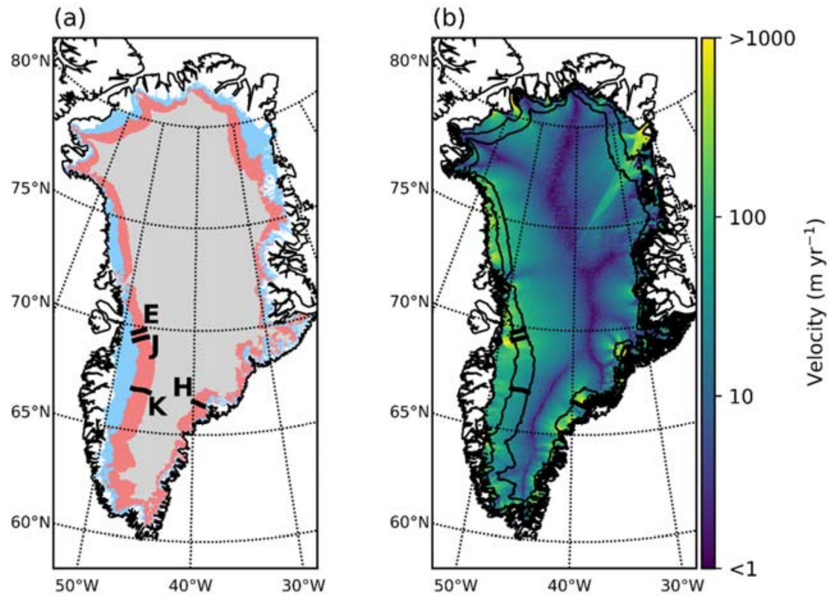

Figure 1. Maps of Greenland. (a) Facies ~~arbitrarily~~ delineated based on modeled 1980-2016 average surface melt (Noël et al., 2018): ablation zone (~~red~~blue) with melt exceeding accumulation; percolation zone (~~yellow~~red), the upper limit of which defined by melt conditions at Crawford Point where infiltration has not warmed firn (Humphrey et al., 2012); dry zone (~~blue~~gray). (b) velocity field from Joughin et al. (2010) with top and bottom of percolation zone shown in (a) delineated by black contour lines. Thick black lines through percolation zone show study transects, where E is EGIG, J is Jakobshavn, K is K-transect, H is Helheim (see Table 1).

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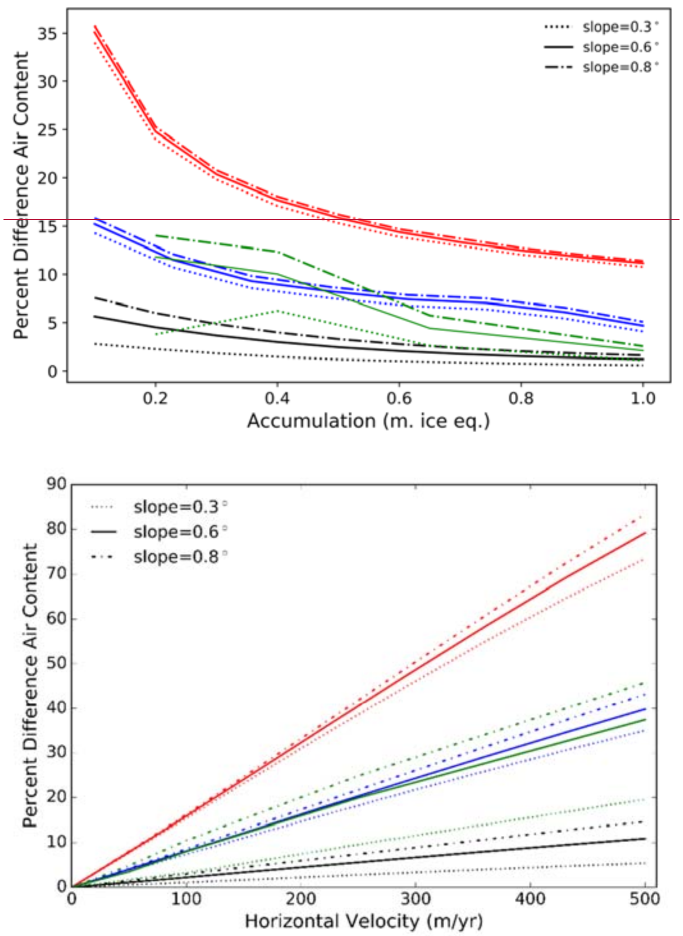

Figure 2. Example sensitivity test. Modeled differences between 1D and 2D for ~~accumulation~~ice speed using dry firn model (black), Reeh model (red), tipping bucket model (blue), and continuum model (green). Base ~~speed~~accumulation is ~~100~~0.5 m a^{-1}, approximately the ~~lowest~~average value of the EGIG ~~transection~~transect shown in Figure 1. ~~Three~~Each simulation is run with surface slopes ~~are used~~of 0.3° (dotted), 0.6° (solid), and 0.8° (dash-dotted) to represent different ~~conditions~~climate gradients that may exist around the ~~ice sheet.~~GrIS.

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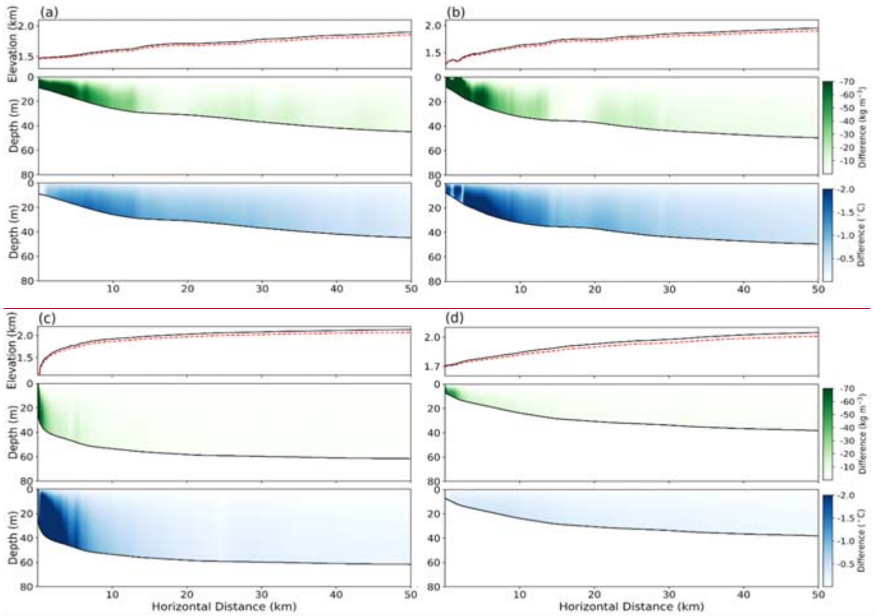
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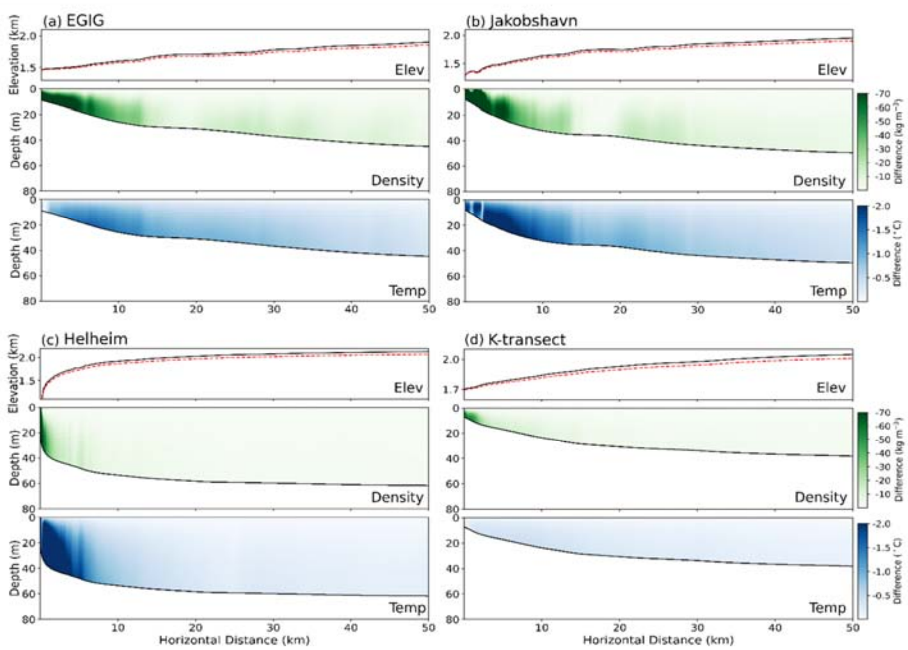
(a) EGIG
(b) Jakobshavn
(c) Helheim
(d) K-transect
Elev
Density
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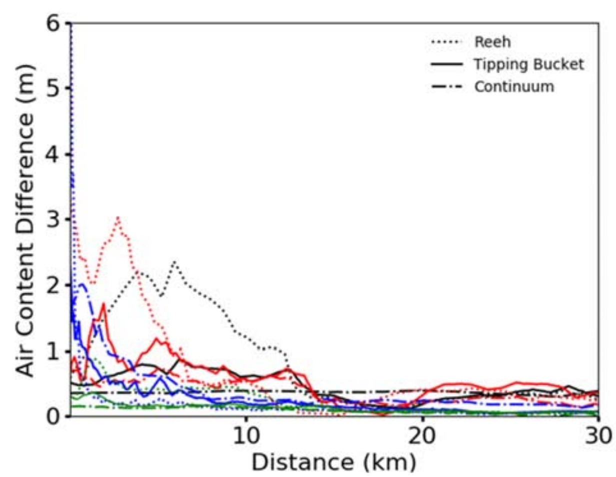
Elevation (km)
Depth (m)
Difference (kg m⁻³)
Difference (°C)
Horizontal Distance (km)

Figure 3. Calculated difference between 2D and 1D simulated firn properties in the percolation zone through the four study transects with ~~tipping buck~~bucket method meltwater infiltration scheme: a) EGIG line; b) Jakobshavn; c) Helheim; and, d) K-transect. Top panel in each transect shows surface topography (black) and pore close-off depth (red dashed). Middle panel shows density differences (2D - 1D), and bottom panel shows temperature differences.



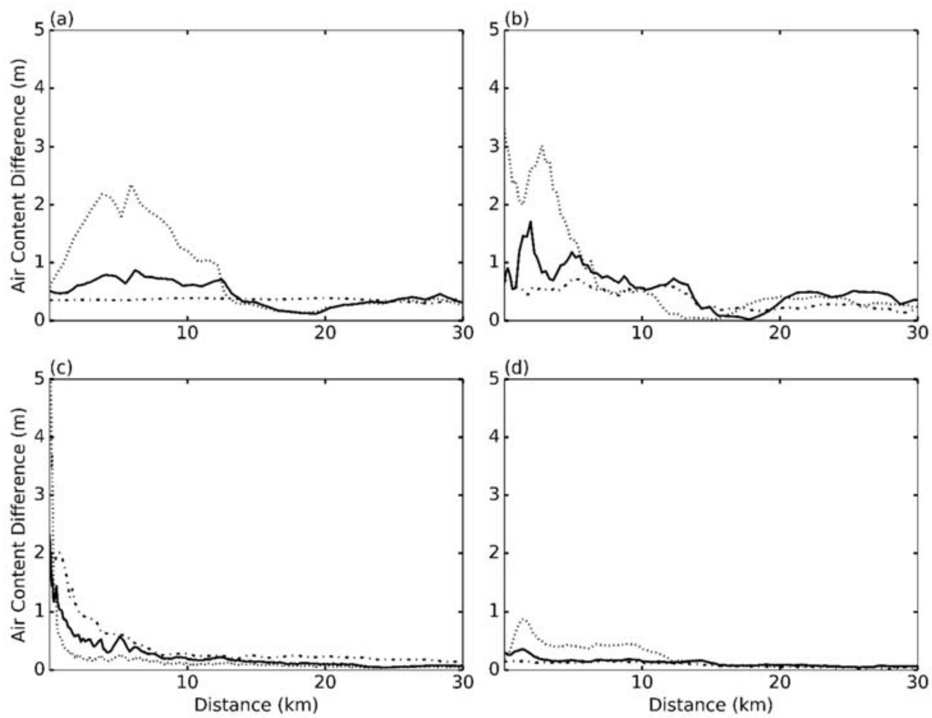
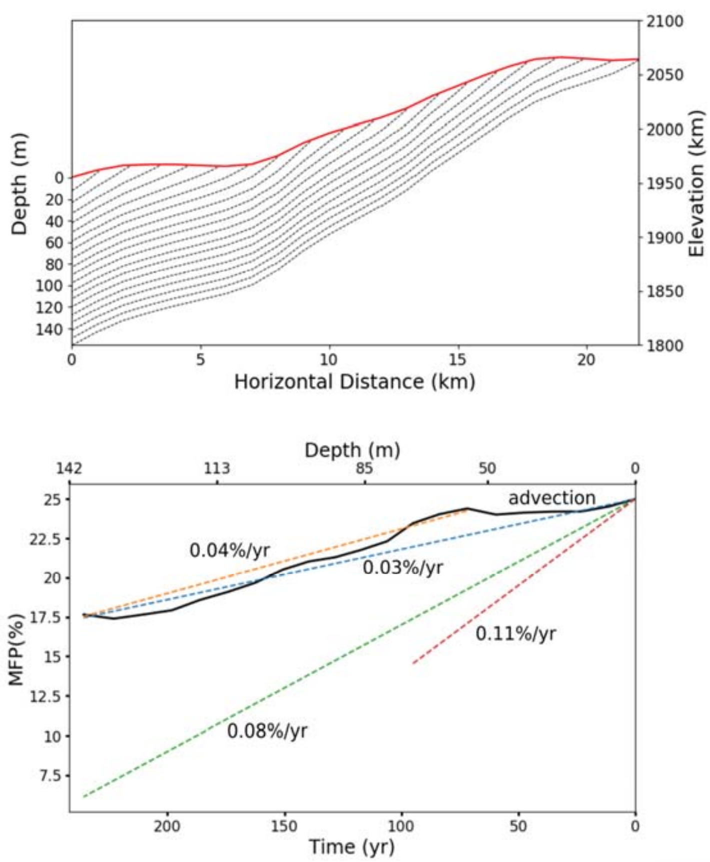


Figure 4. Simulated difference between in integrated firn air content 2D and 1D modeling schemes~~.~~ for EGIG (a), Jakobshavn (b), Helheim (c), and K-transect (d). Differences are presented for each meltwater infiltration scheme: Reeh et al. (2005) (dotted), ~~tipping~~ bucket method (solid), and continuum (dash-dotted). ~~EGIG study transect is shown in black, Jakobshavn in red, Helheim in blue, and K-transect in green.~~


Depth (m)
Elevation (km)
Horizontal Distance (km)
Depth (m)
MFP(%)
Time (yr)
advection
0.04%/yr
0.03%/yr
0.11%/yr
0.08%/yr

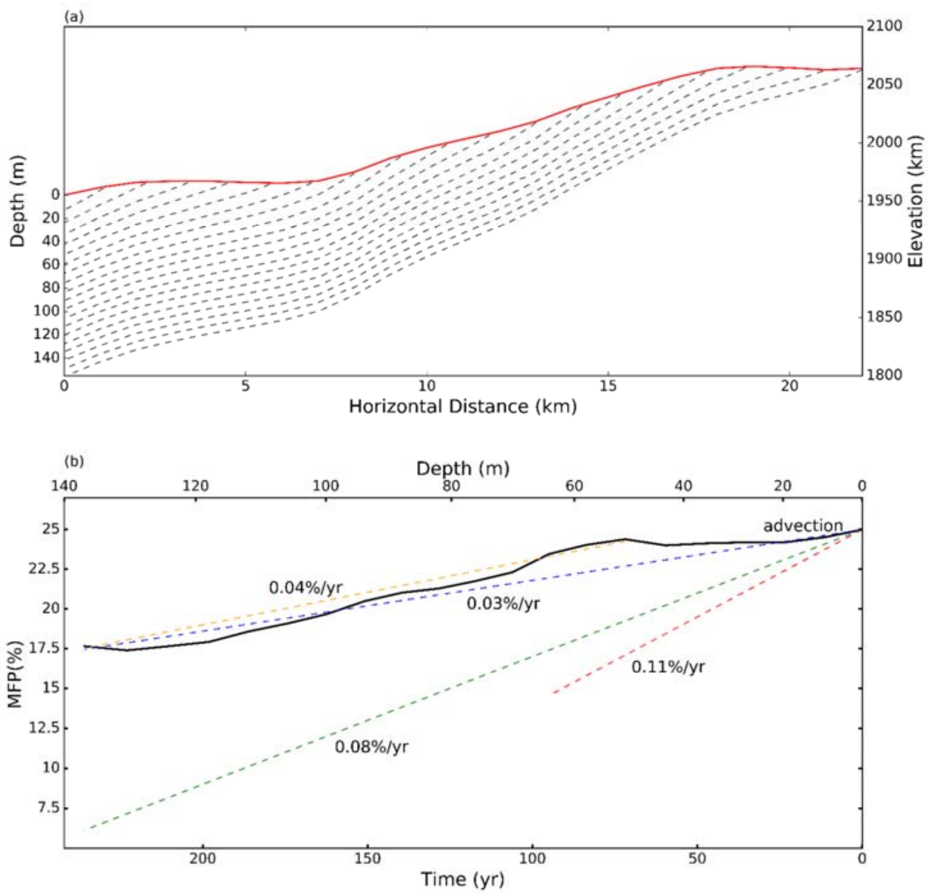


Figure 5. Surface topography and modeled flow lines extending inland from Crawford Point (a). Horizontal distance scale is kilometers from Crawford Point. Bottom panel (b) shows the modeled change in MFP over time (bottom axis) and with depth (top axis) resulting from ice flow alone. Depth scale in (b) corresponds to firn depth in (a). Time trends in ~~calculated~~ MFP at Crawford Point arising from simulated ice flow are shown for the full time/depth period (blue) and for the firn profile below 60 m (orange). Time trends in MFP measured in a Crawford Point ice core and reported by Higgins (2012) entire period (green) and the 1900-2007 period (red) are shown for reference.

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Table 1. Approximate conditions along the four transects used in the study.

Transect	EGIG	Jakobshavn	K-transect	Helheim
Elevation Range (m)	1470-1950	1290-2020	1700-2082	1232-2160
Speed (m yra^{-1})	93-150	85-400	27-71	35-1900
Snowfall (m ice equiv)	0.46	0.55	0.4	0.7-1.3
Temperature (ºC(°C)	-14º14° to -18º18°	-13º13° to -18º18°	-9º9° to -18º18°	-15º15° to -17º17°
Melt (m ice equiv)	0.11-0.43	0.1-0.53	0.15-0.4	0.1-1.3