Review of:

Advection Impacts the Firn Structure of Greenland's Percolation Zone

by Leone et al.

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The presented manuscript studies the impact of ice-flow-driven displacement of snow and firn along a flowline (thereafter called horizontal advection) on the firn density, temperature, pore space and stratigraphy on the Greenland ice sheet. The authors present a novel model that includes the firn horizontal advection and analyze its sensitivity to climate forcing and meltwater routing schemes. The model is then used on four transects in the Greenland ice sheet percolation area and its output is compared with the output from a 1D model to isolate the impact of advection on the simulated firn characteristics at these locations. Eventually, the model is applied on a flowline upstream of Crawford Point, location where a firn core is available, and the impact of horizontal advection on the distribution of Melt Feature Percent through depth, a common indicator for melt, is discussed.

The presented work, and in general the study of the processes controlling the firn characteristics, are highly relevant research topics. Indeed, in a warming climate and with increasing surface melt on the Greenland ice sheet, the firn can buffer the ice sheet's sea-level contribution though the retention of meltwater. Additionally, firn characteristics such as temperature, density and stratigraphy are commonly used to describe the recent evolution of the climate. It is the first time, to my knowledge, that the firn horizontal advection is explicitly included in a firn model and that its impacts on the firn physical characteristics are being discussed. I am therefore confident that the presented manuscript has good potential for being published in the Cryosphere. However, several major limitations need to be addressed, or discussed, before publication. The major comments are listed below while specific remarks are enclosed in the commented manuscript and supplements.

1. Scope: The current manuscript does not assess where advection may have an impact on the density, temperature and stratigraphy of the Greenland firn. I believe that, from the presented model runs, simple rules based on surface velocity, topography, temperature and/or accumulation can be established to map areas where advection is relevant. Without a clear understanding of where this study applies, I am afraid that the manuscript only present model outputs and sensitivity and do not reach a sufficient scientific impact for publication in the Cryosphere.

2. Presentation of the results: In a similar way, the manuscript currently gives examples of transects where the firn advection may or may not have a significant impact on the simulated firn characteristics. These impacts are presented in a qualitative manner (in particular in the abstract and conclusion). I believe that presenting the same results in a more quantitative way would help to fully qualify the study for publication in the Cryosphere. The model can be used to give numerous metrics to quantify the impact of advection at each transect. Quantitative knowledge at each site can then be extrapolated over broader regions of the ice sheet using the rules mentioned in the previous paragraphs.
3. The structure of the manuscript should be modified because i) key information from the model are missing from the main text and should be brought in from the supplementary material: and ii) currently results are being discussed (intercompared) in the Results section and many items in the discussion are repetition from the results. The second point could be solved by either merging results and discussion sections or by clarifying what is simple description of the results and what is discussion of the results.

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Advection Impacts the Firn Structure of Greenland's Percolation Zone

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ABSTRACT. One dimensional simulations of firn evolution neglect horizontal transport during burial. Using a suite of model runs, we demonstrate the impacts of advection on the development of firn density, temperature, and the stratigraphy of melt features the Greenland ice sheet percolation zone. The simulations isolate processes in synthetic runs, and investigate four specific transects and an ice core site. The 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 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% 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). 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.

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 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 of the firn column, the amount of deep pore space that

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could absorb meltwater and heat, and 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. We utilize previous approaches for modeling firn densification and meltwater infiltration, but extended the analysis to two dimensions to include advection of the domain due to ice flow. 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 ice cores 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

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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 (1980), based upon it's relatively simplistic formulation with few tuning parameters and favorable comparison with other densification schemes (Lundin et al., 2017). Temperature, density, 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 accumulation rate) are imposed at the model surface, and vertical gradients in these variables are set to 0 at the model base.

Modeling complex and heterogeneous meltwater infiltration in firn remains an outstanding problem of critical importance that solving 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), 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 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.

2.3 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

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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.

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.

2.3.2 Greenland Transects

Our 2D modeling approach was implemented at four test transects spanning the GrIS (Figure 1): 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). 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). This time period roughly captures the increase in GrIS melt since the late 20th century (Fettweis et al., 2011). In addition to the 2D simulations of the transects, we also completed 1D simulations at 600-1700 locations in each transect, variably spaced between profiles based at annual displacements. The latter were used for baseline comparisons of the effects of including or not including advection of the firn column.

2.3.3 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;

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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 (Mote, 2007).

We modeled the 2D firn evolution on a flow line leading to Crawford Point using datasets for the modern state. Ice surface geometry (Morlighem et al., 2017) and velocity (Joughin et al., 2010) datasets were used for converting from space to time; and, mean 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 employ the (Reeh et al., 2005) model for infiltration to be consistent with the assumption of shallow infiltration employed by MFP observational studies.

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 1D results (Figure 2; Figure S2). Greater ice flow speed clearly influences advection based results, but the impacts are strongly modulated by the magnitudes and gradients in other variables. For example, the impact of advection is also a function of accumulation, with smaller accumulations causing a 25-35% increase in the depth to pore close off 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.

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Adding 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 choice of melt 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). Steeper topography yields larger along-flow gradients between melt, temperature, and accumulation, causing greater disparities between 2D-avection and 1D-profile simulations. The ice flow speed has potential to strongly impact simulations with 2D-advection, but importantly, the impact of speed is strongly modulated by the values and gradients in other variables. In 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 including ice flow differ from 1D by up to four-fold at highest speeds.

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 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 advection on the underlying firn structure, complicating the 2D firn geometry of the percolation zone. The changes to density structure throughout the K-transect are

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comparatively small because the topography and speeds are so much lower than most places on the ice sheet (Table 1), all but eliminating the impact of ice flow (Figure 3d).

The process of advection generates colder firn temperature profiles. Along the EGIG transect 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 by as much as 3° C by including advection.

3.3. Core Stratigraphy Example

Our modeling indicates that 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 deposited along the first ~5km above Crawford Point, a region with very low slope and essentially no horizontal climate gradient caused by elevation. Below this 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. 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 advection 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 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

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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) disregards the complex physics governing flow of water through it's own solid matrix, simplifying the problem to just density and cold content and assuming the flow of meltwater is instantaneous.

With firn advection 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. 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 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% per year. However, melt events prior to 1900 were minor and infrequent; the more recent trend from 1900-2007 therefore increases to 0.11% per year.

The 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 advection because this firn has formed along a locally flat spot

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in the topography extending about 5 km up flow from Crawford Point (Figure 5a). However, over the ~100 years during which significant melt increases are observed in the core, our modeling suggests that approximately one third of the MPF change is attributable to the 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 profiles of firn density and temperature are barely impacted by advection at Crawford Point, yet the MFP record is strongly influenced by advection, 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 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 per year, an important indicator of changing climate, but not large enough to completely mask advection. Where the advection signal is strong it may be likely that it 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 core depth corresponding to a time before present (t), the firn package originated at a location (x) upglacier from the core location, where x is the integral of the spatially varying velocity (v) along the flowline over t years:

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

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

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

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Equations 1 and 2 can thus be combined to generate a time series of MFP 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 advection are highly variable around the ice sheet, but accounting for 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 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.

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 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 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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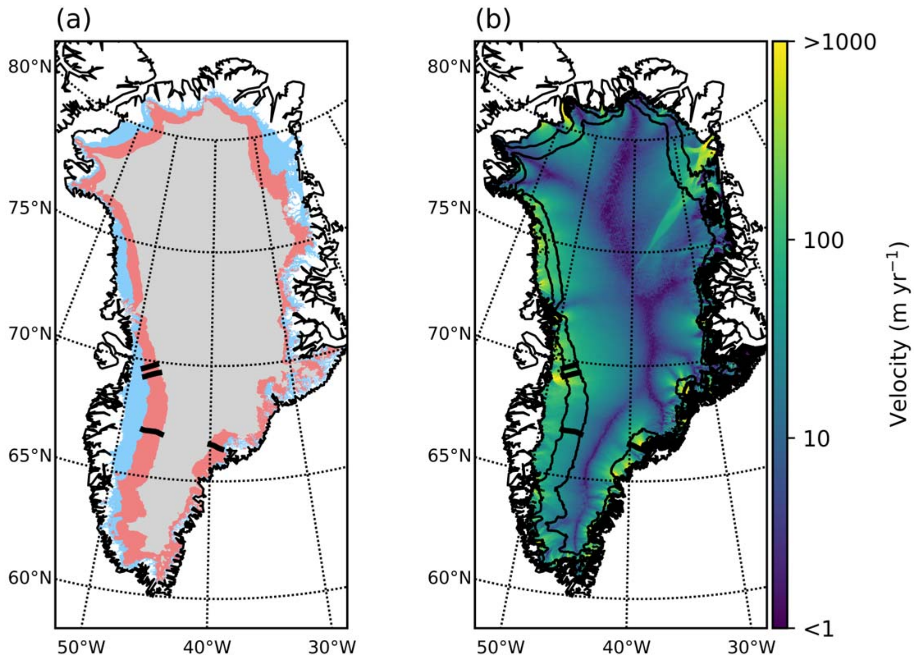

Figure 1. Maps of Greenland. (a) Facies arbitrarily delineated based on modeled 1980-2016 average surface melt (Noël et al., 2018): ablation zone (red) with melt exceeding accumulation; percolation zone (yellow), the upper limit of which defined by melt conditions at Crawford Point where infiltration has not warmed firn (Humphrey et al., 2012); dry zone (blue). (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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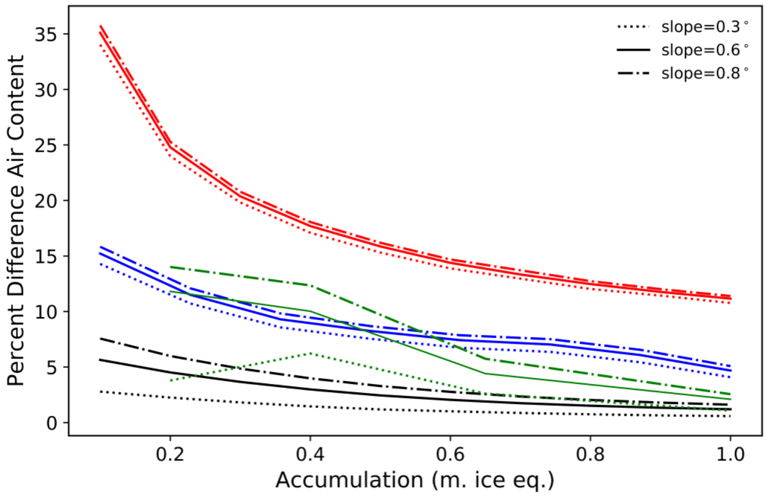

Figure 2. Example sensitivity test. Modeled differences between 1D and 2D for accumulation using dry model (black), Reeh model (red), tipping bucket model (blue), and continuum model (green). Base speed is 100 m a^{-1}, approximately the lowest value of the EGIG transection shown in Figure 1. Three slopes are used to represent different conditions around the ice sheet.

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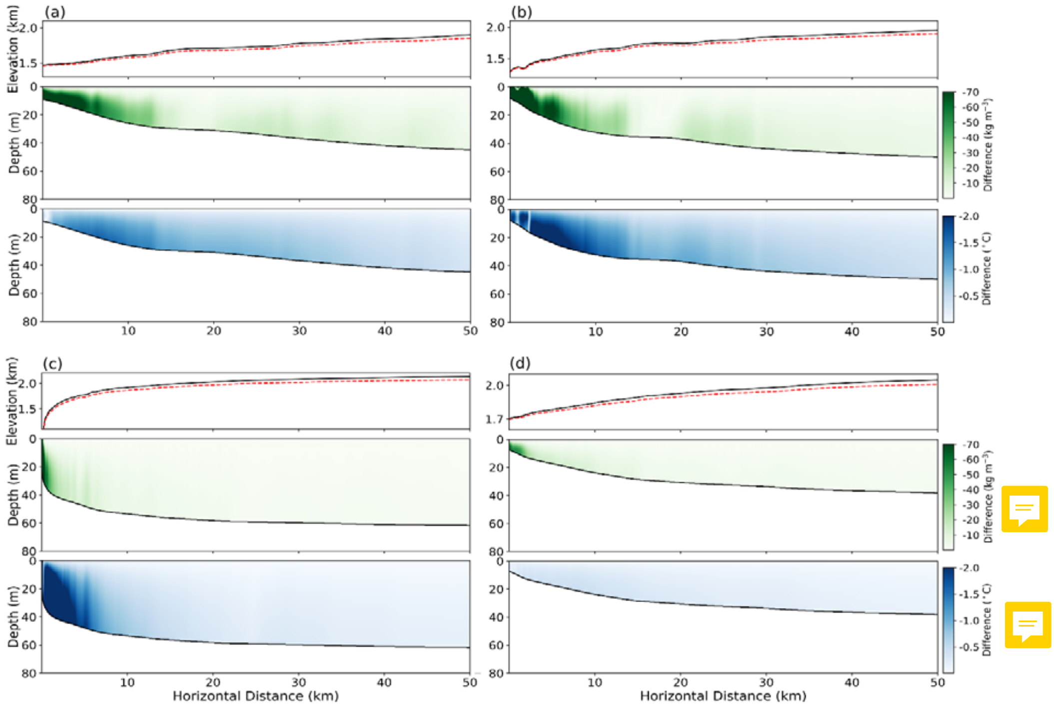

Figure 3. Calculated difference between 2D and 1D simulated firn properties in the percolation zone through the four study transects with tipping buck meltwater infiltration scheme: a) EGIG line; b) Jakobshavn; c) Helheim; and, d) K-transect. Top panel in each transect shows surface topography (black)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

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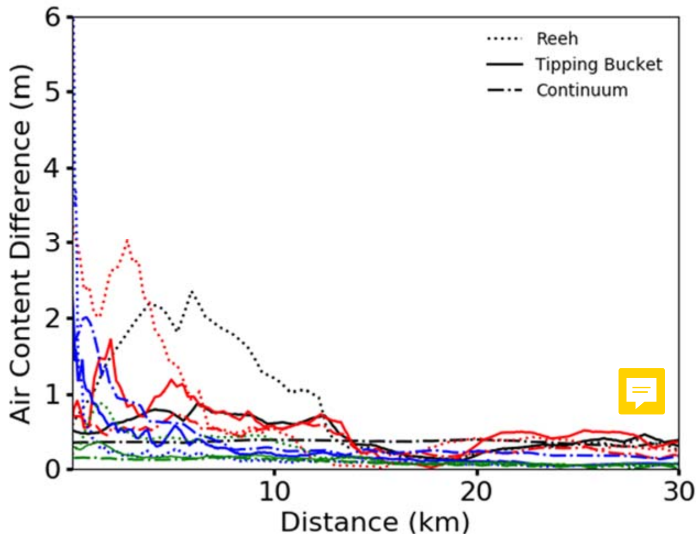

Figure 4. Simulated difference between in integrated firn air content 2D and 1D modeling schemes. Differences are presented for each meltwater infiltration scheme: Reeh et al. (2005) (dotted), tipping bucket (solid), and continuum (dash-dotted). EGIG study transect is shown in black, Jakobshavn in red,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

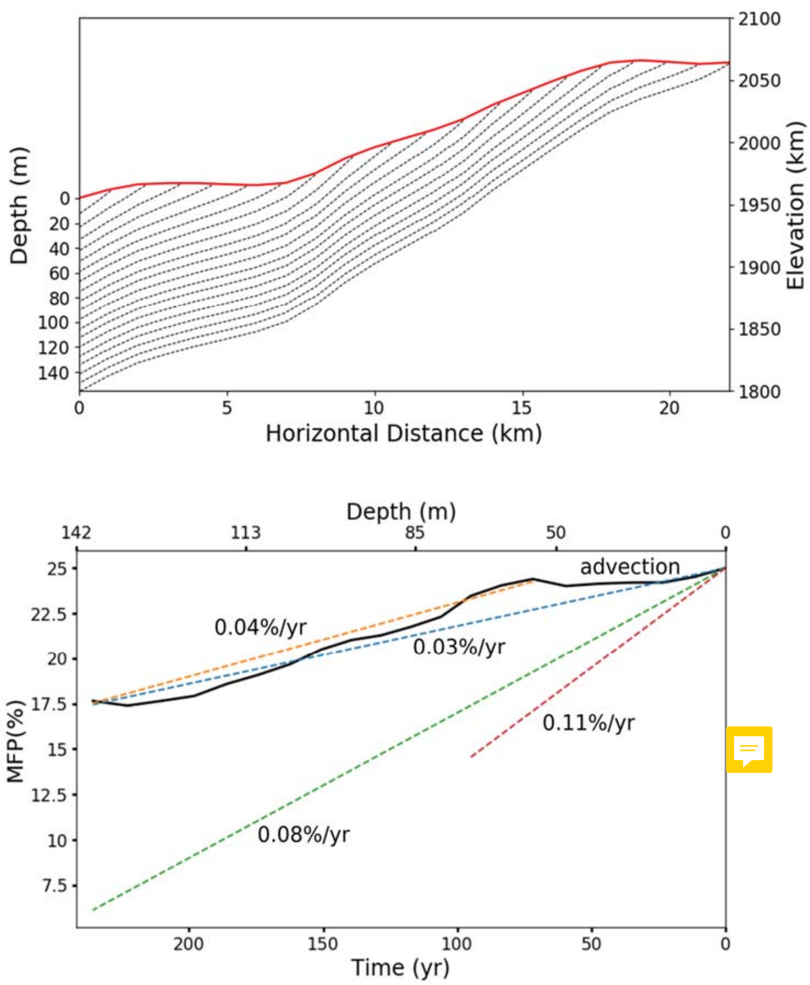

Figure 5. Surface topography and modeled flow lines extending inland from Crawford Point (a). Horizontal distance scale is kilometers from Crawford Point. Bottom panel (b) shows the modeled change in MFP over time (bottom axis) and with depth (top axis) resulting from ice flow alone. Depth scale in (b) corresponds to firn depth in (a). Time trends in calculated MFP 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 yr^{-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)	-14º to -18º	-13º to -18º	-9º to -18º	-15º to -17º
Melt (m ice equiv)	0.11-0.43	0.1-0.53	0.15-0.4	0.1-1.3

Supplementary Material for

Advection Influences the Firn Structure of Greenland's Percolation Zone

R. Leone, J. Harper, T. Meierbachtol, N. Humphrey

S1. Model Setup

S1.1 Firn Densification

We use the transient Herron and Langway (1980) (HL) model for firn densification, which is based on the assumption that the densification rate is linearly related to the change in overlying snow/ice load (Robin, 1958):

$$\frac{D\rho}{Dt} = \begin{cases} c_0(\rho_i\text{-}\rho) & \text{if} \quad \rho \leq \rho_c \\ c_1(\rho_i\text{-}\rho) & \text{if} \quad \rho_c < \rho \end{cases} \tag{S1}$$

where the critical density $\rho_c = 550$ kg m^{-3}. Temperature-dependent constants c_0 and c_1 are defined as:

$$\begin{cases} c_0 = 11\left(\frac{1000}{917}\right) b \cdot \exp\left(\frac{\text{-}10160}{RT}\right) & \text{if} \quad \rho \leq \rho_c \\ c_1 = 575\left(\frac{1000}{917}\right) b^{0.5} \cdot \exp\left(\frac{\text{-}21400}{RT}\right) & \text{if} \quad \rho_c < \rho \end{cases} \tag{S2}$$

where *R* is the gas constant (8.314 J K^{-1} mol^{-1}) and accumulation rate *b* is in ice equivalent units. We use an initial snow density (ρ_0) of 360 kg m^{-3} for the top boundary condition and an initial vertical velocity of $w = b \cdot \frac{\rho_w}{\rho_0}$. Equation S1 is then expanded out by applying the chain rule to the total derivate.

$$\frac{D\rho}{Dt} = \frac{\partial\rho}{\partial t} + w\frac{\partial\rho}{\partial z} \tag{S3}$$

S1.2 Temperature Evolution

Firn temperature was modeled by solving the standard one-dimensional time-dependent heat-transfer equation with latent heat from the refreezing of meltwater (Cuffey and Paterson, 2010).

$$\rho c \frac{\partial T}{\partial t} = k_T \frac{\partial^2 T}{\partial z^2} + \left[\frac{dk_T}{dz} - \rho c w\right] \frac{\partial T}{\partial z} + S \tag{S4}$$

where ρ is density, c heat capacity, k_T thermal conductivity, w vertical velocity, T temperature of the firn, and S as heat sources and sinks. We used thermal conductivity of firn as described in (Arthern and Wingham, 1998):

$$k_T = 2.1 \left(\frac{\rho}{\rho_i}\right)^2 \tag{S5}$$

and a constant heat capacity for simplification. We use a constant boundary condition at the surface based on the annual mean air temperature.

S1.3 Horizontal Motion

In order to decrease run times and increase flexibility for including meltwater schemes, which are all 1D, we used a pragmatic approach that considers 1D model profiles moving through the percolation zone. Profiles are initiated high on the ice sheet and are transported through the percolation following a prescribed horizontal velocity, which is constant with depth. Horizontal motion through the percolation zone is achieved by translating spatially varying surface conditions (temperature and accumulation rate) to time-varying boundary conditions using surface velocities. This approach captures the processes of burial, ice layer formation/preservation, and vertical heat transport, but lacks horizontal heat diffusion.

S1.4 Firn Air Content

The capacity of the percolation zone to store meltwater is quantified by the firn air content. The cumulative air content is the integrated difference between infiltration ice density and firn density:

$$C(z) = \int_0^z \left(\rho_{ii}(\zeta) - \rho(\zeta)\right) d\zeta \tag{S6}$$

where ρ is firn density and ρ_{ii} is infiltration ice density, and z is depth. We used an average density of 843 kg m^{-3} for infiltration ice (Harper et al., 2012).

This calculation does not take into account perennial firn aquifers where capacity must be adjusted by 8.9% due to density differences between water and ice (Koenig et al., 2014). In order to obtain meters of air content of ice (and thus avoiding the complications that arise between the differences of water and ice density) we divide the total capacity by the density of ice.

S1.5 Horizontal Heat Transfer

To assess the consequences of neglecting horizontal heat diffusion in our modeling scheme, we developed an explicit 2D model for densification and heat transport for testing. While the formulation includes horizontal diffusion, it lacks meltwater infiltration schemes. In this formulation, 2D firn densification is defined as:

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + w\frac{\partial \rho}{\partial z} + u\frac{\partial \rho}{\partial x} \tag{S7}$$

where *u* corresponds to the horizontal velocity. The temperature equation was also updated to include horizontal advection terms:

$$\rho c\frac{\partial T}{\partial t} = k_T\left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial x^2}\right) - \rho c u\frac{\partial T}{\partial x} + \left[\frac{dk_T}{dz} - \rho c w\right]\frac{\partial T}{\partial z} \tag{S8}$$

The surface boundary condition for temperature varied by several degrees across the surface domain to simulate the lower elevations of the percolation zone.

Both modeling frameworks were tested over a 90 km model domain, with a constant accumulation rate of 0.5 m a^{-1}. Surface temperature varied from -19 to -13 over the model domain, in approximate agreement with observations along the EGIG transect. Model simulations were executed with a prescribed surface velocity of 100 m a^{-1}, which approximates conditions along the EGIG transect, and with a surface velocity of 1000 m a^{-1} to test the consequences of neglecting horizontal diffusion under an extreme scenario.

Comparison results for the 100 m a^{-1} scenario are presented in Figure S1. The consequences of neglecting horizontal diffusion are negligible for both density and temperature results. Neglecting horizontal diffusion is more consequential when surface velocity is 1000 m a^{-1}, but even in this extreme scenario the maximum temperature difference is ~0.15°C; a difference which has essentially no impact on modeled density. This supports our modified approach, which we use for its flexible implementation of melt schemes and its fast runtime.

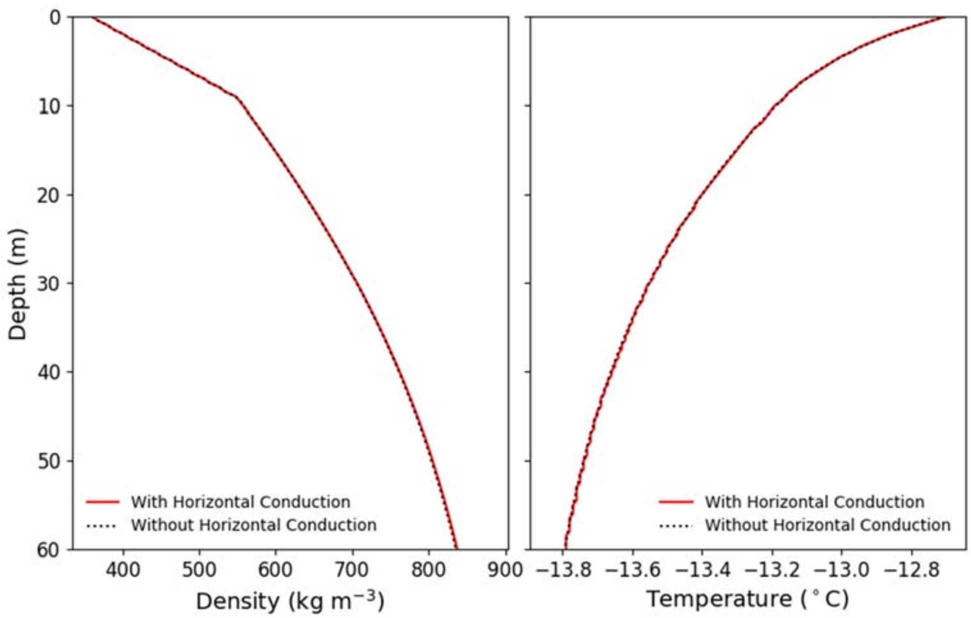

Figure S1. Simulated density (A) and temperature (B) results 80 km from the inland model boundary with, and without horizontal heat conduction.

S2.1 Sensitivity Testing

A range of sensitivity tests were performed to assess the role of ice forcing processes, in the presence of horizontal ice motion, on model results. Two dimensional simulations were performed over an 80 km model domain with constant velocity and accumulation. Surface temperature varied following a lapse rate and prescribed surface slope, and melt rates linearly increased along the model domain from zero at the model inland boundary, to a percentage of the accumulation value at the downstream boundary. This percentage was varied in testing. Two dimensional model results at 80 km were compared against 1D steady state results at that location. Sensitivity testing was performed around a base case scenario with horizontal velocity of 100 m a^{-1}, an accumulation rate of 0.5 m a^{-1}, and melt rate of 85% of the accumulation at the lower model boundary.

Horizontal velocities were varied from 0 - 500 m a^{-1}, accumulation rates were varied from 0.1 - 1.0 m a^{-1} ice equivalent, and maximum melt was varied from 0 - 85% of the accumulation value. The ranges of values tested was chosen to approximately span the spectrum of conditions that may occur in GrIS' percolation zone. Additionally, we impose three different surface temperature gradients in each simulation to determine model sensitivity to a spatially varying surface temperature boundary. Simulations are performed for horizontal temperature gradients manifested in surface slopes of 0.3°, 0.6°, 0.8° assuming a temperature lapse rate of -7.4 °C/km (Fausto et al., 2009).

We used temperature at pore close off and total air content (see S1.2) as comparison metrics. Both 2D and 1D model simulations were performed for each sensitivity scenario, and the difference was calculated as a percentage:

$$\sigma_{\%diff} = \frac{\sigma_{2D} - \sigma_{1D}}{\left(\frac{\sigma_{1D} + \sigma_{2D}}{2}\right)} \tag{S9}$$

where σ is the metric of interest. Note that given this formulation, because firn temperatures are never >0°C, the denominator in S9 is negative and so temperatures in 2D simulations that are colder than the 1D counterpart reflect a positive difference.

S2.2 Sensitivity Test Results

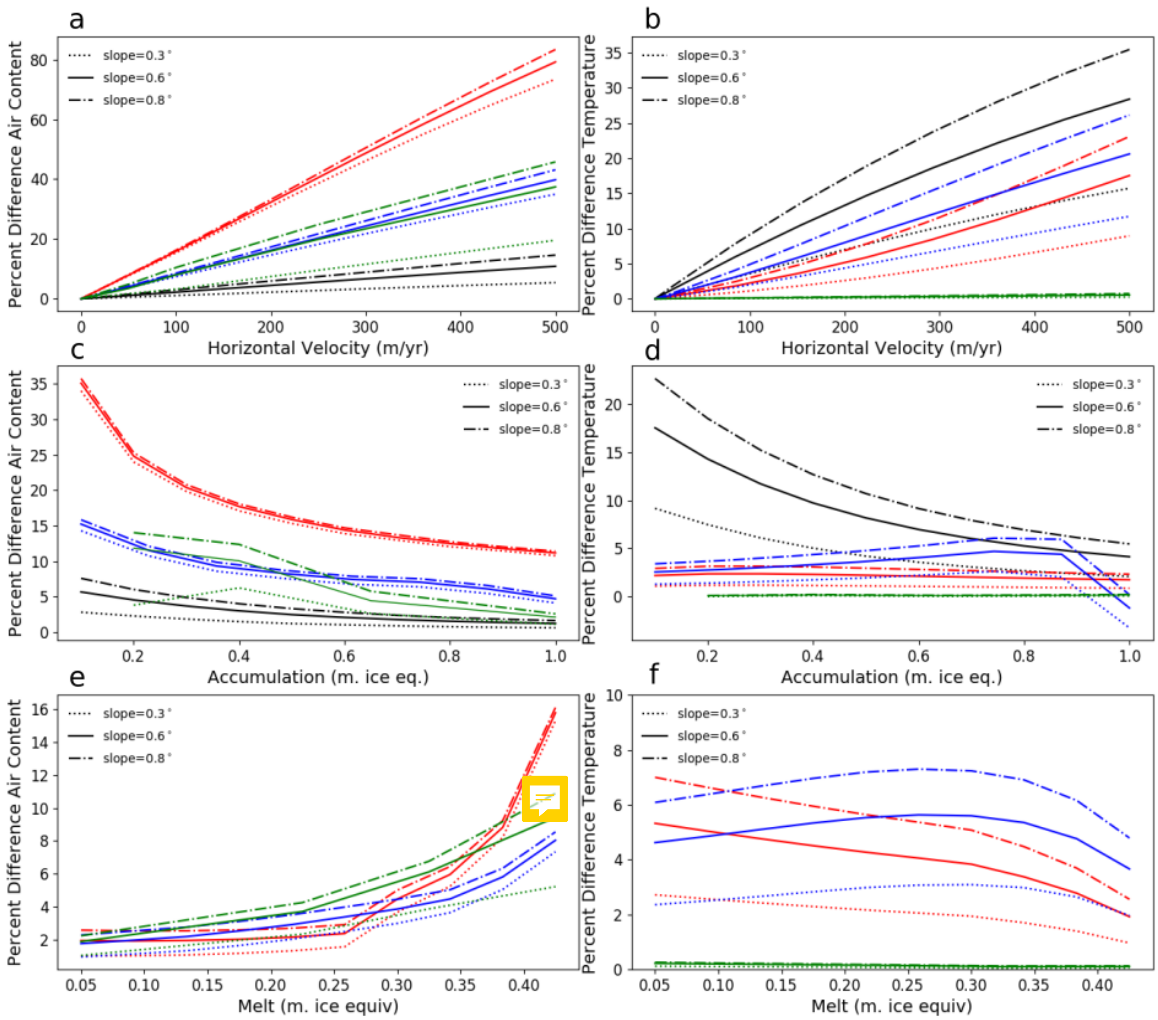

Figure S2. Modeled percent differences for sensitivity test forcings using dry model (black), Reeh model (red), tipping bucket model (blue), and continuum model (green). Left panels show percent difference in air content and right panels show percent differences in temperature. (a-b) show results from varying horizontal velocity, (c-d) represent testing of variable accumulation rates, and (e-f) show results for different melt rates.

S3. Model Results along GrIS Transects Under Different Melt Infiltration Schemes

The influence of horizontal ice flow on firn density and temperature is explored over 4 different GrIS transects. The difference between 2D and 1D model results is calculated as:

$$\sigma_{diff} = \sigma_{2D} - \sigma_{1D} \quad \text{(S10)}$$

where σ is the metric of interest. Figure S1 shows surface conditions; Figure S4 and S5 present results for the Reeh et al. (2005) and continuum meltwater infiltration schemes.

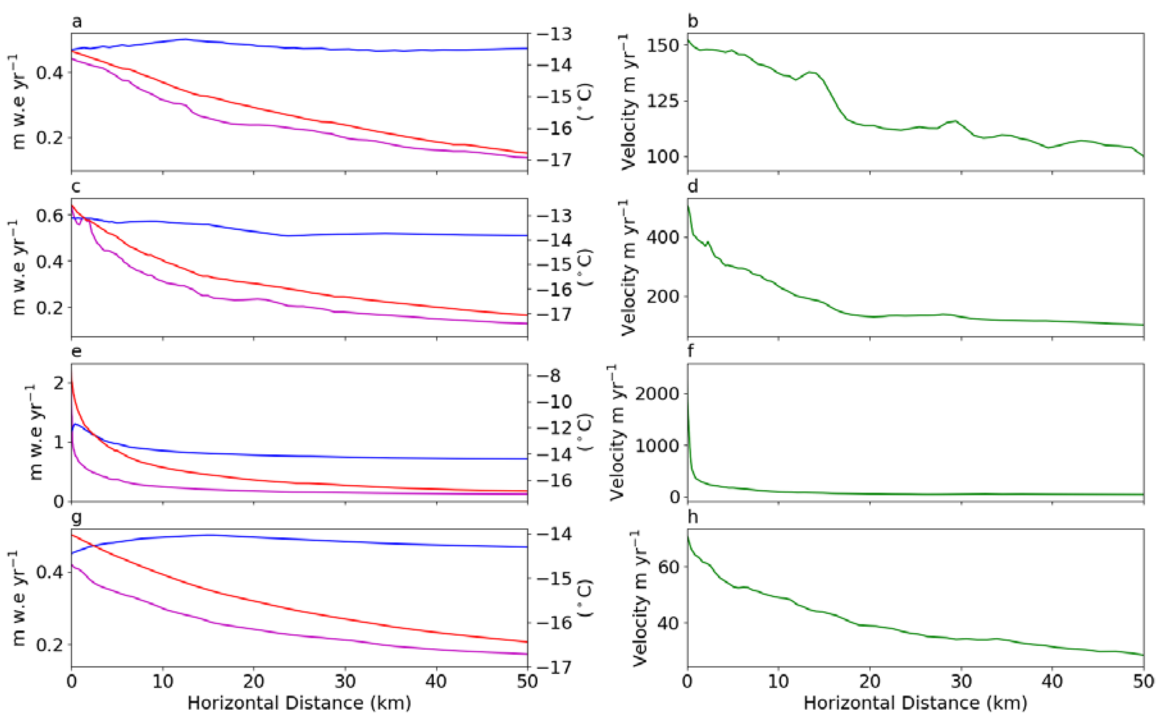

Figure S3. Surface conditions used for transect simulations. Left column shows snowfall (blue), temperature (red), and melt (magenta) extracted from RACMO2.3p2 (Noël et al., 2018) for 1980-2016 average. Right column snows speed extracted from (Joughin et al., 2010). Transects: EGIG (panels a,b); Jakobshavn (panels c,d); Helheim (panels, e,f); K-transect (panels g,h).

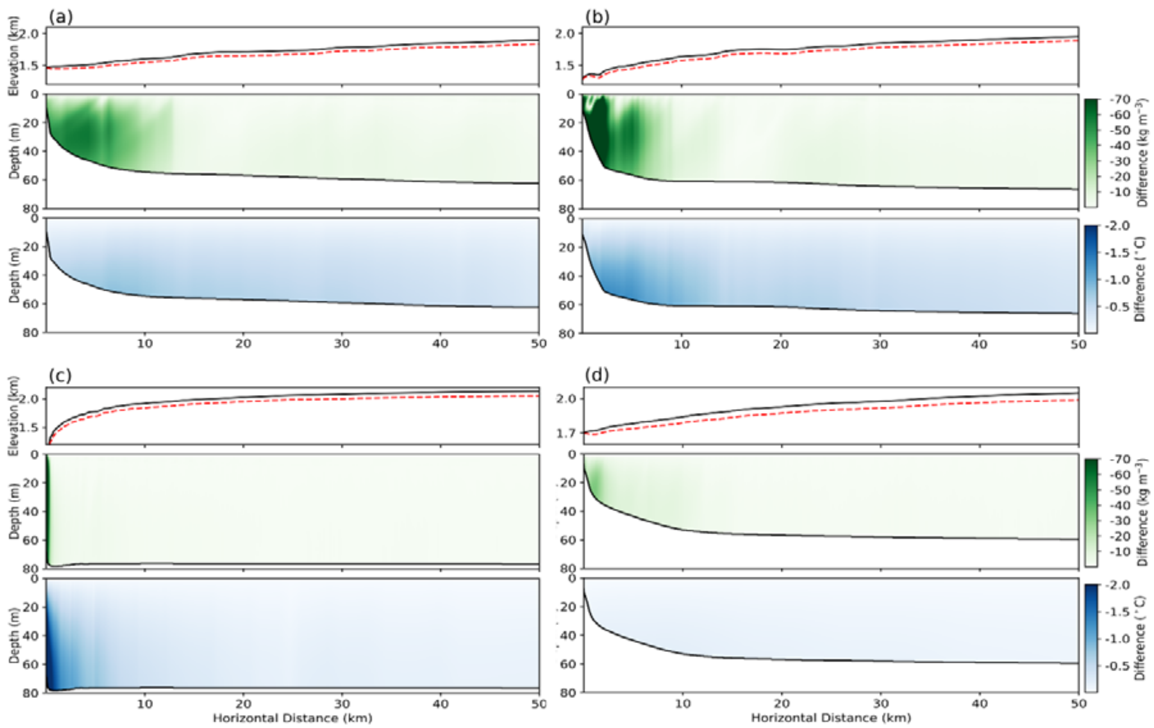

Figure S4. Modeled density and temperature differences between 1D and 2D results using the Reeh et al. (2005) infiltration scheme at the EGIG (a), Jakobshavn (b), Helheim (c), and K-transect (d). Top panel in each shows surface topography (black line) and 2D modeled depth to pore close-off (dashed red line).

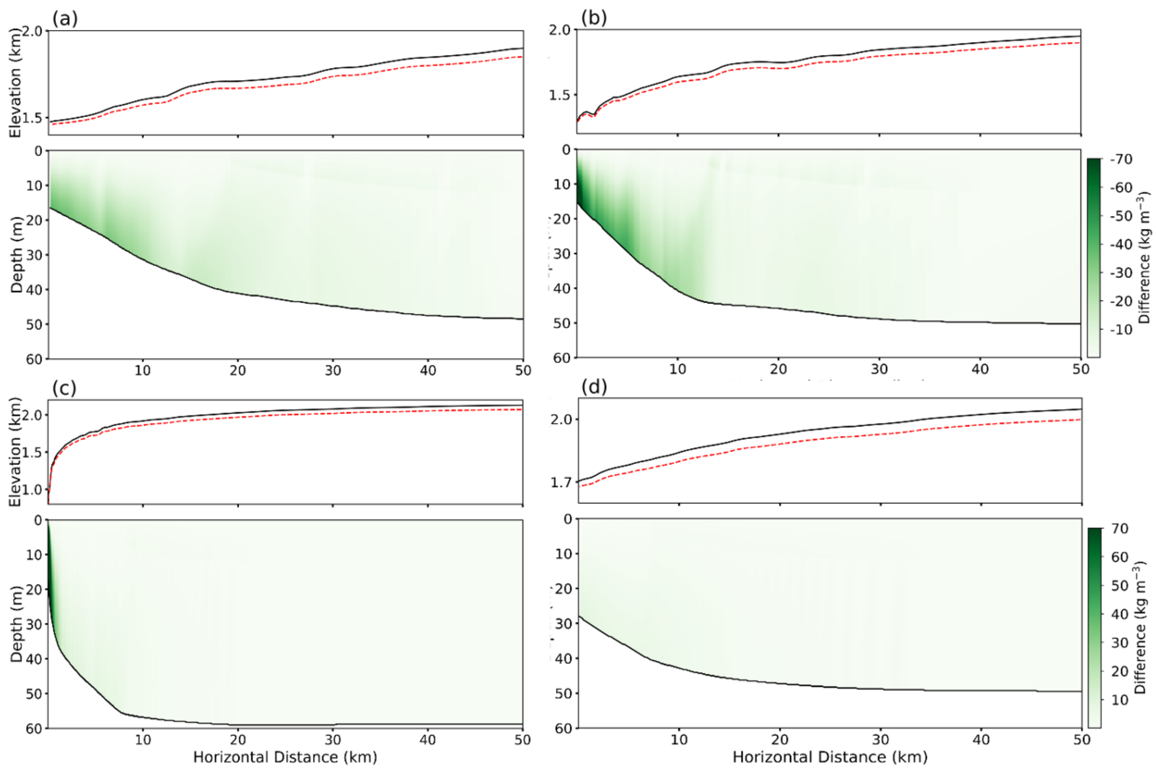

Figure S5. Modeled density differences between 2D and 1D simulations for GrIS transects as in Figure S3, but for the continuum meltwater infiltration scheme. Continuum model results were found to be insensitive to temperature (Figure S2) and are not displayed.

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