BACHELOR RESEARCH

Firn Compaction in Greenland

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Abstract

The Greenland ice sheet is for a large part covert with a layer of firn. This layer of firn influences the average density of the total ice sheet, therefor knowing the density of the firn layer will be very important for researches about the ice sheets water content.

The density of the layer of firn is modelled, using a one-dimensional time-dependent firn model, together with the firn layer temperatures and the amount of liquid water inside this layer. Model runs have been performed, for some locations at Greenland with a wide variability in climate forcing, as gives by the RACMO2 model. Al these locations gave us firn layers with widely varying characteristics. Melt occurs almost everywhere at greenland, with mid greenland, where the temperatures remain far under the melting point as exception. Some of the layers where melt occurs contain aquifers, most of them do not. These differences make the Greenland firn layer an interesting place for firn layer research.

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1 Introduction

A large part of Greenland's ice cap is covered with a layer of firn, the transitional product between the fresh snow and glacial ice. Fresh snow has a density in the order of 300 kg m^{-3} and (glacial) ice has a density around 917 kg m^{-3}. The density of the firn at the top of the ice sheet will be in the order of the density of fresh snow. While descending into the firn column, if no melt occurs, the density will slowly increase until it reaches the ice density.

Since the introduction of the empirical model from Herron and Langway Jr [1980], several densification models have been proposed. Some of those are based on semi-empirical parameterisation [Barnola et al., 1991; Zwally and Li, 2002; Helsen et al., 2008; Arthern et al., 2010; Ligtenberg et al., 2011], and some are based on physical parameterisation (like Wilkinson [1988]).

The early firn models (e.g. Herron and Langway Jr [1980]) only described the densification due to snow compaction. Later firn densification models (e.g. Ligtenberg et al. [2011]) also contain other processes, like melting, freezing and conduction.

In April 2011, just before the start of the melting season, the Arctic Circle Traverse expedition found liquid water in the upper $10-25$ meters of the southeast Greenland firn layer: the first sign of the existence of perennial aquifers. Two years later this discovery has been validated by Forster et al. [2013] and Koenig et al. [2014] using ground penetrating radar, airborne radar and firn cores.

The overall goal of this research is investigating Greenland's firn layer. This will be done using a time-dependent one-dimensional densification model, as described in Section 2.1 and a forcing as described in section 2.3. Using this one-dimension model we want to find the answers to some questions. Do we find aquifers? If so, at which locations do we find them? And can we identify these aquifers while looking at other firn layer properties? In section 3, some basic properties of the firn layer will be illustrated using the modelled results. After this we will take a look at the firn layer properties of a cross-section through southeast Greenland. This will give a better overview of the Greenland firn layer.

2 Methods

2.1 Model

In this study a time-dependent one-dimensional firn model, as described in Ligtenberg et al. [2011] with minor adjustments described by Kuipers Munneke et al. [2014], is used.

The vertical model firn column consists of many thin layers, with thicknesses varying between the 4.5 and 10.5 cm. For every model layer firn density, temperature, liquid water content and depth are calculated. Each time step snow will be added on top of the firn layer. When a single layer exceeds 10.5 cm the layer will split into two layers. When a layer reaches the defined lower limit for layer thickness of 4.5 cm, this layer will merge with the upper neighbours and the new layer properties will be the mass-weighted mean of the two merged layers [Kuipers Munneke et al., 2014]. The layers in this model are all stacked upon each other in a Lagrangian setting, meaning that properties of the layer (e.g. density and temperature) will move downwards through the firn layer as a consequence of accumulation.

2.1.1 Densification

The fresh snow density is taken to be 300 kg m^{-3}. By keeping this constant we are able to focus on the sensitivity of the firn layer to other processes.

In this model the dry firn compaction equation from Arthern et al. [2010] is used:

$$\frac{d\rho}{dt} = MO \cdot C\dot{b}g(\rho_i - \rho)e^{\frac{-E_c}{RT_s} + \frac{E_g}{RT_s}}, \tag{1}$$

where $\dot{b}$ is the annual accumulation rate, g the gravitational acceleration, ρ_i the ice density, T_s the surface temperature, E_c, E_g and R are constants and $C = 0.07$ for $\rho < 550$ kg m^{-3} and $C = 0.03$ for $\rho \geq 550$ kg m^{-3}. The extra factor MO (compared to the model from Arthern et al. [2010]) is empirically determined by Ligtenberg et al. [2011] using Antarctic firn core observations.

$$MO = 1.435 - 0.151 \ln{(\dot{b})} \text{ for } \rho < 550 \text{ kg m}^{-3} \tag{2}$$

$$MO = 2.366 - 0.293 \ln{(\dot{b})} \text{ for } \rho > 550 \text{ kg m}^{-3}. \tag{3}$$

The difference in the densification rate is caused by the different processes that take place. In a layer with a density lower than 550 kg m^{-3}, the most important process is grain settling, where the grains of snow will get as close together as they can without deforming. When the firn density reaches 550 kg m^{-3}, grain settling will stop. At densities larger than 550 kg m^{-3}, the most important process is grain boundary sliding (a form of deformation/sintering). This process will continue until the ice density of 917 kg m^{-3} is reached.

2.1.2 Hydrology

When melt occurs on an particular place at the Greenland ice sheet, the surface meltwater will percolate into the firn column. Here it will refreeze when it reaches a layer where the temperature is below the freezing point. The latent heat released by refreezing, heats up the layer where the water refreezes, ensuring that the energy in the firn column is conserved [Kuipers Munneke et al., 2014]. If the firn layer contains not enough energy to refreeze all the water, the liquid water can percolate downwards into the next layer. However, not all the water will percolate downwards, as capillary forces hold a part of the liquid water inside the firn layer. The maximum capillary water storage capacity of a layer W_c (in mass percent) is a function of the porosity $P = 1 - (\rho/\rho_i)$ based on Coleou and Lesaffre [1998]:

$$W_c = 1.7 + 5.7\frac{P}{1-P}. \tag{4}$$

This model assumes that the percolation of water in the column is happening in one single time step. The water that reaches the firn-ice interface will runoff directly [Kuipers Munneke et al., 2014].

2.1.3 Thermodynamics

The thermodynamics in the model is split into two parts. The first part is the conduction of heat, described by a one-dimensional time-dependent heat-transfer model:

$$\frac{\delta T}{\delta t} = k\frac{\delta^2 T}{\delta z^2}, \tag{5}$$

with thermal diffusivity k. The second part of the thermodynamics is the conservation of energy in the column, due to melting and refreezing. The third method of heat transport, advection of heat is included in the model by the downward motion of the layers [Helsen et al., 2008].

2.2 Atmospheric forcing

In addition to the fresh snow density (section 2.1.1), a temperature and an accumulation rate are needed. To mimic the seasonal cycle in temperature, a sine-function with mean temperature T_a and amplitude T_0 is used, as in Figure 1.

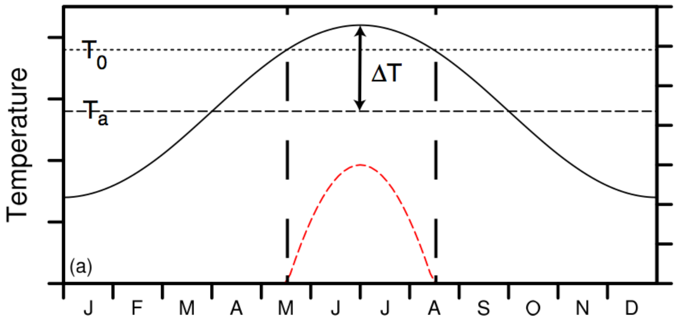


Figure 1: Schematic picture of the surface temperature forcing T and surface melt flux M (equation 6), as used as input for the firn model (from Kuipers Munneke et al. [2014])

The surface melt can be described using a simple form of positive degree day (PDD) formulation as in Braithwaite [1984] and Kuipers Munneke et al. [2014]:

$$M = DDF_s \sum (T - T_0) \Delta t, \tag{6}$$

where DDF_S is a degree day factor (mm w.e. d^{-1} °C^{-1}), T_0 a threshold temperature for melting and Δt a period of time (Figure 1). For Greenland the daily mean temperature, $DDF_s = 1.5$ mm w.e. d^{-1} °C^{-1} and $T_0 = -5$ °C [van den Broeke et al., 2010] will be used.

For the mean temperature and accumulation rate, the average output of a regional atmospheric climate model (RACMO2) over the period 1960-1979 [van Angelen et al., 2012](Table 1), are chosen as the atmospheric forcing parameters. The amplitude of the temperature T_0 can be calculated out of the results for the melt found by RACMO2, over the 1960-1979 period, using the positive degree day formulation from equation 6.

2.3 Modelled locations

The firn layer varies over the Greenland ice sheet. To demonstrate the varieties in firn layer properties, four locations and a cross-section are selected to run the model. One run in a high accumulation regime (G158_086), one at a location with almost as much melt as accumulation (G140_040), one location similar to mid Greenland (with no melt at all) (G174_160), and at last one with a more average climate forcing (G154_088). The cross-section is set to go through G158_086 and ranges from the inlands to the coast. As aquifers are found at this side of Greenland [Forster et al., 2013; Koenig et al., 2014]. All described locations are depicted in Figure 2 and listed in Table 1.

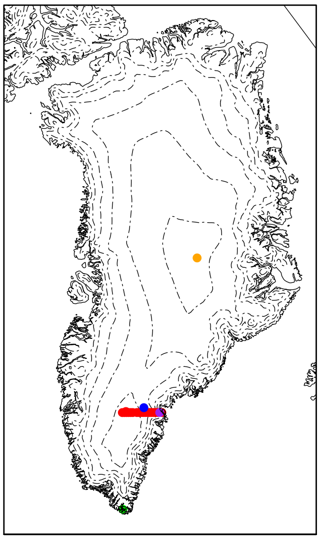


Figure 2: Locations for which the firnlayer is modelled. The dots indicate the locations, G140_040 (green), G158_086 (purple), G154_088 (blue) and G176_160 (orange), as used in the analysis in Section 3. The red line represents the cross-section as analysed in Section 4.

	Latitude (°N)	Longitude (°E)	accumulation (mm w.e. yr^{-1})	melt (mm w.e. yr^{-1})	T-skin (K)	T-skin (°C)
G140_086	64.584	-45.263	420	103	251.28	-21.9
G141_086	64.597	-45.034	388	94	251.13	-22.0
G142_086	64.608	-44.804	385	88	251.06	-22.1
G143_086	64.621	-44.575	403	79	251.12	-22.0
G144_086	64.632	-44.345	445	86	251.36	-21.8
G145_086	64.643	-44.115	508	93	251.67	-21.4
G146_086	64.654	-44.884	593	105	252.03	-21.1
G147_086	64.665	-43.654	707	115	252.45	-20.7
G148_086	64.675	-43.423	839	129	252.97	-20.2
G149_086	64.684	-43.192	984	147	253.58	-19.6
G150_086	64.693	-42.961	1137	190	254.29	-18.9
G151_086	64.702	-42.730	1262	216	255.09	-18.1
G152_086	64.711	-42.498	1320	272	255.94	-17.2
G153_086	64.719	-42.267	1396	329	256.74	-16.4
G154_086	64.727	-42.035	1684	385	257.52	-15.6
G155_086	64.734	-41.804	2373	479	258.44	-14.7
G156_086	64.741	-41.572	3493	634	259.76	-13.4
G157_086	64.747	-41.340	4612	890	261.57	-11.6
G158_086	64.753	-41.107	5148	1182	263.47	-9.7
G159_086	64.759	-40.875	4915	860	264.77	-8.4
G140_040	60.017	-44.073	886	783	269.15	-4.0
G174_160	72.198	-36.682	132	0	240.00	-33.2
G154_088	64.926	-42.926	2192	334	256.78	-17.6

Table 1: RACMO2 climate characteristics of G174_160, G158_086, G140_040, G154_088 and the cross section: latitude, longitude, average annual accumulation, melt and temperature over the 1960-1979 period.

3 Results and Discussion

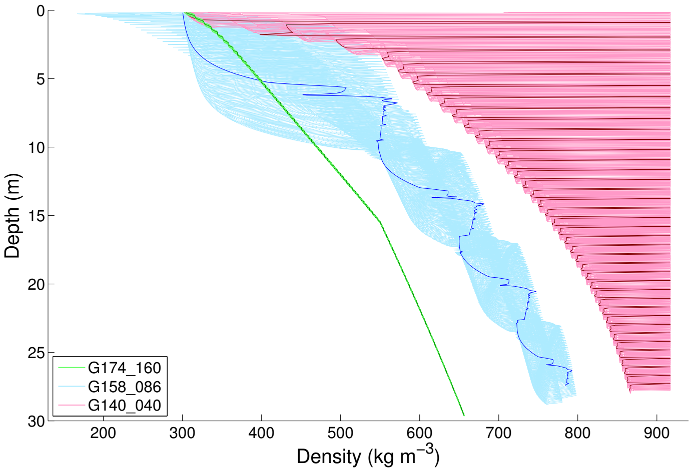


Figure 3: Firn density profile for three locations at the Greenland ice cap. The light coloured areas represent the possible density range at a depth throughout the year. The darker lines within the lighter coloured areas represent the winter profiles of the different locations.

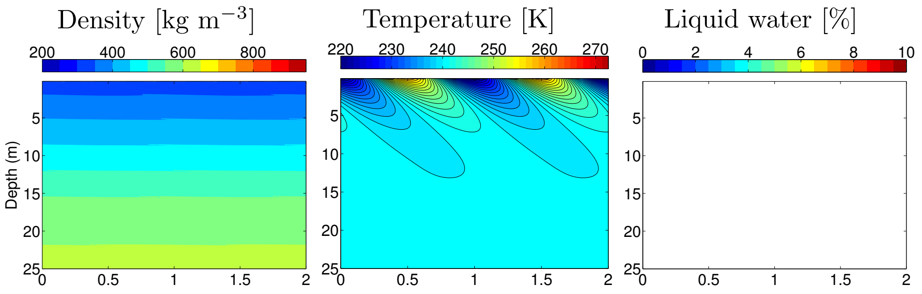
In this Section the firn layer will be described for the points in Figure 2 (and Table 1). This will be done using Figure 3 for G176_160, G158_086 and G140_040. Figure 4 will be used for those three locations as for location G154_088.

A firn layer location where no melt occurs, like G174_160 has a density profile like the green line in Figure 3. This profile shows small seasonal variations in the density, in the order of 5 kg m^{-3}. These little oscillations are probably caused by the temperature dependent densification (Equation 1) and temperature difference between the summer and winter (Figure 4b). This temperature difference ensures a faster summer densification rate compared to the winter rate, and makes sure that the melt takes place in the summer. At a depth of 15 meters there is a transition of density rate with depth. This is when the density reaches a value of 550 kg m^{-3}, the density where the compaction rate changes (Section 2.1.1). The surface temperature on this location oscillates between the 220 and 260 K. Beneath the 15 m line the temperature oscillation has been damped. The temperature here is 240 K, equal to the mean surface temperature (Figure 4b and Table 1). Figure 4c is empty because no melt occurs at this location.

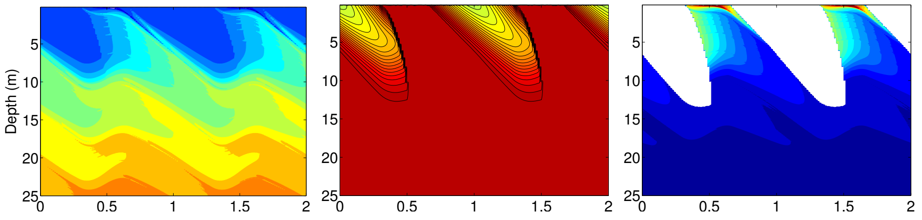
Moving to a location with a high accumulation rate and melt (G158_086), a completely different profile is found (Figure 3 the blue line). This figure shows large seasonal variations in the density depth profile. The winter profile in Figure 3 (the darker blue line) displays a very steep line in the first few meters. This is characteristic for a low temperature, as in the winter, combined with a high accumulation rate, whereas the profile turns into an almost horizontal line at about 5 meters depth, this feature is also shown by Figure 4d. At time=0, the first 5 meters show a dark blue colour. Around a depth of 5 m a sudden jump in density takes place, represented by the closely-spaces contours. This irregular pattern of closely and widely-spaced contours remains in the rest of the firn column. The densities in the upper layer at G158_086 are highly temperature dependent. Lower temperatures in Figure 4e indicate low densities in Figure 4d, while high temperatures indicate higher densities and higher densification rates. This can be identified by looking at the distance between the density contours. Comparing the amount of liquid water in the firn layer (Figure 4f) with the temperature (Figure 4e), shows that liquid water is only found at depths where the temperature is around 0 ℃. When the temperature would be lower than 0 ℃ (273 K) this energy would be used to refreeze the liquid water. Since energy is needed to start the freezing process, the water will remain liquid if there is not enough refreezing energy available. This effect is, together with the capillary forces the reason that perennial aquifers have been found at such locations at Greenland.

An other extreme climate forcing can be found at location G140_040. On this location, the model simulates an intermediate accumulation rate and a melt rate of $\sim$ 90% of the accumulation rate. With this amount of melt there are two options; a firn layer exists or it does not exist. If there are high ice temperatures, firn layer would be expected because of the small amount of available energy to refreeze the water. In this case, there probably is a significant amount of runoff water. If the ice temperature is low, it is likely that all the meltwater refreezes into the firn layer, leading to a layer of ice. Figure 3 and 4h display a relatively high ice temperature and a density profile indicating a firn layer exists at this location. Inside the density profile of this firn layer (Figure 3) we can distinguish a pattern of thin peaks in the direction of the ice density (917kg m^{-3}). These little plates of ice are called ice lenses. In Figure 4g, these ice lenses are represented by the almost horizontal red lines. These lenses can also be found in the liquid water plot (the white Figure 4i). This plot shows thin white lines where the firn layer is not containing liquid water, indicating the depths where ice lenses can be found. Apart from the ice lenses Figure 4i shows that liquid water remains in the firn layer, all through the year. Indicating G140_040 has a perennial aquifer, just as location G158_86 (Figure 4f).

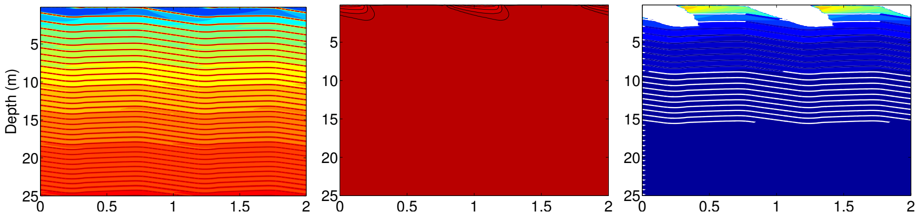
A more common Greenland climate forcing can be found at G154_088. This forcing lies between the three aforementioned locations. While Figure 4e and 4h (G158_086 and G140_040 respectively) display a deep firn temperature equal to the summer surface temperature, Figure 4b (G174_160) shows a deep firn temperature equal to the mean surface temperature. Location G154_088 (Figure 4k) has got a deep ice temperature between the mean surface and the summer surface temperature. This results in a deep ice temperature under the 273K margin and makes it impossible to form perennial aquifers at this location (Figure 4l).



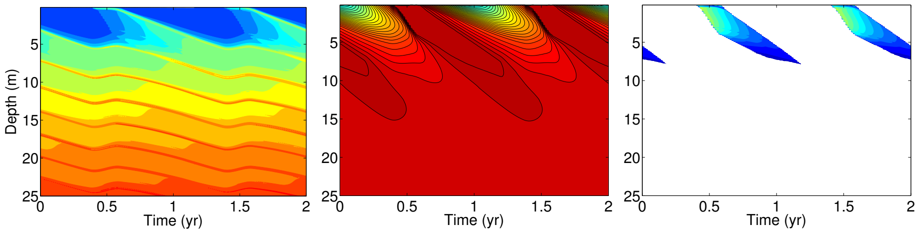
(a) G174_160 (b) G174_160 (c) G174_160



(d) G158_86 (e) G158_86 (f) G158_86



(g) G140_040 (h) G140_040 (i) G140_040



(j) G154_088 (k) G154_088 (l) G154_088

Figure 4: Vertical firn density (a,d,g,j), temperature (b,e,h,k) and liquid water profiles (c,f,i,l) for 4 locations (as in Figure 2 and Table 1) over a two-year period. The white area's in (c,f,i,l) represent the area's without liquid water. The integers at the horizontal axis represent January.

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4 Results and Discussion Cross-section

In this section a transect from the middle of south Greenland to the east coast (Figure 2 and Table 1) will be analysed to describe the dependency between the climate forcing (Table 1) and the temperature and amount of liquid water of the firn layer (Figure 5 and 6 respectively).

At locations close to the coast (G154_086 - G159_086), a high accumulation rate is found together with relative high averages annual temperatures and a medium to relatively high annual melt rate (Table 1). Moving away from the coast, year averaged temperatures get lower just as the accumulation and melt rates.

The modelled firn temperatures along the transect are displayed in Figure 5. This figure shows high temperatures at the coast (G154_086-G159_086) and lower temperatures further inland, just like in Table 1. In the winter, low temperatures can be found at the surface and higher temperatures are deeper in the firn layer. This is due to the low temperature forcing and the small conductivity of the firn. In the spring the surface temperature rises due to a raising temperature forcing. Isolating some colder firn between the warmer surface and the deeper firn layer. In the summer, there are high surface temperatures (high temperature forcing) and the colder area of firn is almost disappeared in the figure. In the autumn the atmospheric temperature forcing and therefor the surface temperature decreases again. Resulting in an inclusion of higher temperatures deeper in the firn layer.

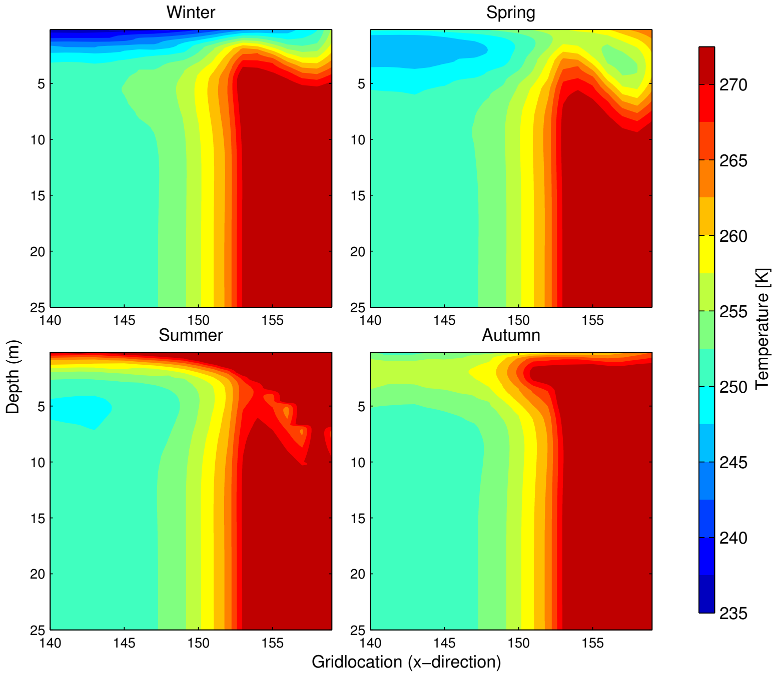

Figure 5: Two dimensional temperature profiles, for al four seasons, along the cross-section as displayed in Figure 2 and listed in Table 1.

Comparing the firn temperatures (Figure 5) with the amount of liquid water in the firn layer (Figure 6), shows that liquid water can only be found at places in the firn layer where the temperature is higher than 270 K. This is due to the fact that energy is needed to freeze the liquid water in the firn layer. When a temperature of 273 K is reached this refreezing energy is all used and the water will remain as a liquid in the firn layer. Resulting in a aquifer, as shown for locations G154_086 to G159_086 (Figure 6).

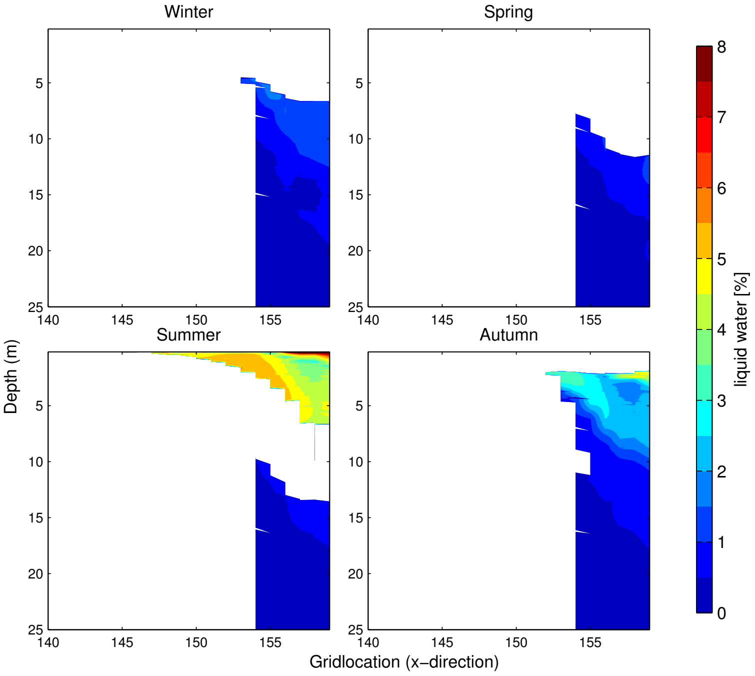

Figure 6: Two dimensional liquid water content profiles, for al four seasons, along the cross-section as displayed in Figure 2 and listed in Table 1.

5 Conclusions

Firn aquifers can exist at different kinds of places. One thing we surely need for firn aquifers to exist is a summer temperature above 0°C, ensuring enough melt can occur. Next to this requirement we also need a relatively high winter temperature, both summer and winter temperature have to be low enough to ensure that the firn layer remains through the year. This is the case in location G140_040. Another possibility for a aquifer to exist is at a location with relatively high summer temperatures as with the last option. Combined which a high accumulation rate isolating the liquid water from the winter temperature influence, this is the case in location G158_086. As the cold from the winter temperature forcing at this location penetrates till a depth of about 13 meters, it doesn't reach all the liquid water, resulting in a aquifer under this depth.

Another thing to conclude is that liquid water can only be found at locations where the temperature is at the melting point (0°C), for all the freezing energy is used at these locations. Thus knowing if the firn layer contains liquid water can give a better idea of the firn layer temperature. And as aquifers can be identified using a ground penetrating radar or airborne radar, there is a chance that this technic could be used, along with good atmospheric climate models (like RACMO2), to estimate the temperature distribution of the firn layer. Giving us a way to validate the present firn models while needing to drill less boreholes.

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