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formation of subsurface ice layers
in the RACMO snow model of Greenland's ice sheet

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abstract:
Machguth et al, 2016 [2] showed that the capacity of the Firn in Greenland to retain meltwater is lower than previously assumed, due to the formation of thick ice layers that prevent the meltwater to percolate to underlying firn. Hence, to accurately estimate the amount of runoff water in models, the process of the formation of ice layers and their influence on the water percolation should be implemented. In this thesis we explored on how to improve the snow model used by RACMO (Regional Atmospheric Climate Model) by implementing and testing radiation penetration, capillary diffusion and free water percolation, and qualitatively analysing the resulting density plots and the impact on the mass balance. Although no quantitative measurements on how well the model approximates reality were done, we can safely say that the effects of these processes can have a significant influence on the structure of Greenland's firn and snow, and on the surface mass balance of Greenland's ice sheet. This means that more research is needed on how to accurately model the snow, firn and underlying ice sheet, if one wants to make predictions on a larger scale concerning the surface mass balance or sea level rise.

Contents

1 Introduction

It is well known that snow can retain a significant amount of water, and it was assumed that most of the Greenlands firn and snow would function as a buffer for meltwater, before it would attribute to runoff. This would mean that the ice sheet's mass loss would be much less considering the refreezing of the meltwater in the porous space in the firn. *van den Broeke et al, 2009*[1]

However, extensive measurements by *Machguth et al*, showed that the abnormal warm summers of 2010 and 2012 significantly altered the density structure of the firn, causing it to lose most of its ability to retain meltwater. More specifically, the formation of near-surface ice layers in the firn forces the meltwater to undergo an efficient discharge mechanism, and hence the retaining capacity of the porous space in underlying layers will not be available for the meltwater. This implies that we can not simply assume that all of the Greenlands firn can be used as a buffer for meltwater before it runs off, and the ice sheet's mass will decrease at a faster rate.

In this thesis we will show the results of a qualitative research of the formation of these near-surface ice layers using an one dimensional model that uses racmo weather reports to simulate the characteristics of the snow and underlying firn of the Greenland's ice sheet. Note that the focus of this research is not on prediction of the future of the ice sheet but rather the investigation of the development of an accurate model. More specifically, the effect of the implementation of certain thermodynamic and mechanical processes that are important for the formation of near surface ice sheets in the snow and firn is explored.

2 Background

2.1 The model

RACMO was first constructed in 1990 by the Danish Meteorological Institute and KNMI based on the HIRLAM (High resolution Limited Area Model) weather prediction model. RACMO2 combined the dynamic core of HIRLAM with the atmospheric physics module from ECMWF-IFS (European Centre for Medium-range Weather Forecasts Integrated Forecast System). To make RACMO more suitable for extreme conditions over glacier surfaces, the IMAU department of Utrecht University made a polar version of RACMO2. This version is based on an interactive coupling between the atmospheric model and a snow model. The snow model is a one dimensional bucket model that simulates the properties of snow and firn such as water percolation, snow grain size, water refreezing and runoff, and the interaction with the atmospheric. (*Brice Noël et al, 2015*) [7]

The model consists of homogeneous layers each spanning a certain depth. The thickness of the layers gets bigger as the layers gets deeper, because in reality the snow near the surface experiences the most change and is the most heterogeneous. In order to improve and test new implementations, the snow model was taken apart from RACMO2 by IMAU, referred to as the offline version, in which atmospheric data from RACMO is used to account for the interaction between the snow and the atmosphere. The research described in this thesis is all done with this offline version of the snow model.

The snow model is a multi-layered model storing data of each layer for each timestep following a chosen time interval (note that the duration of a step in the calculations of the model is smaller than the duration of the time steps in the output data). To keep the model balanced layers can fuse and split.

In the offline model we noticed the formation of an ice crust on the surface forms during the melt season. This problem is probably caused by the bucket method: Only if the water in a layer exceeds the maximum capacity of this layer, the exceeding fraction will percolates to the underlying layer. When this melted snow will refreeze an icy layer with high density will be formed at the surface. Another cause might be the approximation used that all the atmospheric radiation is absorbed in the infinitesimal skin layer of the model.

2.2 The implemented processes

In this thesis we will quantitatively evaluate the impact of the implementation of different configurations of approximations of three processes in the model. These processes are the atmospheric radiation penetration, capillary diffusion of water, and the percolation of water through the snow and firn.

2.2.1 Radiation penetration

In the model the incoming radiation was initially implemented as added heat to the infinitesimal skin layer, taking the albedo in consideration. In reality the radiation penetrates the snow following an exponential decay function dependent on the wavelength, with the constraint of the snow being homogeneous. For simplicity reasons the wavelength dependency is not implemented in the model for now. Instead the atmospheric radiation was split in short and long wave radiation, and only the short wave radiation is implemented in the penetration process. To deal with the heterogeneous nature of the snow, the effective thickness of each layer, the thickness multiplied by the density divided by the density of ice, the maximum density in Greenlands firn, is used instead of the actual thickness, ignoring other properties of the snow that are heterogenous. The amount of heat that is added to a layer *i* due to radiation absorption can now be calculated by subtracting the amount of radiation at the the bottom of the layer from the amount of radiation at the top of the layer:

$$\Delta Q_i = R_i - R_i e^{-D_i^{eff}/\delta^{eff}} , \tag{1}$$

where ΔQ_i (J) is the added heat to layer *i* in one time step, R_i the radiation energy before penetrating layer *i*, D_i^{eff} (m) the effective thickness of layer *i* and δ^{eff} (m) the effective penetration depth, the parameter of interest. that The radiation that enters the underlying layer now becomes:

$$R_{i+1} = R_i e^{-D_i^{eff}/\delta^{eff}} . \tag{2}$$

2.2.2 Capillary diffusion

When snow contains water, it exerts an capillary pressure on its environment. If two layers with different capillary pressures are in contact, water will be pushed to the layer with the lowest pressure. This is called capillary diffusion. The amount of water that flows between two layers with index i and i+1 in one time step can be approximated with the equation

$$J_{i\to i+1} = \Gamma \, \frac{K_i^{sat}+K_{i+1}^{sat}}{2} \, \frac{(\rho_{i+1}^{l,m}+\rho_i^{l,m})}{D_i+D_{i+1}} (S_{i+1} - S_i), \tag{3}$$

where $J_{i\to i+1}$ (kg/(m^2 s)) is the water flux from layer *i* to layer *i*+1, Γ a dimensionless constant in the order of 10^1, K_i^{sat} (m^2 /s) the water permeability, $\rho_i^{l,m}$ (kg/m^3) is the maximum water density, D_i the thickness and S_i the dimensionless saturation of layer i (*W.J. van den Berg, 2017*[3]).

The water displacement from layer *i* to layer *i*+1 in one timestep of the model can now by calculated with

$$\Delta W_{i \to i+1} = (J_{i \to i+1}) \Delta t, \tag{4}$$

where $\Delta W_{i \to i+1}$ (kg/m^2) is the water displacement in one timestep , and Δt (s) is the duration of one timestep.

2.2.3 Water percolation

Another force on the water in the firm is gravity, causing the water to percolates downwards. Originally this is implemented in the model with the bucket method. With the bucket method water only percolates to the next layer if the capacity is exceeded, and all of the exceeding water percolates instantaneously, which are two unrealistic approximation. The percolation of water is a constant process, and takes place way before the capacity is exceeded. In a more realistic approximation we limited the rate at which the exceeding water percolates, in another approximation the water percolation prevented by the constraint that the capacity of a layer should be exceeded. The big question is, how fast does water percolates through snow or firn?

Because all possible characteristics of snow determine the percolation speed, approximations need to be made. *Richard Kittelmann, 1987*[4] made an overview of results of more than a dozen researches on water speed through snow, varying from 0.03 to 1.8 m/hour, and even 36 m/hour in old snow is reported. All of these researches are done on somewhat homogeneous snow and none relate a property of snow like density to the percolation speed. *R.A Summerfield and J.E. Rocchio, 1993* [5] found a relation between the permeability of snow for water and the density of the snow:

$$K = 1.096 \times 10^{-8} e^{-9.57\rho} . \tag{5}$$

A relation between the percolation speed, the permeability and the saturation is obtained by *S.C. Colbeck and Gail Davidson in 1972*[6], namely

$$J_i = \alpha K S_i^n , \tag{6}$$

where J_i is the percolation speed in layer i, α a scalar factor, and n an power factor which they found to between 2.8 and 4. If we combine the exponential relation between density and permeability of eq. 5 with the linear relation between permeability and percolation speed of eq. 6, an exponential relation between the density and the percolation speed is found. This relation can be broken down to the exponential factor and a scalar factor. To limit the domain of our research the exponential factor will be kept fixed and the scalar factor becomes the parameter of interest. The domain of this parameter is chosen so that the resulting percolation speed in a density of 300 kg/m^3 (dry snow) is in the same order of magnitude as the results presented by *Kittelmann*.

2.2.4 Runoff

Because it is a 2-dimensional model in the vertical direction, and water runoff is the amount of water that flows horizontally away from a site, a rather rough approximation is implemented in the model. Every time water percolates a fixed part of this water becomes runoff and no longer participates in the processes in the model.

3 Method

For each combined configuration of these three processes, the model gives its own set of resulting data. In the results the dataset of each configuration is visualized and analyzed, by looking at the behaviour of the process through the course of time, and by looking at its resulting impact on the SMB.

To examine the behaviour, depth-time profiles of certain quantities are made for each configuration. Specifically, the formation of ice layers is visualized in the density profile, the movement of water in the water density profiles, and the conduction of heat in the temperature profiles. To give the analysis of the configurations more focus, the profiles are made of the summer of 2012, a particularly warm one. This summer is chosen because it can be compared with the density measurements done by *Machguth et al* in may 2013, among other years.

To examine the effect of the different settings of the approximations on a larger time scale, the summed values of melt, refrozen water and water runoff over a time period of 5 years of each configuration are plotted in SMB plots.

In the results the effective penetration depth of 1 mm, 5 mm and 2 cm will be evaluated.

The capillary diffusion is explored by setting the scalar factor Γ to 1, 5 and 20.

The gravitational percolation is tested by toggling the constraint that the water in a layer must exceeds the capacity before percolation, by varying the speed of percolation in 300 kg/m^3 snow, by setting the speed to 2 m/day, 5 m/day and 10 m/day, by adding the saturation dependency S^3, and by adding a factor 10 to compensate for the S^3 factor.

The runoff is either turned off completely or 0.01% of the percolating water becomes runoff.

Also a combination of settings of these three processes is tested. For an overview of all configurations explored by the model see the table [figure 1] on the next page:

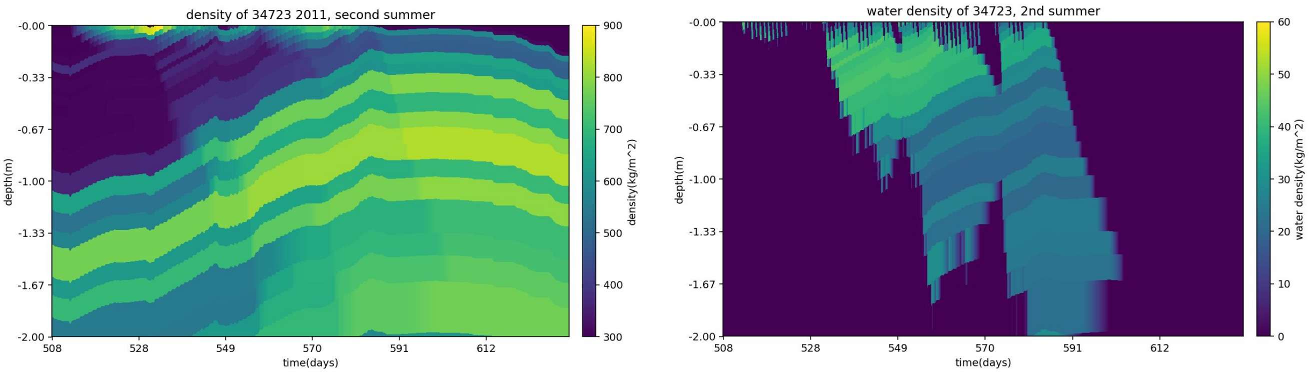
configuration	radiation	capillary diffusion	percolation
a	all absorbed at skin layer	none	bucket method
b	$\delta^{eff} = 1\ mm$	none	bucket method
	$\delta^{eff} = 5\ mm$	none	bucket method
	$\delta^{eff} = 2\ cm$	none	bucket method
c	all absorbed at skin layer	$\Gamma = 1$	bucket method
	all absorbed at skin layer	$\Gamma = 5$	bucket method
	all absorbed at skin layer	$\Gamma = 20$	bucket method
d	all absorbed at skin layer	none	- must exceed capacity - 1 m/day - 0.1% runoff
	all absorbed at skin layer	none	- must exceed capacity - 5 m/day - 0.1% runoff
	all absorbed at skin layer	none	- must exceed capacity - 10 m/day - 0.1% runoff
e	all absorbed at skin layer	none	- free percolation - 10 m/day - 0.1% runoff
	all absorbed at skin layer	none	- free percolation - 5 m/day - 0.1% runoff
	all absorbed at skin layer	none	- free percolation - 1 m/day - 0.1% runoff
f	all absorbed at skin layer	none	- free percolation - 1 m/day - 0.1% runoff - speed multiplied by S
	all absorbed at skin layer	none	- free percolation - 5 m/day - 0.1% runoff - speed multiplied by S
h	$\delta^{eff} = 5\ mm$	none	- free percolation - 10 m/day - 0.1% runoff - S^3*10
i	all absorbed at skin layer	none	- free percolation - 10 m/day - 0.0% runoff - S^3*10

figure 1: table with all the tested configurations. Note 1: the percolation speed is the speed at a density of 300 kg/m^3. Note 2: when the configuration is saturation dependent the speed is first scaled to 300 kg/m^3 before the saturation factor is added, so the given speed is now representing 300 kg/m^3 snow which is also fully saturated (S=1). Note 3: because it is a 1 dimensional model horizontally flowing water cannot be simulated, and hence runoff is approximated by taking a percentage everytime water percolates.

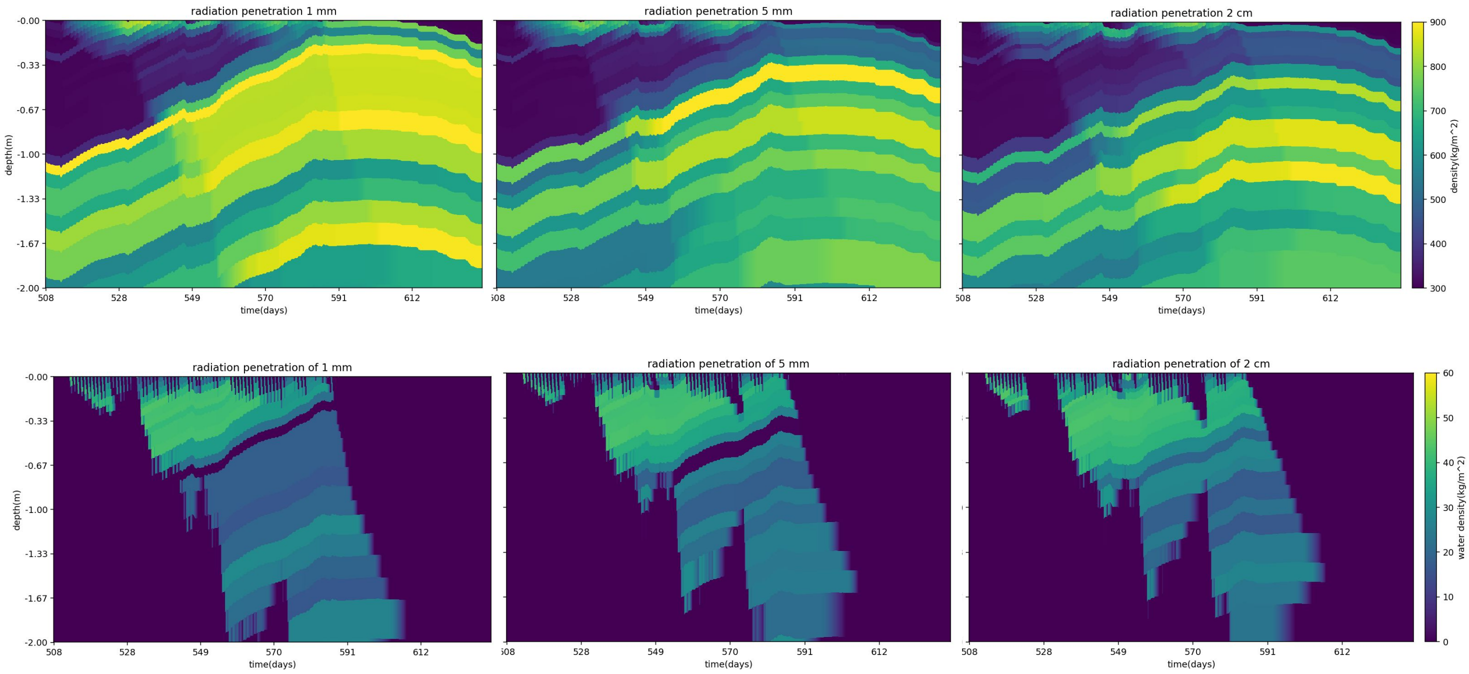
4 Results

4.1 Density plots and mass balance

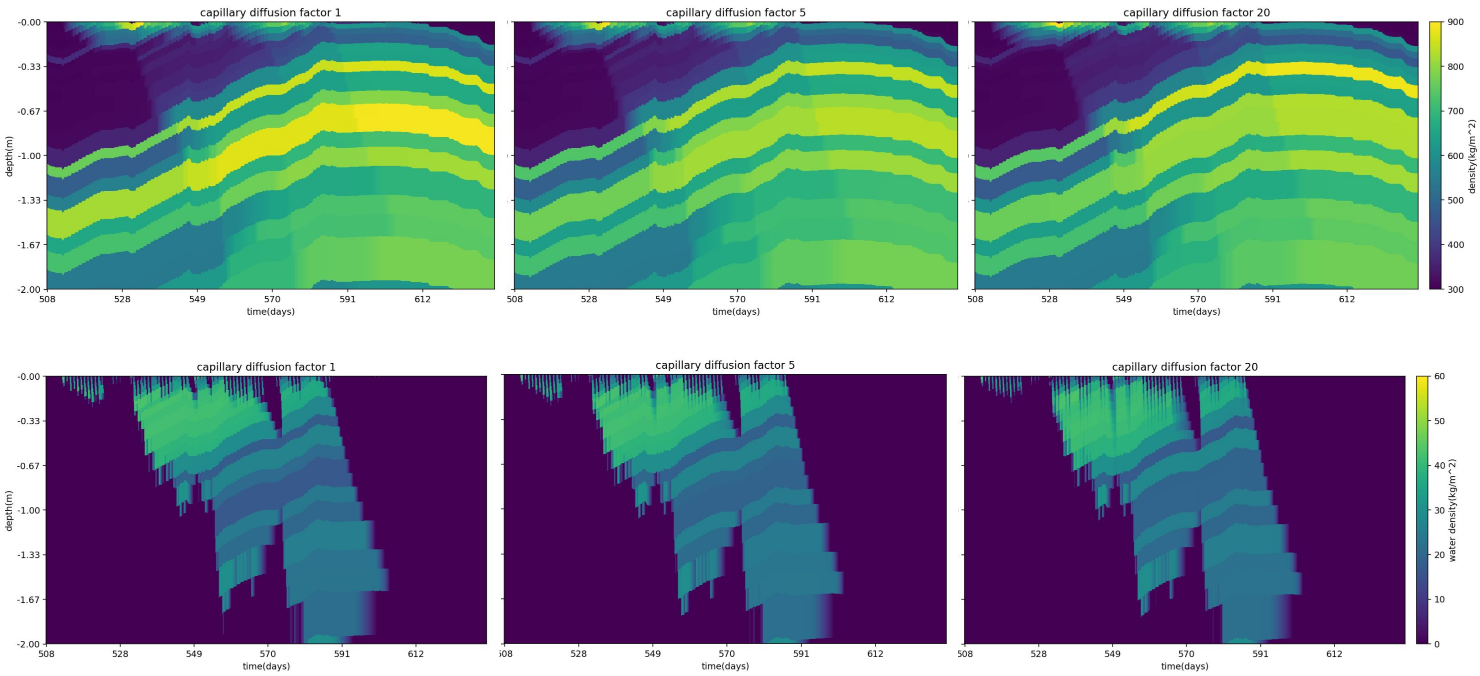
The results of each configuration is shown below [figure 2] with an density and a water density profile of the first two meters over a time period of 124 days which span the time period from May 23 till september 24 of 2012, starting the model in 2011. In figure 2 g the impact of these configurations on the mass balance is shown.



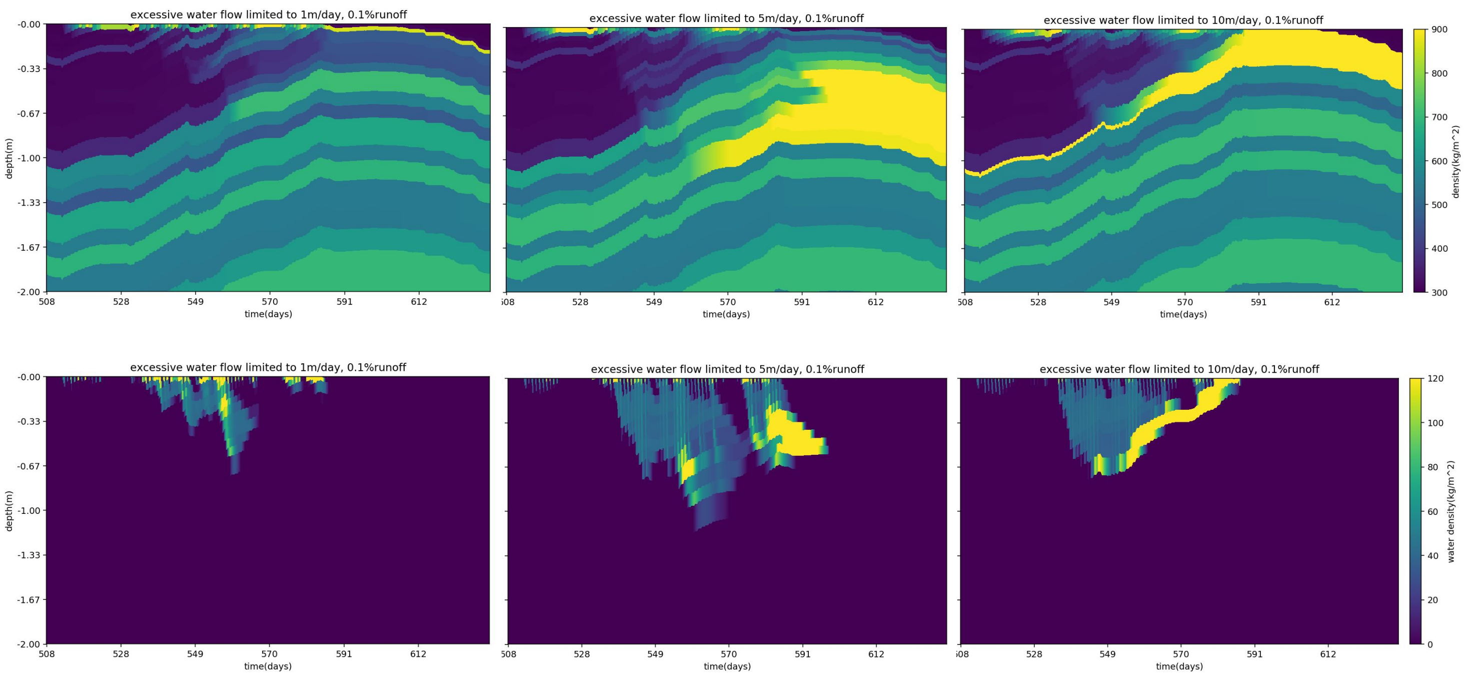
(a) There is no radiation penetration and no capillary diffusion, the bucket method is used for percolation.



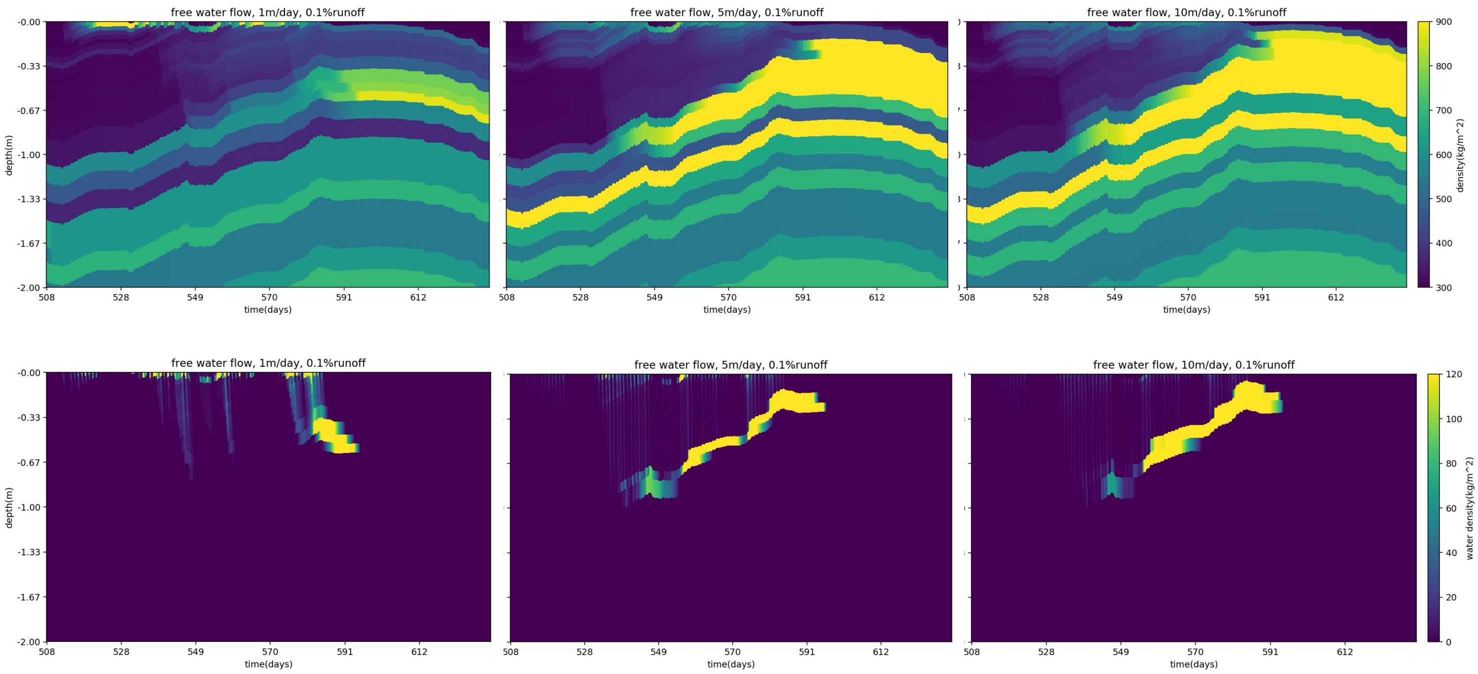
(b) Radiation penetration depth set to 1, 5 and 20 mm. There is no capillary diffusion and the bucket method is used for percolation.



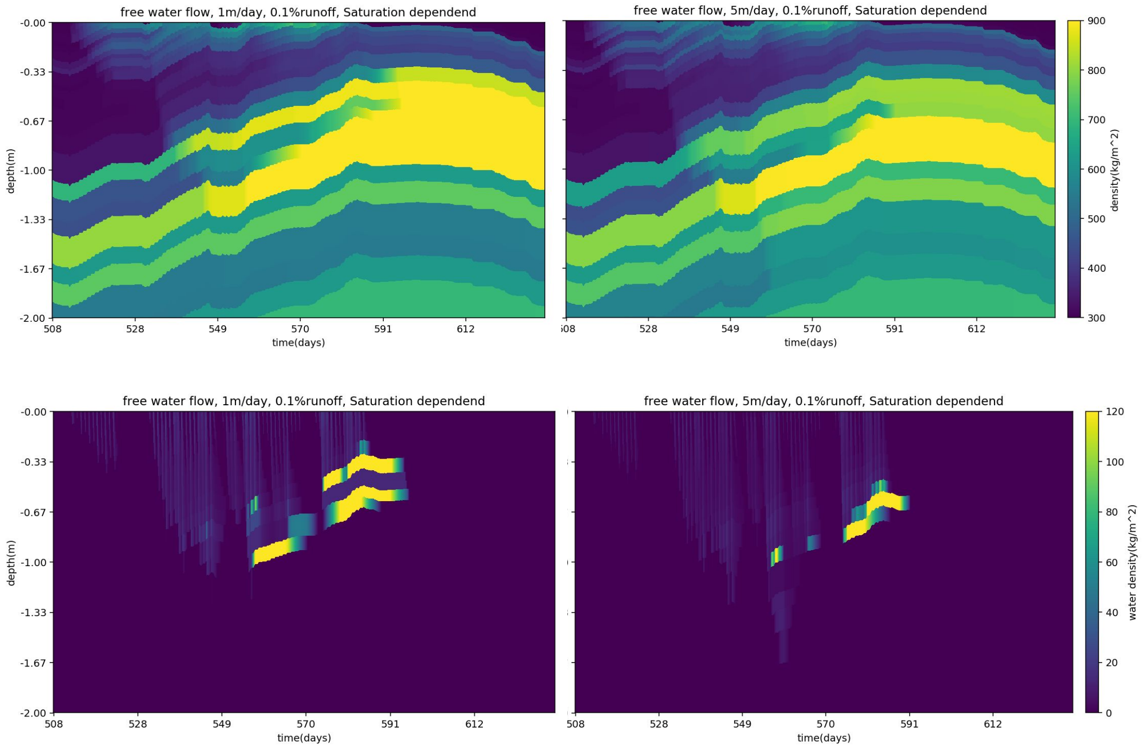
(c)There is no radiation penetration, a capillary diffusion factor of 1, 5 and 20 is used. The bucket method is used for percolation.



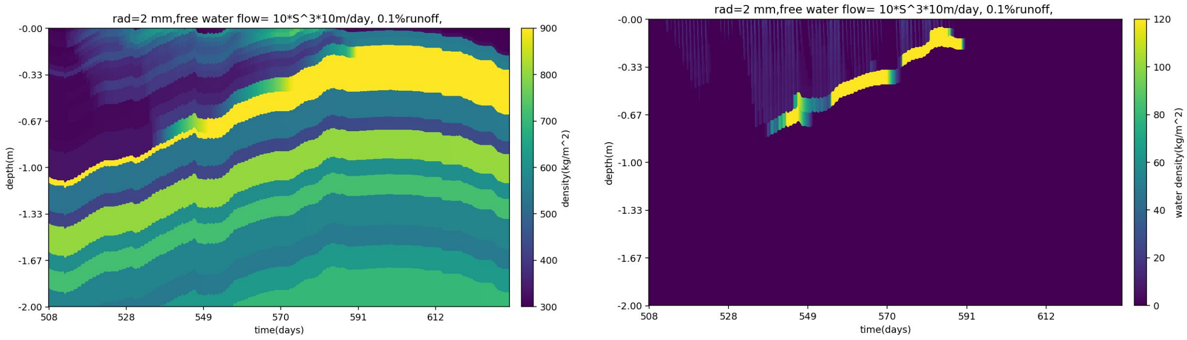
(d) There is no radiation penetration and capillary diffusion, the excessive water percolation speed is limited to 1, 5, and 10 m/day, with 0.01% runoff.



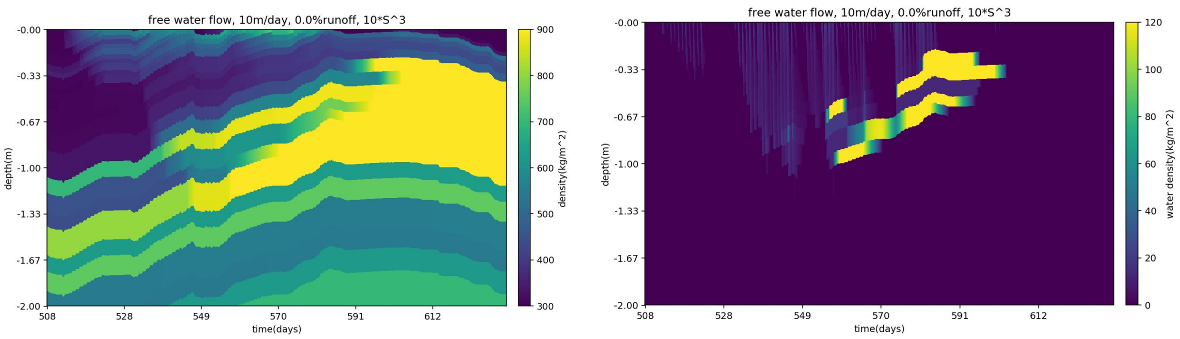
(e) There is no radiation penetration and capillary diffusion, the percolation speed is limited to 1, 5 and 10 m/day, with 0.01% runoff.



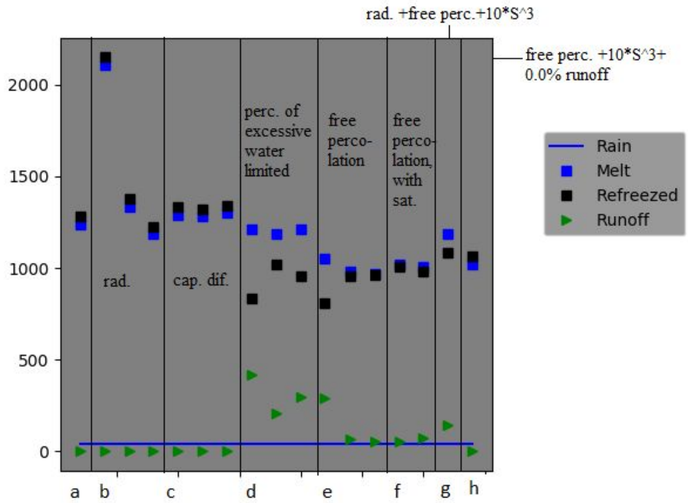
(f)There is no radiation penetration and capillary diffusion, the percolation speed is limited by 1 and 5 m/day and is linearly dependent on the saturation



(g) An effective radiation penetration depth of 2 mm is combined with a percolation speed of 10 m/day, multiplied by a $10*S^3$.



(h) No radiation penetration, no capillary diffusion, and the percolation speed is set to 10m/day multiplied by $10*S^3$, with 0.0% runoff



(i) effect on the mass balance of each configuration after 5 years in terms of rain, melt , refreezed water and runoff

figure 2: In a to h density and water density plots of all the tested configurations of the summer of 2012 are shown. In i the impact of these configurations on the mass balance after 5 years is shown.

4.2 Observations

When there is no radiation penetration and capillary diffusion using the bucket method [fig 2: a], some ice is formed at the surface around day 528. This is important because it would be more realistic if the meltwater was percolated in the snow before it would refreeze at the surface. It can be seen that the bucket method is working because the water percolates downwards, although the percolation is not restricted by dens ice layers. We will compare these density profile with the results of the other configurations.

4.2.1 Radiation

When the penetration depth of the radiation is set to 1 mm, the overall density in the first 2 meter is higher. This is caused by a increase in melt [figure 2: g], due to the fact that the skin layer exchanges less energy with the atmosphere through longwave radiation, and the albedo increases because of surface refreezing.

When increasing the penetration depth to 5 mm or 2 cm, the melt drops again and the density profile looks more similar to the profile of no penetration. This can be explained by the fact that the heat is more distributed and hence there are less layers where the temperature drops sub-zero. In the water profiles of 1 mm and 5 mm a dry layer of respectively ~6 cm and~10 cm is visible, caused by an ice layer which is unable to retain water. For these configurations this ice layer was formed before the summer of 2012. This is not the case for no penetration and 2 cm penetration. Because there is no density dependent water percolation, this ice layer does not decreases the percolation to deeper layers. Because of the larger amount of melt for 1 mm penetration, it has the highest water density at 2 m depth.

Another observation is the increased density of the layers below the winter snow.

Because runoff is not implemented in the model all the melted water refreezes at some point, as can be seen in figure 2: i.

4.2.2 Capillary diffusion:

The implementation of capillary diffusion seem to have little influence compared to all the other configurations we tested. The similarity can be seen in the density profile, the water density profile and the mass balance, while one could have expected the water to percolate deeper due to the diffusion.

4.3 Water percolation

When tuning the way the water percolates through the snow and firn a much clearer impact is visual. The biggest difference when implementing density dependence percolation can be seen in the water density plots. In figure 2: a,b c and d (using the bucket method) the water density is always below 50 kg/m^3 and it reaches layers below the more ice layers. In figure 2:e, f, g and h the water is slowed down by more dense layers and gets stuck entirely on the first ice layer, no matter how thin. If this is more or less realistic will be discussed in section 5.

4.3.1 Exceeded water percolation limited via density dependence

First the percolation was limited to 1 m per day in dry snow. With no diffusion and almost no percolation, and with no radiation penetration most of the melt happens on the surface and only a small part of the meltwater escapes the surface. This is clearly visible in the density profile where a thin ice layer is formed on the surface, with not enough percolation to form deeper ice layers, as can be seen in the water profile.

Increasing the percolation to 5 m per day, most of the surface melt water percolates until it reaches the layers with densities higher than 600 kg/m^3. Because the percolation is density dependent, the water refreezes and an ice layer of ~60 cm is formed. This process is clearly visible in the water density profile, where most of the water is stored in this region of high density until it refreezes. Still an ice layer is formed at the surface because of the constraint that the water capacity has to be exceeded before percolation.

When the percolation is increased to 10 m per day, there already is an ice layer from previous summer at a depth of ~1 m. The meltwater percolates faster to this layer where the percolation stops completely even though the ice layer is only 5 cm thick, and the water on top of this ice layer refreezes, making the ice layer thicker, until it reaches the surface. The layers underneath this ice layer remain its density.

In the mass balance plot the melt doesn't change much, but due to the implementation of 0.01% runoff there is a fraction of the melt water that doesn't refreezes. This fraction is the highest when the percolation speed is the lowest, which is unexpected because the runoff is a percentage of the percolation.

In the next configuration the constraint of the bucket method is removed so that the water can percolate freely long before the capacity is exceeded. Because the percolation is dependent on the density, no water percolates deeper than the ice layer from the previous summer, and most of the water not even deeper than the layer with density of ~600 kg/m^3, as one can see in the water density profile. Here an ice layer of ~40 cm is formed. Except for when the percolation speed is set to 1 m/day, there is no surface ice layer anymore.

When the saturation dependency is added the water seems to percolate easier through denser layers, because denser layers saturate faster. At the first configuration with the speed set to 1m/day, two ice layers with lower density layers in between becomes one ice layer after enough water reaches these layers and refreezes. Without the saturation dependency the water would refreeze on top of the first ice layer.

5 Conclusions and discussion

The results show us that the implementation of density dependent water percolation will ensures the formation of subsurface ice layers, unlike with the bucket method from RACMO2.3.2. If the ice layers get thick enough, they can transform a percolation region into an runoff region by forcing the water to flow horizontally when it cannot percolate through the ice layer according to *Machguth et al.* The results show us that layers beneath these ice layers are not reached by percolation water and hence remain their density. We should take in consideration that this is an one dimensional model where the runoff is merely approximated by a percentage of the percolating water and holes in ice layers that allow water to percolate through ice are not implemented. This causes the thinnest ice layers to prevent water to percolate to deeper layers, which is unrealistic. Still it proves the necessity of accurate approximations of the formation of ice layers and water percolation, when one's intentions are to make mass balance predictions, because the alteration of the structure of Greenland's firn due to these processes have a significant impact on the amount of runoff.

As one might have noticed was the effective penetration depth of the solar radiation rather small, when taken in consideration that below a thick pack of snow during day time there is plenty of light. Still, the amount of radiation that is absorbed decays faster, because it is a net result of the constant scattering of the radiation in all directions. Thats is why the penetration depth used in our approximation is not the same as the distance the radiation reaches through snow. However, one could reason that if a black plate is placed underneath a layer of 1m snow, this plate would absorb a lot of radiation, while this would not be the case in our model. Now lets say this black plate is a layer of old, dense snow filled with water, with a low albedo compared to fresh snow. To accurately handle these situations research on how radiation behaves in all kinds of conditions of snow is needed.

Other research that could be done to improve the model is an extensive lab research on the percolation speed and capillary diffusion of water trough snow in a large variety of combinations of saturation, density, grain size, and approximate ways to handle 3-dimensional processes in the 1-dimensional model, such as holes in ice layers and runoff, as reseasoned in the first paragraph of this section. It would be even better to build a 2-dimensional model, so these processes can actually be implemented instead of estimations of the effects of these processes.

6 References

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