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Modelling albedo in the ablation zone of the Greenland ice sheet

Abstract

An ice sheet always experiences more or less melting during the summer. How much melting that occurs is mostly determined by the albedo. Albedo is defined as the amount of the incoming shortwave radiation that gets reflected by a surface. When the sunlight starts melting the ice and snow in the summer, the albedo gets lower. The lower albedo itself causes more absorption of radiation, which makes the melting increase even more. Measuring the albedo on an ice sheet can be tricky. Therefore, a climate model is often used.

In this study the albedo parameterization for the ablation zone of the Greenland ice sheet in the model HIRHAM5 was improved, by using equations by Essery and Oerlemans & Knap. From the beginning the albedo in the model only depended on the temperature. Things like precipitation and snowmelt were included in the new model. The parameters for the albedo were investigated to get as good results as possible. The new model showed sharper and more detailed results than the original, which were smoother. The results collaborate well with the usual weather phenomena in Greenland, and should therefore be possible to use for studies of the relationship between the albedo and the melting.

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1. Introduction

The Greenland ice sheet is getting thinner and thinner and is losing mass at an accelerated rate [1]. Melting ice in Greenland corresponds to a sea level rise all around the world, but especially in the southern hemisphere [2]. Therefore, it is important that the parameters that affect the melting are studied so the system can be understood better.

The melting of an ice sheet depends on the amount of radiation absorbed by it. By looking at the albedo, which describes how much of the incoming radiation that is absorbed, studies on the melting can be done. In the snow-covered areas of the Greenland ice sheet, the albedo is high and most of the sunlight is reflected. During summer, the melting causes bare ice areas to appear. These darker areas contribute to even more melting, since the albedo is lower and the ice sheet can absorb more radiation.

The aim of this project was to look at albedo in the ablation zone of the Greenland ice sheet in the model HIRHAM5. The goal was also to improve the model by implementing a new albedo parameterization for snow and bare ice. Moreover, a parameterization for underlying ice under a thin snow layer was implemented in the model. The values for these parameters were determined in a sensitivity test, and the result was compared with a study by Abdalati and Steffen (2001).

2. Background

2.1 Ice sheets

The Greenland ice sheet is the largest ice sheet in the Northern hemisphere [3]. An ice sheet can be seen as a large mass that stores water [3]. It contains 10 percent of the Earth's fresh water and has an area of 1 736 000 km^2 [3]. If all of the Greenland ice sheet would melt, and the melt water was spread out evenly across the oceans, it would cause a sea level rise of 6.5 meters [3]. In the cold, dark winters in Greenland, the snow covered glacier is growing. During the summer the sunlight starts to melt the snow and large areas of bare ice appear. The change in mass is described by the mass balance. The glacier gains mass by getting snow and ice from precipitation or avalanching, also called accumulation [3]. When the ice melts, evaporate or breaks from the ice sheet, mass is lost [3]. This mass loss is called ablation [3]. The melt water peculates through the ice sheet, and can either run off or refreeze. How much of the water that refreezes is determined by how much water the ice sheet can take in. The mass balance of an ice sheet is the sum of the accumulation, ablation and calving [4]. In this project the calving was neglected from the mass balance, since only the ice sheet on land was studied. Calving is a process where big parts of ice break from the ice sheet and drift away out in the ocean and therefore mostly affects the ice in the sea. The mass balance without calving gives the surface mass balance, SBM [4].

The system of a glacier is divided into two parts; see Figure 1 [3]. The part were the ice sheet gains mass is called the accumulation zone [3]. Here ice and snow are added to the system, and these inputs are greater than the losses from ablation [3]. The snow and ice from accumulation are transferred downhill until it is lost from the system [3]. This area where the loss is greater than the gain is called the ablation zone [3]. The two zones are separated by an equilibrium line, where the mass is constant [3]. The focus in this project is on the ablation zone of the Greenland ice sheet. In the summer the ablation zone mostly consists of bare ice.

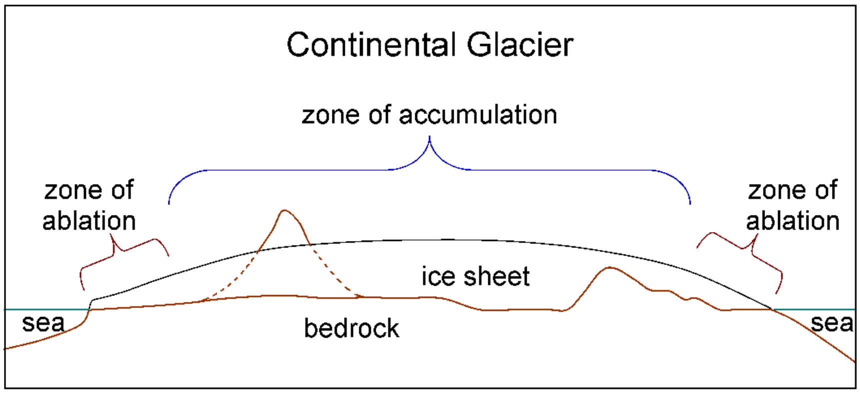

Figure 1. Description of the two zones of an ice sheet.
http://commons.wvc.edu/rdawes/G101OCL/Basics/glaciers.html

The SMB of an ice sheet can vary from year to year. It depends on the ablation and the accumulation, and therefore variability of the temperature [3]. Years with warm winters are associated with a positive phase of the North Atlantic Oscillation, NAO [3]. NAO is a large scale weather system that consists of a low pressure over Iceland and a high pressure over the Azores [5]. The low and high pressure varies over time. When the Icelandic Low is deep and the Azores High is strong, a cold winter is expected in Greenland [3]. This is the positive phase of NAO. A weak high or low pressure corresponds to a negative phase and a warm winter [3]. These variations in climate affect the Greenland ice sheet. A weak low pressure can also give summers with nice weather and clear skies, which increases the melting of the ice sheet [4]. There has also been an increase in temperature in Greenland since 1980 [3]. The temperature change gives a longer period with high temperatures, which causes longer melt periods [3].

In the summer of 2012, 97 percent of the surfaces of the Greenland ice sheet experienced melt [4]. This is very unusual, even though studies of the ice core show some traces of earlier events like this [6]. A way to study the Greenland ice sheet melt is to use microwave satellite data. This was done by Abdalati and Steffen (2001), who studied the annual summer mean melt for the period 1979-1999, see Appendix 1 [7]. They found that for the 21-year period there was a positive trend of 0.97% melting per year [7]. The summer of 1991 experienced a melting well above the average, while the summer of 1992 had a melting below average [7]. These years were used as a reference in this project, to see how well the model works.

The melting of glaciers causes a sea level rise in the oceans. Different glaciers contribute with a sea level rise in different regions [4]. When an ice sheet melts, it loses mass. This makes the gravitational field weaker, which causes a sea level sink around the ice sheet [8]. The glacier can no longer attract as much water as it did before. The melt water from the ice sheet will therefore affect other parts of the world instead, and the sea level rise will be extra-large due to the additional water from the sea level sink around the ice sheet. [8]. If the Greenland ice sheet melts, there would be a sea level rise in the southern hemisphere, and if the ice sheet of

Antarctic melts there would be a sea level rise in the northern hemisphere [4]. If the ice should be able to melt, there must be an energy source that increases the temperature. This energy mostly comes from absorbed sunlight [9]. The absorption is controlled by the albedo.

2.2 Albedo

Albedo is defined as the percent of the incoming radiation that is reflected by a surface [5]. It determines the amount of radiation that is absorbed. Absorption of short wave radiation is the most important factor that causes melting of the snow and ice [9]. A high albedo means less energy for the snow to melt [3]. Therefore, the albedo of a glacier can affect the amount of melt water and sea level rise in the oceans. Different surfaces have different albedos. Dark areas absorb a lot of radiation, and therefore have a low albedo.

In the accumulation zone of an ice sheet the albedo is very high, >0.75. The high albedo is due to the snow cover [8]. Snow has an albedo of approximately 0.85 [6]. The high reflection is caused by the shape of the snowflakes [6]. Newly fallen snow has a very edgy character. These edges reflect a lot of radiation, and therefore newly fallen snow has a very high albedo [6]. The fact that the snow is white and clean when it falls is also one of the reasons to the high reflectivity [6]. With time, the edges of the snowflakes get smoother, and the white snow gets darker due to dirt. These changes cause the albedo to sink [6]. When new snow falls the albedo gets higher again.

During the winter, the ablation zone is also covered in snow. In spring or early summer the snow begins to melt, and parts of the ablation zone is left with bare ice. In the bare ice areas the albedo is much lower than in snow areas, since ice is darker than snow [8]. This causes the glacier to absorb more radiation, and to melt faster. Melting snow contains more liquid than dry snow. Since water has a lower albedo than snow, the albedo for melting snow is less than for dry snow [6]. Dry snow therefore reflects more radiation than wet snow.

2.3 Energy balance

An ice sheet is constantly exchanging mass and energy with the environment [3]. The energy exchange between the ice sheet and the atmosphere can be described with a surface energy balance, see Equation 1 [3]. The balance can be affected by changes in the state of water and by temperature changes [3]. Temperature changes are driven by short and longwave radiation. Shortwave radiation from the sun can be absorbed or reflected by the glacier, S_{in} and S_{out}. Longwave radiation is added to the system from the atmosphere or the terrain that surrounds the glacier, L_{in} [3]. It is also emitted by the glacier itself, L_{out} [3].

When water changes state, energy is either absorbed or released. This transforming energy is called the latent heat, Q_L [5]. An energy transfer may also involve a temperature change. The temperature change is different depending on the substance involved, due to its specific heat capacity [3]. The specific heat capacity also determines how much heat the ice sheet exchanges with the surroundings, the sensible heat, Q_H [3].

Equation 1 gives the surface energy balance. When it does not equal zero, the ice sheet either melts or refreezes. This is described by Q_m.

$$Q_m = S_{in} - S_{out} + L_{in} - L_{out} + Q_H + Q_L \qquad (1)$$

The albedo is defined as a relationship between the incoming and reflected shortwave radiation [3].

$$\alpha = \frac{S_{out}}{S_{in}}$$

The net shortwave radiation for the surface energy balance can be seen in Equation 2, where α is the albedo.

$$S_{net} = S_{in}(1 - \alpha) \quad (2)$$

This can be put in equation 1.

$$Q_m = S_{in}(1 - \alpha) + L_{in} - L_{out} + Q_H + Q_L \qquad (3)$$

Equation 3 shows that the albedo and shortwave radiation are related to the melt of an ice sheet. A high albedo makes it difficult for the ice sheet to absorb energy, which gives a low melting rate. The relationship can be hard to measure, since clouds and the angle of the incoming light determine how much shortwave radiation that reaches the surface. Clouds block the sunlight and for the surface to get the highest amount of sunlight, the angle to the surface needs to be 90° [3]. Therefore, also the latitude and the time of the day matters [3].

3. Method

3.1 The model

Measurements on the albedo of an ice sheet are hard to do, and often contain a lot of errors due to the instruments [9]. Therefore, a numerical model is often used to study the albedo, together with a surface energy balance model [10]. The model used in this project is called HIRHAM5, and is a regional climate model, RCM [12]. It is built up by a general circulation model, ECHAM5, and a weather forecast model, HIRLAM7 [10]. HIRHAM5 combines the physics from ECHAM5 with the dynamic scheme from HIRLAM7 [11]. However, due to lack of measurements it is difficult to know how valid the results from the model are [12].

A climate or weather forecast model is looking at an area build up by squares, so called grids [11]. For each grid, a number of equations are calculated, which gives outputs of data [11]. Together these outputs for the different grids give data for the whole area, both for the surface and for the atmosphere [11]. The model contains many different parameters, and some of them have to be parameterized since they all should fit the resolution in the model. Parameterization is a process in which a small scale process is approximated over a larger area [11].

A model can have different resolutions, which described the size of the grids. HIRHAM5 has grids of 0.55°, which gives a high resolution. The high resolution is needed to model small changes properly. This is especially important in the ablation zone, which contains a lot of fjords [12]. A 0.55° resolution means that the grids are approximately 5.5 km broad, but it varies a bit depending on which part of Greenland that is being studied [11]. In northern Greenland the grids are expanded due to the fact that the earth is round, and the resolution for the grids is approximately 6 km [11]. In the south they are instead smaller. For this reason the equilibrium line for the grids, or the equator, is placed in the middle of Greenland to get as small variations as possible [11]. There are also 31 different levels up in the atmosphere included in the model [11]. The levels depend on the pressure, and may therefore vary in height [11].

To give outputs, the grids need to be feed by some initial conditions. This feed is called the reanalysis data, and comes from ERA-Interim [11]. ERA-Interim includes all available data there are, such as satellite data, ground observations and ship observations [11]. It contains information about for example the wind, temperature and relative humidity for the period covered. The data are given to the model, which makes it possible to model other things like the amount of melt from the ice sheet [11]. The outputs from HIRHAM5 are many, and since it has to be run by time steps of 90 seconds, it takes a long time to go through a decade or two. Therefore, it is convenient to run the model offline. The offline model takes out the things needed from HIRHAM5, and uses it to calculate fewer outputs [11]. It has time steps of 6 h, which comes from a mean over 6 hours from the 90 second time steps in HIRHAM5 [11].

In this project the offline model was used, and was only calculating the SMB for the Greenland ice sheet. This means that the focus was on the ice sheet, and the area around it was neglected. The model it is build up by a main code together with a number of subroutines.

The subroutines consist of different information that is used by the main code. It can be things like the albedo or the snow depth. Before running the code, a spin up must be made. A spin up is a way for the model to find an equilibrium to use as an initial value in the real run [6]. From the beginning the model is set on a snow depth of 2 meters over the whole ice sheet. This is not very realistic. For example does the south east of Greenland often experience snowfall, and therefore should have a thicker layer snow [6]. The north east on the other hand often has a very thin snow layer [6]. During the spin up, the model runs the same weather condition for one year several times. This gives more realistic conditions; see the difference between Figure 2 and 3.

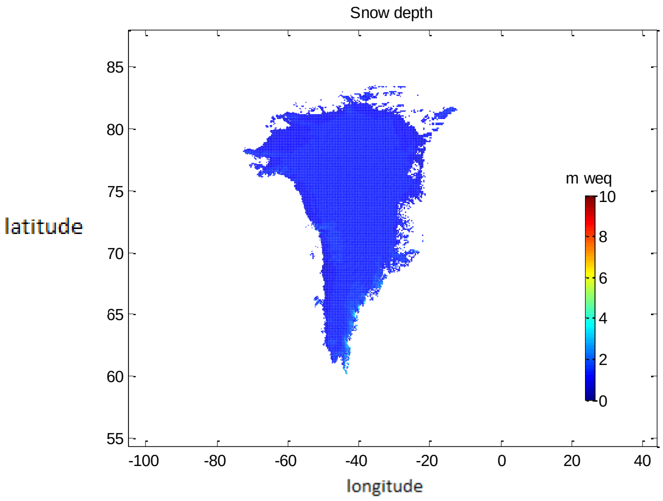

Figure 2. The monthly mean for the snow depth during June for the first run by the spin up

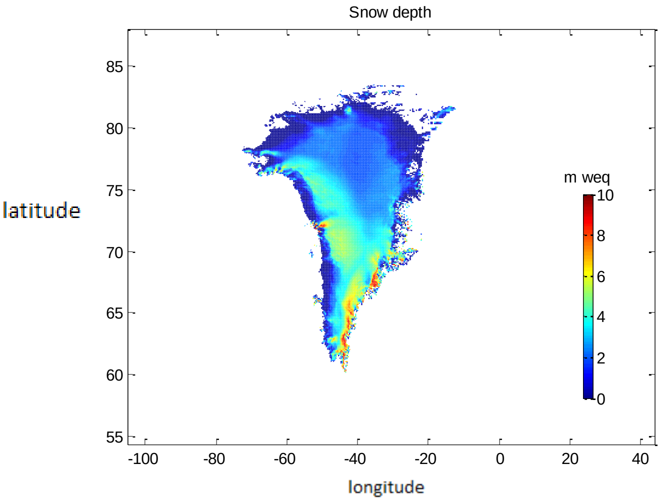

Figure 3. The monthly mean for the snow depth during June for the last run by the spin up.

The spin up is usually runs the same year 10 times, with the same weather conditions. This is enough to get good starting values. Figure 2 shows the monthly mean for the snow depth in June, during the first run by the spin up. The snow depth is evenly spread out over the ice sheet, which is not that realistic. Figure 3 shows the monthly mean for the snow depth in June during the 10th and last run by the spin up. The spin up has now found equilibrium for the snow depth that is more realistic than the values in Figure 2. The end value for the spin up is used as the starting value for the real run.

3.2 Modelling snow albedo

In the beginning with the original code, the model could only tell if it was snowing or not and the albedo was determined by the temperature. Therefore a new subroutine for snow albedo was made in an attempt to improve the model. When it comes to snow, there are several parameters that affect the albedo. When the snow is fresh, the snowflakes have an edgy shape. With time, the shape of the snowflakes changes and the edges get rounder. The snow then reflects less sunlight, which causes the albedo to sink. Mathematically, this change in albedo can be integrated in time steps of δt; see Equation 4.

$$\alpha_s(t+\delta t)=\alpha_s(t)-T_\alpha^{-1}\delta t \qquad (4)$$

This linear correlation was first introduces by Dickinson et al (1993) [13]. It is suggested as an albedo parameterization for dry snow in "*A comparison of 1701 snow models using observations from an alpine site*" by Richard Essery et al (2012) [14]. α_s is the snow albedo at the time t. T_α^{-1} is the decreasing of the albedo at the time step δt, and was treated as a constant in Essery et al with a value of 10^7 seconds.

When the temperature is rising, the snow begins to melt. Melting also causes the snowflakes to transform to a more softly shape. Moreover, the amount of water in the snow is increasing. Since water has a lower albedo than snow, the albedo for melting snow is less than for dry snow. To handle the melting mathematically, Essery et al suggest a different snow albedo parameterization; see Equation 5 [14].

$$\alpha_s(t+\delta t) = (\alpha_s(t) - \alpha_{min}) \exp(-T_m^{-1}\delta t) + \alpha_{min} \qquad (5)$$

For melting snow the albedo decreases exponentially byT_m^{-1}, and was just like T_α^{-1} treated like a constant in Essery et al [14]. The decrease of the albedo is described exponentially since the decrease in melting snow happens faster than in dry snow. α_{min} is the minimum albedo value for snow, which according to Essery et al is 0.5 [14].

If the albedo would be decreasing all the time, there would be no snow or ice left. Therefore there must be a factor that refreshes the albedo. This happens when new snow is added to the ice sheet. Equation 6 shows the equation for $\delta\alpha_s$, which represents the increase in albedo due to snowfall.

$$\delta\alpha_s = (\alpha_{max} - \alpha_s)\frac{S_f\delta t}{S_0} \qquad (6)$$

$S_f\delta t$ is the rate that describes how fast it is snowing. S_0 represents the amount of snow that is needed to refresh the albedo to its maximum value, α_{max}. S_0 was set to 10 kg/m^2 by Essery et al, and the maximum albedo to 0.85 [14]. The snowfall rate affects the increase in albedo. In the model a random number generator was used to give the experiment different scenarios.

3.3 Modelling bare ice albedo

In the summer when the amount of radiation from the sun increases, the snow melts away in the ablation zone, and is left with bare ice [3]. For this a different albedo parameterization is needed. From the beginning the model treated the bare is albedo as a constant, 0.65. This was also the lowest value for the snow albedo. Also the subroutine needed to use something else to get a better value for the albedo in the transition between the dry snow and the bare ice. From the beginning the albedo was just a decreasing linearly from $\alpha_{max} = 0.85$ to $\alpha_{min} = 0.65$ when the temperature got above -5 ˚C, see Figure 2. Instead a new subroutine based on the snow depth was made. When there is a thin layer of snow on top of the ice, the albedo gets lower due to the fact that the dark ice shines through, and absorbs more radiation than the snow itself would do.

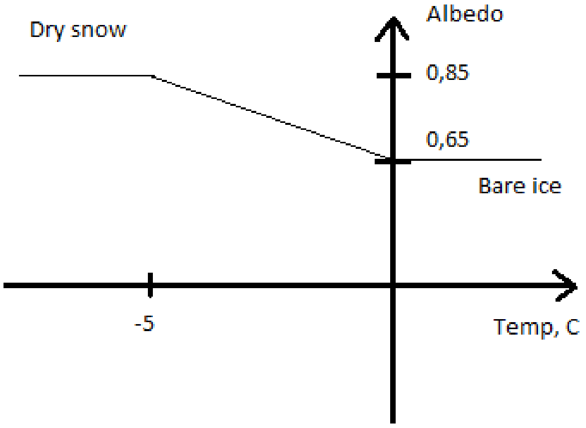

Figure 4. The theory behind the original snow albedo subroutine.

The idea in the new subroutine was first used by Oerlemans & Knap (1998), and is based on Equation 7 [15].

$$\alpha(t) = \alpha_{snow}(t) + \left(\alpha_{bi}(t) - \alpha_{snow}(t)\right) * \exp\left(-\frac{d}{d_1^*}\right) \qquad (7)$$

The albedo $\alpha(t)$ is here affected by the snow depth, d, and the characteristic snow depth, $d*_1$. Oerlemans & Knap (1998) set the value for $d*_1$ to 3.2 cm snow [15]. HIRHAM uses the unit water equivalent when it comes to snow. This means that the snow depth is represented by the amount of water in the snow per meter. Therefore, the value of d_1^* had to be transformed, see Equation 8.

$$d^* = d_1^* * \frac{\rho_{snow}}{\rho_{water}} \qquad (8)$$

This gives the characteristic snow depth in water equivalent meters, d^*. ρ_{snow} and ρ_{water} are the density for snow and water respectively. The snow albedo in Equation 5, $\alpha_{snow}(t)$, could be taken from the Essery equations. The value for bare ice albedo, $\alpha_{bi}(t)$, was set to 0.55 in the beginning.

3.5 Method

The project started with a learning period, to learn about the Greenland ice sheet, the model and Linux commands. To understand the model better, a spin up and a test run was made in the original code with maximum snow albedo 0.85 and the minimum snow albedo 0.65, see Figure 2. The bare ice albedo in this code was set as the same as the minimum snow albedo, 0.65. Since the model gives outputs from every day, a PPscript was used. The PPscript calculates means for every month and year.

The Essery equations were rewritten from IDL code to a MATLAB code. This part was done in cooperation with Johanna Eggeling, who was working on the same model looking at the albedo in the accumulation zone of the Greenland ice sheet. This was made to improve the knowledge on how the variables affect each other, and how it is modelled in the model. The code was then rewritten to fortran code and implemented as a subroutine in the model by Peter Lang Langen. To see how the different parameters affect the albedo, some adjustments were made in the model before every run. These adjustments are called a sensitivity test. According to Essery, the snow albedo parameters should have the values in Table 1 [14].

Table 1, Essery's values for the different parameters

Parameters	**Values**
T_α	10^7 s
T_m	3.6^5 s
$S0$	10 mm

First the parameters for the Essery code were investigated in MATLAB to see what happens when a parameter is changed. The parameters were then tested in the model in a run for ten days. When the values for the albedo looked good, the Essery code was ready to be used. This part was also made in cooperation with Johanna Eggeling.

Since the ablation zone transforms to a bare ice area during the summer, a bare ice albedo parameterization needed to be implemented in the code as well. This was done by Peter Lang Langen, who used the Oerlemans & Knap code. The Oerlemans & Knap code also includes the snow-depth, which is important when the snow layer is thin and the bare ice shines through it. The code now consisted of a snow albedo parameterization from the Essery equations and a bare ice albedo parameterization from Oerlemans and Knap.

When the code and the parameters were prepared, spin ups needed to be done to find good initial values for the actual runs. This was done both for the original code and the Essery and Oerlemans & Knap code. When the spin ups were done the runs were started. The values for the bare ice albedo were set to 0.45 and 0.55 in both the original code and the Essery and Oerlemans & Knap code. The Oerlemans & Knap code was also started with a bare ice albedo set to 0.65, just like the test run with the original code. These runs were made to be able to compare the results from the different parameterization codes. To observe the values from the runs, a MATLAB script was used. This was made by Peter Lang Langen. The runs were also compared with the study by Abdalati and Steffen.

4. Results

4.1 Snow albedo parameterization

The MATLAB code for the snow albedo from Essery is presented in Appendix 2. To see if the values were related as wanted they were all plotted against time, see Figure 5. Msn is the melting snow. When the temperature gets higher, the snow should start to melt and the albedo decrease. When it snows, the albedo should increase again. To see that the relationship between the shortwave radiation and albedo in Equation 2 is modelled correctly, they were also compared in plots, see Figure 6. F_{net} is the net shortwave radiation on the ice sheet.

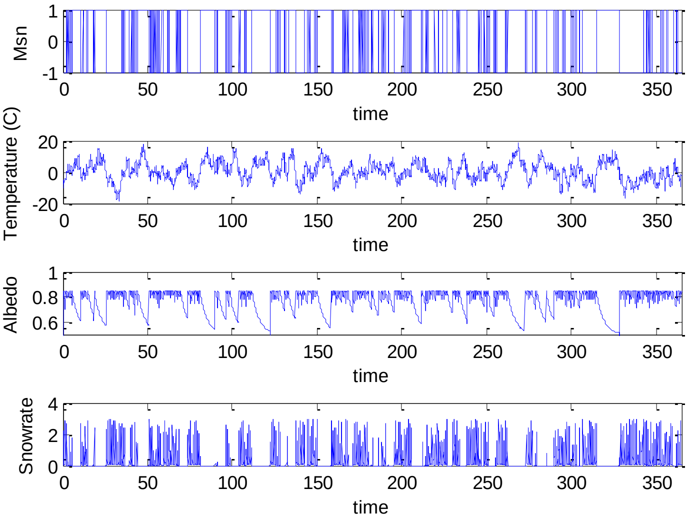

Figure 5. Snowmelt, temperature, albedo and snow rate plotted against time.

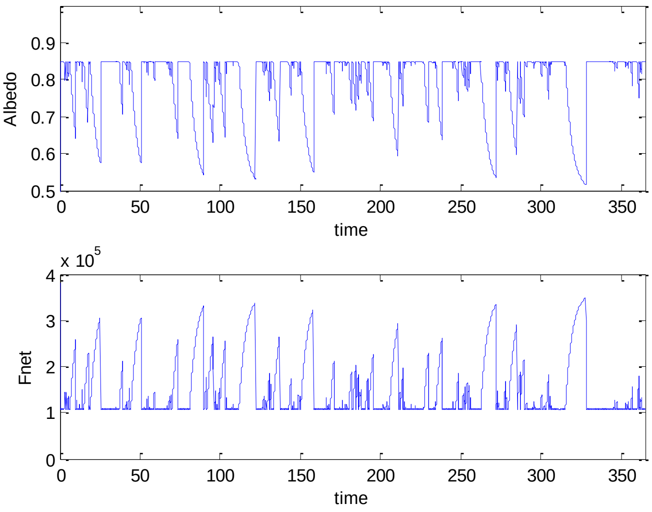

Figure 6. The albedo and the net shortwave radiation plotted against time.

The values for the parameters were determined in a sensitivity test in cooperation with Johanna Eggeling, see Table 2. These values were used as parameters for the snow albedo in the runs where the bare ice albedo parameterization was studied.

Table 2, parameters in the Essery code.

Parameters	**Values**
T_α	7^7 s
T_m	1.8 s
α_{min}	0.65
α_{max}	0.85
$S0$	3 mm

4.2 Bare ice albedo parameterization

The code for the bare ice areas by Oerlemans & Knap was implemented in the model by Peter Lang Langen as a complement to the Essery snow albedo code. To see how well the model models the bare ice albedo, three runs from the original code were used; with $\alpha_{bi}(t)$ equal to 0.66 (which is the minimum snow albedo), 0.55 and 0.45 respectively. These runs were to be compared with three runs from the Oerlemans & Knap code, with the same values on the bare ice albedos. To know which code that gives the best outputs, the runs were compared with the study by Abdalati and Stefen (2001) [7]. The model was run for the period 1990-1999. During this period, the year with the highest amount melting in the summer from the study was 1991. The year with the lowest amount of melting was 1992, so these two years were chosen for comparison.

Figure 7-12 shows the albedo for the Greenland ice sheet during July 1991. Each figure represents one run with different parameters. The runs were either done with the original code or with the Essery and Oerlemans & Knap code. Figure 7 and 8 has a bare ice albedo set for 0.45, Figure 9 and 10 has 0.55 and Figure 11 and 12 has 0.65. The same plots were made for July 1992, see Figure 13-18. To plot the outputs from the runs a MATLAB program was used, see Appendix 3.

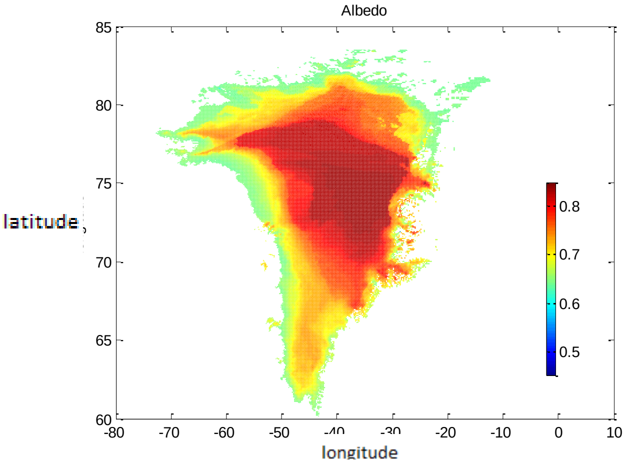

Figure 7. The monthly mean for the albedo in July 1991 from the original code, bare ice albedo set to 0.45.

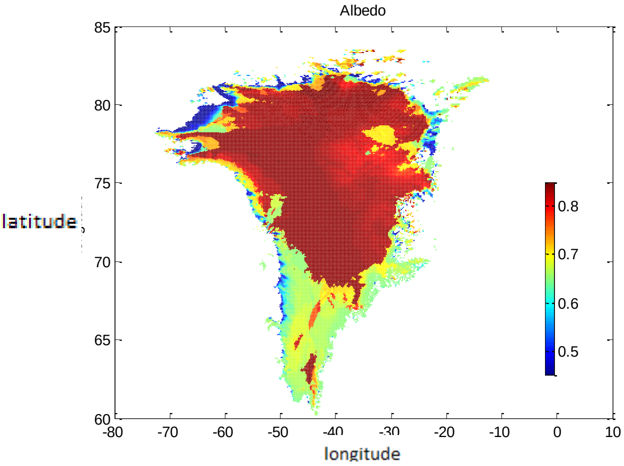

Figure 8. The monthly mean for the albedo in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.45.

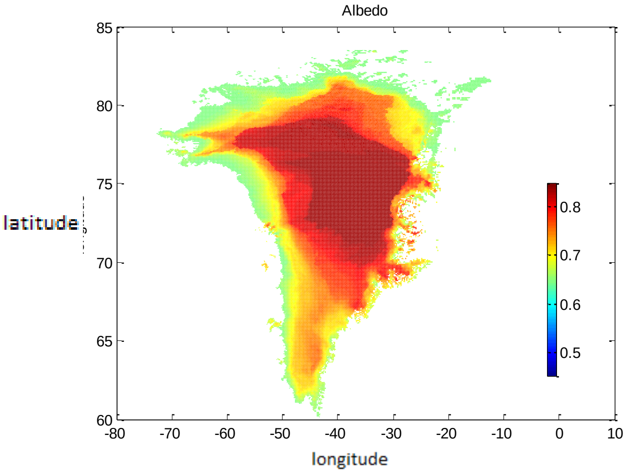

Figure 9. The monthly mean for the albedo in July 1991 from the original code, bare ice albedo set to 0.55

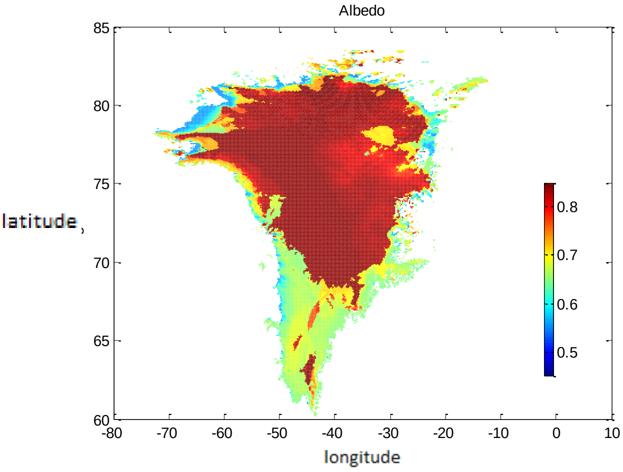

Figure 10. The monthly mean for the albedo in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set 0.55.

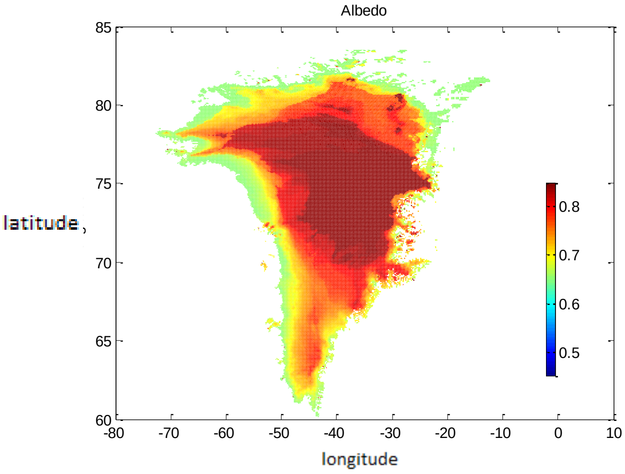

Figure 11. The monthly mean for the albedo in July 1991 from the original code, bare ice albedo set to 0.65.

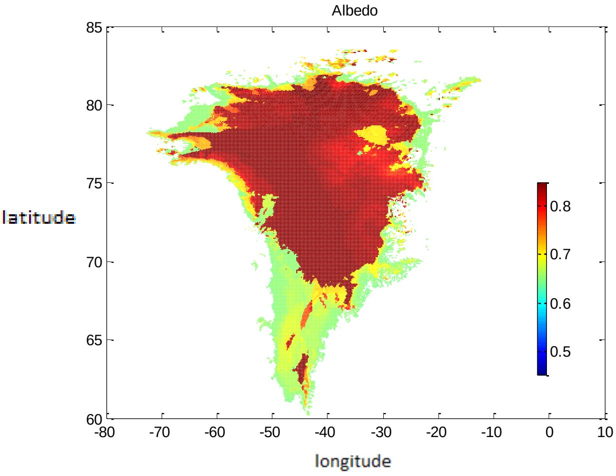

Figure 12. The monthly mean for the albedo in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.65.

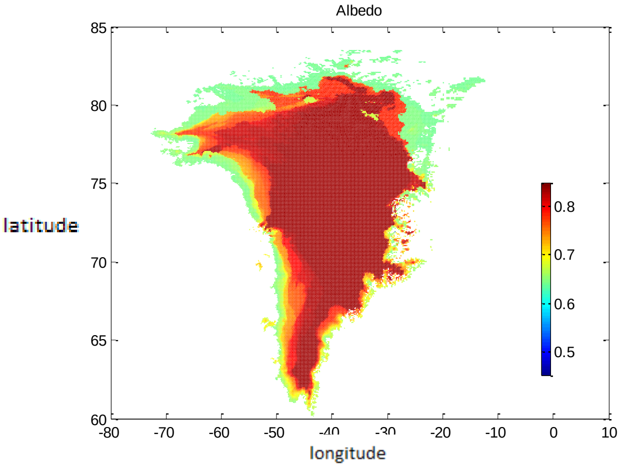

Figure 13. The monthly mean for the albedo in July 1992 from the original code, bare ice albedo set to 0.45.

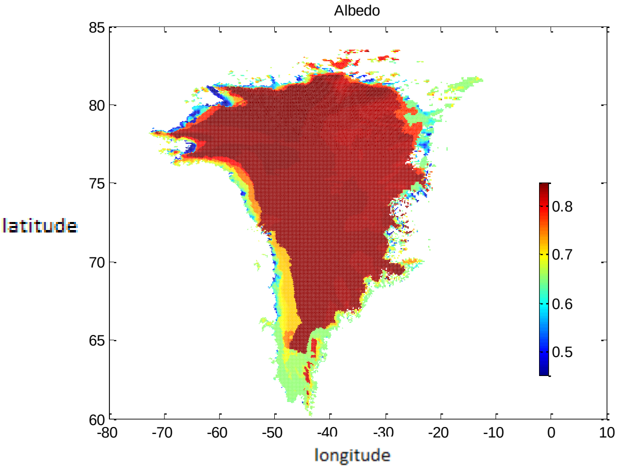

Figure 14. The monthly mean for the albedo in July 1992 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.45.

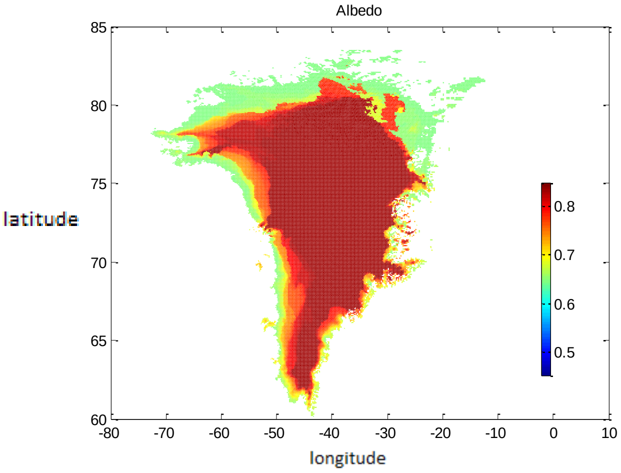

Figure 15. *The monthly mean for the albedo in July 1992 from the original code, bare ice albedo set to 0.55.*

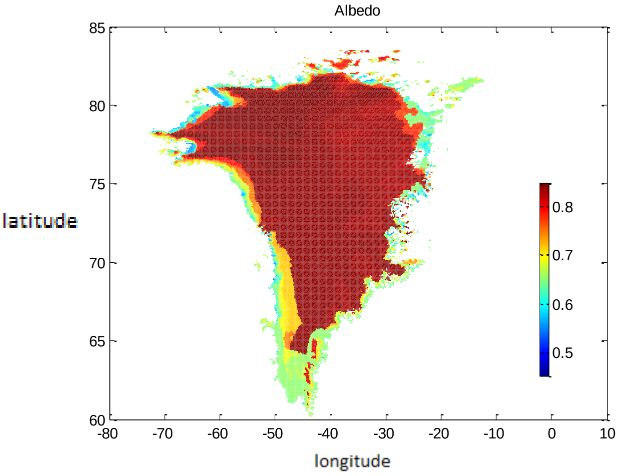

Figure 16. The monthly mean for the albedo in July 1992 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.55.

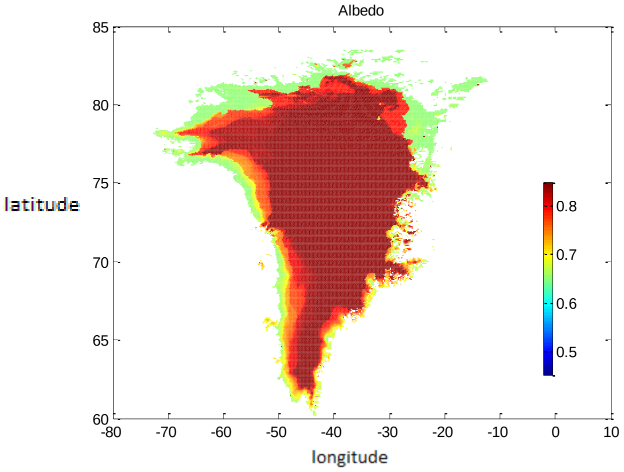

Figure 17. The monthly mean for the albedo in July 1992 from the original code, bare ice albedo set to 0.65.

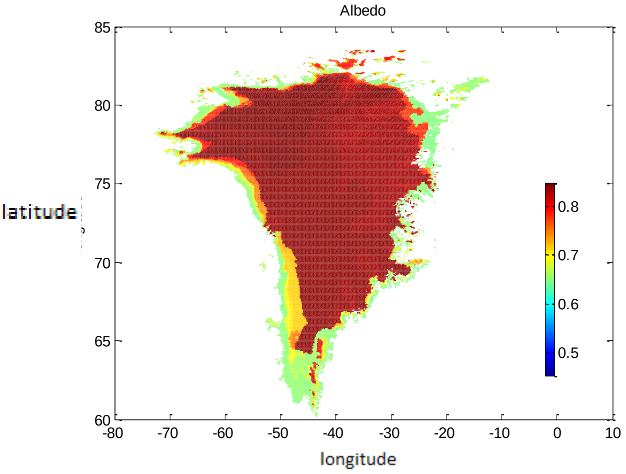

Figure 18. The monthly mean for the albedo in July 1992 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.65.

The albedo parameterization includes things like the melting, the snowfall and the snow depth. Therefore, there should be a relationship between these in the plots. Since the SMB includes melting and snowfall, this was also considered in the comparison. Figure 19-21 show values from the original run with bare ice albedo 0.45 in July 1991. They include the albedo, snowfall, snow depth and SMB. The same variables were also plotted for the Essery and Oerlemans & Knap code, see Figure 22-24.

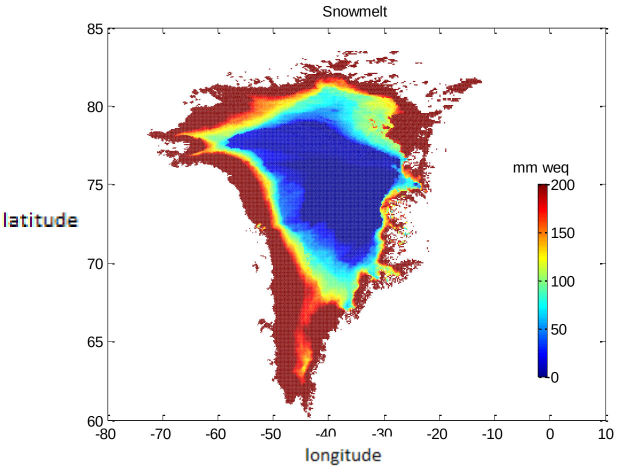

Figure 19. Monthly mean for the snowmelt in July 1991 from the original run, bare ice albedo set to 0.45.

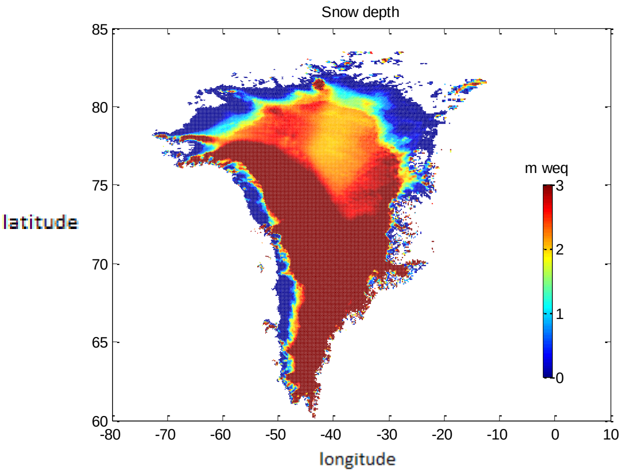

Figure 20. Monthly mean for the snow depth in July 1991 from the original run, bare ice albedo set to 0.45.

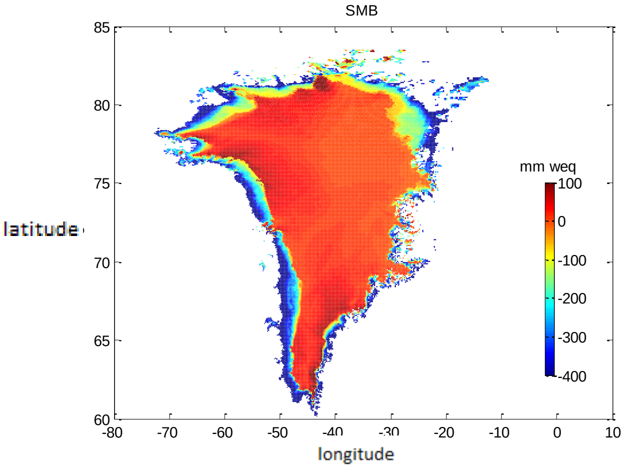

Figure 21. Monthly mean for the surface mass balance in July 1991 from the original run, bare ice albedo set to 0.45.

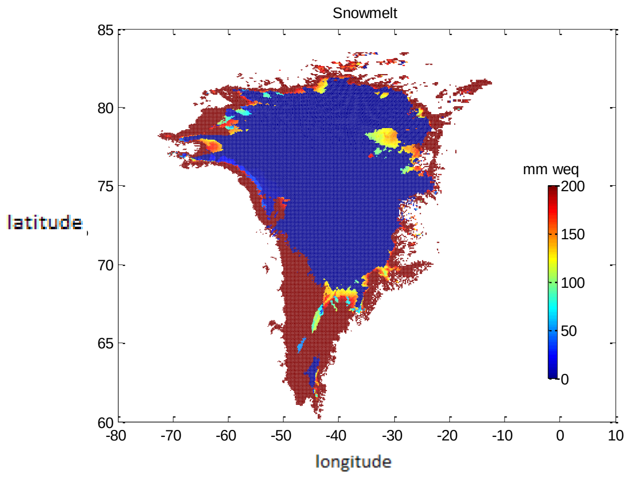

Figure 22. Monthly mean for the snowmelt in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.45.

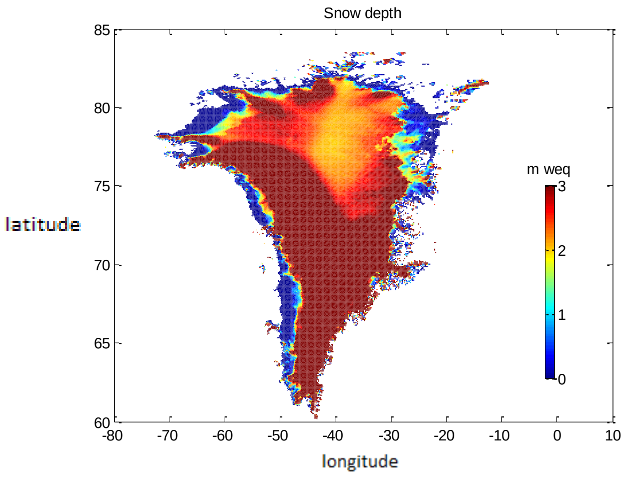

Figure 23. Monthly mean for the snow depth in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.45.

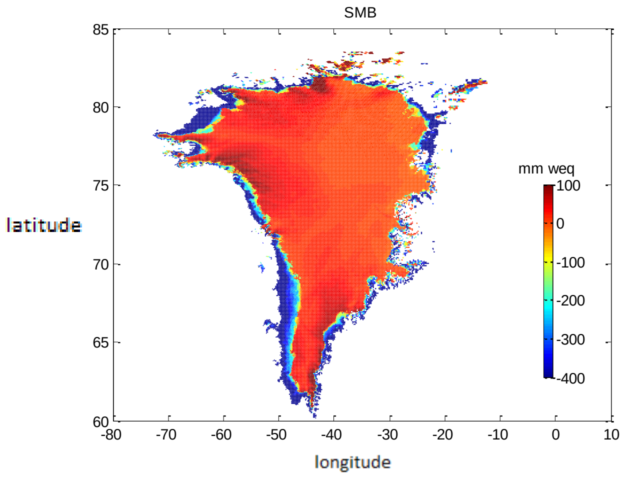

Figure 24. Monthly mean for the surface mass balance in July 1991 from the Essery and Oerlemans & Knap code, bare ice albedo set to 0.45.

5. Discussion

5.1 Modelling the snow albedo

The subroutine for the snow albedo was made in cooperation with Johanna Eggeling since her project was to look at only snow covered areas of the Greenland ice sheet. Figure 5 and 6 were made to look at the relationship between the albedo and the rest of the variables. Note that they are changing in collaboration with each other. When the temperature increases, so does the snowmelt, which lowers the albedo. The figure only shows if it is melting or not, not the extent, but it also cooperates with the other variables. When new snow falls, the albedo increases again. In Figure 6 the net shortwave radiation responds very well to the albedo. A high albedo means a lower net value for the shortwaves, which can be seen as a decrease in the figure.

The parameters set by Essery looked a bit odd when they were implemented in the model. It gave a very low albedo all over the ice sheet, which is not very realistic. The melt mostly occurs in the coast areas during summertime, but the model showed melting everywhere already in January. In the sensitivity test for 10 days were the values in Table 2 the ones that looked most realistic. The melting was not progressing as fast which made the albedo higher. Since the snow usually does not melt in the accumulation zone the albedo there should be rather high. The parameters can surely be improved further, but that requires a more profound study on the subject.

5.2 Modelling the bare ice albedo

Since this project was about the ablation zone, which consists of bare ice or a thin snow layer in the summer, the albedo parameterization for the transition to bare ice was very important. This is what distinguishes the difference between the ablation zone and the accumulation zone. The two different parameterizations, the original and the Essery and Oerlemans & Knap, were first compared with the study by Abdalati and Steffen. It was expected that the summer of 1991 would have a high melting range, and therefore a low albedo. This can be seen as a larger ablation zone than usual. The difference in the figures 7-12 and 13-18 is distinguishable, and is consistent with the Abdalati and Steffen study. In the figures from 1991, the low albedo area is much more extended than in the figures from 1992. This inclines that the model gives reasonable outputs.

Secondly, the differences between the two parameterizations were studied. It is easy to see that the new one (Essery and Oerlemans & Knap) is much more detailed than the original one. In Figure 7, 9 and 11, the albedo is blurred out between the different zones. This does not happen in the new model; see Figure 8, 10 and 12. There may be a risk that the small details end up in the wrong places, and that the edges are a little too sharp. Since observations from the ice sheet are rare, it may be hard to look into this, but the model can be compared with the usual weather phenomena to see if it gets the big picture right. In the summer, the melting starts at low elevations around the coast areas. In southern Greenland melting also occurs due to higher temperatures. This pattern was therefore expected from the model. In both the original runs and the Essery and Oerlemans & Knap runs this can be seen, even though it is more visible in the Essery and Oerlemans & Knap runs. The middle of the ice sheet usually does not experience melt, and therefore the albedo should be rather high there. This can also be seen in the figures, which also indicates a realistic result. In the north-east of Greenland, a small area with a lower albedo can be seen in the Essery and Oerlemans & Knap run for July 1991. This pattern is not expected, and may have occurred since the model is run offline. When changing the parameters on the surface, the variables in the atmosphere also changes. Things like the latent heat and the outgoing longwave radiation are affected when the albedo is changed. The offline model does not have a feedback between the surface and the atmosphere, which gives some errors like this.

Furthermore, the task was to look at three different bare ice albedos for each run, 0.45, 0.55 and 0.65. In the Figures from the original code, the albedo does not get below 0.65, which is the lowest snow albedo. For some reason the bare ice albedo did not show up, not even in 1991, which was a year with a lot of melting. It was later found that the snow depth the model requires to go over to the bare ice albedo instead of the snow albedo was set very low, 0,001 mm. This means that the snow depth had to be approximately zero if the bare ice albedo should show. It is difficult to see in the snow depth figures, but looking at the output numbers from the model it was clear that this did not happen in the monthly means. Therefore, the different bare ice albedos could not be compared from the original runs.

In the new model, the transition from snow to bare ice was included. For that reason, the albedo could go down to the minimum bare ice values, see Figure 8, 10, 12, 14 and 16. This shows that it was important to include the factor that the ice can shine through a thin layer of snow, and therefore also lower the albedo and increase the melting of snow and ice. The melting itself causes even more sinking of the albedo, which was included in the Essery code. Due to these changes, the bare ice albedo can be seen in figure 8, 10, 12, 14 and 16, even though in figure 12 and 16 it merges with the lowest snow albedo. It is hard to say which one of the values for the bare ice albedo that is most realistic. It probably is 0.45 or 0.55 though, since 0.65 is the lowest snow albedo and therefore does not show any difference. As the albedo for ice is lower than for snow, they should differ.

When comparing Figure 19-21 with the albedo in figure 7, there is a similar pattern. The snowmelt in figure 19 is high in the coast area and in the south of Greenland, and therefore agrees well with the albedo. The snow depth is also low around the coast areas, but also a little lower in the north-east of Greenland. In reality the snow pack often is a bit lower there, since it does not snow that much. Both in the snow depth figure and in the SMB figure it can be seen that even though there is a lot of meting in the southern parts, the SMB and snow depth is still high. This has to do with the fact that it snows more here. This is also the case in the north-west of Greenland since the mountains forces the air upwards, which leads to more precipitation. This is the reason to why the SMB is positive in these areas even though the melting is high. In the middle of the ice sheet the albedo is high, above 0.75. The SMB is positive and the snowmelt is very low or absent. Figure 22-24 also shows these patterns, although the edges are sharper. They also match the albedo in Figure 8 well.

6. Conclusion and outlook

The result from this project is a better parameterization for albedo on the Greenland ice sheet in the climate model HIRHAM5. In the original code the result was smoothed out. The new parameterizations for snow and ice albedo have been shown to give more detailed results. It includes things like the snow depth, melting snow and the age of the snow, not only the temperature as before. This makes it possible to distinguish the ablation zone from the accumulation zone. After the sensibility tests on the parameters, the results got more realistic. Since parameterization is an approximation, there are always sources of errors, and the reality can never be correctly modelled. Despite this, the model is now a good appliance to study how the albedo affects the different variables, and how they affect each other.

A way to go on with this study would be to continue with the sensitivity tests. This can be done both for the Essery and Oerlemans & Knap parameters, and for the bare ice albedo. It would also be good to do the runs in the real HIRHAM5 model, not only in the offline version. This would allow feedback between the surface and the atmosphere, and would probably give even better results. Another way to carry on the work is to use the few observations that are available from the Greenland ice sheet, and compare with the model data. There are a few observation stations on the ice sheet that can be used, and also satellite data. Afterwards, it should be possible to use the new parameterization to study the relationship between the albedo and the melting in the ablation zone of the Greenland ice sheet.

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Figures

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Acknowledgement

To my supervisors Ruth Mottram and Peter Lang Langen, thank you for sharing your knowledge and time. It was a very interesting subject to work on and I learned a lot from you. I would also like to thank Elna Heimdal Nilsson for the advices and the help with the writing process, and Johanna Eggeling for the cooperation with the snow albedo parameterization. I am also grateful to everyone at DMI that help me when problems occurred.

Appendix 1

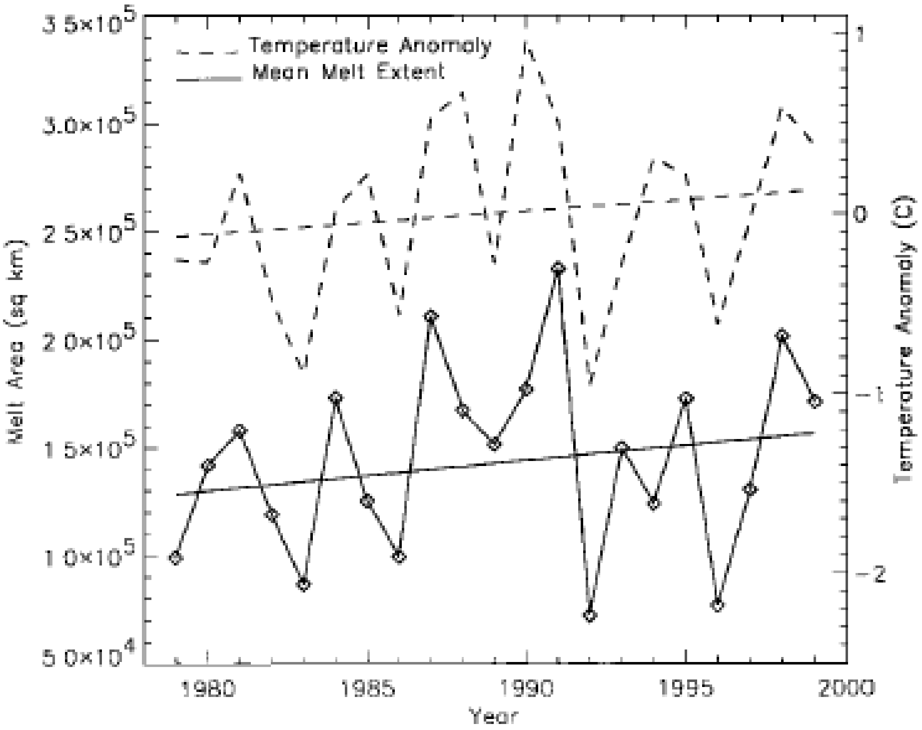

Figure 2, the average summer mean melt for 1979-1999 from the study by Abdalati and Steffen 2001

Appendix 2

```
%PARAMETERS
delta_t=3600; %Time step length in seconds
ntimes=365.*24.; %Number of timesteps
tau_alfa=4*1e7; %Seconds
tau_m=8*3.6e5; %seconds
alfa_min=0.65; %Lowest value for the albedo
alfa_max=0.85; %Highest value for the albedo
Fin=200; %Incoming power in W/m2


%Autocorrelation of time series
AC1=0.99; %Gives a memory of the temperature, takes 99 percent of the old
temperature

%Starting values for T and alfa
alfa1=0.85;
temperature1=-10;



snow=zeros(1,ntimes);
alfa=zeros(1,ntimes);
Msn=zeros(1,ntimes);
temperature=zeros(1,ntimes);
snowrate=zeros(1,ntimes);

% Treat first time step separately:
temperature(1) = temperature1;
Msn(1)=melted(temperature(1));
alfa(1) = alfa1;

% Integrate 2nd timestep and forward
s = 4. ; % Seed for random numbers
rng(s);
rands = randn(1,ntimes);

for i=2:ntimes;

     temperature(i)=temperature(i-1).*AC1+rands(1,i);  %Gives a random
temperature

    snow(i)=snowfall(i); %Gives a random snowfall rate

     if temperature(i) > 0
        snow(i)= 0; %If the temperature is above 0 degree C the snow melts
into rain
     end

     Msn(i)=melted(temperature(i)); %decides if the snow will melt or not

    if Msn(i) < 1   %when temperature < 0
        alfa(i)=alfa(i-1)-delta_t/tau_alfa; %Equation for dry snow
    else        %Msn=1 when temperature > 0
        alfa(i)=(alfa(i-1)-alfa_min)*exp(-delta_t/tau_m)+alfa_min;
%Equation for melting snow
    end
```

```
     %let snowfall refresh the alfa
   % snowrate(i)=min([1 snow(i)*delta_t/10]);
   % alfa(i) = alfa(i)+snowrate(i).*(alfa_max-alfa(i));



end


time = (1:ntimes)/24; %x-axis

clf

Fnet=(1-alfa).*Fin*3600; %Net power for shortwave radiation


figure (1)


subplot(2,1,1)
plot(time,alfa)
axis([0 ntimes/24 0.5 1])
xlabel('time')
ylabel('Albedo')

subplot(2,1,2)
plot(time,Fnet)
axis([0 ntimes/24 0 4e5])
xlabel('time')
ylabel('Fnet')

figure (2)

subplot(4,1,1)
plot(time,Msn)
axis([0 ntimes/24 -1 1])
xlabel('time')
ylabel('Msn')

subplot(4,1,2)
plot(time,temperature)
axis([0 ntimes/24 -20 20])
xlabel('time')
ylabel('Temperature (C)')

subplot(4,1,3)
plot(time,alfa)
axis([0 ntimes/24 0.5 1])
xlabel('time')
ylabel('Albedo')

subplot(4,1,4)
plot(time,snow)
axis([0 ntimes/24 0 4])
xlabel('time')
ylabel('Snow')
```

Appendix 3

```
clear all; pack
clc
%load C:\Users\Marie\Documents\DMI\V3_ERAI_A65-
85_R02_SNMELT_1989_1999_YM.nc;
fname = 'C:\Users\Marie\Documents\DMI\V3_ERAI_A65-
85_R02_ALBEDO_1989_1999_MM.nc';

% set cmap limits
%CAmin = -0.6; CAmax = 2.6;
%coldiv = CAmin:0.1:CAmax;

% set colormap
%cmap = jet(length(coldiv)-1);

lon = ncread(fname,'lon');
lat = ncread(fname,'lat');
alfa = ncread(fname,'albedo');
albedo = squeeze(alfa
albedomonth = 7:12:120; %vald månad : 12 månader : tidsvektorn

%test=mean(albedomonth); %Medelvärdet för den valda månaden, alla år
test=albedomonth(:,4); %Den valda månaden för valfritt år
albedoplot = albedo(:,:,test); %plotta albedot för test

%snmeltm = mean(squeeze(snmelt),3);
%snmeltjul = snmelt(3,:)
%snmelt = ncread(fname,'snmelt');
%snmeltm = mean(squeeze(snmelt),3);

%clf;
%colormap(cmap); caxis([CAmin CAmax]);
handle=pcolor(lon,lat,albedoplot);
set(handle,'edgecolor','none')
axis([-80 10 60 85])
caxis([0.45 0.85])
title('Albedo')
%contourf(lon,lat,albedoplot,0:200:3000,'LineStyle','none'); colorbar
%set(h,'edgecolor','none');
colorbar('vert','position',[0.80 0.20 0.015 0.40]);
%title(h,'m weq')
ylabel('longitude')
xlabel('latitude')
%set(gca,'FontSize',13);
%set(gcf,'PaperPositionMode','auto');
%print -r400 -dpng 'C:\Users\Marie\Documents\DMI\V3_ERAI_A65-
85_R02_SNMELT_1989_1999_YM.nc';
```