Modeling albedo in the dry snow zone of the Greenland Ice Sheet

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Abstract

Hirham5, a weather model developed at DMI, does not have a very good approximation for the snow albedo. To make the model better a snow albedo code, based on Dickenssen's equation for snow albedo, was implemented in the model where the albedo depended on more variables than just the temperature. This change is important since the radiation contributes more to the melt than the temperature. The surface mass balance (SMB), which is the difference between accumulation and ablation, is also important for the albedo. A positive SMB often contributes to a higher albedo and a negative SMB contributes to a lower albedo. The main area in this project was to look at the snow albedo in the dry snow zone over Greenland. The snow code in the model made it possible to change the parameters and to see how a small change in one parameter could change the albedo drastically. Due to the short time this project had, only three different runs were made in the offline model of Hirham5, which ignores the vertical layers. Despite only three runs, the data gave quite interesting result which did differ from each other and could be analysed by comparing the albedo, SMB and snowmelt for January and July during different years. The result showed how important parameterisation is for the albedo and how hard it is to find reasonable values for the parameters.

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Introduction

Four times during the last decade, year 2005, 2007, 2010 and 2012, Greenland experienced usually large melt extent, especially in the percolation zone (Brown et al., 2012). However the most surprising factor was that in 2012, almost the whole dry snow zone exposed melting (DMI, 2014). Since the Greenland ice sheet covers such a large area and holds so much water it will affect the global sea level. The average global sea level rise is 0.5 mm/year and if the whole ice sheet would melt the sea level would rise with over 7 m (Kahn, 2012).

A very important variable for the ice sheet is the albedo since it determines how much of the incoming solar radiation that is absorbed by the earth's surface (Barrett et al., 2013). If the value of the albedo is low the surface absorbs most of the incoming radiation which leads to a higher amount of melt. Fresh snow has a much higher albedo than e.g. firn or bare ice (Benn and Evans, 2010). The most important factor for the change in albedo in the dry snow zone is the shape of the snow crystals, which changes with age.

The regional climate model HIRHAM5, developed at the Danish Metrological Institute, with an improved albedo code was used to complete this project. In the code, equations for the snow albedo was included which were based on Dickensson's work (Essery et al., 2013 and DM 2014). In this project the dry snow zone was in focus and to see how important the albedo is for the ice sheet, the parameters in the code were changed and analysed for 10 years.

Background

Greenland ice sheet

Greenland is a Danish island in the northern hemisphere in the Atlantic and is the second largest island in the world. It has an area of 2,166,086 km^2 but only 57 000 people live here, whereof 15 000 lives in the capital, Nuuk (Norden).

The Greenland ice sheet has the second largest ice volume, after the Antarctic ice sheet (Ettema, 2010). The ice sheet covers almost 80% of the island and consists of compressed snow layers from more then 100 000 years, is about 2500 km long and 1000 km wide (Benn and Evans, 2010). 10% of the earth's fresh water is stored in the ice sheet, which answers to a volume of 2,600,000 km^3 and an area of 1,736,000 km^2 (Benn and Evans, 2010). Due to global climate warming, leading to warmer air and sea temperatures, the ice sheet is melting and loses a lot of mass. The mass loss of the ice sheet leads to an increase of the global sea level rise (Kahn, 2012). Current conditions contribute to an average sea level rise of 0.5 mm per year and if the whole ice sheet would melt the sea level could rise by more than 7 m (Kahn, 2012). The effects of the melt of the Greenland ice sheet mostly affect the southern hemisphere and the melt of the Antarctic ice sheet affects the northern hemisphere the most (DMI, 2014).

The North Atlantic Oscillation (NAO) has a great impact on the weather over Greenland (DMI, 2014).The NAO-index is based on a low pressure over Iceland and a high pressure over Bermuda-Azores (Donald Ahrens, 2013). A very deep low pressure over Iceland and a very strong high pressure over Bermuda-Azores is called a positive phase and gives Greenland cold and dry winters (Donald Ahrens, 2013). During the negative phase the low pressure is weak and the high pressure dominates. The negative phase gives rise to milder winters which slows down the accumulation processes (DMI, 2014). The summers become affected by smaller high pressures which give rise to clear skies which in its turn contributes to more melt of the ice sheet (DMI, 2014). The effects from the NAO on the precipitation are not fully understood (Benn and Evans, 2010) and the snowfall is not evenly spread over the island (DMI, 2014). Over the higher elevations the snowfall is typically 0.5 m/ year but along the coast it can fall up to 7 m/year (DMI, 2014).

The different snow and ice zones

The ice sheet is divided into different zones- the accumulation and ablation zone, with different snow and ice metamorphism (Benn and Evans, 2010), see figure 1. Snowfall and refreezing are the most important sources for the accumulation zone (Nolin and Payne, 2007). For the ablation zone the melting, evaporation, sublimation and ice calving play an important role (Benn and Evans, 2010).

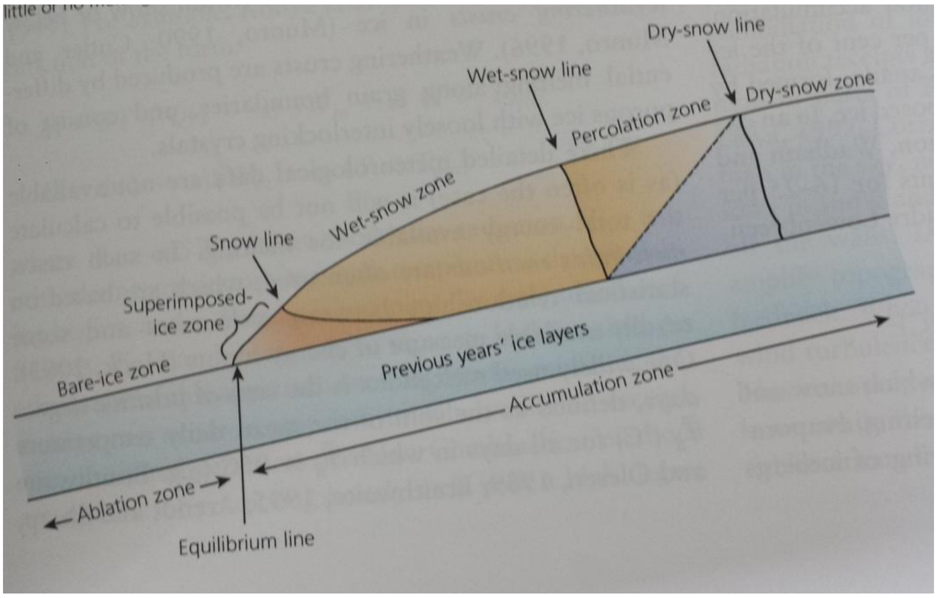


Figure 1: The differentt zone on the ice sheet (Benn and Evans, 2010).

The accumulation zone is divided into several other zones (Benn and Evans, 2010). The first zone, on the highest elevations of the ice sheet, is called the dry-snow zone where no melting occurs (Nolin and Payne, 2007) and the temperature is below 0°C (Benn and Evans, 2010). The dry snow zone covers the major part of the accumulation zone (DMI, 2014). The next zone, the percolation zone, represents the area where some surface melt occurs (Benn and Evans, 2010). The melted water percolates down through the snowpack and refreezes which can be observed as ice lenses or ice glands (Benn and Evans, 2010). When the whole area is affected by percolation and refreezing of melted water, the zone is called the wet-snow zone (Nolin and Payne, 2007). The wet snow zone can sometimes be counted as the percolation zone (DMI, 2014). A very small part of the accumulation zone is covered by the superimposed zone where the refreezing has caused the formation of continuous mass of superimposed ice (Benn and Evans, 2010). It is often determined by the snow line which is the boundary between snow and no snow (DMI, 2014).

The bare-ice zone is the only zone in the ablation zone where old glacier ice can be observed since the snow and ice from the previous years is removed due to melting of snow and ice (Nolin and Payne, 2007).

The line between the ablation and the accumulation zone is determined by the equilibrium line altitudes (ELA) (DMI, 2014). At the ELA the surface mass balance is equal to zero, that is no loss or gain of mass on the surface (DMI, 2014). Since the weather conditions are not the same every year the ELA moves up and down. If there is more ablation and less accumulation than previous years the ELA will move higher up on the ice sheet and vice versa (DMI, 2014).

Albedo

All incoming radiation from the sun is reflected, transmitted or absorbed by the striking surface. The amount that is reflected from the surface is called albedo (Donald Ahrens, 2013). It is the surface layer of the ice sheet which is relevant for the albedo since the radiation does not reach through the whole snow pack. A high albedo value indicates low absorption of energy which contributes to a low amount of ablation (Benn and Evans, 2010), the high albedo value also keeps the surface temperature low (Barrett et al., 2013).

The incoming solar radiation is mostly shortwave radiation present as visible and ultraviolet light (Donald Ahrens, 2013) and the net shortwave component, SW_{net}, is described by;

$$SW_{net} = SW_{in} * (1 - \alpha) \qquad (1)$$

where SW_{in} is the incoming solar radiation and α is the albedo (Benn and Evans, 2010). The albedo is the ratio between the outgoing, SW_{out}, and the incoming solar radiation and can be determined by,

$$\alpha = \frac{SW_{out}}{SW_{in}} \qquad (2)$$

Different surfaces like, clouds, water or snow, have different albedos (Donald Ahrens, 2013). The albedo even differs for different types of snow and ice, see table 1 (Benn and Evans, 2010).

Table 1: The different values of the albedo for different types of snow and ice (Benn and Evans, 2010).

Snow type	Albedo
Dry snow	0.80-0.97
Melting snow	0.66-0.88
Firn	0.43-0.69
Clean ice	0.34-0.51
Slightly dirty ice	0.26-0.033
Dirty ice	0.15-0.25
Debris-covered ice	0.10-0.15

The table shows that fresh snow, usually very white, has a much higher albedo than bare ice and that clean snow has a higher albedo than dirty snow or ice (Benn and Evans, 2010).

At time, when snow gets older, the albedo becomes lower due to that the snow becomes denser and the structure of the snow crystals starts to change. Therefore the structure of snow is rather important for the value of the albedo (Essery et al., 2013). Fresh snow has a more crystal-like structure with sharp edges while old snow gets a more rounded shape which does not reflect the solar light that well. Due to pollution and age the snow becomes darker which also contributes to a lower value of the albedo (Essery et al., 2013), since a dark surface absorbs more radiation then a light surface. That is why the albedo increases when it starts to snow because the snow gets whiter and get a better structure for reflection. For fresh snow the grain radius also determines the value of the albedo. With age the size of the grains increases which leads to a lower value of the albedo (Nolin and Payne 2007).

Surface mass balance

The surface mass balance, *SMB*, is defined as the sum of the added and removed mass from the ice sheet (DMI, 2014) and can be described with the following equation

$$SMB = Accumulation - Ablation \qquad (3)$$

The added mass comes from condensation, snowfall and refreezing and the removed mass comes from melt, ice calving, runoff and sublimation (DMI, 2014).

The transitions between different states of water are due to an energy exchange between the atmosphere and the ice or snow surface, which also leads to a temperature change (Benn and Evans, 2010). Energy is released through condensation, freezing and deposition and is absorbed trough evaporation, melting and sublimation (Benn and Evans, 2010). The energy balance model helps us to understand how to calculate the amount of melt, and due to the conservation of energy, the sum of the components must be zero.

$$SW_{net} + LW_{net} + QE + QL + GE - ME = 0 \qquad (4)$$

SW and *LW* are the net shortwave respectively net longwave radiation, *QE* is the sensible heat flux, *QL* is the latent heat flux, *GE* the ground energy and *ME* is the melt energy (DMI, 2014). These are the most important component of the energy balance for glaciers (Benn and Evans, 2010).

The first component, the net short wave one, is described in the albedo section above. The longwave radiation is emitted as infrared light (IR) from the surrounding terrain and the atmosphere (Benn and Evans, 2010). Generally, clouds contribute to the incoming longwave radiation when outgoing longwave radiation reflects and scatters back to the surface (DMI, 2014). Since the glaciers also emit longwave radiation the net longwave radiation is in balance

$$LW_{net} = LW_{in} - LW_{out} \qquad (5)$$

The outgoing longwave radiation is dependent on the temperature near the surface and if the ice or snow is melting, the net longwave radiation is usually negative (Benn and Evans, 2010).

Sensible and latent heat are both two types of turbulent fluxes (DMI, 2014). The sensible heat is the transfer of heat between the atmosphere and the surface (The Science of Doom, 2010).

Latent heat is the transfer of heat through the transition between different phases, that is, when freezing or condensation occurs etc (Benn and Evans, 2010). When the temperature is above 0 °C melt occurs due to the additional energy (DMI, 2014).

To study the *SMB* a hydrological year is often used which usually is from September 1st to August 31st. It starts when the accumulation period begins and the ablation period stops and the normal conditions can be observed in FIGURE 2.

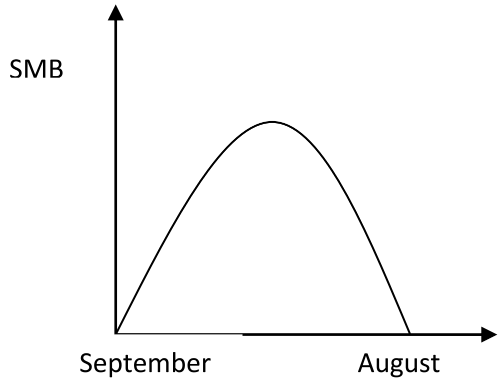


Figure 2: The average variety of the SMB during a hydrological year.

Method

HIRHAM5

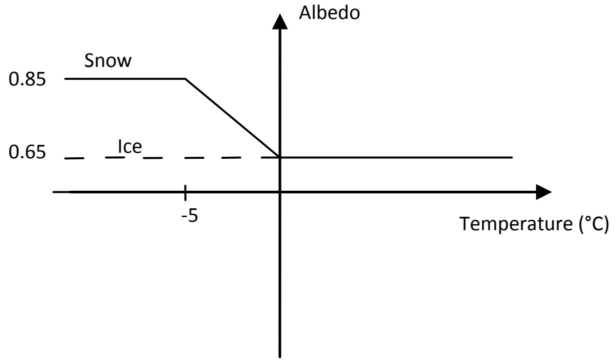
The model used, HIRLAM5, is a regional climate model (RCM) developed at the Danish Metrological Institute (Aðalgeirsdóttir, 2012b). It is a combination of the High Resolution Limited Area Model HIRLAM7 atmospheric dynamics and the global modell, ECHAM5 physics (Aðalgeirsdóttir, 2012a and 2012b) and has a resolution of 0.05deg which corresponds to approximately 5km in the southern part and approximately 6 km in the northern part of Greenland (DMI, 2014). It also has 31 vertical layers in the atmosphere which are determined by the pressure (DMI, 2014). Where glaciers are present the land surface scheme in the model does not consider snow processes e.g. sublimation and snowmelt (Aðalgeirsdóttir, 2012b). Instead, the glaciers are covered with a snow layer of 10 m thick water equivalent which determines the energy and moisture flux (Aðalgeirsdóttir, 2012b). When the temperature is -5° C or below the albedo reaches a maximum value of 0.8 and a minimum value of 0.6 when it starts to melt. Since Greenland is mostly covered by snow the entire year, the effect of the albedo approximation on turbulent fluxes, air temperature and radiative fluxes is very small and therefore the influence in the ablation zone during melt season is limited (Aðalgeirsdóttir, 2012b).

To calculate the *SMB* in HIRHAM5 the precipitation and the evaporation must be combined with a separate melt model (Aðalgeirsdóttir, 2012b). For *SMB* of glaciers the snow processes are really important (Aðalgeirsdóttir, 2012b).

Since HIRHAM5 is not a weather forecast model, specific data like the temperature on a special day will not be possible to find. Instead an average value of the climate data for 30 years is available. The input in HIRHAM5 comes from the reanalyze which comes from the ERA_Interim, a global atmospheric reanalysis (DMI, 2014 and ECMWF).

Since the grid square in the big HIRHAM 5model not only consists of grid squares but also 31 vertical layers it would take a very long time to do a run. Instead an offline model can be used to only look at the surface, by taking the output data from HIRHAM5 and implement it in the offline code. The output from HIRHAM5 comes as atmospheric data and surface data and it s the surface data which are important for the offline model. The purpose of the offline model is to calculate the *SMB* and therefore it has a fixed ice mask which tells the model only to collect information where the land surface is covered with ice or snow. The main equation for this model is the energy balance model, see Equation 4.

Both for the big HIRHAM5 model and the offline model the equations for the albedo is very simple. In the offline model the maximum value of the albedo is set to 0.85, see Figure 3.When the temperature is below -5 °C the albedo is constant but when it reaches -5 °C the albedo starts to decrease linearly until it reaches the minimum value. The minimum value in the offline model is set to 0.65 and is reached when the temperature is 0 °C.



Figur 3: The value for albedo for ice and snow.

Spinup

The spinup's main purpose is to find an equilibrium. Before the spinup is started the snow depth on Greenland is set to be 2 m over the whole ice sheet (DMI, 2014). Although an evenly spread snow cover is not realistic. The snow depth contributes to the value of albedo; for example, if the snow layer is very thin the radiation can reach the ice sheet underneath which lowers the albedo (DMI, 2014). By taking the weather conditions for a specific year and run that conditions 10 times, an equilibrium will be reached, see Figure 4 and Figure 5. Figure 4 shows how the snow depth is equally spread over the whole ice sheet in January before the spinup has been done. In Figure 5 the equilibrium has been reached and a more natural snow cover has been created. The new snow cover is used as the initial conditions when the main run is started.

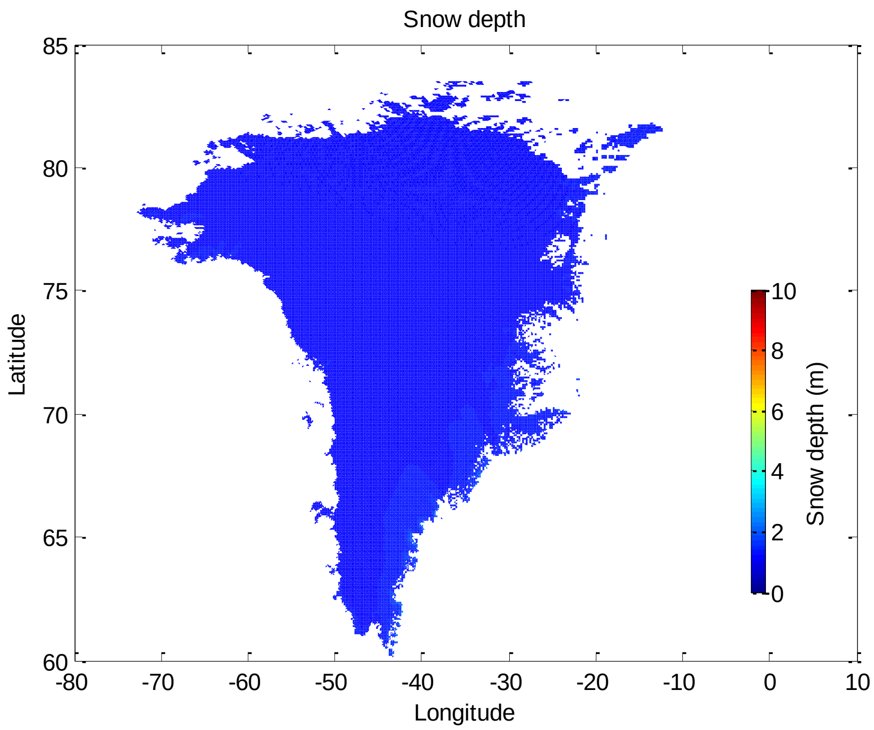


Figure 4: The Snow depth for January the first run.

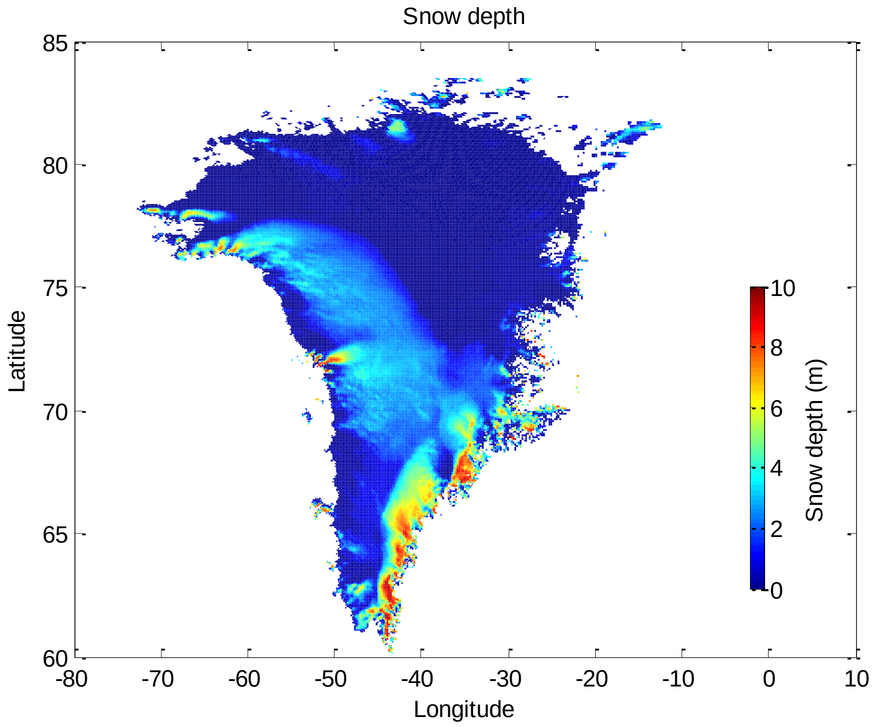


Figure 5: The snow depth in January the 10th run.

If the main run should be started without the spinup, the spinup will still be running in the background (DMI, 2014). Therefore, it will not be clear in the result if the change in albedo is due to the spinup in the background trying to reach its equilibrium or due to an actually change in the albedo (Dmi, 2014).

Snow albedo code

The offline model did not have a good approximation for the snow albedo and had to be improved. Peter Theil at DMI had developed a code in IDL based on Dickenson's equations for snow albedo (DMI, 2014). The values of the parameters used were taken from the Essery paper (Essery et al., 2013) and can be observed in table 2.

Table 2: Original values for the Essery -code.

Parameter	Value
So	10 mm
τ_m	3.6*e5 s
τ_α	1*e7 s
α_{min}	0.65
α_{max}	0.85
α_{ice}	0.55
Threshold	-0.1

The code needs an initial value for the albedo to work since the code uses the albedo from the previous time step and therefore starting value for the temperature and the albedo were set. The value for the temperature and the snow rate are then determined by random numbers which MATLAB chooses. Equations 6 and 7 are used in the code as they are but equation 8 needed to be rewritten (DMI, 2014).

$$\alpha_s(t + \delta t) = \alpha_s(t) - \tau_\alpha^{-1}\delta t \qquad (6)$$

$$\alpha_s(t + \delta t) = [\alpha_s(t) - \alpha_{min}]e^{\tau_m^{-1}\delta t} + \alpha_{min} \qquad (7)$$

$$\delta\alpha_s = (\alpha_{max} - \alpha_s)\frac{S_f\delta t}{S0} \qquad (8)$$

The variables is described in table 3

Table 3: The meaning of the different parameters for equation 6, 7 and 8 (Essery et al., 2013 and DM 2014).

α_s	The albedo for snow
α_{min}	The lowest value the albedo can take
α_{max}	The lowest value the albedo can take
τ_α	Melting rate for cold snow
τ_m	Melting rate for warm snow
t	Time
So	How deep the snow pack has to be to reach α_{max}
S_f	Snow rate

The sixth and seventh equations describe the changes for the snow albedo. Equation 6 is valid for dry snow and equation 7 is valid for melting snow. The eighth equation describes how the albedo changes if it snows due to refreshment of the snowpack (DMI, 2014). Equation 6 has a linear decay and it shows how the snow becomes darker with time due to no snowfall or melting of the snow. In equation 7 the decay is exponentially (Essery et al., 2013). The snow becomes darker much faster than in equation 6 due to melting. The melting lead to a more rapid change in the crystal structure and the snow becomes more homogeneous like water which has a lower albedo than snow (DMI, 2014). The difference between the offline model and the snow-code is that the albedo in the offline model is only dependent on the temperature. The albedo in the snow-code has a lot more variables to depend on, that is the temperature, snowfall, melt and time.

Working flow

To be able to use the program, Unix, which is used at DMI, some knowledge was needed. Therefore, Ruth Mottram and Peter Lang Langen showed the most important commands, like how to create a directory, copy files, to do a spinup , how to start a run etc. To make it even more clear some tutorials' where made at the internet.

The snow albedo code was rewritten by Marie Rasmussen and me. To rewrite the code from IDL to an understandable language for us MATLAB was used. Since the two languages differs a lot when using different commands it had to be considered if all lines in the code were relevant. During the rewriting google and books were used to solve the problems and to know what commands to use. Help were also given by Peter Theilj, Ruth Mottram and Peter Lang Langen.

When the code worked without any problem, plots could be made which showed the temperature, snow rate, albedo and melt. To get an even clearer result a code for the net short wave radiation was implemented and could be plotted. Sensitivity tests were made by changing the parameters and observe what happened.

The snow albedo code was implemented by Peter Lang Langen as a subroutine in the HIRHAM5 model and in the offline model. To find the best initial value of the parameters, sensitivity tests were made. The parameters, see Table 3, were changed and the runs were started for ten days and from January 1 to July 31. By doing this it could be seen if the values were reasonable and nothing odd has happened to the ice sheet, like too much melt in July. After several attempts the values could be set and used in the snow code. The values can be observed in table 4 in the result section.

The time for this project was limited and three different runs were possible to be done, the Essery-test, the Essery-original and the control-run. Three different spinups over ten years were made to find the equilibrium for the snowpack. The parameters were set to the preferred values. For the Essery-test and the Essery-control year 1990 was chosen for the spinup and for the control-run year 1989 was chosen. The control-run used the present parameters from the offline model, the Essery-test used the parameters from the sensitivity test and Essery-original used the values from the table 2.

The processes to get data from the runs, which could be analysed, were all made in the same way. The only difference was the parameters and that the control-run did not have the snow-code implemented. The first script to be started was the commandtostage-script to make the code readable for the computer. When the Commandtostage-script was ready the spinup could be started and after that the PP-scripts was started which sorted out all the daily values and gave annual and monthly means. To be sure that it was worth going on, using the chosen parameter values, a look at the result from the PP-data was made. The PP-data is then used for the actual run so that it could be started. PP-scripts were also needed to be started for the run as the data come as daily values. To be sure that the system does not crash Cleanup-scripts were started to get rid of all the daily values.

In the first run, the control-run, the parameters from the offline model were used. To be able to start the first run, Ruth and Peter needed to give a little assistance. The spinup was made for the year 1989. The control-run used the years 1989 to 1999 for the main run. The second run, the Essery-test, was made in the offline model with the implemented snow-code. The parameters from the sensitivity test were used and the main run used the years 1990 to 1999. The third run, Essery-original, used the original parameters and the same years as for Essery-test were used.

To analyse the data from the runs, MATLAB was used to get plots over the ice sheet. A code was given by Peter Lang Langen which could be used for this purpose. The code was improved by Marie Rasmussen and me to be able to plot the data from a specific month and a specific year. Christian Rodehacke at DMI gave some ideas of how we could solve some problems and gave a command to get an even better plot. The data for the plots came from the PP-data, both annual and monthly values. Only the data from the most relevant variables, albedo, snowmelt and SMB, were observed and analysed. All the data for these variables could not be analysed and therefore certain monthly and annually values selected were.

Result

The MATLAB-code which was improved and implemented in the offline-code can be seen in appendix 1.

Figure 6 and 7 show the temperature, albedo, msn, snow rate and net shortwave radiation which were obtained from the MATLAB-code when the original values from the Essey article were used for the parameters. These plots were mostly made to be able to see if the code was working and some sensitivity test was made to see what happened when the parameters changed.

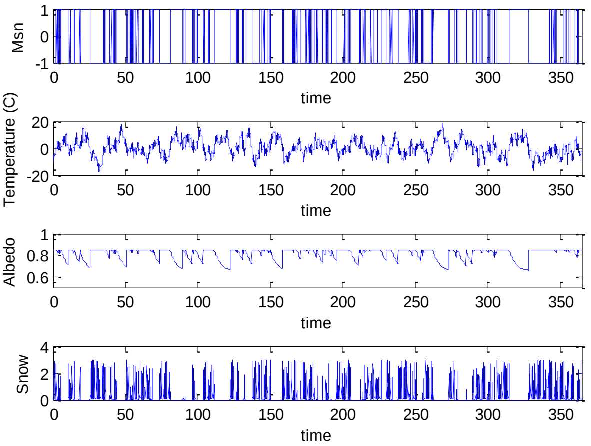


Figure 6: Snow rate, albedo, temperature and msn for the original Essery-values.

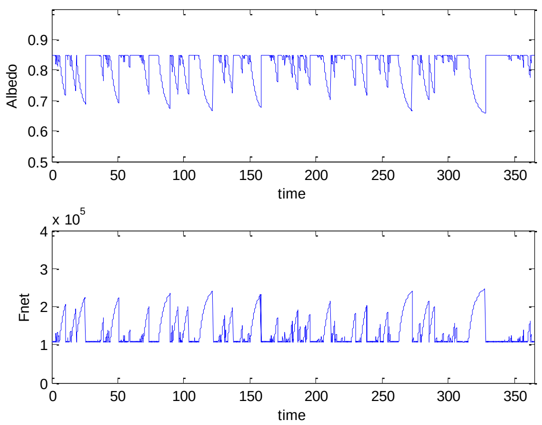


Figure 7: Albedo and the net shortwave for the original Essery-values.

Some examples from the sensitivity test can be observed in figure 8 and 9. Figure 8 shows how the *SMB* looked like when the original values for the Essery-code were used. The red area shows a very low *SMB* value. Figure 9 shows the albedo with the parameters from table 4, the blue area indicates a lower value of the albedo. These parameters were the best values after the sensitivity test. The values from table 4 were used to do the second run, the Essery-test.

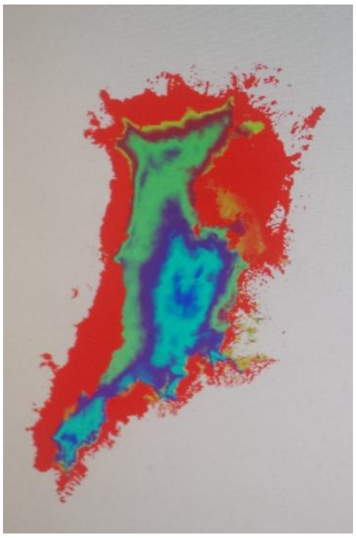


Figure 8: The surface mass balance for the Essery-original.

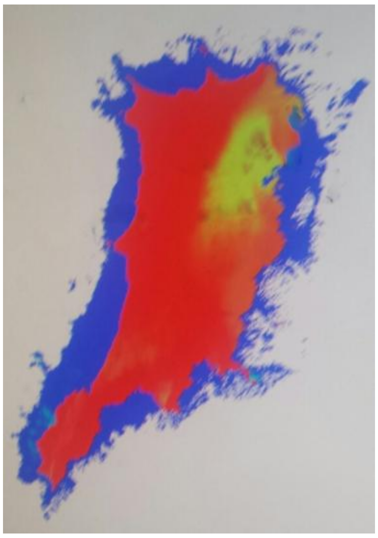


Figure 9: The albedo for the Essery-test.

Table 4: Used values for the Essery-test.

Parameter	Value
So	3 mm
τ_m	1.8*e1 s
τ_α	7*e7 s
α_{min}	0.65
α_{max}	0.85
α_{ice}	0.55
Threshold	-0.1

Parameterization

The following figures show the results from the three different runs which were made, the Essery-test, the Essery-original and the control-run. The code used for plotting the data can be seen in appendix 2.

Figure 10, 11 and 12 show the monthly value of the albedo for January 1999 for the Essery-test, Essery-original and the controll run. Figure 10 and 12 show a relativly high albedo over the whole island whilst the albedo in figure 11 indicates bare ice.

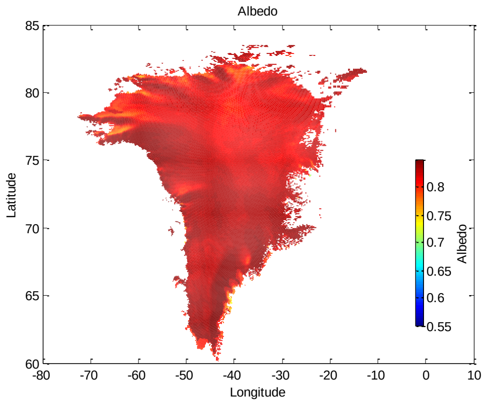


Figure 10: The albedo for the Essery-test in January 1999.

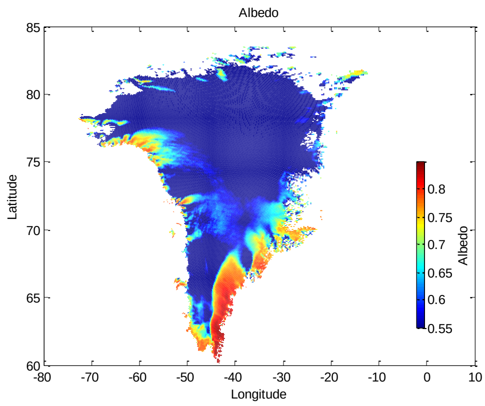


Figure 11: The albedo for the Essery-original in January 1999.

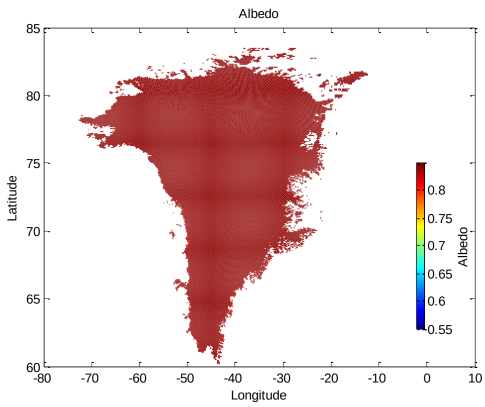


Figure 12: The albedo for the control-run in January 1999.

Figures 13, 14 and 15 show the monthly albedo for July 1991 for the Essery-test, Essery-original and the control-run. In figure 13 the albedo is high in the northern part whilst it is a little bit lower in the south and along the coasts. Figure 14 has a very low albedo in the northeastern part and a albedo around 0.7-0.75 along the western part. The albedo in figure 15 is high except along the coasts.

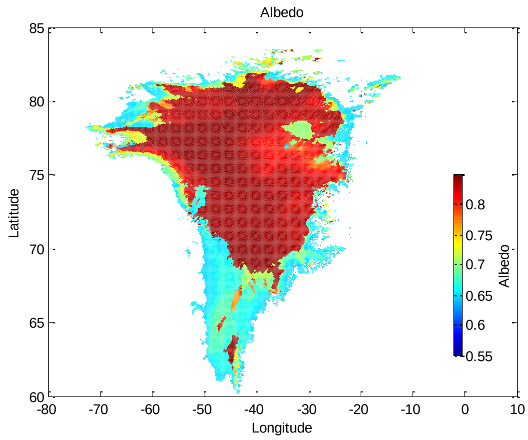


Figure 13: The albedo for the Essery-test in July 1991

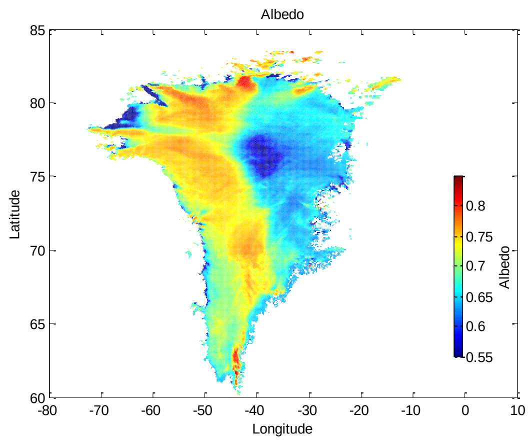


Figure 14: The albedo for the Essery-original in July 1991

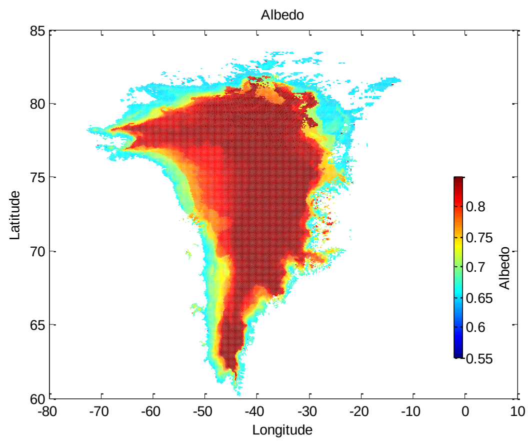


Figure 15: The albedo for the control-run in July 1991

The following figures 16, 17, 18, 19, 20 and 21 show the monthly snowmelt and *SMB* in July 1991 for the Essery-test, Essery-original and the control-run. In figure 16 there is snowmelt in the southern part and along the coasts of the island. The snowmelt in figure 18 can be observed in the south and in the northeastern part. Figure 20 has mainly melt along the coasts. The *SMB* in figure 17 and 21, is positive over the inland of island and negative along the coasts for both the Essery-test and the control-run. In figure 19, the *SMB* looks almost the same except over the northern pat where it is negative.

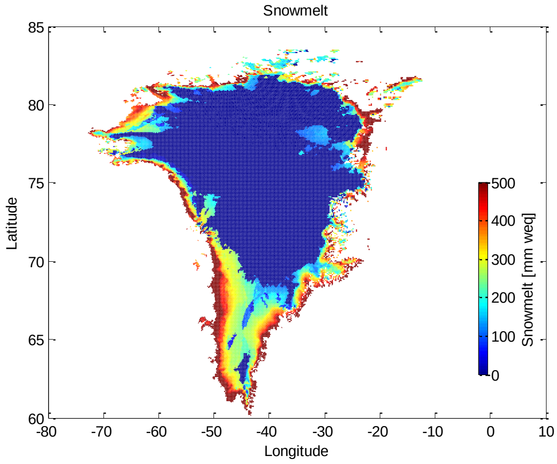


Figure 16: Snowmelt for the Essery-test in July 1991

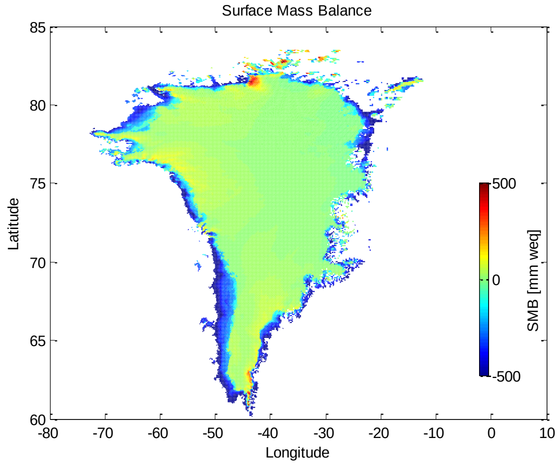


Figure 17: The surface mass balance for the Essery-test in July 1991

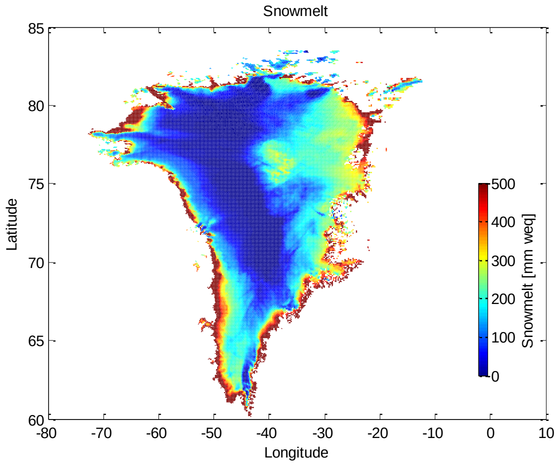


Figure 18: Snowmelt for the Essery-orginal in July 1991

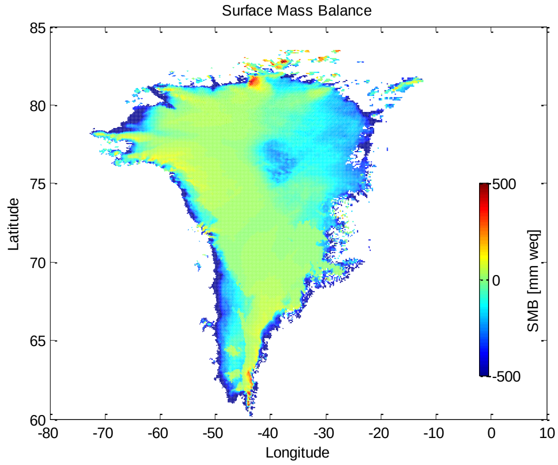


Figure 19: The surface mass balance for the Essery-original in July 1991

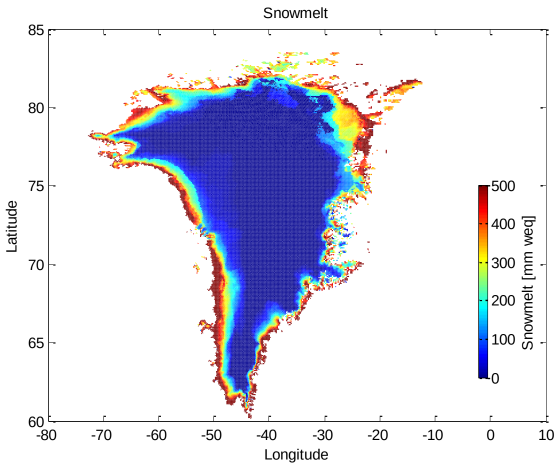


Figure 20: Snowmelt for the control-run in July 1991

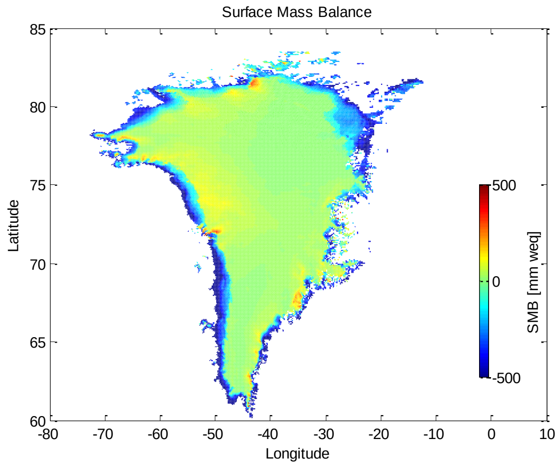


Figure 21: The surface mass balance for the control-run in July 1991

The monthly values of the albedo for July in 1999 for the Essery-test, Essery-original and the control-run can be observed in figures 22, 23 and 24. The albedo in figure 22 is high in the middle of Greenland but the lower albedo goes a little bit further in than just along the coasts.

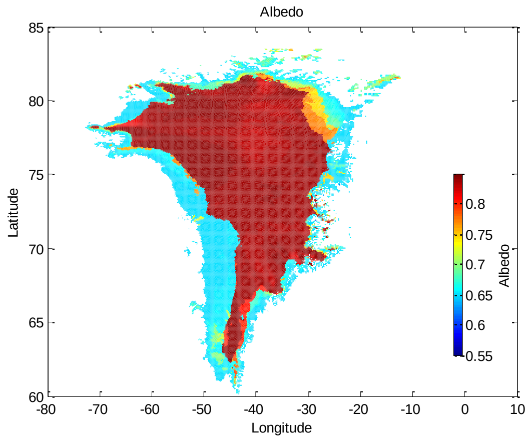


Figure 22: The albedo for the Essery-test in July 1999

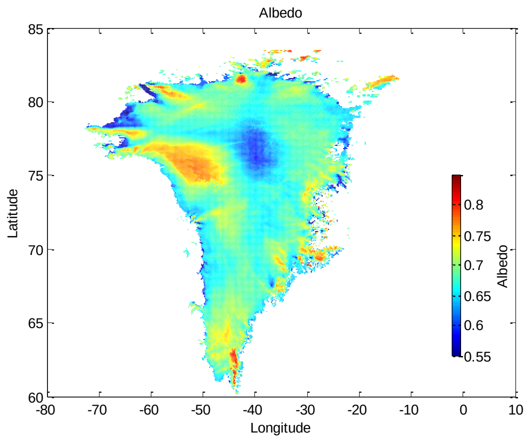


Figure 23: The albedo for the Essery-original in July 1999.

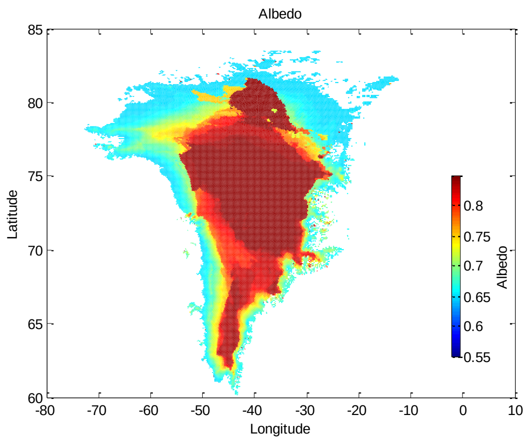


Figure 24: The albedo for the control-run in July 1999.

The figures 25, 26, 27, 28, 29 and 30 show the monthly snowmelt and *SMB* for July 1999 for the Essery-test, Essery-original and the control-run. The snowmelt is very low in figure 25 over almost the entire island. In the southwestern part the snowmelt is much higher. Figure 27 shows that snowmelt occurs over almost the entire island with the highest value along the coast. In figure 29 there is a very low amount of snowmelt except along the coasts and in the northern part of Greenland. The *SMB* is positive except for along the coasts in figure 26 and 30. In figure 28 the *SMB* is negative in the northern part of Greenland.

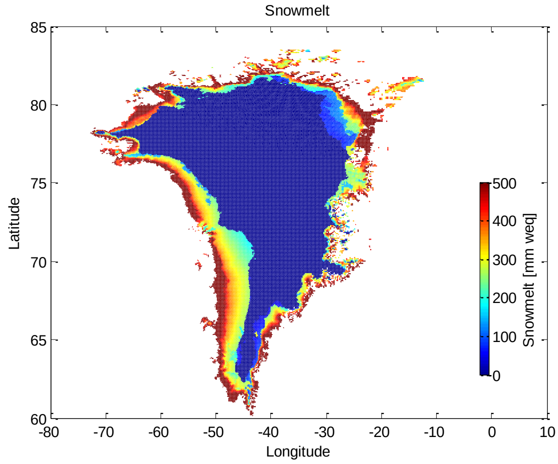


Figure 25: Snowmelt for the Essery-test in July 1999

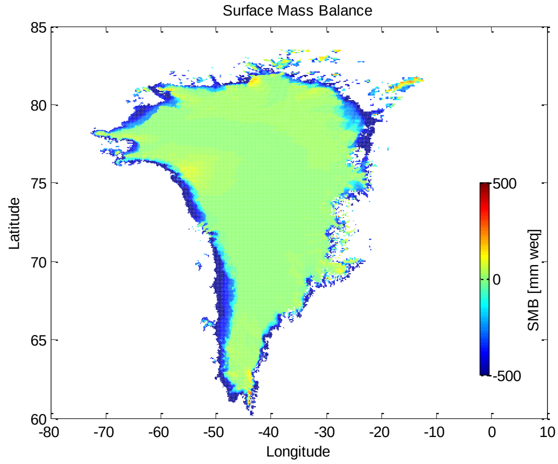


Figure 26: Surface mass balance for the Essery-test in July 1999

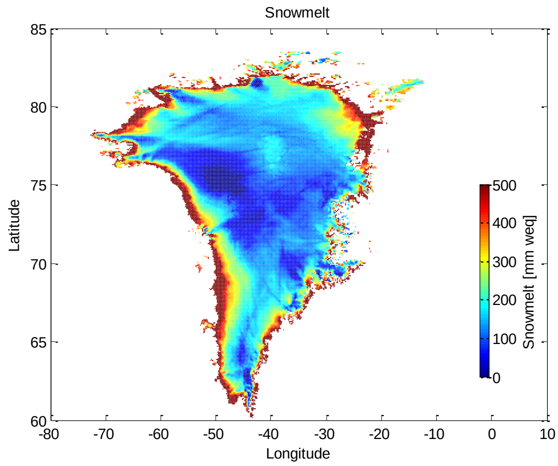


Figure 27: Snowmelt for the Essery-original in July 1999

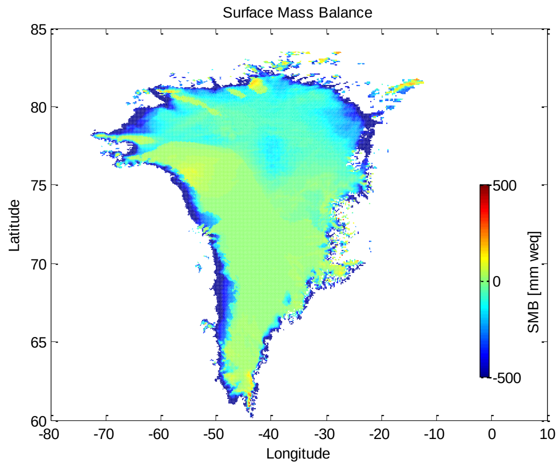


Figure 28: Surface mass balance for the Essery-original in July 1999

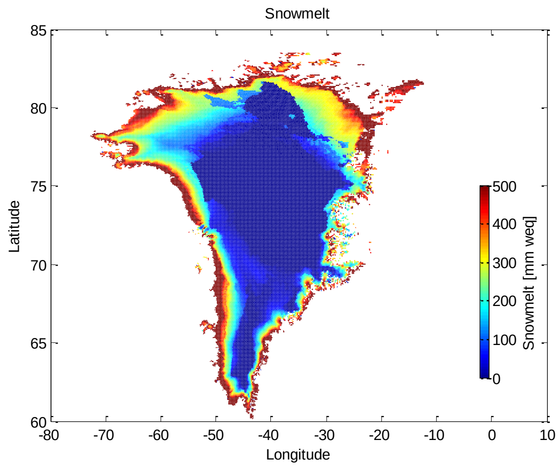


Figure 29: Snowmelt for the control-run in July 1999

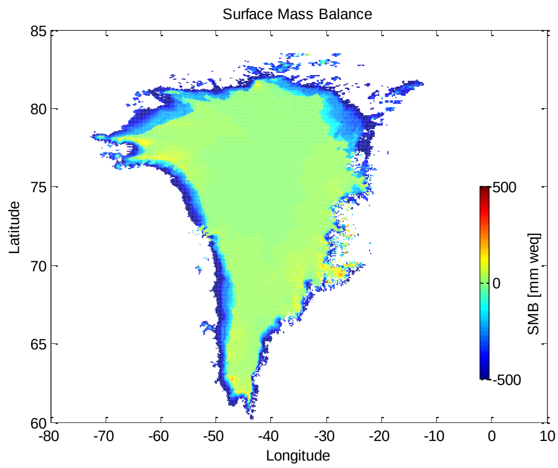


Figure 30: Surface mass balance for the control-run in July 1999

Discussion

In figures 6 and 7 it could be seen that the different plots follow each other quite well. The albedo decreases quite fast when the temperature is above zero and the ice sheet starts to melt. It can also be seen when looking at the absorbed solar radiation, F_{net}, that when the absorption is high the albedo decreases due to a change in the crystal structure. When it starts to snow the albedo reach its maximum value due to new fresh white snow.

The result from the sensitivity test with the original Essery-values gave a very unrealistic picture of the *SMB*, Figure 8. Even if the test was for July there should not be that much melt in the northern part of Greenland. Since the melt rate was determined by τ_m, this parameter was changed to a lower value which gave a much better result, figure 9. Figure 9 shows the albedo but it can still be observed that there occurred less melting since the albedo is not that low in the northern part. The *So* and the τ_α was also changed to a lower and a higher value, respectively. A higher value of τ_α makes the decay of the albedo slow down which keeps the value of the albedo a little bit higher than before. The *So* was changed from 10 mm to 3mm. It gave a better value but it is not quite realistic that the snow depth only needed to be that thin to reach α_{max} because the solar radiation can reach through the surface layer to the older snow pack or it may be bare ice underneath which lowers the albedo.

The value of the albedo in figure 11 is very odd. According to the figure, there would occur melting over the entire island. Since it is January this melting is unrealistic since it should not occur any melting at all due to low temperatures and no solar radiation due to the winter darkness. The parameters in the code were obviously not good. The melting rate was far too fast as was the change in the albedo for cold snow. Because of this unrealistic value it is hard to believe that the other result from the Essery-original runs would be truthful. The other two figures 10 and 12 show a much more reasonable result. The two figures have both a very high albedo, about 0.85, which is more normal for January.

Figure 14, which has used the Essery-original-code, looks very different compared to figure 13 and 15, especially over the northeastern part. Once again the albedo is too low, it lies between 0.55 and 0.65. Such low values almost indicate that it should be bare ice there. Though, the yellow part of the map which indicates to a little bit higher value, lies around 0.75, is more realistic since it shows the classic precipitation patterns over Greenland. Figure 23, which also shows the albedo in July but for a different year, does not have the same classic precipitation pattern as figure 14. This can indicates to different weather conditions with more precipitation in 1991 than in 1999. In figure 27 it can be observed that more melting occurred compared to figure 18 which also leads to a lower albedo due to the crystal structure change. When looking at *SMB* for the Essery-original-run the strange spot in the middle of northern Greenland is still there, Figure 28. According to both figure 19 and 28 there should be a negative value on the *SMB* which claims that it should occur more ablation than accumulation.

Figure 13 and figure 15 are quite alike except in the southern part where the albedo for the control-run is much higher. In figure 13 the lower albedo can depend on warmer temperatures in the south and lower elevations. Warmer temperature leads to melt and when the snow starts to melt the albedo decreases more rapidly. The albedo in the control-run did only depend on the temperature which could be the reason why they look unlike.

The southern part of Greenland in figure 13 is quite like the southern part in figure 16 which shows the melt. Though, when looking at the *SMB* in figure 17, one can see that the value of the *SMB* lies around zero, except along the coast. Cleary, melt has had a great impact on the albedo but the temperature may have become a little bit lower so that the melt water refreezes or there has been snow fall which increases the *SMB* value.

The control-run shows in figure 20 that the melt is limited along the coasts which are normal since the temperature usually is a little bit higher there. The *SMB* in figure 21 also shows that the coasts are influenced by the milder weather since the *SMB* is negative due to more ablation. Figures 20 and 21 go well along with the albedo plot for the same year and month. The red area of the albedo is slightly lower in the western part of Greenland where it lies between 0.75- 0.8, except along the coast where it is lower. In figure 20 it can be observed that a little more melt occurred along the western coast but the *SMB* in figure 21 is positive which indicates to refreeze of the melt water.

All figures, figure 17, 19 and 21, show a small spot in the northern part of Greenland where the *SMB* is quite high. The high value probably depends on the topography and the reason why the spot has a little bit lower value for the control-run may be because more ablation occurs. The difference between the snowmelt for the Essery-test and the control-run, Figure 16 and 20, is most significant in the southern part but it can still be observed that the snowmelt differs a bit. The Essery-test that, among other parameters, depends on τ_m has a more rapid melt rate compared to the control-run.

The albedo for July 1999 for the Essery-test, see Figure 22, has a different albedo due to the albedo from 1991. It is especially the southern part that differs. The south-eastern part has a much higher value compared to the 1991 values which can be explained by figure 25 which shows that the snowmelt was lower in 1999 than in 1991. The *SMB* in July 1999, Figure 26, follows the plot over the snowmelt except along the western coast. This may be due to snowfall or refreezing. Figure 24, which shows the albedo for the control-run for July 1999, has a lower albedo in the north compared to the control-run from 1991. It seems like there was less snow 1999 than 1991. According to figure 29 there was more snowmelt 1999 than 1991 but the *SMB*, Figure 30, is almost the same as for 1991 except for some spots in figure 21 with a higher *SMB* value indicating refreeze.

Conclusion

It could clearly be seen that the Essery original code not was very reliable. The plots showed too much snowmelt over Greenland which is not realistic, especially not in the higher elevations in the northern part. The code with the chosen values after the sensitivity test, the Essery-test, gave a much more truthful result. The control-run did differ from the Essery-test but not as much as it differed between the control-run/Essery-test and Essery-original. The difference with the Essery-test shows that the snow-code which was applied in the offline model is important for the change of the albedo. One cannot know if the result from the Essery-test is completely correct but this project shows how important the parameterization is to get a good approximation of the albedo in different weather models.

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I would also like to thank Elna Heimdal Nilsson for the guidance with the report.

Appendix 1

```
clear all
clc

%PARAMETERS
delta_t=3600; %Time step length in seconds
ntimes=365.*24.; %Number of timesteps
tau_alfa=1e7; %Seconds
tau_m=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
S0=10 %Snow depth to reach alfamax

%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/S0]);
    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 2

```
clear all; pack
clc
%load C:\Users\Marie\Documents\DMI\V3_ERAI_A65-
85_R02_SNMELT_1989_1999_YM.nc;
fname =
'C:\Users\Johanna\Documents\MATLAB\V3_Essery_original_SNW_1001_1010_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,'snw'); %öppnar filen
albedo = squeeze(alfa); %Trycker ihop filen från 4 till 3

%albedoyear = :,:,120; %Väljer vilket år vi vill kolla på
albedomonth = 1:12:120; %vald månad : 12 månader : tidsvektorn

%test=mean(albedomonth); %Medelvärdet för den valda månaden, alla år
test=albedomonth(:,1); %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')
caxis([0 10])
axis ([-80 10 60 85])
%contourf(lon,lat,albedoplot,0:200:3000,'LineStyle','none'); colorbar
%set(h,'edgecolor','none');
c=colorbar('vert','position',[0.80 0.20 0.015 0.40]);
ylabel(c,'Snow depth (m)')
title ('Snow depth')
xlabel('Latitude')
ylabel('Longitude')
%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';

%%%%%%%%
```