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Changes in Surface Mass Balance on the Devon Ice Cap in the Canadian Arctic

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Abstract

Climate change is an ongoing process that contributes to changes in the climate on a global scale down to a local scale. The Arctic sea ice and the glaciers have continued to decrease at the same time as the rate of sea level rise has increased. Ice caps are vulnerable to the climate change, because they are located adjacent to the Greenland ice sheet and near coastal areas in the Arctic.

In the present work, the surface mass balance is analyzed at the Devon Ice Cap that is located in the Canadian Arctic Archipelago. The difference between the surface mass balance for different time periods within the period 1980-2014 are studied as well as some of the surface mass balance components. The high resolution climate model HIRHAM5 is used to evaluate both the precipitation at the shallow ice cores and the temperature of the automatic weather stations with the observations at the Devon Ice Cap.

It is shown that the Devon Ice Cap is well represented in the runs that is driven with HIRHAM5. It is also shown that the precipitation and the snowmelt has an increasing trend, while the surface mass balance has a decreasing trend.

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Abbreviations

AWS	**A**utomatic **W**eather **S**tation
CAA	**C**anadian **A**rctic **A**rchipelago
CDO	**C**limate **D**ata **O**perator
DMI	**D**anmarks **M**eteorologiske **I**nstitut (**D**anish **M**eteorological **I**nstitute)
HIRHAM	**HI**gh **R**esolution **HA**mburg Climate **M**odel
RCM	**R**egional **C**limate **M**odel
SMB	**S**urface **M**ass **B**alance
WE	**W**ater **E**quivalent

Contents

1 Introduction

Climate change is a change in the usual weather found in a particular place and a change in Earth's climate. Climate change is something that concerns us all and everyone can relate to the climate change in different ways. Places on Earth where water freezes in the form of snow and glaciers, is called the cryosphere. Climate change is affecting both local and regional atmospheric circulation. Over the two last decades, the ice sheets in the Antarctic and Greenland have been losing mass. The Arctic sea ice and the snow cover during spring in the Northern Hemisphere have continued to decrease in high extent and glaciers have continued to shrink nearly globally. Since the mid 19^{th} century, the rate of sea level rise has been larger than the mean rate of sea level rise during the past two millennia [1]. These are some of the effects on the cryosphere.

Ice sheets are large and change relatively slow compared to the small glaciers, where the small size means small changes in e.g. melt and precipitation are quickly incorporated into the glacier. It is very important to understand how the climate works near the coasts where the ice caps, which are studied in the present work, are more vulnerable to the climate change. That is why researchers are very interested in investigating these areas and try to understand how the mass loss processes are related to the climate change.

The regional climate model (RCM) HIRHAM5 is used in the present work and compared with observation data from the Devon Ice Cap. Focus is on the surface mass balance components including snowmelt, runoff, evaporation and precipitation.

This thesis aims to analyze how the trends have changed for the surface mass balance components during the last decades and also the trend for the surface mass balance. The aim is also to evaluate the regional climate model HIRHAM5 over the Devon Ice Cap, including temperature biases for the Automatic Weather Stations (AWS) and precipitation biases for the shallow ice cores.

2 Background

2.1 Glaciology

At the present day glaciers and ice sheets cover a tenth of the Earth's surface. Glaciers are the most dramatic element in the Arctic landscape [2]. Glaciers influence both the local and the regional climate. They transport sediments and rocks far from their source and modify the landscape through erosion and deposition. Meltwater from glaciers drives turbines and yields mineral-rich soils. Global warming is affecting the glaciers which has been a threat to human property and life, because of their contribution to sea level rise as they melt. The glaciers are also important sources of freshwater for farming and hydropower [2].

A glacier starts to form when snow remains in the same area during the whole year and enough snow accumulates and transforms into ice. The glacier continuously moves from higher to lower ground under gravity and can be approximated as a viscous fluid. An ice sheet is defined as a mass of ice and snow of considerable thickness that covers more than 50 000 km^2. An ice cap, which is a small glacier, is defined as an ice mass that covers less than 50 000 km^2. Ice caps are shrinking much more than the ice sheets because they are smaller and therefore melt much faster [2].

2.2 Surface mass balance

The surface mass balance is the difference between accumulation, which is a positive mass term, and ablation, which is a negative mass term. Accumulation includes all processes by which snow or ice are added to a glacier and snow accumulation is most common where snow slowly is transformed into ice. Ablation includes a couple of combined processes that remove snow or ice from the surface of a glacier or reduction of water equivalent (we) [3]. Accumulation is the sum of snowfall, condensation and refreezing and ablation is the sum of runoff, evaporation and sublimation. The mass balance is closely linked to climate as it controls the rates of accumulation and ablation. With help from the mass balance data, the causes of changes in ice cap geometry can be determined. When looking into the past, it is important to see how the surface mass balance have changed over the course of several years [4].

Atmospheric circulation controls accumulation and ablation that contributes to surface mass balance, as can be seen in Figure 1. It shows how the mass balance is distributed over the glacier, which forms when accumulation of snow exceeds its ablation. On the top of the glacier the mass is redistributed by the wind and the ice is moving down because of the gravitation. Above the equilibrium line is the accumulation zone, where more mass is gained than lost, and below the equilibrium line is the ablation zone, where snow and ice ablation exceed accumulation [3]. If the equilibrium line goes up then the ice cap has lost large part of accumulation area and if the equilibrium line goes down then the ice cap gains accumulation area. It is therefore the ice caps are sensitive to the equilibrium line, while ice sheets are big and therefore small changes in equilibrium line are not so important.

Iceberg calving and submarine melt are also important dynamical mass loss processes in Antarctica and Greenland. Iceberg calving means that a huge block of ice breaks loose and crashes into the water. Meltwater from the glacier follows the ground under the water because it is denser than the incoming warm water at the surface. One third of mass loss is attributed to iceberg calving in Greenland and it is much more that is attributed to iceberg calving in Antarctica. During the time period 1992-2011, Greenland changed in mass by -142 ± 49 Gt/year [5].

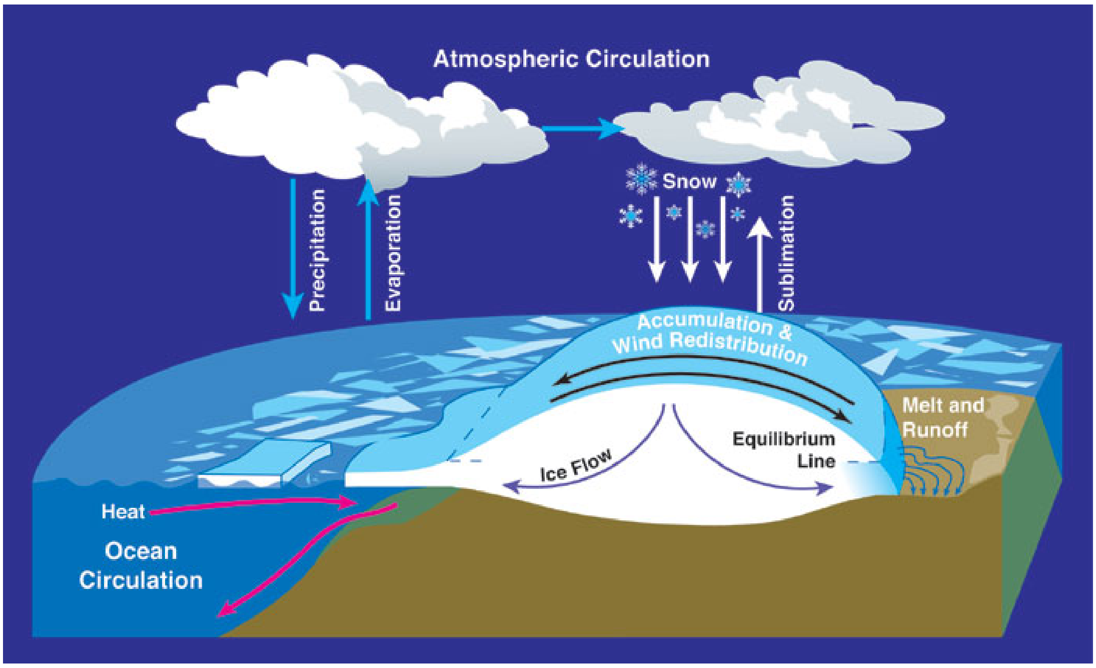


Figure 1: Glacier mass balance and atmospheric circulation [6].

Accumulation and ablation is included in the surface energy budget shown in Figure 2. Climate change affects glaciers in different ways. Glaciers are influenced by sensible heat flux, which is warm air that blows over the glacier. The higher temperature in these winds causes the glaciers to melt. When the water is changing phase then latent heat is emitted and the glacier starts to melt faster from inside. Shortwave radiation is emitted from the sun and reflected at the surface and the clouds, while longwave radiation is emitted by the Earth's surface and reflected at the clouds. Therefore the cloudiness changes have a larger impact on the climate. Albedo describes how much the surface reflects the radiation and the albedo feedback is much lower for bare ice than for ice with snow on the top [7]. The amount of precipitation affects how large the glaciers can be. If the atmosphere gets warmer it can carry more moisture, which means that heavier snowfall can be expected.

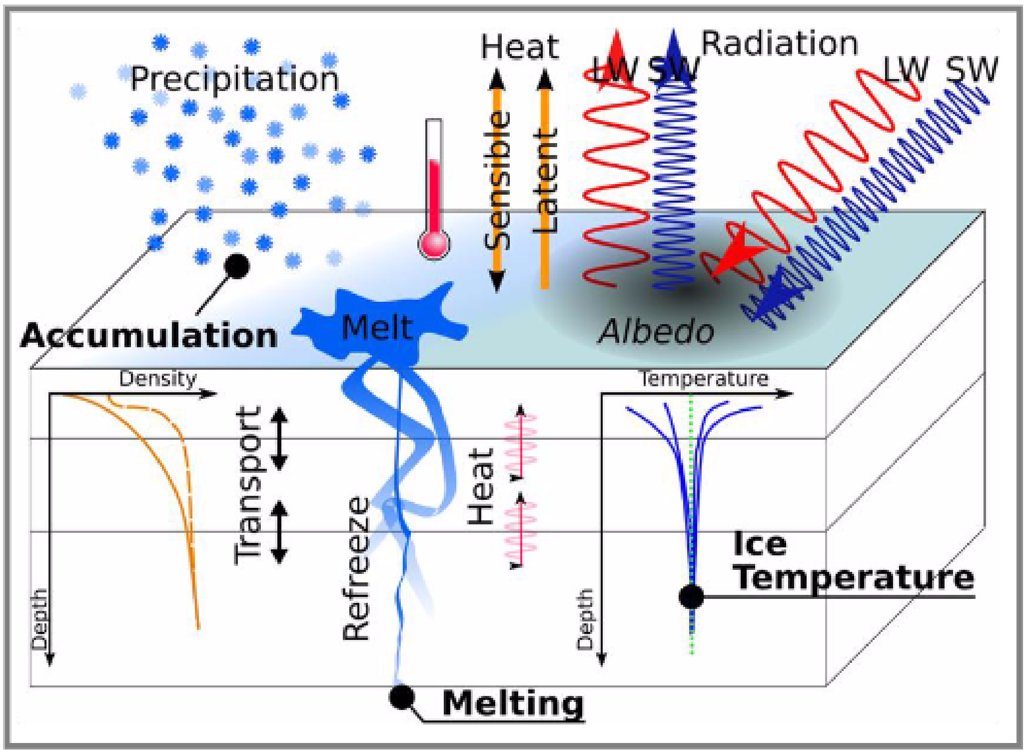


Figure 2: Surface energy budget (courtesy of Christian Rodehacke, 2016, via personal communication)

2.3 Devon Ice Cap

The Devon Ice Cap is located on Devon Island, Nunavut, in the Canadian Arctic Archipelago (CAA). Devon Island is the largest uninhabited island in the world (approximately 66 800 km^2) [8]. A large area of the island consists of a high plateau that is bordered by deep fjords and sea cliffs in many places. The ice cap is located in the eastern part of the island (approximately 14 000 km^2) [9]. The ice cap is slightly asymmetrical with a east-west ridge that is more pronounced where it gradually tilts downward to the west than to the east. The southern ridge begins around 20 km south of the summit and the highest point is 1930 m a.s.l. [10]. This is a good ice cap to investigate because it has long records of observations and can therefore be used as a reference point together with other ice caps at the coasts around Greenland.

2.4 Observational datasets

Other researcher have previously analyzed measurements of surface air temperatures and lapse rates from AWSs in the CAA. The measurements were made during the time period 1988-2007 at different sites that is located in the CAA including the Devon Ice Cap [9].

Previous researcher has extract shallow ice cores on the Devon Ice Cap. Eight shallow ice cores less than 20 m deep were drilled on the ice cap during April-May in the year 2000. The ice cores are sited in the accumulation area, which can be seen in Figure 3. The densities for snow and firn, an intermediate state between snow and glacier ice, were determined to estimate the average mass balance for each core site during the time period 1963-2000 [10].

3 Method

3.1 HIRHAM5

High Resolution Hamburg Climate Model 5 [11] is a regional climate model that covers Greenland and part of the CAA. The model is run and developed at the DMI. Surface mass balance is calculated in the model with melt calculated based on the full surface energy balance. The HIRHAM5 model is driven by the historical ERA-Interim reanalysis at the boundaries. Retention and refreezing are parametrized in a multi-layer snow pack of up to 25 layers in the subsurface and retention is density dependent. The dynamics in the model come from HIRLAM7 [11], that is a numerical weather prediction forecast system. The physics have been modified from the ECHAM5 [11] global climate model. The model has $\sim$5 km resolution in the horizontal and 31 vertical layers for the atmosphere, the model time step is 90 seconds [11].

ERA-Interim is the latest global atmospheric reanalysis from 1979 and continuously updated in real time produced by European Centre for Medium-Range Weather Forecasts [12]. The ERAI product gives output every three hour for surface parameters including the weather and conditions for both ocean-wave and land-surface. Data for upper-air parameters including the troposphere and stratosphere comes every six hour. The HIRHAM5 model is forced every six hour on the boundaries with a daily sea surface temperature and sea ice forcing. The purpose with a reanalysis is to produce an homogeneous record of atmospheric evolution in the past. By assimilating observations into a forecast model, the goal is to make more accurate weather products [13].

3.2 Data analysis

Data was analyzed using a Climate Data Operators (CDO) and MATLAB software. CDOs are a collection of command line operators to manipulate and analyze climate model data and numerical weather prediction model data. Modeldata is output in GRIB (Gridded Binary) format and converted to a network Common Data Form (netCDF). NetCDF is a set of software libraries and self-describing, machine-independent data formats for representing scientific data. These were used in statistical operations and the plots were made in MATLAB [13].

Research has been done at the location of eight different shallow ice cores, marked in Figure 3. Observation data for these locations [4] has been compared with the HIRHAM5 model in the present work. The elevation and accumulation rates for the ice cores are needed to validate the model. The surface mass balance in the model is also compared with the observed mass balance.

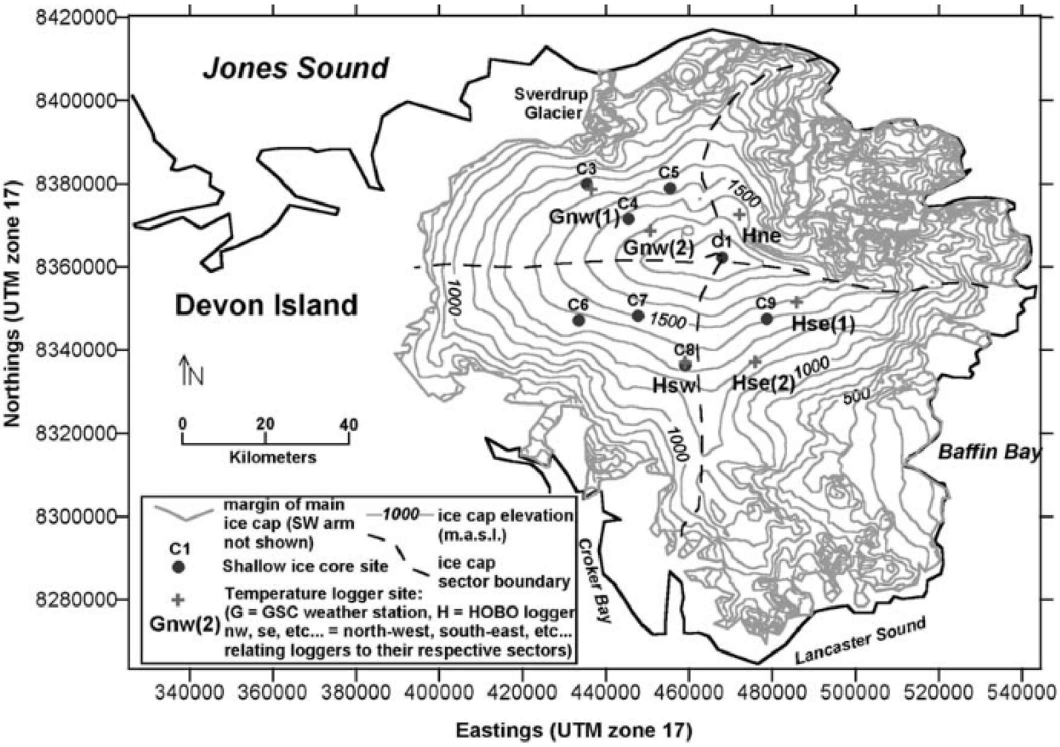


Figure 3: Map of the Devon Ice Cap, where the dots mark out the eight shallow ice cores, taken from ref [10].

26 automatic weather stations have been placed at different locations on the Devon Ice Cap. The transect for 6 of these stations are marked as Devon_N and the transect for 20 of these stations are marked as Devon_S in the lower part of Figure 4. Observation data is named Devon North and Devon South and downloaded from ref [9].The stations at the Devon North transect spans a horizontal distance of >40 km and were distributed at an elevation range from 330 to 1880 m a.s.l. The stations at Devon South were distributed at 2 km intervals along the 50 km long transect at an elevation range from 480 to 1800 m a.s.l. The stations on the north slope have been installed between 1992 and 2005, while the stations on the south facing slope of the ice cap have been installed between 2004 and 2007 [9]. Observation data records cover the time period between 22^{nd} of March 1992 until 21^{st} May 2005 and the time period from 15^{th} of April 2004 until 19^{th} of May 2007, for Devon North and Devon South respectively. Data for the time period with observations are compared with the corresponding period in the model. A selection of these 26 figures has been made in the present work focusing on some typical and interesting graphs. The differences in elevation for each of the stations are validated for the observations and the model data.

Focus is on surface mass balance, snowmelt, runoff, evaporation and precipitation in the present work. All these surface mass balance components that cover the whole ice cap are summed up in one figure to see how the annual changes relate to each other.

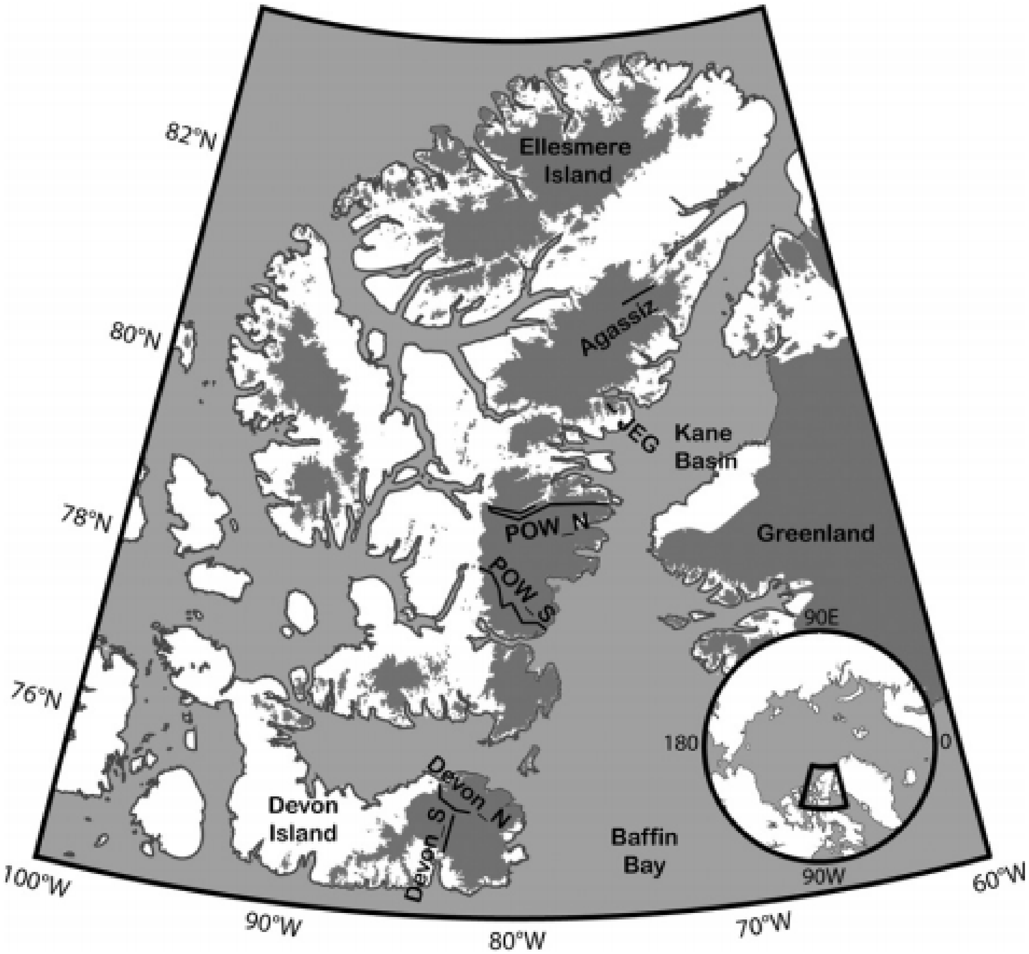


Figure 4: Map of Canadian Arctic Archipelago with heavy black lines at the Devon Ice Cap in the south, for both Devon North and Devon South respectively. The lines show temperature-elevation sensor transect, the picture is taken from ref [9].

3.3 Working process

The sub-domain for the Devon Ice Cap was cut out of the wider Greenland domain and used when creating all the files during this project. A map over the Devon Ice Cap was made to illustrate how the temperature, precipitation and surface mass balance was distributed over the ice cap between 1980 and 2014. The surface mass balance was made for three interannual time periods and a anomaly was made between each of the time periods.

To make a figure with different components, the dataset is composed of daily means which was converted to annual sums by using CDO. A land-sea mask was applied to the script. The relevant components were picked out and summed up to be plotted in the same figure. The standard deviation is calculated for each of the surface mass balance components.

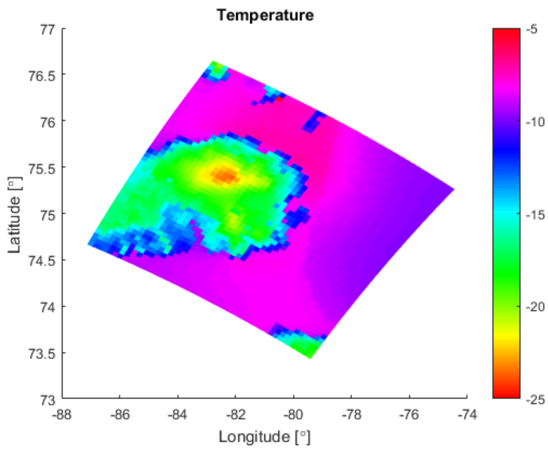
The locations for the shallow ice cores were translated into latitudes and longitudes from UTM coordinates. These datasets are composed of daily means which were converted to time mean by using CDO and a land-sea mask was applied to the script. The model output for the shallow ice cores was compared with observations by using MATLAB. The observed elevation for the ice cores was verified in the model.

All the locations for AWS were given with latitudes and longitudes. The model dataset contains daily mean temperatures and a land-sea mask was applied to the script. The model output for the temperatures was selected to fit the same time period as that of the observed data for Devon North and Devon South respectively, in order for them to be compared to each other.

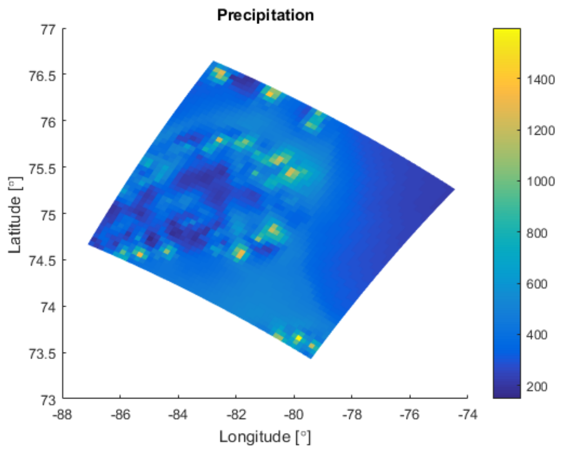
4 Results

4.1 Temperature and precipitation

The Devon Ice Cap on the Devon Island is the coherent area in the middle of each subfigure in Figure 5. The two subfigures display maps of climate variables over the Devon Ice Cap region. Figure 5a shows how the annual mean temperature is distributed in the Devon domain. The larger area in the figure is the sea, where the mean annual temperature fields are approximately -8°C. At the Devon Ice Cap the temperature gradually gets lower, down to -25°C at the top of the ice cap. Figure 5b expresses the annual precipitation for the ice cap in mwe/year. Precipitation is mostly snowfall, which can be very hard to measure at the surface. Most of the precipitation falls around the coasts (yellow dots in the figure) and less precipitation falls, for instance, at the top of the ice cap (dark blue area in the figure).



(a) Temperature

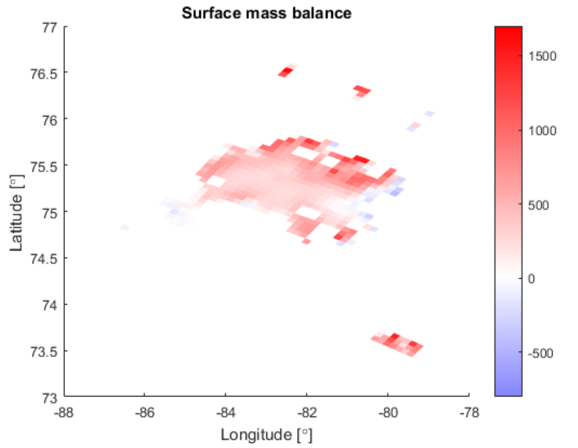


(b) Precipitation

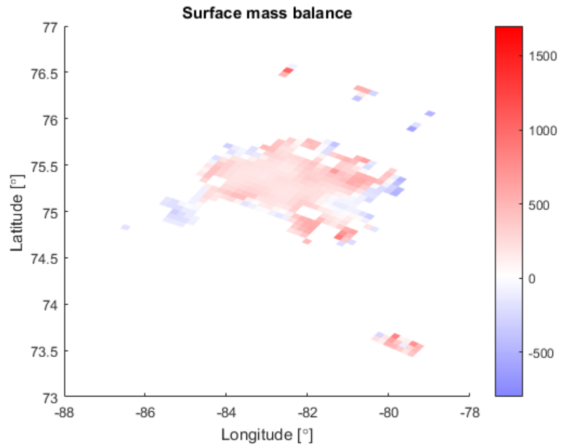
Figure 5: Maps over Devon Ice Cap for the time period 1980-2014. Figure a) shows annual temperature in degree Celsius and Figure b) shows annual precipitation in mwe/year.

4.2 Surface mass balance

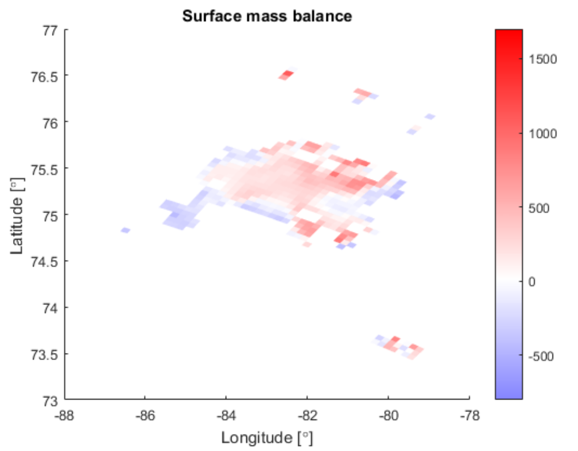
Annual surface mass balance at the Devon Ice Cap is expressed in Figure 6 for different time periods. The white color shows where it is in balance, at the equilibrium line (SMB=0) and note that non-glacier points are also always white. Accumulation and ablation are displayed as red and blue respectively. The equilibrium line is between the accumulation and ablation zones. The color bars have a range from -800 to 1700 mmwe/year to include the total minimum and maximum values. Figure 6a displays the time period 1980-1989, which has the highest accumulation rates compared to the other subfigures. The accumulation zone covers almost the whole ice cap, where the highest values are observed near the coast in the north and in the southeast. The ablation zone is concentrated at the coasts and the lowest values are found in the east. For the time period 1990-1999 in Figure 6b the equilibrium line has moved up at a higher altitude. The maximum accumulation is lower and the minimum ablation is higher than in Figure 6a. For Figure 6c the accumulation at the top of the Devon Ice Cap is smaller during 2000-2014 than in Figure 6a and 6b. The ablation zone is found at the coast around the whole ice cap and the equilibrium line is even higher in Figure 6c than previous time periods.



(a) Time period 1980-1989



(b) Time period 1990-1999

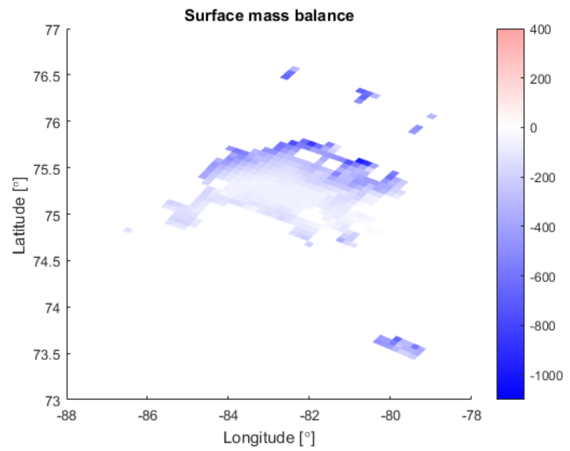


(c) Time period 2000-2014

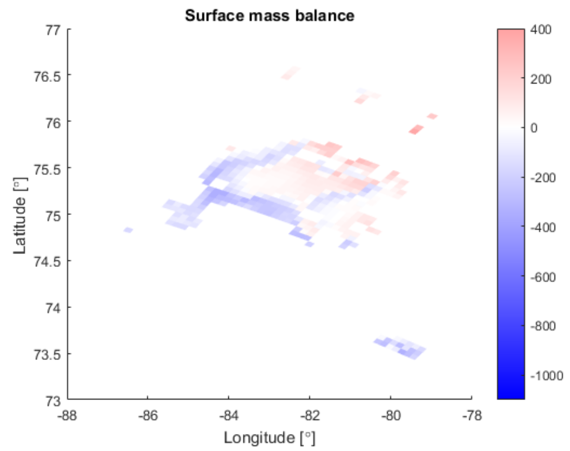
Figure 6: Maps over Devon Ice Cap show annual surface mass balance in mmwe/year for the time periods; a) 1980-1989; b) 1990-1999; c) 2000-2014.

The anomalies between the subfigures in Figure 6 are displayed in Figure 7. Note that the color bars in Figure 7 have a different range compared to Figure 6. The range is from -1100 to 400 mmwe/year because it includes the total minimum and maximum values. The difference between time period 1980-1989 and 1990-1999 is expressed in Figure 7a. The difference over the whole ice cap is negative which means that the ice cap has lost mass.

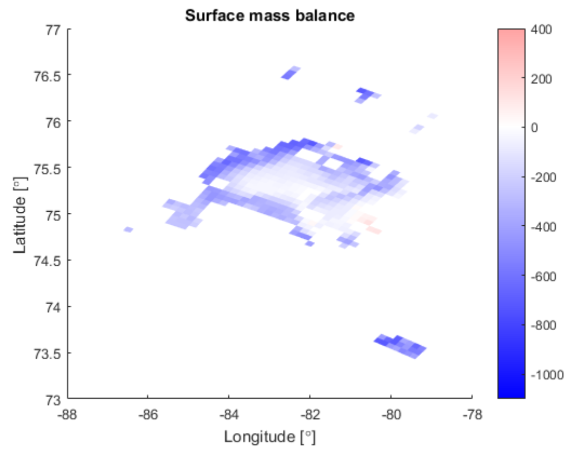
The largest difference is at the northern part of the ice cap and the smallest difference is at the top of the ice cap. Figure 7b displays the difference between the time periods 1990-1999 and 2000-2014. The Devon Ice Cap has both gained mass and lost mass in the Millennial shift. The highest accumulation in the northeast and the lowest ablation in the southwest is approximately the same but with different sign. The difference between the earliest and the latest period is displayed in Figure 7c. Overall the Devon Ice Cap has lost mass, especially in the northwest but the ice cap has also a small positive difference in the southeast.



(a) 1990-1999 minus 1980-1989



(b) 2000-2014 minus 1990-1999



(c) 2000-2014 minus 1980-1989

Figure 7: Maps over Devon Ice Cap show anomalies in annual surface mass balance in mmwe/year for the time period differences between; a) 1980-1989 and 1990-1999; b) 1990-1999 and 2000-2014; c) 1980-1989 and 2000-2014.

4.3 Surface mass balance components

The surface mass balance components for the Devon Ice Cap are shown in Figure 8. Each component has a separate line that expresses an annual value for the mass during the time period 1989-2012. The surface mass balance correlates with precipitation and snowmelt correlates with runoff. All these parameter changes have high interannual variability except the annual changes for evaporation which are relatively low.

According to Figure 8, snowmelt has had an increasing trend during the whole time period. The annual runoff is connected to the annual snowmelt and it displays an increasing trend. The annual mass for runoff is less than the annual mass for snowmelt, indicating that retention and refreezing are important on the Devon Ice Cap. Precipitation follows the same pattern as the surface mass balance, but has higher annual mass. The surface mass balance seems to vary a lot during this time period, but has probably a decreasing trend that anticorrelates with the snowmelt and runoff.

An average for the annual mean in Figure 8 is expressed in Table 1. The standard deviation is calculated for each of the components, which shows the degree of uncertainty for every component.

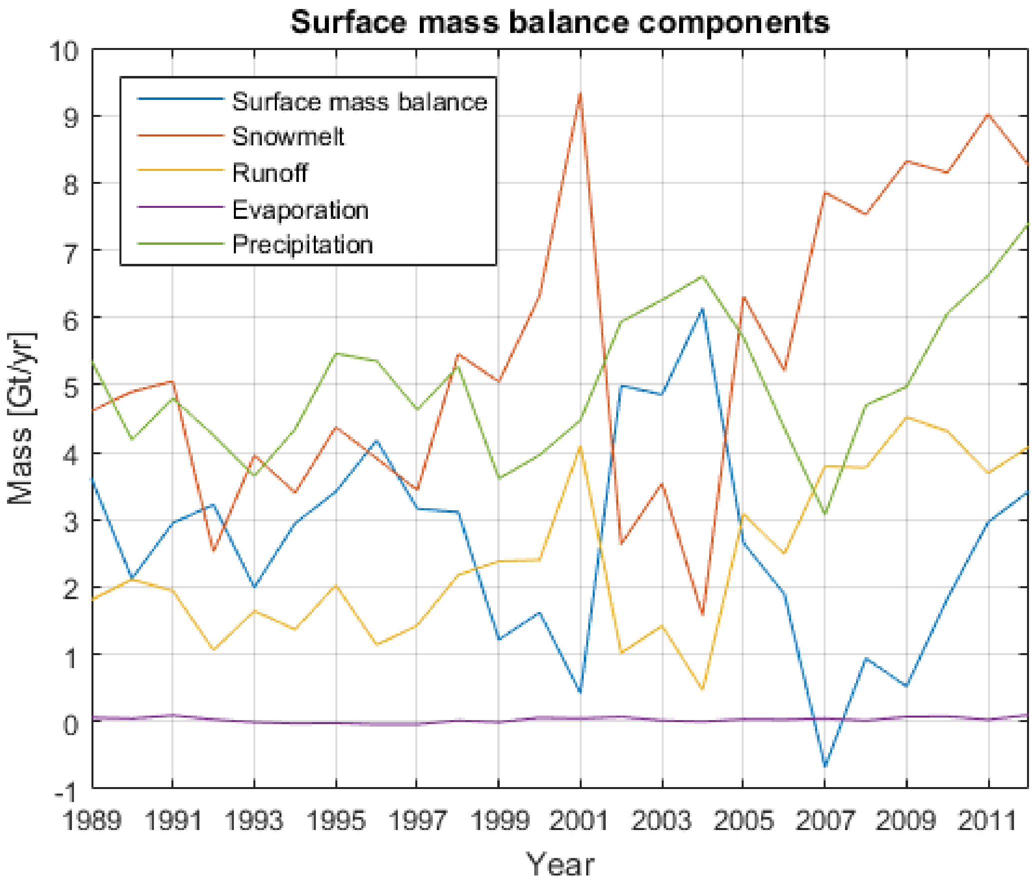


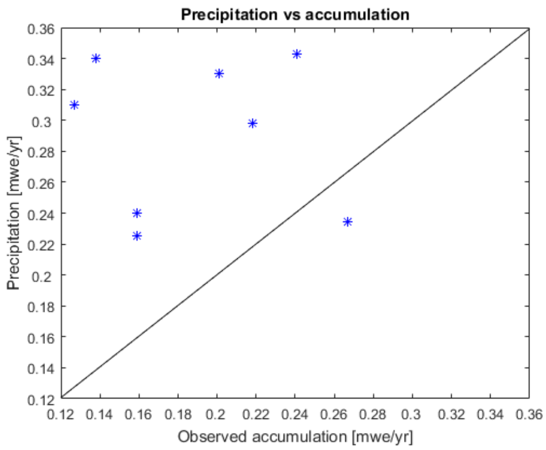
Figure 8: Surface mass balance components for the time period 1989-2012.

Table 1: Surface mass balance components.

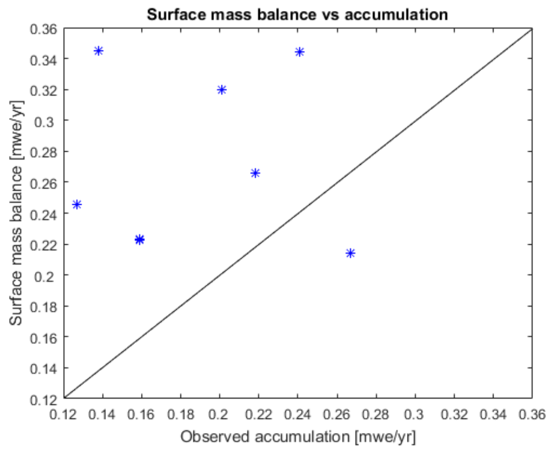
Component	Annual mean [Gt]	Standard deviation [Gt]
Surface mass balance	2.6463	±1.5681
Snowmelt	5.4467	±2.2211
Runoff	2.4271	±1.2011
Evaporation	0.03019	±0.04046
Precipitation	5.0432	±1.0791

4.4 Shallow ice cores

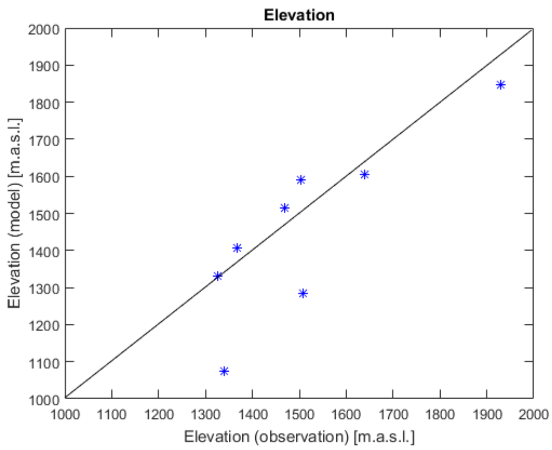
Eight shallow ice cores are represented by the blue stars in Figure 9. Model data are compared with observational data in these subfigures. Precipitation in the model is compared with observed accumulation in Figure 9a. Accumulation includes the difference between precipitation and evaporation. If the dots are to the left of the 1:1 line it means that the model has a positive bias (the model is overestimating the amount of precipitation) and if the dots are found to the right of the line, then the model has a negative bias (the model is underestimating the amount of precipitation). The surface mass balance is compared to the observed accumulation in Figure 9b. The elevation of the model data and the observational data is plotted against each other for each of the ice cores, shown in Figure 9c. Note that the time period for the observed accumulation is between 1963 and 2000 and the time period for the model output in Figure 9 is between 1980 and 2000. This may introduce some errors when plotting the different time periods against each other.



(a) Precipitation vs accumulation



(b) Surface mass balance vs accumulation

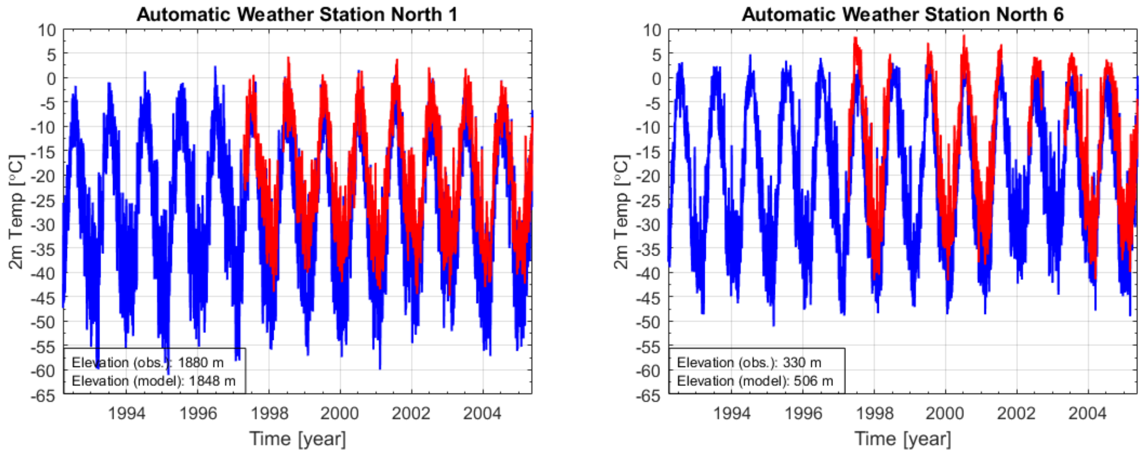


(c) Elevation

Figure 9: Scattered plots for eight different shallow ice cores. Figure a) shows precipitation in the model versus observed accumulation; b) shows surface mass balance in the model versus observed accumulation; c) shows elevation for model versus observation data. The model has the time period 1980-2000 and the observations have the time period 1963-2000.

4.5 Automatic weather stations

The subfigures in Figure 10 visualize two examples from the north temperature-elevation transect (see Fig. 4). The figures describe the annual temperature from March 1992 until May 2005. The blue curve is the model output and the red curve is the observational data. The AWS north 1 in Figure 10a is sited at the top of the Devon Ice Cap and the elevation for the measured elevation is higher compared to the elevation for the model. The AWS north 6 in Figure 10b is sited at a very low altitude near the land surface close to the coast. The measured elevation is lower compared to the elevation for the model. The model has a negative bias in Figure 10 in wintertime, where the model temperature is lower than observations. When looking at all figures for Devon North transect (not included in the report), the measured temperature could reach a minimum of -50°C. Generally the AWSs at the Devon North transect have long records with observational data that covers all seasons.

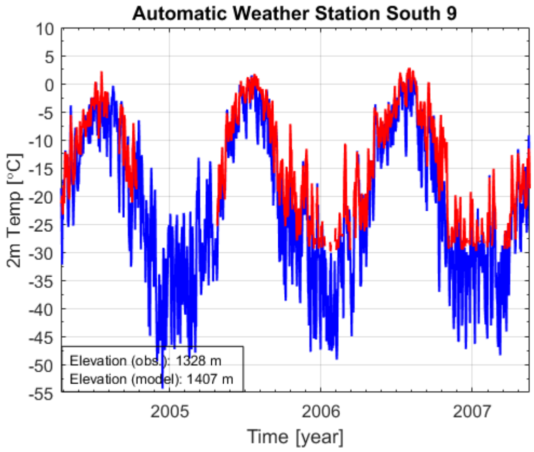


(a) Automatic weather station north 1.

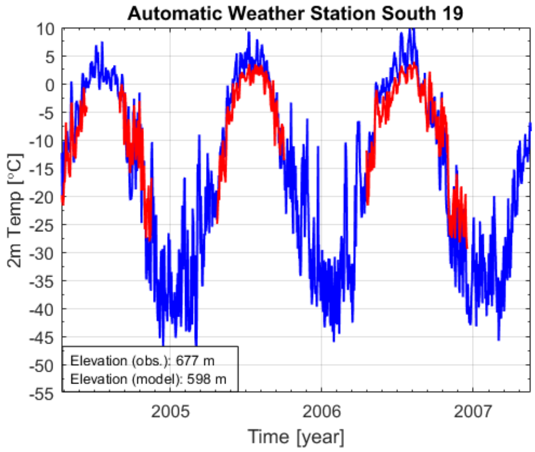
(b) Automatic weather station north 6.

Figure 10: Temperatures for two automatic weather stations in the north for the time period between 22^{nd} of March 1992 until 21^{st} of May 2005. The model and observational data are visualized as blue and red respectively.

The subfigures in Figure 11 visualize two examples from the south temperature-elevation transect (see Fig. 4). The figures describe the annual temperature from April 2004 until May 2007. The blue curve is the model output and the red curve is the observational data. The AWS south 9 in Figure 11a is sited at a relatively high altitude on the Devon Ice Cap and the elevation for the measured elevation is lower compared to the elevation for the model. The AWS south 19 in Figure 11b is sited at a low elevation near the land surface close to the coast. The measured elevation is higher compared to the elevation for the model. The model has a negative bias in Figure 11a and a positive bias in Figure 11b. In wintertime the model has substantially lower temperatures than the observations. When looking at all figures for Devon South transect (not included in the report), the temperature could reach a minimum of -30°C, which is demonstrated in Figure 11a. The AWSs at the Devon South transect has relatively short records with observational data that rarely covers all seasons. Note that the temperature axis is different for Figure 10 and 11.



(a) Automatic weather station south 9.



(b) Automatic weather station south 19.

Figure 11: Temperatures for two automatic weather stations in the south for the time period between 15^{th} of April 2004 until 19^{th} of May 2007. The model and observational data are visualized as blue and red respectively.

5 Discussion

5.1 Evaluation of the Devon Ice Cap in HIRHAM5

The annual temperature is continuously decreasing with elevation, which is captured in the model for Figure 5a. Most of the precipitation falls close to the coast of the ice cap, as can be seen in Figure 5b. The precipitation falls from humid air when the air mass is pushed over the ice cap, hence it is less precipitation that falls at the top of the Devon Ice Cap compared to lower elevations. In which location the precipitation falls depends also on the atmospheric circulation. The surface mass balance is related to the precipitation and if the precipitation falls as snow that stays at the ice cap, the surface mass balance is increased. Darker red in Figure 6 corresponds to snow accumulation, which is related to the sites with more annual precipitation in Figure 5b.

The measured elevation and the model elevation is validated for all the AWSs and the ice cores. The topography is very varying at the ice cap, even a high model resolution (∼5 km) is not enough to capture the differences within a gridbox. The elevation difference within a gridbox could be up to 300 m for the shallow ice cores, so the model performance needs to be further scaled compared with observations. The largest deviation of the elevation for the AWSs was found to be near the land surface and the coast of Devon Ice Cap, where the elevation difference could be up to 200 m. The variation in elevation causes changes in atmospheric conditions, known as an orographic effect. The orographic effect is related to the steep slope around the Devon Ice Cap. If the model does not capture the elevation the temperature measurements at a height of 2 m can be affected.

In Figure 9a, most of the dots for the shallow ice cores are placed above the 1:1 line, which means that the model probably is overestimating the amount of snow that falls at the ice cap. The snow at the ice cap is often redistributed by the wind and this is very hard for the model to capture. The model cannot be expected to capture refreezing, which is a very heterogeneous process. The time period for the observations is between 1963 and 2000 and the time period for the model is between 1980 and 2000. This may introduce some errors but the model output for HIRHAM5 extends only back to 1979 (the first year is not included in the time series).

Generally for the AWSs, the model does not perform well in wintertime where the model has a substantial bias. The model is probably more stable than the actual climate in wintertime. This could depend on that the model allowing cold air to accumulate at the surface and does not taking into account that the wind creates turbulence and therefore redistributing the air. The cloud cover is affecting how much radiation that reach the surface and which temperature it is at the surface. The measured minimum temperature for the north and south weather stations could depend on a instrumental tolerance. The lack of data can be controlled of how good the equipment is in low temperatures or if the equipment has been damaged in some way.

It is interesting that the model has a positive bias for the site in the southern part of the ice cap (Fig. 11b) and a negative bias for the site in the north (Fig. 10b). The stations are located at approximately the same elevation according to the model. AWS north 6 is observed to be located at lower elevation and AWS south 9 is observed to be located at higher elevation than the model. AWS north 1 is also sited at a higher elevation than in the model and the model has a negative bias. If the AWS is located near the edge of the ice cap it could be a difference in albedo. The temperature decreases with elevation and this makes a bigger difference at lower elevations than higher elevations at the Devon Ice Cap.

5.2 Trends in surface mass balance of Devon Ice Cap

Unusually good records from the Devon Ice Cap have been used in this thesis compared to records from other ice caps in the Arctic and this makes it easier to see trends.

Since 1980 the Devon Ice Cap has lost mass more than gain mass until today. It seems like the time period 1980-1989 were a much colder period than 1990-1999, because Figure 7a displays a huge mass loss compared to Figure 7b that displays both a positive and a negative mass difference. This means that the time period 1990-1999 was a relatively warm period and that the ice cap has recovered during the time period 2000-2014. The equilibrium line has moved up towards the top of the Devon Ice Cap and it is not good if this trend continues, because it means that the ice cap can melt away in the future. The annual temperature is below 0°C in the Devon domain, as can be seen in Figure 5a, but the interannual temperature could be above 0°C that is a threat to the ice cap.

The trends for some of the surface mass balance components can be analyzed in Figure 8. The snowmelt and the runoff tend to increase during the time period 1989-2012, which influences the climate that gets warmer. The snowmelt needs to refreeze instead of runoff to stabilize the surface mass balance and retain the Devon Ice Cap. The climate change impacts the amount of precipitation. Warmer air can retain more water than colder air and this may lead to heavier precipitation. Evaporation does not have a large impact on the climate but it is included when calculating the accumulation. The surface mass balance is related to the sea level rise and if the surface mass balance decreases it means that the global sea level increases.

6 Conclusions

The regional climate model HIRHAM5 is evaluated for the Devon Ice Cap. It is shown in the present work that the ice cap is well represented in high resolution runs that is driven with HIRHAM5.

The surface mass balance has changed during the time period 1980-2014 and the anomalies show that the surface mass balance has a decreasing trend. The surface mass balance components are analyzed for the whole ice cap during the time period 1989-2012. The snowmelt and runoff has an increasing trend as well as the precipitation has an increasing trend.

HIRHAM5 has captured the right order of magnitude for the point measurements of the shallow ice cores, but some biases are identified for the precipitation and the surface mass balance. The model has captured the interannual temperature for the automatic weather stations, but some biases are identified for the temperature.

The surface mass balance is influenced by the climate change and because the Devon Ice Cap is located at the coast in the Arctic, the ice cap is vulnerable to the climate change.

7 Outlook

Further research is needed to predict how the climate will change in the future. For example improving the resolution of the model may reduce the biases for the temperature.

It is good to have long records for as many different locations in the Arctic as possible. One thing to do is to follow up the measurements and extend the time periods to get a better overview of trends in the datasets. More observations is needed from the Devon Ice Cap and other ice caps as well, to improve and reduce the biases in the model.

More surface mass balance components can be added to get a better overview to see how the components are related to each other during a longer time period. It would be good to drill more ice cores in the future and also set up more automatic weather stations that can collect measurements during a long time period.

It would be interesting to run HIRHAM5 for future simulations of the Devon Ice Cap. Based on the results from the present work it should be possible to refine estimates of the future evolution of the ice cap.

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