LUND UNIVERSITY
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Importance of large scale extreme precipitation to the surface mass balance of the Greenland Ice sheet

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Abstract

The ongoing climate change has affected Greenland's ice sheet with heighten near surface temperatures, an extended melt season and change in precipitation. These effects have caused Greenland's ice sheet to melt at an accelerating rate.

This study focuses on the importance of large scale extreme precipitation to the surface mass balance of Greenland. The surface mass balance of Greenland's ice sheet is the difference between the accumulation and ablation. The large scale extreme precipitation in this study is mainly focused on the precipitation brought to Greenland by atmospheric rivers. An atmospheric river is a weather phenomenon were a large amount of water is being transfered over large distances in the atmosphere.

The precipitation and surface mass balance data is calculated by HIRHAM5 and the atmospheric river data retrieved from ERA-Interim AR detection catalog.

How the surface mass balance is affected by atmospheric rivers depends to a large extent on the season. The result showed that an atmospheric river occurring during the summer season most likely will negatively affect the surface mass balance, as the one occurring in 2012 did, while atmospheric rivers occurring during the winter usually has a positive influence, as seen in 1996. During the summer season a decreasing trend in the surface mass balance can seen due to the increasing near surface temperatures and the extended melt season. The west coast of Greenland is the most affected by atmospheric rivers, since the main precipitation brought to the west coast of Greenland is by atmospheric rivers even if the east coast experience a higher amount of daily precipitation.

Acknowledgment

I want to especially thank my two supervisors Ruth Mottram at the Department of Climate and Arctic Research at DMI and Elna Heimdal- Nilsson at Lund University. Ruth, for her help with all the practical parts and her expertise and discussions about the field. Elna, for her help and guidance in the academical work during this thesis.

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List of Abbreviations

AR	Atmospheric River
CDO	Climate Data Operator
DMI	Danmarks Meteorologiske Institut (Danish Meteorological Institute)
ECHAM	ECMWF Hamburg Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA-Interim	ECMWF Interim reanalysis
GRACE	Gravity Recovery and Climate Experiment
HIRHAM	High Resolution Hamburg Model
HIRLAM	High Resolution Limited Area Model
IVT	Integrated Vapour Transport
NWP	Numerical Weather Predictions
RCM	Regional Climate Model
SMB	Surface Mass Balance
weq	Water Equivalent

Contents

1 Introduction

This thesis aim is to assess the importance of atmospheric rivers to Greenland's surface mass balance, SMB, by looking at data from ECMWF, Interim reanalysis, ERA-Interim, and HIRHAM5. ERA-Interim is a global atmospheric reanalysis with a spatial resolution of approximately 80 km. The reanalysis in ERA-Interim refers to the reuse of archived observations from forecast models and the observations assimilated into it to create a global data set [2]. HIRHAM5 is a regional climate model with a resolution of 5.5 km, more about HIRHAM5 in Section 3.1 [1].

The past decades have affected Greenland's ice sheet in an overall negative way due to the ongoing climate change. Climate model simulations is used to assess the effect of climate change on Greenland's ice sheet. The ice sheet mass budget on Greenland is currently decreasing in an accelerating rate [3]. Greenland contains 2.85 million km^3 of ice over an area of 1.71 million km^2 [4] and if all of Greenland's ice were to melt the global mean sea level will rise approximately 7 metres [3].

However, there have been some heavy precipitation events which have had a positive effect for the Greenland ice sheet. In 2016 there was a large amount of heavy snow and rain, which influenced the annual mass budget of the ice sheet in a positive way. The snow and rain was brought to Greenland by an atmospheric river, AR, from the tropics. An AR is a weather phenomenon where a large amount of water is transferred in the atmosphere from one place on Earth to another, see Section 2.4 [5]. The precipitation delivered to Greenland by two successive ARs in October 2016, in combination with a subsequent cool summer, to temporarily stop the trend of increased mass loss observed over the last few years [6]. In 2012 the ARs had the opposite effect on the surface mass of Greenland, due to the unusual high temperatures, the AR caused a large decrease in the surface mass [16].

In this project the output from the regional climate model HIRHAM5 is used to assess the importance of high magnitude precipitation, associated with ARs found in the ERA-Interim AR detection catalog, to the present day SMB of the Greenland ice sheet. The ERA- Interim AR detection catalog is based on a model with some observations assimilated into it, see Section 3.2.

2 Background

2.1 Climate change

The average temperature on Earth has increased around 0.8 degrees Celsius during the past 100 years. Earth temperature is affected by ocean and atmosphere circulation, clouds, ice and snow, natural and anthropogenic gases, solar output and Earths orbital characteristics. Earth is heated by incoming radiation and cooled down by emitted infra-red radiation, IR radiation [7]. The IR radiation is calculated by Stefan- Boltzmann's law, where Earth is considered to be a black body, see Equation 1.

$$\frac{dQ}{dt} = \sigma(T^4 - T_0^4)4\pi R_{\text{Earth}}^2 \tag{1}$$

In Equation 1 sigma is Stefan-Boltzmann's constant of $5.67 \cdot 10^{-8}$ W/(mK^4), $4\pi R_{\text{Earth}}^2$ is the area of Earth where R_{Earth} is the radius of Earth. $\frac{dQ}{dt}$ is the amount of heat transport between the black body and the surroundings. T is Earth's temperature, and T_0 is the surrounding temperature. The law implies that a small change in temperature result in a large change of radiation [7].

The incoming solar radiation, I, which has a heating effect, is calculated by Equation 2.

$$\mathrm{I} = (1 - A)S\pi R_{\text{Earth}}^2 \tag{2}$$

In the equation for solar radiation, A is the global albedo, where albedo is the measure of the reflective solar radiation out of the total solar radiation. S is the average solar constant of 1368 W/m^2 and R_{Earth} is the radius of Earth. In the solar radiation equation the area of Earth is not considered to be a sphere but a disk because it only considers the side of Earth where the sun is shining [7]. There are more factors affecting the heating and cooling down of Earth. If only the outgoing IR radiation and incoming solar radiation where the two aspects that has an impact on Earth's temperature, the temperature would be around -18 degrees Celsius compared to Earth average temperature of 15 degrees Celsius today [8].

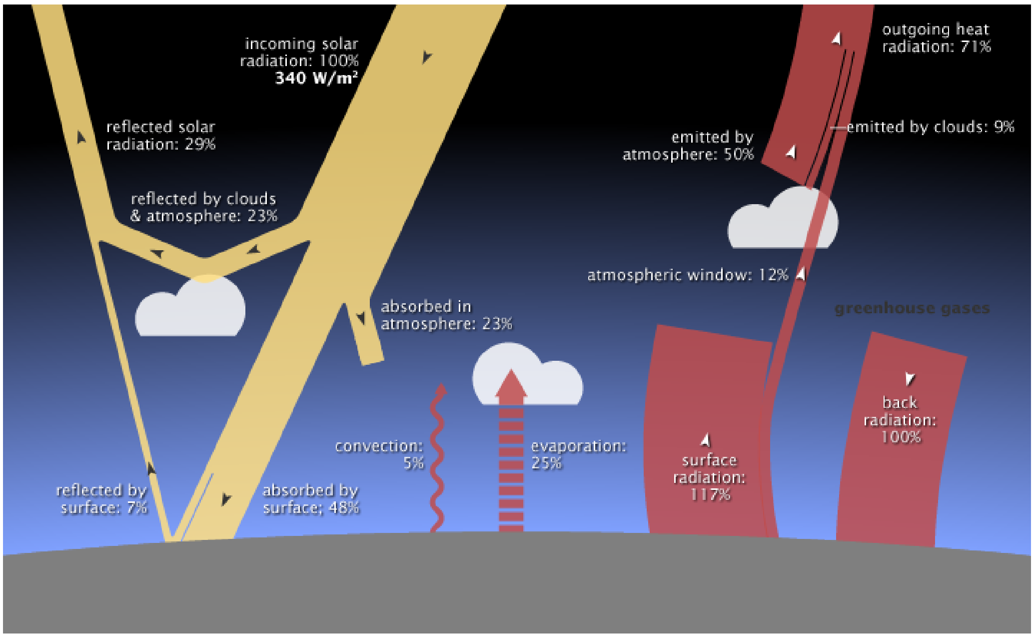


Figure 1: An illustration of the radiation balance on Earth [9].

Another important aspect of Earth's climate are greenhouse gases. The greenhouse gases play an important part in why Earth is warmer than -18 degrees Celsius. Figure 1 is an illustration of how different kinds of radiation are being absorbed and emitted on Earth. Greenhouse gases absorb the outgoing IR radiation before they leave the atmosphere, which is called the greenhouse effect. The greenhouse gases can emit back the IR radiation they absorbed to Earth and heat up the surface, see Figure 1. The increased temperatures on Earth is due to the increase of greenhouse gases in the past decades. The main anthropogenic enhancement of the greenhouse effect is due to the increase of the greenhouse gas carbon dioxide, CO_2, which mainly is produced through combustion [8].

2.2 Climate change in Greenland

The ongoing climate change has during the past decades affected Greenland's ice sheet. Greenland contains 2.85 million km^3 of ice over an area of 1.71 million km^2. If all of Greenland's ice sheet were to melt it would lead to a sea level rise of approximately 7 metres [4]. The ice mass loss of Greenland is responsible for approximately 25 percent of global mean sea level rise, which corresponds to around 0.85 mm per year. The increase of the mean sea level is rising at an accelerated rate [3].

In 2003 to 2012 the Gravity Recovery and Climate Experiment, GRACE, satellite data was used to investigate the ice mass loss over Greenland. The result showed an average ice mass loss of 183 Gt per year [10]. A more recent update made by the Arctic program of GRACE satellite data from 2002 to 2016 indicate an increase of ice loss to 269 Gt per year instead of 183 Gt per year [11].

The near surface temperatures on Greenland has increased during the past decades. A study of the temperature and pressure gradient changes over Greenland showed that between 1996 to 2014 the temperatures changed up to 0.15 degrees Celsius per year, which is a temperature increase of 2.7 degrees Celsius [12]. The reason for increases in near surface temperatures is likely due to increases of greenhouse gases. Greenhouse gases have contributed to a rise in global temperatures. The records of temperature and precipitation's natural variations over Greenland is very little which makes it hard to find the anthropogenic climate forcings that have significantly affected Greenland's climate in the past years [13].

The increase in greenhouse gases have caused the melting season on Greenland to increase due to their contribution in rising near surface temperatures, which contribute to more melting of the ice. The melt season occurs in general between June to August in Greenland and it is a big correlation between ice sheet fluctuations and the rise of temperatures, especially during the summer [3].

2.3 Surface mass balance and total mass balance

SMB is the difference between the accumulation, which is the positive mass term, minus the ablation, the negative mass term. Accumulation is the positive term adding mass to the ice sheet in form of snow, rain, condensation and refreezing. The atmospheres circulations affecting the ice sheet are displayed in Figure 2. The most effective way of adding mass is snowfall accumulating over the ice sheet creating thicker layers. Ablation is the negative term in form of melt water runoff, evaporation and sublimation. SMB is measured in mm water equivalent, mm weq [15]. Greenland's SMB is therefore mainly determined by the melt rate and the precipitation. In 2012 the SMB was negatively affected by an AR with warm air brought to Greenland from the tropics which accelerated

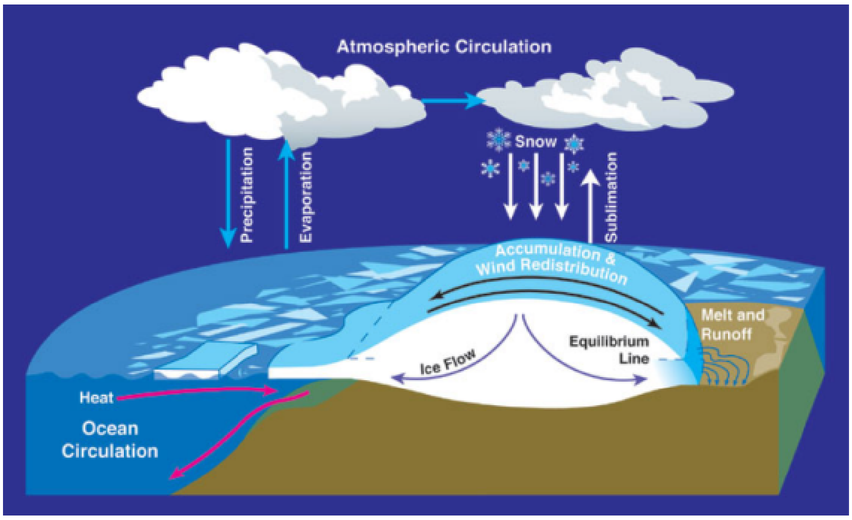


Figure 2: An illustration of the atmospheric circulations and the mass balance of the glaciers [14].

the melting of the ice in 2012 [16].

$$\text{Surface mass balance} = \text{Accumulation - Ablation} \tag{3}$$

The total mass balance includes the SMB and the dynamic component, made up of calving icebergs and submarine melt at marine glaciers termini [17]. The decrease of Greenland's surface mass is a result of different factors, the increase in runoff due to melt, a higher ice discharge and the loss in surface mass gained due to precipitation. During the past two decades there has not been enough precipitation over Greenland to increase the total ice mass, with the exception of the AR in October 2016 [18].

The decrease in ice mass over Greenland affect the albedo. Albedo is the measure of the reflective solar radiation out of the total solar radiation as mentioned in Section 2.1. Lower albedo leads to an increase in absorption of solar radiation. If more solar radiation is absorbed the melting of the ice mass increase, creating a positive feedback. In 2012 a record low summer albedo was recorded of 68.2 percent which is approximately 7 percent lower than the average summer albedo between 2000 to 2001. The south west region of Greenland was the most affected and the summer albedo decreased to around 20 percent lower than average [11].

2.4 Atmospheric rivers

ARs are, as their name suggests, river-like events in the atmosphere. They contribute to most of the water vapour transported to the northern latitudes. ARs are defined as narrow corridors of increased moisture transported in the troposphere with a short lifetime, usually less than a few days. To measure ARs integrated water vapour transport, IVT, is used, more about IVT in Section 3.2. The term river is used to describe an AR since they transport water at a volume flow rate comparable to those of the world's largest rivers. They are about 2000 km long and between 300 to 500 km wide in the atmosphere [5].

ARs are associated with extra-tropical cyclones. Extra-tropical cyclones are common and ordinary low-pressure systems, they are the largest contributor of precipitation to the mid-latitudes. The ARs moisture origins from the cold front of the extra-tropical cyclones and/or direct water transport of water vapor from the tropics towards the North Pole. ARs making landfall in Greenland are usually direct water transport from the tropics. The characteristics of an AR is their strong low level winds and high water vapour content [5].

When ARs are forced upwards due to high orography the water vapour cools down. Orography refers to high mountain areas or elevated landscapes. Cold air can hold a much smaller content of water compared to warm air which cause an "overload" of water. The "overload" will then precipitate. Therefore, ARs can cause extreme amounts of precipitation when entering colder areas or encounter high orography [5].

An overview of an example of how an AR can develop is given in Figure 3. Figure 3 illustrates how the synoptic development can cause an AR to reach high latitudes. The low pressure system, blue, air moving anticlockwise and high pressure system, red, air moving clockwise force the moisture to move upwards from the tropics, see green arrow, all the way to Norway [19].

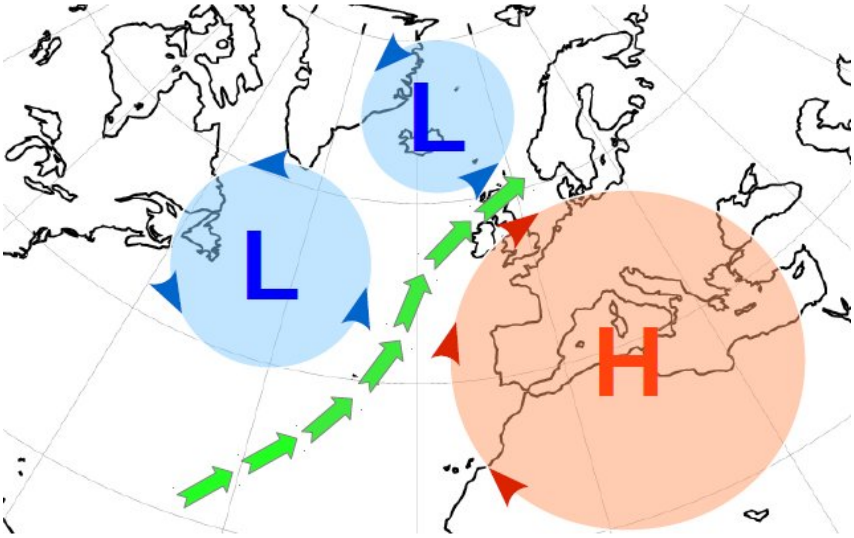


Figure 3: An AR from the tropics brought up to higher latitudes due to influences of large scale weather systems, blue illustrating a low pressure system and the red a high pressure system [19].

2.5 Climate and numerical weather prediction models

In this project a regional climate model, RCM, was used to assess the importance of ARs to Greenland ice sheet. Numerical weather prediction, NWP, models uses mathematical equations based on laws of physics to forecast the weather. The mathematical equations are integrated over time, but the atmosphere is to complex for the models which result in inaccurate weather predictions over time. Climate models function in a similar way as NWP models, but they are designed to calculate averages to predict trends and not weather situation. NWP models today is not sufficient when it comes to predicting weather several weeks or months ahead even if they have improved in the last decade. When forecasting weather there are a lot of uncertainties, but to accurately calculate the weather occurring in real life with mathematical equations is possible [8].

In climate models the average is calculated over a long time period to see trends, this makes the climate model more reliable when investigating future scenarios compared to a NWP model. In climate models there are three important conservation laws applied to the atmosphere, conservation of mass, momentum and energy. These three laws are applied in the models as an input with the radiation laws, mentioned in Section 2.1, and some observational data [20].

The conservation of mass is known as the continuity equation, which describe conservation of mass for a fluid,

$$\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0 \tag{4}$$

The conservation of energy is based on the first law of thermodynamics,

$$DQ = c_v DT + pD\alpha \tag{5}$$

The conservation of momentum equation is a rewrite of Newton's second law in a three-dimensional rotating system,

$$\frac{Du}{dt} = \frac{uvtan(\phi)}{a} - \frac{uv}{a} + \frac{1}{\rho}\frac{\partial P}{\partial x} + 2\Omega sin(\phi) - 2\Omega cos(\phi) + F_{rx} \tag{6}$$

$$\frac{Dv}{dt} = -\frac{u^2 tan(\phi)}{a} - \frac{uw}{a} - \frac{1}{\rho}\frac{\partial P}{\partial y} - 2\Omega sin(\phi) + F_{ry} \tag{7}$$

$$\frac{Dw}{dt} = -\frac{u^2 + v^2}{a} - \frac{1}{\rho}\frac{\partial P}{\partial z} - g + 2\Omega cos(\phi) + F_{rw} \tag{8}$$

The conservation of momentum equation describes the forces acting on an air parcel. $\frac{Du}{Dt}$ is the total derivative in time considering in the x plane and the same for $\frac{Dv}{Dt}$ and $\frac{Dw}{Dt}$ but in the y and z plane. They are dependent on the pressure gradient force, Coriolis force, the curvature and the friction force and in the z direction gravity also play an important part. The first law of thermodynamic states that the heat added to the system, DQ, is equal to the internal energy, $c_v DT$, and the work done by the system, $pD\alpha$ [20].

Precipitation is a large uncertainty in forecasts even just a few days ahead for both NWP- and climate models. There are two kinds of precipitation strati-form precipitation and convective precipitation. Convective precipitation is short lived and happens due to an unstable atmosphere, where air parcels get heated and rise. When the air parcel rise it cools down forcing the air parcel to become more and more saturated while rising, increasing its relative humidity. When the parcel is saturated or supersaturated a cloud can form, containing cloud droplets. The cloud droplets can grow larger by condensation and coagulation inside the updraft of the cloud creating rain droplet. When the gravitational force on the rain droplets exceed the updraft it starts to precipitate [20]. Convective precipitation can occur on such a fine scale that is not resolved by climate- or NWP models, making it difficult for the models to forecast. The scale of convective precipitation can be less than 1 km, which is the smallest resolution for NWP models [8].

3 Methodology

3.1 HIRHAM5

During this project the main data used was output from High Resolution Hamburg Climate Model 5, HIRHAM5. HIRHAM5 is a RCM with a resolution of 5.5 km. The model has 31 vertical levels. The forcings on the lateral boundaries comes from the ERA-Interim climate reanalysis dataset. The wind vectors, temperature, specific humidity at all 31 vertical levels are given to the model at 6 hour intervals with the surface pressure in HIRHAM5 [1]. All the precipitation data used to produce figures are results of simulations from HIRHAM5 data. HIRHAM5 is built from, High resolution limited area model, HIRLAM [21], and ECMWF Hamburg model, ECHAM [22]. HIRLAM is a NWP forecasting model used by numerous meteorological institute and developed by the international HIRLAM programme. ECHAM is a circulation model developed at Max Planck Institute for Meteorology [23]. HIRHAM5 combines the physic scheme from ECHAM and the dynamical forecasting core from HIRLAM [24].

The HIRHAM5 model has change from a Eulerian time scheme in HIRHAM4 to a semi-lagrangian scheme in HIRHAM5. The change has made it possible for high resolution simulations since a semi-lagrangian scheme uses longer time steps than a Eulerian time scheme. When considering the Lagrangian atmosphere the model follow the air parcels along their trajectories while using the Eulerian way the model consider the change in different variables at a fixed point. HIRHAM5 is a quasi-hydrostatic model. A quasi-hydrostatic model refers to a model that filter out the disturbances of higher frequencies, such as sound waves, from the fundamental equations used to calculate weather and climate situations. The model considers the small vertical motions without constraining them to zero as a non-hydrostatic model would do, which improves the models weather simulations to be closer to reality. This improves the weather and climate forecasts [23].

3.2 Atmospheric river detection catalog

When investigating the amount of ARs making landfall in Greenland the ERA-Interim AR detection catalog was used. ERA-Interim AR detection catalog is based on ERA-Interim, which is a data set with 6 hourly runs with a resolution of approximately 80 km made by European centre for medium range weather forecasts, ECMWF [2].

In the ERA-Interim AR detection catalog by B. Guan and D. E. Waliser the IVT is used to detect ARs. IVT is calculated from the wind fields between 1000 to 300 hPa, the specific humidity and IVT is measured in kg/ms. A threshold for the strength of the IVT is set in each grid cell and the threshold is given in percentiles, standard percentile is 85. Increase in IVT is mostly seen along extra-tropical storm tracks for both summer and winter with some seasonal variability. The direction, length and width of the IVT is looked at to identify an AR, if the direction in half of the different grid cell deviate 45 degrees or more from the mean IVT the reading is ignored. A reading is also discarded if the IVT does not have a poleward component since atmospheric rivers transport water from low to high latitudes [25].

The AR catalog has detected ARs all over the globe between 1979 to 2015. To find the atmospheric rivers occurring over Greenland the data set was altered by changing the latitude and longitude. The south west sector, latitude 55° to 72° N and longitude 45° to 75° W, south east sector, latitude 55° to 72° N and longitude 15° to 45° W, north west sector, latitude 72° to 85° N and longitude 45° to 75° W and the north east sector, latitude 72° to 85° N and longitude 15° to 45° W. By changing the latitude and longitude it made it possible to see how different parts of Greenland are affected by ARs. When looking at the different sectors only the ARs that made landfall was investigated. To see how ARs influenced the SMB of Greenland, data from HIRHAM5 was compared where large ARs made landfall to see how the SMB was affected.

3.3 Data analysis

The data for this thesis was collected from HIRHAM5 and the ERA-Interim AR detection catalog. The data was analyzed using climate data operators, CDO [26]. CDO is a data manipulation software that includes multiple statistical possibilities to modify and analyse data outputs from datasets.

HIRHAM5 has calculated daily precipitation data for precipitation over Greenland between 1980 to 2016. Greenland is divided up in grid points, 402 times 602 grid points. The grid points over Greenland experience different amounts of precipitation. Each year the highest annually precipitation value was extracted from the HIRHAM5 data set and put in a ranked list by magnitude, giving an output for 37 values in each grid point. A linear slope value of those 37 values was calculated, with the amount of precipitation on the Y-axis and the logarithmic scale of the return value on the X-axis, thus a steep slope indicates more events with large amounts of precipitation. The return value refers to the probability of a precipitation value to occur over those 37 years. The largest amount of precipitation has a probability of occurring once in 37 years. This was done to get an overview of where heavy precipitation is more common. The linear slope will not fit the curve completely, but to get an overview in which regions heavy amount of precipitation is more common the slope value is sufficient. The 37 years where divided in to years with more precipitation compared to years with less precipitation by adding up all the precipitation occurring over Greenland into one combined value for each year. A slope was calculated for the years with higher amount of precipitation and another slope for years with less amount of precipitation. The difference of the two sloped where then put on a map to see how the distribution of large amount of precipitation compared to less amount of precipitation looked. All the data was processed in MATLAB to create figures, see Section 4.1 and used script in Appendix.

The data for the SMB was calculated by HIRHAM5. Years with high amounts of ARs were compared with calculated SMB data to see how the ARs have influenced the SMB on Greenland. Precipitation data, AR data and SMB data were all divided into the four different sectors mentioned in Section 3.2, North West, NW, North East, NE, South East, SE and South West, SW, to see how the different variables looked in each sector. The AR data and SMB data were compared seasonally to get an overview of how the AR affected the SMB during different seasons.

4 Result and discussion

The selected figures in this section is used to display the progression of this thesis. All figures for SMB and precipitation illustrating a map have been processed with a glacier mask. The glacier mask is used to cut away unnecessary data outside the geographically wanted domain so the only focus is how the ice sheet has been affected by the different variables.

4.1 Precipitation

Greenland experience different amount of precipitation in different grid points. To see in which grid points extreme precipitation is more common the highest measured value of precipitation each year was extracted from the data in each grid point for all 37 years as explained in Section 3.3. Figure 4 shows a return value of large amounts of precipitation in one grid point for 37 years, which gives a slope value. The highest precipitation value occurs one time in 37 years, which gives a return value of log(37/1), this is the dot furthest to the right. The second dot from the right is the second highest precipitation value in 37 years, which gives log(37/2) etc. The slope values was calculated in each grid point over Greenland to get an illustration of where extreme precipitation is common. The plot does not give a linear slope, see Figure 4, which will create errors, but to get an overview of where extreme precipitation is common the slope value is sufficient and is therefore used.

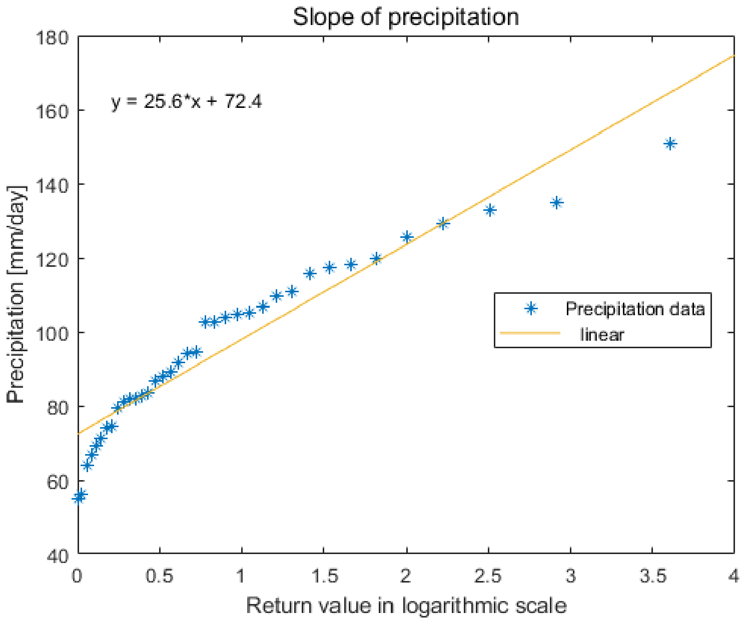


Figure 4: Slope of return value of large amount of precipitation in one grid point.

All slope values for each grid point where put on a map, as seen in Figure 5. High slope values indicates a higher return value of large amounts of precipitation. The maximum precipitation values over the 37 years differs between 0 to around 900 mm per day, where 900 mm in a day is the highest precipitation value measured during those 37 years. Yellow in Figure 5 shows steep values of the slope and blue indicates shallow slope values. The map displays a clear picture in where extreme precipitation is more common. The figure shows that the south eastern part of Greenland have more years with large amount of extreme precipitation and the north west experience the least amount of extreme precipitation. To see how the distribution of years with large amount of precipitation compared to years with less precipitation looked, a comparison was made, see Figure 6. The difference in distribution between years with large amount of precipitation compared to years with a less amount of precipitation is the largest in eastern part of Greenland, where red indicates a large difference and blue a small difference or no difference. The result of Figure 6 show that the precipitation in the eastern region of Greenland differs a lot from year to year compared to the western region.

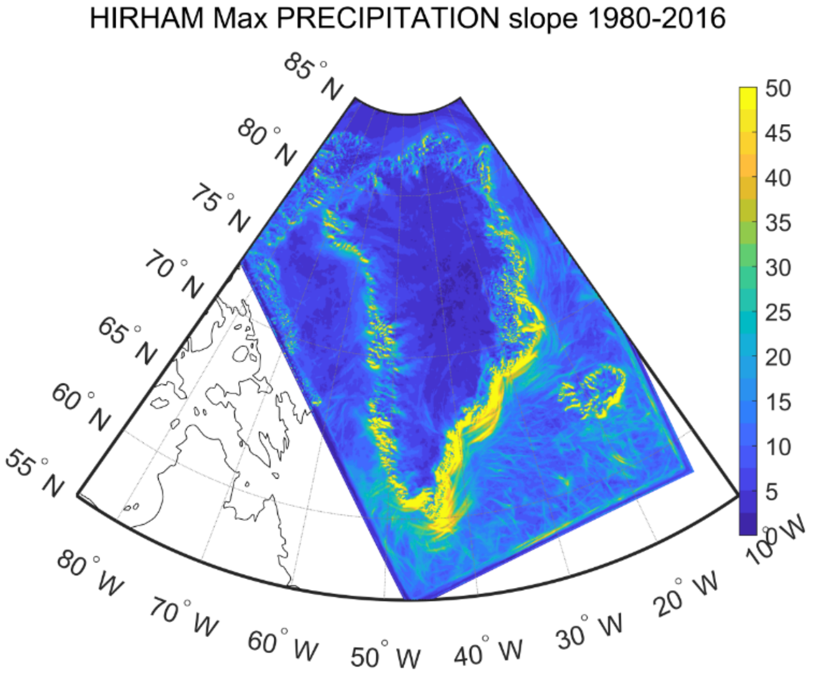


Figure 5: Slope values of annual max precipitation.

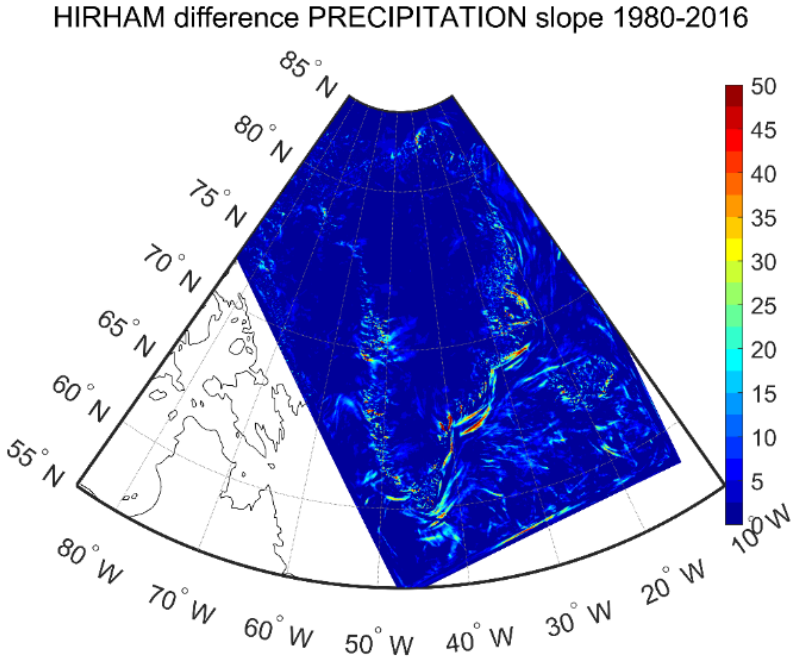


Figure 6: Difference in slope values between years with a lot of precipitation compared to years with less precipitation.

The daily mean precipitation over Greenland is distributed similar to where extreme precipitation is more common. Figure 7 displays how the daily mean precipitation is distributed in mm per day in a logarithmic scale between 1980 to 2016, where the red shows

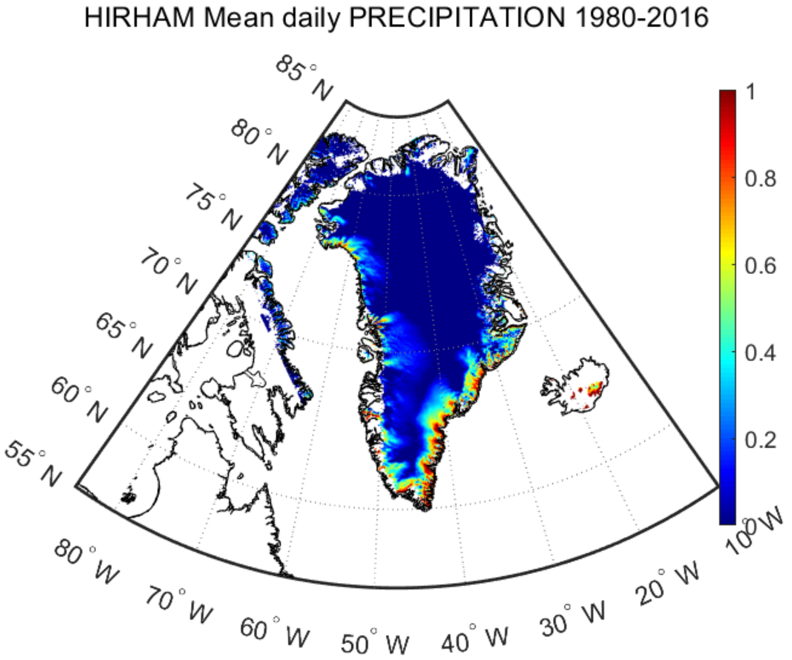


Figure 7: The daily mean precipitation over Greenland 1980 to 2016 in a logarithmic scale.

around 10 mm per day and the dark blue around 0 mm per day. The illustration shows how the south eastern coast generally experience the highest amount of precipitation, around 10 mm per day, while in the northern part of Greenland there are only a very small amount of daily precipitation, around 0 mm per day. Both Figure 5 and 7 indicate a similar result, that the south eastern part of Greenland experience the highest amount of daily mean precipitation and also the highest return value of years with large amount of precipitation. The four different sectors surface mass balance is therefore affected differently by precipitation.

4.2 Atmospheric rivers

To get an overview of how different part of Greenland are affected by ARs Greenland was divided in to four different sectors, South East, South West, North East and North West Greenland. The four different sectors experience different amount of precipitation, as seen in both Figure 5 and 7, where the northern part of Greenland experience less amount of precipitation than the southern parts do. The ARs were found in an ERA-Interim AR detection catalog as mentioned in Section 3.2, which is based on an algorithm made by

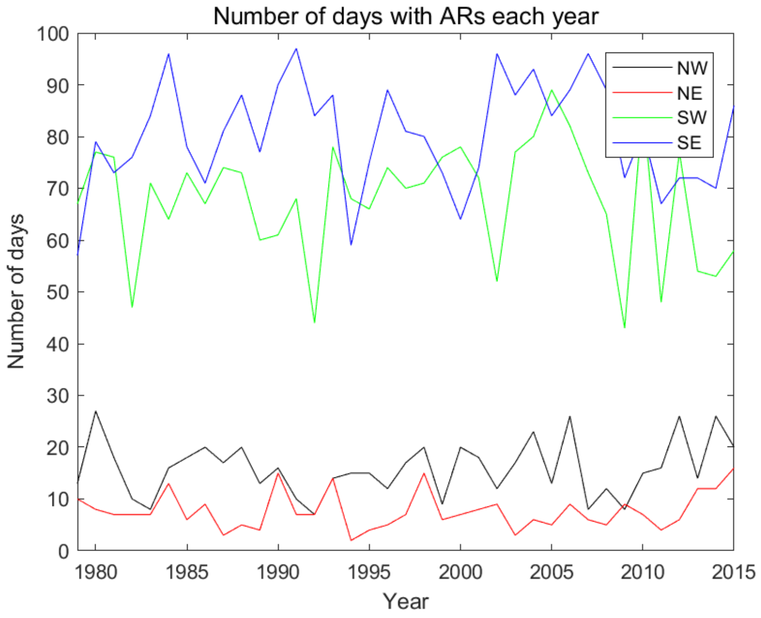


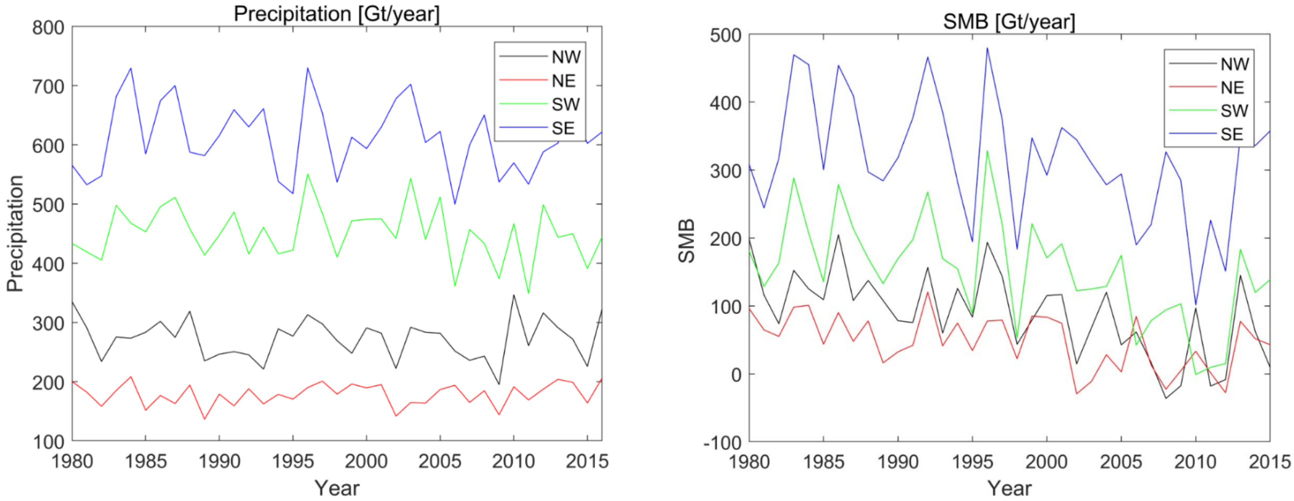
Figure 8: The number of days ARs occur every year in each sector.

B. Guan and D. E Waliser at NASA to identify ARs all over the globe. To assess the influence of ARs on SMB only the ARs that made landfall was taken in consideration. In Figure 8 the number of days ARs made landfall every year is on the y axis and the year they occurred on the x- axis. The figure display a large number of days with ARs for the south eastern and south west parts of Greenland. In the figure the blue lines are SE, the green SW, the black NW and the red line is NE parts of Greenland.

4.3 SMB and the impact of ARs and precipitation on SMB

To assess how ARs correlates with precipitation and SMB a comparison of Figure 8 and Figure 9 can be made. Figure 9 visualises the precipitation, see Figure 9a, and the SMB, see Figure 9b, converted into gigatonnes per year in each of the four regions. The precipitation in Figure 9a shows a similar trend as the numbers of days with ARs does. A trend of years with high numbers of ARs usually indicates a years with higher amount of precipitation. It can also be seen that the south east sector which experience the highest amounts of precipitation usually also have more days with ARs.

The number of ARs varies during the different years as seen in previous figure. The SMB is mainly positive, but with seasonal variability. The total mass balance is always negative since it also include calving iceberg and submarine melt. The SMB is affected differently

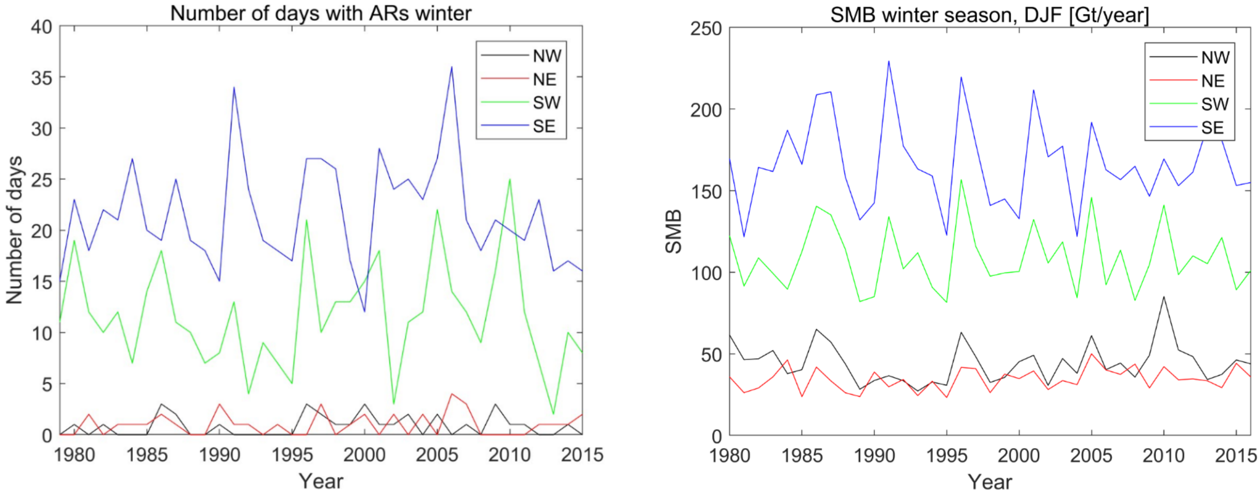


(a) *Precipitation in each sector.*

(b) *Surface mass balance in each sector.*

Figure 9: Surface mass balance and precipitation sum measured in gigatonnes per year in four different sectors over Greenland.

by ARs depending in what season the AR is occurring in. To assess a view of how the ARs occurring in different seasons may affect the SMB, the ARs and SMB where divided into winter and summer seasons.



(a) *Number of days with ARs during the winter.*

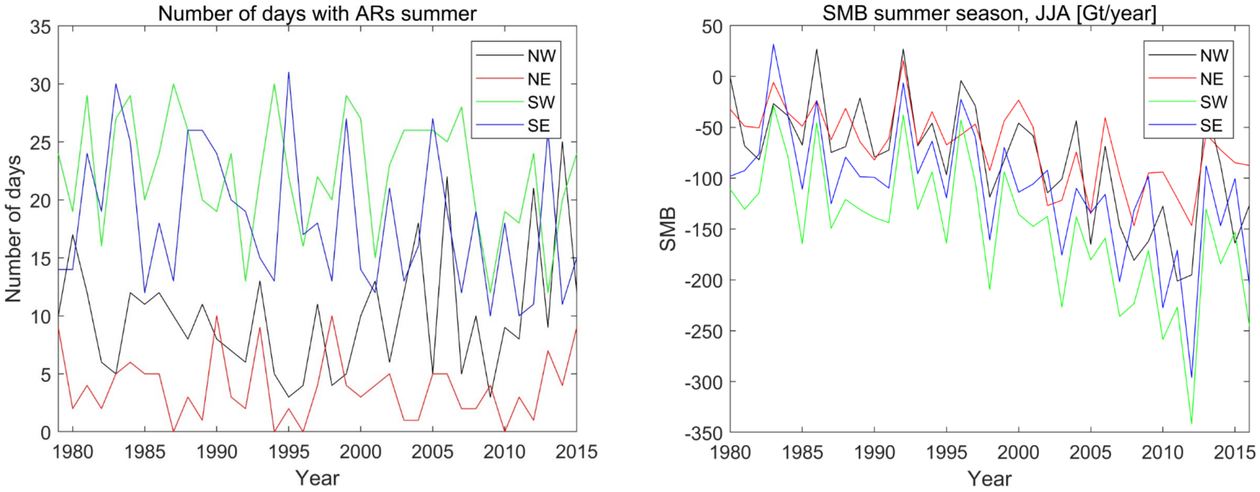
(b) *Surface mass balance during the winter.*

Figure 10: Number of days with ARs and surface mass balance measured in gigatonnes per year in each sector during the winter season, December, January and February.

To start the winter season was looked at. In Figure 10a the number of days with ARs in each sector is shown. Figure 10b shows how the SMB was affected each year. The two figures show how years with high amount of days were ARs occur have higher SMB.

This correlates to the cold temperatures during the winter season. If a large amount of precipitation is brought to Greenland and precipitated during the winter, the SMB will most likely be positively affected with gained mass, which is why the SMB is positive in all sectors during the winter as seen in Figure 10b. An increase of ARs can be seen in 1996. The increase of ARs also shows an increase of SMB in Figure 10b, indicating a correlation between SMB and ARs.

During the summer season the SMB is mostly negative, see Figure 11b. In the case of ARs during the summer a trend can be seen in the other direction compared to the winter season. The peaks in number of days with ARs results in a decrease of the SMB, as seen in comparison of Figure 11a and b. The trend of SMB also show a decrease in general from 1980 to 2015, with a large decrease in 2012. The SMB trend is decreasing due to global warming. The large dip in 2012 was due to the AR in July which brought up a lot of moisture accelerating the melt.



(a) Number of days with ARs during the summer. *(b) Surface mass balance during the summer.*

Figure 11: Number of days with ARs and surface mass balance measured in gigatonnes per year in each sector during the summer season, June, July and August.

Figure 12 shows how Greenland's SMB was affected in 2012, the blue indicates a loss of surface mass and the red an increase in surface mass, the SMB is measured in mm weq. The figure indicates a loss in SMB around all the coasts of Greenland and it show a large loss on the western side of Greenland where a large amount of ARs made landfall. The moist warm air brought up from the tropics accelerated the melting of the ice sheet resulting in a rapid decrease of surface mass around Greenland's coasts and since a large

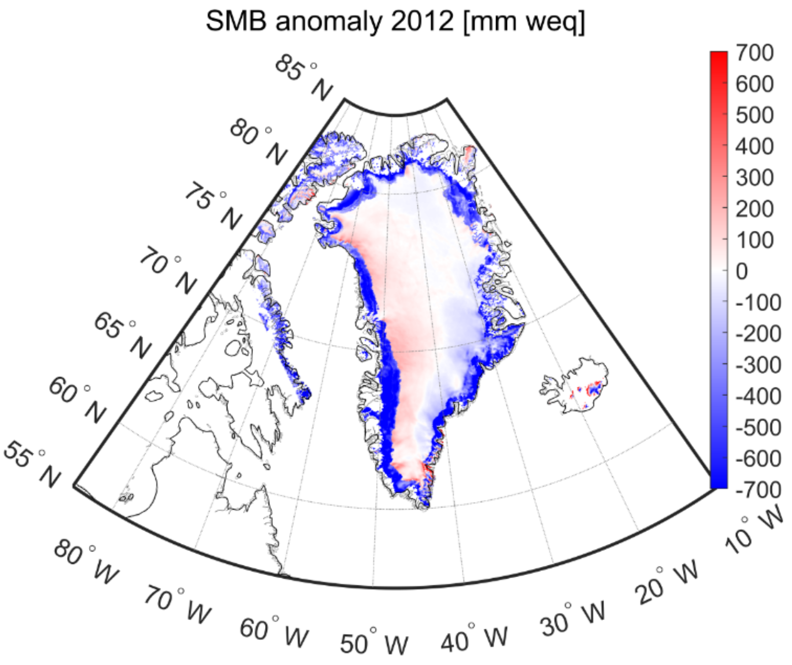


Figure 12: The surface mass balance anomaly in 2012 compared to average 1980-2015 SMB.

amount of the ARs that made landfall in 2012 occurred during the summer, see Figure 11b, the SMB decreased.

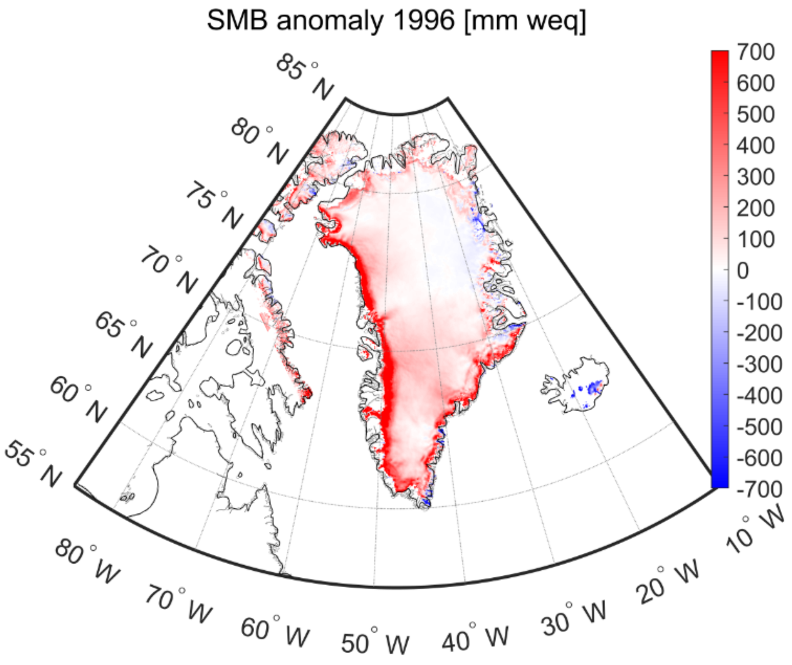


Figure 13: The surface mass balance anomaly in 1996 compared to average 1980-2015 SMB.

The AR figure, Figure 10a, shows a peak of ARs in 1996, especially in the south eastern region and the south west region. When looking at Figure 10 in 1996 a peak is shown both for the precipitation and SMB the same year in the same sectors. In 1996 the precipitation from the ARs and precipitation in general affected the SMB in a positive way, see Figure 13, where the SMB is increased from the average almost all over Greenland, with an especially large increase on the south west coast. The red area in Figure 13 indicates an increase of SMB compared to the average calculated between 1980 to 2015. The main reason why in 1996 the SMB was increased compared to the average SMB is because the ARs occurring in 1996 happened in the winter season, see Figure 10a, which can benefit the SMB and even the total mass in rare cases.

The previous figures show that the influence of large scale precipitation on the SMB depends on the season. During the summer the decrease of SMB can not be avoided, due to higher seasonal temperatures, and during the winter the precipitation can accumulate and increase the SMB. If the melting period will increase even more a decrease in the SMB trend, as seen in Figure 11b, during the summer will accelerate. If more ARs occur during the winter it will increase the possibility of mass gained to the ice sheet. Both Figure 12 and 13 indicated how the SMB in the south western sector is most affected by changes in precipitation by ARs.

5 Conclusion

This thesis shows how the affects of large scale precipitation and ARs could both positively and negatively influence the SMB of Greenland. The ice mass of Greenland can be positively influence with gained mass through more large scale precipitation. The heighten temperatures over Greenland due to climate change could on the other hand also lead to an accelerated ice mass loss with large scale precipitation.

The ARs influence on the SMB are to a large extent dependent on the season. During the summers the possibility of ARs negatively affect the ice sheet on Greenland increases, as seen in 2012 and Figure 12. An increase of ARs during the winter seasons could lead to a positive influence on the SMB with gained mass, as seen in 1996 and Figure 13. It can be seen in both Figure 12 and 13 that the SMB on the west coast of Greenland is most affected both in 2012 and 1996 by the ARs.

The AR detection catalog and HIRHAM5 is both modeled data with some observations assimilated into them. As mentioned in Section 2.5 models struggle to accurately predict and calculate convective fine scale precipitation which can contribute to calculated errors in the precipitation, but overall ARs occur on a larger scale which minimize the errors.

6 Outlook

To be able to predict how the large scale precipitation and atmospheric rivers will affect Greenland's ice sheet in the future further researches are needed. This thesis uses HIRHAM5 and datasets from ERA- Interim, which are both models with some observations assimilated into them, but it could benefit future researches if more observations could be taken in consideration when looking at trends, since another model could give a different outcome. It is important to further investigate the importance of the ice sheet and how it will be affected in the future by the ongoing climate change in general and how to prevent the worst case scenarios from occurring in the future.

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7 Appendix

MATLAB script used for the slope value map.

```
clearvars; %pack;

%Load variables
file = 'C:\Users\Moa\Documents\MATLAB\DMI-HIRHAM5_GL11_GL2_1980-2016_PR_YEARMAX.nc'
ncid = netcdf.open(file,'NC_NOWRITE');
lon = double(ncread(file,'lon'));
lat = double(ncread(file,'lat'));
prec = double(ncread(file,'pr'));
netcdf.close(ncid);

Z=zeros(402,602);

%Extract needed column
for i=1:402
    for j=1:602
        A=squeeze(prec(i,j,:));
        B= sort(A);
        C=37:-1:1
        D=C'
        E=log(37./D);
        F=polyfit(E,B,1);
        Z(i,j)=F(1);
    end
end

hFig = figure(2); set(hFig, 'Position', [100 20 700 600])
clf; axes('position', [0.04 0.08 1.0 0.8]);
worlddatamap('landareas.shp',[55 85],[-85 -10],'line')
```

```
setm(gca,'Grid','on','GColor',[0.5 0.5 0.5],'GLineStyle',':','Frame','on','MeridianLabel','on','ParallelLabel','on','MLabelLocation',10,'PLabelLocation',5,'MapProjection','eqdconicstd','FontSize',16); %'lambertstd'); %'eqdcylin');

% colormap def
cmap = colormap(parula(20));
surfacem(lat,lon,Z);
colormap(cmap);

% add colorbar
h = colorbar('vertical','position',[0.92 0.20 0.02 0.60],'YTick',0:5:50);
% map plot
caxis ([0 50]);
title('HIRHAM Max PRECIPITATION slope 1980-2016','FontSize',12,'FontWeight','normal')
%save fig
set(gca,'FontSize',16);
set(gcf,'PaperPositionMode','auto')
file = char(strcat('C:\Users\Moa\Documents\MATLAB\DMI-HIRHAM5_GL11_GL2_ERAI_1980_2016_SLOPEMAP_DM.png'));
print('-r600','-dpng',file);
```