Lund University
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Climate Change and Precipitation Variability Influence on the Greenland Ice Sheet

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Abstract

Climate changes have a large impact on precipitation patterns and precipitation variability change. With this in mind, precipitation over Greenland is studied. This is done for present day precipitation model data from 1991-2010 compared to future model simulations of precipitation for 2081-2100. Furthermore, precipitation drives Surface Mass Balance (SMB), which is the sum of accumulation and the loss of mass by melting of the ice sheet, meaning it decides the evolution of glaciers. In order to find more information about future changes of precipitation distribution between the seasons of the year and possible changes, precipitation variability is investigated. Also, the aim includes an examination of the difference in mean annual precipitation between the time periods. Model simulations with EC-Earth downscaled through HIRHAM5 is mainly used for this study. Also the global atmospheric re-analysis ERA-Interim is used and a new model with modified ice sheet topography called GT2. There will be an increase in mean annual precipitation over Greenland for 2081-2100 compared to 1991-2010, a conclusion made according to the results obtained using RCP8.5, a scenario with high rates of combustion. The SMB mass term will with this scenario, become more negative in the future compared to present day, meaning there will be a greater mass loss of the Greenland ice sheet. In the final analysis, the precipitation variability as well as the seasonality will change for Greenland in the future according to the RCP8.5 scenario.

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Abbreviations

CDO	**C**limate **D**ata **O**perator
DMI	**D**anmarks **M**eteorologiske **I**nstitut (**D**anish **M**eteorological **I**nstitute)
EC-earth	Global climate model system
ECMWF	**E**uropean **C**entre for **M**edium-Range **W**eather **F**orecasts
ERA-Interim	Global atmospheric re-analysis
GCM	**G**lobal **C**limate **M**odel
GT2	Simulation with artificially reduced ice sheet
HIRHAM5	Regional climate model run at DMI
IPCC	**I**ntergovernmental **P**anel on **C**limate **C**hange
MATLAB	**MAT**rix **LAB**oratory
NWP	**N**umerical **W**eather **P**rediction
RCM	**R**egional **C**limate **M**odel
RCP	**R**epresentative **C**oncentration **P**athways
SMB	**S**urface **M**ass **B**alance

Contents

1 Introduction

This project is a study of precipitation over Greenland, for present day precipitation model data compared to future model simulations of precipitation. Periods with high rates of precipitation are of interest as it drives Surface Mass Balance, SMB. The SMB is the sum of accumulation and the loss of mass by melting of the surface ice sheet. Furthermore, by driving ice dynamics, SMB determines the evolution of glaciers. The aim is to analyze model data, to observe how it predicts precipitation for Greenland in the period 1991-2010 compared to 2081-2100 in a climate model.

Climate change will cause a sea level rise. As the global mean temperature rises, the glaciers will melt and contribute to this rise. One example of climate impact is by emission of greenhouse gases from combustion. An increase in greenhouse gases enhances the Greenhouse effect, equally, increasing the global mean temperature. Further, an increase in extreme weather events can be expected, affecting humans, sea cities and ecosystems. A higher mean temperature results in more variable weather and more extreme precipitation along with increasing droughts [1].

The aim of this project is to compare the precipitation for the two time periods, 1991-2010 and 2081-2100. Moreover, the precipitation for both of the periods is output from HIRHAM5, downscaled from the global climate model system EC-Earth. The 2081-2100 period is forced using the future scenario RCP8.5 (RCP stands for Representative Concentration Pathways and it gives a future scenario based on a certain degree of emissions) [1]. Likewise, the project aims to look at how precipitation patterns will vary across Greenland compared to the present day, and to see if there will be an increase in precipitation or an increase in precipitation variability, in the event that it might affect the seasonal weather. Precipitation variability is a field within active climate research.

The project will focus on the following questions:

- How will precipitation patterns look for Greenland in the future compared to the present day?
- How will a possible change in precipitation patterns affect the Greenland ice sheet Surface Mass Balance in the future?
- Will the precipitation variability for Greenland change in the future?
- Will there be a difference in seasonality in precipitation for Greenland in the future compared to present day?

2 Background

2.1 The Greenhouse Effect

Climate models forecast that if the global warming continues at the same rate as today, the Earth's average surface temperature will rise 3 degrees Celsius until the end of this century, compared to present day [2]. Greenhouse gases are a highly contributing factor when it comes to global warming. Greenhouse gases can be natural or anthropogenic. Anthropogenic greenhouse gases are greenhouse gases created by human activity. The greenhouse effect is necessary for the life on our planet. Indeed, the atmosphere together with the greenhouse effect are fundamental for us [3]. The problems increase when the Greenhouse effect is reinforced by anthropogenic impact.

Greenhouse gases emitted and existing in our atmosphere are many, water vapor is one of them. It is a natural species in the atmosphere, and it also acts as a greenhouse gas. Carbon dioxide, methane, nitrous oxide, ozone and chlorofluorocarbons are other greenhouse gases present in the atmosphere which can affect the radiation balance [2].

All objects with a temperature above the absolute zero (0° Kelvin) emit radiation and the wavelength depends on the temperature of the object. The Stefan-Boltzmann law, Equation 1, states that all objects with a temperature above this absolute zero emit radiation proportional to the fourth power of the objects absolute temperature. E is the maximum radiation emitted by each square meter of the object, T is the surface temperature in degrees Kelvin of the objects surface and $\sigma \sim 5.67 \cdot 10^{-8}$ Wm^{-2} K^{-4} is the Stefan-Boltzmann constant [4].

$$E = \sigma T^4 \tag{1}$$

The Sun emits incredibly large amounts of energy by radiation. With Wien's displacement law, Equation 2, the wavelength at which the maximum radiation will occur, λ_{max} can be calculated. T is the temperature of the object in degrees Kelvin and b is Wien's displacement constant $b \sim 2900$ μmK. The law gives the relationship between the wavelength at which the maximum radiation is emitted and the temperature of a black body [2].

$$\lambda_{max} = \frac{b}{T} \tag{2}$$

With Wien's displacement law, λ_{max} for both the Sun and the Earth can be calculated. For the Sun it is 0.5 μm and for the Earth, it is 10 μm. The Sun emits radiation in most wavelengths but this number tells where the maximum will be found. The Sun radiates more high-energetic radiation than the Earth and some of its light can be seen by humans (in contradiction to the light emitted by the Earth, which is in infrared wavelengths and not visible to human). Both the Sun and the Earth does approximately behave as blackbodies and this is the reason why both the Stefan-Boltzmann law and Wien's displacement law can be implemented [2].

The Earth and its objects are steadily radiating energy through infrared radiation. On sunny days, the Earth gains energy by absorption of solar radiation more than it loses, and at night the Earth loses more energy than it receives. The Earth's atmosphere does not behave as a blackbody, as the Earth does. This is since the atmosphere is composed of various gases, which cause this action. These gases can selectively absorb or emit radiation of specific wavelengths and are therefore called selective absorbers. Kirchoff's law of thermal radiation states that selective absorbers will emit radiation of the same wavelength and that poor absorbers at a certain wavelengths will also be poor emitters at this wavelength. Hence, these gases are the greenhouse gases. In brief, the greenhouse gases selectively absorb infrared radiation in different wavelengths, preventing it from escaping out into the space. Figure 1 shows the energy balance existing between the incoming solar radiation, the atmosphere and the Earth. In the figure, it is supposed that are 100 units of incoming solar radiation and the other numbers are proportional to this [2].

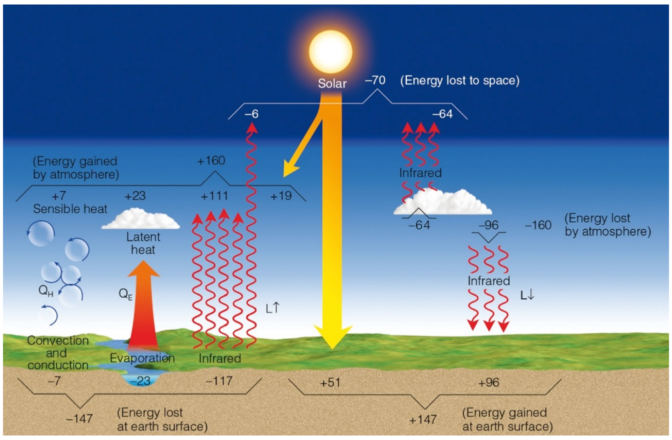


Figure 1: The energy balance between the Earth and the atmosphere [2].

2.2 Representative Concentration Pathways

Representative Concentration Pathways (RCP) are different greenhouse gas concentration trajectories, which give contrasting future scenarios. These vary due to the amount of combustion. Four RCPs commonly referred to are RCP2.6, RCP4.5, RCP6.0 and RCP8.5, where RCP8.5 is the "worst case scenario" among these four [1]. The different RCPs are tools used for research and modeling, when investigating climate change.

2.3 Surface Mass Balance

The amount of precipitation that falls in Greenland is of importance to the Surface Mass Balance (SMB), as it can contribute to ice growth. SMB means comparing ice growth with its loss of mass which is of importance for the development and the mass change of the ice sheet. SMB is the sum of the accumulation and the ablation. Accumulation is the processes of adding mass to the ice sheet, it consists of precipitation, condensation and refreezing. Ablation is the processes which reduce the ice sheet, it consists of melting and sublimation [5]. A factor which also affect the SMB is the albedo of the ice sheet. The albedo is the factor giving information about the amount of solar radiation reflected from a surface. A high albedo means a high reflectivity [2]. In Figure 2 the mass budget for glaciers is illustrated.

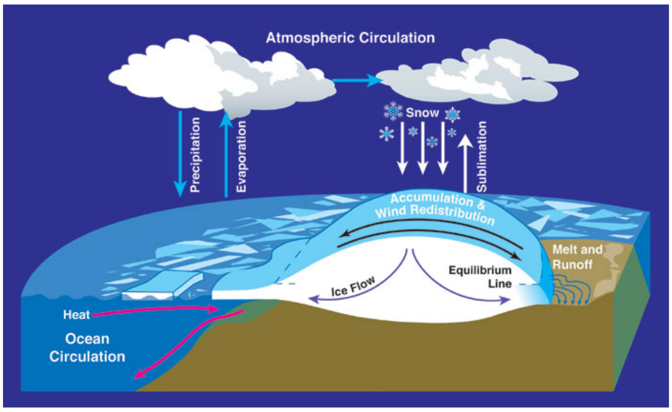


Figure 2: Atmospheric circulation and mass balance for glaciers [6].

2.4 Greenland Ice Sheet

The Greenland ice sheet is the second largest glacier in the world, after Antarctica and Greenland is the world's largest island, located in the northern hemisphere. The ice sheet loses large amounts of mass each year. This will contribute to the flow of freshwater into surrounding systems and to the sea [7].

2.5 Precipitation Variability

Precipitation variability is how much the amounts of precipitation varies over a specific area over a given amount of time. This is not as well investigated as extreme precipitation events [8]. Certain location can have, for instance, dry winters and rainy summers, this would be the precipitation pattern for this location. To find out how this pattern will change in the future is significant, since this will affect the weather and the seasons.

3 Methodology

3.1 HIRHAM5

HIRHAM5 is a regional atmospheric climate model (RCM) developed by the danish meteorological institute, DMI, with 402 x 602 grid boxes at 0.05 degrees resolution. HIRHAM5 is based on the operational short-range limited area models HIRLAM7 and the global climate model ECHAM. HIRHAM5 stands for High Resolution Limited Area Model 5 [9]. HIRHAM5 was used to downscale EC-Earth and ERA-Interim dynamically, from a 75 km resolution to a 5 km resolution. A reanalysis output with boundary forcing of temperature, relative humidity, pressure, and wind components were delivered every 6 hours.

3.2 EC-Earth

EC-Earth is a global climate model system (GCM), which is describing the global climate system. EC-Earth is using, for the atmospheric component, the European Center of Medium Range Weather Forecast (ECMWF) weather forecast model. The model is often used in the context of studying climate change, as the model can provide simulations of future climate [10]. The model is not based on actual observations, except for Carbon dioxide and Greenhouse gases, in the historical run 1991-2010. The quadratic grid boxes in EC-Earth are 120 km, and EC-Earth is downscaled through HIRHAM5 to a 5 km resolution.

EC-Earth is a suitable model when investigating climate research problems, as it can be used for any timescale [11]. All the model data sets for 1991-2010 and 2081-2100 were created using EC-Earth.

3.3 ERA-Interim

ERA-Interim is a global atmospheric re-analysis from 1979, used for weather forecasting and the model is repeatedly updated [12]. In ERA-Interim a 75 km grid box is used. Downscaled EC-Earth model data for 1991-2010 was statistically compared with downscaled ERA-Interim data for historical observations, to see if EC-Earth is good at reproducing what ERA-Interim observed for the present day climate data. If the comparison of the two models give a similar result, there is a good chance that EC-Earth will represent the future climate and precipitation well, and conclusions with good certainty can be made.

3.4 GT2

A simulation was also analyzed where the ice sheet was artificially reduced by about 100 km all around the circumference for 2003-2008, in order to determine how the ice sheet controls the precipitation distribution in Greenland.

3.5 Working Process

All main data files used for programming (EC-Earth model data for 1991-2010 and 2081-2100) have been based on the daily mean of precipitation for the time period on 20 years. These have been modified to provide data sets suitable for programming in MATLAB. This has been done with the help of Climate data operator, CDO. All figures in the work are created in MATLAB.

CDO is a collection of operators, developed to be used for processing climate data and Numerical Weather Prediction (NWP) model data. It is a tool which is very useful for processing data of precipitation , as well as climate or forecast model data. CDO has over 700 accessible operators [13].

3.6 Precipitation over Greenland

Slope of Daily Maximum Precipitation

To get a picture of how precipitation will look for 2081-2100 compared to 1991-2010, model data sets were used to create annual maximum daily precipitation values for Greenland. Plots showing a slope created with the maximum precipitation event for every year, with a return value of 20 years, were created. The return value tells how likely it is that a certain scenario will occur within a certain time frame, to clarify, how often the scenario is repeated [14].

The higher the line (the linear regression) fitted to the points in a slope plot is located in the plot relative to the y-axis, the higher the annual maximum precipitation amount in millimeters per day during the 20 year period. In simple terms, the more precipitation fell in the grid box. Also, the steeper the slope is for a specific location (the greater difference between the highest and the lowest precipitation event), the higher the variation in precipitation for this location. These slopes are referred to as slope plots. This data was used to create slope plots for ten different locations in Greenland, for both 1991-2010 and 2081-2100 and the two time periods were plotted in the same slope plot. The different locations were selected with their amount of precipitation in mind. This was in order to find locations which differ greatly from each other in amounts of precipitation, so that the upcoming results would be as reliable as possible.

The 20 events with the maximum precipitation for every year, for every location, are ordered by size (the amount of precipitation) in the plots, in other words, regardless of the year, and a linear regression is adjusted to the points in the plot. Approximately the points should make a good linear connection, however, this is not always true. If there is a point that differ very much from the rest, this may affect the adjustment. Therefore, the robust regression is also fitted to the line. The robust regression is used to give a regression which is more adapted to where most of the items are located, and it is not as affected by single points as the linear regression [15]. Both are used in the plots, as it is good to see that a result can be interpreted in different ways. It is good to be able to take this into account when making conclusions.

Mean Annual Precipitation

Maps of the difference in mean annual precipitation between 1991-2010 and 2081-2100 were created for Greenland. These are a good addition to the slope plots when looking at the difference between the two time series. One map showing the difference in millimeters per year and one in meters per year were created, to give a clear picture of the changes both around the coasts and inland since only one map would not represent all of Greenland as well.

Precipitation Slope Maps

Maps showing the slope of the precipitation over the two time periods for all the grid boxes were created. These maps are referred to as slope maps. They show information about all of the grid boxes over Greenland in one map, and in this way, it can be seen where there will be considerable changes between 1991-2010 and 2081-2100 in the slope of the maximum precipitation. A slope map showing the difference between 1991-2010 and 2081-2100 was created. Another data set, created with ERA-Interim was used to create a slope map showing the difference compared to the 1991-2010 EC-Earth model data. By doing this, information will be obtained about how good EC-Earth is in line with reality.

3.7 Surface Mass Balance

Model data collected showing the daily mean of Surface Mass balance across Greenland for the two time periods was modified in order to obtain the time mean. With this data, two maps showing the mass balance were plotted, one for 1991-2010 and one for 2081-2100. Also, a map showing the difference between the two was produced, in order to get information about the possible mass loss.

3.8 Modified Ice Sheet Topography

GT2 is the model run used in the 2003-2008 time period with a modified ice sheet, this is to examine how the ice sheet affects the precipitation pattern over Greenland. A precipitation data analysis was carried out for a simulation using this model with modified ice sheet topography for 2003-2008. This data was used to create a map showing the year maximum for precipitation over the period. Again, the data was used to create a slope map showing the difference between different models GT2 and ERA-Interim.

3.9 Precipitation Variability

To see if there is a change precipitation variability between the periods 1991-2010 and 2081-2100, model data sets with the daily mean of precipitation for the two periods were used to create monthly mean, monthly maximum and monthly minimum and these were used for programming. The model data sets were plotted as histograms for every month. A fifth degree polynomial curve was adjusted to the bars in the histogram. This curve will give information about precipitation variability.

To easier see how the precipitation amounts differ from one season to another, December to January, March to May, June to August and September to November were added together in another plot. This was done for monthly mean, monthly maximum and monthly minimum for both time periods. Similarly, plots were made for six months so that January to June and July to December were added together. For these plots, the percentage differences between the first and the second half of the year were calculated and the two time periods were compared to each other, to see if there is an actual change in precipitation variability in the second half of the year, compared to the first half of the year or if the percentage increase is the same for the two time periods.

4 Results

4.1 Precipitation over Greenland

Slope of Daily Maximum Precipitation

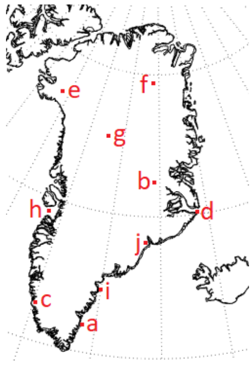
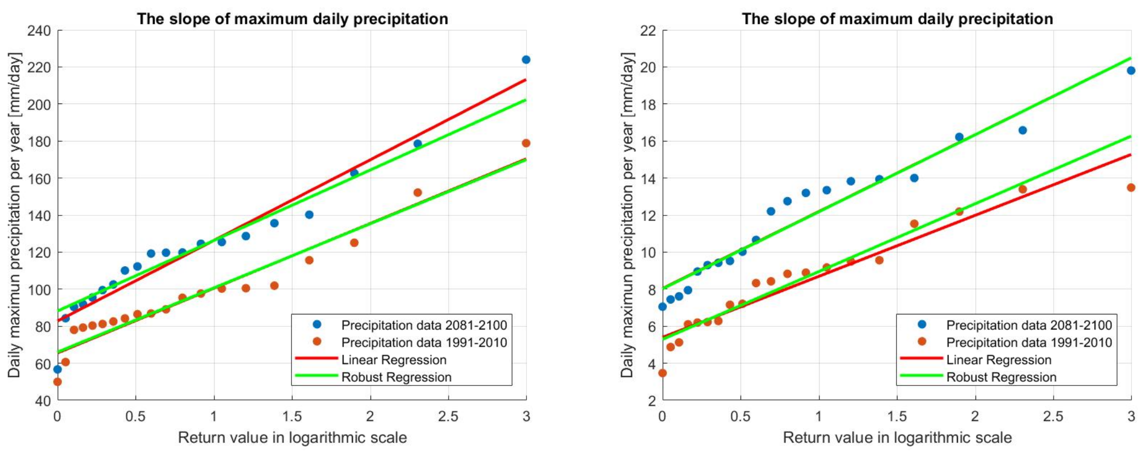


Figure 3: The coordinates for all slope plot locations.

Figure 3 shows the coordinates chosen for investigation of the difference in precipitation rates between 1991-2010 and 2081-2100. Figure 4 shows the slope plots for the two first chosen locations, point a) and b) in Figure 3. As seen in Figure 4a, the slope of the 2081-2100 precipitation model data is located higher in the plot than for the 1991-2010 precipitation model data meaning, an increase in precipitation. In fact, the event with the highest amount of precipitation increased from 180 mm/day to above 220 mm/day for this specific location. Figure 4b shows a location in Greenland with less precipitation. Likewise, for this location, the slope of the 2081-2100 precipitation model data is located higher and the event with the most precipitation over the 20 year period went from below 14 mm/day to above 20 mm/day.



(a) Location a) in Figure 3.

(b) Location b) in Figure 3.

Figure 4: The slope of Locations a) and b) in Figure 3.

In Figure 5, the slope plots from Figure 4 are combined in one plot. With the same axes, it is clear how the two locations differ from each other in amount of precipitation. Location a) will have a larger increase in total amount of precipitation and the slopes for both of the time periods are much steeper than for location b). But even though it looks like the increase is larger for point a), the percentile increase (between the events with the most precipitation for each of the time periods, for each of the points) for point b) is the largest one with an increase of 41% between 1991-2010 and 2081-2100. For point b), the increase is only 25%.

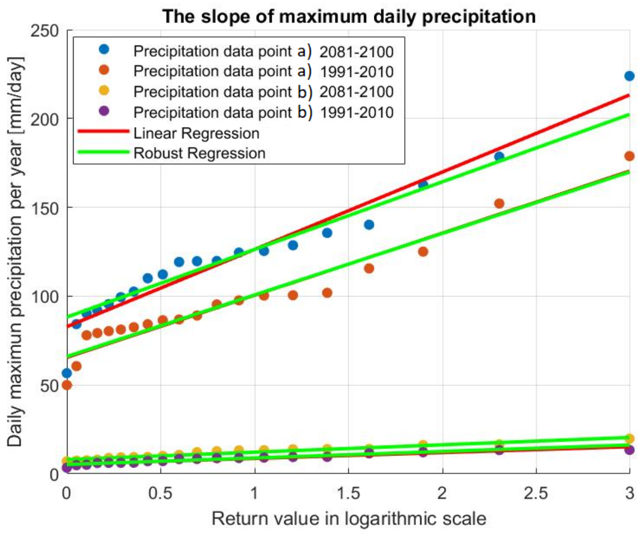
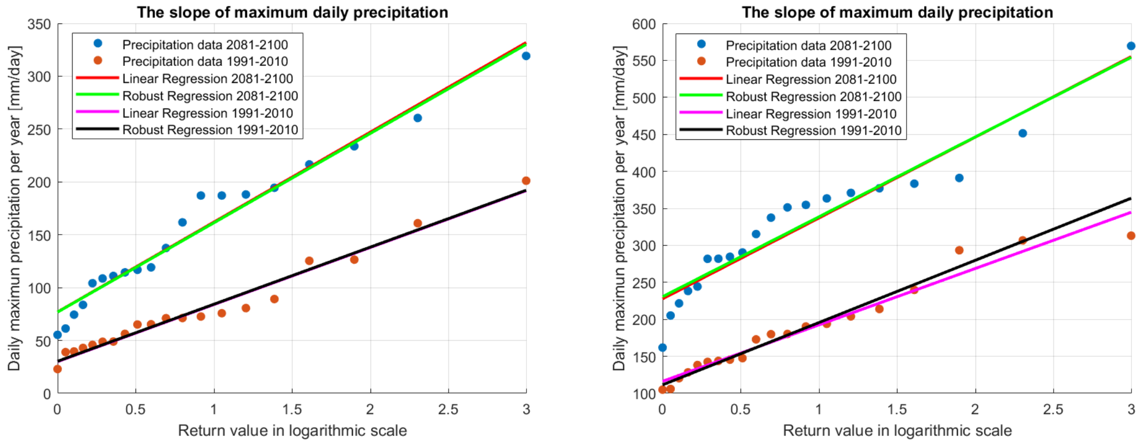


Figure 5: Locations a) and b) in Figure 3 combined.

Figure 6 and Figure 7, shows four other slope plot locations.

In Figure 6a, a location with a high amount of precipitation, the increase in precipitation is very high and the increase in the tilt of the slope is significant. The percentile increase (between the events with the most precipitation for each of the time periods) is 60%. Figure 6b shows the same result regarding the amount of precipitation, but the slope does not increase as much. The percentile increase (between the events with the most precipitation for each of the time periods) is 78%.

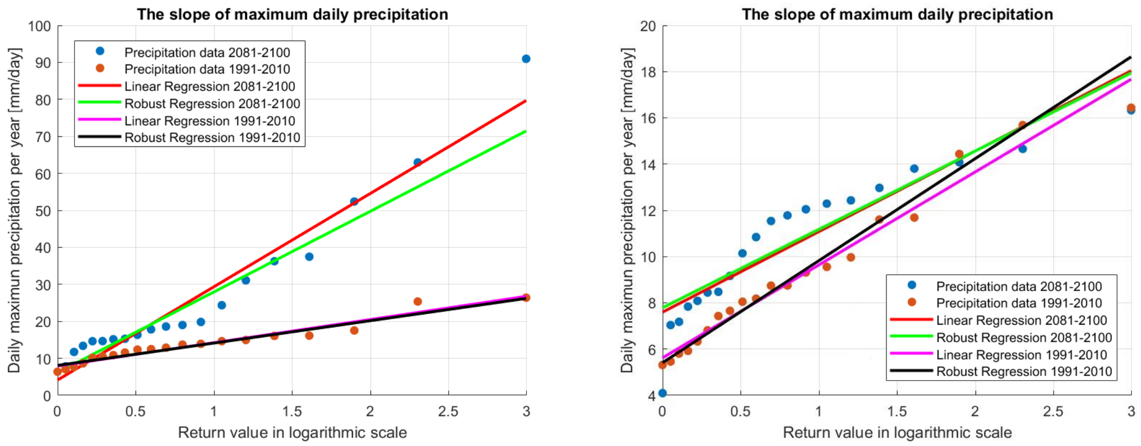
In Figure 7a, both the increase in the amount of precipitation and the increase in tilt of the slope is convincing. The percentile increase (between the events with the most precipitation for each of the time periods) is 260%. Figure 7b shows a different result. The events with the highest amount of precipitation for each year is overall higher in the future than in the past, but the robust regression for the 1991-2010 model data is the one that has the steepest slope. The percentile increase (between the events with the most precipitation for each of the time periods) is here almost zero.



(a) Location c) in Figure 3.

(b) Location d) in Figure 3.

Figure 6: Locations c) and d) in Figure 3.



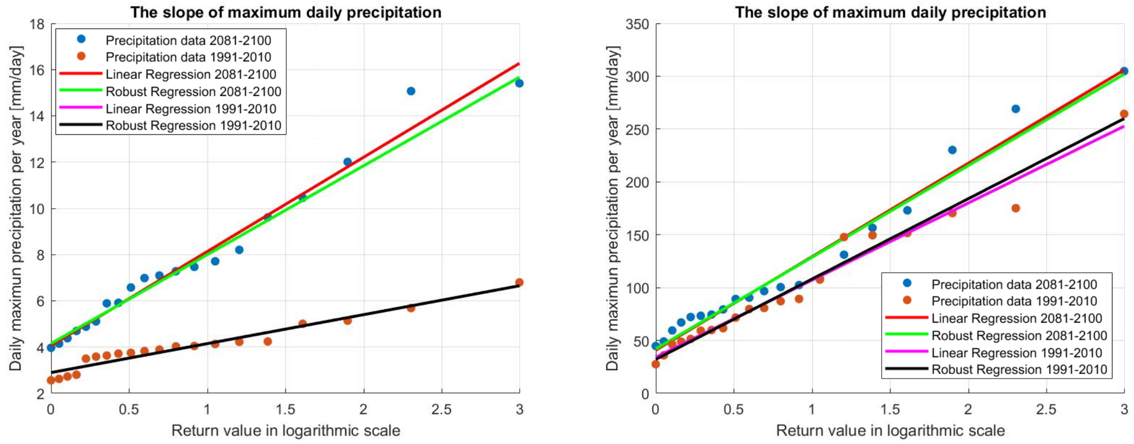
(a) Location e) in Figure 3.

(b) Location f) in Figure 3.

Figure 7: Locations e) and f) in Figure 3.

Figure 8 and Figure 9 shows four locations, chosen due to their precipitation situation in 1991-2010. Figure 8a is a location which was very dry 1991-2010, and here there is a very high increase in both the precipitation amounts and in the tilt of the slope. The percentile increase (between the events with the most precipitation for each of the time periods) is 138%.

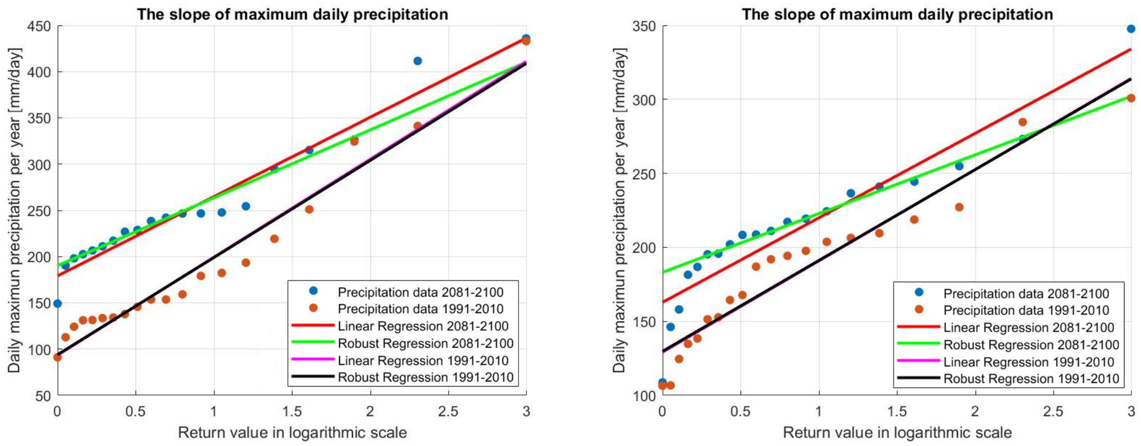
The Figures 8b, 9a and 9b were chosen from different locations in Greenland with very high amounts of precipitation for the 1991-2010 model data, to see if there would be an increase even here and the results prove the same trend. The increase in the amount of precipitation and the slope tilts are not as significant for these three. In Figure 8b the percentile increase (between the events with the most precipitation for each of the time periods) is 15%, for Figure 9a the increase is almost zero and for Figure 9b it is 17%.



(a) Location g) in Figure 3.

(b) Location h) in Figure 3.

Figure 8: Locations g) and h) in Figure 3.



(a) Location i) in Figure 3.

(b) Location j) in Figure 3.

Figure 9: Locations i) and j) in Figure 3.

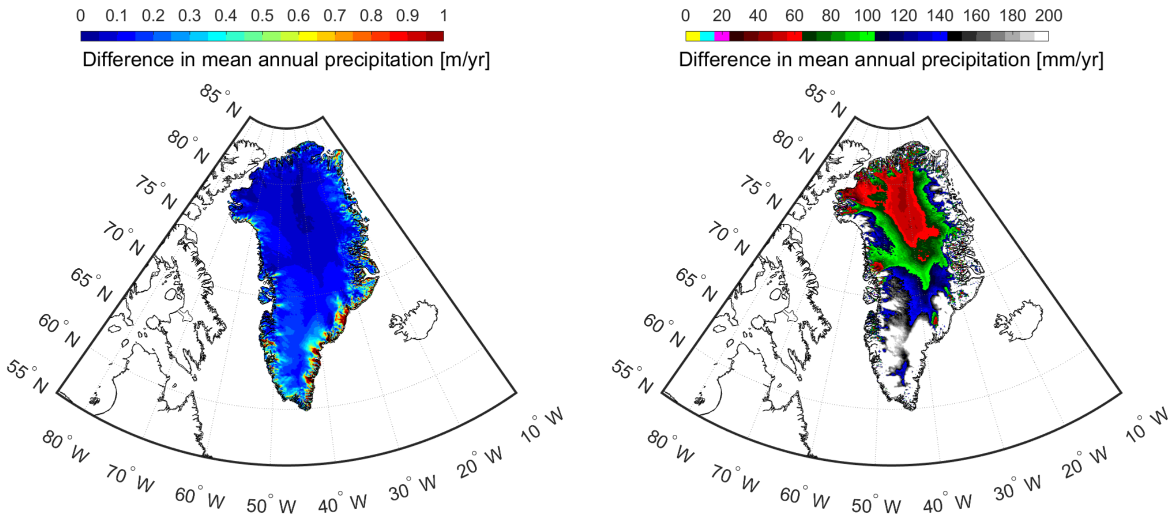
The y-axis is the daily maximum precipitation event per year in millimeters per day and the x-axis is the return value in logarithmic scale for the years. In Table 1, all the slope plot equations for the ten locations are shown for the both time periods. The equations are calculated from the linear regression. For eight of the ten locations, the slope is steeper for the future, meaning a greater variation in precipitation.

Table 1: Slope plot equations for all linear regressions.

Location	1991-2010	2081-2100	Location	1991-2010	2081-2100
a)	y = 36x + 66	y = 45x + 83	f)	y = 4.1x + 5.6	y = 3.6x + 7.6
b)	y = 3.4x + 5.5	y = 4x + 8	g)	y = 1,2x + 3	y = 4x + 4
c)	y = 50x + 30	y = 80x + 75	h)	y = 75x + 35	y = 84x + 46
d)	y = 75x + 115	y = 100x + 235	i)	y = 112x + 88	y = 90x + 180
e)	y = 6.3x + 8	y = 25x + 4	j)	y = 57x + 128	y = 58x + 162

Mean Annual Precipitation

Figure 10a shows the difference in mean annual precipitation between 1991-2010 and 2081-2100. Around the coasts there are places where the change is as much as a meter per year or more. There are values that go over a meter, but the scale in the picture goes only as far, since areas with values higher than this are minimal.



(a) The difference in mean annual precipitation between 1991-2010 and 2081-2100 in meters per year.

(b) The difference in mean annual precipitation between 1991-2010 and 2081-2100 in millimeters per year.

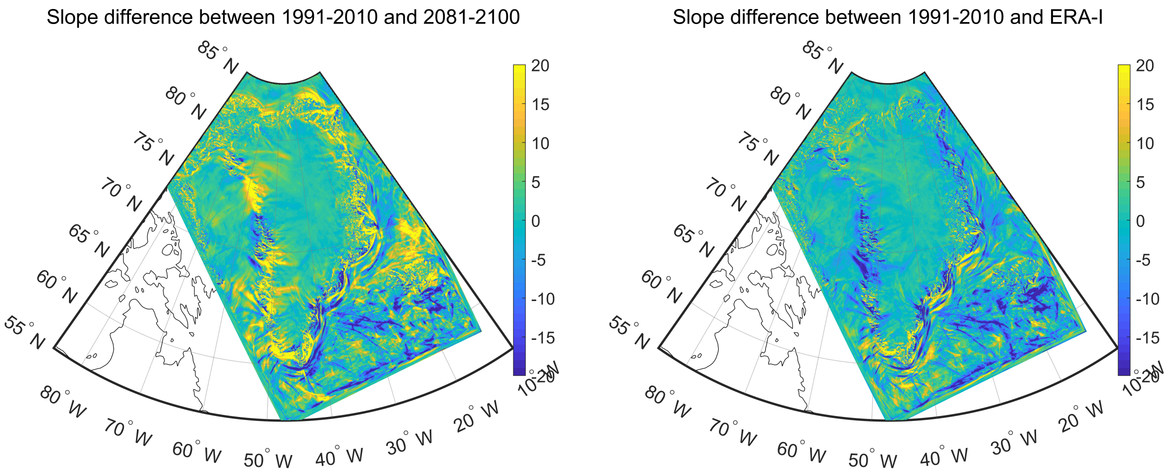
Figure 10: Two maps showing the difference in mean annual precipitation for the two time periods.

Figure 10b gives a more detailed picture of how the difference in mean annual precipitation between 1991-2010 and 2081-2100 will look for the northern Greenland inland. The map shows that precipitation will increase between 50 to 200 millimeters per year across most of the Greenland inland from 1991-2010 to 2081-2100. There are values that go over 200 millimeters per year around the coasts, but the scale in the picture goes only as high as it does because the focus is directed at the inland variations. The white areas in the picture have values that are 200 millimeters per year or higher.

Precipitation Slope Maps

Figure 11a shows the slope map of the difference between the slopes of the data from 1991-2010 and 2081-2100. In this slope map it is easy to see where there will be differences in precipitation and where there will be an increase in precipitation in the future. The steeper the slope is, the greater the variation in precipitation.

Figure 11b shows the difference between the slope maps from EC-Earth 1991-2010 and ERA-Interim. This slope map gives an idea of the difference between EC-Earth (based only on model data) and ERA-Interim (a model with real observations). The range of the slope for the slope map is the same as for Figure 11a. Hence, the differences between 1991-2010 and 2081-2100 using EC-Earth are greater than the differences between 1991-2010 using EC-Earth and ERA-Interim. According to this result, EC-Earth can be seen as reliable for the majority of Greenland.



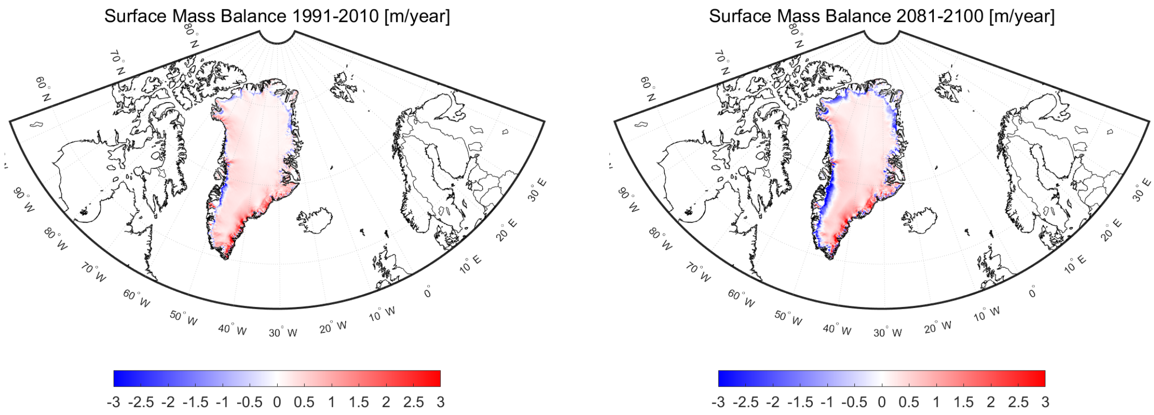
(a) The slope map of the difference between 1991-2010 and 2081-2100 using EC-Earth.

(b) The slope map of the difference between EC-Earth and ERA-Interim.

Figure 11: Slope maps showing the difference between different model runs.

4.2 Surface Mass Balance

Figure 12, shows the SMB for the two time periods, and the differences are displayed. For the 2081-2100 model data, Figure 12b, there will be more melting and less accumulation of the ice sheet than for the 1991-2010 model data, in Figure 12a.



(a) Surface Mass Balance 1991-2010.

(b) Surface Mass Balance 2081-2100.

Figure 12: The Surface Mass Balance for the two time periods.

Figure 12 shows the difference in SMB between the two time periods. Here, it can be seen that there will be mass loss between the time periods around the coasts for all of Greenland and a great mass loss across the western coast of Greenland. For the inland the difference in mass balance will be zero or slightly positive.

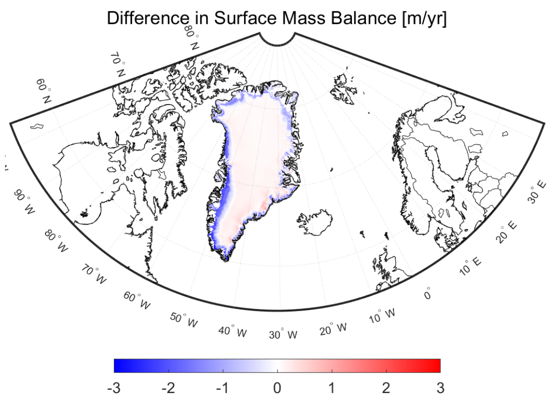
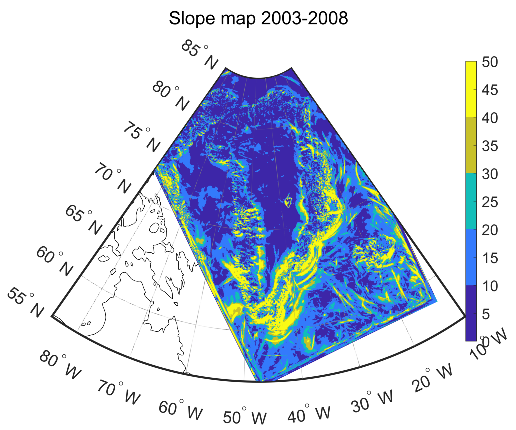


Figure 13: The difference in SMB between 1991-2010 and 2081-2100.

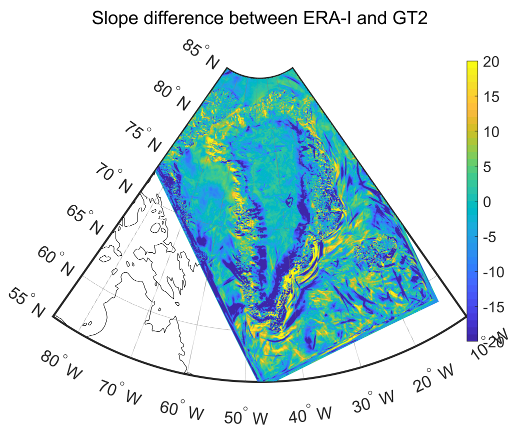
4.3 Modified Ice Sheet Topography

Figure 14a shows the year maximum slope map for the precipitation from 2003 to 2008 with a modified ice sheet. It is apparent that ice sheet does affect the precipitation pattern, as the shape of the ice sheet can be seen in Yellow just inside the coast of Greenland, where the slope is steep, meaning a high variation in precipitation events.

Figure 14b shows the difference between the slope maps for ERA-Interim and GT2, meaning the difference between present day data with real observations and present day model data run with a modified ice sheet. The result shows great differences in the precipitation distribution. Changing the ice sheet changes the location of where the maximum amounts of precipitation falls dramatically.



(a) The slope of the year maximum precipitation 2003-2008.



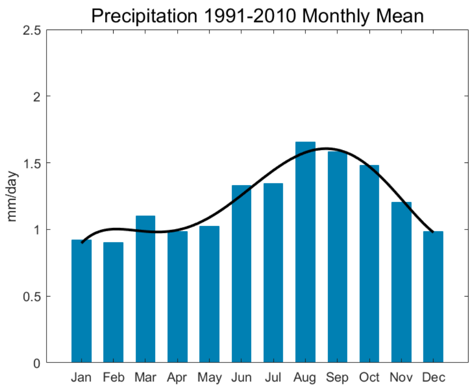
(b) The slope difference between ERA-Interim and GT2.

Figure 14: Two results using modified ice sheet topography.

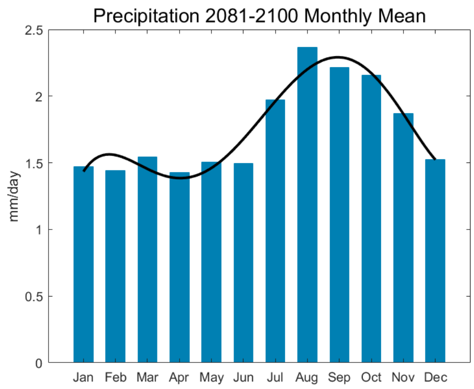
4.4 Precipitation Variability

Figure 15 shows the monthly mean of the precipitation for the two time periods. It looks as if the line fitted to the 2081-2100 model data in Figure 15b is steeper over July to December than it is for the 1991-2010 model data in Figure 15a for these months. The curve has another shape for the 2081-2100 data, meaning there will be a change in precipitation variability between the two time periods. The curve fitted to the bars is used to show the change in precipitation variability between the time periods. Figure 16 also shows the monthly mean, but for the four seasons for both time periods. In these plots, it is easier to see how the precipitation variability will change in the future.

For 1991-2010 in Figure 16a, June to August was the season with the most precipitation, but for 2081-2100 in Figure16b, it will instead be September to November and the plots show that overall there will be greater amounts of precipitation in the future.

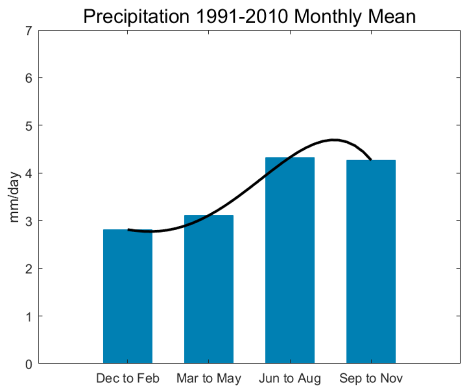


(a) Monthly mean precipitation 1991-2010.

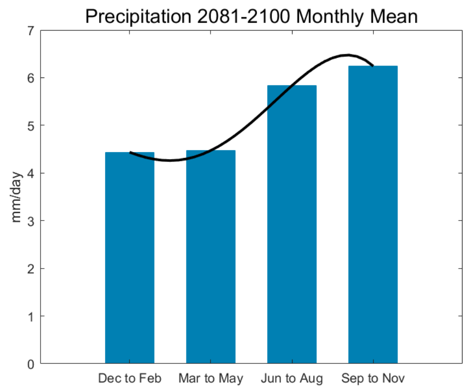


(b) Monthly mean precipitation 2081-2100.

Figure 15: The mean precipitation for every month for the two time periods.



(a) Seasonal mean precipitation 1991-2010.

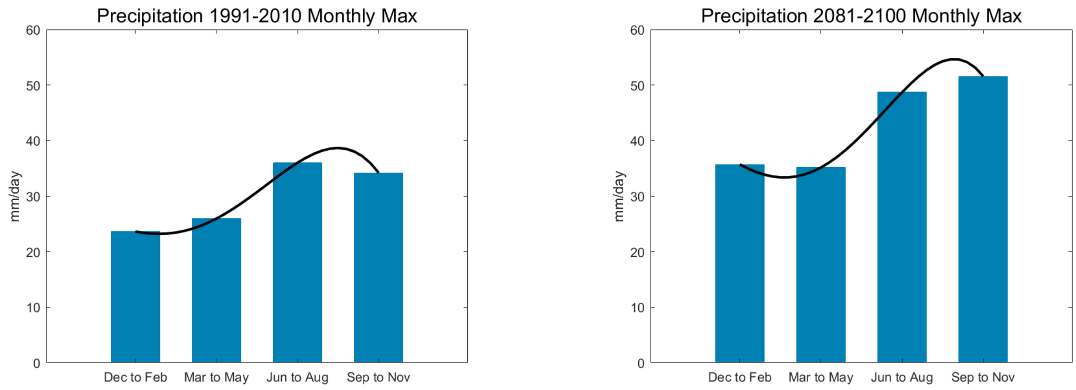


(b) Seasonal mean precipitation 2081-2100.

Figure 16: The mean precipitation for every season for the two time periods.

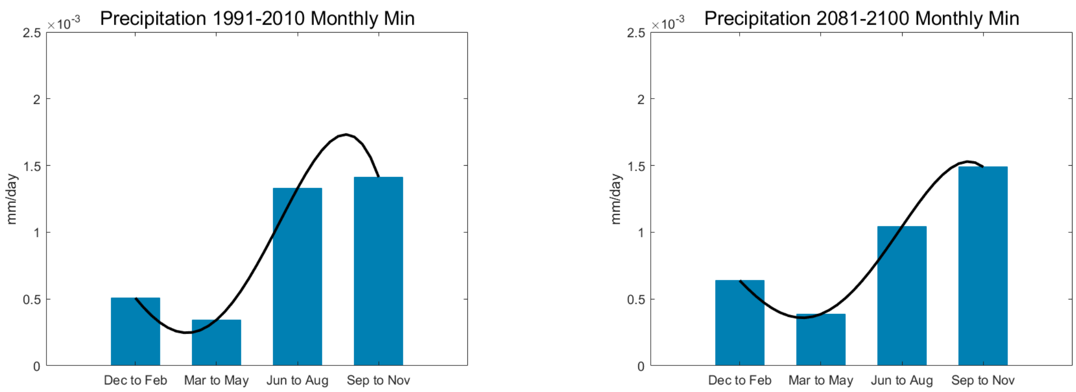
Figure 17 is showing the maximum precipitation for the seasons, both time periods. I can be seen that there is an overall increase in maximum precipitation and these plots one show the same tendency as for the monthly mean in Figure 16, which is that the season with the most precipitation changes from being June-August for 1991-2010 in Figure 17a to instead September to November for 2081-2100 in Figure 17b.

Figure 18 shows the monthly minimum for both time periods. For 2081-2100 in Figure 18b there is an increase in minimum precipitation for all seasons except for June to August, compared to 1991-2010 in Figure 18a, meaning there will be a precipitation variability in the future due to this result.



(a) Seasonal maximum precipitation 1991-2010. (b) Seasonal maximum precipitation 2081-2100.

Figure 17: The Figure shows the maximum precipitation for every season for the two time periods.

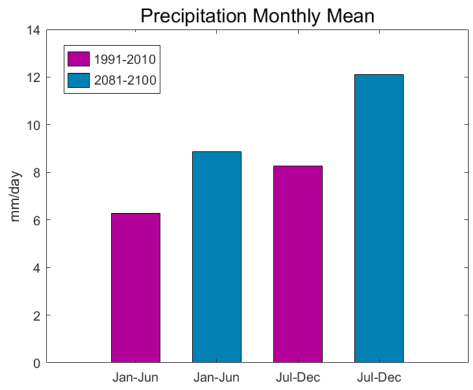


(a) Seasonal minimum precipitation 1991-2010. (b) Seasonal minimum precipitation 2081-2100.

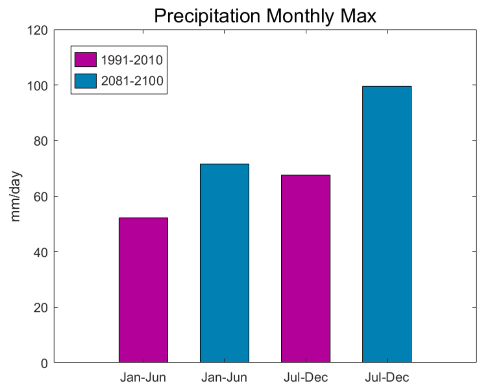
Figure 18: The minimum precipitation for every season for the two time periods.

Half Year assembled

In Figure 19a the monthly mean for six months is assembled for the both time periods and in 19b the monthly maximum for six months is assembled for the both time periods. The percentage difference between January to June and July to December for 1991-2010 for the monthly mean is 32,5% and for 2081-2100 it is 37,6%. The percentage difference between January to June and July to December for 1991-2010 for the monthly maximum is 28,3% and for 2081-2100 it is 37,5%. In Figure 20 the monthly minimum for six months is assembled for the both time periods. The percentage difference between January to June and July to December for 1991-2010 for the monthly minimum is 200% and for 2081-2100 it is 173%. It should be kept in mind that these precipitation amounts are very small and the possibility of a source of error making a great impact is significant.



(a) Monthly mean precipitation for six months assembled, both time periods.



(b) Monthly maximum precipitation for six months assembled, both time periods.

Figure 19: Precipitation data for six months assembled for the monthly mean and maximum, both time periods.

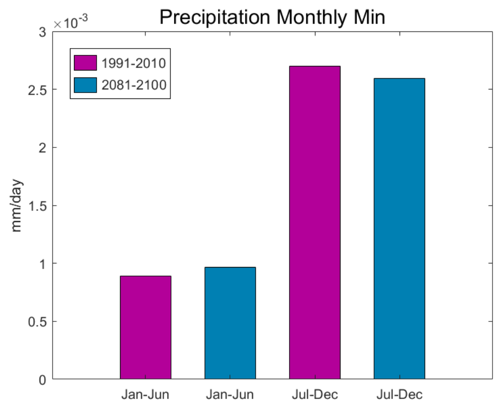


Figure 20: Monthly minimum precipitation for six months assembled, both time periods.

5 Discussion

Generally speaking, one can see an increase in precipitation between 1991-2010 and 2081-2100 for all controlled locations in the Figures 4, 6, 7, 8 and 9. As can be seen, for some of the plots, the linear regression is located behind the robust regression, as they are almost the same. In some cases, it was very useful to have the robust regression, as this gave a slightly different result than the linear regression, for instance, in the Figures 7b, 9a and 9b, where the robust regression causes the lines of the different periods to cross. In these three slope plots it is more difficult to draw definite conclusion about the change in precipitation, therefore, it is good to have the slope plot equations. For two of these slope plots, the slope plot equations in Table 1, are steeper for the present day model data than for the future model data. In the other seven plots, it is easier to see that it will increase for 2081-2100, both the amount of precipitation and of the variation in precipitation, compared to 1991-2010. In these plots, the precipitation increases most in terms of the total amount of precipitation for places with already high precipitation amounts during 1991-2010, but in percentage difference it increases more for places with medium or little precipitation in 1991-2010. In Table 1, it can be seen that the slope is steeper, based on the slope plot equations, for the 2081-2100 model data for eight of the ten controlled locations. Furthermore, ten different locations were chosen for the possibility to make conclusion with high certainty. The result proves that for 80% of the controlled locations, the slopes of precipitation will become steeper in the future, based on the linear regression.

The inland of Greenland is today relatively dry as seen in the Figures 4b, 7b and 8a (based on the amount of precipitation) and as mentioned earlier, the highest percentage difference can be seen inland. Thus, an increase in precipitation at inland locations is more interesting than a change around the coasts, where there are already high amounts of precipitation, since this will change the inland climate. It is clear that there is not a general increase in the total amount of precipitation everywhere, there is as greater increase inland.

Location g) in Figure 3, is a location in the inland of Greenland. Figure 8a shows the slope plot for this location. Looking at this slope plot, it is apparent that the changes in precipitation between the time periods are significant here. The slope of the 2081-2100 model data is much steeper than for 1991-2010, this means that the variation between the precipitation events will be higher in the future. Also, the 2081-2100 model data have several precipitation events that are much higher than the highest event between 1991-2010.

Figure 10b shows a detailed picture of how the difference in mean annual precipitation will change for the inland between 1991-2010 and 2081-2100. When looking at this figure, it seems that the mean annual precipitation for the inland of Greenland will increase by around 40 to 140 millimeters per year in the future. Not to mention, this is an interesting result in view of the SMB, since precipitation is the source of growth of the ice sheet, and can give rise to accumulation. In Figure 13, showing the difference between the SMB for the two time periods, it can be seen that the mass balance difference will be positive for the inland. Figure 10a, shows the difference in mean annual precipitation between 1991-2010 and 2081-2100, but with a detailed picture of the coast. There are areas that will have an increase in mean annual precipitation up to a meter per year. Despite this, the difference in SMB between 1991-2010 and 2081-2100, seen in Figure 13, will be negative around the coasts nearly everywhere, the ice sheet SMB will likely be more negative for the years in the future.

Point d) in Figure 3 is a location that will have a large amount of additional precipitation in the future, it is located near the eastern coast. In Figure 10b it is located in an area that will have a difference of 200 millimeters per year or higher in mean annual precipitation. Despite this, in Figure 6b, one can see that the slope is located higher, but the slope of the 2081-2100 data is only marginally steeper than for the 1991-2010 data. This means that there will be higher amounts of total precipitation here in the future, but the variation in precipitation events will not increase noticeably here.

The slope in the slope maps gives information about where there will be a greater or a smaller variation in precipitation events in the future compared to present day. Figure 11a shows the difference between 1991-2010 and 2081-2100. Overall, there will be steeper slopes across Greenland, meaning there will be more variations in precipitation in the future compared to present day. Comparing the slope of the EC-Earth plot with ERA-Interim is interesting because it can tell if the EC-Earth plots look realistic compared to the ERA-Interim, meaning it gives a picture of how good EC-Earth is in line with reality. In figure 11b it can be seen that there are variations in the slope map difference of the two climate models, mostly around the coasts of Greenland, the differences are smaller than in Figure 11a. EC-Earth differs some from ERA-Interim around the south-eastern coasts of Greenland, otherwise it gives a good representation of the actual precipitation. This provides confidence for the EC-Earth climate projection, but of course, there is a possibility that the future will not look exactly as the prediction based on EC-Earth model data. It is, as mentioned before, based on the RCP8.5, one of several future scenarios.

The slope maps from the time series based on the model data running on EC-Earth was not as detailed as the slope plot of the data based on ERA-Interim. A possible cause for this is the short range of time for the EC-Earth model data compared to the ERA-Interim data. The data sets from EC-Earth are only 20 years and the ERA-Interim is 37 years. It can also be that the resolution of the forcing on the boundaries is affecting.

120 km is downscaled to 5 km with EC-Earth and HIRHAM5 and for ERA-Interim the downscaled grid size is 75 km.

With a modified ice sheet the precipitation pattern would look different. This is since precipitation will fall to the ground when it reaches an area with high topography, as the ice sheet. If the ice sheet are further inland the precipitation will fall further inland as well. This is interesting, since for a future scenario after the greater mass loss of the ice sheet, this could be the scenario. When parts of the ice sheet is gone, precipitation will not be able to recreate the ice sheet. A smaller ice sheet covering Greenland will affect the albedo in the sense that areas which lost the ice sheet will not reflect the sun's incoming radiation as well anymore and these areas will get more heated by radiation, which will result in even more warming.

When looking at precipitation variability, it can be seen that the monthly mean of the precipitation is increasing for all months of the year in Greenland. When switching from looking at the mean precipitation for each month to looking at three months at a time instead when investigating the precipitation variability, the error margin decreases and it is easier to make conclusions with greater certainty. When looking at the bars for six months assembled for the monthly mean and maximum, the percentage difference between the amount of precipitation in the first half of the year and the second half of the year is greater in the future than in the past. This is not the case for monthly minimum, where it is decreasing in the future. However, for this plot there are very small amounts of precipitation, since it is the minimum value. It is about 0.0025 mm/day for the greatest value, compared about 12 mm/day for the greatest value for the monthly mean. With such small amounts, it is not as easy to draw concrete conclusions, since the standard deviation for the minimum would most certainly be high compared to the actual precipitation. Therefore, this result should not be taken into account. These results indicate that there will be a change in precipitation variability in the future, compared to present day. There will be more precipitation 2081-2100 overall. The amount of precipitation in the second half of the year is increasing more compared to the first half of the year for 2081-2100 than it does for 1991-2010 in percentage difference. This means that there will be a greater increase in precipitation for the months July to December compared to the present day and there will be a difference in precipitation variability.

6 Conclusions and Outlook

On the whole, it appears that there will be more precipitation throughout Greenland in 2081-2100 compared to the 1991-2010.

The results indicate that for coastal climates there will be a general increase in precipitation, but no difference in the variation of precipitation, compared with the inland climate where there will be both a general increase and a change in the variation of precipitation. Thus, this may point to a change in the climate for, in particular, Greenland's inland. It should be kept in mind that results can be interpreted differently and that this is one interpretation. As can be seen, the SMB will be positive for Greenland's inland, but negative around the coasts, meaning, a large relative increase in precipitation for the inland gives a positive mass balance there, but however, the increase around the coasts of the total amount of precipitation is still not enough to give an unchanged or positive mass balance in the future. This provides answers to the first two questions in the introduction.

To answer the other two questions, there is a change in precipitation variability between 2081-2100 and 1991-2010, specifically for the second half of the year, where the precipitation will increase more in percentage than for the first half of the year. Also, there will be an increase in precipitation in the autumn compared to the other seasons. Wet seasons will get even wetter in the future and there are indications that the dry seasons might become even drier.

More research needs to be done on the subject to ensure that the results are completely reliable. These future predictions are made with the future scenario RCP8.5 and it cannot be said with certainty now if this will be met in the future, or if any of the RCPs will instead be achieved by the end of the century. RCP8.5 is a scenario where there is a continued high combustion and can be said to be the worst case scenario among commonly used RCPs. For instance, RCP 4.5 or RCP 6.0, would possibly not give a future prediction with as high amounts of precipitation as RCP8.5 did. Although, RCP8.5 did predict large increase of precipitation in all of the various studies, and the other RCPs will probably do as well, only maybe not as large.

To ensure that EC-Earth provides a good representation of the future scenario, present day EC-Earth model data was compared with present day ERA-Interim. More similar comparisons could be made to find out if EC-Earth appears to be able to provide a good representation even according to other models.

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