Comparison between Greenland precipitation observations and a regional climate model.

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April 20, 2008

Contents

1   A short summary in danish

Denne opgave omhandler nedbør på Grønland. I opgaven er observationsdata fra Danmarks Meteorologiske Institut (DMI) taget i perioden 1950-2006 sammenlignet med en regional klimamodel (HIRHAM) også udarbejdet på DMI.

Nedbørsmålinger tages på Grønland, som regel med en Hellmann gauge, med et påsat Nipher shield for at modvirke vindeffekt. Beholderen bliver tømt hver 6. time.

I alt er udvalgt 8 stationer rundt Grønlands kyst: Danmarkshavn, Illoqqortoormiut, Tasiilaq, Prins Chr. Sund, Julianehaab, Nuuk, Egedesminde og Upernavik. Observationerne langs Grønlands kyst viser en tydelig nord-syd gradient og også en øst-vest gradient. Der er mindre nedbør på vestsiden af Grønland, som følge af mindre åbent vand og dermed luft med lavere fugtighed.

Derudover sammenlignes model og nedbørsdata fra en iskerne NordGRIP og yderligere er en sammenligning mellem et nedbørskort og modellen udført, for at se, hvorvidt modellen kan reproducere nedbør over iskappen.

Den regionale klimamodel (RCM) har en opløsning på 25 km og er på randen styret af en global klima model, men kan ellers løbe frit. Klimamodelen er i et roteret koordinatsystem, hvor nordpolen ligger mellem Greenwich medianen og Ækvator, for at undgå matematisk tunge udregninger.

Modellen klarer ikke at reproducere størrelsen af nedbør over iskappen. Den er ca. en faktor 2 for lav overalt. Dog er nord-syd og øst-vest variationener repræsenteret omtrent som på Calancas nedbørskort. Iskernen NordGRIP rammer indenfor modellens forudsigelser de fleste år, men modellen ser dog også her noget lav ud.

Ved sammenligning mellem modellen og kystobservationerne ses at modellen rammer det rigtige niveau ved nogle stationer: Thule, Danmarkshavn og Prins Chr. Sund men dog kun i halvfemserne. Modellen viser for høje værdier når man sammenligner med stationerne Illoqqortoormiut, Julianehaab og Tasiilaq, men sammenligner man med de fire nærmeste gridpunkter, nås niveauet dog med de laveste værdier for modellen. Modellen fejler helt i repræsentationen af Egedesminde og Nuuk. Modelværdierne er her alt for lave, det kan skyldes enten at modellen fejler, eller de lokale forhold.

Konkluderende må man sige at modellen helt fejler i simulationen af nedbørs niveauet på iskappen, som er meget højere i virkeligheden. Langs kysterne opnår modellen også sjældent det korrekte niveau for målt nedbør, men det ser dog noget bedre ud. At modellen ikke rammer det rigtige niveau kan enten skyldes at modellen ikke producerer de virkelige vejrsystemer. Det er dog mindst lige så sandsynligt at observationsdataene ikke er helt korrekte. Stationer kan f.eks. være uhensigtsmæssigt placeret.

2   Abstract

In this report observations of precipitation from weather stations along the coast of Greenland, and a single ice core as well as a precipitation map made by Calanca [2007] on the basis of observations collected by Ohmura and Reeh [1991] is compared to a regional climate model, HIRHAM. This is done to asses wether the model can reproduce the precipitation observed from 1950 until 2006. The model seems to fail in reproducing the level of precipitation on the ice cap of Greenland. The level along the coast is sometimes reproduced, but seldom. The fact that the model fails to reproduce the level could be due to the model failing in simulating the weather systems observed. But the observations of precipitation might as well have an incorrect level. Stations can e.g. be placed badly.

3   Weather conditions on Greenland

Greenland generally has an arctic climate and a mean annual precipitation of 340 millimeter according to *Ohmura and Reeh* [1991]. There are however great differences in precipitation from north to south and also from east to west. Accurate understanding of the precipitation pattern has a large influence on understanding the dynamics of glaciers, and the hydrological cycle in the area. If one understands these processes, one will also be able to make estimates on mass balance changes on the Greenland ice sheet and sea level change [*Ohmura and Reeh*, 1991].

Greenland is a huge island, 2.2 million km^2 in area. Its northern most point is positioned just 700 km from the North Pole and it passes from north to south almost 24 degrees of latitude or 2600 km, which leads to a large variation in the climate of the island. Greenland has a clear north-south precipitation gradient. This is among others because the southern part is lying close to open water almost all year, while the northern part is further away from the water source because of ice covering the seas, and therefore the air reaching the north contains less moisture [*Cappelen et al.*, 2001].

In the summer the precipitation is mainly rain in the southern part and in winter time it is snow. In the northern part of Greenland the precipitation almost always falls as snow, though some rain may be observed in July. The south-east Greenland can almost drown in up to 3.5 meters yearly precipitation, while the far north-east stays desert dry [*Cappelen et al.*, 2001].

The central part of Greenland is covered by a huge ice cap, covering roughly 4/5th of Greenland. The highest point is positioned more than three kilometers above sea-level. In the southern part the ice cap is maintained by high amounts of precipitation, while the ice cap further north is maintained by very low temperatures preventing high melting rates [*Gregersen*, 1995].

The large East Greenland Polar Current runs along the east coast of Greenland, transporting loads of sea ice south along the coast, cooling this area, particularly during spring and summer. West of Iceland the stream joins the warm Irminger stream, which is an off-spring of the warm Gulf stream. The Irminger stream has the greatest influence in autumn and spring and is able to maintain the south-eastern part of Greenlands coast ice free. Open water makes the air more humid and when reaching the shore, more precipitation is produced on the eastern side, than on the western side[*Gregersen*, 1995]. This latitudinal gradient is very clear south of 65° N on the eastern side and 70° N on the western side [*Ohmura and Reeh*, 1991]. During wintertime the wind system is mainly dominated by two semi permanent cyclones: The Baffin Bay low in the west and the Icelandic low in the east. The general windpattern for january is shown in figure 1, left. In wintertime, the southeast of Greenland is directly hit by onshore flow, causing heavy precipitation when the air mass starts ascending in the coastal areas. It is also interesting to observe that the ice sheet is under influence of the Atlantic Ocean and not from dry air emerging from Canada. The west coast is mainly dry in wintertime, because the air is continental, though it has been slightly modified coming through Baffin Bay and Davis Strait [*Ohmura and Reeh*, 1991].

In the summertime the wind system changes (see figure 1, right). The Baffin Bay low and the Icelandic low are still present. In addition to those a low is present in the polar basin. This changes the precipitation pattern: A significant precipitation on the north-western slope is present, due to the advection from west. The western side in general has a summer peak in precipitation due to the high water content of the air mass. The northeast stays dry and the southeast becomes dryer in summer compared to winter, because the
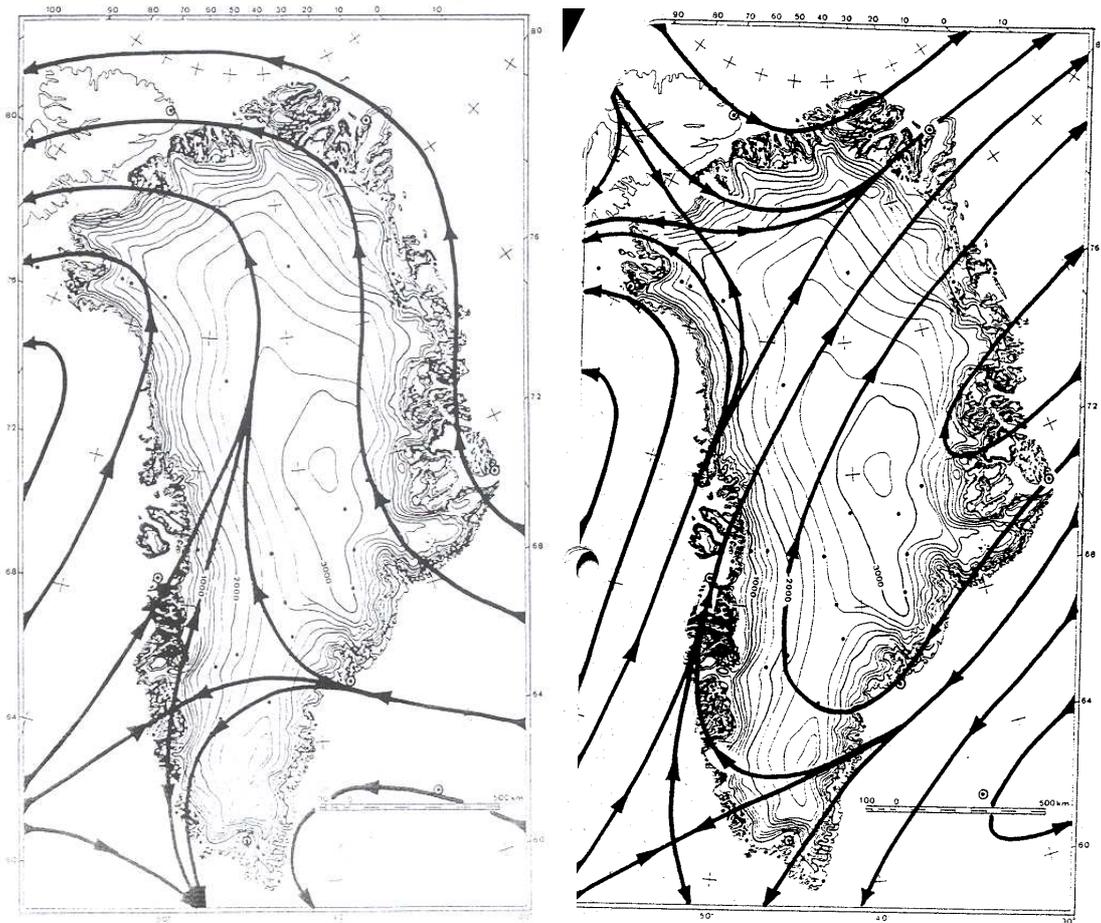
Figure 1: The general wind pattern for 850 hPa height in January (left) and in July (right). The concentration of streamlines is expressed as being proportional to the wind speed [*Ohmura and Reeh*, 1991].

wind comes from the north where the ice is still present [*Ohmura and Reeh*, 1991].

There is also a significant height gradient along the coast, which calls for variations both in temperature, wind and precipitation even over a very short distance [*Cappelen et al.*, 2001]. The wind is significantly affected by the temperature gradient between land and sea. The temperature gradient causes a cold moist sea breeze in the summertime and a cold dry land breeze in wintertime in the coastal areas. However above the inversion layer (typical in a height of 150-200m), the wind is no longer controlled by the land/sea effect [*Gregersen*, 1995]. Above the inversion layer katabatic winds are dominating, because of the constant heat drain taken from the air to the ice cap, an effect maintained by the high albedo. The heat drain supports a continuing land breeze circulation and it turns to katabatic winds, since the ice cap is very high and steep. When the height gradient steepens, the wind canalizes, and can reach extreme speed when reaching the coast *Gregersen* [1995]; *Cappelen et al.* [2001]. Precipitation mainly occur along the coast in wintertime and can be found inland due to the sun heating in the summertime [*Cappelen et al.*, 2001].
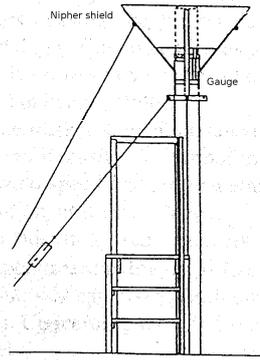
Figure 2: The precipitation sampling equipment used in Greenland: A Hellmann gauge with a Nipher Shield [*Allerup et al.*, 2000b].

4 Precipitation observations from Greenland

Precipitation is defined as the amount of precipitation falling on the ground in a certain period, this means that both rain, sleet, snow, hail, white frost, and deposit from snow is part of the precipitation. All these different types of precipitation are affected by wind in distinct ways. This makes it very difficult to measure the precipitation correctly[*Allerup et al.*, 1997].

The instrument that the Danish Meteorologic Institute (DMI) uses for measuring precipitation in Greenland is a Hellmann gauge of 200 cm^2 orifice placed 2.5 m above ground surface to prevent accumulation from drifting snow. Further a Nipher shield is positioned on top of the measure stations at Greenland to damp the influence of wind [*Allerup et al.*, 2000b]. Figure 2 is a drawing of a typical station. Some of the newest measurements have been taken with GeoNord stations, which instead of measuring the precipitation by amount, measures the frequency of the movements of the buckets. The gauge is filled with antifreeze liquid and hence hangs in a line. The frequency of the line is measured and the precipitation is then calculated from the frequency [*Cappelen*, 2007].

The wind has great influence on particularly the solid precipitation, since only a fraction of the precipitation that falls as snow will fall into the gauge, due to the wind making the precipitation fall at an angle from the vertical into the bucket. The amount of collected precipitation will therefore decline with the wind.

Further the aerodynamics of the snowflakes will make them move turbulently. This means that the measured precipitation not only is affected by wind speed, but also by the temperature which defines the shape of the snowflake. These two effects; the wind speed and the aerodynamical effect is called the wind effect [*Allerup et al.*, 2000a]. In the case of wet precipitation, the temperature is not as important, but the intensity of the shower is important since small water drops are easier caught by the wind. In this case the wind still has an important effect on how much precipitation is deposited in the gauge[*Allerup et al.*, 1997].

Further loss happens while the precipitation is in the gauge: Snow can be blown up from the gauge, the gauge can be filled if not emptied frequently enough, and most important a wetting loss due to evaporation and adhesion takes place. The evaporation loss is in this case the part that has actually fallen to the bottom of the gauge, and from here evaporates, while the adhesion loss is the part of the precipitation that sticks to the side of the gauge, and therefore does not add to the total measured precipitation [*Allerup et al.*, 2000a].

If the wind speed (V (m/s)), fraction of solid precipitation (α), air temperature (T ($C°$)) and intensity of precipitation (I ($mm/hour$)) are known at the height of the gauge,

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Table 1: Precipitation correction values for the different stations based on annual observations as calculated by *Allerup et al.* 2000a. H is the observed precipitation in the period 1994-1998, α is the amount of snow in percent, V_{cor} is the percentual correction due to wind, W is the percentual correction due to wetting loss, R is the corrected values and K is the correction coefficient between H and R, and V is the wind speed.

Station	Number	H (mm)	α (%)	V_{cor} (%)	W (%)	R (mm)	K	V (m/s)
Danmarkshavn	4320	188	78	78	19	371	1.97	4.1
Egedesminde	4220	270	58	43	16	430	1.59	3.5
Illoqqortoormiut	4339	393	70	47	10	617	1.57	3.9
Julianehaab	4272	1043	27	28	3	1368	1.31	4.1
Nuuk	4250	737	72	56	6	1191	1.62	5.2
Prins Chr. Sund	4390	1399	37	45	3	2065	1.48	2.2
Tasiilaq	4360	836	49	15	5	1011	1.21	2.2
Thule	4202	162	72	69	25	314	1.94	4.1

one can correct for the inaccuracy of the measurement using $K = R/H$. Here, K is the correction factor, R is the true precipitation and H is the measured precipitation. K is further dependent on the above mentioned parameters and can be calculated using the empirical equation (1).

$$
\begin{aligned}
K(\alpha) &= \alpha \cdot PS(V,T) + (1-\alpha) \cdot PL(V,I) \\
&= \alpha \cdot e^{\beta_0 + \beta_1 \cdot V + \beta_2 \cdot T + \beta_3 \cdot V \cdot T} + (1-\alpha) \cdot e^{\gamma_0 + \gamma_1 \cdot V + \gamma_2 \cdot log(\frac{I}{1\frac{mm}{hour}}) + \gamma_3 \cdot V \cdot log(\frac{I}{1\frac{mm}{hour}})}
\end{aligned}
\tag{1}
$$

The intensity is calculated from observations of the length of the precipitation period and how much precipitation that has fallen through the same period, PS is the snow part and PL is the liquid part. The constants β and γ are empirically determined and they are: $\beta_0 = 0.07556, \beta_1 = 0.10999\frac{s}{m}, \beta_2 = 0.012214(C^\circ)^{-1}, \beta_3 = -0.007071\frac{s}{mC^\circ}$ and $\gamma_0 = -0.04230, \gamma_1 = 0.034331\frac{s}{m}, \gamma_2 = -0.00101$ and finally $\gamma_3 = -0.012177\frac{s}{m}$ [*Allerup et al.*, 2000b].

Allerup et al. [2000a] have calculated correction values for some stations in Greenland in the period 1994-1998 using equation (1) (see table 1). To do this, the rain intensity was fixed to 1mm/hour, the wind was allowed to change between 0 m/s and 8 m/s and the temperature was forced to be above -20 C°. If the wind speed was greater than 8 m/s it was lowered to $8m/s$ and temperatures below -20 C° were raised to -20 C°. This was done to make the coefficients equal in the intervals.

Note that the wetting loss is highest in the north and lowest in the south. This is due to the very low precipitation in the north, making the relative wetting loss higher.

Allerup et al. [2000a] concluded that approximately 75% of the yearly precipitation in the north was snow, and 30-40% in the south. This leads to a yearly correction value of up to 95% in the far North and only 30-40% in the south.

4.1 Stations along the coast

In total eight stations were chosen for comparison mainly due to their geographical covering of the Greenland coastline and also because of the long time period of measurements. The stations are Danmarkshavn, Egedesminde (Aasiat), Illoqortoormiut (Scoresbysund), Julianehaab (Qaqortoq), Nuuk (Godthaab), Prins Chr. Sund, Tasiilaq (Ammassalik) and Thule (Pituffik) (see table 2 and map 3). The data is from Cappelen et al., (2001).

Table 2: The station name, number, position and period of measurements. Be aware that the measure period has some gaps. Thule has a gap in the period 1976-83 and Prins Chr. Sund has a gap in the period 1980-1991. The first seven stations are weather stations whereas the eight NorthGRIP is an icecore drilling location.

Station	Number	Latitude	Longitude	Height(m)	Period
Danmarkshavn	4320	76.45	-18.40	11	1949-2006
Egedesminde	4220	68.42	-52.45	43	1958-1999
Illoqqortoormiut	4339	70.29	-21.57	65	1950-2006
Julianehaab	4272	60.43	-46.03	32	1961-1999
Nuuk	4250	64.10	-51.45	80	1890-2006
Prins Chr. Sund	4390	60.03	-43.10	88	1959-2006
Tasiilaq	4360	65.36	-37.38	50	1898-2006
Thule	4202	76.32	-68.45	77	1961-1999
NorthGRIP		75.10	-42.3	2950	1950-1996

4.1.1 Monthly means

Figures 4 and 5 show monthly precipitation means evaluated for the different stations over different time spans due to the stations various measuring periods. The eastern stations are represented in figure 4 and figure 5 represents the western stations.

First of all it is important to state that the figures are based on the raw data collected in the gauges. Despite this fact a clear north-south tendency can be observed in both plots, with the northern stations having very little precipitation and the southern stations larger amount. This tendency would perhaps have been less clear, if one had corrected for the precipitation not collected in the gauge, since this would have led to more precipitation shown in the northern part. The correction values will be discussed in chapter 4.1.2.

There seems to be a slight increase of precipitation on the eastern side, even if one excludes Prins Chr. Sund station, though not very large. The high amount of precipitation in Prins Chr. Sund is caused by the position of the stations on the southern tip of Greenland, where it receives precipitation from both east and west.

Of the west Greenland stations (figure 5) all but Egedesminde show a peak in precipitation in the summer period, when most of the precipitation falls as rain. This peak could be an artefact, since a part of the snow probably never reaches the gauge due to wind, causing especially the winter observations of precipitation to be lower than what they really were. If it is a real feature it can be explained by the wind being advected to the west from the eastern side, bringing in more precipitation. In addition the sea is not ice covered in the summertime which makes the air more humid.

The top peak seen for Egedesminde in November and for Julianehaab in April could be due to local conditions such as wind direction.

The east Greenland stations (figure 4) do not peak in the summertime, but rather peak in wintertime. This is explained by the onshore wind that hits the southeast directly during wintertime. There is indication of a spring peak for Prins Chr. Sund and Tasiilaq which are both southeastern stations.

In general the monthly mean measurements seem to support the known weather systems for Greenland, but with some features caused by local conditions.

4.1.2 Trend in the yearly precipitation mean

The annual observations have been corrected for wind effects using the correction coefficients from table 1. The correction values are based on the period 1994-1998 and one
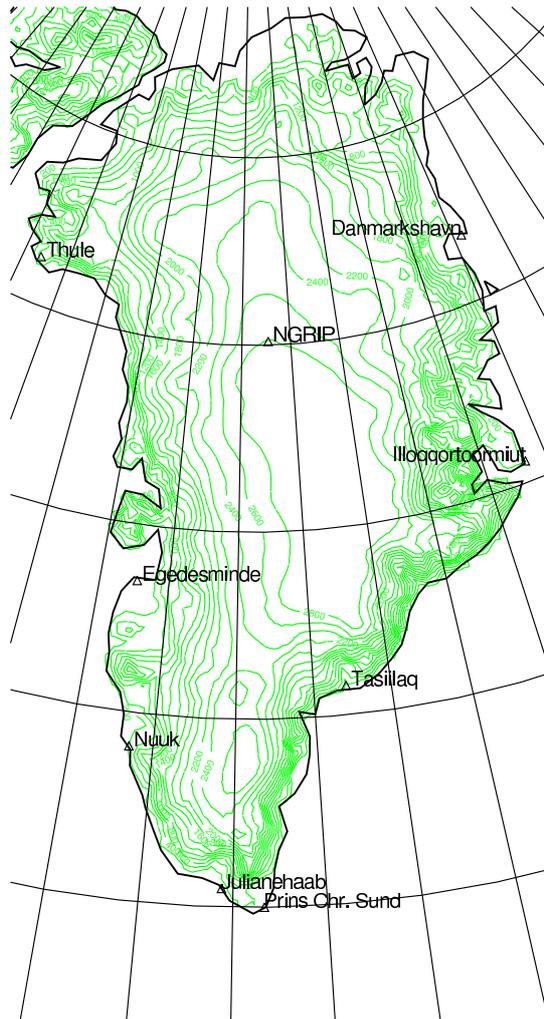
Figure 3: Positions of the stations, and the orography of the Regional Climate Model (RCM), see section 5

can, assuming no climate change in either temperature, wind speed or intensity, use the correction values on the period 1950-2006. This is not the case, especially when speaking of temperature, but in order to have values closer to the actual precipitation the correction is done anyway.

For the longer trends (see figure 6 and 7), the most striking feature, is the high annual variability. Especially the southern stations have a strong interannual variability. Both on the eastern and the western side of Greenland: The highest variance is found, where the highest amount of precipitation is. In table 3 correlation coefficients of yearly precipitation between the coast stations are represented. They are all very low in the range of -0.50 and 0.48. This is not high correlations.

Prins Chr. Sund station in the far south has very high values before year 1981. An explanation of this is not easy to obtain. One could be that the observations before 1992 were obtained without a Nipher Shield, but this would usually lead to lower values. Another possibility is that the stations has been moved during the period from a place with lots of drifting snow, to place without. But data of such a movement has not been traceable [*Jensen*, 2007; *Cappelen*, 2007]. This makes it difficult to extract a trend for this station.

When comparing the pattern for Prins Chr. Sund with the other stations for the short
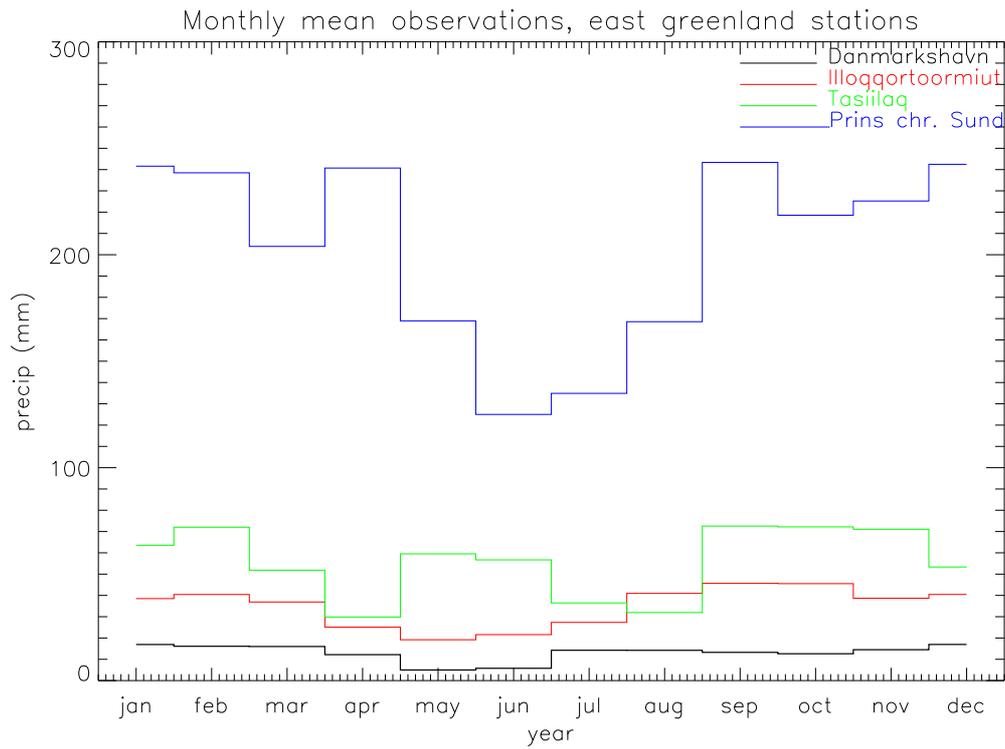
Figure 4: Monthly mean precipitation at the stations on the eastern coast of Greenland. The averages are over different time periods (see table 2) and the precipitation is not corrected for wind, intensity and temperature effects.
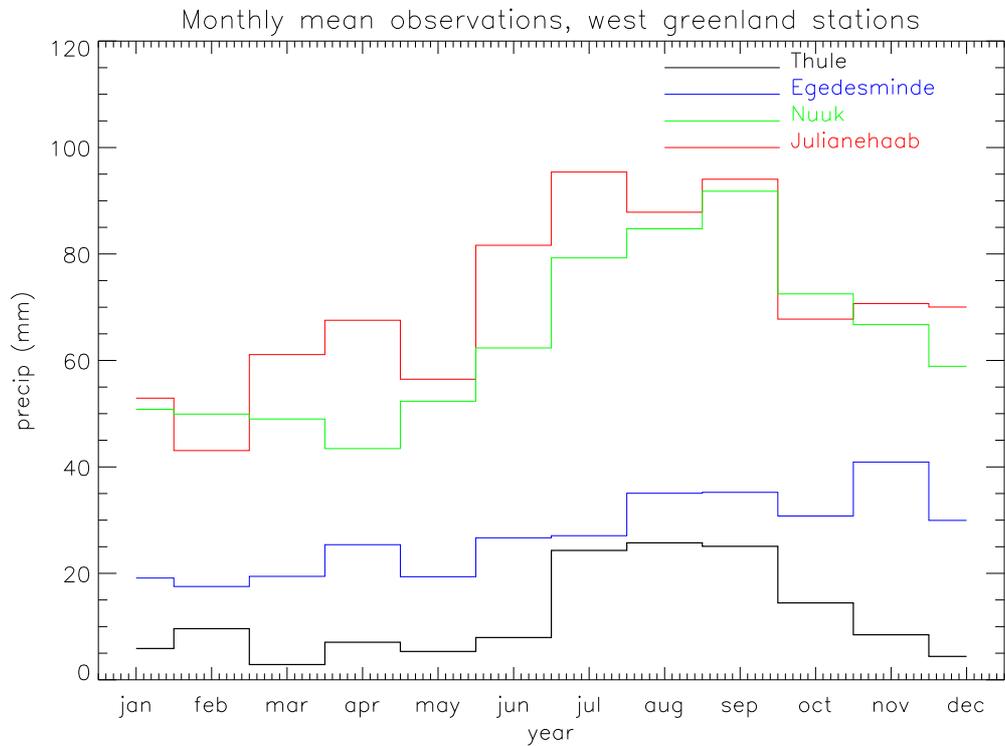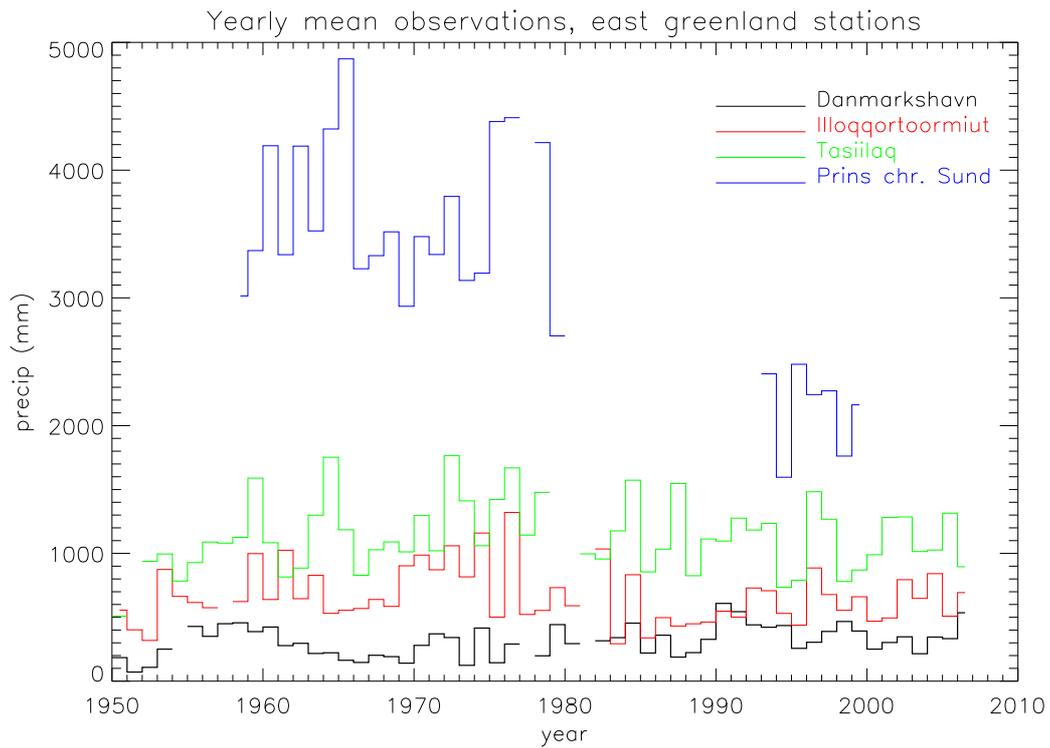

Figure 5: Monthly means at the stations on the western coast of Greenland. The averages are over different time periods (see table 2) and the precipitation is not corrected for wind, intensity and temperature effects.

Figure 6: Yearly mean observations from the stations on the eastern side of Greenland. Corrected for wind factor.
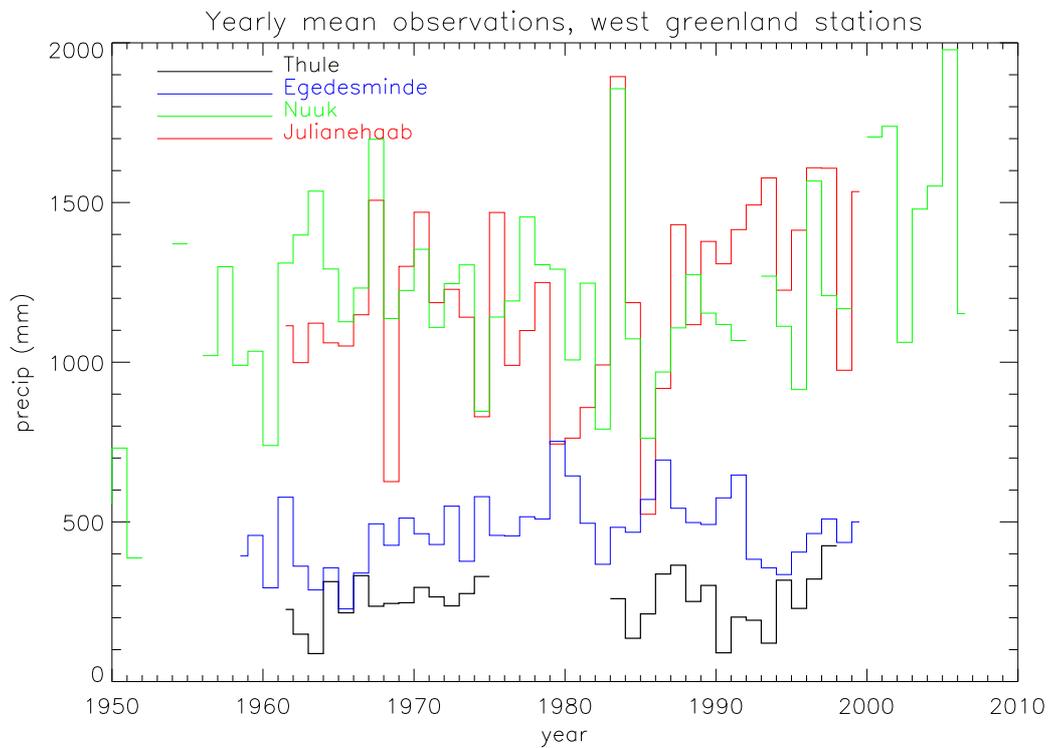
Figure 7: Yearly mean observations from the stations on the western side of Greenland. Corrected for wind factor.

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Table 3: Correlation coefficients of yearly mean precipitation between the stations, based on the annual tendency and the longest period available (see table 2)

Station	Thule	Julianehaab	Nuuk	Egedesminde	Danmarkshavn	Illoqortoormiut	Tasiilaq	Prins Chr. Sund
Thule	1	0.05	-0.10	0.19	-0.27	-0.04	0.08	-0.23
Julianehaab	0.05	1	0.51	-0.17	0.13	-0.11	0.21	-0.19
Nuuk	-0.10	0.51	1	-0.04	-0.03	-0.03	0.19	-0.03
Egedesminde	0.19	-0.17	-0.04	1	0.26	-0.02	0.03	-0.23
Danmarkshavn	-0.27	0.13	-0.03	0.26	1	0.17	-0.02	-0.50
Illoqqortoormiut	-0.04	-0.11	-0.03	-0.02	0.17	1	0.30	0.12
Tasiilaq	0.08	0.21	0.19	0.03	-0.02	0.30	1	0.48
Prins Chr. Sund	-0.23	-0.19	-0.03	-0.23	-0.50	0.12	0.48	1

period available, a correlation coefficient of 0.48 is to be found between Tasiilaq and Prins Chr. Sund, suggesting that, as according to theory, the stations monitor almost the same weather systems. But it is based on a very short period of data.

Illoqortoormiut, positioned between the Tasiilaq to the south and Danmarkshavn in the north, seems in some years to follow the pattern of Tasiilaq, with a correlation coefficient of 0.30, and in some years the pattern of Danmarkshavn, correlation value of 0.17 (see table 3). Whether Illoqqortoormiut follows the pattern for Tasiilaq or Danmarkshavn is likely determined by which weather system was predominant at the time, the Polar low or the Icelandic low.

The stations Illoqortoormiut and Tasiilaq have the highest values of annual precipitation in the seventies, while Danmarkshavn seems to have the highest values in the nineties. This again supports that they are influenced by different weather systems, which can have different strength in separate time periods.

On the western side of Greenland (fig 7) the north-south gradient is present, though Julianehaab and Nuuk show more or less the same values of precipitation. The two stations also show a high correlation coefficient; 0.51(see Table 3), being coherent with the fact that the wind systems hitting the two places are the same. Both stations also show a trend of precipitation increase starting in the nineties, maybe as an effect of global warming, making the air more humid. According to *Trenberth et al.* 2007 an increase in water vapor, would lead to more intense precipitation but on the other hand reduce the duration and therefore a change that way would not be detectable in yearly amounts. It is thus more likely that it is just the normal yearly variability. The amount of precipitation is the same for the two stations as the level for Tasiilaq on the west side.

In the north Thule and Egedesminde show more or less the same pattern, both have very little precipitation and their correlation coefficient is 0.19, probably due to the winter wind system (see figure 1 left). But even more interesting is that the correlation coefficient between Danmarkshavn in North-east and Egedesminde in mid-west has a correlation of 0.26. This is most likely due to the summer wind system (see figure 1, right).

The highest negative correlation is found between Prins Chr. Sund in south and the two most northern stations, Thule and Danmarkshavn, with correlation of -0.23 and -0.50, so when it is dry in the north it is wet in the south and vice verse.
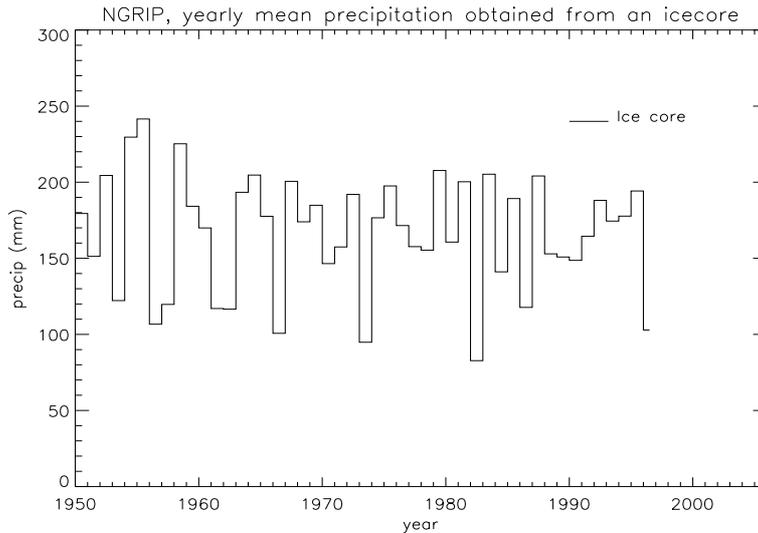
Figure 8: Precipitation for NorthGRIP based on the top 17 meters of the NorthGRIP ice core.

4.2 The Ice cap

Unfortunately it is not possible to measure precipitation the way it is done at the coast at the ice cap, since there is accumulation of snow, which would bury the gauges in a few years. Instead one can use thickness of yearly layers of ice cores to get an idea of the precipitation level on the ice cap. Since the snow can go nowhere on the huge ice cap, the hole question of loosing precipitation due to wind is nonexisting when looking at averages. The precipitation simply has nowhere to go. This of cause only counts in sights were there is no melting. In such places one can believe that the annual average of precipitation in the ice core is correct [*Svensson*, 2007]. When an ice core is retrieved the annual layer thickness is measured as well as the density profile. The density from the NorthGRIP ice core is taken from *Vinther et al.* 2006. The density profile from NorthGrip was fitted with a 7th degree polynomial in the top years (1950-1996). The precipitation in water-equivalence can then be calculated using the density of the snow/ice from the core and correlate this to water equivalence by multiplying by the ratio of density of the snow over water. Next the thickness of the yearly layer is multiplied.

The data from NorthGRIP is represented in figure 8. It is assumed that no precipitation is lost due to evaporation or melt. Further the thinning due to the flow of the ice is ignored, which is reasonable in the top 17 meters, especially since NorthGRIP is positioned on an ice divide.

First to be noticed is the low values as compared to the coastal stations. The mean is 166 mm/year. There is no clear trend to observe, but one should notice the relatively large variation from year to year.

Further Calanca has collected observations and ice cores from the last 100 years and on this basis made a precipitation map covering the Greenland ice sheet [*Calanca et al.*, 2000]. On the map (see figure 9, left) a north-south gradient is represented as well as a coast-inland gradient, caused by the height advection. The highest amounts of precipitation are in the south-east as expected, and the lowest values are found in the north-east. Calancas map and the mean from the NorthGRIP ice core are correlating, which is expected since Calanca has based his map on the NorthGRIP ice core as well as on other ice cores.
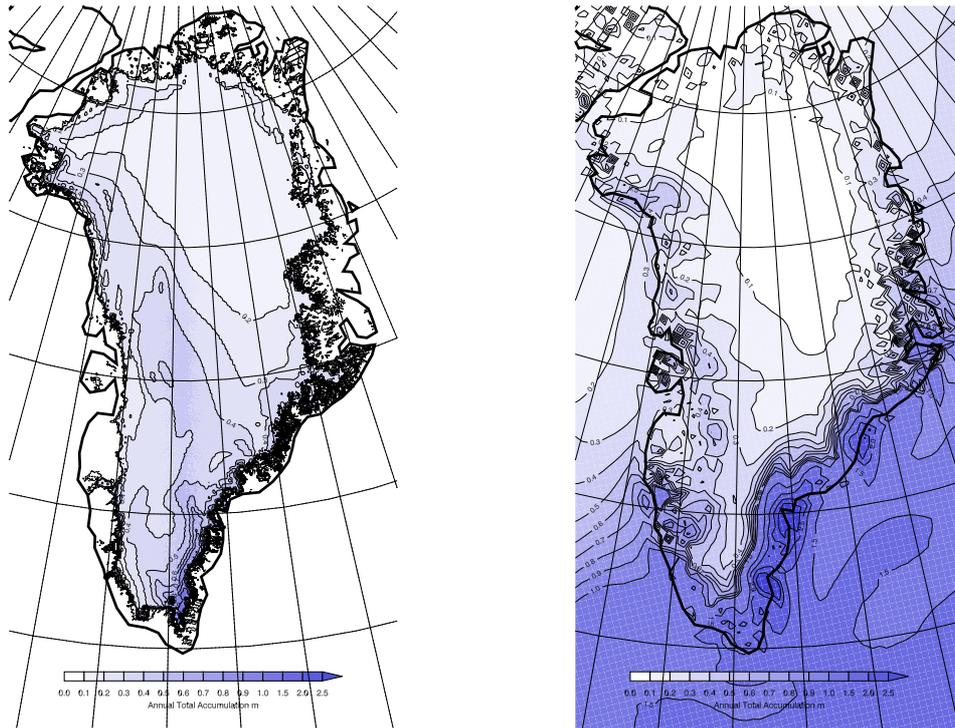
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Figure 9: Precipitation climate normals for the period 1961 to 1990 in meters. To the left based on observations of precipitation from the ice sheet as from *Calanca et al.* 2000 are represented and to the right regional climate model values are represented.

5 Model

When creating a climate model a number of choices exists. The gridsize can be changed, both horizontal and vertical. A decision of the temporal resolution of the model has to be made as well. The model can either have free boundaries or be controlled by boundaries coming from another model or from real observed data. In some models both observations and other models are used. Before a model can be used one has to run it until it reaches some kind of stability. Comparing the model with real life data is also important to see whether the model is obtaining the right values for known periods, but even more important is the variation in model output [*http://www.dmi.dk*, 2007].

The arctic climate is highly non linear when one looks at interactions between atmosphere, cryosphere, ocean, land surface and ecosystems. This is a challenge for any model trying to predict the precipitation over Greenland [*Stendel et al.*, 2007].

5.1 The regional climate model HIRHAM

Due to limited computer resources it is common that global models has low horizontal resolution, often a gridsize of 200 km is used, which is large, when comparing to point observations such as those mentioned in the previous chapter. An attempt to make a regional climate model (RCM) over Greenland and the surrounding area has been made at the Danish Meteorological Institute (DMI) by Martin Stendel and others. The model is called HIRHAM. The model has a 25 km grid. [*Stendel et al.*, 2007].

Further, the model contains 19 vertical layers. Layer 19 follows the ground quite exact, and further up, the layers are less curved, up to layer 1 being horizontal. This is done to ease the solutions of the model. It does e.g. cause severe mathematical problems if a layer

suddenly disappears into the ground [*Stendel*, 2007].

Another thing done to ease calculations is a rotation of the poles of the reference grid, positioning Greenland on the equator. The reason to do this is that the longitudes gets closer and closer together near the pole which leads to very close datapoints and a need to throw some points away in order to obtain a 25 km grid. When positioning the area of interest, in this case Greenland, close to the equator, one can assume that longitudes and latitudes are consistent. A reference grid, where the South Pole is turned so it is positioned on the intersection between equator and the Greenwich meridian, is therefore used [*Stendel et al.*, 2007].

This Regional Climate Model (RCM) is forced on the boundaries by a global climate model (GCM), known as ECHAM5 (European climate model Hamburg) combined with an Ocean circulation model (OM1). The ECHAM5 model is produced in Hamburg and has a horizontal resolution of 200 km. The values from the combined ECHAM5/OM1 model are transferred from the border to the 10 outer gridpoints of the HIRHAM by equations of continuity, dynamics, thermodynamical energy(adiabatic), momentum, energy and mass balance. But inside the HIRHAM runs freely based on the same equations. This allows the model to interact with itself, any sea level temperature changes, will lead to changes in the atmosphere flux and so on. The HIRHAM receives data from the Global model every 6th hour and hence it is constrained at the border, but inside, it is running freely, and can obtain extreme values. The fact that these parameters do not run off indicates that the model works as intended, there is no climate drift in it, though there could be [*Stendel*, 2007].

When starting a model, one can not be sure that the model is stable right away. This especially applies to the ocean, which may need up to several thousands of years to adapt. The atmosphere has a faster response time and therefore does not need as long time to stabilize.Ttherefore the Global climate model runs for thousands of years, before the HIRHAM model is started, to make sure that the GCM is stable. The HIRHAM is run from year 1760 and data is not extracted until 1950. So the HIRHAM model should be stable as well [*Stendel*, 2007].

The data from the HIRHAM model is saved in SI units, which in the case of precipitation is meter/second, which is a little difficult to compare with any measured data, which is often given in millimeters and is seldom resolved better than every third hour. Postprocessing is therefore done and the values are, in the case of this report, calculated to monthly mean and to yearly mean values [*Stendel*, 2007].

5.2 Development of precipitation over the last 50 years according to the HIRHAM model

In figure 9 (right) the precipitation climate normal for the period 1961-1990 according to the model is shown. It is clear that the model has a north-south gradient especially on the western side of Greenland, as well as an orography determined gradient especially in the southern part. The climate normal of precipitation ranges from 0.1 meter on the ice cap up to 3 meters in the south-east.

Figure 10 shows the temporal development of mean annual precipitation with respect to the climate normal, which is represented in figure 9 (right). According to the model the mean period 1950-1964 experienced slightly less precipitation than the climate normal. The greatest percentual changes are seen in the north, but this may be due to lower precipitation in the north and therefore a small absolute change will be discovered in this area, and not further south.

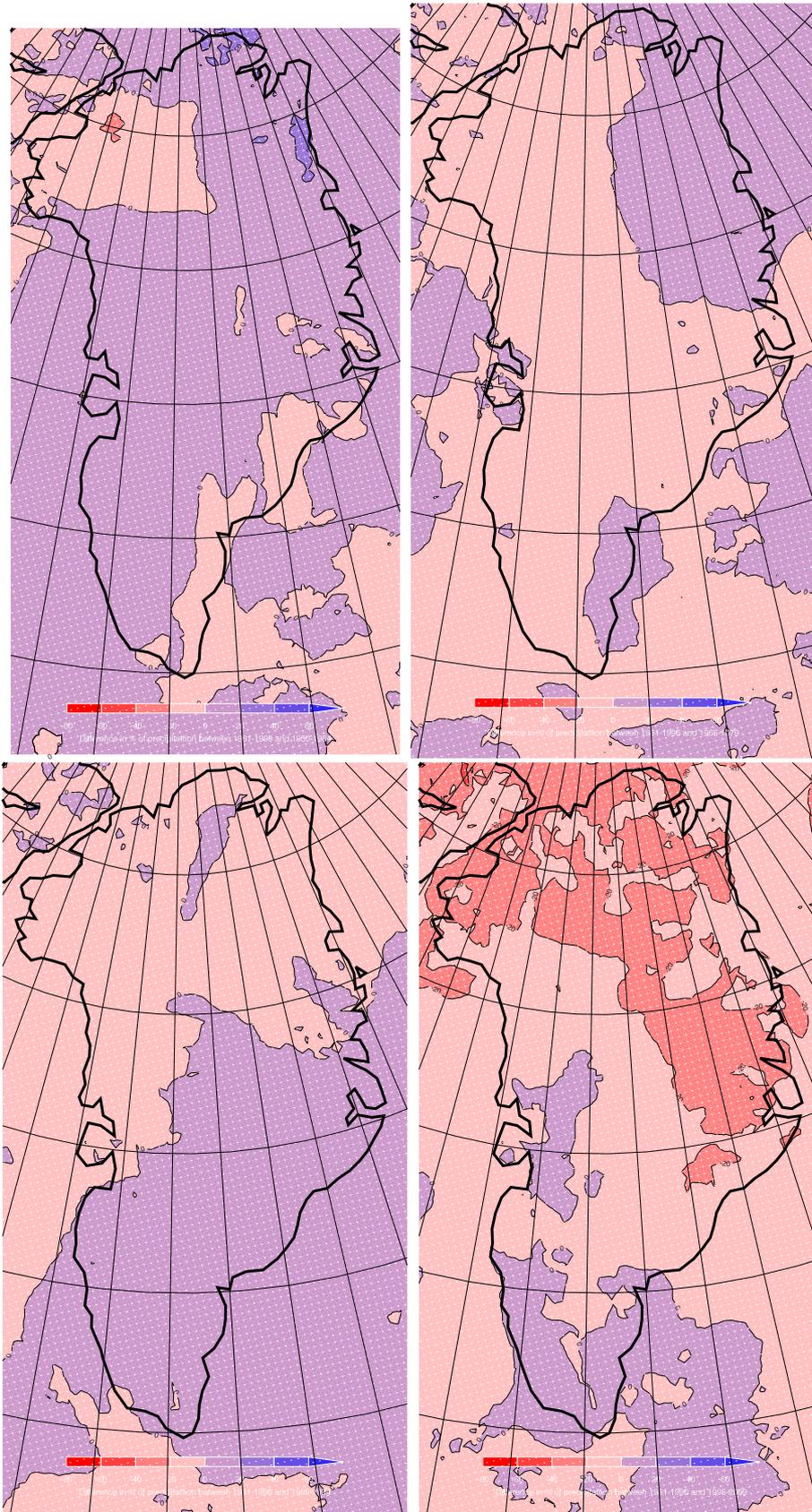In the period 1965-1979, no great changes are occurring compared to the climate mean

Figure 10: Precipitation changes according to the model. The periods 1950-1964 (upper left), 1965-1979 (upper right), 1980-1994 (bottom left), and 1995-2009 (bottom right) are all compared to the climate mean (1961-1990) (see fig. 9). Negative values means that the period has more precipitation than the climate mean (red colors), and positive that the period has less precipitation than the climate mean (blue colors).

period. This is probably because the period 1965-1979 is the main period that counts in the climate mean period (1961-1990). Though there seems to be less precipitation in the north-east and south-east, but this tendency is not as present in the middle-east. There is slightly more precipitation on the western side of Greenland.

Neither the period 1980-1994 has important changes compared to the climate normal. The same reason as for the previous period may explain this. Here the precipitation is higher in different areas, higher precipitation is mainly found in the north and less is found in the south.

For the last period, it is interesting to see that the model predicts the period 1995-2009, to have 20-40 % more precipitation in the north, a significant difference compared to the other periods. This might be a consequence of climate-warming, resulting in a more humid air reaching and hence precipitating over Greenland. It is though difficult to say exactly why the model predicts higher values of precipitation in the north, and one should still be aware that the low real values of precipitation will cause even small changes to be shown very clearly, when looking at a percentual change.

6 Model compared with observations

6.1 The coast

6.1.1 Comparison on a yearly basis.

The precipitation means, the standard deviation and the ratios between model and observations can be seen in table 4. The means are all over the period 1961-1990, but since there are missing data and stopped measurements at some stations the values are not always directly comparable. Never the less one can get a pretty good idea, which of the stations the model can reproduce. The means are means of the closest lying model point and thereby at most $\frac{25}{\sqrt{2}} \approx 17.7$ km away from the observations.

One should notice the generally agreement within a factor 2 for the means. Especially one should notice the very high agreement between model and station for Thule.

The standard deviation ratio between model and observations are within a factor 1.5. The model underestimates variance for the stations Nuuk and Prins Chr. Sund. The standard devistion ration is almost perfect for Egedesminde and Julianehaab and the model overestimates the variation at the stations Danmarkshavn, Illoqqortoormiut, Tasiilaq and Thule.

It seems that the stations for which the mean ratio between model and station has been high (station values higher than model values) also have a tendency of having a high ratio between the standardeviations and vice verse.

It is only the nearest model-point that has been used in this comparison, better agreement is sometimes found moving a model point further away. The fact that the nearest model point is not always the "correct" one to choose, is because of the gridsize being large compared to point-observations. In some cases the nearest model point is in the sea, if the station is lying close to the sea, and in other cases orography changes has a large influence. But when making the ratio of precipitation means based on the means of the four nearest stations it does not improve the ratios of the means for any of the stations, except Julianehaab which has a ratio of 1.05 when comparing with the four nearest modelpoints instead of the nearest.

To better check whether the model has the level of the point-observations, the four nearest model-points was chosen and the highest and lowest value of these each year, has been plotted against precipitation measurements. Then a much better agreement is seen.

Table 4: The table shows mean and standard deviation for the observations and the nearest model-point.

	Mean (mm)		STD (mm)		Ratio	
	Model	Station	Model	Station	Mean	STD
Danmarkshavn	404	288	127	62	0.71	0.49
Egedesminde	252	470	73	74	1.87	1.01
Illoqqortoormiut	1049	692	231	164	0.66	0.71
Julianehaab	1402	1117	217	219	0.8	1.01
Nuuk	671	1214	123	148	1.81	1.20
Prins Chr. Sund	1940	3689	291	402	1.90	1.38
Tasiilaq	1550	1193	320	220	0.77	0.66
Thule	249	251	47	36	1.01	0.77
NorthGRIP	106	166	28	40	1.57	1.43

Figure 11 represents data from Thule, Nuuk, Tasiilaq and NorthGRIP. Representations of the yearly means for the remaining stations can be found in Appendix (8.1).

Here, it is clear that the model represents Thule nicely, almost all of the observed precipitation is in the range of the four nearest model-points. The same is true for Danmarkshavn and Prins Chr. Sund using the values measured in the nineties.

For Illoqqortoormiut, Tasiilaq (see figure 11) and Julianehaab the model values are higher than the observed amounts. But the lower values of the four model-points do reach the level of what is measured at the stations. All these stations are in the southern part of Greenland, and Illoqqortoormiut and Tasiilaq are both on the eastern side. This suggests that the model overestimates the precipitation from the weather systems approaching from the south-east.

Some of the stations are poorly reproduced even by the four nearest model points, as the model values are too low. This is the case for Nuuk and for Egedesminde. Both stations are positioned on the western-coast in mid Greenland. Maybe it is caused by the model not giving the Baffin-Bay low enough strength, which would lead to less precipitation, or it could be due to the position of the gauges the two places, they might be positioned underneath a hill or behind a building such that snow could drift into the gauges. This is not taken into account, when calculating the correlation coefficients.

6.1.2   Comparison of monthly means

When looking at monthly means the level of precipitation according to the measurements is again not corrected for wind, intensity and precipitation type. This, as mentioned in section 4.1.1, could cause the true monthly value of precipitation to be higher level than what is observed especially in wintertime. The nearest model point is used here. Overall the shape of the model representation and observations of the monthly means is coherent.

Representations for the monthly means for Thule, Nuuk and Tasiilaq are presented in figure 12. Representations of the remaining stations monthly means is given in Appendix (8.2).

The pattern for the observations at Thule, Nuuk and Prins Chr. Sund (not shown) observations are well represented by the model. The minima, and maxima are in the right months; The pattern for Illoqqortoormiut is approximately right, but the lowest values comes a month later in the model. Tasiilaq, Julianehaab (not shown) and Danmarkshavn (not shown) are poorly reproduced, and the model representation for Egedesminde (not shown) is not good. Whether the differences represented above are real, is difficult to
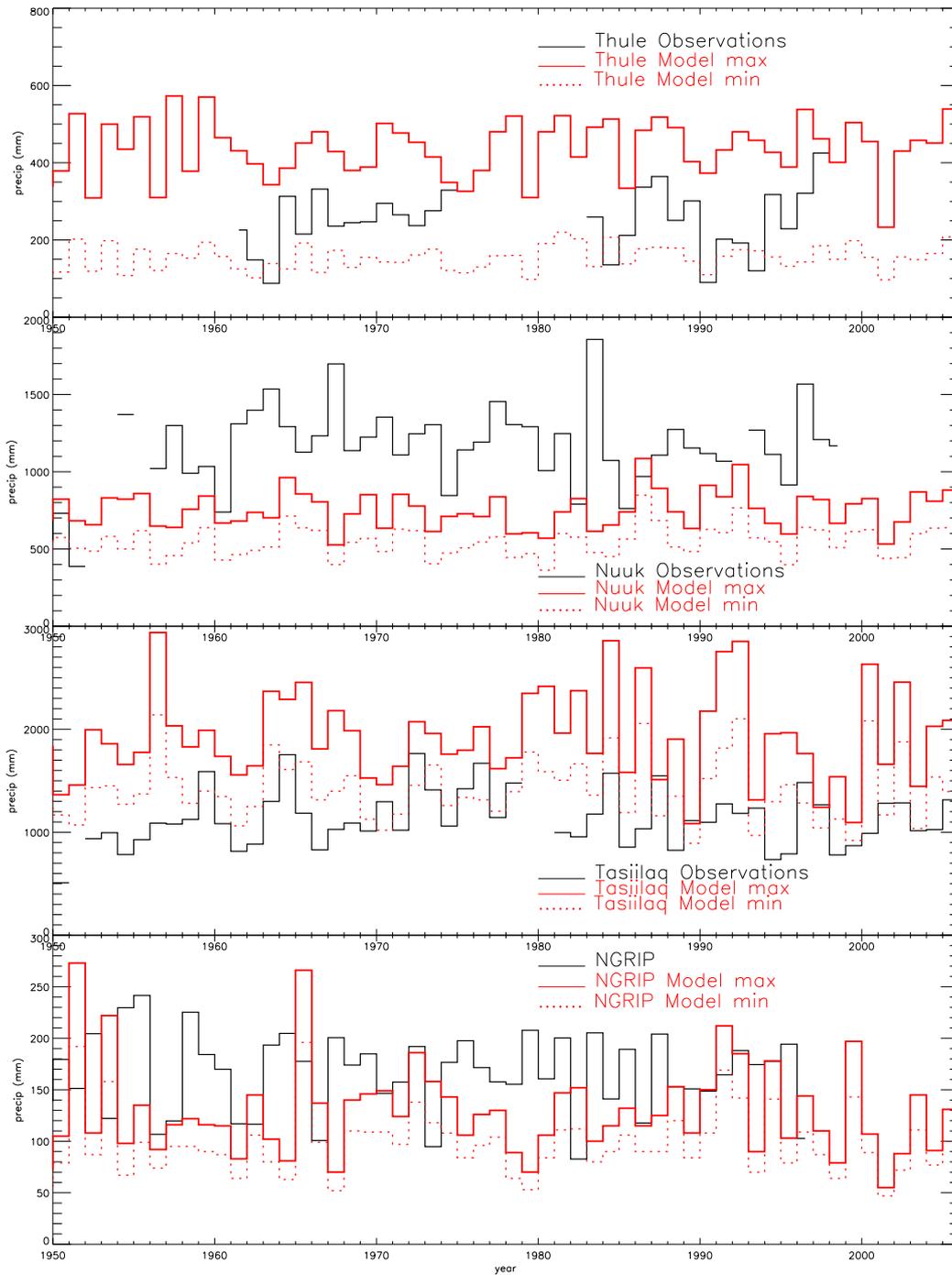
Figure 11: Yearly mean precipitation values from observation (black) and the highest value (red, solid) and lowest value (red, dotted) for the 4 nearest model points. From top to bottom: Thule, Nuuk, Tasiilaq and NorthGRIP. Please notice that the y units are not identical.
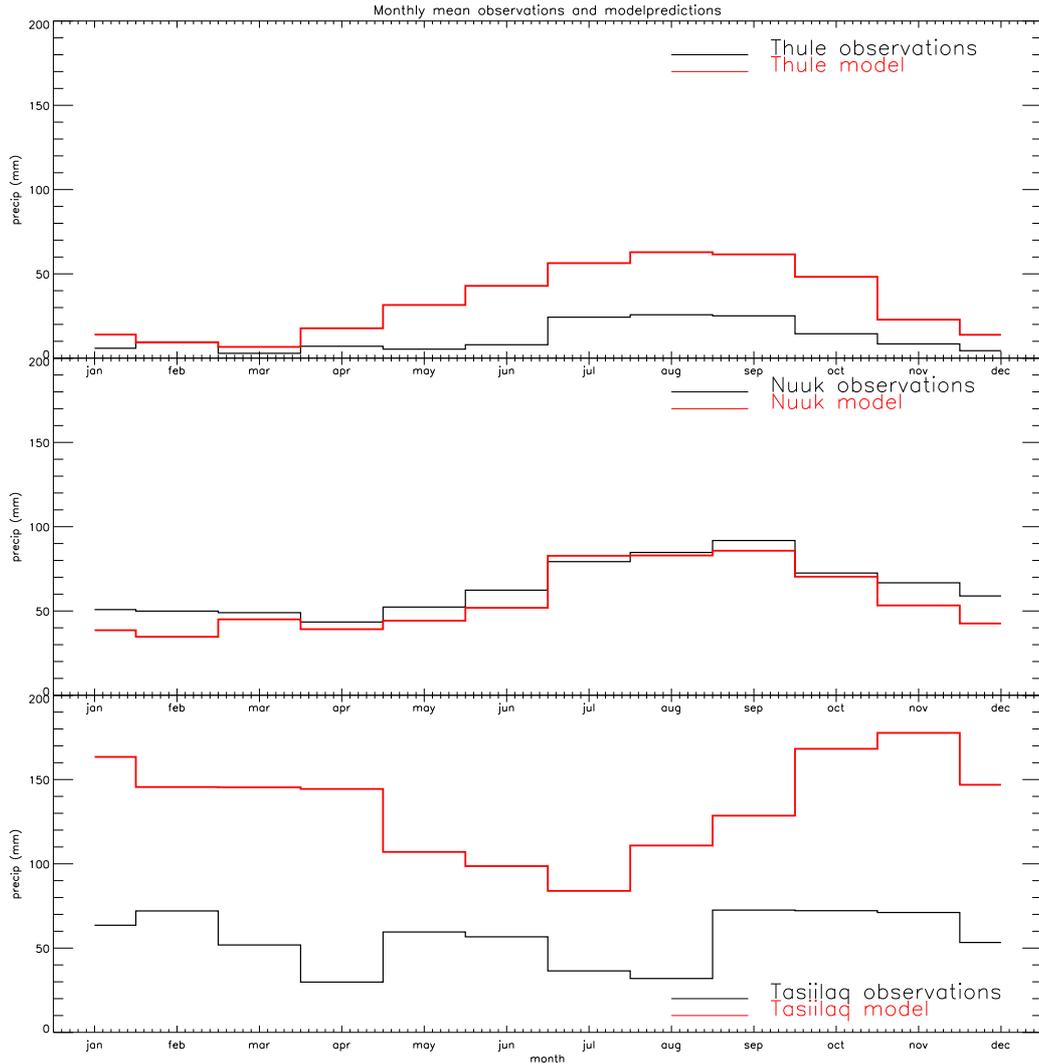
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Figure 12: Monthly mean for the model and Thule station on top. In the middle Nuuk is represented and bottom graph represents Tasiilaq. All monthly means are done on basis of the period of measurements available (see fig 2) and the figures are therefore not directly comparable.

answer, since the monthly precipitation values for the observations have not been corrected, and I will therefore not go into further detail with this comparison.

6.2 Comparison on the ice cap

The map of the precipitation on the ice sheet made by Calanca (figure 9, left) and comparing it with the model prediction (figure 9, right) for the period 1961-1990, the most striking feature is that the model shows lower values in the central part of the ice. Especially in the northern part, the model predicts only 0.1 m of precipitation a year, while the observations indicate twice that. For the model this will have a large effect on the model mass balance of the Greenland ice sheet.

Though the level of precipitation is very different between the observation based map, and the model, the pattern of where there is little and where there is more precipitation is similar in both the map based on observations [*Calanca et al.*, 2000] and the 1961-1990 mean from the RCM. The lowest precipitation is in both maps found in the north and a east on the ice cap. The model predicts higher levels of precipitation toward the border of

the ice in the north-west, while the map by Calanca shows no such tendency. The low level of precipitation stretches down on the western side. Both figures show a clear north-south gradient as well as a gradient caused by hight differences. The model also gives higher precipitation on the south-eastern side, in agreement with the Calanca map.

All in all, the model simulates too low precipitation on the central part of the ice sheet, and a tendency of overestimating the precipitation on the boarder of the ice sheet in the southern part. This does make the question of the model overestimating the Baffin Bay low as suggested in 6.1.1 less likely. Most likely the model overestimates the effect of orography, delivering too much of the precipitation in the south-eastern part, leaving to little for the inner parts of the ice sheet.

When comparing the modeled precipitation with the data from NorthGRIP (figure 11, bottom) it appears that the model generally has too low values of precipitation, but in some years the model does reach the level of the observations. Anyway the deviation is less than a factor 2 in difference, actually only a factor 1.57, when comparing means for the period 1960-1991, between the two. The ratio of the standard deviation between model and icecore observation is 1.43 and shows that the yearly variance for the model is not high enough at the spot of NorthGRIP. It seems that the comparison at the NorthGRIP spot all in all supports the comparison between Calancas map and the model. But too much value must not be given the one spot at NorthGRIP, and wether this lack of yearly variance is present all over the icecap must be left for further investigation.

The conclusion must be that the model clearly fails to reproduce the level of precipitation on the ice sheet.

7   Conclusion

The goal of this project was to compare the precipitation simulated by the HIRHAM model with observations from Greenland.

First of all it is hard to obtain observations of precipitation in Greenland in particular in the coastal areas, where orographic differences has influence. The wind influence is significant and can cause the observed precipitation to be as much as 30-40% too low in the south and up too 95% too low in northern Greenland. This makes it difficult to determine the actual level of precipitation. One needs values for the wind, temperature and intensity of the shower as well, to find the "actual" amount of precipitation. Even after correcting for wind effects, the gauge can measure too much or too little precipitation due to its position underneath a hill or behind a building.

Though there are difficulties in obtaining measurements, it is clear from observations that there is a distinct north-south gradient for precipitation in Greenland as well as a height gradient.

The HIRHAM model succeeds in showing the north-south gradients, but fails in reproducing the right level. On the western side of Greenland the model simulates too low values of precipitation (Nuuk and Egedesminde) while on the eastern side it shows higher values compared with the observation from the stations having a ratio of 0.66 to 0.77. This means that the model overestimates the east-west gradient that especially is present in the southern part of Greenland.

On the eastern side and in the north of Greenland the variance is too high in the model. Nuuk and Prins Chr. sund has not a high enough variance and the variance of Julianehaab and Egedesminde are represented nicely.

The monthly mean values for the period 1961-1990 are fairly well reproduced, but it is difficult to conclude anything on these values, since the observations are not corrected

for wind effect.

On the ice cap the model represents too low values of precipitation, when comparing it with the map of Calanca. This is clearly a problem if one would like to look at the future use of the model. The ice cap would slowly disappear according to the model.

One must conclude that the model fails to present the level of precipitation observed by gauge and ice cores.

A way to improve the comparison between the model and the observations of precipitation, could be to deduct correction coefficients for the observations based on data from each year and month for the last 50 years, and not assume that they are constant in the whole period. Also a correction for the position of the gauge is clearly needed, to obtain values directly comparable to the model. These positions might be available through old pictures. This would make it easier to conclude whether the model has the right monthly means.

Also better computers are needed to make models with smaller grids able to simulate local conditions. This would help to obtain a better simulation of precipitation values especially near the coast where orography has high influence. Also the ice cap predictions would benefit from a smaller grid, which might lead to better understanding of the future of the ice cap of Greenland.

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8 Appendix

8.1 Figures of observations and model predictions yearly mean.

The figure 13 to 20 shows yearly mean of the observations of precipitation and the four nearest model points.
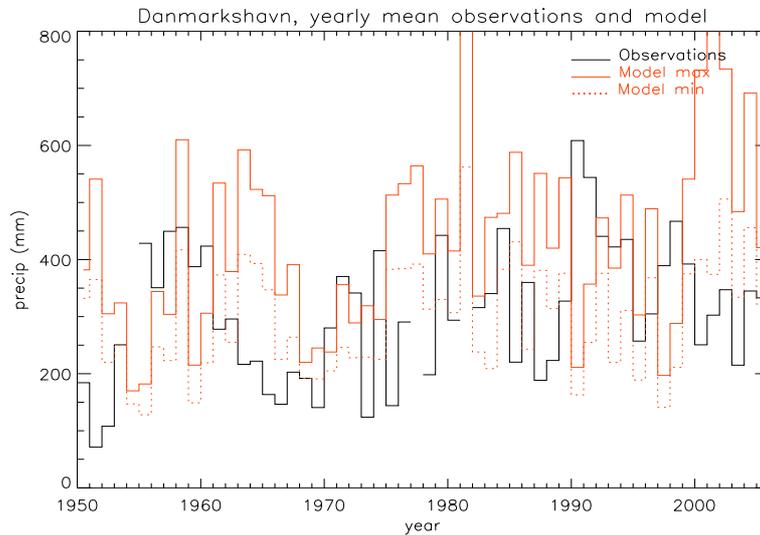
Figure 13: Danmarkshavn yearly mean. Observations and model.
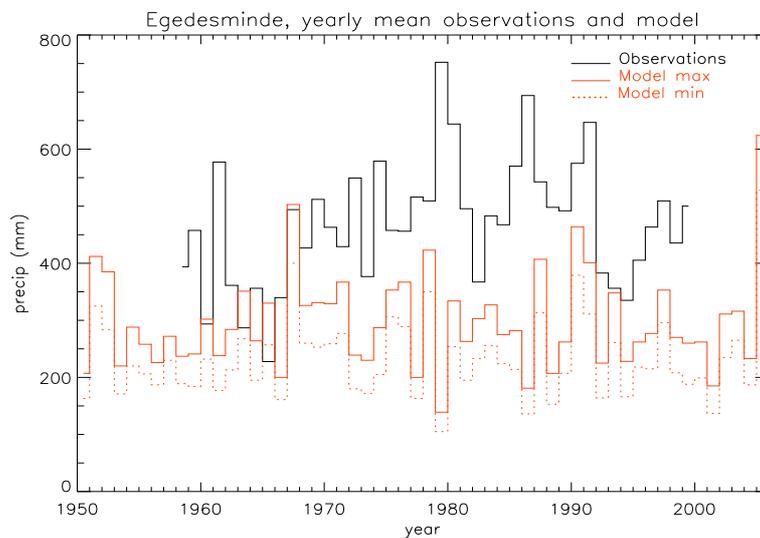
Figure 14: Egedesminde yearly mean. Observations and model.

8.2 Figures of observations and model predictions monthly mean

The figure 21 to 28 shows monthly mean of the observations of precipitation and the nearest station. The figures are in alphabetic order:
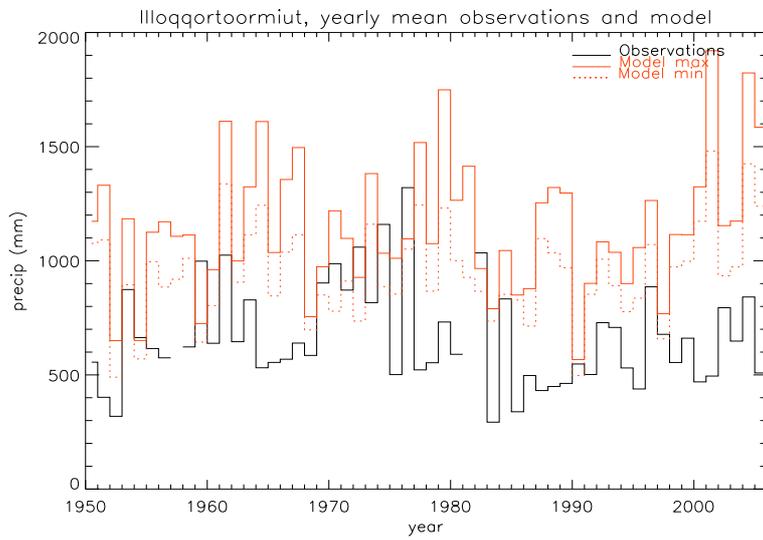
Figure 15: Illoqqortoormiut yearly mean. Observations and model.
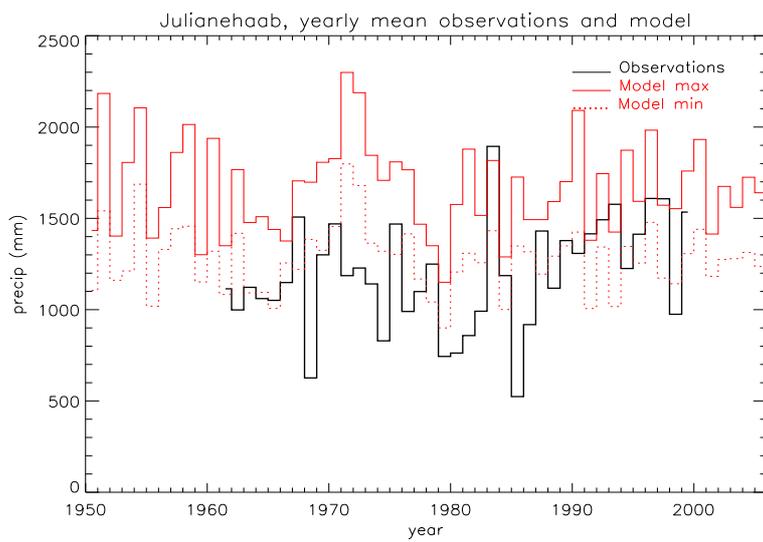
Figure 16: Julianehaab yearly mean. Observations and model.
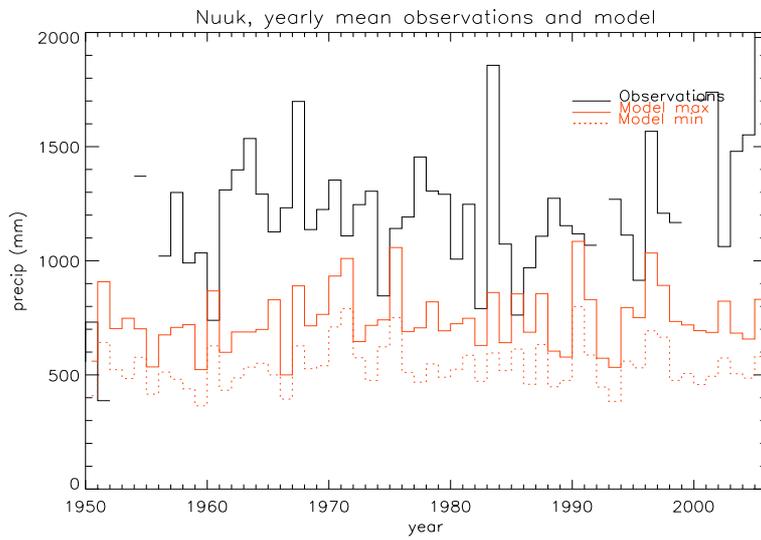
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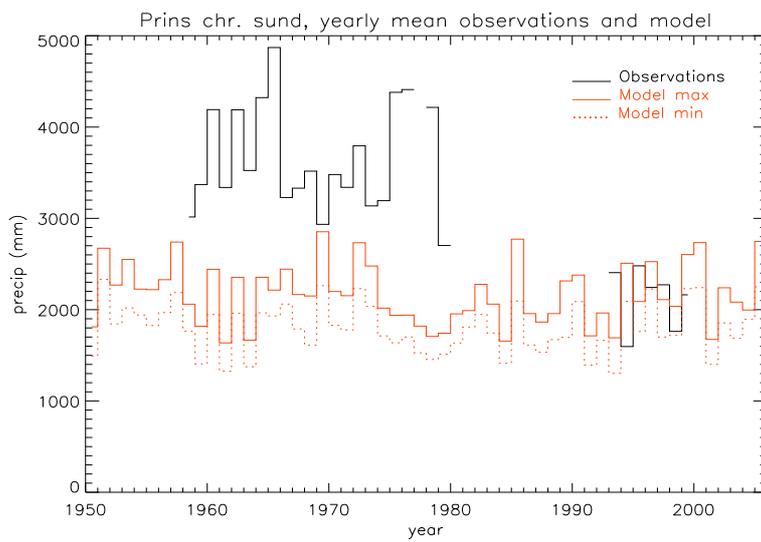
Figure 18: Prins Chr. Sund yearly mean. Observations and model.
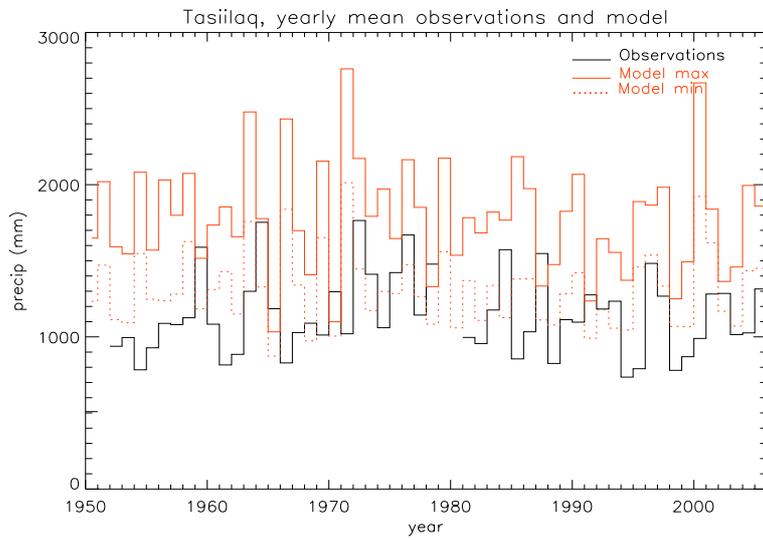
Figure 19: Tasiilaq yearly mean. Observations and model.
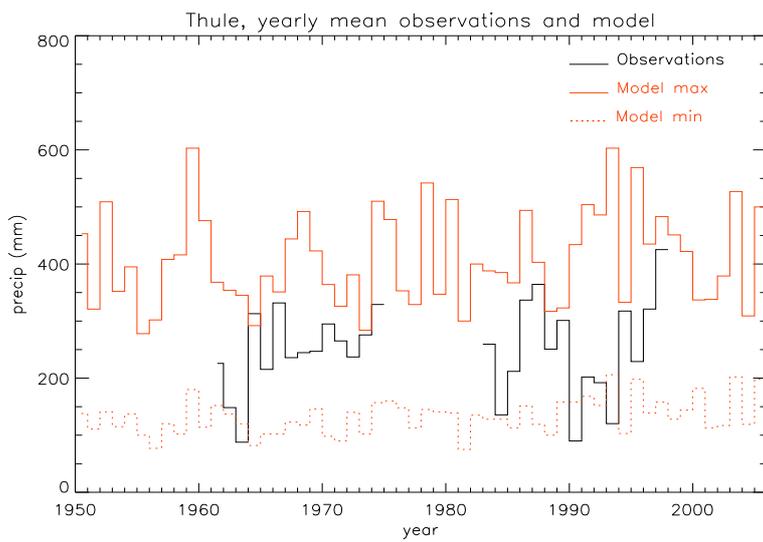
Figure 20: Thule yearly mean. Observations and model.
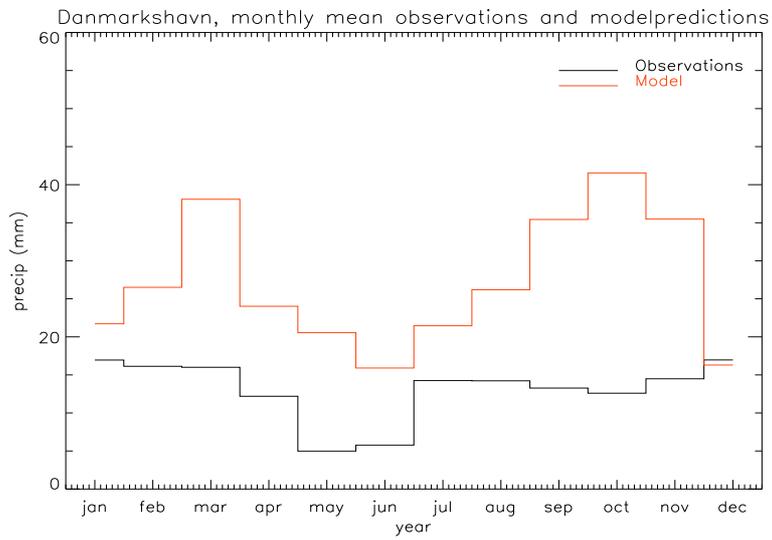
Figure 21: Danmarkshavn monthly mean. Observations and model.
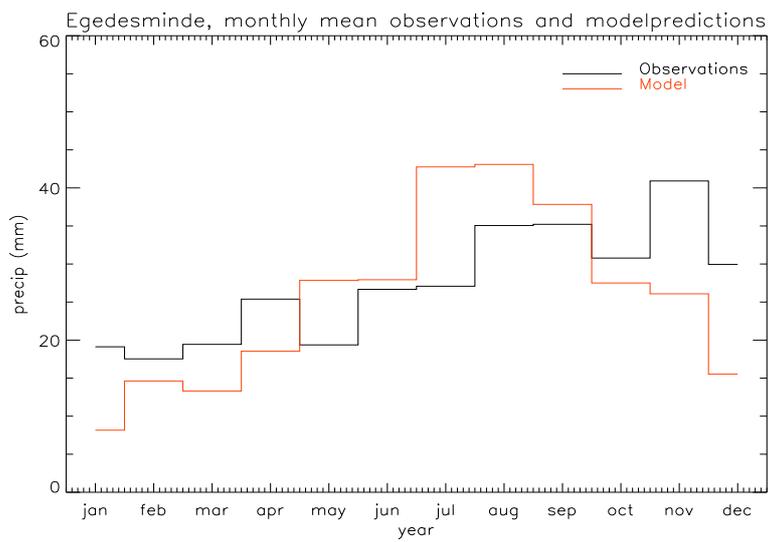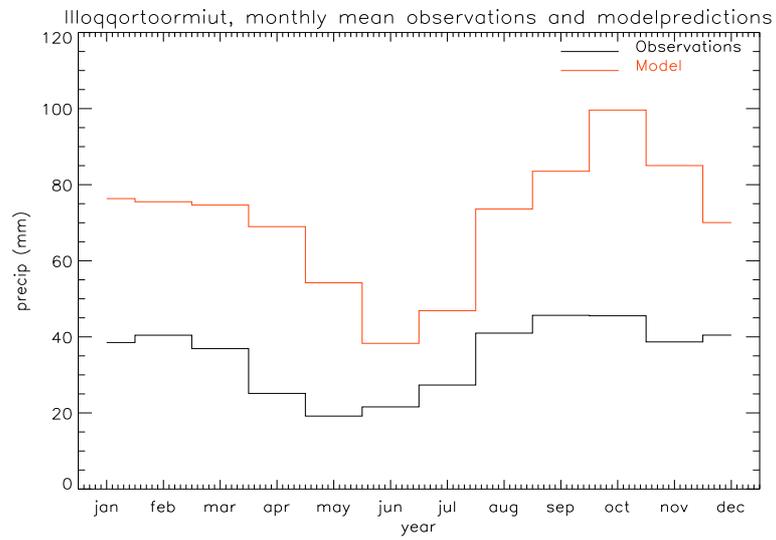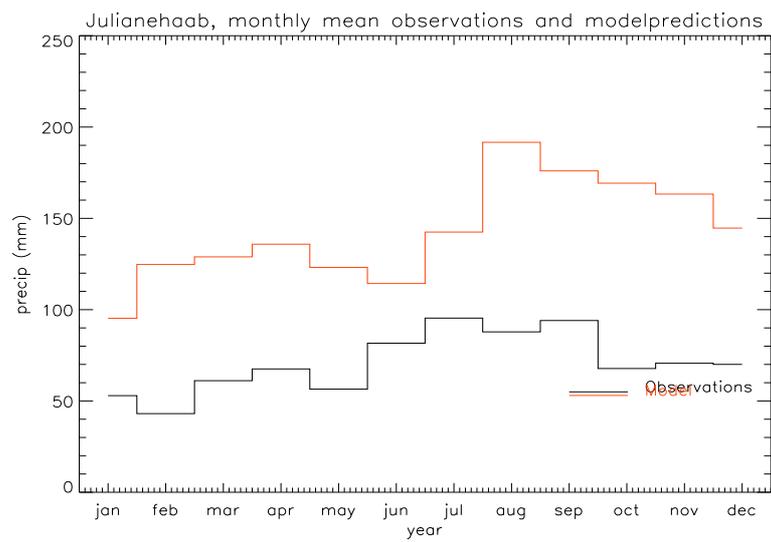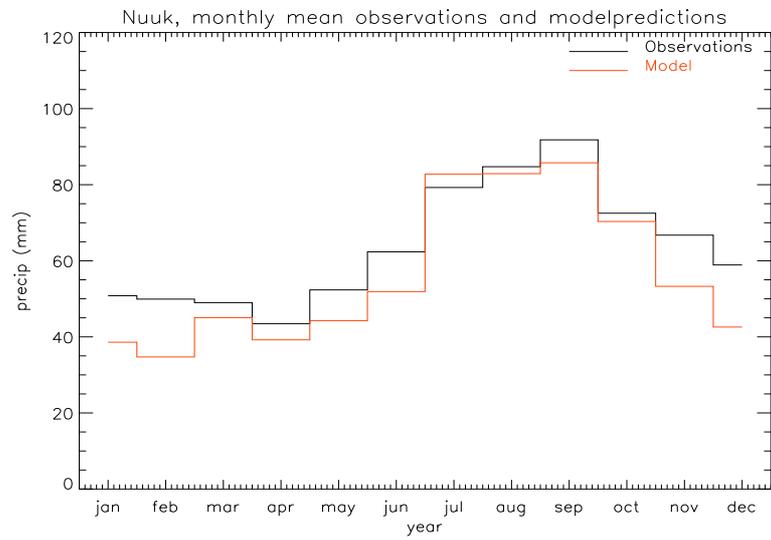

Figure 22: Egedesminde monthly mean. Observations and model.

Figure 23: Illoqqortoormiut monthly mean. Observations and model.

Figure 24: Julianehaab monthly mean. Observations and model.
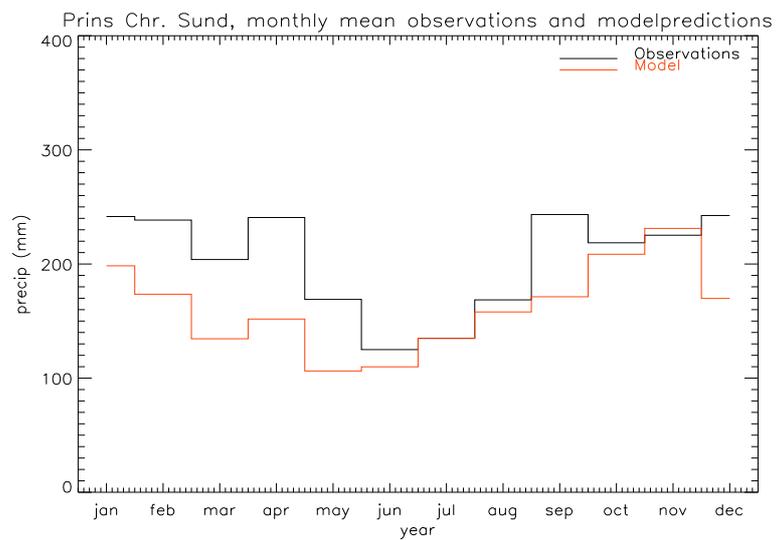
Figure 25: Nuuk monthly mean. Observations and model.

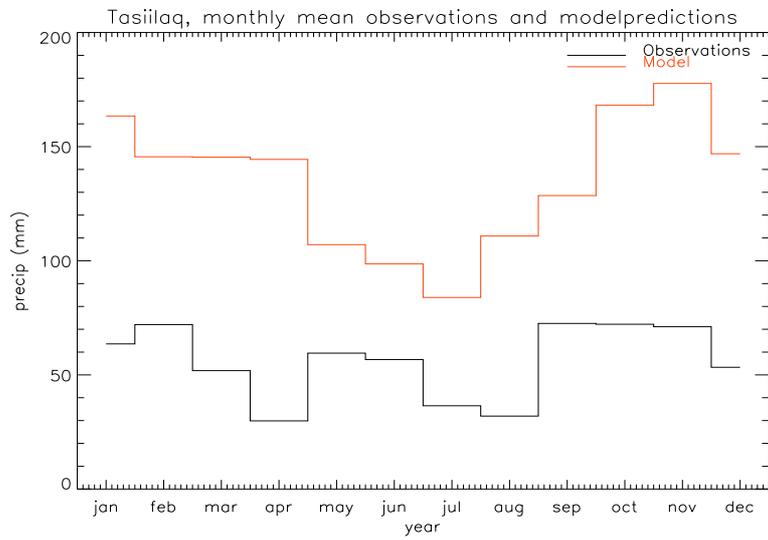**Figure 26:** Prins Chr. Sund monthly mean. Observations and model.
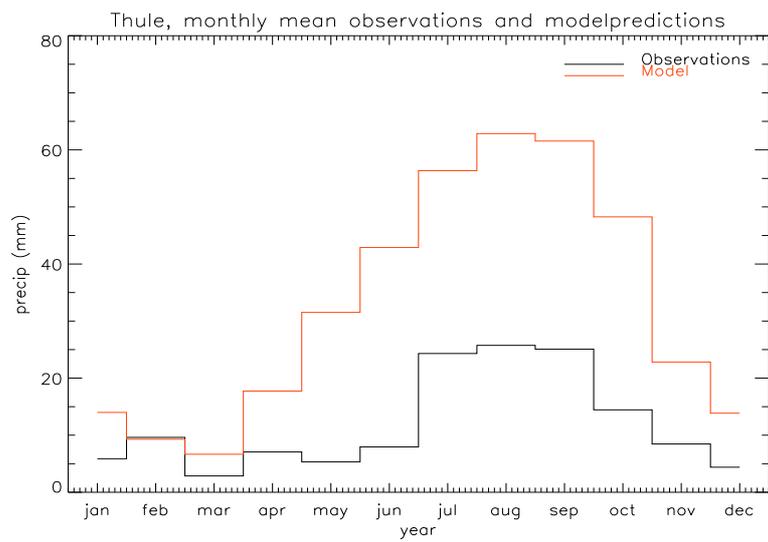
Figure 27: Tasiilaq monthly mean. Observations and model.

Figure 28: Thule monthly mean. Observations and model.