Ice Sheet Surface Mass Balance at Paakitsôq, West Greenland, Derived from Future Scenario Regional Climate Model Data

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1 Introduction

Greenland has a large potential for hydro-power production due to its abundant availability of melt water. In the past GEUS has performed intensive glacio-hydrological investigations at Paakitsôq, West Greenland, to evaluate the potential for hydro-power production (*Thomsen et al.*, 1989; *Ahlstrøm*, 2007). Future melt-water availability at Paakitsôq was assessed by *Ahlstrøm et al.* (2008a) based on a scenario run of a Regional Climate Model (RCM). The present study is performed in the framework of the Climate and Energy Systems (CES) project with the aim to better specify uncertainties in future scenarios of hydro-power potential. The previous investigations are revisited using scenario runs of two different RCMs, an updated downscaling procedure and additional data for model validation. In the center of the work stands the analysis of the output of the two RCMs with respect to their suitability to calculate regional scale glacier mass balance scenarios.

In the following we will first expand on model domain and data followed by the description of the mass balance model. Subsequently modeled mass balance will be presented along with the evaluation of the RCM output. Finally we will discuss the relationship of modeled mass balance and biases in the RCM data and will conclude on the suitability of the latter for future scenarios.

2 Model Domain and Data

2.1 Model Domain

Paakitsôq is the name of an area at the ice sheet margin close to Illulisat, West Greenland (Fig. 1). In this study we focused on a glacierized area of approximately 200'000 km^2 (Fig. 1). The model domain is larger than in previous studies (i.e. *Thomsen et al.*, 1989; *Ahlstrøm et al.*, 2008a) and was chosen to get a broader picture of the performance of the mass balance model and the regional climate models (RCMs).

2.2 Observational Data

Data from four weather stations is used to validate the RCMs : Illulisat and Station 437 are coastal stations being operated by the Danish Meteorological Institute (DMI) and Asiaq,

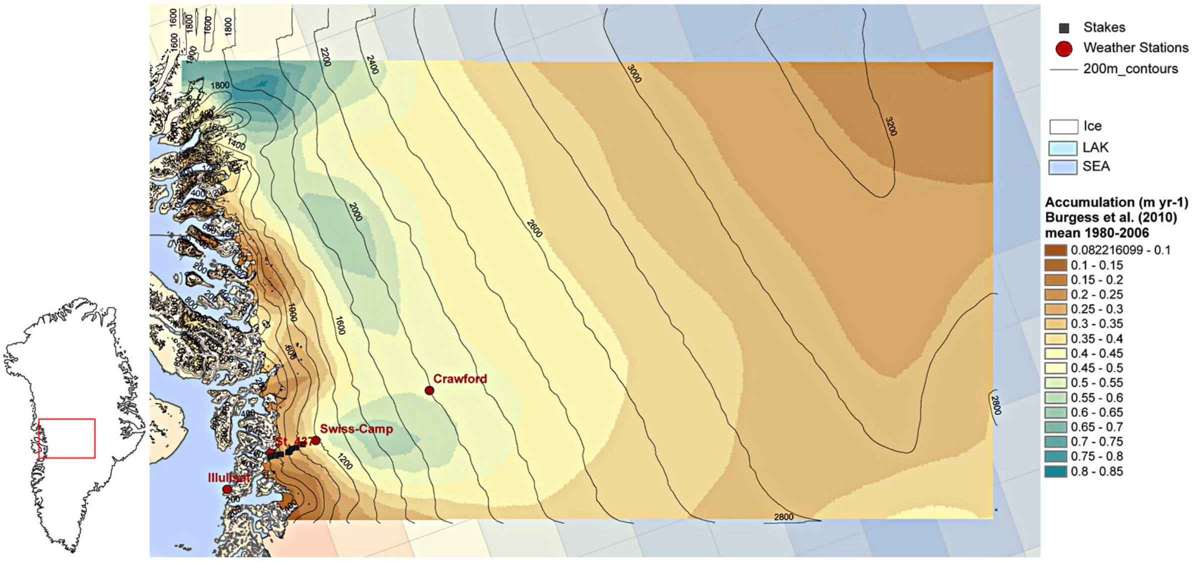

Figure 1: Overview of the study site. The location of the four weather stations is indicated and in the background mean annual accumulation distribution (1980–2006) according to *Burgess et al.* (2010) is shown. At the margin the grid boxes of the RCAO RCM are visible. The area between Illulisat and Swiss camp is commonly called Paakitsôq.

respectively. The Automatic Weather Stations (AWS) Swiss Camp and Crawford are located on the ice sheet and are operated by the Greenland Climate Network (GC-net) (*Steffen and Box*, 2001). The locations of the stations are indicated in Fig. 1, further details are given in Table 1. *Burgess et al.* (2010) provide maps of annual accumulation distribution over Greenland for the years 1958–2007 (see `http://bprc.osu.edu/wiki/Greenland_Accumulation_Grids`). The maps are constructed from calibrating Polar MM5 with a large number of data from shallow-core and ice core records as well as weather stations. In the framework of previous investigations at Paakitsôq a stake network has been maintained in the ablation area from 1982–1992 (*Ahlstrøm*, 2007). Data for the years 1982–1987 were available and were used in this study to validate modeled mass balance.

Table 1: Weather stations measuring air temperature (T_a) or global radiation (S_{in}) used for comparison to RCAO and HIRHAM4

name	operated	elev. (m a.s.l.)			coord.		param.	data used	
		station	RCAO	HIRHAM4	(UTM zone 22N)			from	till
Illulisat	DMI	50	10	105	497382	7681278	T_a	1.1.81	6.4.06
Station 437	ASIAQ	275	340	311	531316	7709513	T_a	5.9.83	1.6.06
Swiss Camp	GC-net	1150	1115	780	566396	7719204	T_a, S_{in}	1.1.95	8.5.06
Crawford	GC-net	2022	1795	1982	654464	7757807	T_a, S_{in}	24.5.95	2.5.06

2.3 RCM Data

Output from two RCMs is used: (1) the regional coupled ocean-atmosphere model RCAO (*Döscher et al.*, 2002) and (2) the HIRHAM4 RCM (e.g. *Stendel et al.*, 2007). Both models are at the lateral boundaries driven from the General Circulation Model (GCM) ECHAM5 being forced with the A1B scenario (*IPCC*, 2001). RCAO is a fully coupled model and includes an ocean module which computes e.g. sea currents, sea surface temperatures and sea ice cover within the model domain. On the contrary, HIRHAM4 reads oceanic conditions as a lower boundary condition from the driving GCM. The RCAO model-output is from a pan-arctic run for the years 1960–2080 at approx. 50 km resolution. The first 20 years of the model run must be considered as spin-up time for the ocean module. The RCAO run is experimental since the model is in a development state and the output has not yet been evaluated over Greenland (Ralf Döscher, personal communication). The HIRHAM4 model run reaches from 1950–2100 and incorporates Greenland at a resolution of approx. 25 km. *Ahlstrøm et al.* (2008a) have analyzed its bias in air temperature and precipitation over the ice sheet at Paakitsôq, *Aðalgeirsdóttir et al.* (2009) compared those two parameters to a larger number of weather stations over Greenland.

3 Methods

3.1 Mass Balance Modeling

The applied glacier mass balance model is a simplified version of the energy balance approach. An abstract of the model is given in the following, for a comprehensive model description we refer to *Machguth et al.* (2009). The model requires air temperature (T_a), global radiation (S_{in}) and precipitation (P) for meteorological input. The model runs at daily steps, and the cumulative mass balance b_c on day $t+1$ is calculated for every time-step and over each grid cell of the DTM according to *Oerlemans* (2001):

$$b_c(t+1) = b_c(t) + \begin{cases} \Delta t \cdot (-Q_m)/l_m + P_{solid} & \text{if } Q_m > 0 \\ P_{solid} & \text{if } Q_m \leq 0 \end{cases} \tag{1}$$

where t is the discrete time variable, Δt is the time-step, l_m is the latent heat of fusion of ice (334 kJ kg^{-1}) and P_{solid} is solid precipitation in meter water equivalent (m w.e.). The energy available for melt (Q_m) is calculated as follows:

$$Q_m = (1-\alpha)S_{in} + C_0 + C_1 T_a \tag{2}$$

Where α is the albedo for the surface (three fixed albedo values are applied: snow = 0.8, firn = 0.55 and ice = 0.42), T_a is in °C and $C_0 + C_1 T_a$ is the sum of the longwave radiation balance and the turbulent exchange (*Oerlemans*, 2001). C_1 is set to 10 Wm^{-2} K^{-1} (*Oerlemans*, 2001) and C_0 is tuned to -45 Wm^{-2} K^{-1}. Accumulation equals P_{solid} and redistribution of snow is not taken into account. A threshold range of 1 to 2 °C is used to distinguish snowfall and rain. Melt-water refreezing is parameterized according to *Reeh* (1991), using a melt-water retention capacity of 60% of the water equivalent of the snow cover.

The glacier mass balance model is designed to operate on large areas. For model input entire grids from RCM output are read. Downscaling of the RCM-grids of T_a and P includes the interpolation of the RCM output to 1 km resolution and in the case of T_a a lapse rate

($\Gamma_{Ta} = 0.0065\,^\circ\mathrm{C\,m^{-1}}$) correction to account for variability on a sub-grid scale. Both steps are being performed every time step (daily) during the model run. A direct retrieval of S_{in} from the RCM-output would cause problems due to the influence of local topography (e.g. exposition) at 1 km spatial resolution. Instead, clear-sky global radiation on the 1 km grid is calculated beforehand according to *Corripio* (2003). During the model run daily cloudiness (n) is obtained from the RCM, interpolated to 1 km resolution and is then used to derive attenuation of clouds (τ_{cl}) according to the parameterization of *Konzelmann et al.* (1994) which was derived from observations in the area of Swiss Camp (h is the surface elevation in m a.s.l):

$$\tau_{cl} = 1.0 - 0.78n^2 \exp(-0.00085h) \tag{3}$$

3.2 Validation Procedure

Implemented in the mass balance model is the comparison of the RCM-data (= the model input) to observations from weather stations on the ground. The observations are compared to the values of the RCM grid-cells they are located in. Before comparing T_a the RCM value is lapse rate corrected for the elevation difference between the station and the RCM grid cell. The chosen value ($\Gamma_{Ta} = 0.0065\,^\circ\mathrm{C\,m^{-1}}$) reasonably well represents observed annual mean lapse rates in the area but overestimates summer lapse rates which are around $0.005\,^\circ\mathrm{C\,m^{-1}}$ (*Steffen and Box*, 2001). However, differences between station and grid cell elevation are small except for Crawford and the underlying RCAO grid cell as well as Swiss Camp and the corresponding HIRHAM4 cell (Table 1). RCM-precipitation and modeled accumulation (cf. Section 3.1) are compared to the Greenland accumulation maps from *Burgess et al.* (2010). Measured S_{in} are compared to (1) S_{in} derived as described in Section 3.1 and (2) S_{in} obtained directly from the RCM without any modifications.

4 Modeled Mass Balance

Modeled mass balance is compared to the stake readings. Since the RCMs are driven from GCM output the comparison must be restricted to statistical properties, i.e. mean values and inter annual variability of mass balance.

RCAO: When RCAO data is used for model input very negative mass balances are modeled (Figure 2a). Melt in the lower areas of the ice-sheet is strong and the equilibrium line altitude is very high (approx. 1800 m a.s.l. instead of observed 1100–1200 m a.s.l.; *Ahlstrøm*, 2007). Furthermore there is a pronounced variability in modeled annual mass balances which clearly exceeds observed variability. **HIRHAM4:** When HIRHAM4 is used to drive the mass balance model a reasonable agreement is achieved between observed mean ELA and variability of mass balance(Figure 2b). Melt at the margin of the ice sheet seems somewhat overestimated. However, it must be considered that observations from the Paakitsôk stake network are only available from 1982–1987 (*Ahlstrøm et al.*, 2007) and thus exclude more recent years with strongly increased melt.

5 RCM Evaluation

The reference period where RCM output is compared to measurements is January 1 1981 to June 1 2006. This period was chosen because after 1980 sea ice is fully initiated in RCAO and after 2006 the records from the weather-stations end. (The stations actually continue to

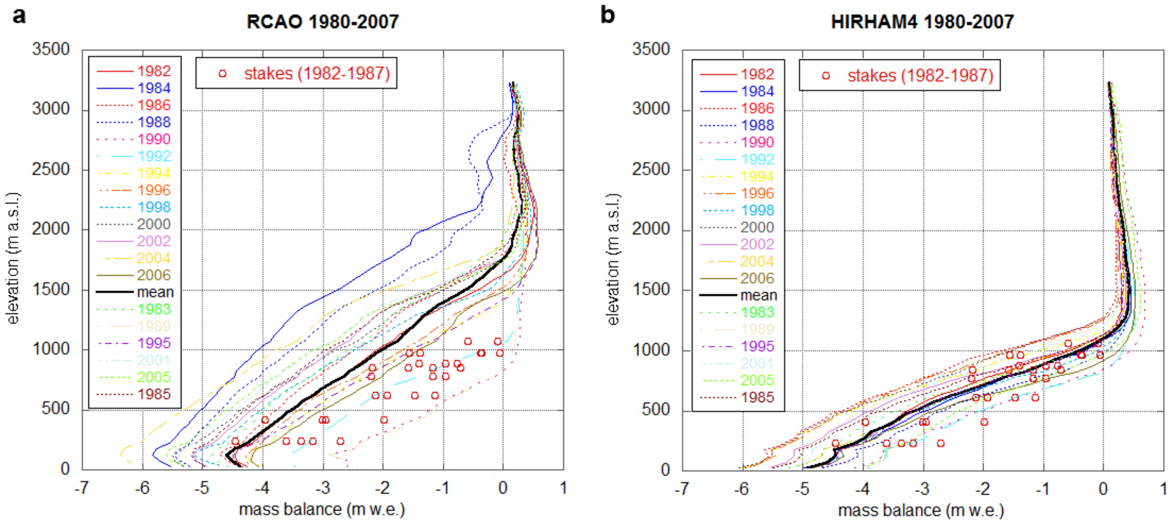

Figure 2: mass balance profiles calculated using RCAO (Plot a) and HIRHAM4 (Plot b) for model input.

measure, but in the short time available for the Paakitsoq mass balance project we did not look for more data.) The reference period is further reduced for individual stations: Station 437 was installed in 1983 and the two GC-net stations in 1995.

5.1 Air Temperature

RCAO: 2 m air temperature (T_a) in coastal areas are similar to observations (Fig. 3a). T_a at Station 437 is well reproduced while for Illulisat the temperature curve in summer and autumn is shifted towards later in the year. T_a on the ice sheet are too high (Fig. 3b). The bias is most pronounced in summer but also exists in winter. Standard deviation of monthly mean T_a is overestimated during summer, in particular at Station 437 (Fig. 4b) and less pronounced at Swiss Camp (Fig. 4a). Figure 5 additionally compares monthly mean T_a from RCAO to Illulisat and Station 437 over the time span 1981/83–2006. It becomes obvious that the large standard deviations of summer T_a at Station 437 are because in the RCM entire summers are either modeled too warm or too cold. The effect, however, is absent at Illulisat.

HIRHAM4: At the coast the annual amplitude of T_a is overestimated resulting in a warm summer and a cold winter bias (Fig. 3c). On the contrary the amplitude is underestimated on the ice sheet, with summer T_a well represented but a pronounced warm bias in winter(Fig. 3d). Standard deviation of monthly mean T_a are in reasonable agreement to the observations except for summer and autumn on the ice sheet where the model underestimates (Fig. 4c and d).

5.2 Global Radiation

Measurements of global radiation are only available from the stations Swiss Camp and Crawford on the ice sheet for a limited time period (1995–2006), including a number of data gaps. Furthermore it is difficult to accurately measure S_{in} on the ice sheet: especially in the ablation

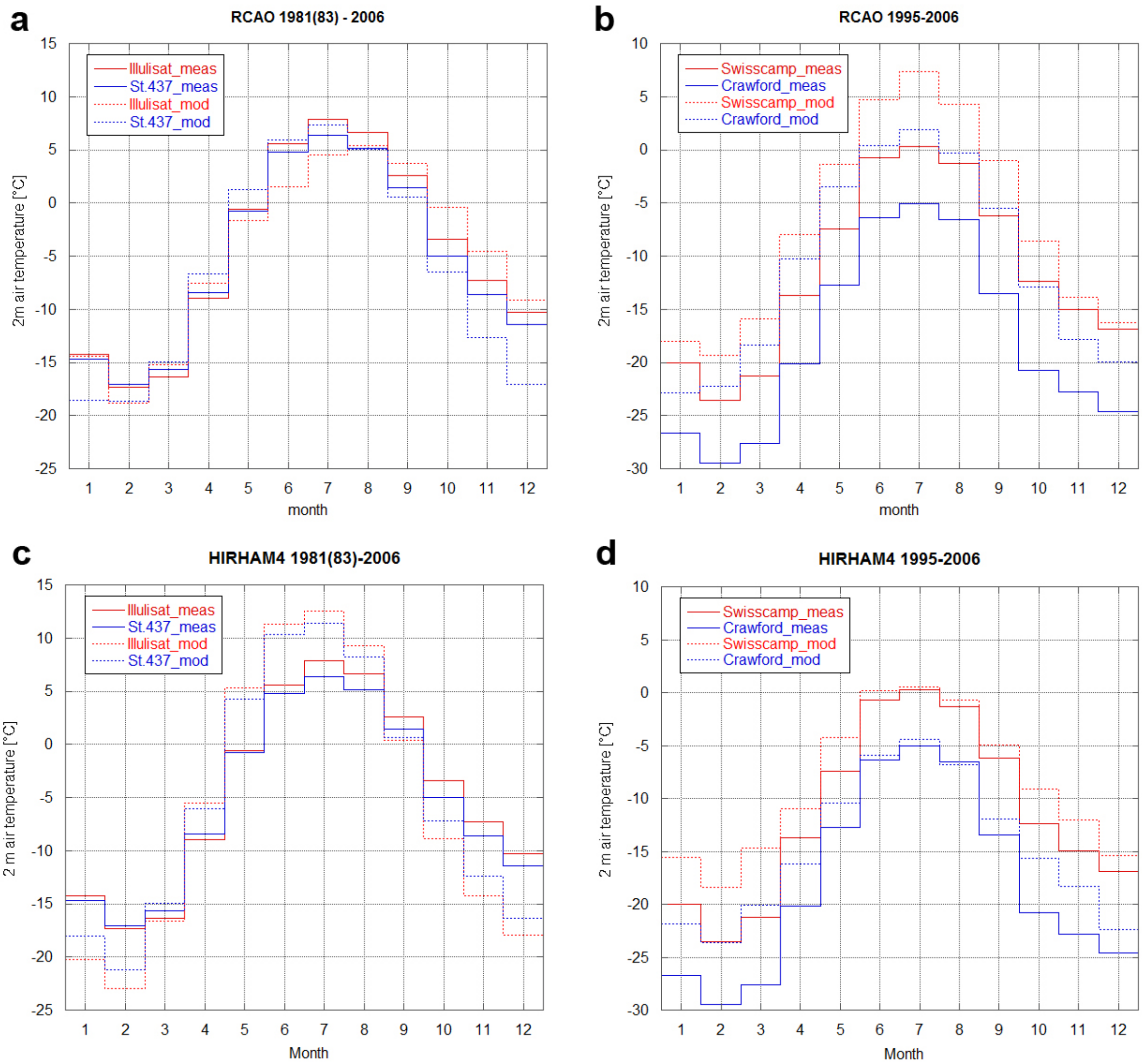

Figure 3: (a) Monthly means of 2 m air temperature measured at Illulisat and Station 437 compared to 2 m air temperature modelled by RCAO for the corresponding RCM grid-boxes. (b) The same for the stations Swiss Camp and Crawford. (c) The same like Plot a) but for HIRHAM4. (d) The same like Plot b) but for HIRHAM4.

area AWS tend to tilt because of the melting surface underneath: the Swiss Camp station was most likely tilted to the south during the summer of 2005, measuring systematically too high values. However, this problem was discovered only recently and thus measured S_{in} in Fig. 6 are too high by approx. 5–6% (corresponding to 15–18 W m^2 during summer). The effect of the parameterization of S_{in} through n (see Chapter 3.1) from the RCM is explored by comparing the measurements to both the parameterized S_{in} and S_{in} retrieved directly from the RCM.

RCAO: Keeping in mind the short observation period and the remarks made above, it is stated that RCAO reproduces global radiation with a moderate to strong negative bias in

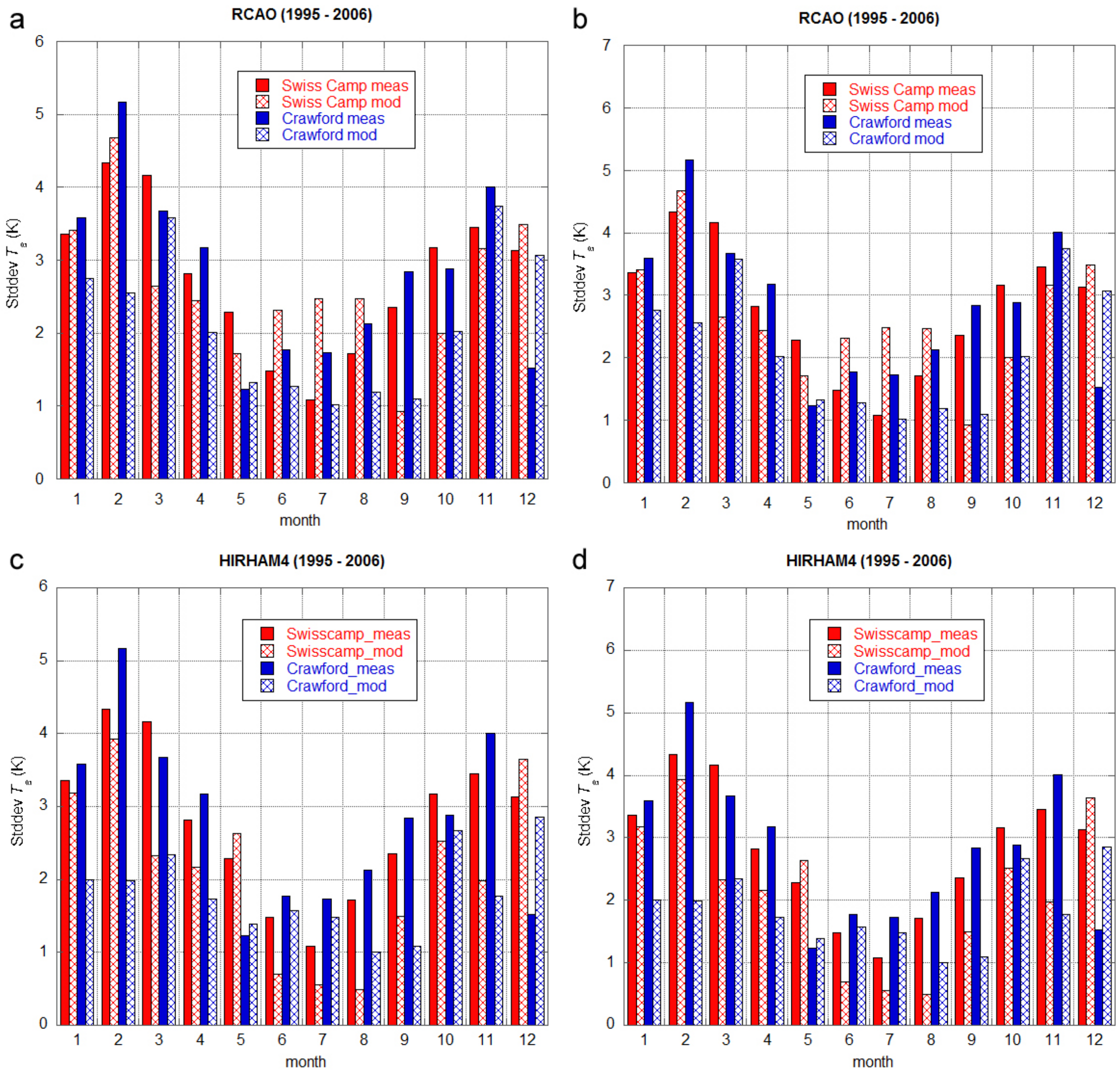

Figure 4: (a) Standard deviation of monthly means of T_a measured at Ilulisat and Station 437 compared to standard deviation of T_a modelled by RCAO for the corresponding RCM grid-boxes. (b) The same for the stations Swiss Camp and Crawford. (c and d) The same as plot a and b, respectively, but for HIRHAM4.

summer (Fig. 6a). Parameterized S_{in} has only a small negative bias during summer (Fig. 6b). Standard deviation of monthly means is similar to the observations at Crawford when S_{in} derived from RCAO is considered (Fig. 7a). The parameterized S_{in} shows strongly reduced standard deviations (Fig. 7b). No standard deviation of monthly means was calculated for Swiss Camp due to the above mentioned errors in the readings. The high standard deviation of observed April-means at Crawford is probably the result of a similar problem.

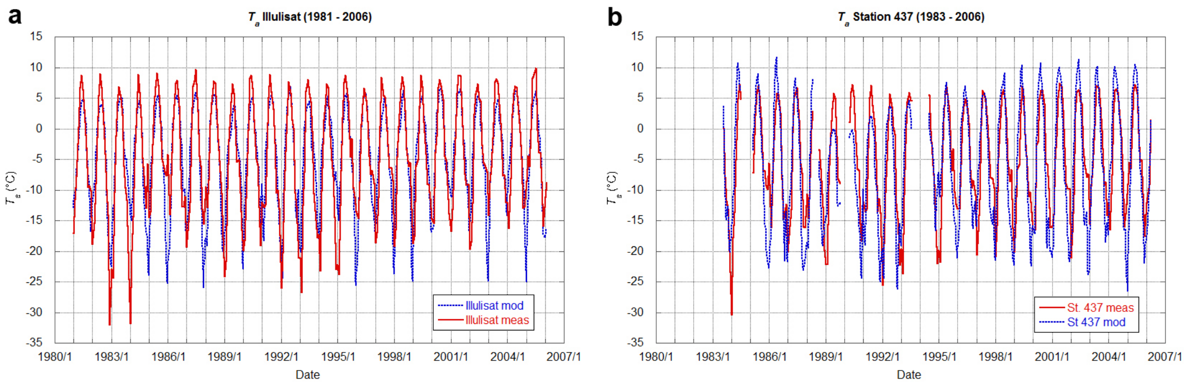

Figure 5: (a) Monthly means of measured T_a at Illulisat compared to T_a modelled by RCAO for the corresponding RCM grid-box. (b) The same for Station 437.

HIRHAM4: Global radiation is not among the available HIRHAM4 output variables (`http://prudence.dmi.dk/datagroenland/daily/`). Adding the two variables "Net Shortwave Radiation Surface" and "Upwelling Shortwave Radiation Surface" resulted in a total that was still too small to represent global radiation. Thus no global radiation data from HIRHAM4 are shown. The agreement of parameterized S_{in} to observations is almost identical to parameterized S_{in} using n from RCAO (Fig. 6b and c). However, standard deviation is larger and rather close to observed variability (Fig. 7b).

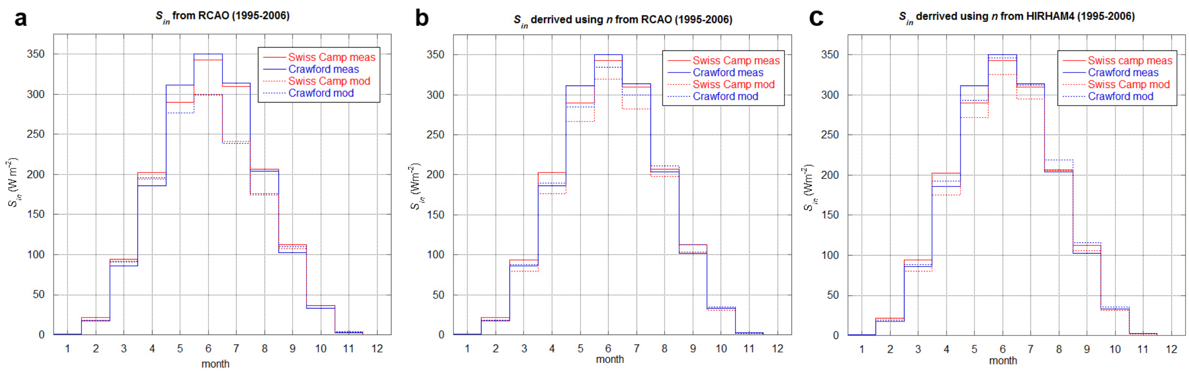

Figure 6: (a): Comparison of monthly means of global radiation measured at Swiss Camp and Crawford and according to RCAO. (b): The same like Plot a) but global radiation is parameterized using cloudiness from RCAO. (c): The same like Plot b) but global radiation is parameterized using cloudiness from HIRHAM4. Note that measured values from Swiss Camp are too high by approx. 15–18 W m^2 as stated in the text.

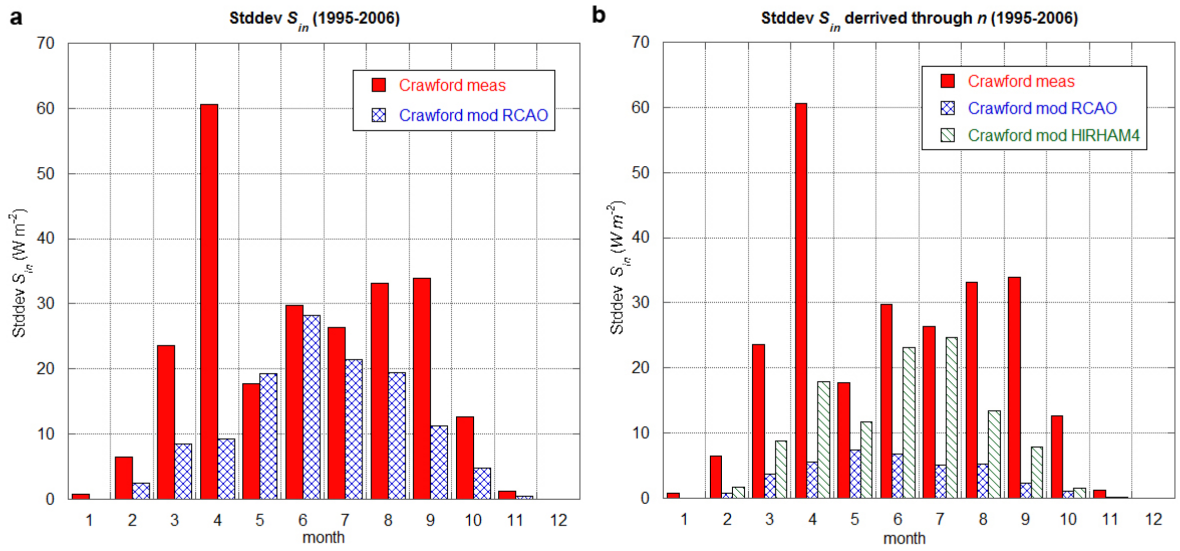

Figure 7: Plot a: Standard deviation of monthly means of global radiation at Crawford, measured and according to RCAO. Plot b: The same but global radiation parameterized using cloudiness from the two RCMs.

5.3 Accumulation

Precipitation from the RCMs is considered as accumulation whenever $T_a <$ approx. 1.5 °C (see Section 3.1). The so derived accumulation is shown in Fig. 8 and compared to the *Burgess et al.* (2010) data (Fig. 9). Mean accumulation distribution according to *Burgess et al.* (2010) is shown in Fig. 1. In the Paakitsôq area the largest portion of precipitation falls as solid precipitation. Total precipitation from the RCMs was also compared to accumulation (not shown here) and the results are very similar to the comparison shown below. This is even the case for the ice sheet margin where air temperatures are highest.

RCAO: Accumulation distribution is reproduced reasonably well. Spatial patterns are also similar to *Burgess et al.* (2010) and there are no areas of pronounced over and underestimation visible in Fig. 9a. Averaged over the study site RCAO has a negative precipitation bias of 0.09 m yr^{-1}, corresponding to 24% of the mean from *Burgess et al.* (2010) (Table 2).

HIRHAM4: Along the coast HIRHAM4 mostly overestimates accumulation while the interior of the ice sheet is somewhat too dry (Fig. 9b). By average a mean negative precipitation bias of 0.16 m yr^{-1} results which equals 43% of the mean from *Burgess et al.* (2010) (Table 2).

6 Bias Correction and Future Scenario Runs

After having specified a number of biases in the RCM output the model runs were repeated with bias-corrected RCM data.

To correct the temporal bias of T_a, daily offsets between measurements and downscaled RCM fields at Crawford and Swiss Camp (1995-2006) are calculated. The offset-values are averaged over both stations and all years to obtain a correction value for each day of the year. Due

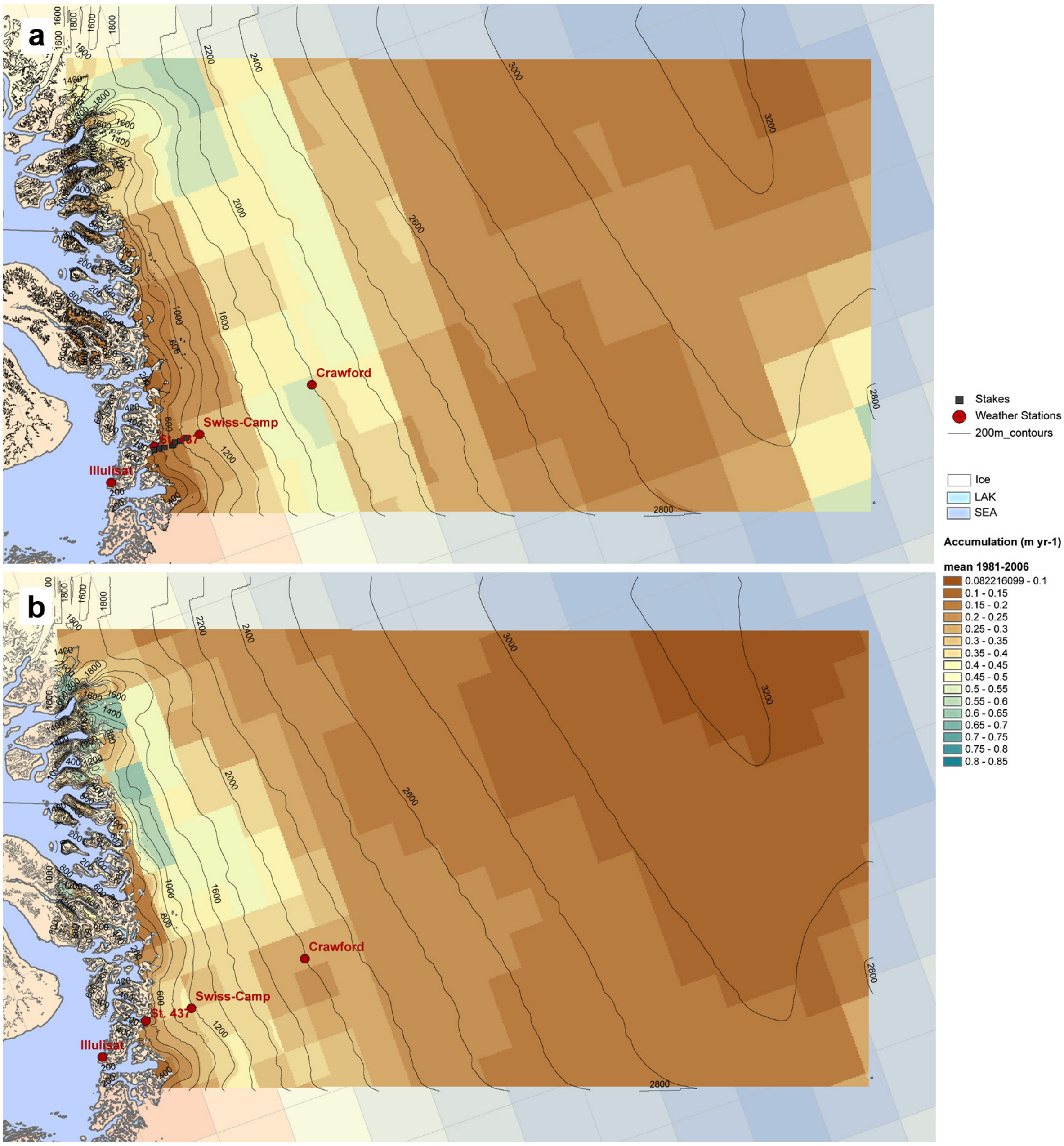

Figure 8: Mean annual accumulation distribution for the Paakitsôq area according to RCAO (Plot a) and HIRHAM4 (Plot b).

to time constraints it was decided to calculate biases only from these two stations because a correct representation of T_a over the ice sheet is crucial. Hereby enhanced biases outside of the ice sheet were taken into account. Most likely biases in T_a are elevation dependent (*Ahlstrøm et al.*, 2008a) and including more stations in the bias correction (also the GC-Net stations JAR1 and JAR2 close to the ice sheet margin) should be investigated in the future.

To correct the spatial bias of P, a spatial correction array (P_{corr}) is calculated from the ratio

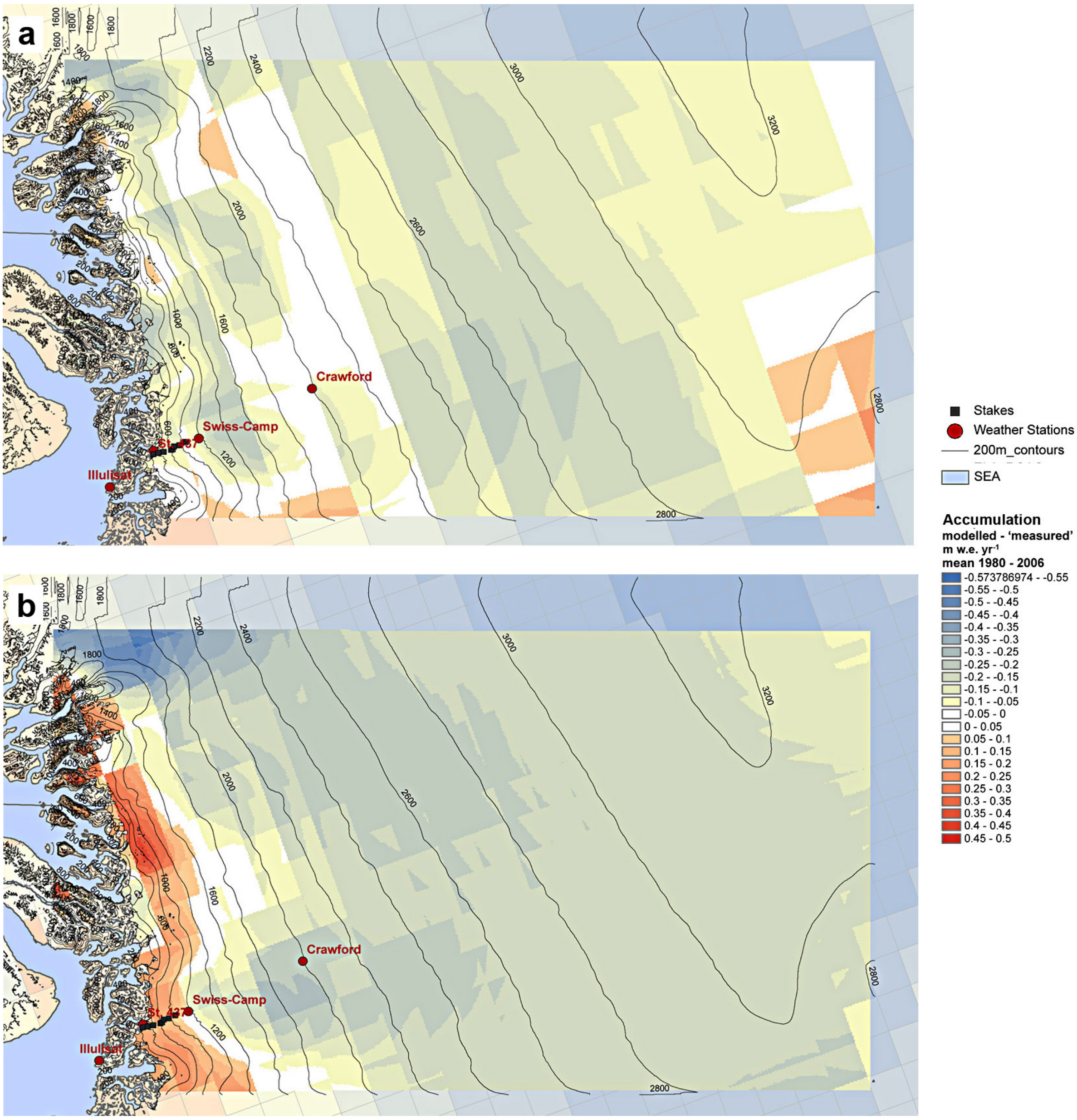

Figure 9: Differences in accumulation from *Burgess et al.* (2010) (referred to as "measured" in the legend), RCAO and HIRHAM4 (referred to as modelled in the legend). Positive values indicate an overestimation of the RCM while negative values indicate underestimation. Plot a shows the comparison for RCAO and Plot b for HIRHAM4.

of mean annual accumulation 1980–2006 according to RCAO and HIRHAM4, respectively, and according to *Burgess et al.* (2010). During the model run, daily precipitation arrays from the RCMs are then multiplied with P_{corr}. This approach ensures that in a long term mean the spatial distribution of P is identical to *Burgess et al.* (2010) whereas temporal variability comes

Table 2: Mean annual accumulation over the study site and standard deviation of annual means for the years 1980–2006.

Data	annual mean	stddev of annual means
	m w.e.	
Burgess et al. (2010)	0.37	~ 0.1
RCAO	0.28	~ 0.1
HIRHAM4	0.21	~ 0.1

from the RCMs.

Biases in parameterized S_{in} are small and thus a bias correction of this parameter is omitted. Figure 10 shows that the bias correction results in almost identical ELAs from both RCMs. The melt at the margin however is less negative when using RCAO (Fig. 10a). Obviously this is a result from the strong bias correction of T_a that is based on comparing RCAO to the measurements at Swiss Camp and Crawford. The much smaller biases observed at Station 437 and Ilulissat indicate that the bias is elevation dependent. The opposite might be the case for the HIRHAM4 driven run: HIRHAM4 has probably a positive bias in T_a at the margin (see Section 5) and average melt at the margin is close to the most negative observed stake readings (Fig. 10b). The large spread from most positive to most negative mass balance years when using RCAO persists (Fig. 10a) because the variability of summer temperatures was not corrected.

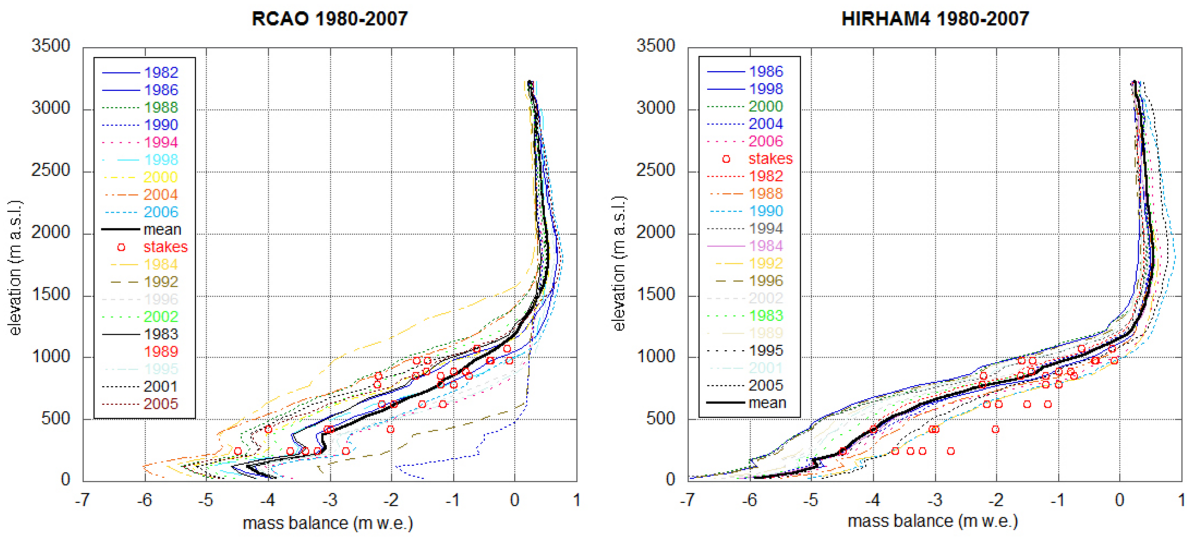

Figure 10: Mass balance profiles calculated using bias-corrected RCAO (Plot a) and HIRHAM4 (Plot b) data for model input.

Future scenarios of surface mass balance showed that the predicted changes are very similar for both RCMs (Fig. 11). Apart from the more pronounced ELA shift when using RCAO (200 m compared to 80 m when using HIRHAM4), the two RCMs predict almost identically predict an increase of melt at the margin and more positive mass balances above 1500 m a.s.l.

Again it must be noted that inter-annual variability modeled when using RCAO is much higher: During the time span 2060–2080 very positive and very negative mass balance years occur.

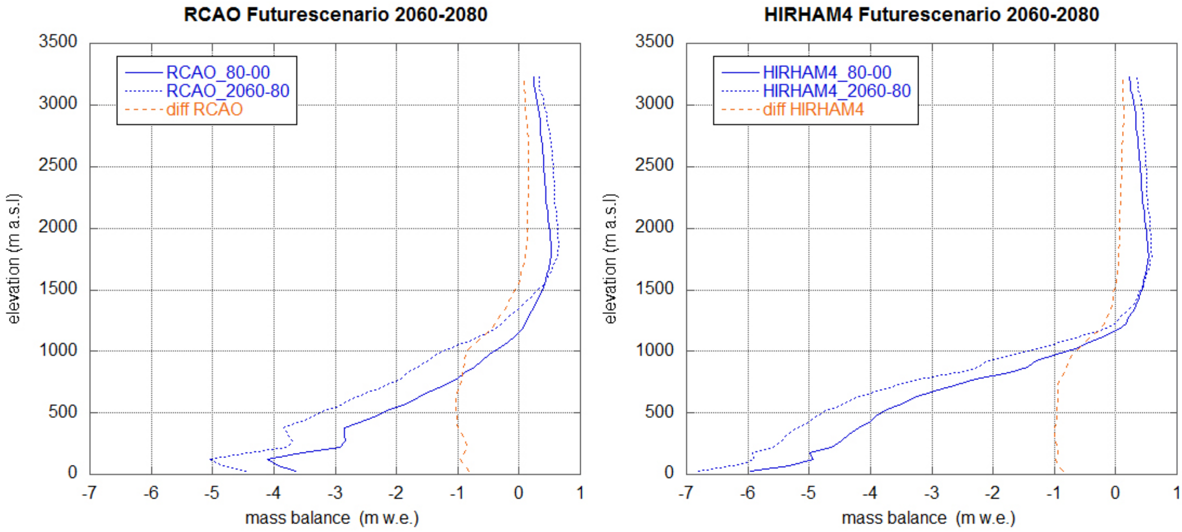

Figure 11: Future scenarios of mass balance profiles calculated using bias-corrected RCAO (Plot a) and HIRHAM4 (Plot b) data for model input. The dotted orange line shows the difference between the years 1980–2000 and 2060–2080.

7 Discussion

It was the original idea of this work to use a mini-ensemble of climate model scenario runs to establish a range of future scenarios of surface mass balance of the ice sheet margin at Paakitsôq. However, it turned out that apart from two older time slice experiments where HIRHAM4 was driven from ECHAM4/OPYC3 (cf. *Stendel et al.*, 2007) only two more recent scenario runs include Greenland. Our calculations of mass balance indicated major problems when using the output of one of the latter two (RCAO). Consequently we focused on a detailed evaluation of the RCM output to evaluate the source of these problems.

Our analysis of the RCM output showed that both RCMs have considerable biases in modeled air temperature, global radiation and precipitation. The biases established in this work for HIRHAM4 are in good agreement with the results from *Aðalgeirsdóttir et al.* (2009). However, it is not the case that biases in RCAO are much larger as could be expected when looking at the modeled mass balance distribution (Figure 2). RCAO even performs better in certain areas and delivers a more reasonable precipitation distribution than HIRHAM4. In the given context the problem with RCAO is that it performs worse where accuracy is needed the most, that is over the ice sheet. Furthermore, RCAO seems to have an exaggerated variability of summer temperatures resulting in an unrealistic spread of annual mass balance profiles (Figure 2). A reason for this variability might be that RCAO is a fully coupled RCM including an ocean module. Possibly this module generates local effects such as too early or too late sea ice breakup as well as ocean currents that agree worse to observations than the GCMs ocean state which is the lower boundary condition in HIRHAM4. HIRHAM4 also includes a simple parameterization for the ice sheet surface properties (*Stendel et al.*, 2007) which is missing in RCAO. This could be a reason for HIRHAM4 producing more realistic summer temperatures over the ice sheet. These questions will be discussed in more detail with the climate modeling groups at the Swedish Meteorological and Hydrological Institute and the Danish Meteorological Institute.

Establishing RCM biases is not trivial: point measurements on the ground are compared to rather abstract modelled values from the RCM grid boxes. The two stations Ilulissat and 437 are located in directly adjacent RCAO grid boxes but the bias in air temperature has different characteristics. Maybe this is because the surface class of the grid cell underneath Ilulissat has a higher fraction of water attributed to it. Nevertheless the example indicates that it might be better to compare measurements to the mean of a few adjacent grid cells (cf. *Frei et al.*, 2003). This would also imply that the small-scale variability of the RCM output contains unwanted noise that should be smoothed out. Smoothing, however, would reduce the actual resolution of the RCM, further hindering its applicability to regional problems like mass balance scenarios for Paakitsôq.

On the other side there is also considerable uncertainties and limitations in the field observations. On the one hand data gaps and inaccuracies in the data are present as the example of global radiation measurements at Swiss Camp shows. On the other hand only one station record (Ilulissat) is long enough to represent a true climatological mean of $\sim$30 years. Scenario runs of climate models should be compared against observed climatological means; looking at shorter time periods bears the risk of missing important characteristics of either of them: Had Station 437 not been used, the exaggerated variability of summer temperatures in RCAO could not have been discovered within the shorter time frame of the two GC-net stations. The *Burgess et al.* (2010) data reach from 1958–2007 and fulfill the condition of representing climatological means. However, the data is established from calibrating Polar MM5 with a number of point measurements of which none is located in the ablation zone. Nevertheless, spring visits to maintain the Paakitsôq mass balance network regularly reported little or no snow cover in the lower ablation area (e.g. *Thomsen et al.*, 1989; *Ahlstrøm*, 2007) and thus indirectly confirm *Burgess et al.* (2010) and contradict the HIRHAM4 accumulation distribution along the ice-sheet margin (Figure 9).

A direct validation of the mass balance model itself was impossible because a year to year comparison of modeled and measured mass balances is not feasible with scenario runs. The comparison to the stake readings which represent only a short time span and exclude the recent very negative mass balance years allows only for a rough assessment of modeled mass balance. Instead, the mass balance model should be evaluated and tuned independently from the RCM data, using only observational data. This, however, was not possible within the short time frame of the project and thus the performance of the mass balance model itself remains insufficiently specified. A future project should include such a more detailed evaluation of the mass balance model, using for instance the sonic ranger data from the GC-Net stations and the recent data from the PROMICE network (cf. *Ahlstrøm et al.*, 2008b).

After bias-correction a reasonable mean mass balance distribution from both RCMs could be achieved. However, as discussed in the previous paragraphs there are numerous uncertainties in the modeling process which cumulate in the uncertainty of the final result. Both models indicate very similar future scenarios, also because they are both forced by the A1B scenario and are driven from the same GCM (ECHAM5). The future scenario runs are based on the assumption that RCM biases calculated for present-day conditions are valid in the future as well. Obviously uncertainties in the scenario outcome are even larger than in the present-day runs. Furthermore the climate sensitivity of the mass balance models is also subject to uncertainty: *Ahlstrøm et al.* (2008a) predict an increase of marginal melt of almost 2 m w.e. compared to 1 m w.e. in the present study. The difference is partly attributed to the surface lowering at the margin which has a positive feedback on melt in the work of *Ahlstrøm et al.* (2008a). Furthermore the sensitivity to temperature perturbations is higher for the degree-day model used by *Ahlstrøm et al.* (2008a) than for an energy balance model as applied in the present study (e.g. *Van de Wal*, 1996).

8 Conclusions and Outlook

A workflow to calculate future scenario surface mass balance for the Paakitsoq area has been presented. On the example of the present-day runs it was shown that RCM biases exhibit a large influence on the modeled mass balance distribution. Biases were corrected and finally future scenarios using both RCMs were computed. Uncertainties in the model output are considered to be large. Within this study potential reasons for the RCM biases could only be briefly outlined. The evaluation of RCAO output has been submitted to Ralf Döscher at the Rossby Center in Sweden. Nevertheless a more intensive exchange of experience and results with climate modelers would be of mutual benefit and is encouraged for future projects.

Three main points have been identified to reduce uncertainties in the model chain: (1) To collect more observed data to specify RCM biases in greater detail, (2) to perform evaluation and tuning of the mass balance model solely based on observations and (3) to use a broader sample size of RCM runs. Currently there exist only two scenario runs covering Greenland available but there will soon be new runs available, for instance from the EU FP7 project "ice2sea".

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