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Model setup and first runs with SICOPOLIS ice sheet model and a new geothermal heat flux estimate for the Greenland Ice Sheet

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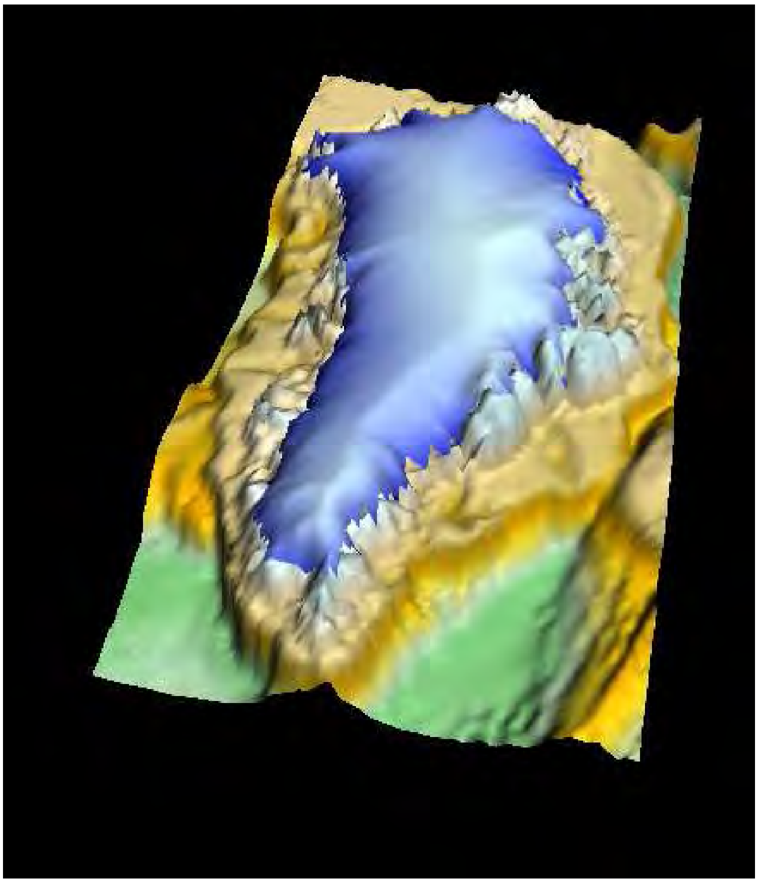

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Contents

1. Introduction

One of the uncertainties identified in the latest IPCC report (*IPCC*, 2007) is how the ice masses will respond to predicted climate change. Observations indicate that the response can be faster and more pronounced than previous modelling efforts have predicted. As a response to these observations and the need for improving model predictions a new activity of coupling an ice sheet model with the already established climate models began in October 2006 within the Danish Climate Centre. An ice sheet model code, that has been developed and applied for the Greenland Ice Sheet was generously provided by Ralf Greve, professor of glaciology at the Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan. We have initiated a collaboration with him as well as the ice sheet modelling group at the Centre of Ice and Climate at the University of Copenhagen and held a 10 day workshop in Copenhagen in May 2007. A new estimate for the geothermal heat flux based on the Ørsted satellite magnetic measurements are also applied with the ice sheet model. Here we report on the model setup, adaption of the geothermal heat flux with the ice sheet model, the challenges in coupling with a regional climate model and the first results of the ice sheet modelling group.

1.1 Ice sheet model

After some consideration it was decided to get access to and set up a state-of-the-art ice sheet model at the Danish Climate Centre. The selected code is SICOPOLIS (SImulation COde for POlythermal Ice Sheets), it is a 3-d dynamic/thermodynamic model which simulates the evolution of large ice sheets (*Greve*, 1997a,b). SICOPOLIS is in continuous development and has been applied to problems of past, present and future glaciation of Greenland, Antarctica, the entire northern hemisphere and also the polar ice caps fo the planet Mars.

The model is based on the shallow-ice approximation, that entails that longitudinal stress gradients are neglected. It is coded in Fortran 90 and uses finite-difference discretization on a staggered grid, the velocity components are computed between grid points. The specialty of SICOPOLIS is the detailed treatment of basal temperate layers, i.e. regions with temperature at the pressure melting point. Within the temperate layer, the water content is computed, and its influence on the ice viscosity is taken into account. The model requires the following input: surface mass balance (accumulation, ablation), mean annual surface temperature above the ice, Eu-static sea level and geothermal heat flux. The model outputs as functions of position and time are extent and thickness of the ice sheet, velocity field, temperature field, water-content field (temperate regions), age of the ice and isostatic displacement and temperature of the lithosphere. Given the applied basal boundary condition the model can compute the basal frictional heating and melt water production.

1.2 Geothermal heat flux

One of the most important, but poorly known, boundary condition for large scale ice sheet models is the geothermal heat flux beneath the ice caps. The geothermal heat flux influences both the thermal regime and the dynamics of the ice sheets. Until now ice sheet models have been run with either constant geothermal heat flux, or estimates based on single borehole measurements. A new estimate for the geographically varying geothermal heat flux underneath the Greenland ice sheet has been derived from magnetic field models based on satellite magnetic field models that use satellite magnetic data from the Ørsted satellite (*Maule*, 2005). The thickness of the magnetic crust is determined, the 1D heat conduction equation is then used to determine the temperature profiles of the curst, and from this the geothermal heat flux is estimated (*Maule et al.*, 2005). This estimate is produced on a georeferenced grid which is then interpolated onto the grid which SICOPOLIS

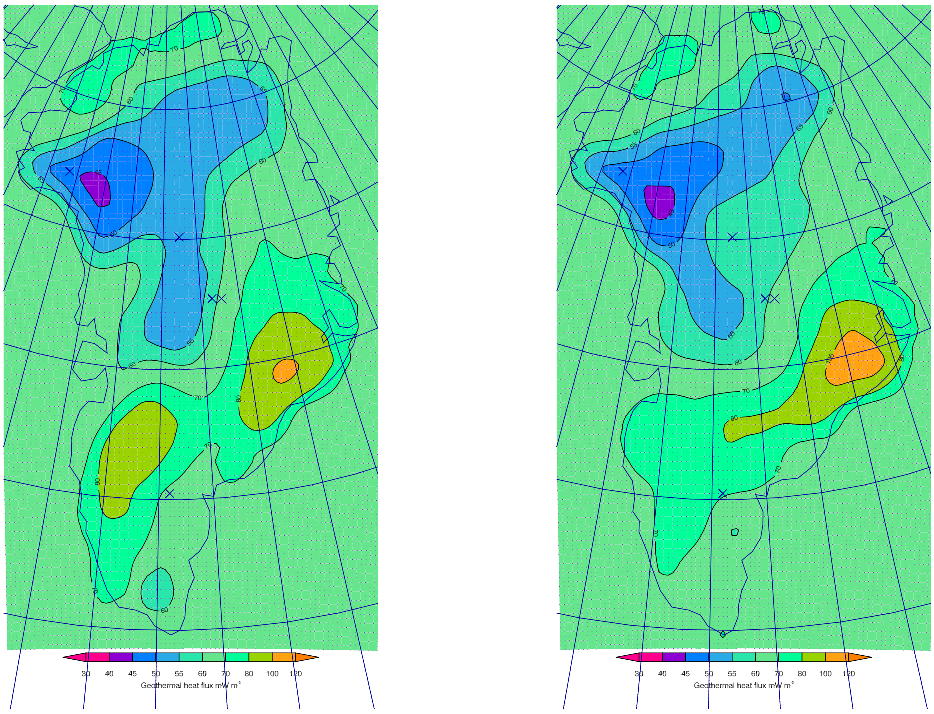

Figure 1.1: The two different geothermal heat flux distributions from model 4 (left) and model 5 (right).

computes on. First, grids that had cut the values outside Greenland were used, but the outline of Greenland is not quite the same in the two reference systems, and therefore another grid, which contains the values outside Greeland was used. The values outside Greenland are, however, not reliable and therefore care has to be taken when estimating at the ice sheet, or land edges. Two different estimates are available based on two magnetic field models CHMF 4 and 5, both are used, with the purpose of assessing the model sensitivity to the applied geothermal heat flux.

A few different interpolation methods were tested and the best result obtained when using a Kriging method to interpolate the grids (see: /Greenlandata/CFoxMaule/interpol_gthf_cfm.pro and interpol_model5.pro for details of the method. First run convert_togrid.pro to get the vectors into idl). The kriged surface was then smoothed with a nine-point filter, which gives a smooth surface. Finally, the land mask from Ralf Greve was used to cut out the ice and land covered points. The remainder of the grid is assigned the value 65 mV m^{-2}. Unfortunately there are some unrealistic peaks in the maps (caused by the high values just out of the coast from Greenland, as well as an ocean point within the ice sheet, (edited the mask file to get this point away, from the eastern part of the ice sheet). Therefore, the final version was edited by hand to get these erroneous points away (see notebook and the .pro scripts for details of the points that were edited).

This procedure gives 4 estimates for the geothermal heat flux, 2 from model CHMF 4 (not smoothed and smoothed) and 2 from model CHMF 5. In figure 1.1 the smoothed versions are shown. Both estimates have a band of higher geothermal heat flux from the central eastern part of Greenland across towards west and south, with highest values in the eastern part. Lowest values are in the northwestern part of Greenland with intermediate values in the central part and furthest south. This new boundary condition is applied with the ice sheet model SICOPOLIS for Greenland ice sheet and comparison with previous results *Greve* (2005) for the basal temperature distribution and ice sheet thickness is done.

2. First model experiments

A number of model experiments were performed. First, a series of model runs with a constant mass balance forcing were done. A model run of 30.000 years takes about 2 hours on the computer asama, 100.000 years take about 6 hours on same computer. When compared with the runs where the ice sheet is run through a few ice age cycles it is clear that it is important to spin up the model in order to get the temperature distribution within the ice sheet right and hence more realistic present day ice cap. Next, the same model setup and climate history forcing as has been developed for Greenland Ice Sheet was used (*Greve*, 2005). A spin up for the ice sheet model is from 422.000 – 250.000 years before present, this provides the initial state for the model run which is from 250.000 years until present day. This longer run, of 422.000 years takes 24 hours on asama and 12 hours on dolph or wulff.

2.1 Constant mass balance forcing

The results are written out in .ser files, .core files and .erg files, which contain time series of key variables, time series of key variables at ice core locations and distributed values for the grids at pre-specified time steps.

2.1.1 Variables for the whole ice sheet

The time series for the key variables (see /SICOPOLIS/noch/plot_ser.pro for details on how files are read in and these plots are created.) are plotted in Figures 2.1 and 2.2. For the colours, Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run. The important result is how the Blue and Orange lines compare with the Red lines.

- Volume

  The ice cap grows the first 1000 years but then the volume reduces until about 5000 model years and after that is grows steadily, after 30.000 years it has not yet reached a steady state, but is approaching one. There is only a small difference in volume between the 5 model runs after 30.000 years, after the initial growth the reference run has the largest volume then the results diverge and at 100.000 years the 4 new model runs have about 0.02 10^6 km^3 larger volume than the reference run, which is about 0.8% difference in volume. This is a rather small difference considering the difference in the applied geothermal heat flux.

- Maximum ice thickness

  The maximum ice thickness decreases the first 5.000 years (despite the initial increase in volume), but then grows steadily (as the volume increase would indicate) and has reached a steady state value at the end of the model run. The reference run has about 20-30 m thinner ice as in the beginning when volume is decreasing, then from 7.000-16.000 years the thickness is virtually the same for all 5 model runs, but after that the values diverge and the reference run has about 30 m thinner ice sheet at the end of the model run. Despite larger volume for the reference run, the max thickness is smaller, the values for model run 4 has slightly thicker ice than model 5. The difference between the reference and the new model runs is 30-40 m in maximum ice thickness.

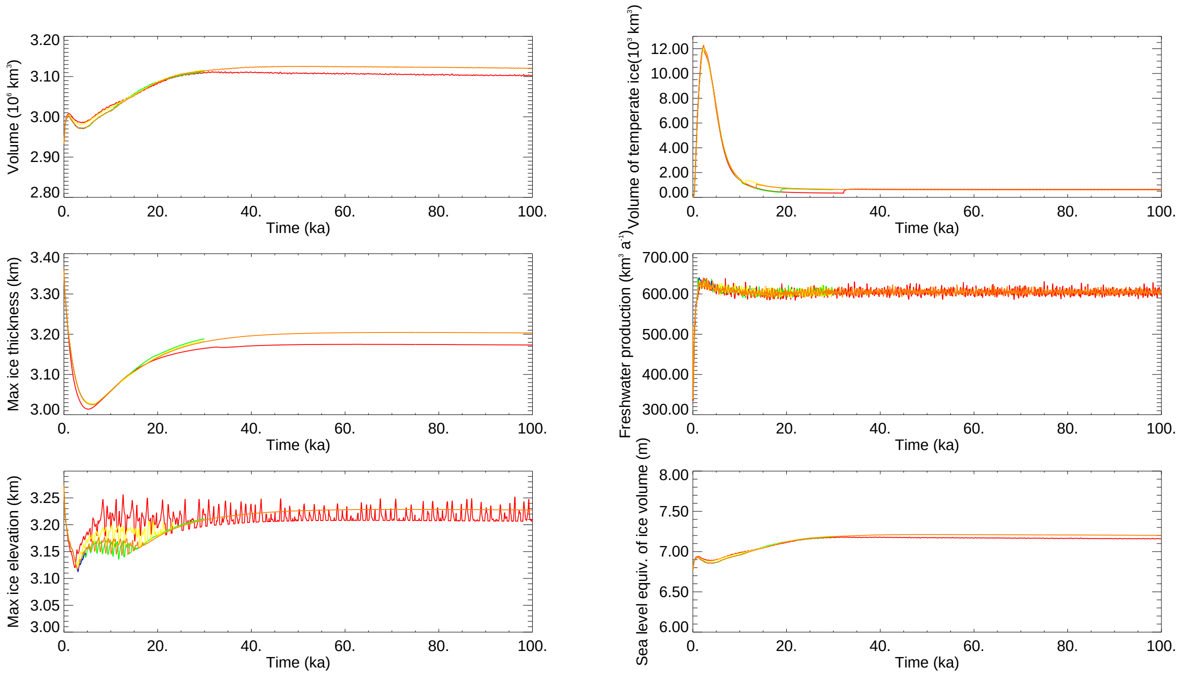

Figure 2.1: Results from first model runs, constant mass balance forcing. Left: Volume evolution (10^6 km^3), Maximum thickness (km) and Maximum ice elevation (km) and Right: Volume of temperate ice (10^3 km^3), Freshwater production (km^3 a^{-1}) and Sea level equivalent of ice volume (m) for the model runs with constant mass balance forcing over 100.000 years. Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run.

- Maximum ice elevation

  This is a strange result, at the same time as the max ice thickness is a smooth function, the max ice elevation is fluctuating. The reference model has max elevation fluctuating 50-100 m, model 4 runs fluctuate < 50 m until year 15.000 and then becomes smooth and model 5 runs are fluctuating 20-30 m until year 16.000 (smoothed) and 30-40 m until year 24.000 (not smoothed) and then the curve becomes smooth. Why the Max ice elevation in the reference run is fluctuating so much while the Max ice thickness is not is strange, need to find out how the max ice elevation is selected, whether it is at different point during the model run, or whether the same point is changing elevation so rapidly. The reference run is fluctuating throughout the 100.000 years, and does not stop fluctuating, like the new model runs.

- Volume of temperate ice

  The volume is increasing rapidly from zero to 12 10^3 km^3 (about 0.4% compared to the total volume of 2.9 10^6 km^3) but it then reduces almost equally rapidly to about 0.5 10^3 km^3 (0.02%). There are step increases in the new model runs, compared to the reference run, first (at a 11.000 years) model 5 (not smoothed) increases the temperate ice volume, then model 5 (smoothed) increases at 13.500 years, model 4 at ca. 18.700 years and smoothed model 4 at ca. 19.100 years. The reference run has a step at about 33.000 years. All the model runs approach the same value of approx. 0.63 10^3 km^3. This is a very small fraction of the total

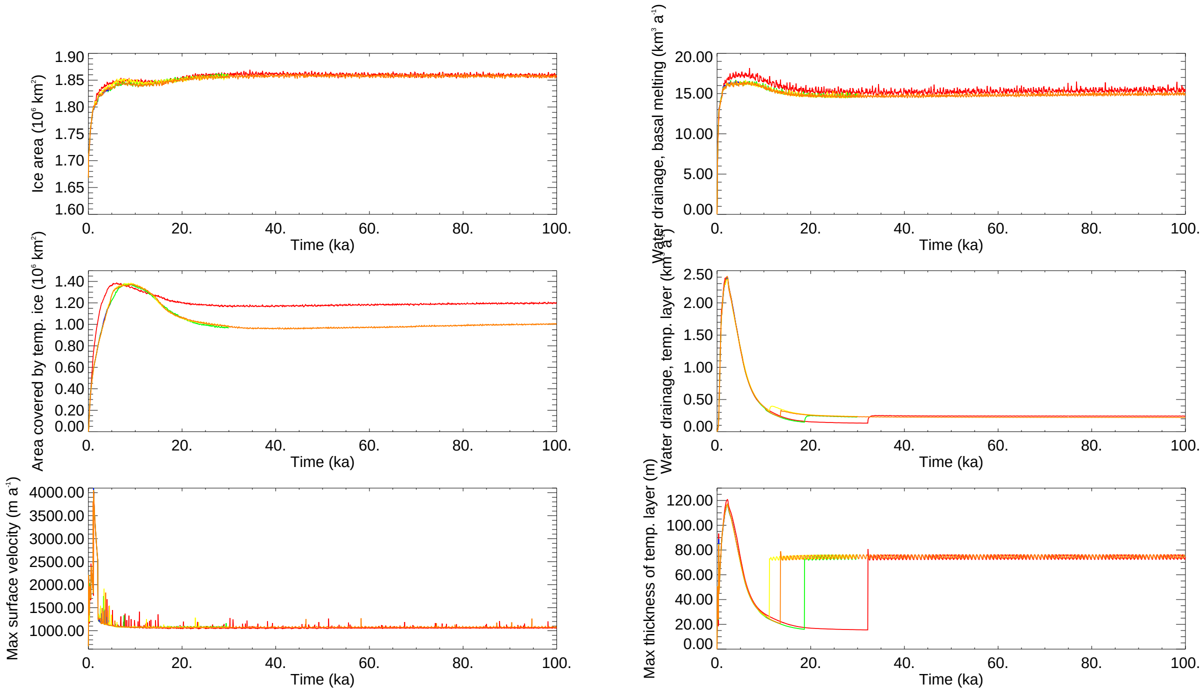

Figure 2.2: Results from first model runs, constant mass balance forcing. Left: Ice area (10^6 km^2), Area covered by temperate ice (10^6 km^2) and Maximum surface velocity (m a^{-1}). Right: Water drainage due to basal melting (km^3 a^{-1}), Water drainage from temperate layer (km^3 a^{-1}) and Maximum thickness of temperate layer (m) for the model runs with constant mass balance forcing over 100.000 years. Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run.

volume of the ice sheet. Model 4 has value of 0.595 10^3 km^3, model 5 has 0.604 10^3 km^3 and Reference has 0.637 10^3 km^3.

- Freshwater production

  This value drops first from its initial value of 519 km^3 a^{-1} to ca. 340 km^3 a^{-1}(similar for all runs) in the first time step, Then increases steadily above the initial value and levels off and fluctuates for all results, about 40 km^3 a^{-1} around the value 600 km^3 a^{-1} (larger than the initial value). The value continues to oscillate during all 100.000 years.

- Sea level equiv. of ice volume

  This curve has same shape as the total volume curve as it is computed from the total volume. It starts at 6.8 m and ends at about 7.2 m. The reference run has slightly higher value during the period 2000-10.000 years but at the end of the 100.000 years model run the reference has a lower value than the rest.

- Ice area

  Ice area increases rapidly in the first time step, by 0.04 10^6 km^2, which is 100 grid points (each representing 400 km^2). Then there is a slower increase in area until about 5000 model years and after that there is about 25 pts variation in area, that appears as noise. All model runs have similar oscillating values throughout the 100.000 model years.

- Area covered by temperate ice

  Area covered by temperate ice is increasing from 0 to about 1.4 10^6 km^2 during the first 7.000 computational years, then it decreases slower and settles to a steady state value, with some wiggles. The reference run has larger area covered by temperate ice during the initial growth, then this run has slightly lower value, but all the new runs have similar values, and then the reference run diverges again from the other runs and settles to a value that is about 0.2 10^6 km^2 larger than the new runs. It is interesting that all model runs have similar values during about 7.000 years and then diverge again. This is where the difference between the reference run and the new runs is the largest. Since the total area is about 1.86 10^6 km^2 the area covered by temperate ice is about 52%, but for the reference run it is about 62% of the total area.

- Max surface velocity

  This variable is varying strangely, for all the model runs the max value is going to very high values, and at about 1000 years it reaches 4000 m a^{-1} and then drops down and settles to a value of about 1100 m a^{-1}, but there are a few jumps in this value, especially in the reference run.

- Water drainage due to basal melting

  This value increases from 0 to about 16-17 km^3 a^{-1} during the first 2000 model years and then fluctuates during the rest of the time. The reference run has larger value than the new runs, throughout the 100.000 years there are large wiggles in the value.

- Water drainage from the temperate layer

  Increases from 0 to 2.4 km^3 a^{-1} during first 2000 model years, then drops rapidly and levels off. Relative to the reference run the water drainage increases in steps for the new model runs, in a similar manner as the Volume of the temperate ice increases, first the model 5 (non-smoothed first at about 11.000 years, then smoothed at ca. 13.500 years) and then then model 4 runs (first non-smoothed ca. 18.700 years and then the smoothed run at ca 19.200 years). Then at ca. 32.000 years the reference value also jumps and at the end of 100.000 years the value is similar for all 5 model runs.

- Max thickness of the temperate layer

  This values has a few jumps in the beginning, starts from zero, does 2 jumps, increases steadily to about 120 m and then drops off and ends in a steady state. The reference model run has slightly higher value during the increase to the peak and decrease, then similar increase in steps as observed for the volume of temperate ice and water drainage from the temperate ice. The jumps are about 40 m and occur at same time as before (ca. 11.000 years, 13.500 years, 18.700 and 19.200 years for the new model runs, and at ca. 32.000 years for the reference run). The value oscillates throughout the whole 100.000 years period, similar for all 5 model runs.

The main difference between the new model runs and the reference run occurs in the temperate layer, water production and max thickness of the temperate layer. The total volume is smaller for the reference run, max thickness is smaller, but the area covered by temperate ice is larger for the reference run, as the whole area beneath NGRIP is frozen in the new model runs. Interestingly the volume of temperate ice is very similar, however, indicating that the model is not so sensitive to the very high geothermal heat flux under N-GRIP. This is due to the fact that increased geothermal heat flux will only increase the basal melt rate. The temperate ice can only be created by frictional heating within the ice, no heat conduction will go into the ice from the bed.

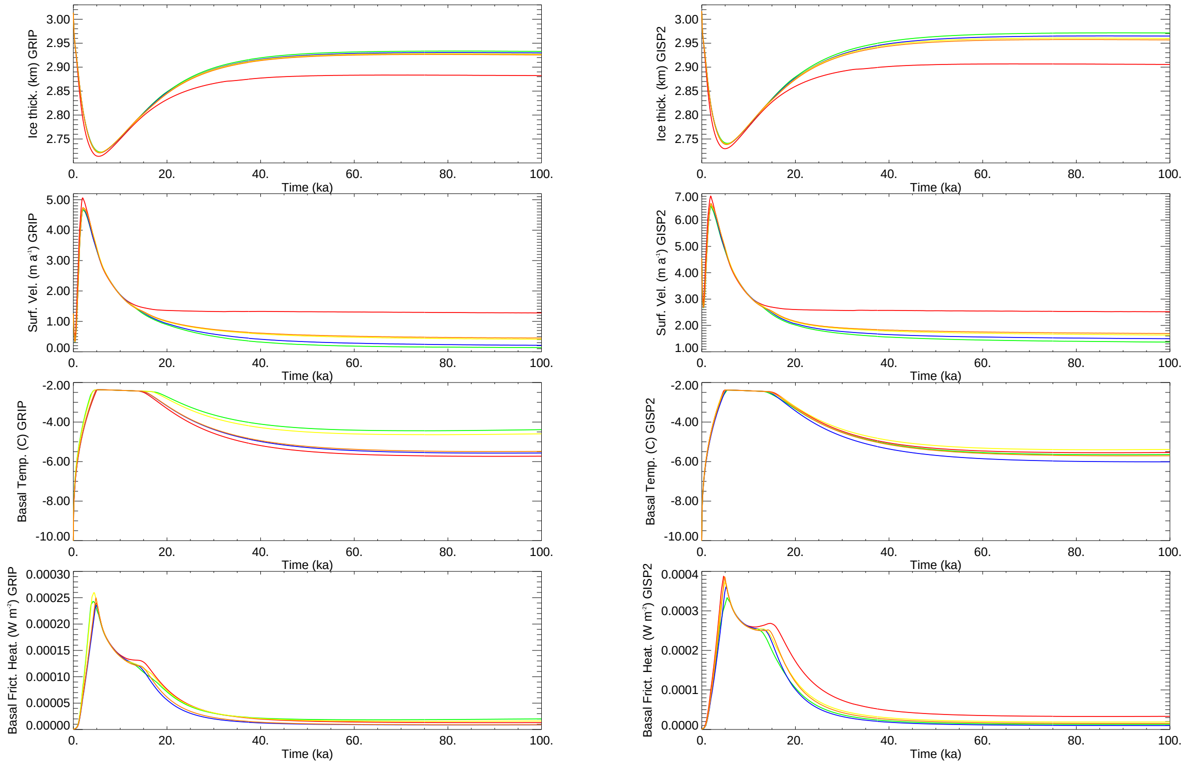

Figure 2.3: Results from first model runs, constant mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for GRIP (left) and GISP2 (right) resulting from the model runs with constant mass balance forcing over 100.000 years. Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run.

2.1.2 Values at each borehole location

For each of the boreholes there are similarly a few values output during each model run; the thickness of the ice, surface velocity, basal temperature and basal frictional heating. These are plotted and discussed below at each borehole location in turn.

- GRIP

  The geothermal heat flux at the GRIP location is quite similar for all the model runs, about 60 mW m^{-2} (60 mW m^{-2} for the reference run, 61.7 mW m^{-2} for CHMF 4, and 61.45 mW m^{-2} for CHMF 5. There are rapid spatial changes for the unsmoothed new models, but the smoothed are quite similar.

  The ice thickness starts to decrease from 3029 m to 2710 m during the first 5000 years, then it starts to increase again and in the end it is larger for the new model runs, about 2930 m, compared to ca. 2880 m for the reference, and the observed thickness is 3029 m, so the new result is closer to observations.

  Surface velocity is highest for the reference run, it is about 1 m a^{-1} in the beginning, drops the first few hundred years, then increases to a value close to 5 m a^{-1} and then decreases during the rest of the model time. At the end the value for the reference run is about 1.3 m a^{-1}, and the others have values in the range 0.5-0.8 m a^{-1}, model 4 lower than model 5.

The basal temperature is increasing from the observed value of -8.56řC to melting point in the first 5000 years, stays at melting point (ca. -2.5řC) and then becomes colder again, the unsmoothed model runs have higher values in the end (-4.5řC - model 4 is slightly warmer), the smoothed runs have values about -5.5řC - model 5 with slightly warmer, and the reference run has value about -5.7řC)

The basal frictional heating varies in a similar way for all the model runs, the unsmoothed models have similar values, rather than model 4 and 5, and the smoothed model runs follow the reference run closely. The shape of the curve is such that it increases from 0 rapidly the first 5000 years, then drops down, stays level from ca 10-15000 years and then drops again to a low value for all the model runs.

- GISP2

  GISP2 is relatively close to GRIP and therefore should have similar values in all the model runs as GRIP.

  The ice thickness is very similar to GRIP, higher values for the new model runs, about 50-70 m thicker ice. There is larger difference between the 4 new model runs at GISP2 than at GRIP. Model 4 has thicker ice and the ice is thicker than at GRIP.

  The surface velocity is very similar to the velocity at GRIP, however slightly higher value, goes up to 6.5-7.0 m a^{-1} and down to 1.6-1.9 m a^{-1} for the new model and velocity is 2.5 m a^{-1} for the reference run (compared to 1.3 m a^{-1} for GRIP).

  Basal temperature is also similar, reaches melting point and stays there until 15.000 model years and then falls down to about -5.5řC, model 4 smoothed has the lowest value of -6.0řC. The reference is between the other runs.

  Basal frictional heating has also similar to that at GRIP, it increases, falls down, stays at level and then drops again. The reference run has higher value than the new model runs, the difference is larger than at GRIP.

- Dye 3

  There is large difference in the geothermal heat flux value for this core location. The reference run has a low value of 20 mW m^{-2}, but it is 57.8 mW m^{-2} in CHMF4 and 71.0 in CHMF 5. The geothermal heat flux in the reference run is therefore only about a third of the values in the new model runs.

  The ice thickness reflects this difference in geothermal heat flux, all the new models have a similar value of 1640 m but the reference run has value of 1710 m, compared to the observed 2037 m.

  Surface velocity increases rapidly up to 60 m a^{-1} during the first 100 years and then drops down and comes to a steady state value of about 30 m a^{-1}, similar for all 5 model results.

  The basal temperature is (obviously) higher in the new runs than for the reference run. It is very close to melting during the whole model period, maybe slightly below melting in the end. The 4 new model runs give basal temperature about -1.5řC, the reference run gives temperature of -6.8. Observations indicate basal temperature of -13.22řC

  Basal friction heating is also higher for the new model runs, slightly lower for the smoothed model 4, the value is about 3 times higher than what the reference run gives.

- Camp Century

  The difference in applied geothermal heat flux is small here, the reference value is 50 mW m^{-2}, it is 46.7 mW m^{-2} in CHMF 4 and 47.5 mW m^{-2} in CHMF 5.

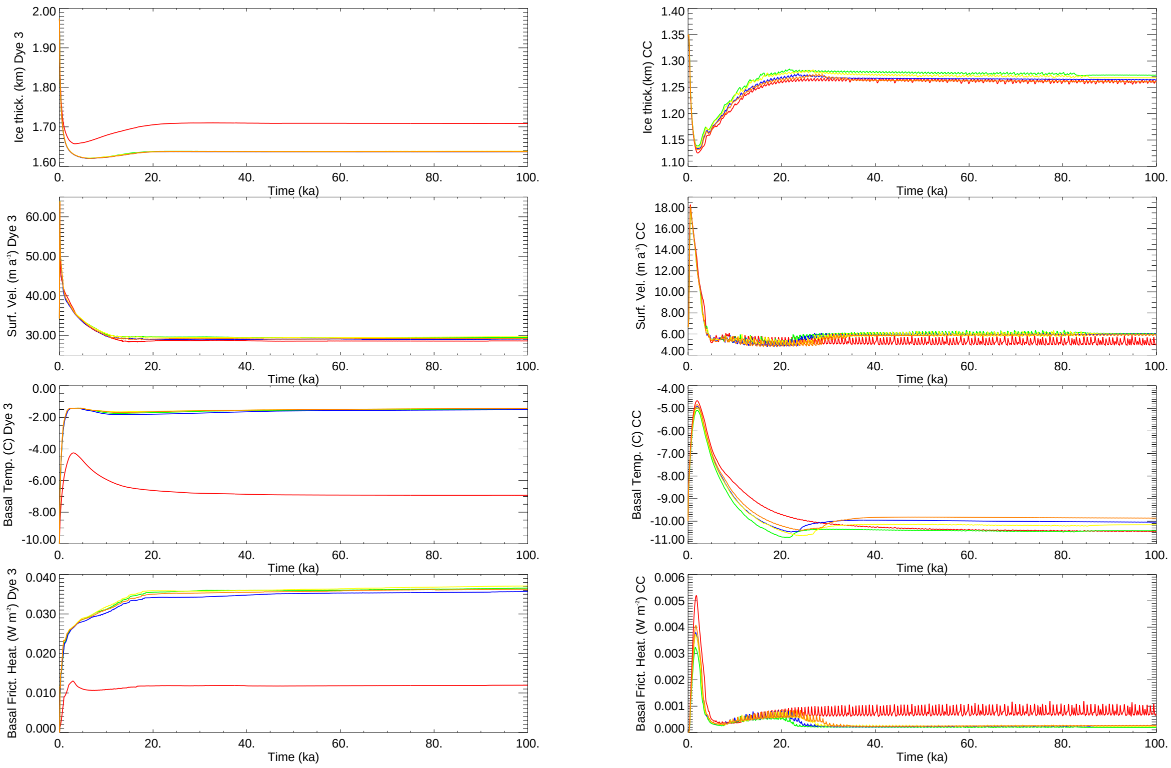

Figure 2.4: Results from first model runs, constant mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for DYE3 (left) and Camp Century (right) resulting from the model runs with constant mass balance forcing over 100.000 years. Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run.

The ice thickness is similar for all 5 model runs, but this time the value is wiggling with amplitude about 10 m for all, the value for the reference is slightly lower that for the others, the range in the results is 1250-1280 m and the observed thickness is 1387.

Surface velocity has similar shape for all model runs, rapid increase to a maximum, then slower decrease and then the curves start to wiggle, so there appears to be some instability in the results. The values increase to about 18 m a^{-1} and then drop to about 5-6 m a^{-1}.

Basal temperature is increasing from about -10.0řC to about -5řC during the first 2000 years and then it drops to about -10řC. Smoothed model 4 has the highest values, model 5 and reference are similar and unsmoothed model 5 has the lowest temperature. The observed temperature is -13.0ř which is considerably lower, which indicates that possibly is the geothermal heat flux lower still.

Basal frictional heating is similar for all the 5 model runs, all rise rapidly from 0 to a max value at about 2000 years. The reference has the highest maximum value, then smoothed model 5, smoothed model 4 and non-smoothed model 5 have very similar maximum value, the non-smoothed model 4 has the lowest value. All curves drop down and reach a minimum value, at about 10.000 years the curves start to wiggle, there are recurring tops that increase with time and the value is wiggling, largest for the reference run. The value is also higher, but smaller wiggles and smaller value for the new model runs.

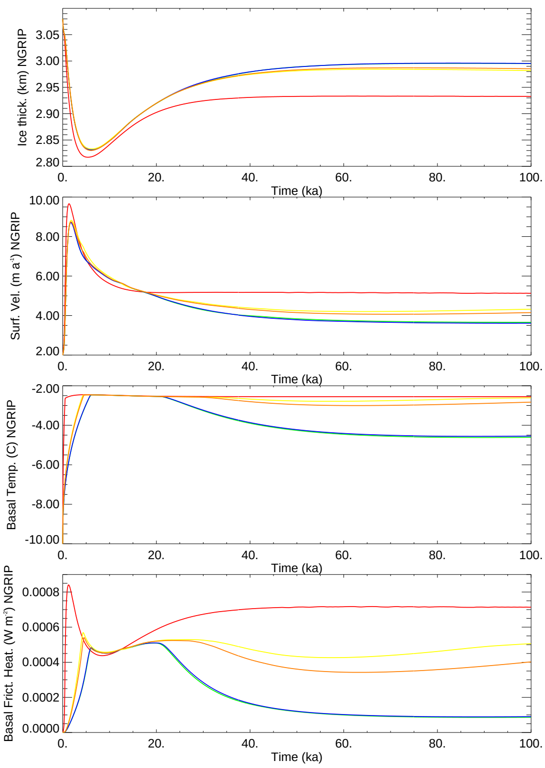

Figure 2.5: Results from first model runs, constant mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for NGRIP resulting from the model runs with constant mass balance forcing over 100.000 years. Red is the reference run, Green shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Yellow shows CHMF 5 results, and Orange CHMF 5 smoothed run.

- NGRIP

  The largest difference in the geothermal heat flux values is between the reference run and the new models in this core location. The value for the reference run is 135 mW m^{-2} and for model 4 the values are ca. 53.51 mW m^{-2} and 52 mW m^{-2} for smoothed and non-smoothed version, respectively. For model 5 the values are slightly higher or about 59.40 mW m^{-2} and 60 mW m^{-2} for smoothed and non-smoothed version, respectively.

  Ice thickness is larger for the new model results, 2960 m, than the reference of 2925 m (the published values are 2937). Remarkably, there is only 50 - 60 m difference between the new result and the reference result, indicating that the ice thickness is not as sensitive to the value of the geothermal heat flux as could be expected when comparing to the other sites with smaller difference in the geothermal heat flux. The difference is similar to the difference at GRIP (33 m), where the geothermal heat flux values are almost the same for all 5 model runs. (the difference is larger, 70 m, at Dye 3, where the ice is also only about half the thickness).

  Surface velocity changes similarly as at the other thick parts of the ice sheet. First a rapid increase up to 9-10 m a^{-1} (reference grows quicker and to higher value than the new runs), then it drops off and is at a steady state value of about 4-5 m a^{-1}. The reference run has about 0.5 m a^{-1} higher value than the other runs.

  Basal temperatures are increasing from -10řC to melting, the reference run increases rapidly, reaches melting point in about 500 years, but the other model runs reach melting temperature after about 4500 years and 6000 years for model 5 and model 4, respectively. The temperature

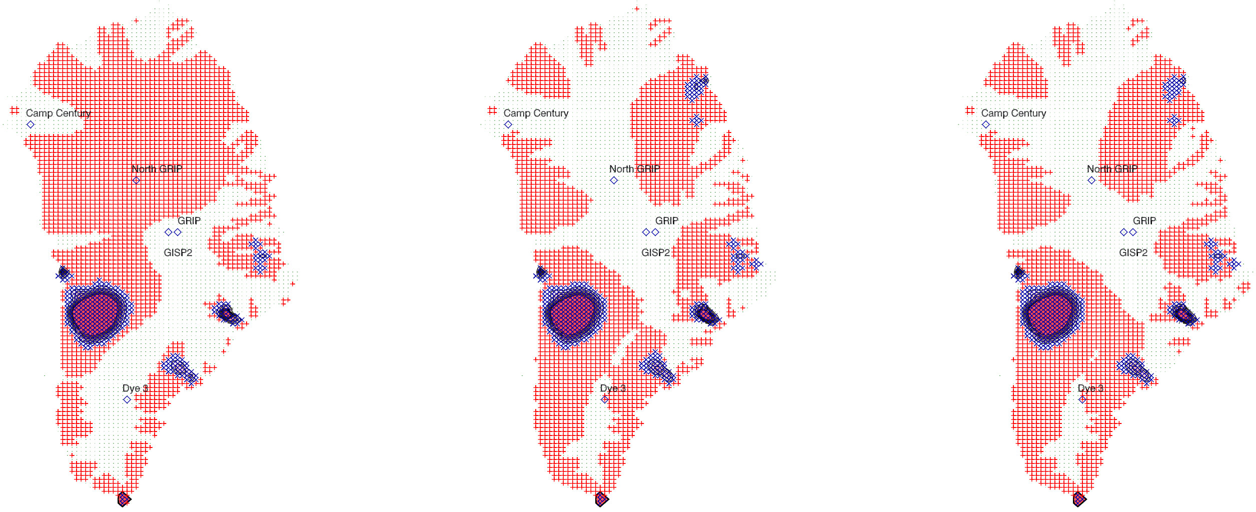

Figure 2.6: Results from first model runs, constant mass balance forcing. Basal conditions at the end of 100.000 years, left the reference, middle from model 4 and right from model 5. Red pluses indicate grid points that are at melting point, blue crosses grid points where there is a temperate layer, contours with interval of 1 m indicate thickness of the temperate layer. Location of the boreholes is shown.

drops for the model 4 run after about 20.000 years the temperature is about -4.5řC even though the difference in geothermal heat flux is rather small, within 10-20 mW m^{-2}, compared to the much larger value for the reference run.

There is larger variation in the Basal frictional heat, it increases rapidly for the reference run, and to a higher value than the new runs. Then it drops and has the same value as the new model runs, for model period 6.000-12.000 years all 5 models have similar values and then they diverge again. The reference has the highest values, then model 5 and then model 4 (same order as the value for the geothermal heat flux), but what is interesting is that the difference is similar, despite less difference in geothermal heat flux. The value for model 5 is between 55 and 60 mW m^{-2} and the value for model 4 is between 50 and 55 mW m^{-2}, difference of 5-10 mW m^{-2}, the difference in basal frictional heating is 0.0002 W m^{-2} (2 mW m^{-2}), which is similar magnitude as the difference between model 5 and the reference (1.7 mW m^{-2}) even though the difference in geothermal heat flux is 90 mW m^{-2}. The basal frictional heating is therefore not very sensitive to the value of the geothermal heat flux. The magnitude of the basal frictional heating is sensitive to the thickness, the values at Camp Century and Dye 3 are about a magnitude higher than in the thicker part of the ice.

2.1.3 Area distributed results of the constant forcing experiment

- Basal conditions

  The basal conditions at the end of the constant 100.000 years model experiments for the reference run, model 4 smoothed and model 5 smoothed is shown in Figure 2.6. There are dots where the ice is frozen to bed, red pluses indicate the area where the temperature is at melting point and blue crosses where there is temperate ice, the thickness of the temperate layer is indicated with contour lines with 1 m interval. It is clear that the high geothermal heat flux under NGRIP has an influence over all the central part of the ice-sheet. Where there is freezing

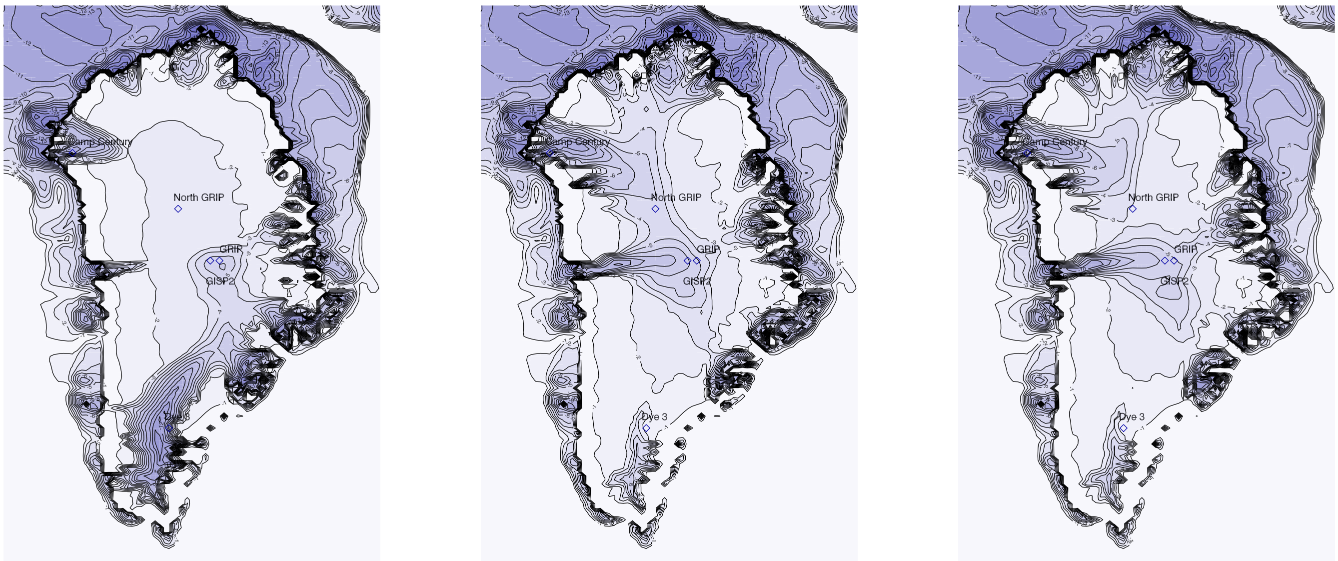

Figure 2.7: Results from first model runs, constant mass balance forcing. Basal temperature at the end of 100.000 years, left the reference, middle from model 4 and right from model 5. Location of the boreholes is shown.

conditions in the new model runs in the centre, there are melting conditions under mostly all of the central northern part. On the other hand there are freezing conditions in the southern part, where there is low geothermal heat flux under Dye 3 in the reference run. Interestingly the location, size and shape of the temperate ice is very similar for all model runs, both the reference and the new model runs, only slight difference in the absence of temperate ice at the northeastern coast. There is a large blob of temperate ice where Jakobshavn isbræ is on the west coast, and two blobs where Helheim and Kangerludsuak glaciers are flowing.

The temperature distribution in the lowest ice (cold) layer is shown in Figure 2.7, it reflects the temperate/frozen areas, which are dependent on the geothermal heat flux boundary. There are cold areas where the ice is frozen to bed and in the temperate areas the temperature is at pressure melting point. There are cold areas in the northwest for all 3 results, colder in the new model results, and also colder in the centre part of the ice sheet. In contrast there is cold ice beneath all the southern part of the ice sheet in the reference run, where there is very low geothermal heat flux, but the ice is warmer in the new model runs.

Surface temperature is similar for all model runs (not shown), it drops down to -31řC in the central highest part. The lowest temperature is about -19řC in the new model runs on the southern dome and goes down to -21řC for the reference run. The geothermal heat flux at the basal boundary therefore evidently influences the surface temperature, where the ice is thinner.

The temperature in the bottom layer in the bedrock is an image of the geothermal heat flux distribution applied in the model runs. This is at 5km depth in the crust. In the reference run there is very high temperature, up to 200řC under the North-Grip area, under the Dye 3 area, the temperature in the bottom layer is only about 30řC. The new model runs have temperature range from 70-170řC and the pattern reflects the boundary condition. A question to ask is what is realistic temperature at this depth, it could be an additional constraint for the geothermal heat flux boundary condition.

The temperature in the top layer of the rock is the same as the basal temperature in the ice, it is the same grid point location.

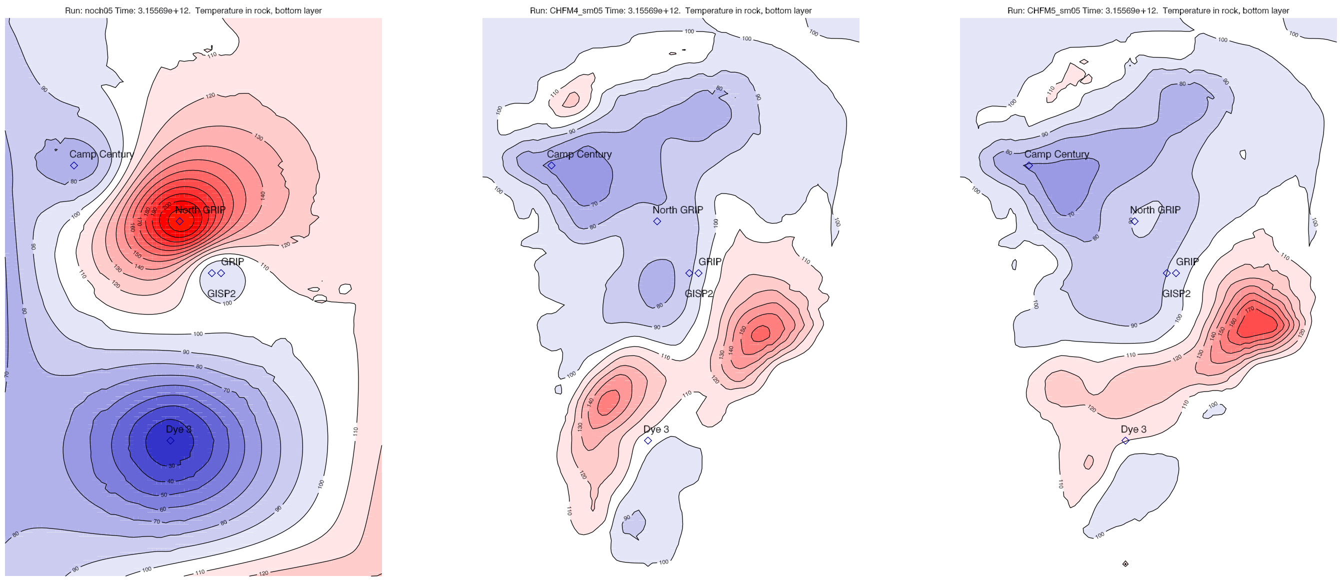

Figure 2.8: Results from first model runs, constant mass balance forcing. Temperature at the bottom of the bedrock matrix at the end of 100.000 years, left the reference, middle from model 4 and right from model 5. Location of the boreholes is shown.

- Other variables

  The surface elevation in all mode runs is similar, the maximum height at the main dome is above 3200 m, but the shape is slightly different. The elevation of the southern dome is higher for the reference run, where the heat flux is smaller than for the new model runs, it is above 2700 m in the reference, but above 2600 in the two new runs.

  The Bedrock elevation is similar as well, as the thickness is almost the same for all model runs. The areas below sea-level are strikingly similar for the reference and the new runs, so geothermal heat flux does not influence this field much.

  The comparison of the modeled present day ice sheet to the measured surface is shown in Figure 2.9. There are differences reflecting the different geothermal heat flux boundary condition. General pattern is that the central area of the ice sheet, the eastern part of the south dome and the area flowing towards the north west are too thin. The ice sheet is too thick at the east coast, on the west coast in the Jakobshavn region and towards south and on the northern coast. There are areas covered with ice that are ice free at present. This general pattern is the same for all model runs, indicating that the surface boundary condition (accumulation, temperature, melting) has probably larger role than the geothermal heat flux at the bed in shaping the ice sheet at the edges.

  The difference in the modelled bedrock elevation to the measured bedrock is also similar, reflecting that the elevation is similar, higher in the centre area, but lower in the areas where the ice sheet is too thick at the edges.

  Basal melt rate is similar for all runs (not shown), not clear why this is the case when the basal temperature is as different as shown in Figure 2.7, there seems to be only basal melt at the edges of the ice sheet, the large areas in the centre that are at melting point do not produce any melt water.

  The water drainage from the temperate layer is the same for all model runs, this is not surprising as the temperate layer is similar for all.

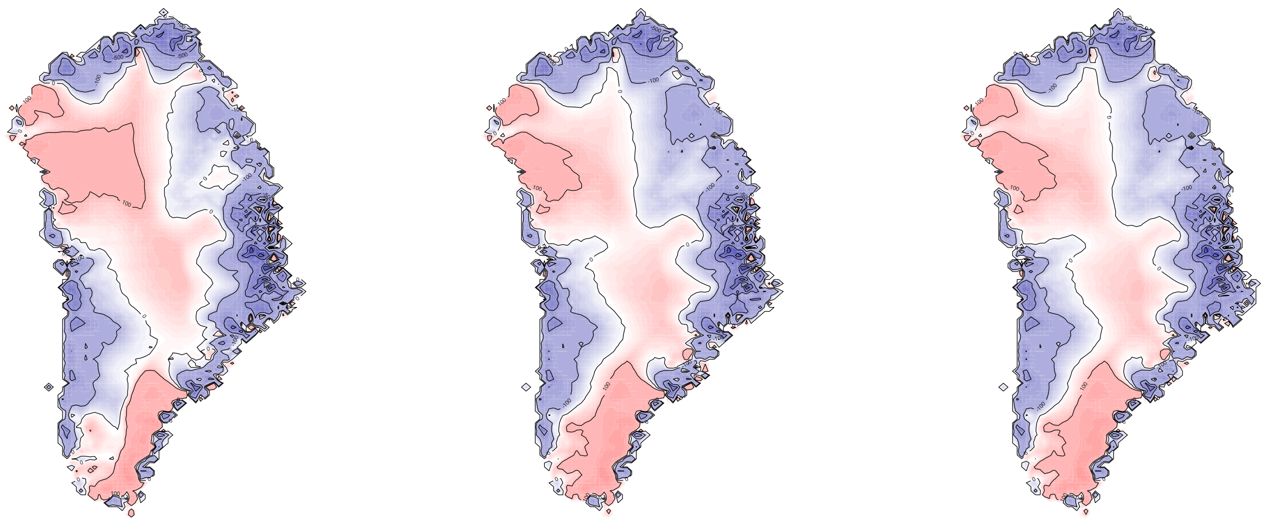

Figure 2.9: Results from first model runs, constant mass balance forcing. Difference between the modeled and the measured surface at the end of 100.000 years, left the reference, middle from model 4 and right from model 5.

The mass flux in x, vertically integrated v_x is also similar for all model runs, almost identical for model 4 and 5, but somewhat different for the reference run. The magnitude is similar and shape of the areas with higher mass flux is also the same.

Same story for mass flux in y, vertically integrated v_y it is almost identical.

Finally, the total mass flux, is naturally the same as this is the product fo the mass flux in x and y. This indicates that despite the differences in the geothermal heat flux, there is not a large change in the structure and dynamics of the ice sheet

2.2 Time dependent mass balance forcing

The above model experiments with constant mass balance forcing indicate that it takes a few thousand years to the Greenland Ice Sheet to settle to a state that is a result of the applied forcing. It is therefore necessary to spin the model up with realistic presentation of the previous climate history to achieve a good starting point for future predictions. In the model experiment discussed below, the spin-up, history and climate fields are the same as used by *Greve* (2005). The glacial index and sea level history shown in Figure 2.10 are used to determine the surface temperature and precipitation distribution over the ice sheet by interpolating between present and LGM conditions. The temperature is based on parameterization by *Ritz et al.* (1997) and precipitation map for present day is based on the digitized accumulation map by *Calanca et al.* (2000). The model run of *Greve* (2005) provides a reference, against which the new results can be tested. Below are the results from model experiments where both model 4 and 5, smoothed and unsmoothed versions were applied, this is for documentation, the unsmoothed version will not be used further, the results are very similar to the smoothed, but the field is unrealistically varying over the domain.

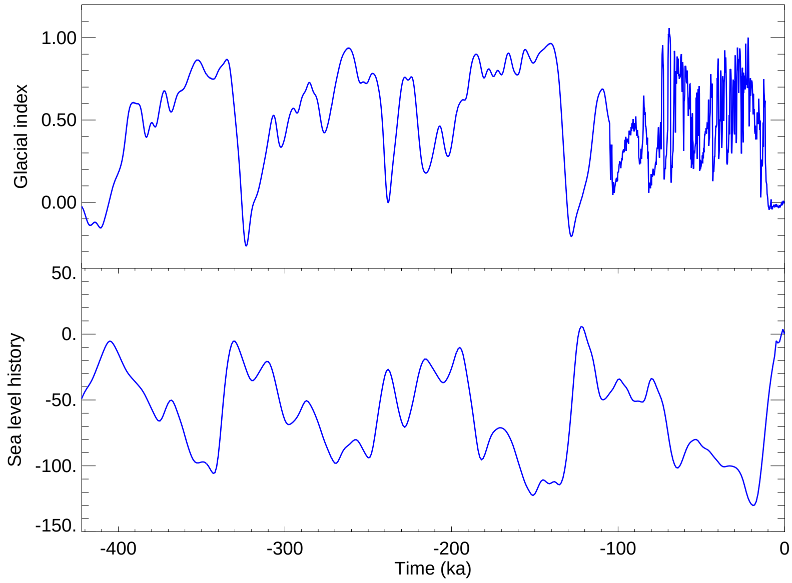

Figure 2.10: Glacier index and sea level history (same as in (*Greve*, 2005)) that are used to force the temperature and precipitation fields in the time dependent model runs.

2.2.1 Variables for the whole ice sheet

- Volume

  The new model runs have a larger volume throughout the time interval, this is to be expected due to the overall higher geothermal heat flux in the central part of the ice sheet. However, in the decreasing periods (-320.000 years and -125.000 years) the volumes merge and are the same for all model runs but the new runs turn around with larger volume than the reference run. The difference is almost constant through the first two ice age computations, but from ca. 100.000 until 20.000 years the volume is similar and then diverges again and the difference is approximately 0.1 10^6 km^3 at present. There is small difference between the 4 new model runs, the lines are basically on top of each other.

- Maximum ice thickness

  The new model runs have thicker ice sheet throughout the computation, almost constant 100-300 m thicker ice sheet, and at the end of the simulations the difference is close to 100 m, again all 4 new model runs are very similar.

- Maximum ice elevation

  For this variable the result is different, the reference run has higher values, until the last 10.000 years, then the new model runs are about 50 m higher. What is interesting is that the shape of the curves is not quite the same. At about -220.000 years there is a shift in the top of the curves, between the reference, that peaks earlier and the new model runs. The reference run is usually higher, but when there are peaks the new model runs shoot over and have higher values. There is also a difference, smaller though, between the smoothed model 5 run and the other new model runs. Elevation is generally higher for this model run, until the very end, where the unsmoothed model 4 run has the highest value. While the maximum ice thickness is

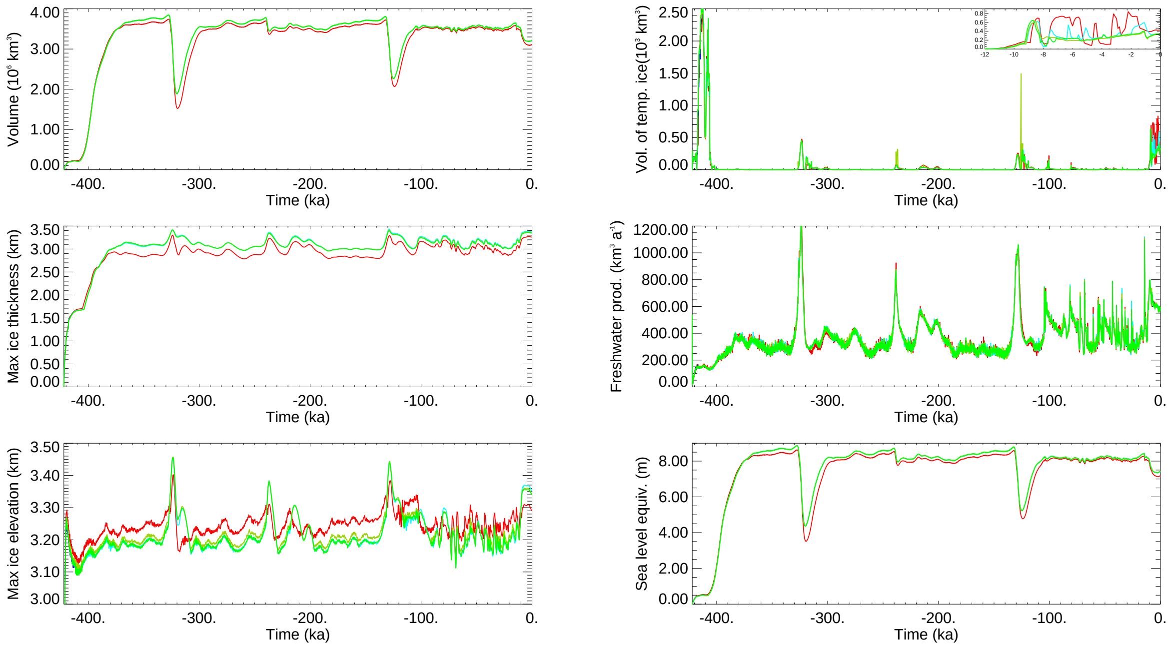

Figure 2.11: Results from model runs with time dependent mass balance forcing. Left: Volume evolution (10^6 km^3), Maximum thickness (km) and Maximum ice elevation (km) and Right: Volume of temperate ice (10^3 km^3), Freshwater production (km^3 a^{-1}) and Sea level equivalent of ice volume (m) for time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Light blue shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Light green shows CHMF 5 results, and Green CHMF 5 smoothed run.

consistently larger for the new model runs, the maximum ice elevation is higher for the reference, except when the elevation increases, then the new runs are higher.

- Volume of temperate ice

  The volume of temperate ice is generally the same for all model runs throughout the computation except the last 10.000 years, which is shown in the inset. The reference run has larger and more variable temperate ice volume. All models runs are fluctuating more than before during the Holocene. A few times the unsmoothed model 5 run shoots up (at -235.000 years and -125.000 years). The geothermal heat flux appears to have large influence on this variable, only at the end of the model run. This may need to be further investigated.

- Freshwater production

  This variable has similar values for all 5 model runs, shape, tops of curves and rapid changes are identical. It appears to be sometimes larger variation for the reference model run, but most of the time the curves are on top of each other.

- Sea level equivalent of ice volume

  This is the same curve as the ice volume, the new model runs have larger volume throughout the simulation.

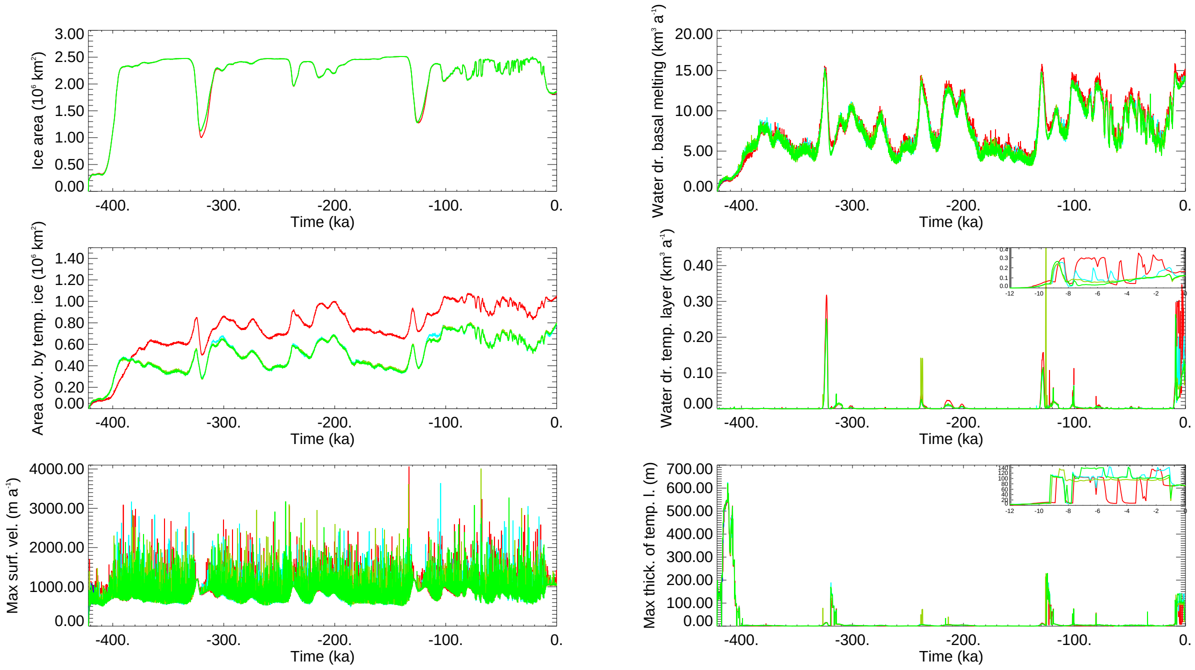

Figure 2.12: Results from model runs with time dependent mass balance forcing. Left: Ice area (10^6 km^2), Area covered by temperate ice (10^6 km^2) and Maximum surface velocity (m a^{-1}). Right: Water drainage due to basal melting (km^3 a^{-1}), Water drainage from temperate layer (km^3 a^{-1}) and Maximum thickness of temperate layer (m) for time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Light blue shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Light green shows CHMF 5 results, and Green CHMF 5 smoothed run.

- Area covered with ice

  This curve is similar for all 5 model runs, it is only during the two retreats at -320.000 years and -123.000 years, that the reference run has smaller area (by approximately 10%), but otherwise the curves are all on top of each other.

- Area covered by temperate ice

  For this variable there is the largest difference, and this is due to the large heat flux under N-GRIP, the whole central part of the northern ice sheet is temperate in the reference run, as opposed to frozen to the bed as it is in the new model runs. The difference is substantial. For the reference run the area covered by temperate ice is 1.05 10^6 km^2 and for the new model runs the area is 0.8 10^6 km^2 or about 20% (comparing the two distributions, for model 4 and 5, it is clear that the area is not identical, even though the total is the same, there are some changes in the coverage, that are due to the different input).

- Max surface velocity

  This variable is varying rapidly, all 5 model runs have similar range in variation.

- Water drainage, basal melting

  This variable is also fluctuating within a similar range for all model runs. The reference run has somewhat higher values throughout the model run, but the new model runs are partly covering the same range, so the difference is not very large. At the end of the simulation the reference run has the highest value and is increasing.

- Water drainage temperate layer

  This variable has similar shape for all 5 model runs, but the unsmoothed model 5 and the reference run have some shootings up above the other results corresponding to the total volume of the temperate layer. The last 10.000 years show increased water drainage and larger fluctuation, the reference run has the highest value and largest range in fluctuation. The shape of the curves is the same as the total volume and therefore consistent with that.

- Maximum thickness of the temperate layer

  All 5 simulations have similar values, but the unsmoothed model 5 results seems to be shooting up above the other results as the volume and water drainage from the temperate layer show. The last 10.000 years show larger fluctuation similar to the water drainage and total volume. However, while the water drainage is largest for the reference run, the maximum thickness is the smallest.

2.2.2 Values at each borehole location

As before, a few values for each of the boreholes are written out during each model simulation; the thickness of the ice, surface velocity, basal temperature and basal frictional heating. These are plotted and discussed below.

- GRIP

  The geothermal heat flux at the GRIP location is similar for all the model runs, about 60 mW m^{-2} (60 mW m^{-2} for the reference run, 61.7 mW m^{-2} for CHMF 4, and 61.45 mW m^{-2} for CHMF 5.

  Despite slightly higher geothermal heat flux (less than 1%) for the reference run the ice thickness is smaller, it is constantly approximately 150 m thinner, but the shape of the evolution is the same. This thinner ice is probably caused by the enhanced geothermal heat flux in the reference run north of this location under N-GRIP, that has influence over larger area than just where the increased geothermal heat flux is. There is almost no difference in ice thickness evolution between the two new runs, smoothed and unsmoothed versions.

  The surface velocity is largest at the beginning of computations and during the warm periods at ca. -320.000 and -127.000 years. The reference run has generally about 1-2 m a^{-1} higher velocity, but during the speed up period in the warmer times the new model runs have larger increase. At the end of the model runs the velocity in the reference run is about 2 m a^{-1} (larger than in the constant forcing run which was about 1.3 m a^{-1}), CHMF4 has about 0.5 m a^{-1} and CHMF 5 about 0.2-0.3, which is opposite to the constant forcing, where CHMF 5 had larger velocity. The surface velocity increases during the warm period when thickness increases, and at the same time the basal temperature decreases and basal frictional heating increases.

  There is some differences in basal temperature between the model runs, the 2 unsmoothed model runs have higher temperature than the smoothed version and the reference run has the lowest. During the last 130.000 years the reference and the smoothed runs have similar values and are both at approx. -9řC at the end. The difference between the smoothed model runs and the reference is not constant. During the period of increasing temperature (after warmer periods) the reference runs is similar to the smoothed model runs, but when the temperature

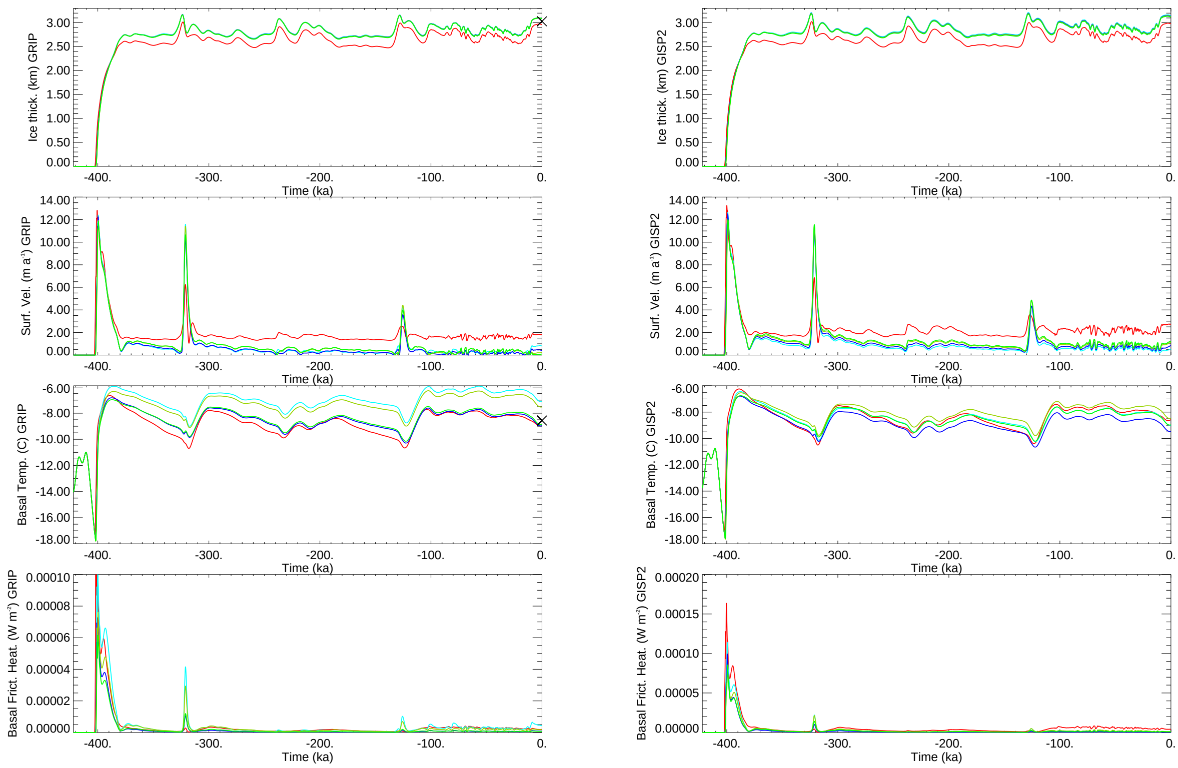

Figure 2.13: Results from model runs with time dependent mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for GRIP (left) and GISP2 (right) resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Light blue shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Light green shows CHMF 5 results, and Green CHMF 5 smoothed run. The crosses on the ice thickness and basal temperature plots indicated the measured values.

drops again the difference increases. However, during the 100.000 period at the end of the model runs the difference is smaller than at earlier time in the model runs. There is a time lag in the increased temperature, the maximum temperature after the interglacial periods is about 20-30.000 years after the warmest time so it appears that it takes some time for the warmer temperature to be advected towards the bed.

The frictional heating has large values at the beginning of the model runs and peak up at the same as the surface velocity. The value is small between the peaks but the last 100.000 years have more variations than other periods. There is not large difference between the various model runs, except that unsmoothed CHMF 4 has the highest value.

Comparison of the ice thickness and basal temperature at present is shown with a cross in the two plots.

- GISP2

The difference in geothermal heat flux at GISP2 is opposite to what it is at GRIP, it is slightly lower in CHMF 4 and 5 (57.78 and 59.17 mW m^{-2}, respectively) than for the reference run (60 mW m^{-2}))

The thickness difference is however the same, which indicates that the few mW difference between the heat flux in the model runs at this location does not affect the thickness as much as the nearby increased geothermal heat flux (up to 135 mW m^{-2}) beneath N-GRIP which apparently thins the ice in a large area.

Surface velocity at GISP2 is similar to the one at GRIP, the new model runs have increase during the warm periods. The difference at the end of the model run is different from GRIP, however, the reference run has higher velocity and CHMF 5 has larger velocity than CHMF 4.

The difference in basal temperatures between the model runs at GISP2 is smaller than at GRIP. The reference run has values that are between the new model runs. The unsmoothed runs have higher temperatures and at the end of the model runs the CHMF 4 has the coldest and reference the warmest (similar to the CHMF 5 unsmoothed run).

Basal frictional heating has similar values at GISP2 as at GRIP, except at the last 100.000 years the reference run has the largest values, and the peaks are not as large during the warmer period.

- Dye 3

  The geothermal heat flux at Dye 3 in the reference run is only 20 mW m^{-2}, but it is 57.8 mW m^{-2} in CHMF4 and 71.0 in CHMF 5.

  The ice thickness is constantly smaller for the new model runs, there is not a large difference between the model 4 and 5 runs despite the 12 mW m^{-2} difference in heat flux. The ice disappears during the two warm periods, but appears again and grows rapidly to previous values.

  Surface velocity has larger fluctuation than at the locations at the centre of the ice sheet. Large values are associated with thinning and thickening periods at then the variation is largest during the last 100.000 years and ends with higher values for the reference run.

  Basal temperature at Dye 3 is naturally lower for the reference run as the geothermal heat flux is much lower. There is also a difference between CHMF 4 and 5, but smaller than between the new and reference runs, which reflects the smaller difference in heat flux.

  Basal frictional heating is fluctuating at Dye 3, largest peaks are for decreasing and increasing ice sheet (before and after it disappears in the model runs). The new model runs have higher basal frictional heating than the reference run.

- Camp Century

  The difference in geothermal heat flux in the various model runs is small at Camp Century, in the reference run it is 50 mW m^{-2}, it is 46.7 mW m^{-2} in CHMF 4 and 47.5 mW m^{-2} in CHMF 5

  The ice thickness is similar for all model runs here, the ice disappears during the warm period at ca. -320.000 years, but only decreases in the second warming at -127.000 years. It is then decreasing again during Holocene.

  The surface velocity has large fluctuation at Camp Century, the values and range of fluctuation is similar for all 5 model runs

  There is larger spread in basal temperature between the 5 model runs at Camp Century than at Dye 3, even though the heat flux difference is smaller. The warmest temperature is for the reference run and coldest for the unsmoothed model runs. The difference decreases during period when the temperature is increasing.

  The basal frictional heating at Camp Century is small except during periods of warmer temperatures and it increases at the end of the model experiments.

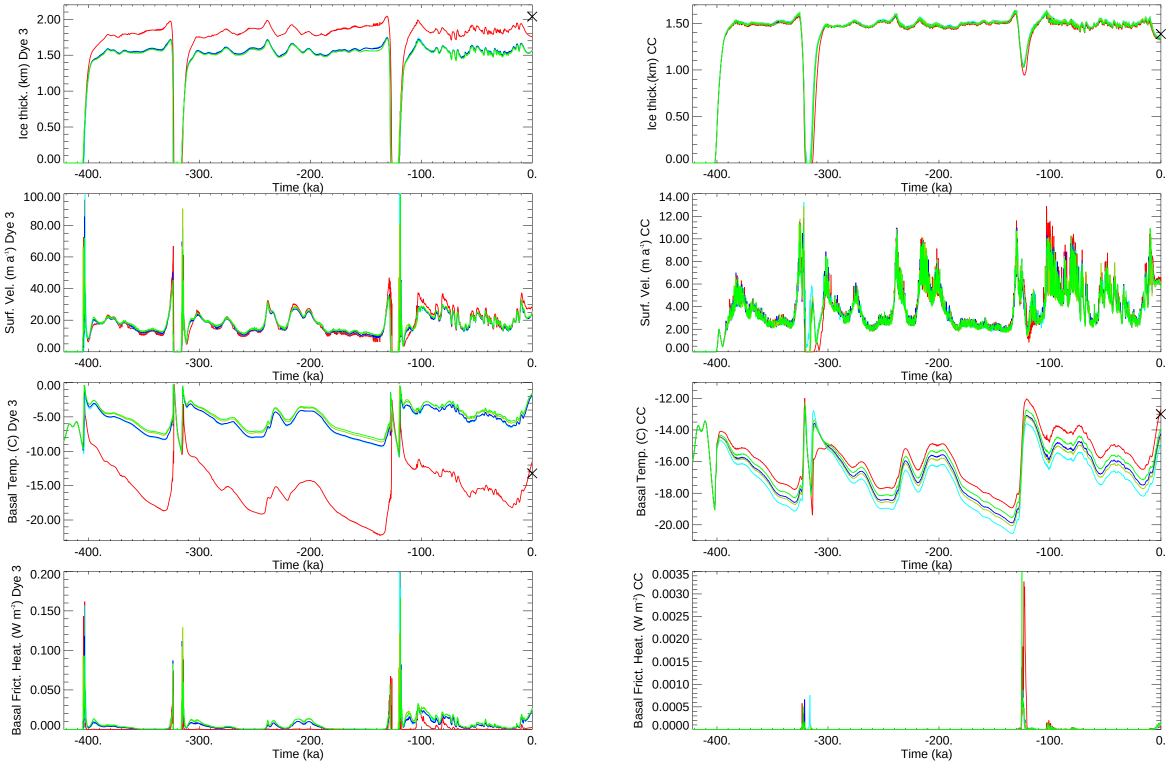

Figure 2.14: Results from model runs with time dependent mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for DYE3 (left) and Camp Century (right) resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Light blue shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Light green shows CHMF 5 results, and Green CHMF 5 smoothed run. The crosses on the ice thickness and basal temperature plots indicated the measured values.

- NGRIP

  The largest difference in geothermal heat flux between the model runs is at NGRIP, in the reference run the value is 135 mW m^{-2}, it is 53.51 mW m^{-2} in CHMF 4 and 59.40 mW m^{-2} in CHMF 5.

  The ice thickness in the reference run is constantly smaller than in the new model runs, which have similar values throughout the model experiment. All 5 model runs have similar variation throughout the experiment.

  The surface velocity is largest for the reference run, about 2 m $a-1$, or more throughout the model experiment. There is increase in velocity during the warmer periods, but not as large fluctuations as seen in the Camp Century time series.

  The basal temperature at NGRIP is at pressure melting point during most of the reference model run, but it is colder for the other runs. There is quite large temperature difference between CHMF 4 and 5 even though the difference in geothermal heat flux is less than 10 mW m^{-2}. This indicates that the threshold for getting temperatures up to pressure melting point lies close to this value and for CHMF 4 the temperatures are cold (-6řC).

  There are relatively high basal frictional heating values for the reference run at NGRIP compared to the other runs. CHMF 5 has highest values of the new runs which indicates that

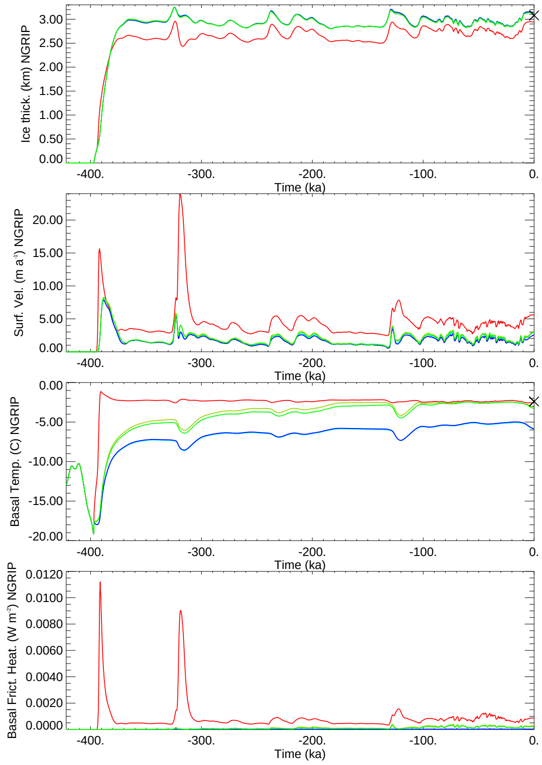

Figure 2.15: Results from model runs with time dependent mass balance forcing. Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for NGRIP resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Light blue shows results from model CHMF 4, Blue shows CHMF 4 smoothed run, Light green shows CHMF 5 results, and Green CHMF 5 smoothed run. The crosses on the ice thickness and basal temperature plots indicated the measured values.

since CHMF 4 does hardly have any frictional heating that just between the two geothermal heat flux values there is a threshold reached.

3. Sensitivity to variations in geothermal heat flux

To test sensitivity of the model to the geothermal heat flux input and assess the impact which changes in the geothermal heat flux have on the model output, a series of time dependent model runs were done and the model outputs were compared. The reference run is the same as before, from (*Greve*, 2005). The geothermal heat flux distribution from the magnetic field model CHMF 5 is used, and to test the sensitivity of the results to the geothermal heatflux this distribution was varied by $\pm 30\%$. In addition, a combination of the reference geothermal heat flux, which was created by fitting the basal temperature with measurements at the 5 boreholes locations, and CHMF 5 was created. This combination uses CHMF 5 as background and includes high heat flux in the area of NGRIP, the area is however smaller and more confined to the area of NGRIP, and low heat flux around Dye 3, also smaller area with lower heat flux than in the reference, as the borehole measurements indicate. The five geothermal heat flux distributions are shown in Figure 3.1, and a discussion of the model results coming from applying these different distributions follows.

3.1 Variables for the whole ice sheet

- Volume

  The total volume of the ice sheet is sensitive to 30% changes in the geothermal heat flux, there is about 10% variation in the total volume for this change in geothermal heat flux. It is not as sensitive to the changes between CHMF 5 and the combination heatflux, there is only a small difference in total volume between these two and the reference run. The difference is smaller in the most recent glaciation than in the previous one. At present, the difference between the reference and the combination run is 3%, between the CHMF 5 and 30% decreased geothermal heat flux is 7% and between CHMF 5 and 30% increased geothermal heat flux it is -10%.

- Maximum ice thickness

  The maximum ice thickness shows similar pattern, the difference between all the model runs is nearly constant throughout the model experiment, but it decreases during the last glaciation period. The combination run and CHMF 5 have similar value, and the reference and plus 30% are similar, until Holocene, then the difference is slightly larger. The difference between CHMF 5 and plus 30% is smaller than between CHMF 5 and minus 30%, indicating that once the melting temperature has been reached the increase has less influence on the ice thickness.

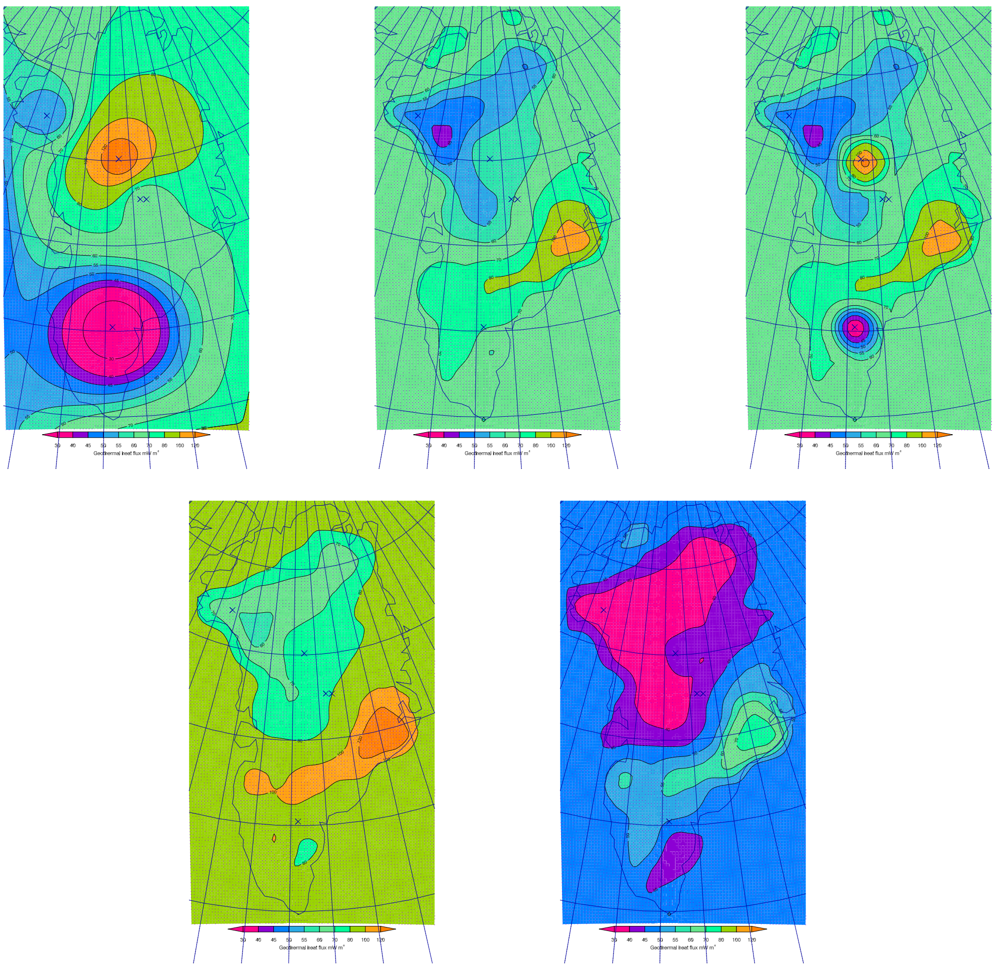

Figure 3.1: The five different geothermal heat flux distributions used as boundary condition in the model runs shown in Figs. 3.2- 3.6. From left top to right bottom: Reference (*Greve*, 2005), from CHMF 5, combination of the two, from CHMF 5 with 30% added to the geothermal heat flux value and CHMF 5 with 30% subtracted from the values.

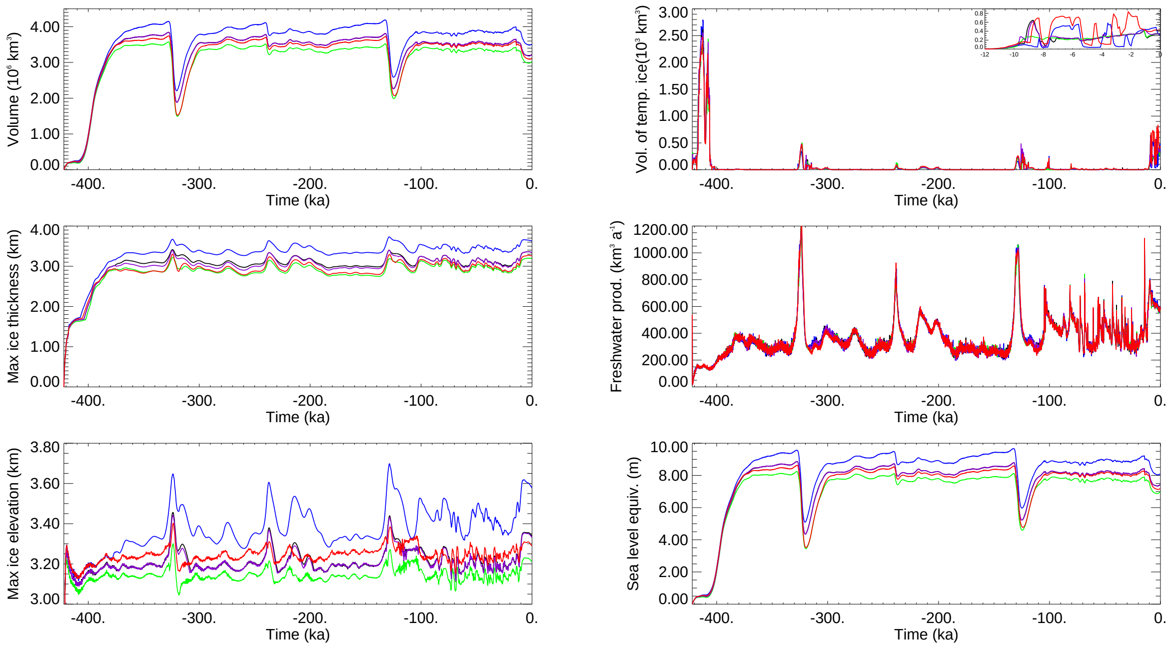

Figure 3.2: Results from sensitivity tests with time dependent mass balance forcing. Left: Volume evolution (10^6 km^3), Maximum thickness (km) and Maximum ice elevation (km) and Right: Volume of temperate ice (10^3 km^3), Freshwater production (km^3 a^{-1}) and Sea level equivalent of ice volume (m). Red is the reference run (*Greve*, 2005), black line shows results from model CHMF 5, blue line shows CHMF 5 with 30% lower geothermal heat flux, green line with 30% higher heat flux and the purple line is the result from the combination geothermal heat flux distribution.

- Maximum ice elevation

  The maximum ice elevation follows a similar pattern, the variation is parallel for the CHMF 5, combination and plus 30% geothermal heat flux, but the minus 30% shows larger fluctuations and the difference is also larger. At present day the difference between CHMF5 and plus 30% is 3.5% and between CHMF 5 and minus 30% is 7%. The reference run has generally higher ice elevation than CHMF 5 run, except during warm periods, then the CHMF 5 and the combination model runs increase max elevation. The reference run has lower ice cap throughout the Holocene, which is opposite to the period before.

- Volume of temperate ice

  The volume of temperate ice is similar for all model runs, except in the Holocene where there are larger differences. The reference run and the run with lower heat flux have large variation in the volume of temperate ice, while the other model runs have nearly constant value, all model runs converge to nearly the same value at present time.

- Freshwater production

  The freshwater production is similar for all model runs, it is varying at high frequency, but also increases considerably during the warmer periods. The largest variation is in the last 100.000 years and then the freshwater production decreases during Holocene.

- Sea level equivalent of ice volume

  The sea level equivalent of ice volume is the same curves as the volume of the ice cap.

- Ice area

  The ice area is almost the same for all model runs, there is only small difference during the warmer periods. The area is more sensitive to the changes during the last 100.000 years than the volume for example, showing larger variation. The area decreased during Holocene, but it increases slightly towards the end of the calculations.

- Area covered by temperate ice

  The area covered by temperate ice is clearly the variable that is most affected by the geothermal heat flux boundary condition. The largest area, and largest fluctuation is for the CHMF 5 plus 30%, then the reference run, the CHMF 5 and the combination are quite similar and smaller than plus 30% and the smallest area and smallest variation in area of temperate ice is observed in the minus 30% run.

- Maximum surface velocity

  The maximum surface velocity is fluctuating quite much, but the fluctuations decrease during the warmer periods and are relatively small during Holocene.

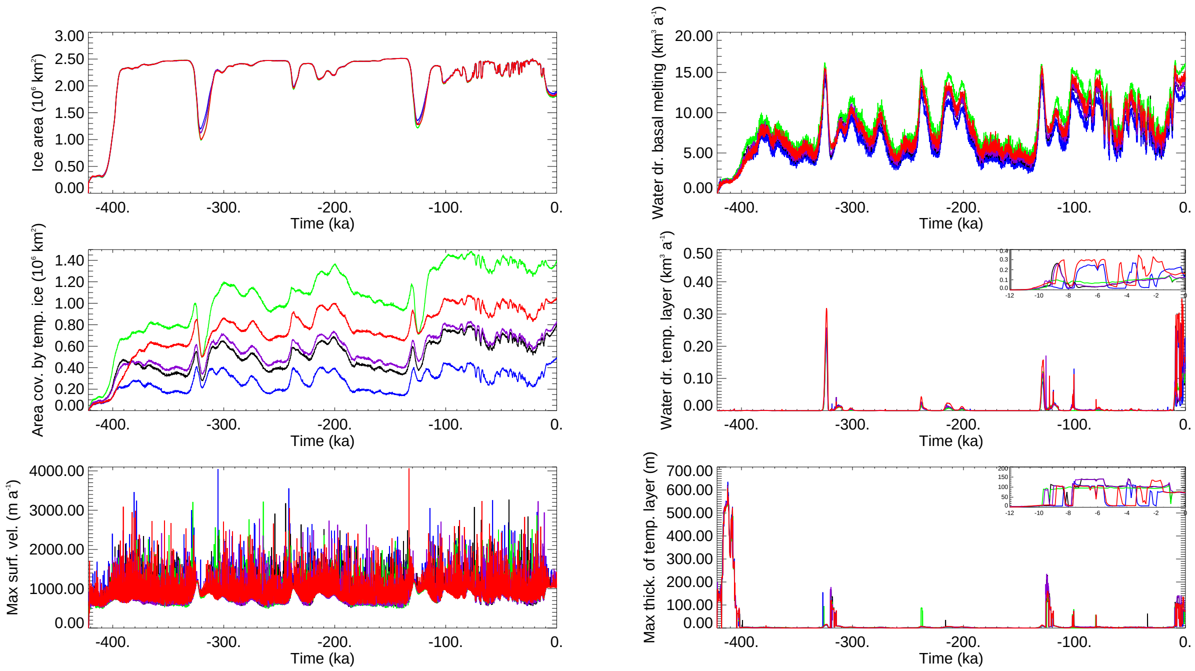

Figure 3.3: Results from sensitivity tests with time dependent mass balance forcing. Left: Ice area (10^6 km^2), Area covered by temperate ice (10^6 km^2) and Maximum surface velocity (m a^{-1}). Right: Water drainage due to basal melting (km^3 a^{-1}), Water drainage from temperate layer (km^3 a^{-1}) and Maximum thickness of temperate layer (m). Red is the reference run (*Greve*, 2005), black line shows results from model CHMF 5, blue line shows CHMF 5 with 30% lower geothermal heat flux, green line with 30% higher heat flux and the purple line is the result from the combination geothermal heat flux distribution.

- Water drainage, basal melting

  This variable is sensitive to the forcing and also to the geothermal heat flux, there is high frequency variation and clear peaks during warm periods. In the last 10.000 years of the model experiment this variable is increasing for all model runs.

- Water drainage temperate layer

  This variable has low values, except during warm periods and throughout the Holocene, where the fluctuation is also large. In the same manner as the variability in the volume of temperate ice, the water drainage from the temperate layer is also more variable for the reference and the lower geothermal heat flux runs.

- Maximum thickness of the temperate layer

  The maximum thickness of the temperate layer is largest in the buildup period when the ice sheet is thinnest, then there is increase during the warm periods, and again largest fluctuations in the Holocene, shown in the inset figure.

3.2 Variables at each borehole location

The model results at each of the ice core locations are discussed below, the measured values of basal temperature and the thickness of the ice can be compared with the model results. In the reference run (*Greve*, 2005) the basal temperature is used to tune the model, by changing the geothermal heat flux until a fit is obtained. The match is therefore expected to be very good for the measured basal temperature (shown with a cross in the Figures 3.4- 3.6) and the reference run result. The validation of the result can be obtained by comparing the modelled and measured ice thickness. The values of the geothermal heat flux at the bed of each of the ice core locations is given in Table 3.1 and the comparison of the ice thickness (H) and basal temperature (T_b) is shown in Table 3.2.

(mW m^{-2})	GRIP	GISP2	NGRIP	Camp Century	Dye 3
Ref.	60		135	50	20
CHMF 5	61	59	59	48	71
Comb.	61	59	114	48	37
5 +30%	80	77	77	62	92
5 -30%	43	41	42	33	50

Table 3.1: Comparison of the values of geothermal heat flux (mW m^{-2}) for the GRIP, GISP2, NGRIP, Camp Century and Dye 3 ice-core locations for each of the model runs.

- GRIP

  The difference in geothermal heat flux between the main runs is small, but as noted above the influence of the higher geothermal heat flux at the NGRIP location can be seen in the reference run which has constantly thinner ice at the GRIP location.

  The thickness is quite sensitive to the forcing and it increases during warm periods, when the surface accumulation increases in the forcing. The 30% change in geothermal heat flux has considerable influence and the thickness decreases by 184 m (6%) with 30% higher heat flux and increases by 308 m (10%) with 30% lower geothermal heat flux. The fit to the measured ice thickness is improved slightly when using the CHMF 5 or the combination (1.3% too thick, compared to 2.2% too thick with the reference run). It is interesting that the thickness seems to

Sim.	GRIP		GISP2		NGRIP		Camp Century		Dye 3	
	H	T_b	H	T_b	H	T_b	H	T_b	H	T_b
	km	°C	km	°C	km	°C	km	°C	km	°C
Obs.	3.029	-8.56			3.080	-2.4*	1.387	-13.00	2.037	-13.22
Ref.	2.963	-8.82	2.979	-8.57	2.941	-2.56*	1.325	-12.66	1.759	-11.47
CHMF 5	3.083	-8.85	3.120	-8.97	3.119	-3.30	1.332	-13.89	1.563	-1.57
Comb.	3.070	-8.88	3.107	-9.09	3.074	-2.67	1.331	-13.90	1.654	-7.88
5 +30%	2.899	-2.52	2.928	-2.56	2.974	-2.59	1.231	-9.85	1.549	-1.35
5 -30%	3.391	-17.04	3.413	-16.89	3.407	-11.47	1.446	-18.04	1.616	-4.86

Table 3.2: Comparison of Observed and simulated ice thicknesses and basal temperature for the GRIP, GISP2, NGRIP, Camp Century and Dye 3 ice-core locations.

be affected not only by the value at the location but also by the surrounding geothermal heat flux. This can be seen in that the reference run, which has nearly the same geothermal heat flux as the CHMF 5 run has thickness that is closer to the 30% higher value. So the relatively large area that has high geothermal heat flux north of this are (around NGRIP) in the reference run draws the elevation down as much as the 30% raised values of CHMF 5 (green line in Figure 3.4). The smaller area around NGRIP with higher geothermal heat flux in the combination run, does not affect the thickness as much. The basal temperature is not affected as much, the temperature for the reference run, the CHMF 5 and the combination run is similar even though the thickness is different. The ±30impact on the basal temperature. It comes out that the pattern of geothermal heat flux in the surrounding areas will influence the ice thickness, but the value at the location impacts the basal temperature.

The surface velocity is constantly higher for the reference run and increases during the warm period when the ice thickness increases, it increases, however, more for the new model runs than for the reference run. Both the plus and minus 30% model runs have higher velocity than the CHMF 5 and the combined run, even though in one case the ice is thinner, so it seems like that not only the thickness, but also the basal temperature influences the surface velocity here.

The basal temperature is sensitive to the geothermal heat flux, the 30% increase and decrease change the temperature by 6.3°C and 8.2°C, respectively. The similar geothermal heat flux values (reference run, CHFM 5 and Combination run) give basal temperatures close to the measured one.

The basal frictional heating is largest for the increased geothermal heat flux (not shown it is about a magnitude larger and the variation is also a magnitude larger, so the increased geothermal heat flux does have a large influence on the basal frictional heating, once it has reached a certain threshold) and it is zero for the decreased run. The value is larger for the reference run, about twice the value compared to the CHMF 5 and combined runs, but during the warm period the increase for these is larger than in the reference run. The difference is also larger during the last 100.000 years, than before the Eemian period.

- GISP2

  The results at GISP ice core locations are very similar to the results at GRIP, the same variance and differences. To show how much larger the frictional heating of the increased geothermal heat flux is, it is shown for GIPS2, in the lowest figure.

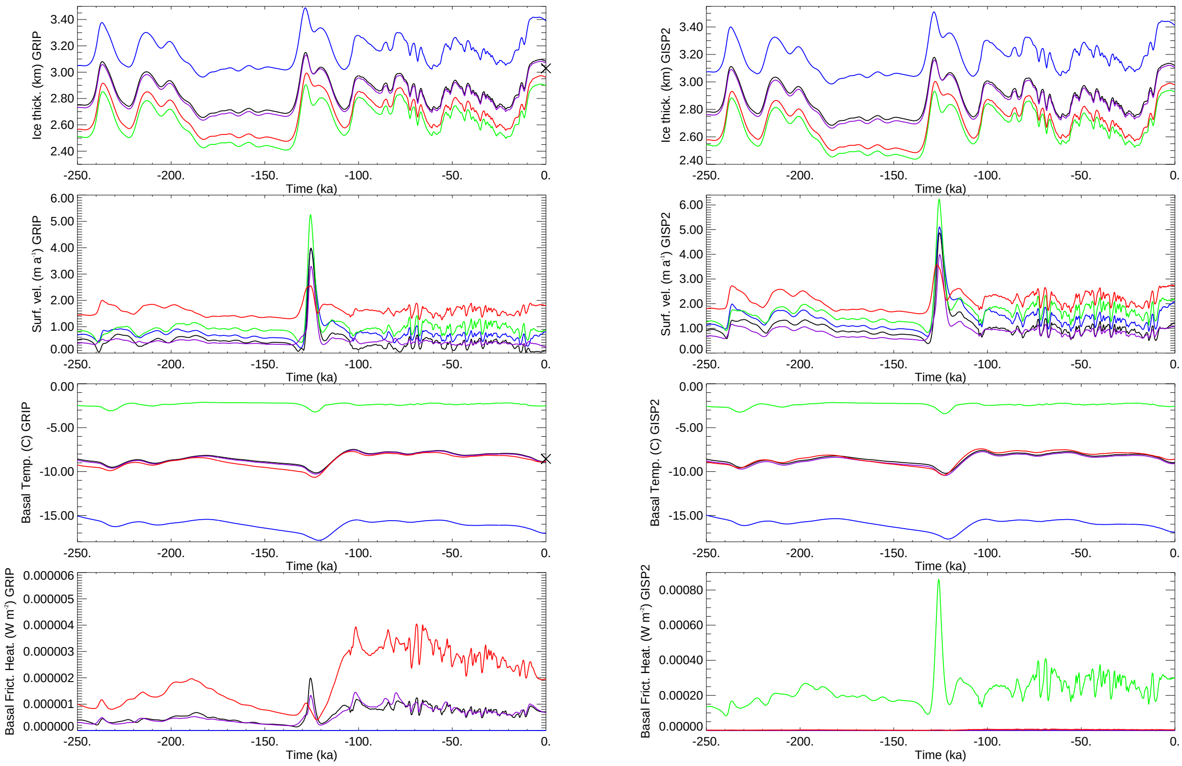

Figure 3.4: Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for GRIP (left) and GISP2 (right) resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Black shows CHMF 5 results, Green CHMF 5 +30%, Blue is CHMF 5 -30% and purple is the combination run.

- Dye 3

  There is a large difference between the geothermal heat flux for this ice core location. The reference run has been tuned such the basal temperature is matched with the observation and that results in a very low geothermal heat flux in this area (20 mW m^{-2}) (*Greve*, 2005). The combination run uses a lower value than the CHMF 5 (37 mW m^{-2} compared to 71 mW m^{-2}). The resulting basal temperature and ice thickness reflect these different inputs.

  The ice thickness at Dye 3 is sensitive to the geothermal heat flux. The sensitivity is larger when lowering the geothermal heat flux, than raising it. Increasing the geothermal heat flux by 30% (green line) does not have as large influence as decreasing it by 30% (blue line). The difference between the model runs is smaller after the Eemian period than before. Decreasing the geothermal heat flux clearly forces the thickness to become closer to the measured thickness, but it results in a very low value. The thickness is however still too small, the modelled ice cap is thinner than the measured, which partly can be explained by the model placing the ice divide wrongly. This indicates that a better constraint on the accumulation and ablation pattern in southern Greenland is needed, to get both the extent and thickness of the ice correct and the location of the ice divide correct. Until this has been achieved it is not possible to resolve whether the geothermal heat flux is really so low in this area. The ice disappears completely during the Eemian period and comes back again rapidly. There is however Eemian ice found in the ice core at this location, whether it has been formed there, or moved from higher location is not certain, but the disappearance of the ice during Eem may be due to wrong accumulation/ablation patterns in the model runs and needs to be further examined.

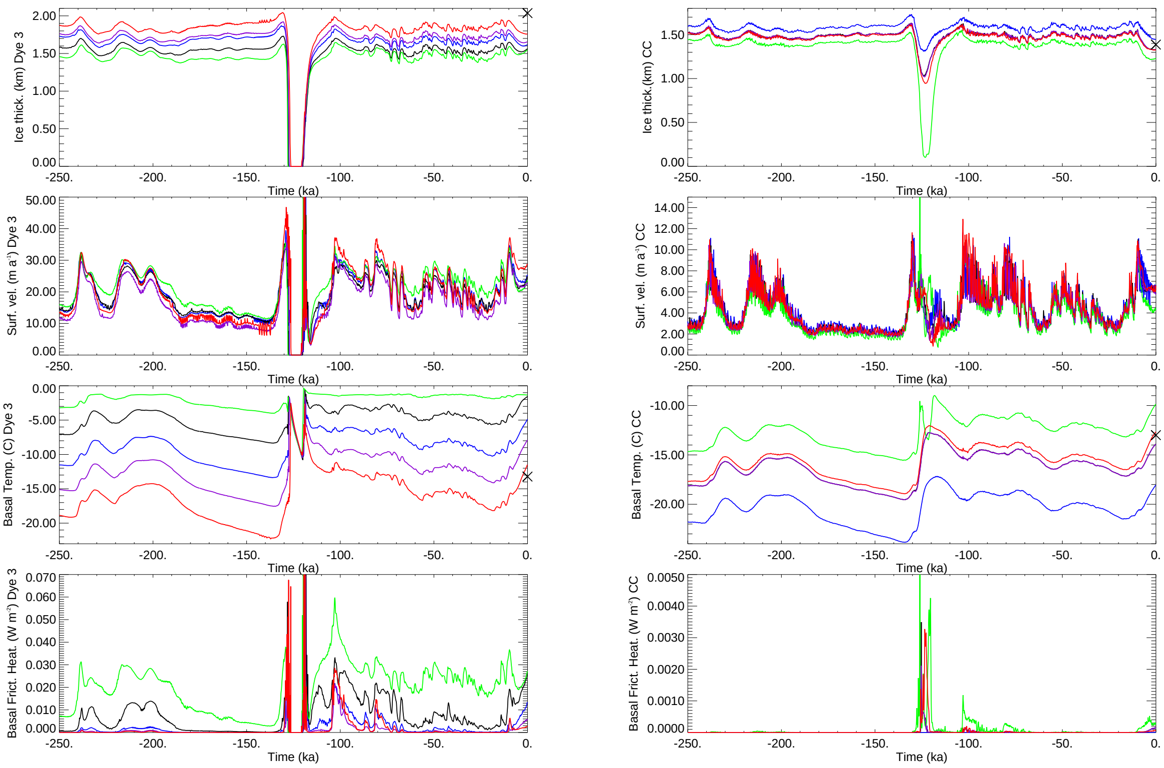

Figure 3.5: Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for DYE3 (left) and Camp Century (right) resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Black shows CHMF 5 results, Green CHMF 5 +30%, Blue is CHMF 5 -30% and purple is the combination run.

The surface velocity is similar for all model runs, it increases when the ice is thinnest, which may be explained by basal sliding, as the temperature is close to the melting point. The lowest velocity is for the combination run. The reference run is sometimes with the highest and sometimes with the lowest velocity, this difference must be due to a combination of effects.

The basal temperature is measured at -13°C, the reference run has such cold temperatures, but only because of the very low geothermal heat flux value. The higher heat flux values raise the temperature, the unchanged CHMF 5 run (and the 30% increased run) reaches melting point at the end of the simulation, the others have colder temperatures. The low basal temperature at Dye 3 is an issue which has to be looked more at.

Basal frictional heating is naturally largest for the increased geothermal heat flux, where the temperature can reach melting which induces basal sliding. During the period of rabid decrease and reappearance of the ice cap there are large values for all model runs. The difference is largest for the increased run and the others, which all have similar values.

- Camp Century

  The geothermal heat at Camp Century is nearly the same in all the model runs (see Table 3.1), the reference value, which fits the basal temperature best, is 50 mW m^{-2}, the CHMF 5 has value of 48 mW m^{-2}, and the combination run has the same value as no change is done in this location while constructing the combination distribution.

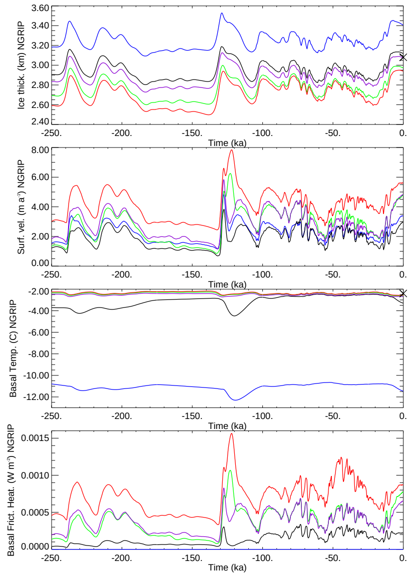

Figure 3.6: Ice thickness (km), Surface velocity (m a^{-1}), Basal Temperature (^{o}C) and Basal frictional heating (W m^{-2}) for NGRIP resulting from time dependent model runs through ice ages, glacier index and sea level history are same as in (*Greve*, 2005). Red is the reference run (*Greve*, 2005), Black shows CHMF 5 results, Green CHMF 5 +30%, Blue is CHMF 5 -30% and purple is the combination run.

The thickness at this core location shows sensitivity of up to 100-200 m for the 30% variation in the geothermal heat flux. The largest difference is during the Eemian period when the ice cap retreats in this area. It does not disappear completely during Eem, as it is modelled to do at Dye 3. The amount of thinning is sensitive to the geothermal heat flux, the ice cap almost vanishes entirely in this area with the increased heat flux, and the 2 mW m^{-2} difference between the reference and CHMF 5 results in about 50-100 m thinner ice at the maximum retreat. The thickness at present is slightly too thin for the reference and CHMF 5, but too thick for the decreased geothermal heat flux run, so the geothermal heat flux is likely to have value somewhere between these two. As at Dye 3 location, it is not possible to determine the heat flux until the surface boundary condition has been improved.

The surface velocity is fluctuating rapidly and has large changes during small thickness changes, the value is similar for all the five model runs.

The measured basal temperature is well simulated with the reference run and by lowering the heat flux as done in the CHMF 5 runs the temperature decreases by 1°C, the basal temperature is therefore shown to be sensitive to the applied geothermal heat flux.

Basal frictional heating has very low values (the temperatures are all cold in this location) but during the warm period when the ice thickness decreases the frictional heating increases and varies rapidly. During Holocene there is indication of increase during the recent past.

- North GRIP

  The largest difference between the geothermal heat flux value obtained with the ice sheet model by fitting to observations (*Greve*, 2005) and the values resulting from the geomagnetic measurements (CHMF 5) is at North GRIP. The very high geothermal heat flux is obtained by fitting the measured basal melting rate of 7 mm ice equiv. a^{-1} (*Dahl-Jensen et al.*, 2003), since the temperature is at pressure melting point and therefore non-determining for the geothermal heat flux. Several studies of the ice core at North Grip, using temperature measurements, isochrones in the core and ice flow modeling indicate that there is basal melting at this location and relatively high geothermal heat flux. A Monte Carlo-tuned model of the flow resulted in an estimate of 98 mW m^{-2} and basal melt rates of 2.7 mm a^{-1} (*Grinsted and Dahl-Jensen*, 2002). Including radio-echo sounding measurements this estimate was updated to basal melt rate at the NGRIP site of about 7.5 mm a^{-1} and variable geothermal heat flow between 50 and 200 mW m^{-2} along a 100 km modeled flowline (*Dahl-Jensen et al.*, 2003). Using both 1D and 2D flow models and Monte Carlo technique and combining the estimated basal melt rates with the observed borehole temperatures to translate the basal melt rates to geothermal heat flow values *Buchardt and Dahl-Jensen* (2007) estimate the variation along a 104 km long section of the ridge starting 82 km upstream from NGRIP and ending 22 km downstream to be 5.3-21.2 mm a^{-1} in basal melt rates and in geothermal heat flux the variation is 121-231 mW m^{-2}. The value for NGRIP is 129 mW m^{-2}. These large variations over short spatial scales indicate shallow source for the heat flux, which the method using the satellite magnetic measurements will not be able to resolve, as the whole section between the surface and the depth of the Curie temperature is considered as homogeneous material with constant conductivity.

The model runs presented in Figure 3.6 have the values 135 mW m^{-2} for the reference run, 59 mW m^{-2} for CHMF 5 and 114 mW m^{-2} for the combination run. The +30% increase from the CHMF 5 model is lower than the high value of the reference run (see Table 3.1).

The elevation evolution during the model simulations is similar as before, like for the other boreholes there is smaller difference during the last 100.000 years than before Eemian time, this is interesting and should be explored further. There is surprisingly small difference in thickness between the CHMF 5 model run and the combination run, even though the heat flux is almost twice as high in the combination run. It is relatively small area that has raised geothermal heat flux in the combination run. This is similar as was seen in the thickness evolution for GRIP and GIPS2 boreholes. The ice thickness of the reference run and the 30% increased geothermal heat flux is more similar even though the difference in heat flux is nearly twofold. The large area with increased heat flux in the reference run thins the ice in a large area (including GRIP and GISP2) more than the increase over smaller area in the combination run. This is the reason why the ice is thinner for the +30% run than for the combination run, even though the geothermal heat flux is higher for the combination run. This difference clearly demonstrates how important the geothermal heat flux is for accurate modeling of the the ice sheet thickness.

The surface velocity is also here (like at GRIP and GISP2 locations) not only dependent on the ice thickness. The reference run, with the thinnest ice, has the highest velocity, but probably most basal melt as it has the highest geothermal heat flux/basal temperature. Both + and - 30% runs have higher velocity than the CHMF 5 and the combination run has also higher velocity (higher than the -30% run), even though the ice is thinner for that run.

Basal temperature is at pressure melting point in all the model runs, except the CHMF 5 model run and -30%. It is therefore not only the basal temperature but also the basal melt that is matched to determine the geothermal heat flux for the reference run. It is interesting that for the -30% run which is frozen to the ground the velocity is higher than for the CHMF 5 run, which is also frozen, but not nearly as cold. Not sure if I understand how this is possible.

Basal frictional heating is largest for the reference run with the highest geothermal heat flux and there is no frictional heating for the -30% run which has cold bed. The combination run and the +30% run have similar frictional heating even thought there is quite a large difference in the geothermal heat flux value between these runs, larger than the difference between the CHMF 5 and +30%. The thickness is also more different than between the CHMF 5 and the combination run.

3.3 Area distributed results of the sensitivity experiment

Comparison of the basal temperature conditions for the different model runs reveals that there are significant differences, dependent on which geothermal heat flux distribution is applied with the model (Figure 3.7). The reference run, with the high geothermal heat flux underneath NGRIP and large surrounding area has most of the centre of Greenland at pressure melting point. There are cold ice tongues in the northwest and north and in the central southeastern part and to the south. Cold ice tongues reach the coast in numerous locations. The CHMF 5 results in cold central part, but melt conditions at the NE ice stream and also on the west coast and in most of the southern Greenland, except at the centre of the southern dome, where the ice is frozen to the ground. The bed is frozen in most of the northern part and around Camp Century, with a few areas of pressure melting point on outlet glaciers. The difference between the CHMF 5 and the combination run is that there is increased heat flux in the centre under NGRIP and lower under Dye 3. This is reflected in the basal temperature, in the result for the combination run the temperature has increased under NGRIP and there is larger area that has temperatures below freezing at the southern dome under Dye 3, but it is not as large as in the reference run. The location, shape and size of the temperate ice of any thickness is quite similar for all the model runs, indicating that the extra heat provided by the enhanced geothermal heat flux does not influence the extent of the temperate ice. It is created from enhanced deformation and frictional heating.

The temperature conditions beneath all the bore holes, except NGRIP, are below freezing for all the model runs. Note though that the 30% increase in geothermal heat flux results in pressure melting point beneath most of the ice cap, there are only areas close to the coast on the eastern side and a cold line north of Jakobshavn and around Camp Century in this model run. On the other hand, 30% uniform decrease in geothermal heat flux causes the whole central part of Greenland to have freezing conditions, there are only a few tongues at the coast and most of southwest coast, including Jakobshavn, that still have pressure melting point at the bed. Only available temperature measurements from the bed are these from the boreholes, which have been used to tune the geothermal heat flux in the reference model run. It is therefore impossible to validate these results against other measurements. Other model runs, for example results from Huybrechts (*Huybrechts*, 2006, Plate 80.2 in), show that using a constant geothermal heat flux of 50.4 mW m^{-2} have similar pattern of cold and warm base, as the reference run. It is cold in the centre of the southern dome and continuous band up northeast and towards west. There is difference in that most of the centre north area in the reference run is warm based, but Huybrechts has cold areas in the western side of the ice cap. The north eastern ice stream is warm based in both experiments. There is therefore not much that can be used to verify these results. However, one way to validate them is to compare the modeled ice thickness with the measured ice thickness, in a similar manner as Ralf Greve has done and above for each of the boreholes.

In Figure 3.8 the difference between the modeled and measured surface of each of the model runs is shown. This figure reveals the spacial distribution of the fit between the model and the measured surface. Note that the contours shown have uneven intervals, of 0, 100 m, 500 m, 1000 m, 1500 m and 2000 m. Blue colours show the area where the modeled ice sheet is too thick and red where the modeled ice sheet is too thin, compared to the measured ice sheet. The reference run has relatively good fit in the centre of the ice sheet, but the north west area, around Camp Century has too thin ice, more than 100 m too thin in large area. The northern most part of the ice sheet is too thick, however, and this is the case in all model runs. There is modelled ice in the far north where presently no ice is. This is area where it is very dry and possible that the forcing is not correct in this area. The central eastern and western coasts have too thick ice as well. These areas have too thick ice in all the model runs. The southern dome has somewhat shifted summit, as the western part is too thick and the

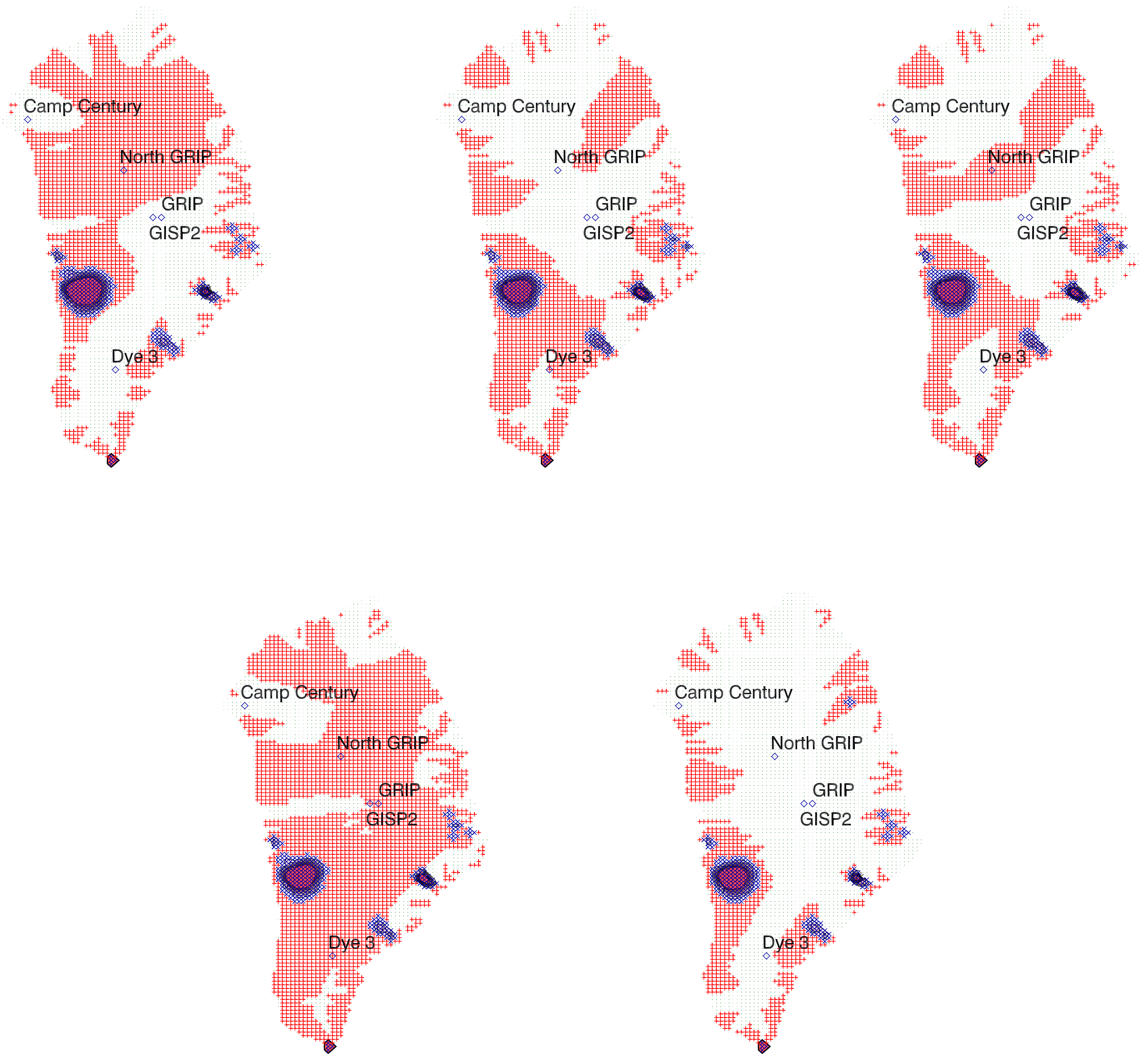

Figure 3.7: The resulting basal condition for the five sensitivity model runs with different geothermal heat flux distributions as boundary condition. Red pluses indicate points where ice is at pressure melting point and blue crosses where there is temperate ice above (contours indicated thickness, interval 1m). From left top to right bottom: Reference (*Greve*, 2005), from CHMF 5, combination of the two, from CHMF 5 with 30% added to the geothermal heat flux value and CHMF 5 with 30% subtracted from the values.

eastern part is too thin. The comparison of the CHMF 5 model run and the measurement has similar pattern, the northern most part of the ice sheet and the central eastern and western part have too thick ice, the ice is more than 100 m too thick in the northeast. The whole southern dome is too thin and also the areas north and south of Camp Century. For the combination run the fit improves somewhat in the NGRIP area, but the areas with too thin and too thick ice are similar as before. The comparison of the $\pm 30\%$ runs with the measurements show that the geothermal heat flux influences the thickness of the ice sheet significantly, the ice sheet becomes too thin or too thick, but there are some areas that do not change the sign despite the large variation in the geothermal heat flux. The areas furthest north, and on the central east and west coast are too thick in all model runs, more than

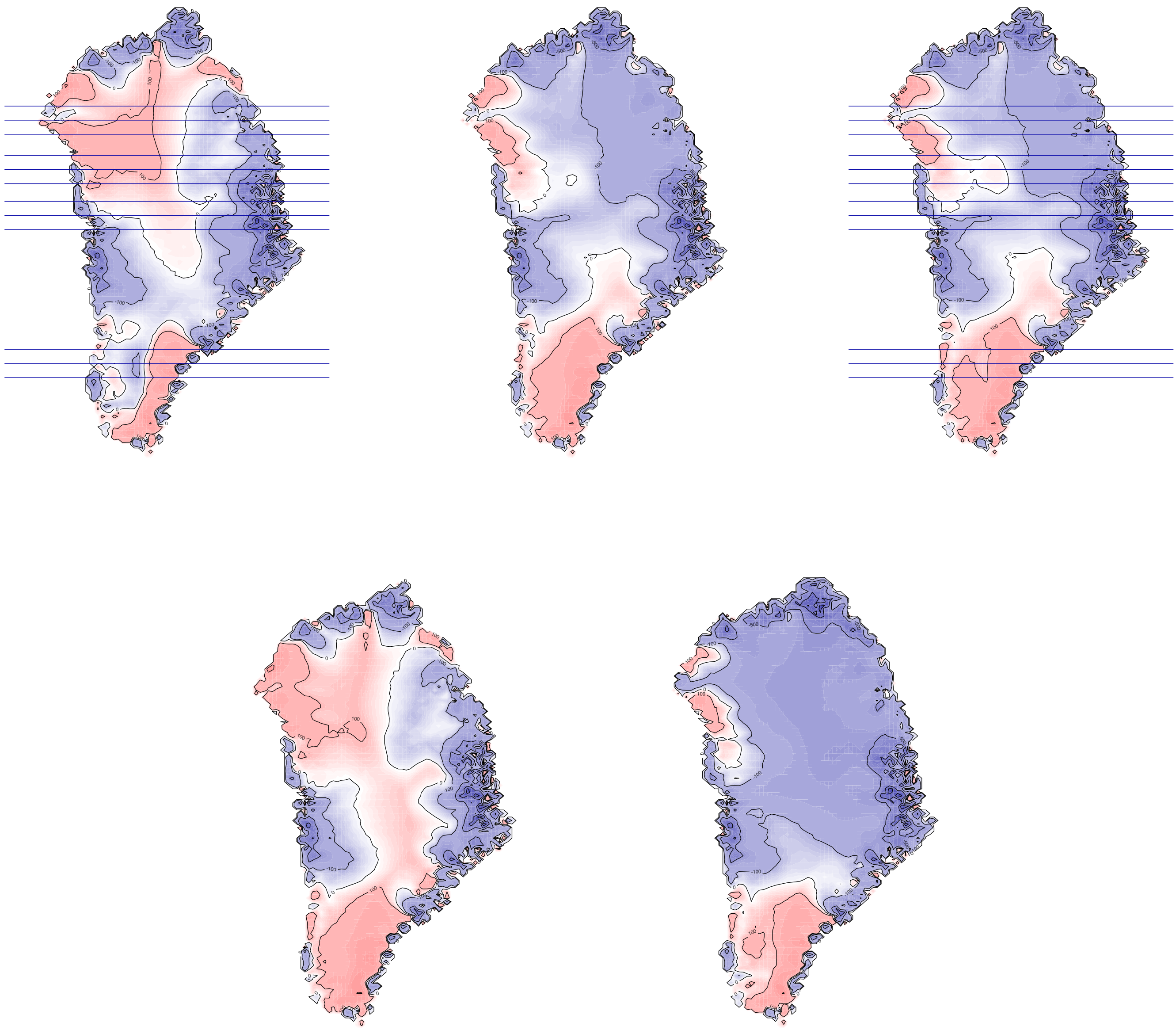

Figure 3.8: Difference in surface elevation (Measured-Modelled) for the same model runs as before. Blue areas show locations where the modeled ice sheet is too thick and red where the modeled ice is too thin (note uneven contour intervals: 0, 100 m, 500 m, 1000 m, 1500 m, 2000 m). From left top to right bottom: Reference (*Greve*, 2005), from CHMF 5, combination of the two, from CHMF 5 with 30% added to the geothermal heat flux value and CHMF 5 with 30% subtracted from the values. The lines on the reference and combination run plots indicate the location of the cross sections shown in Figures 3.9– 3.12
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500 m too thick in some areas. On the other hand, the southern dome and the area on the north west coast, south and north of Camp Century are too thin in all the model runs. The quality of the fit can be assessed by taking the average or the root mean square (rms) of the difference in each ice covered point. The reference model has average difference of -73.5 m and rms of 266.7 m. The CHMF 5 model has average difference of -112.5 m and rms 283.6 m. The combination model has average difference of -110.8 m and rms of 281.5 m. The overall fit to the measured surface does thus not improve when using the new geothermal heat flux distribution. However, as can be seen there are

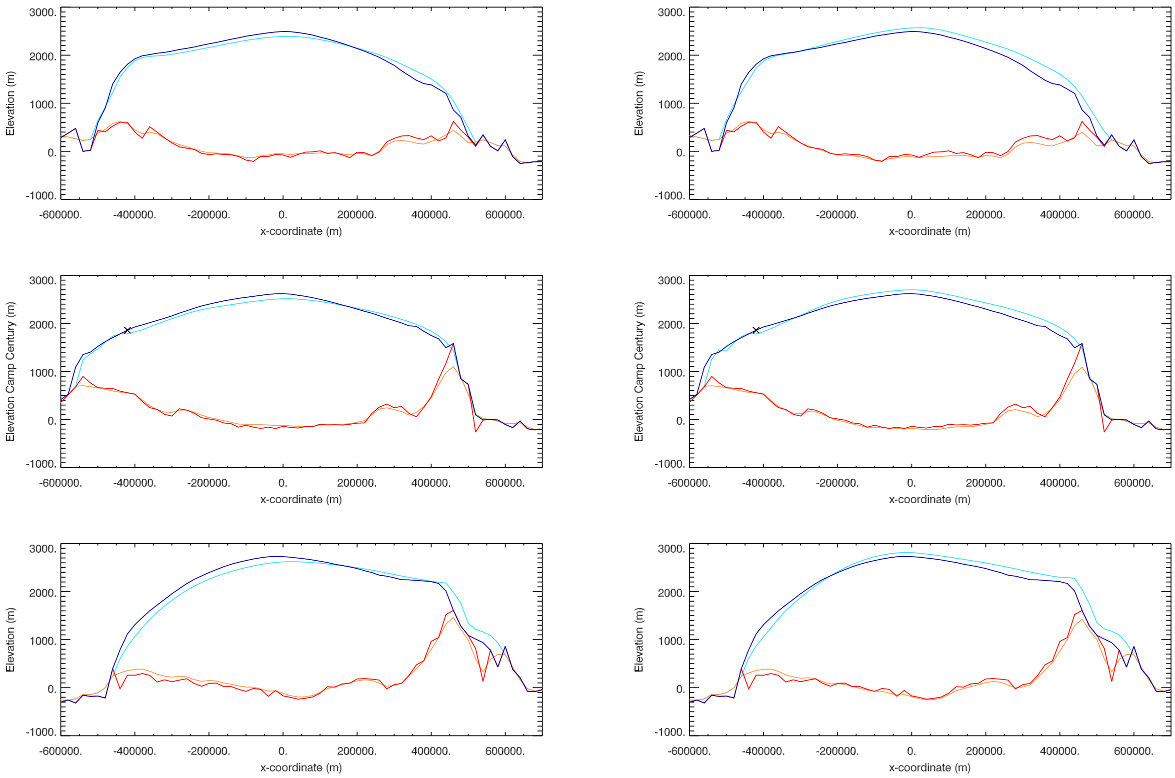

Figure 3.9: Cross section through bedrock and ice sheet at the latitude close to Camp Century. The location of these cross sections is shown with lines in Figure 3.8. The measured bedrock and surface topography is shown with read and blue colours and the modeled result is shown with orange and light blue. Left figures show results from the reference run (*Greve*, 2005), and right figures from the combination run. The location of the core is shown with a cross in the centre figure, note however, that the closest grid point is shown, not the actual core location.

some areas that improve and other that are further away from the measured surface. In these model runs the surface mass balance has been computed with parameterized temperature and precipitation, the pattern of misfit may change when using the output from the climate model.

To obtain a better view of the comparison between the reference run and the combination run with the measured surface a few cross sections are drawn. The location of the cross sections are shown with lines in Figure 3.8. Three lines for each ice core location are drawn, one on the grid line closest to the core location and the two others are 4 grid points north and south of the centre one.

Figure 3.9 shows the cross sections around Camp Century. The modeled ice sheet with the reference geothermal heat flux is too thin on the western side and in the ice divide area, but too thick on the eastern side. The combination run has slightly better fit on the western side, with the ice sheet, however, too thin compared to the measured surface. The ice divide area has too thick ice and also the eastern side. The fit is similar for both models (the value of the geothermal heat flux is similar) at the borehole location, in both cases about 60 m too thin (62 m for the reference run and 56 m for the combination run) The combination run has larger area with lower geothermal heat flux, which contributes to the thicker ice in the centre, but it appears that it is possible that even lower heat flux around Camp Century is necessary to improve the fit. In the ice divide area the heat flux needs to be between the reference run (which in the centre is influenced by the high heat flux at NGRIP) and the combination run. On the east coast there is large difference in the geothermal heat flux (higher heat

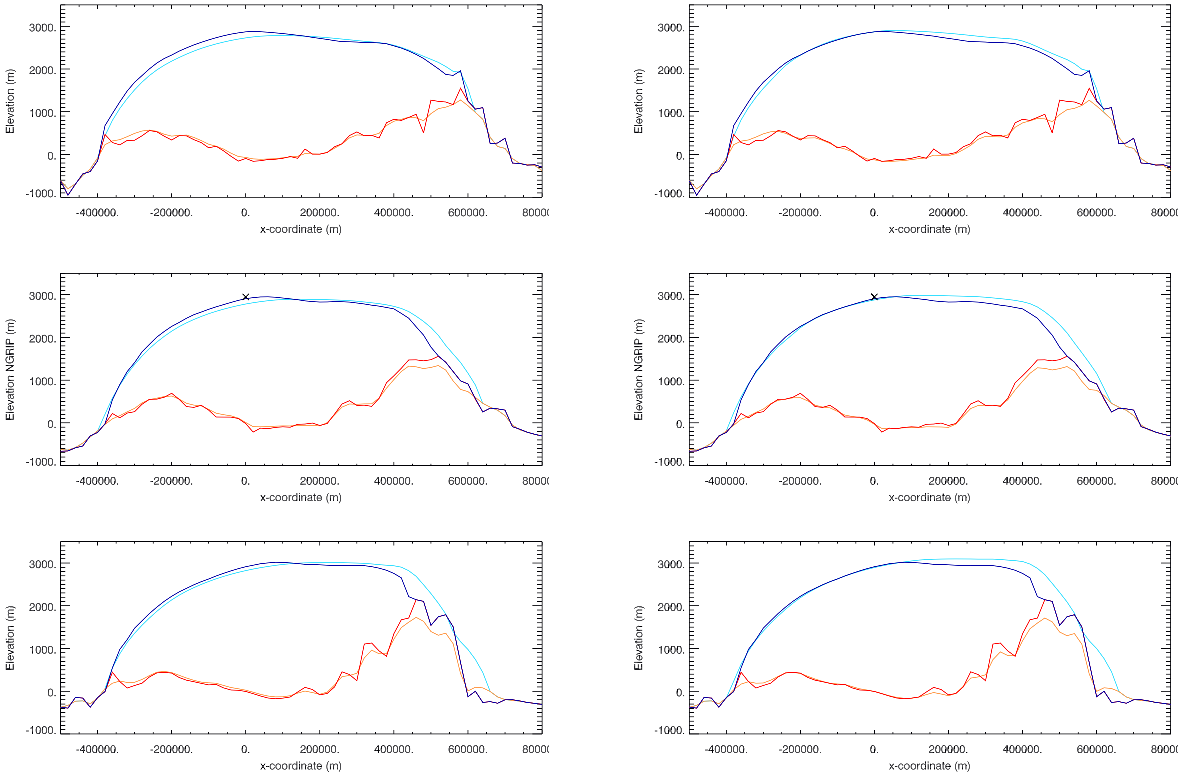

Figure 3.10: Cross section through bedrock and ice sheet at the latitude close to NGRIP. The location of these cross sections is shown with lines in Figure 3.8. The measured bedrock and surface topography is shown with read and blue colours and the modeled result is shown with orange and light blue. Left figures show results from the reference run (*Greve*, 2005), and right figures from the combination run. The location of the core is shown with a cross in the centre figure, note however, that the closest grid point is shown, not the actual core location.

flux for the reference run), but the modeled ice is too thick in both runs. This indicates that there are likely other processes, for example the precipitation, that could be more important to decrease the thickness here than the geothermal heat flux.

The cross sections for the area around NGRIP are shown in Figure 3.10. The reference run has too thin ice on the western side, with somewhat too large extent at the line that goes through NGRIP, it is too thin in the ice divide area, further east the fit is relatively good, but the modeled ice sheet becomes too thick and extends too far east, resulting in suppressed bedrock, compared to the reference bedrock. The combination run has better fit at the western side, with similar too large extent towards west in the centre cross section. The fit at the borehole location is better, but from the ice divide and towards east the modeled ice sheet is too thick, it is thicker for the combination run than for the reference run. The geothermal heat flux is higher for larger area east of NGRIP, which indicates that the combination run has too low heat flux, as the ice is too thick. Further to the east, closer to the coast both models have too thick ice, again indicating that there are possibly other processes that have larger influence on the extent here.

The comparison of the fit to the measured surface is quite good for both the reference run and the combination run in the area close to GRIP and GISP2. The geothermal heat flux is lower for the combination run, which results in thicker ice sheet, but the difference is not large. At the ice divide the reference run has too thin ice, but the combination run too thick, the difference is -66 m and +54

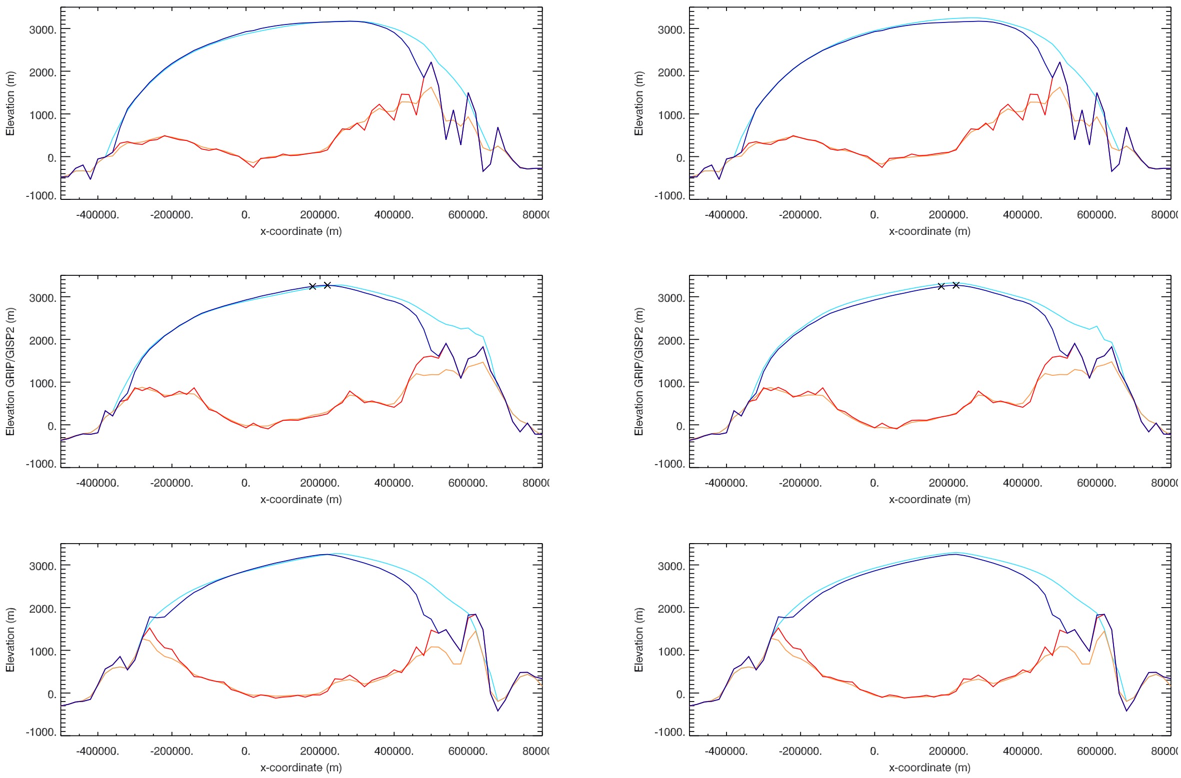

Figure 3.11: Cross section through bedrock and ice sheet at the latitude close to GRIP and GISP2. The location of these cross sections is shown with lines in Figure 3.8. The measured bedrock and surface topography is shown with read and blue colours and the modeled result is shown with orange and light blue. Left figures show results from the reference run (*Greve*, 2005), and right figures from the combination run. The location of the core is shown with a cross in the centre figure, note however, that the closest grid point is shown, not the actual core location.

m so the difference in geothermal heat flux results in 100 m difference in the ice divide thickness. Towards the east coast both models produce to thick ice, which extends much further east than the measured ice sheet, and results in depressed bedrock geometry, so the thickness of the ice is actually much larger than the measured (up to a few hundred m), in the terminus area of the measured ice.

For the Dye 3 area the reference model gives ice sheet that is similar to the measured one on the west coast, but thinner on the east coast. The dome itself is not in the right location, resulting in too thick ice to the west of the divide and too thin to the east. The ice is too thin for the whole east coast and the extent is larger on the northern most line. The combination run results in too thin ice sheet for the whole southern dome, the ice divide location is also too far to the west and the ice is too thin on the eastern side, but with similar too large extent on the line furthest north. The geothermal heat flux is low in large area, the whole southern dome area, for the reference run, but in the combination run it is only small area around the Dye 3 location that has lower heat flux. That is apparently not large enough area to improve the fit with the measured surface. The wrong placing of the ice divide and the too thin and large extent on the eastern coast indicates that there is likely other processes, such as the accumulation/ablation pattern that causes the misfit.

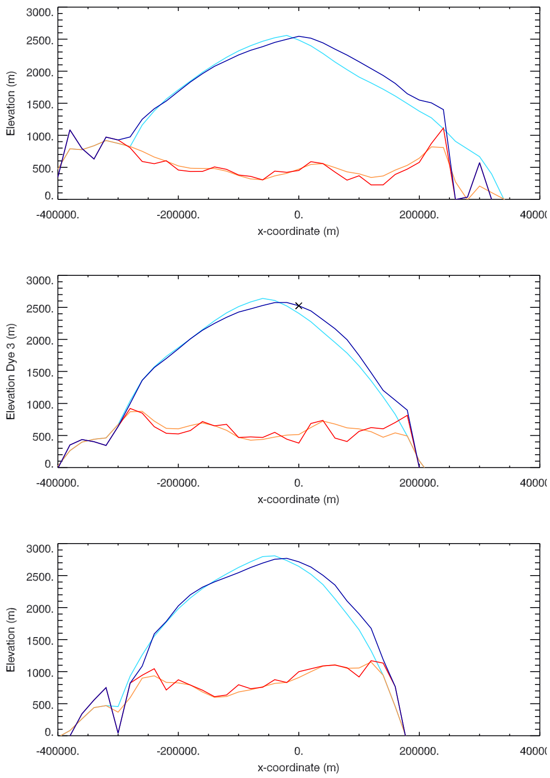

Figure 3.12: Cross section through bedrock and ice sheet at the latitude close to Dye3. The location of these cross sections is shown with lines in Figure 3.8. The measured bedrock and surface topography is shown with read and blue colours and the modeled result is shown with orange and light blue. Left figures show results from the reference run (*Greve*, 2005), and right figures from the combination run. The location of the core is shown with a cross in the centre figure, note however, that the closest grid point is shown, not the actual core location.

4. Sensitivity to grid resolution

The above model runs were repeated using a 10 km grid resolution instead of 20 km. This increases the time that that each model run takes considerably. The time increases from about 9-10 hours to about 8 days. (a faster computer is used than the first runs, the 20 km run on asama takes about 24 hour, but only about 10 hours on dolph/wulff).

A comparison of the basal temperature and ice thickness at the ice core locations, where measurements are available (Table 4.1, reveals that the 10 km grid resolution does improve the fit slightly at GRIP and Dye 3. However, there is a better fit for ice thickness using Model 5 at GRIP and the Combination at NGRIP and Camp Century. The basal temperature is best fitted with 10 km grid at GRIP, NGRIP and Dye 3 (and 20 km grid at Camp Century, the difference is small between 10 and 20 km grid results). The influence the horizontal resolution has is not everywhere the same, at GRIP the ice becomes thicker and warmer, at GISP2 it becomes thinner and warmer, at NGRIP it becomes thinner for the reference run but thicker for CHMF 5 and combination runs, very small difference in basal temperature. At Camp Century the ice becomes thicker, and closer to the measurements, and colder, and at Dye 3 the ice becomes thicker and colder, except with the CHMF 5 model run, there is not much difference in temperature, which is close to melting point.

Sim.	GRIP		GISP2		NGRIP		Camp Century		Dye 3	
	H	T_b	H	T_b	H	T_b	H	T_b	H	T_b
	km	°C	km	°C	km	°C	km	°C	km	°C
Obs.	3.029	-8.56			3.080	-2.4*	1.387	-13.00	2.037	-13.22
Ref. (20km)	2.963	-8.82	2.979	-8.57	2.941	-2.56*	1.325	-12.66	1.759	-11.47
Ref. (10km)	3.002	-8.65	2.961	-8.51	2.939	-2.56*	1.358	-13.84	1.923	-13.27
CHMF5 (20km)	3.083	-8.85	3.120	-8.97	3.119	-3.30	1.332	-13.89	1.563	-1.57
CHMF 5 (10km)	3.122	-8.09	3.110	-8.83	3.125	-3.36	1.386	-14.88	1.690	-1.59
Comb. (20km)	3.070	-8.88	3.107	-9.09	3.074	-2.67	1.331	-13.90	1.654	-7.88
Comb. (10km)	3.110	-8.12	3.096	-8.95	3.080	-2.68	1.387	-14.89	1.834	-11.38

Table 4.1: Comparison of Observed and simulated ice thicknesses and basal temperature for the GRIP, GISP2, NGRIP, Camp Century and Dye 3 ice-core locations for both 20km and 10km simulations.

The basal conditions in model runs with the 10 km grid resolution are similar to the 20 km runs (Figure 4.1. There are more details in the outline of the frozen areas and a few areas at the coast where there are faster flowing outlet glaciers in Northern Greenland that have temperate ice that did not have that in the 20 km model run. The general shape of the frozen vs. temperate areas is however, the same. The comparison of the surface elevation of the modelled ice sheet with the measured for the 10 km model runs is shown in Figure 4.2. The general results is the same as in the model runs with 20 km horizontal resolution, there are more details in the 10 km results and the shape of the Southern Dome has changed with higher resolution. The fit to the measurements is still similar, with modelled ice on the North coast and the east coast where there is no ice at present, too thin ice on the north west close to Camp Century and too thin southern Dome.

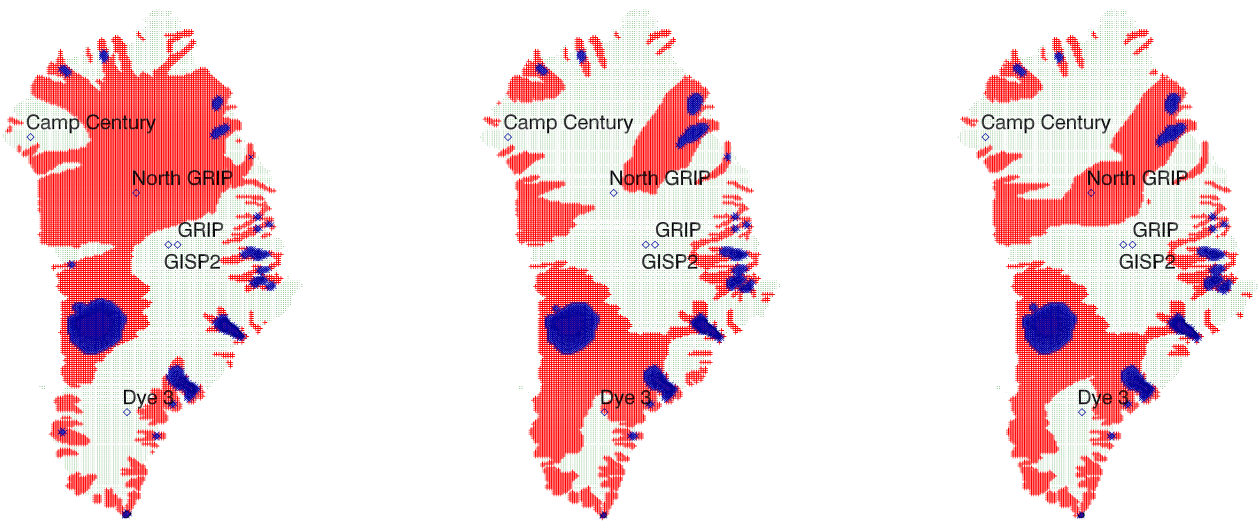

Figure 4.1: The resulting basal condition for the model runs on 10km grid resolution with different geothermal heat flux distributions as boundary condition. Red pluses indicate points where ice is at pressure melting point and blue crosses where there is temperate ice above (contours indicated thickness, interval 1m). From left to right: Reference (*Greve*, 2005), from CHMF 5, and combination of the two.

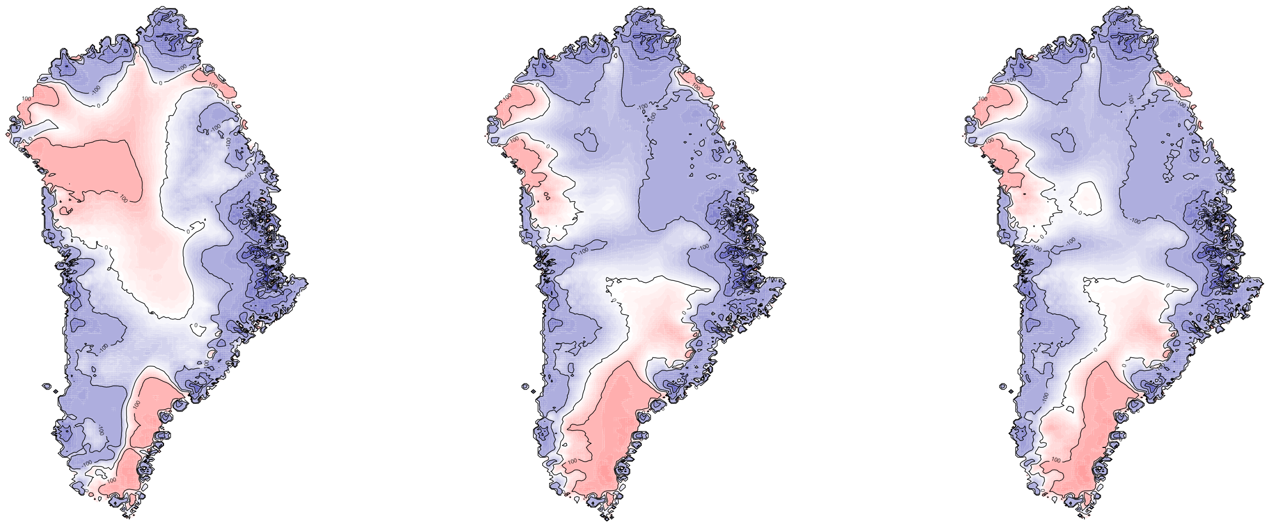

Figure 4.2: Difference in surface elevation (Measured-Modelled) for the model runs on 10 km grid. Blue areas show locations where the modeled ice sheet is too thick and red where the modeled ice is too thin (note uneven contour intervals: 0, 100 m, 500 m, 1000 m, 1500 m, 2000 m). From left top to right bottom: Reference (*Greve*, 2005), from CHMF 5, combination of the two
.

5. Summary

The state-of-the-art ice sheet model SICOPOLIS (*Greve*, 1997b), which code and model setup was generously provided by Ralf Greve, professor of glaciology at the Institute of Low Temperature Science Hokkaido University, Sapporo, Japan, has been installed and is running on the computers of DMI. A close collaboration with Ralf Greve, as well as the ice sheet modelling groups at the Copenhagen University and GEUS, has been established around applying this model for climate change experiments and assessment of the response of Greenland Ice sheet to climate change.

A new estimate for the geothermal heat flux boundary condition *Maule* (2005) has been adapted to be applicable in SICOPOLIS, and the model has been run with a number of different geothermal heat flux boundary conditions. The model runs show that the results are sensitive to the applied geothermal heat flux. Further work on gathering more information about available measurements or other indirect ways of estimating the geothermal heat flux is needed to establish a new boundary condition that will be applied in future model runs. Following model experiments will work with this new estimate as well as improved versions as they become available.

This model setup gives remarkably good results for present day geometry of the ice cap which can be used as base line for model experiments for future evolution of the ice cap. There is, however, room for improvements, as there are areas in the model that are ice covered where at present there is no ice in reality (at the northern most part of Greenland and on the east coast) and areas where the modelled ice cap is thicker, or thinner, than the measured ice cap.

The spin up of the model is important for the present state of the ice cap. The model experiments shown here show that the history of the climate forcing as far back as a few hundred thousands years impacts the temperature distribution within the ice, as well as the extent of the present modelled ice cap.

Further work and the next steps in establishing a model for the Greenland Ice Sheet will be to continue working on the surface and bed boundary conditions, including coupling the ice sheet model with a regional climate model, first as off-line and then further as two-way coupled model. Work on improving the geothermal heat flux boundary will be advanced along side this work, as both the surface and the bed forcing impact the model runs.

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