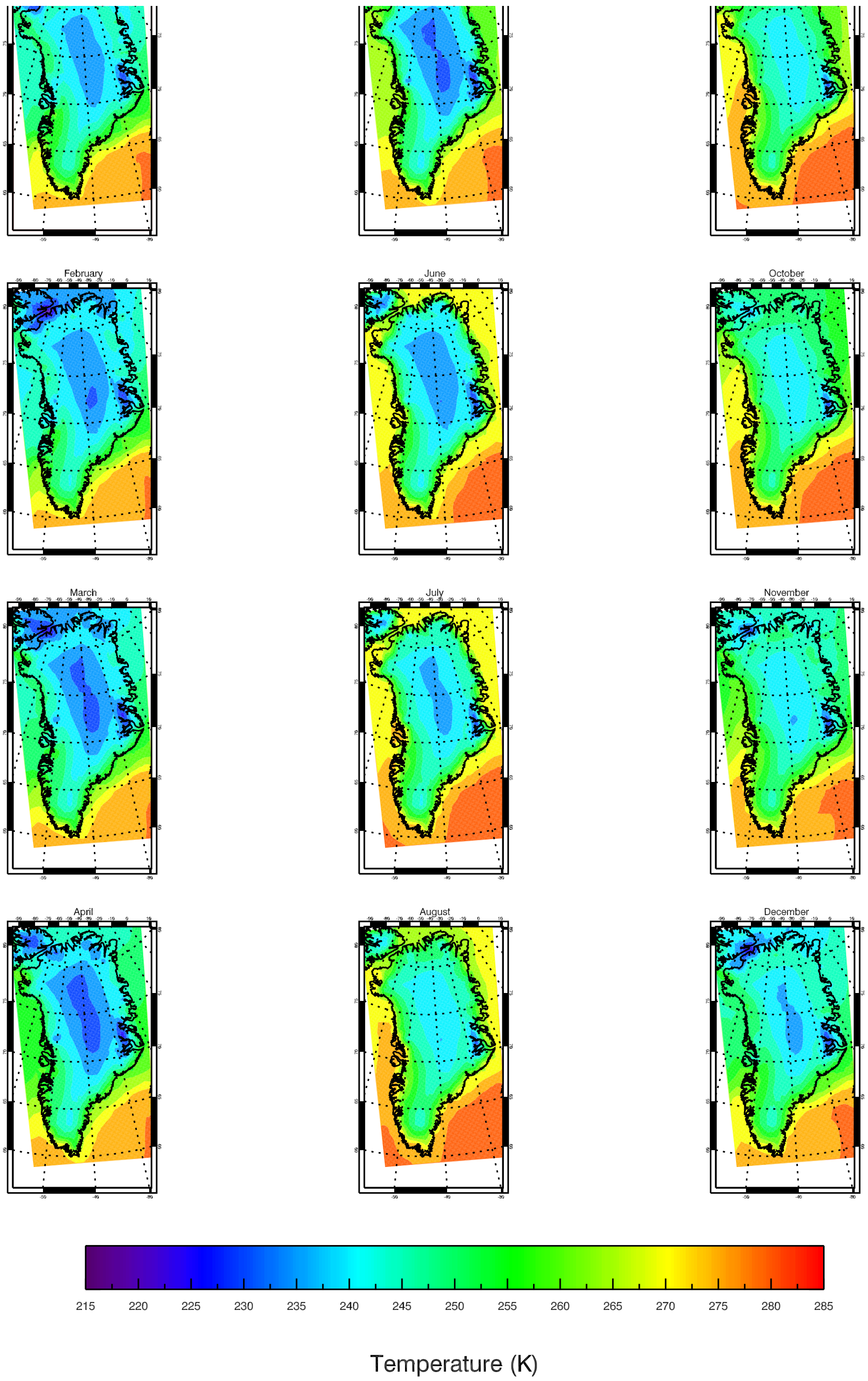

Figure 6.2: Monthly temperature fields used to drive the spinup run.

temperature data [Bindschadler et al., 2013] to drive PISM. This spinup run through the past glacial cycle is an exact replica of the procedure described in the PISM documentation [Albrecht et al., 2012] and will therefore not be decribed here. After the glacial cycle spinup, PISM is run with constant forcings based on 30-year means of surface mass balance and temperature based on a preindustrial control run of EC-Earth for 100.000 years, thereby ensuring that the ice sheet is in thermal equilibrium with the driving climate model. In figs.(6.1)-(6.2), the monthly fields of surface mass balance and temperature used to drive the spinup run are shown. The monthly fields are given as 30-year means of a preindustrial PISM control run. Note the negative surface mass balance along

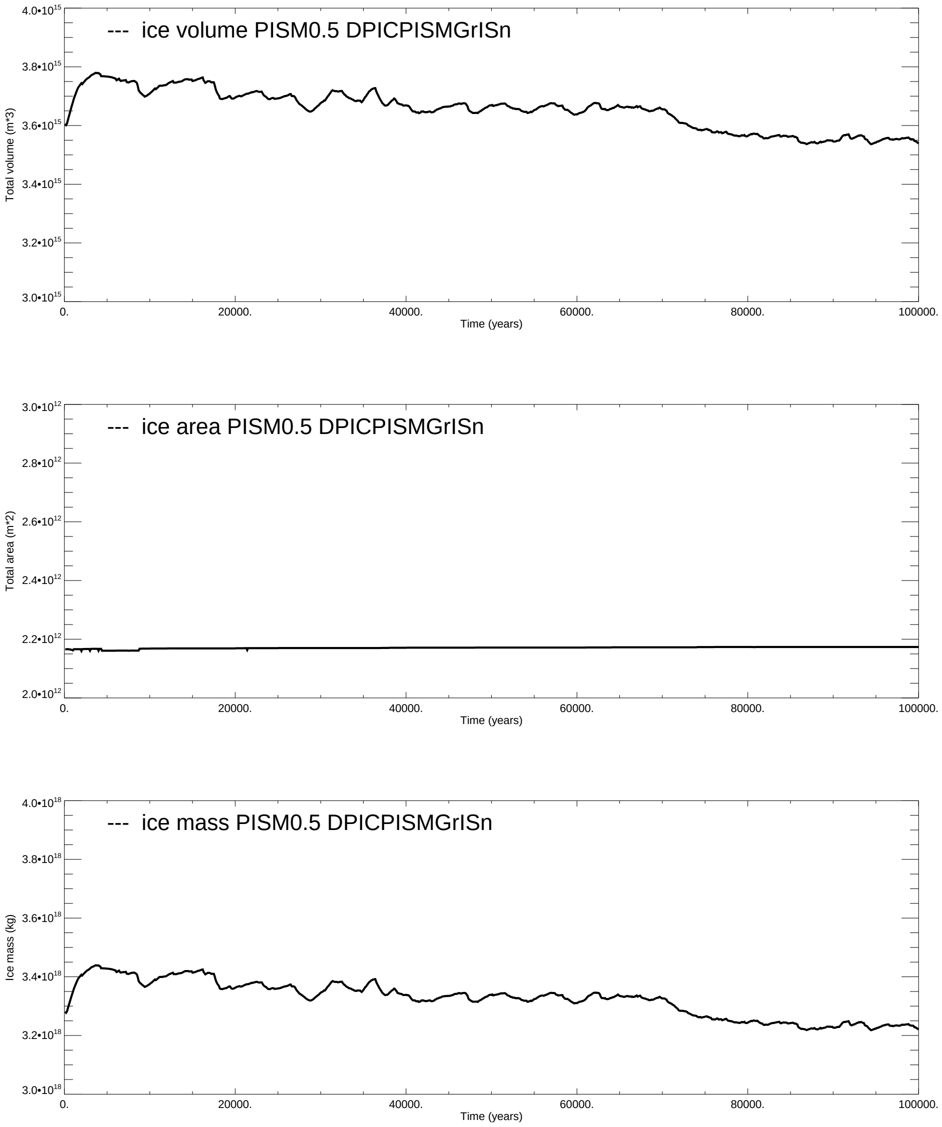

Figure 6.3: Time series of the ice sheet total volume, area and mass of the spinup run.

the entire coast during the summer months and the positive surface mass balance that dominates in the southeastern parts. The annual cycle is evident in the temperature fields.

Fig.(6.3) shows time series of the total ice volume, ice area and ice mass of the ice sheet for the duration of the spinup run. After some initial transient behaviour the ice sheet stabilises, displaying near-constant behaviour for the last 25.000-30.000 years of the spinup run.

A comparison of the observed ice sheet (as given by [Bamber et al., 2013b]) and the post-spinup ice sheet (i.e. after 100.000 years) is shown in figs.(6.4)-(6.5). Three (roughly) west-east transects are indicated by red lines, the geometry of the bedrock and the ice sheet surface along these transects,

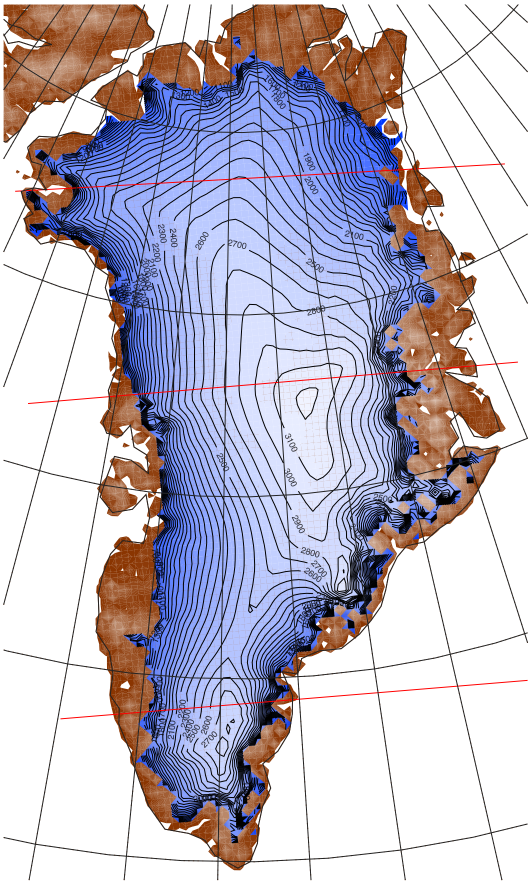

Figure 6.4: The observed Greenland ice sheet using data from [Bamber et al., 2013b]

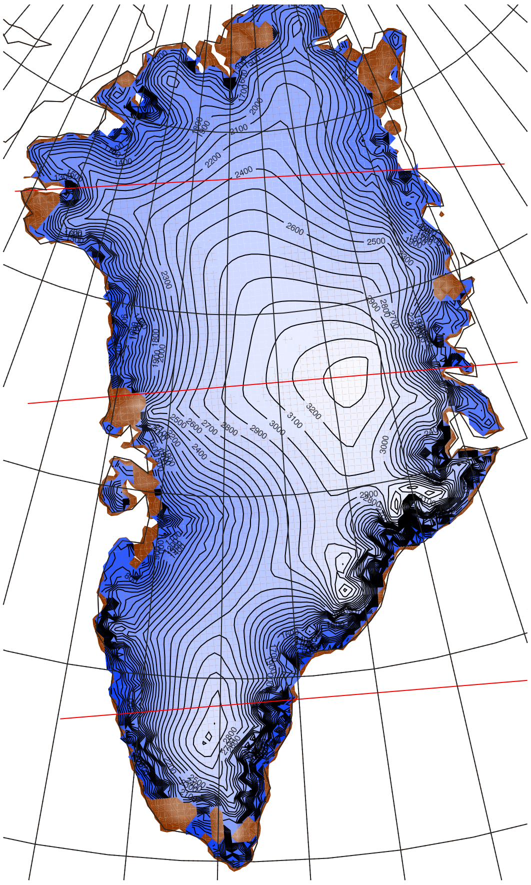

Figure 6.5: The post-spinup Greenland ice sheet.

both from the observations and the spinup run, is shown in fig.(6.6). It is evident that the modelled spinup state is larger than the observed ice sheet, both regarding surface altitude and spatial extent. Several factors come into play concerning this discrepancy; one being the influence of the model resolution on dynamics. The larger ice sheet may be due to the merging of smaller ice caps and glaciers which cannot be resolved with the current resolution and are thus merged with the main ice sheet. The differences could also relate to inconsistencies in the forcing fields as well as the simplified representations of physical processes used in the ice sheet model itself.
Figs.(6.7)-(6.9) shows the observed bedrock topography [Bamber et al., 2013b] interpolated onto the PISM grid at three different resolutions, 20×20 km, 10×10 km and 5×5 km. Note that as resolution increases, more and more bedrock features are discernable and, in particular, the ability to resolve the outlet fjords. The lack of outlet fjords at the coarser resolutions reduces the dynamic loss from the ice sheet, simply by the failure to provide proper outflow channels. In this case, dynamic ice loss is inhibited and making any ice loss dependent on melt instead. An increase in resolution would increase the dynamic ice loss, thereby reducing the overall size of the ice sheet. Changing the PISM resolution from the current 20×20 km to either 10×10 km or 5×5 km is recommended in order to increase dynamic ice loss through outlet fjords. However, given the resolution of the driving climate model EC-Earth ($\sim$125 km, care must be taken to ensure sensible interpolations of the forcing fields. Validations of the EC-Earth model indicates a cold bias in the Arctic *citation*?? and such a bias would reduce the amount of melt, thereby contributing to the build-up of ice. In addition, it is a common feature of ice sheet models making use of the shallow ice approximation (SIA), that the resulting ice sheets have a tendency to overestimate the spatial extent of the ice sheet and in previous

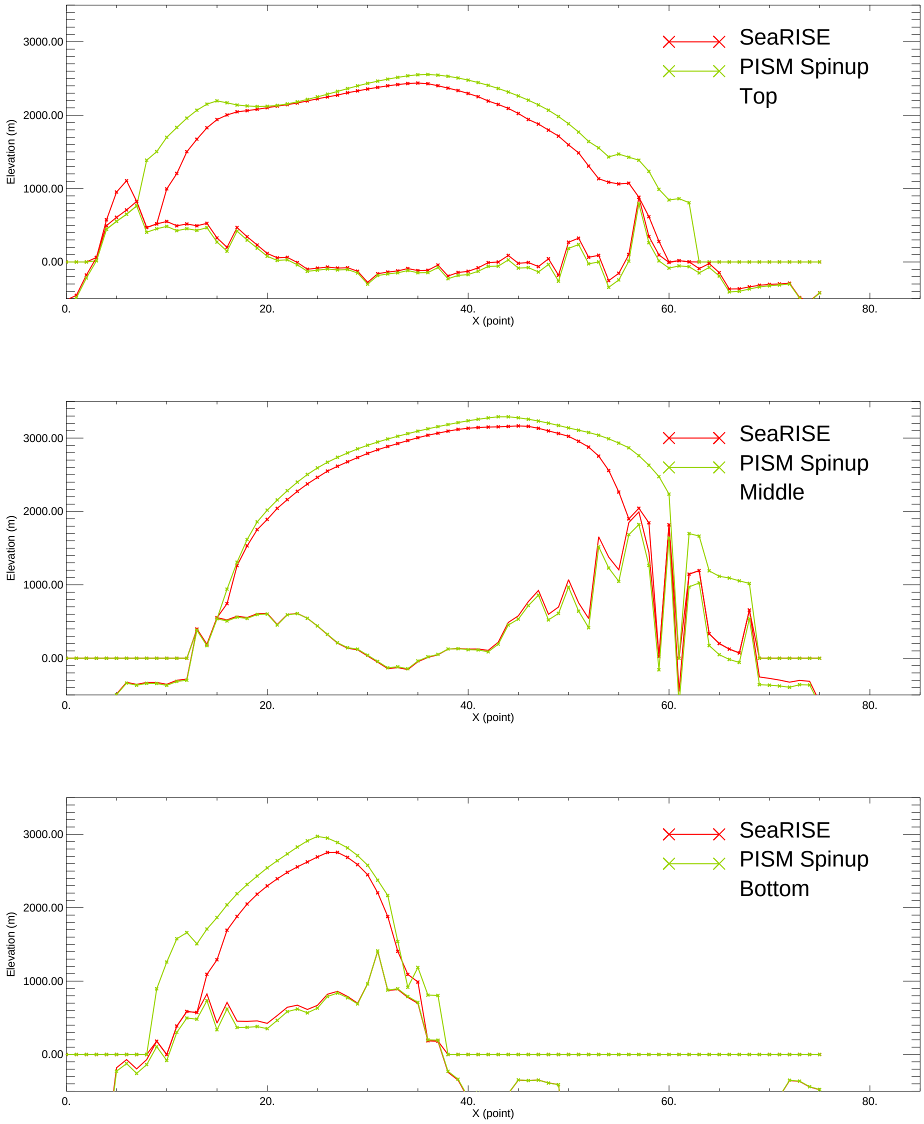

Figure 6.6: The bedrock and ice sheet surface topography of the Greenland Ice Sheet at the three transects indicated by red lines in fig.(6.5). The transects are labeled 'top', 'middle' and 'bottom' corresponding to the northernmost, middle and southernmost of the three transects, respectively.

studies PISM has shown a tendency to produce ice sheet states that are too large [Nowicki et al., 2013].

During the spinup process, flux-corrections may be applied to force the thickness of the ice sheet to match a given (observed) geometry. However, such an initial state is not in equilibrium with the applied forcing fields and may lead to model drift once the flux corrections are released [Aschwanden et al., 2013, Adalgeirsdóttir et al., 2014, Price et al., 2011]. Given the ambition of

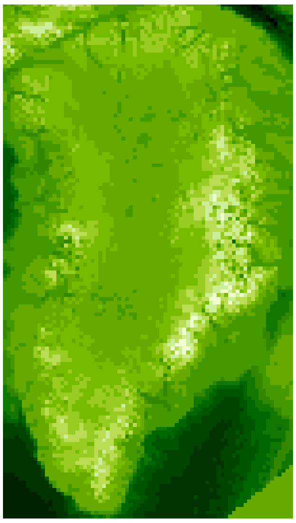

Figure 6.7: The observed Greenland bedrock topography from [Bamber et al., 2013b] interpolated onto the 20×20 km PISM grid.

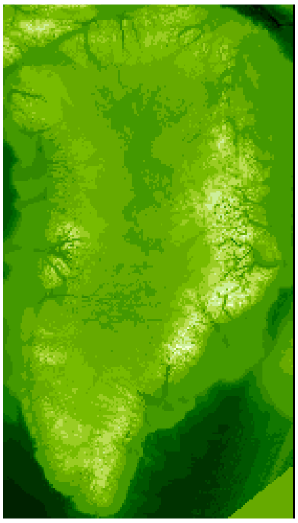

Figure 6.8: The observed Greenland bedrock topography from [Bamber et al., 2013b] interpolated onto the 10×10 km PISM grid.

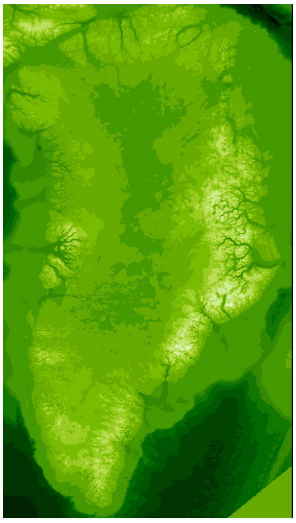

Figure 6.9: The observed Greenland bedrock topography from [Bamber et al., 2013b] interpolated onto the 5×5 km PISM grid.

investigating the effect of climate change on the ice sheet and mutual feedbacks between the ice sheet and the rest of the climate system, ice sheet model states in equilibrium with the mean state of the driving climate model are needed. Consequently, less emphasis has been put on obtaining ice sheet model states with spatial extents matching observations and more emphasis has been put on ensuring thermomechanical equilibrium with the driving model. The spinup state of the ice sheet model has a spatial extent that is too large, but exhibits overall flow patterns and velocities with reasonable agreement with observations and is in thermomechanical equilibrium with the mean state of the driving climate model.

6.2 Spinning up the Coupled System

Following the spinup run of the ice sheet model, a spinup run of the two-way coupled system is carried out in order to make sure any transients stemming from the introduction of feedbacks between the ice sheet and the surrounding climate have subsided. This is done by running the fully coupled system using constant radiative forcing corresponding to the mean preindustrial conditions for a prolonged period of time.

7. Coupled and Uncoupled PIC and 4xCO2 Runs

A number of simulations have been run using the fully coupled EC-Earth-PISM model system including the new surface scheme. After the spinup-process described in chap.(6) the model was run for 350 years under pre-industrial conditions (PIC-Cpl). To investigate the response of the system in significantly warmer scenarios, another 350-year simulation was run with the atmospheric $\mathrm{CO_2}$ abruptly quadrupled as compared to the preindustrial level ($4{\times}\mathrm{CO_2}$-Cpl) as well as a run with a 1% annual increase in $\mathrm{CO_2}$ concentration until $4{\times}\mathrm{CO_2}$ concentration is reached ($1\%\mathrm{CO_2}$-Cpl). In addition to these coupled runs, their uncoupled counterparts have been run (PIC, $4{\times}\mathrm{CO_2}$ and $1\%\mathrm{CO_2}$, respectively), allowing for comparisons and an evaluation of the effect of the coupling on both the ice sheet and the climate response. An in-depth analysis of these runs is given in [Madsen et al., 2016], but here a few of the main findings is summarized.

In the coupled pre-industrial control run (PIC-Cpl), the ice sheet mass gain is mostly balanced by ice discharge. The seasonal and geographical variation of the surface mass balance is resaonable even though the overall mean of the total SMB is somewhat large (~ 510 Gt/year) compared to other studies.

When considering the mean near surface air temperature (SAT) averaged over all grid cells north of $60°$N, the coupled and the uncoupled setups show little difference in the case of the stable and relatively cold PIC case. However, in the warm scenarios ($4{\times}\mathrm{CO_2}$ and $1\%\mathrm{CO_2}$), the response is different in the coupled and uncoupled scenarios.

As expected, the temperature rises in both the warm scenarios. In the $4{\times}\mathrm{CO_2}$ case, an abrupt increase in SAT is seen already within the first year of simulation, reflecting the response of the climate system to the sudden increase in radiative forcing. The rapid temperature increase continues for approximately a decade before gradually slowing down and approaching a constant state around 13K warmer than the preindustrial case. The gradual increase in $\mathrm{CO_2}$ concentration in the $1\%\mathrm{CO_2}$ case stabilises at the same level, even though the temperature increase is much more gradual compared to the $4{\times}\mathrm{CO_2}$ case and takes approximately 200 years to reach its final stable regime. Comparing the coupled and the uncoupled runs, the total temperature increase once stability is reached is larger by about 1K in the case of the uncoupled runs compared to the coupled runs for both the $4{\times}\mathrm{CO_2}$ and $1\%\mathrm{CO_2}$ case.

Due to the enforced melting of excess snow (any snow exceeding 10 m.w.eq.) which ensures stability of the ice sheet in the ucoupled version of EC-Earth, the whole ice sheet experiences year-round surface melt. In the coupled setup, a much more realistic melting pattern is seen, with higher melt along the ice sheet margin and a clearly visible seasonal cycle.

In both the coupled and uncoupled PIC case, a steady ice sheet is seen without any noticeable changes in volume. The uncoupled scenario runs ($4{\times}\mathrm{CO_2}$ and $1\%\mathrm{CO_2}$) maintain a steady ice sheet whereas the total volume of the ice sheet show a steady decrease in the corresponding coupled runs, with similar loss rates even though there is a lag in the $1\%\mathrm{CO_2}$ run compared to the $4{\times}\mathrm{CO_2}$ run to account for the transient period of gradual $\mathrm{CO_2}$ increase. Even though the temperature increase in both scenarios levels off after approximately 200 years in both scenarios, the decrease in volume continues unchaged, hinting at the long response times of the ice sheet.

The fresh water flux from the Greenland ice sheet into the ocean shows a very large sensibility to the coupling. In the PIC case, the fresh water flux increases from the uncoupled to the coupled case, the cause most likely being the change from one surface scheme to another given the stability of the ice sheet in the PIC case. The uncoupled $4{\times}\mathrm{CO_2}$ and $1\%\mathrm{CO_2}$ runs both roughly double the fresh water flux compared to the preindustrial case, the $1\%\mathrm{CO_2}$ case clearly displaying the transient nature of the radiative forcing at the beginning of the run. The coupled runs, however, both increase the fresh water flux more than fourfold, again with the $1\%\mathrm{CO_2}$ case exhibiting a transient response before settling on a level comparable to that of the $4{\times}CO_2$ case, clearly indicating how the coupling of the ice sheet to the climate introduces feedbacks in the system which magnify the effect of changes in the radiative forcing. The fresh water input to the ocean from the Greenland ice sheet affects global sea level, but may in addition have an effect on ocean circulation. In the simulations, the strength of the Atlantic meridional circulation (AMOC), defined here as the maximum discharge stream function at $30°$N is clearly affected. In both the coupled and uncoupled PIC run, the AMOC is on average 16 Sv, although large interannual and decadal variability is evident. The coupled run generally has the smaller values and the decadal-scale variability is smaller. In the $4{\times}CO_2$ runs, the AMOC shows a drastic decrease followed by a gradual, although not complete, recovery. The recovery is quicker in the uncoupled case, with the AMOC in the coupled case being weaker than the AMOC in the uncloupled case. This pattern is reproduced in the $1\%CO_2$ scenario, although the initial drop of the AMOC is much more gradual.

It is evident that including the coupling affects not only the Greenland ice sheet, but the climate system as a whole, emphasizing the need for such couplings in order to estimate the full effect of changes in radiative forcings on the climate system.

8. Coupled Runs Driven by the RCP8.5 Scenario

After spinup runs of both the ice sheet model and the coupled model system, scenario runs may be performed. The model system has been through a spinup process based on the mean preindustrial climate, so it is in equilibrium in a pre-1850 state. Based on this model state, runs may now be carried out driving the model with historical emissions from 1850 to 2005 and using emission scenarios from 2006 onwards.

8.1 Historical run - 1850-2005

The historical run (1850-2005) was done using the CMIP5 experiment design [Taylor et al., 2012]. In figs.(8.1)-(8.4) some key aspects of the Greenland ice sheet are shown. The total surface mass balance over the Greenland ice sheet is shown in fig.(8.1). Only grid cells which according to PISM's mask variable are taken up by grounded ice are contributing to the total surface mass balance. Throughout the years 1850-2005, the total surface mass balance remains stable, with annual values around 400 GT/year. This is comparable to values of total surface mass balance from a number of other models as given in [Vernon et al., 2013]. Fig.(8.2) shows the corresponding time series of the total volume, area and enthalpy of ice sheet. All three time series show little variation and are indicative of a stable ice sheet.
The surface topography of the ice sheet in year 1850 and 2005, respectively is shown in the left and middle panel of fig.(8.3). The rightmost panel of the figure shows the relative change in surface altitude between 2005 and 1850. From 1850 to 2005, the ice sheet shows a reduction in surface

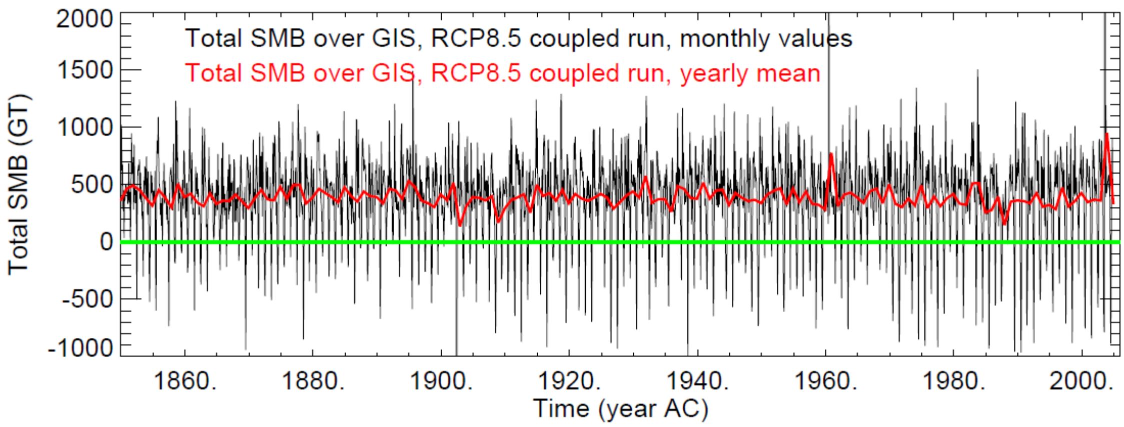

Figure 8.1: The field sum of the surface mass balance field over the Greenland Ice Sheet. Only points labelled as 'grounded ice' in the PISM mask are included in the field sum.

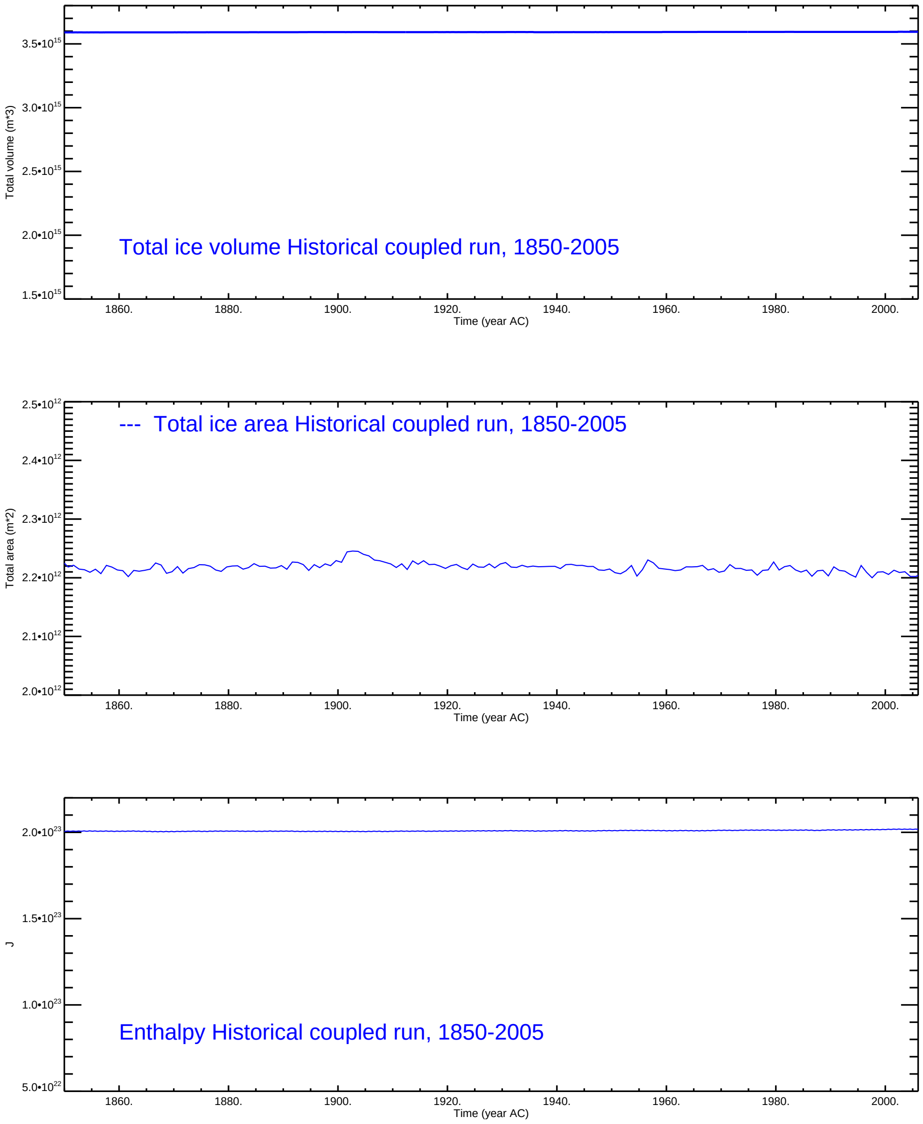

Figure 8.2: Total ice sheet volume, area and enthalpy for the historical run.

altitude along the west coast, in the northwest, in the area of the North East Greenland Ice Stream and at the east coast near Scoresbysund. A small reduction of surface altitude is seen in small parts of the interior as well. The rest of the ice sheet shows a small increase in surface altitude. Apparently, these changes mostly balance each other out in this historical part of the run, as seen from the time series of the total ice sheet volume in fig.(8.2), but may be interpreted as early signs of change in the ice sheet. In fig.(8.4), the ice velocity for 1850 is shown in the left panel and for 2005 in the middle panel. The relative velocity change is shown in the rightmost panel. The black line marks the zero contour of the velocity change. In the interior, not many changes are evident, but a

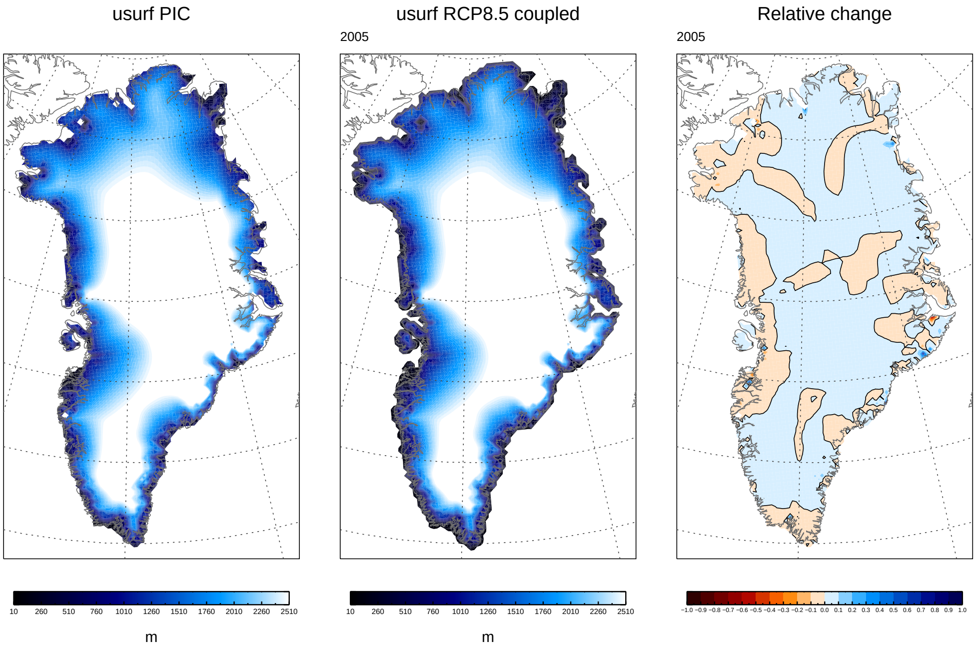

Figure 8.3: The ice sheet surface topography at the beginning of the historical run (1850) to the left. The middle plot shows the ice sheet topography by 2005 and the plot to the right shows the relative change between 1850 and 2005.

speed-up is discernable along the ice sheet margins, with a notable speed-up of the Jakobshavn Isbræ. Thinning and speed-up of the Jakobshavn Isbræ since the early 1990s has been reported by numerous authors, e.g. [Joughin et al., 2004].

8.2 RCP8.5 scenario run

The previous chapters have described the setup of the coupled EC-Earth-PISM system. In this section, results from scenario runs driven by the RCP8.5 scenario are described. Starting from the end of the historical run described in sec.(8.1), the model is run forward in time, using the representative concentration pathway RCP8.5 [Riahi et al., 2007, van Vuuren et al., 2011], a high-end emission scenario, to drive the model. The model run is extended beyond the end point of the RCP8.5 scenario by maintaining a constant forcing based on a 30-year mean of the late part of the forcing scenario. This makes it possible to investigate the long-term effects of a constant, warm climate on the Greenland ice sheet.
The total surface mass balance field is shown in fig.(8.5). This is the field sum of the surface mass balance field from EC-Earth used to drive PISM, masking out any points of the surface mass balance field that are not grounded ice according to PISM's mask variable. With this definition, the total SMB is not necessarily constant even though the surface mass balance field is if the surface area of the grounded ice changes. The lack of data from 2100 to 2400 reflects an error in archiving the output data, not an actual interruption in the simulation. A change from a positive yearly mean total SMB to a negative is observed shortly before 2100. Considering the monthly SMB values, there is a slight increase in size of the positive SMB, most likely caused by precipitation increase, but a

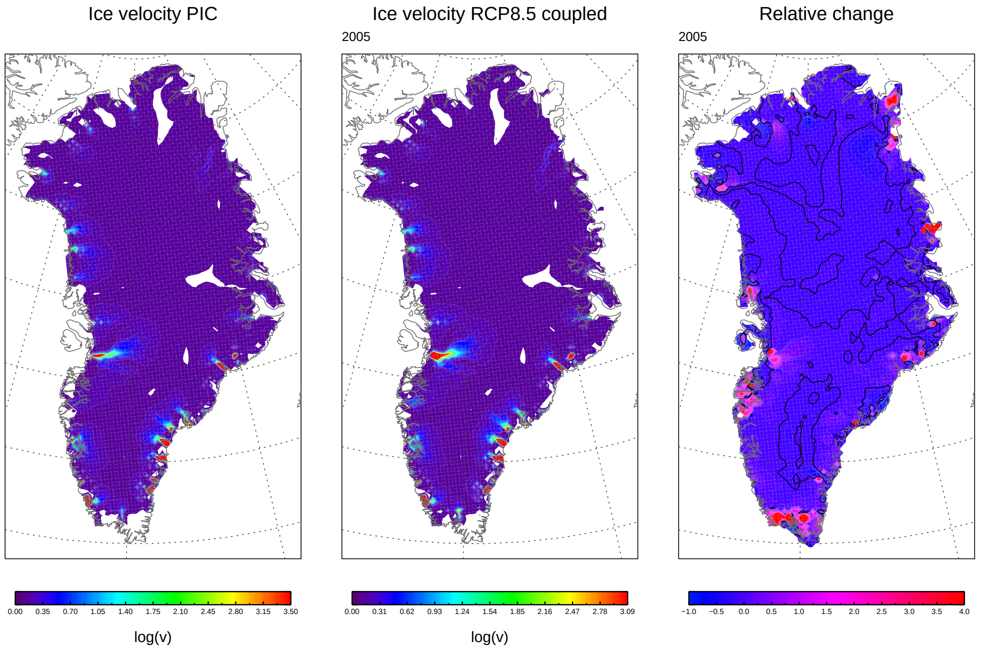

Figure 8.4: The ice velocity at the beginning of the historical run (1850) to the left. The middle plot shows the ice velocity by 2005 and the plot to the right shows the relative change between 1850 and 2005.

massive change in the size of the negative SMB values, indicating that whereas snowfall may even increase slightly over the ice sheet, this is by far outweighed by the massive increase in melt. Throughout the simulation, the total volume of the ice sheet is moving from a near-constant regime in the historical part of the simulation to a steadily decreasing one, see top plot of fig.(8.6). The bottom plots shows the total enthalpy of the ice sheet. Early in the run, a slight enthalpy increase is evident, caused by the heating of the entire ice sheet. However, this is counteracted by the volume decrease, the latter being the dominant effect after around 2200. In fig.(8.7), the middle and lower plot show the annual calving and basal melt, respectively. The basal melt goes from relatively constant values through a peiod of increasing values until basal melt reach a fairly constant, albeit higher level at the point in time where the forcing goes from time-varying, to a constant level. The calving decreases throughout the sceanario run, approaching near-zero values around 2400. In the present configuration of PISM, calving is done by a mask, so if the ice retreat behind the perimeter outlined by the mask, calving will not take place.
Figs.(8.8)-(8.9) shows the development in ice sheet surface topography and velocity, respectively, from 1850 to 2100. The leftmost plots show the ice sheet state in 1850, the middle plots show the ice sheet state in 2100 and the rightmost plots the relative change. Considering the ice sheet surface topography, with a few exceptions, thinning is evident all along the coast of Greenland. Particularly around the Jakobshavn Isbræ, the thinning stretches far inland, indicating thinning of the ice in large areas of the basin. The central and northern part of the ice sheet experiences build-up of ice, a consequence of increased snowfall in these areas due to an overall intensification of the hydrological cycle in a warmer climate. As for the ice sheet velocity, the speed-up of the Jakobshavn Isbræ is clearly visible. Compared to the historical part of the run, see fig.(8.4), extensive areas of the ice

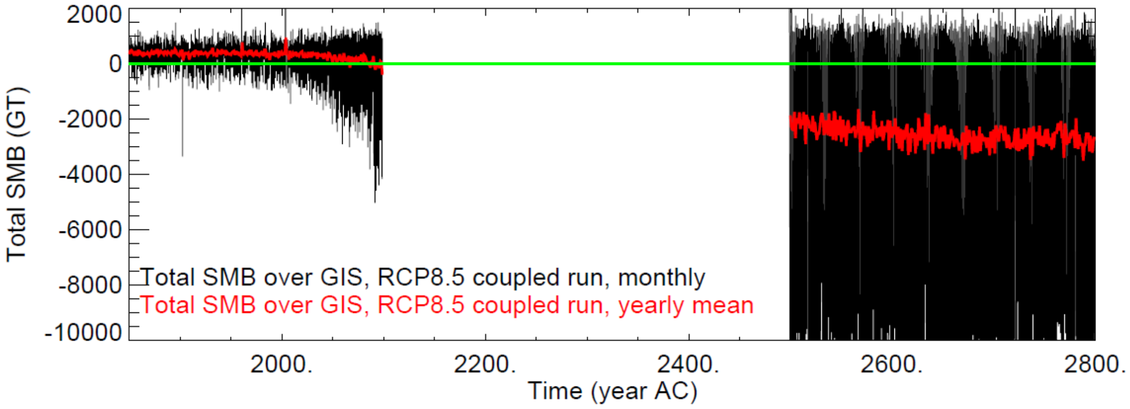

Figure 8.5: The field sum of the surface mass balance field over the Greenland Ice Sheet. Only points labelled as 'grounded ice' in the PISM mask are included in the field sum.

sheet has seen an increase in velocity, indicating a shift in ice dynamics towards larger flow speeds. By the year 2300, changes have progressed even further, see figs.(8.10)-(8.11). Extensive areas that used to be ice covered are now virtually ice-free and at the same time the central areas of the ice sheet, which previously were increasing in thickness due to an increase in snow accumulation caused by intensification of the overall hydrological cycle have decreased greatly, leaving the majority of the ice sheet in a state of thinning. In the case of the flow velocities, Jakobshavn Isbæ seems to be slowing down compared to the preindustrial (1850) case, reflecting the retreat of the ice sheet from this area. The overall speed-up of the entire ice sheet is clearly seen in the plot showing the relative changes.
Further on in the simulation, by 2750, the areas with a gain in ice thickness caused by increased snowfall have almost disappeared, putting the entire ice sheet in a thinning state, see fig.(8.12). The ice has retreated far inland in many areas and the ice velocities are indicative of a highly dynamic and fast-flowing ice sheet compared to the preindustrial case, see fig.(8.13).
The ice sheet response in the coupled EC-Earth-PISM system is indicative of a stable ice sheet in constant climate conditions, with total SMB values comparable to other models [Vernon et al., 2013]. The response of the ice sheet in a run from 1850 to 2005 shows reasonable behaviour, providing confidence in the model as a predictive tool for the Greenland ice sheet in a changing climate.

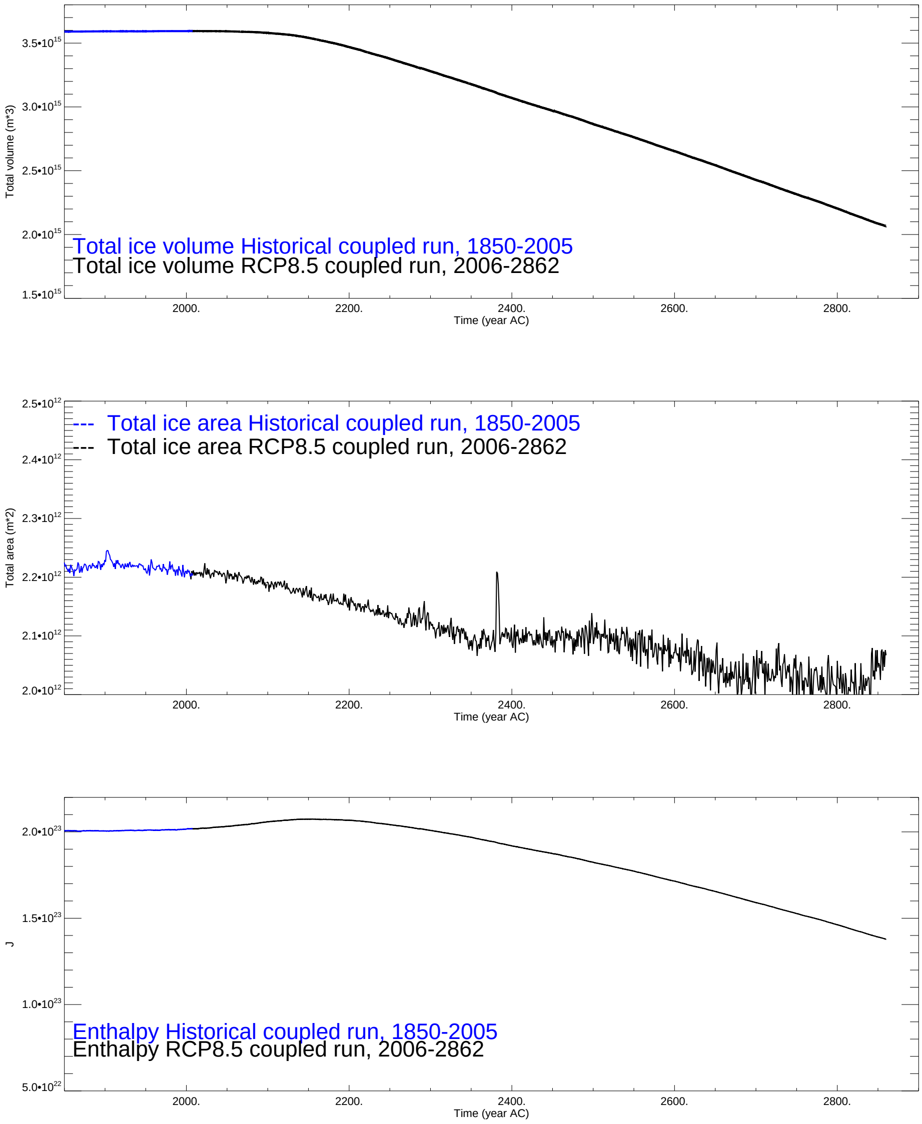

Figure 8.6: Total ice sheet volume, area and enthalpy for the RCP8.5 scenario run.

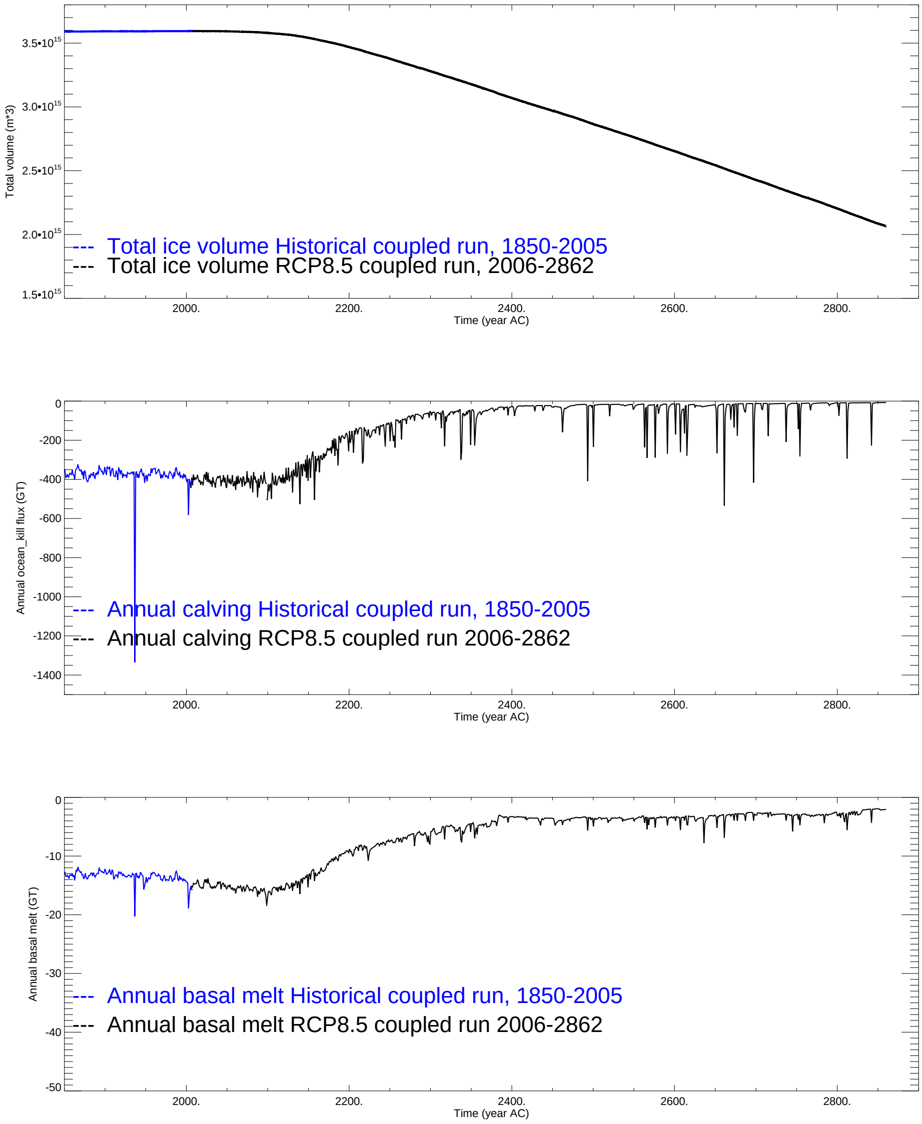

Figure 8.7: Total ice sheet volume, calving and basal melt for the RCP8.5 scenario run.