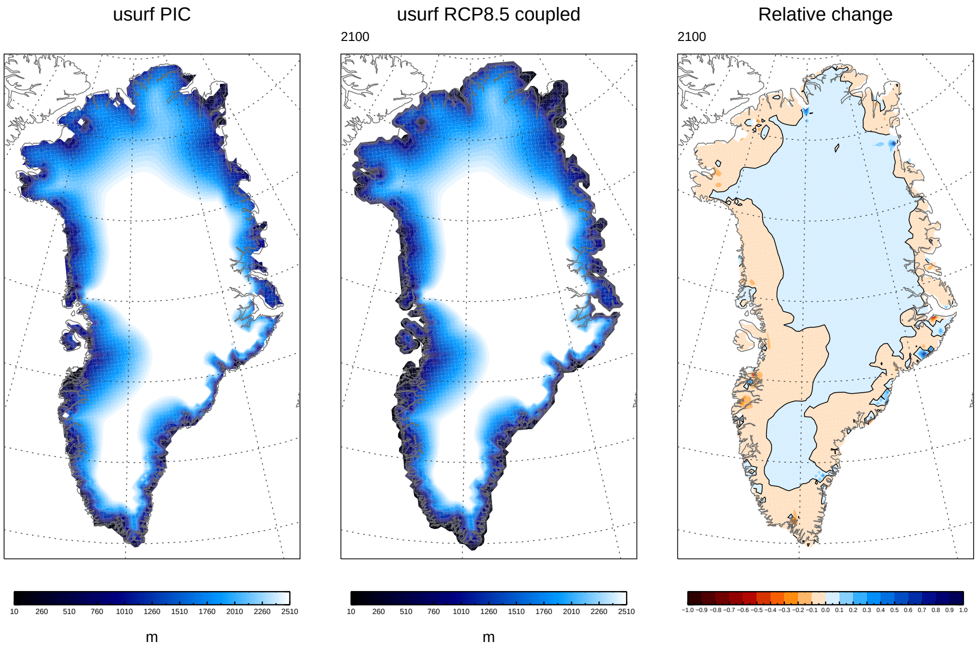

Figure 8.8: The ice sheet surface topography at the beginning of the historical run (1850) to the left. The middle plot shows the ice sheet topography by 2100 and the plot to the right shows the relative change between 1850 and 2100. In the rightmost plot, the black line indicates the zero contour of the relative change.

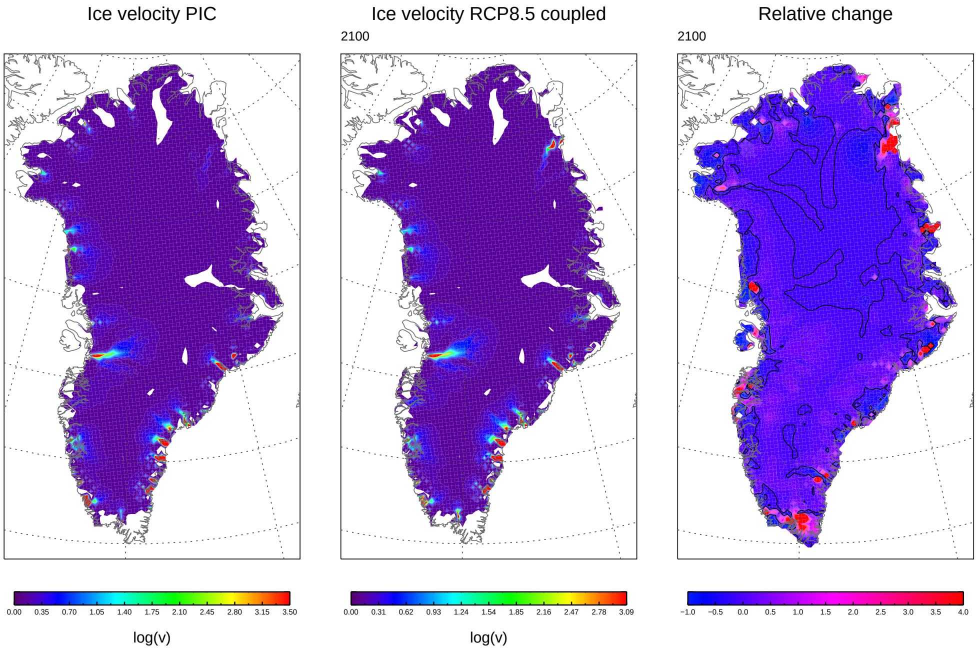

Figure 8.9: The ice velocity at the beginning of the historical run (1850) to the left. The middle plot shows the ice velocity by 2100 and the plot to the right shows the relative change between 1850 and 2100. In the rightmost plot, the black line indicates the zero contour of the relative change.

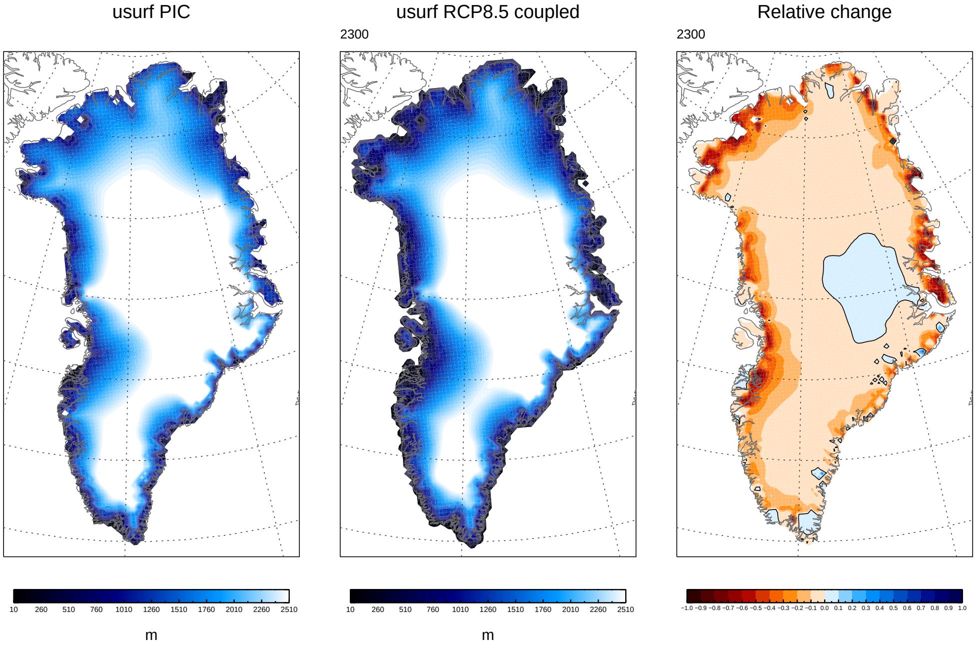

Figure 8.10: The ice sheet surface topography at the beginning of the historical run (1850) to the left. The middle plot shows the ice sheet topography by 2300 and the plot to the right shows the relative change between 1850 and 2300. In the rightmost plot, the black line indicates the zero contour of the relative change.

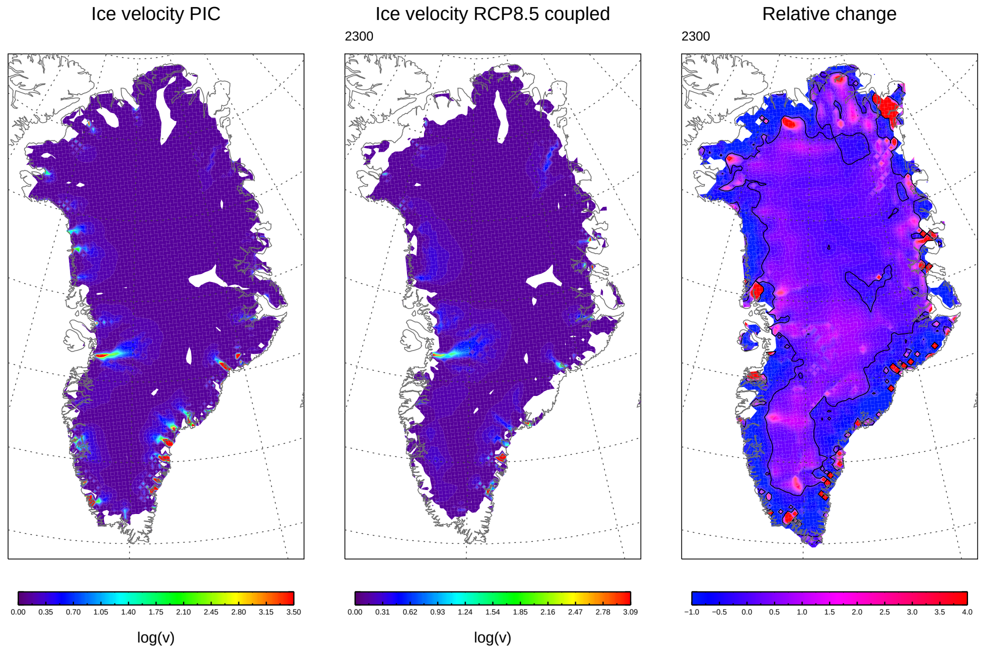

Figure 8.11: The ice velocity at the beginning of the historical run (1850) to the left. The middle plot shows the ice velocity by 2300 and the plot to the right shows the relative change between 1850 and 2300. In the rightmost plot, the black line indicates the zero contour of the relative change.

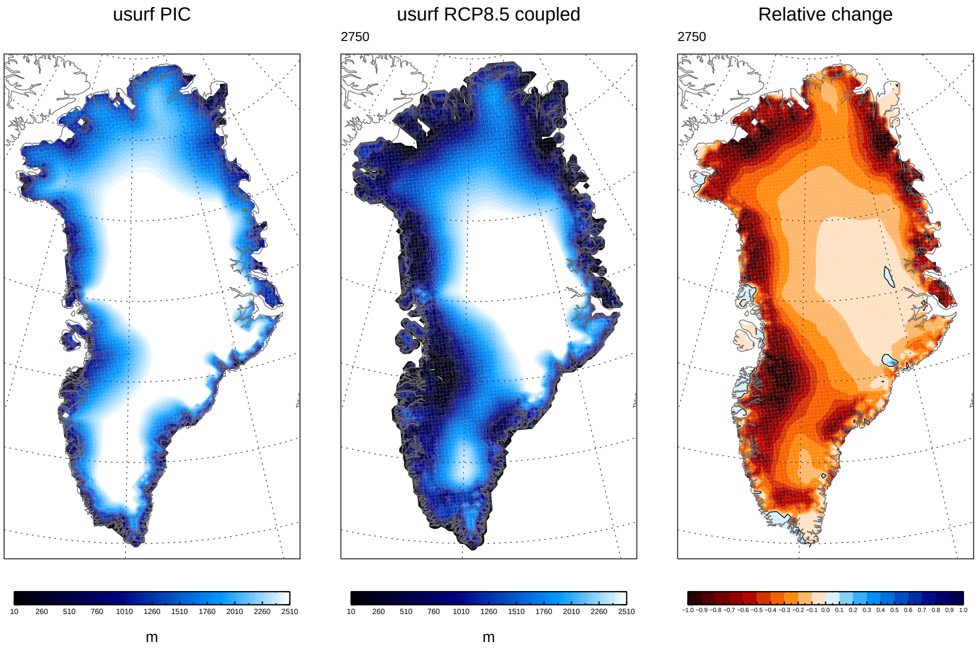

Figure 8.12: The ice sheet surface topography at the beginning of the historical run (1850) to the left. The middle plot shows the ice sheet topography by 2750 and the plot to the right shows the relative change between 1850 and 2750. In the rightmost plot, the black line indicates the zero contour of the relative change.

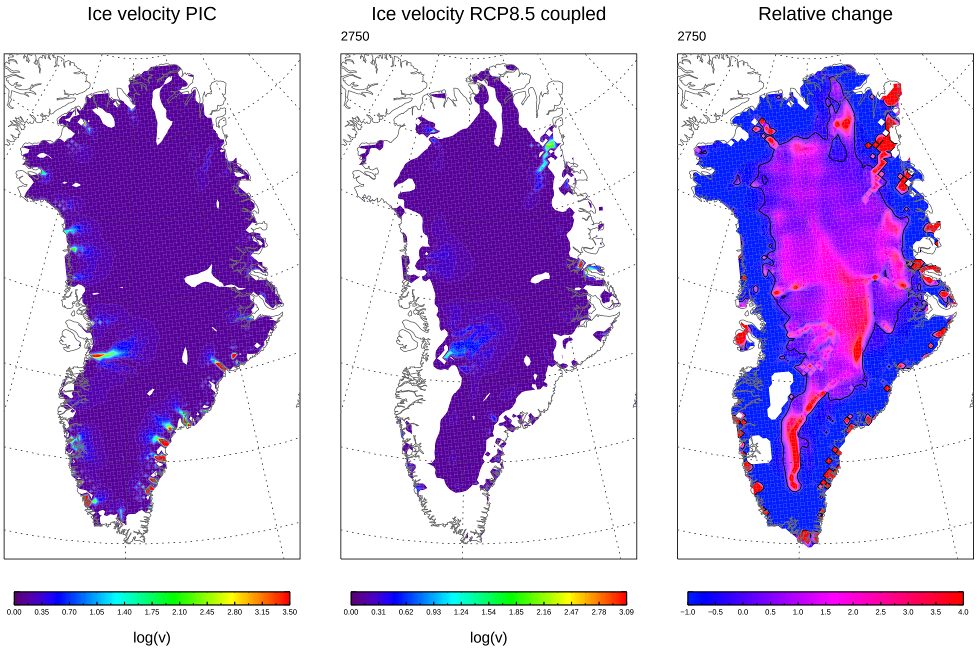

Figure 8.13: The ice velocity at the beginning of the historical run (1850) to the left. The middle plot shows the ice velocity by 2750 and the plot to the right shows the relative change between 1850 and 2750. In the rightmost plot, the black line indicates the zero contour of the relative change.

9. Conclusions and Future Work

In the preceding chapters, the structure of the coupled ice sheet-climate model system EC-Earth-PISM has been described along with some preliminary model results. Here we describe some of the focus areas regarding further development of the model system and present some concluding remarks.

9.1 Future Work

The EC-Earth-PISM coupled model has been shown to be a viable tool for testing the effects of ice-sheet-climate interactions in a changing climate, yet, some elements of the model would benefit from further development in order to improve model performance. Three issues are considered to be the main focus areas of continued development of the model system: Ocean forcings, calving and resolution.

9.1.1 Ocean Forcings

Including temporal and spatial variation in the ocean forcing is essential. Currently, heat flux from the ocean to the ice sheet is represented by a constant value controlled by a single model parameter, see sec.(3.4.2). However, the influence and importance of warmer ocean temperatures on ice melt are well-known, see e.g.
[Holland et al., 2008, Rignot et al., 2010, Straneo et al., 2010, Jacobs et al., 2011], leaving the inclusion of spatio-temporal variations in the ocean forcing a priority. As mentioned, the version of PISM used in the current EC-Earth-PISM system does not include variations in the ocean forcings. However, in later releases of PISM, variable heat fluxes from the ocean to the ice are now possible. Updating the PISM version in the coupled system and developing methods for extracting ocean forcing fields from the ocean model output would add significant value to the coupled model system.

9.1.2 Calving

Calving is an essential mechanism for removing ice from ice sheets and shelves. In Greenland, iceberg calving is a significant component of the total mass balance of the ice sheet. Calving from Greenland shows strong interannual variability with a significant increase in amplitude in recent decades as well as an overall increase in recent years [Bigg et al., 2014]. The inclusion of calving processes in ice sheet models is therefore of great importance. PISM has a calving scheme which is based on eigenvalues of the horizontal strain rate tensor
[Winkelmann et al., 2011, Martin et al., 2011, Levermann et al., 2012]. Unfortunately, this calving scheme is only applicable for large floating ice shelves and, hence, does not apply to Greenlandic conditions. As a first approach in the coupled model setup, calving is approximated by applying a mask beyond which any ice is removed. This is, however, not the most useful solution, particularly not in the case of a changing climate, where glacier fronts and overall glacier geometry are expected to change.
The inclusion of a physically-based calving scheme applicable to Greenlandic conditions in the ice sheet model PISM is a matter of priority in order to improve the overall performance of the coupled model system. One way of defining a calving law is to consider the crevasses in the ice and letting the depth of these compared to the ice height above sea level determine whether or not calving takes place [Benn et al., 2007a, Benn et al., 2007b, Nick et al., 2010]. Flow-line models where calving is introduced whenever the crevasse depth exceeds the height of the ice above sea level have been developed and tested for single outlet glaciers [Nick et al., 2010]. Developing a PISM version where this calving law is included is currently an area of research and the inclusion of such a

physically-based calving scheme for Greenland rather than the current mask-based approach would most likely improve the performance of the model, particularly in situations where climate is changing.

9.1.3 Resolution

An increase in resolution of each of the coupled model system's constituents would be an improvement. Currently, increases in resolution are planned for the atmospheric part of EC-Earth and for PISM. In the coming CMIP6 study [Meehl et al., 2014], the standard configuration of IFS (the atmosphere part of EC-Earth) will be increased from the current T159L62 to T255L91, the PISM resolution will change from 20km×20km to 10km×10km, whereas the NEMO (ocean part of EC-Earth) resolution will remain unchanged. In the case of the Greenland ice sheet, many of the important outlet glaciers have horizontal dimensions of only a few kilometres, and hence, the current model resolution of PISM (20km×20km) is insufficient to resolve the outlets. As a consequence, flow dynamics is hampered due to a reduction in available outlets for the ice and the model relies too heavily on ice melt as a mechanism for ice removal. This may be part of the reason for the too large geometry of the Greenland ice sheet in the current PISM runs at 20km×20km resolution (see e.g. sec.(6.1.2)). Increasing the model resolution and the degree of detail of the bedrock topogaphy would yield more accurate flow patterns and dynamics. In the coupled system, PISM is not the most computationally-heavy model constituent; apart from the spinup runs, the single-year PISM simulations run at a fraction of the cost of the whole system, so, from a computational perspective, increasing the PISM resolution is no obstacle. However, considerations regarding the scalability of the forcing fields extracted from EC-Earth, there are limits. In the current setup, the EC-Earth resolution of T159L62 corresponds to an approximate spatial resolution of 125km and the PISM resolution of 20km was chosen as a reasonable spatial scale. In the light of an upcoming increase in EC-Earth resolution, the PISM resolution would surely be recommended considering the possible improvements to the flow field of the ice sheet.

9.1.4 Snow Model

In the current setup of the coupled model system, the surface mass balance is determined as $P - E - R$, P being the precipitation, E the evaporation, and R the runoff. This is a rather simplistic approach and other methods of determining the SMB could be implemented in order to improve model performance. Given the script-based coupling where the SMB calculation is carried out as a separate script between the separate run cycles of EC-Earth and PISM, any changes to the SMB could be introduced without changing the rest of the model setup. A more physically-based SMB calculation using a surface energy balance approach as opposed to either the present setup or degree-day schemes as seen in e.g. [Vizcaíno et al., 2010] would be an asset to the coupled model system [Rae et al., 2012]. The current model setup works with a single layer snow scheme and does not include retention and refreezing, which makes the necessary energy balance calculations impossible. An improved multi-layer snow-scheme including retention and refreezing would be an interesting avenue for future improvements of the system.

9.1.5 Albedo

As mentioned in sec.(9.1.4) above, switching from the current SMB calculation to a setup based on the surface energy balance is of great interest. The albedo of the ice sheet and its associated feedbacks is essential to the melt of the Greenland ice sheet [Box et al., 2012]. Consequently, apart from changing the snow scheme, an improvement of the albedo representation in the model would be needed as well. The surface mass balance is very dependent on the choice of albedo parameterization, see [van Angelen et al., 2012]. Improving the albedo scheme would be an obvious focus area in terms of improving the model performance.

9.2 Conclusions

Coupled model systems capable of resolving the mutual interactions between the Greenland ice sheet and the overall climate system are in great demand, particularly considering the current climate changes and possible implications for the global sea level stemming from changes in the Greenland ice sheet caused by climate change. EC-Earth-PISM is a newly developed model system that couples a global climate model with a model for the Greenland ice sheet. The model system takes temperature and precipitation fields from the atmospheric component and uses these to determine forcing conditions for the ice sheet, which in turn provides the ocean component with fresh water input and the atmosphere with information on ice sheet extent and height. This way, interaction between the ice sheet, the ocean and atmosphere can be simulated and the response of the whole climate system to changes in greenhouse gas concentrations may be studied, taking various feedback processes into account. The EC-Earth-PISM model is suited for studies of impacts of anthropogenic climate change.

Spinup runs show a reasonably stable state of the ice sheet and climate and runs driven by historical forcings show sensible behaviour and response of the Greenland ice sheet to the changing conditions. Scenario runs following the RCP8.5 scenario shows noticeable changes to the Greenland ice sheet, that are in agreement with what is to be expected on an ice sheet in a warmer climate. EC-Earth-PISM is a viable tool for studying the full climate system and the interactions between its various components and will be useful in the study of the stability of the climate system and in identifying tipping points for the Greenland ice sheet and the climate system as a whole.

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