Final report

Greenland glacial system and future sea-level rise (GreenRise)

Leibniz-Institute: Potsdam Institute for Climate Impact Research
Reference number: SAW-2014-PIK-1
Project period: 1.1.2014-31.12.17
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Inhalt

Executive Summary of the Project GreenRise

In the course of the project, the research subject of the Greenland ice-ocean interaction via fjords and outlet glacier gained am immense importance. During last several years, more and more works were devoted to this subject and large amounts of new observational data became available. Therefore, we launched the project at a favourable time. Important to mention is that our project also facilitated the launch of the BMBF project GROCE (Greenland Ice Sheet Ocean Interaction), which led to further cooperation in the German research community including IOW, AWI and many others.

Aim of the GreenRise project was to better understand the response of the Greenland glacial system to future climate change and to gain improved estimates of the contribution of the Greenland ice sheet and outlet glaciers to future sea level rise. The Greenland glacial system consists of the ice sheet, the outlet glacier system, the fjords into which most of the outlet glaciers terminate, the sub- and englacial hydrological system and the surface snow pack. The interactions between the ice sheet and the ocean occurs in the adjacent fjords, which transport warm ocean subsurface water to the tongue of the outlet glaciers and causes submarine melting primarily by rising turbulent plumes. For understanding this system, we started development of the new model of the Greenland glacial system IGLOO (Ice-sheet model for Greenland including Ocean and Outlet-glaciers). At present, all components of IGLOO have been developed or adapted for the purpose of the project. Some components of IGLOO are coupled fully interactively, while others are still coupled offline (via manual exchange of data). IGLOO consists of the 3-D thermomechanical ice sheet SICOPOLIS, the model of basal hydrology HYDRO, the hydrostatic estuarine circulation model GETM and models for outlet glaciers and meltwater plumes. Based on these components, we developed three fully interactively coupled model configurations: (1) the ice sheet model coupled with basal hydrology, (2) the outlet glacier model coupled with a meltwater-plume model and (3) the hydrostatic fjord model coupled with a turbulent meltwater-plume model. Furthermore, we developed an improved model of basal hydrology (CUAS, Confined and Unconfined Aquifer System), which emulates forming of channels over time scales in the order of weeks. These tools enabled us to address the research questions and we found that:

- With our suite of coupled models, we performed projections of the contribution of the Greenland glacial system to sea level rise until year 2100 and year 2300.
- By applying two different scenarios (RCP 4.5 and RCP 8.5) and results of simulations with several different CMIP5 climate models, we found the Greenland ice sheet to contribute to global sea level rise between 1.9 and 13.0 cm until the year 2100 and between 3.5 and 76.4 cm until the year 2300.
- Applying the RCP 8.5 scenario and medium sensitivity in surface mass balance, we found an additional sea level rise of 5 cm due to the retreat of Greenland outlet glacier by the year 2100.
- In the RCP 8.5 scenario, the Greenland outlet glaciers show a much stronger response to ocean temperature and subglacial discharge than to surface mass balance.
- Increasing ocean temperature and subglacial discharge are of comparable importance for the future contribution of Greenland's outlet glaciers to sea level rise.
- With GETM coupled to a meltwater-plume model, we demonstrated explicitly that the height of sills at the mouth of fjords considerable impacts the transfer of heat via fjords and with this strongly changes the submarine melt of outlet glaciers.
- Simulations with CUAS showed a notable improvement of resembling the velocities of the North-East Greenland ice stream.

Report

1. Original research questions and aim of the project

The aim of the project was to gain a better understanding of the response of the Greenland land ice to future climate change and to improve the projections of its contribution to global sea level rise for time scales from decades to millennia. For this purpose, we planned to develop a model of the Greenland glacial system (IGLOO, Ice-sheet model for Greenland including Ocean and Outlet-glaciers). IGLOO describes the Greenland ice sheet, basal hydrology of the ice sheet, and numerous marine-terminated outlet glaciers, which drain into their adjacent fjords. The main idea of the project was to treat the large ice sheet by the 3-D dynamic-thermodynamic ice sheet model SICOPOLIS, while the outlet glaciers, melt water plumes and fjords – as comparable smaller-scale components of the Greenland glacial system – are treated with generic 1-D models. The state-of-the-art coastal-ocean model GETM was planned to be used to understand the interaction between glaciers and ocean water masses in Greenland's fjords and, eventually, to help in the design of the simpler generic fjord model. The coupling of all model components was recognized as one of the major challenges of the project.

One objective of the project was to better understand the role of fast ice flow and ice sheet-ocean interaction for the contribution of the Greenland glacial system to future sea level rise. The project also included an uncertainty analysis of the Greenland ice sheet (GrIS) response to future climate change using observational and palaeoclimatic constraints. With the fully coupled model IGLOO, we planned to perform large ensembles of transient simulations under different climate change scenarios from centennial to multi-millennial time scales. For the centennial time scale, we planned to use results of the state-of-the-art climate models performed in the framework of the CMIP5 intercomparison project, while for the multi-millennial time scale we wished to exploit the model of intermediate complexity CLIMBER-2 coupled with an improved version of REMBO developed at PIK. On the longer time scale, we additionally planed investigation of irreversible changes of the GrIS. The project objective and scientific question are summarized as follows.

I. Development of IGLOO (Ice-sheet model for Greenland including Ocean and Outlet-glaciers).

II. Understand the role of fast processes and ice ocean interaction for the mass loss of the GrIS.

III. Analysing the major sources of uncertainties in the response of the Greenland glacial system to climate change and how to use available observational and palaeoclimatic constraints to reduce these uncertainties.

IV. Assess the contribution of the Greenland glacial system to future sea level rise ("improved estimates").

2. Project development

An essential part of the project was the development and coupling of models. Therefore, the major challenge was to find appropriate personnel able to deal with code development. This is the reason why recruitment took some months. At PIK, we opted to replace one postdoc with a doctoral student. The other postdoc responsible for coupling left PIK before schedule without accomplishing projected work. To continue this work, we replaced him with a scientific associative who was good in coding and was made responsible for the model of outlet glaciers and its coupling with the ice sheet model. As we already stated in the proposal, there was the risk of insufficient scientific resources. The cost-neutral prolongation helped in accomplishing the project work but not all the way, as one senior scientist had to work for another project during the last year of the present project. These are the reasons why we were not able to fulfil all projected work. Still the project was rather successful, as most of the research objectives have been achieved and a large number of publications were brought on its way (12 papers plus one planned monography, see the publications section for details).

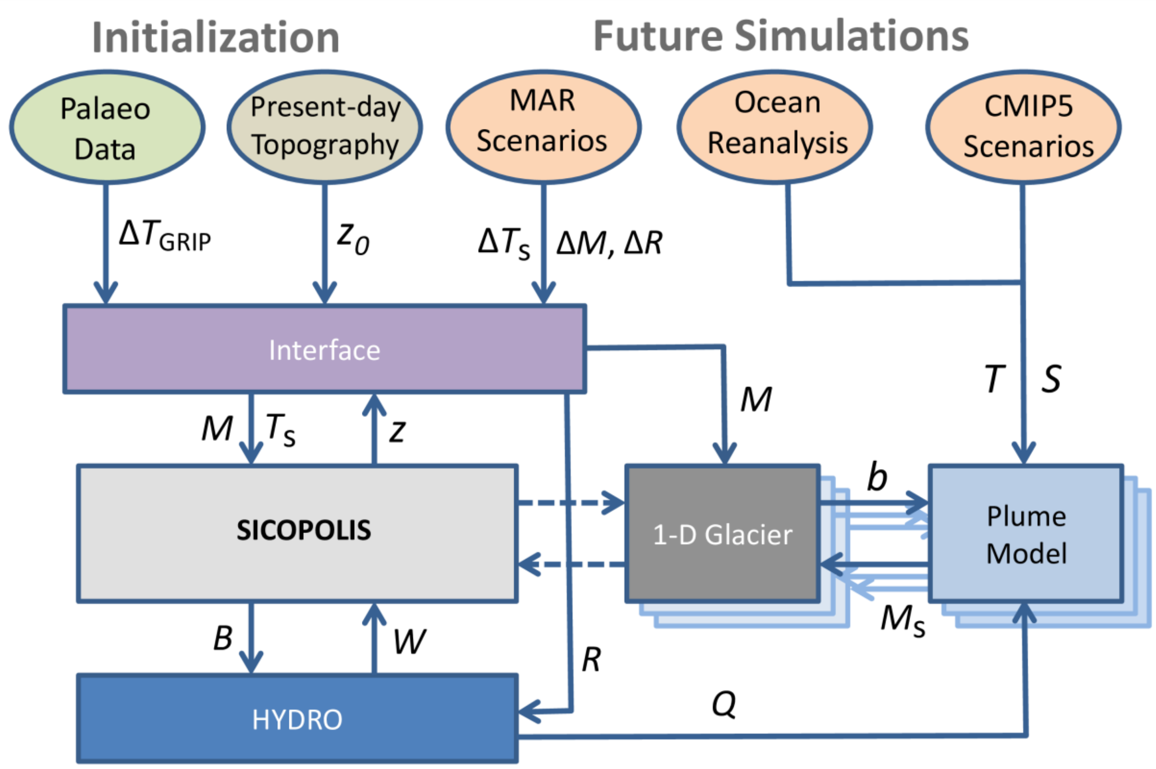

Figure 1: Flow diagram of the model IGLOO and the interaction between its components. Figure adopted from Calov et al. (2018).

Since we realized that the development of the comprehensive IGLOO model (Fig. 1) is a very complex and time consuming task and we needed tools to address our key research questions, we began model development from interactive coupling of individual components with each other, while others have been coupled only offline so far. This way we developed – besides of implementing the forcings from atmosphere and ocean – three fully coupled subcomponents of IGLOO: (1) the ice sheet model coupled with basal hydrology, (2) the outlet glacier model coupled with a turbulent plume model and (3) the hydrostatic fjord circulation model coupled with a turbulent plume model. With these three model configurations, we were able to study ice-ocean interaction, ocean-fjord interaction, fast processes in ice movement and their impact of contribution of the Greenland glacial system to future sea level rise. There are still some processes in the Greenland glacial system, which are potentially important, e. g. interaction between outlet glaciers and ice sheet through changes in the lateral flow, which we cannot study using these three model configurations.

It was planned initially that the basal hydrology component of IGLOO developed in cooperation with the AWI group will be based on an advanced model that resolves channels in the subglacial hydrologic system. However, the development of such a channelizing model of basal hydrology showed to be more difficult and time consuming as previously thought. Further on, unforeseen conceptual problems concerning the coupling procedure appeared. Therefore, we decided to use instead a simpler model of basal hydrology – HYDRO. This model is based on a water-sheet model improved at AWI and was coupled with the ice sheet model SICOPOLIS in cooperation with AWI, ILTS and PIK. In parallel to this activity, the improved model for the basal hydrology (CUAS, Confined and Unconfined Aquifer System) was newly developed at AWI (Beyer et al., 2018). PIK needed the coupled model in operation before the development of CUAS would have been finalized, because PIK relied on a model for basal hydrology to perform future sea level rise projections. Indeed, the advanced CUAS module was developed from scratch and hence a significant time has been spent on developing the concept. CUAS is published is published in The Cryosphere (Beyer et al., 2018). This model due to its high computational cost was not used in the framework of IGLOO.

Another line of development was a generic 1-D model for Greenland's outlet glaciers and its bi-directional coupling with the ice-sheet model. Basis for the 1-D flowline model was a model by Enderlin et al. (2013), which was improved and recoded into FORTRAN. To apply this model to large number of Greenland glaciers, a tool for automated aggregation and calibration of outlet glacier has been developed. Since the task of incorporating all 200 outlet glaciers was very ambitious and much more complex than previously thought, the model so far has been applied only to 12 representative Greenland glaciers (Beckmann et al., 2018a).

The implementation and adaption of a simple turbulent plume model (Jenkins, 2011) was duly accomplished. Beckmann et al. (2018b) publish the model, its calibration and comparison with state-of-the-art 3-D general circulation models of the ocean. The basal hydrology model so far has been coupled with the plume model in offline mode only, i. e., the coupling is implemented via read and write of data from files without direct dynamic exchange via code elements. The plume model has been coupled fully with the 1-D flowline glacier model and applied to 12 representative Greenland outlet glaciers. For the projections of the contribution of outlet glaciers to future sea level rise, we applied an upscaling procedure (Beckmann et al., 2018a).

For the fjord modelling at IOW, the hydrostatic model GETM (General Estuarine Circulation Model) was coupled with a turbulent plume model similar to the model used at PIK. We opted for this, because a first approach with non-hydrostatic extension in GETM turned out to be computationally too expensive and prone to numerical instabilities. Furthermore, GETM had to deliver the submarine melting rate for the outlet glaciers to complete this IGLOO component. The coupled hydrostatic fjord-plume model is fully operational.

As there were high-quality data available from the regional model MAR (Fettweis et al., 2013) for both the recent past and several future climate change scenarios, we used these MAR data to force the ice sheet and the outlet glacier models. To correct surface mass balance for changes in surface elevation, we used the method by Helsen et al. (2012), the results which favourably agrees with results from fully coupled regional climate models (Le clec'h et al., 2019).

Research questions related to the importance of fast glacial processes, ice-ocean interaction, uncertainties in the response of the Greenland glacial system to climate change were addressed. Among our most important findings is a quantification how changes in subglacial discharge and ocean warming impact the mass loss by outlet glaciers. We found that outlet glaciers forced with changes in subglacial discharge, ocean temperature and surface mass balance show a sevenfold higher contribution to sea level rise compared to those simulations which were forced by surface mass balance only; i. e., dynamical changes in outlet glaciers caused by an increase of subglacial discharge and ocean temperature are extremely important (Beckmann et al., 2018a). On the other hand, we found for the coarse resolution ice sheet model (5 km × 5 km) that the role of higher order physics in the catchment area of the outlet glaciers has a certain impact on the regional velocity field, but might be less important for projections of sea level rise than previously thought. Finally, future projections with RCP 4.5 and RCP 8.5 scenarios have been performed with the ice sheet model coupled with basal hydrology and with the outlet glacier model coupled with a meltwater-plume model. Improved estimates of the contribution of the Greenland glacial system to global sea level rise have been reported in (Calov et al. 2018; Beckmann et al., 2018a). The main results of the project are summarized in the next section.

3. Results

3.1. Model development (project objective I)

The first approach for the advanced model of basal hydrology was the development of a network that could serve as pathways for subglacial channels that could be switched on/off. This network was developed based on the concept of contact arrested propagation (Hafver et al., 2014), which has been used in deriving networks of cracks in geological applications. While the concept for forming the network can be adapted to subglacial locations well, the question of how to decide when a pathway is activated or shutdown cannot be solved easily. This led us to search for a different solution. While activating a network would model channels individually and explicitly (with numerous unknown parameters), the contrary approach is an efficient water layer, in which channels are not resolved individually. Because the existing efficient layer approaches are getting unphysical solutions for pressure, we developed the idea to combine a confined and unconfined aquifer system (CUAS; Beyer, et al., 2018) into one efficient layer, allowing the subglacial channels to fall dry, e. g. after the supraglacial supply of water vanishes at the end of the melt season. This concept solves the vertically integrated mass balance for water of the hydraulic head and assumes the constitutive equation to be a Darcy relation. Both, transmissivity and specific storage depend then on relations different for confined and unconfined aquifers, which are governed by equivalent layer thickness and a gradual transition parameter between the confined and unconfined aquifer system. The porosity in this effective layer is given by the solid ice matrix and the void space is the channel volume. Here, it is important to note, that there is no geometrical link between the geometry of an individual channel. The evolution of the channel is determined by the temporal evolution of the conductivity, which consists of two contributions: (i) a thermodynamical component representing melt at channel walls and (ii) opening and closure by creep of the overlying ice sheet. These equations have been solved on a regular grid using finite differences. This choice was made as coupling with the finite difference grid of SICOPOLIS was originally planned. During the project we recognized, that the experience of the groundwater modelling community with finite differences for Darcy unveiled some specific problems of numerical instability, which can be prevented using finite elements. In particular, the checkerboard problems had to be solved. For the development and testing of the new model CUAS, we used geometries of the international benchmark experiment for subglacial hydrology SHMIP, to which we also contributed our results. This benchmark targets simple, artificial geometries and water supply, like valley glacier geometries with different numbers of moulins and seasonal melt water supply. Figure 2, shows the evolution of conductivity, as a measure for channel evolution over times scales of weeks, driven by water supply in numerous moulins. The glacier terminus is located at x=0 and location of moulins appear as spots of high K with downstream tails in the distribution of K. Further experiments are targeting the seasonality.

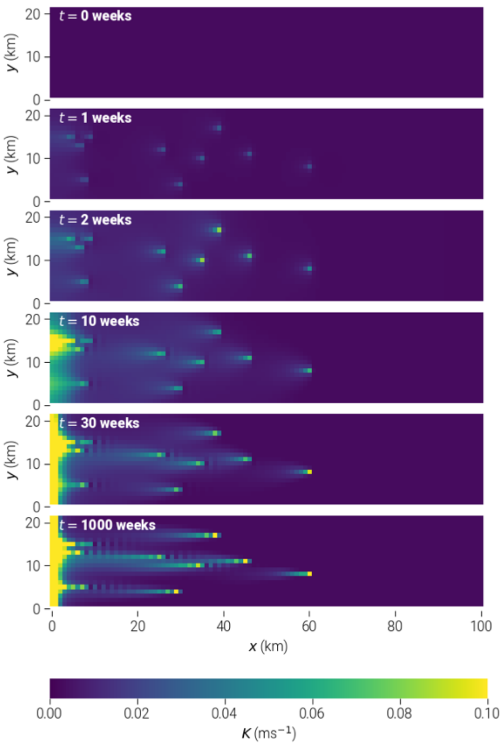

Figure 2: Evolution of conductivity K in the advanced model of basal hydrology using a schematic setup. Figure adopted from Beyer et al. (2018).

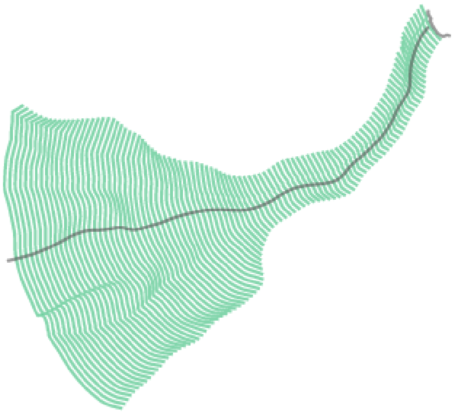

Figure 3: Catchment area of a typical Greenland outlet glaciers, central line (grey) and cross sections (green).

Part of the project was the coupling of a generic 1-D outlet glacier model with a 3-D ice sheet model. Therefore, we first had to aggregate the 2-D glacier geometry into a single 1-D flowline and weight the involved quantities as ice thickness and velocity in order to enable comparison with observations. We determined the width of each individual outlet glacier by taking cross-sections along their flow lines (Fig. 3). Along these cross-sections, we calculated the flux-weighted average for bedrock elevation, ice velocity and thickness. The width of the outlet glacier is chosen such that the flux along the cross-section is conserved. The 1-D flowline model was taken from Enderlin et al. (2013) and modified considerably. The model balances driving stress, longitudinal stress, lateral stress and basal shear stress. The main differences compared to their original MATLAB code is that we include a subgrid-scale treatment of the calving front boundary and an improved treatment of the submarine melting. Additionally, we developed a framework for joining together nearly all Greenland outlet glaciers enabling semi-automated calibration of parameters and including the possibility of coupling with the ice sheet model. This framework is rather high developed by applying structured object oriented data types.

At PIK, we implemented two simple turbulent plume models, which differ in the representation of the plume geometry, in order to analyse the submarine melt of Greenland outlet glacier. We opted for the simple models, because of their low computational costs. For the line plume model, we followed an approach by Jenkins (2011) and for the cone plume by Cowton et al. (2015). Comparison of the line and cone plume models with general circulation models (GCMs) showed qualitatively similar melt-rate profiles. In most cases, the line plume model overestimates the results of the GCMs, while the cone plume model underestimates melt rate from GCMs. Comparison with empirical data showed that the line plume model is more appropriate for simulating the melt rate of real Greenland outlet glaciers compared to the cone plume model. In practise, we had to adjust a melt parameter to a given outlet glacier. Anyhow, the number of channels feeding the cones is unknown and adjusting one melt parameter is the easier choice (Beckmann, 2018b).

The bi-directional coupling between the ice-sheet model SICOPOLIS and the basal hydrology model HYDRO is described in Calov et al. (2018). In the one direction, the ice-sheet model delivers the near-base water fluxes (basal melt rate and water drainage rate from temperate layer) to the model for basal hydrology, which distributes the water over the base of the ice sheet and computes the thickness of the basal water layer. In the other direction, the basal water layer thickness determined in HYDRO affects the basal sliding computed in the ice sheet model. Basal sliding is determined via a relation by Kleiner and Humbert (2014).

The 1-D outlet glacier-plume model is coupled bi-directional with the plume model Beckmann (2018a). The submarine melt, computed by the plume model, is send to the outlet-glacier model, while the plume model adapts to the shape and depth of the outlet glacier. Ocean temperature is taken from observations. The subglacial discharge is routed to the outlet glaciers with the model for basal hydrology of the ice sheet, HYDRO.

As GETM was not explicitly designed for fjords, several changes were necessary. A simple plume model by Jenkins (2011) together with a melt parameterization by Hellmer and Olbers (1989) was coupled with the hydrological model GETM. Input for the plume model is (prescribed) subglacial discharge as well as temperature and salinity of the surrounding fjord water. The entrainment and melt rates calculated from the melt-plume model and the maximum height of rise of the plume, the neutral buoyancy height and the vertical transport are used to calculate the dynamic boundary conditions for the fjord-plume boundary. In order to yield better agreement with the non-hydrostatic model, detrainment was implemented in the simple plume model. The coupled plume-fjord model is now able to handle changing grounding line positions of tidewater glacier and glacier with long floating tongues. Furthermore, this model is a good alternative for the higher developed and computational even more expensive non-hydrostatic models (Caroll et al., 2015).

For the climate forcing of SICOPOLIS-HYDRO, we used surface temperature, surface mass balance (SMB) and surface runoff from the regional climate model MAR (Fettweis et al., 2013) and implemented a correction of the MAR model output for the change in surface elevation by applying the gradient method of Helsen et al. (2012). In their method, they derived a representative local elevation gradient of the SMB in each grid point from a regression of simulated SMB and surface elevation within a given radius. This elevation gradient enables us to correct the simulated SMB for changes in surface elevation.

Model initialization serves the purpose to yield the correct present-day topography and velocity-temperature fields as initial conditions for the climate change projections. The present-day temperature distribution is generated by running the model over one glacial cycle and applying temperature anomalies derived from the GRIP ice core to the present-day surface temperature field simulated by MAR using re-analysis data as boundary conditions. For the SMB forcing, we followed Aschwanden et al. (2013) and forced the model with the deviation of observed surface elevation from simulated surface elevation adapted by a relaxation constant. For present day, this procedure yields the implied SMB, which is assumed the present-day SMB including the errors of the model (Calov et al., 2018). In our future projections, the implied present-day SMB is added to the SMB anomalies from the MAR regional climate model using CMIP5 models as boundary conditions.

3.2. Simulations of the present-day state of the Greenland ice sheet, its outlet glaciers and fjords (project objectives II and III)

The initialization of SICOPOLIS-HYDRO (required for research question IV) for yielding a favourable present-day state of the GrIS is described in Calov et al. (2018). We showed that there is a tradeoff between optimal representation of present-day surface elevation and at the same time simulating a reasonable SMB field. As optimal relaxation constant, we found a value of 100 years. Further on, Calov et al. (2018) used optimal sliding parameters, which were found in the course of this project by inspecting the RMS error of simulated and observed horizontal velocities of the ice sheet. In that paper, we showed that there is good agreement between observed and simulated velocity fields. We used a new version of the ice sheet model SICOPOLIS, which includes hybrid dynamics (Bernales et al, 2017). Hybrid dynamics incorporates via the shelfy stream approximation (SStA) longitudinal and lateral stresses, which are important for nearer-margin fast flow areas, along with horizontal plane shear via the shallow ice approximation (SIA), important for the slow-flow regions in the more central regions of the ice sheet. However, for sensitivity test we did not fully abandon the SIA, because of its computational efficiency and because the SIA largely captures major aspects of ice-sheet dynamics.

For the ice sheet, we inspected the role of fast processes (scientific question II) by comparing the shallow ice approximation with the hybrid approach. It showed that at least in the used horizontal resolution of 5 km the simulated surface velocity cannot be improved too much in the hybrid approach. One might think that one can always find optimal sliding parameters for the SIA mode or the hybrid mode which give comparable velocities, because the lateral drag which is included in the hybrid mode can be compensated with higher basal drag in the SIA mode wherein lateral drag is excluded. Nevertheless, one must consider that the ice bed of Greenland has a spatially dependent roughness (troughs on spatial scale of some kilometres), what affects lateral drag. Deeply incised troughs supports more lateral drag compared to wide and flat toughs. Therefore, in our experiments with spatially constant sliding coefficient, we can gain regional improvements with the hybrid: Compared to the SIA model, the hybrid model is able to better resolve the velocity over regions with different bed roughness (Fig. 4). This fact can be overlooked in simulation which optimize for a spatially dependent sliding coefficient, because such optimization could hide differences based on model physics. In conclusion, incorporating lateral and longitudinal drag is important even for rather coarse resolution ice sheet model. Certainly, this effect depends on horizontal resolution for the ice sheet model.

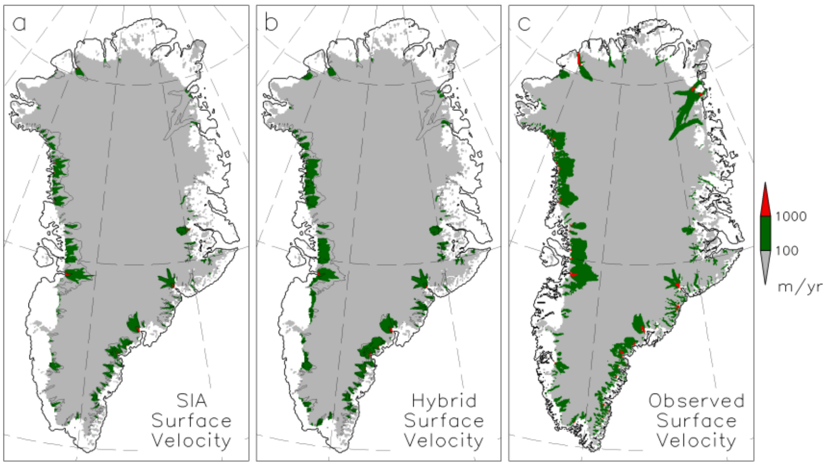

Figure 4: Present-day surface velocity of the Greenland ice sheet. (a) simulated with shallow ice approximation, (b) simulated in hybrid mode and (c) observed surface velocity by Rignot and Mouginot (2012). Colours show regions of fast flow, while grey indicates regions of slow flow.

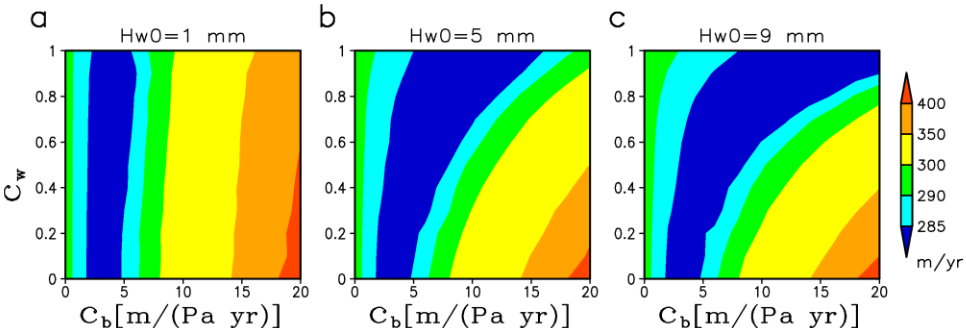

Figure 5: Parameter space for the present-day state of the Greenland ice sheet from large ensemble simulation over one glacial cycle varying three sliding parameter. Panels (a) to (c) differ in thickness for the basal water layer H_w^0 = 1, 5 and 9 mm. Axes include background sliding C_b and strength of water layer sliding C_w. Every panel corresponds to 121 simulations.

Applying SIA mode for basic sensitivity tests and for the calibration of the parameters of the ice sheet model (project objective III), we thoroughly inspected the parameter space of the parameter in the sliding law, which we extended in order to introduce the effect of basal layer the basal water layer (Kleiner and Humbert, 2014). For this purpose, we run the model over one glacial cycle until present-day and varied three sliding parameters. We found that a slight improvement in the accuracy of modelled horizontal ice velocity can be yielded (Fig. 5). However, the improvement was not fully satisfactory. The reason for this could be the still too coarse horizontal resolution or that improvements in resolving velocity rather should be sought in the course of seasonal cycles by applying the improved model for basal hydrology CUAS.

With the outlet glacier meltwater plume model, Beckmann et al. (2018a) simulated the present-day state of 12 Greenland outlet glaciers using an elevation-relaxation method similar to

Calov et al. (2018). This simulation served as model validation and as model initialization for treating research objective IV. Our simulated submarine melt rate compare relatively well with available data for most of inspected outlet glaciers (Enderlin and Howat, 2013). For Kong Oscar and Docker Smith our results nearly match. Only for Upernavik North and Kangerlussuaq our submarine melt rates are much lower that in the data source (Enderlin and Howat, 2013). However, it should be noted that many glaciers accelerated since 2000, so it is not clear whether the fluxes reported by Enderlin and Howat (2013) are true equilibrium fluxes.

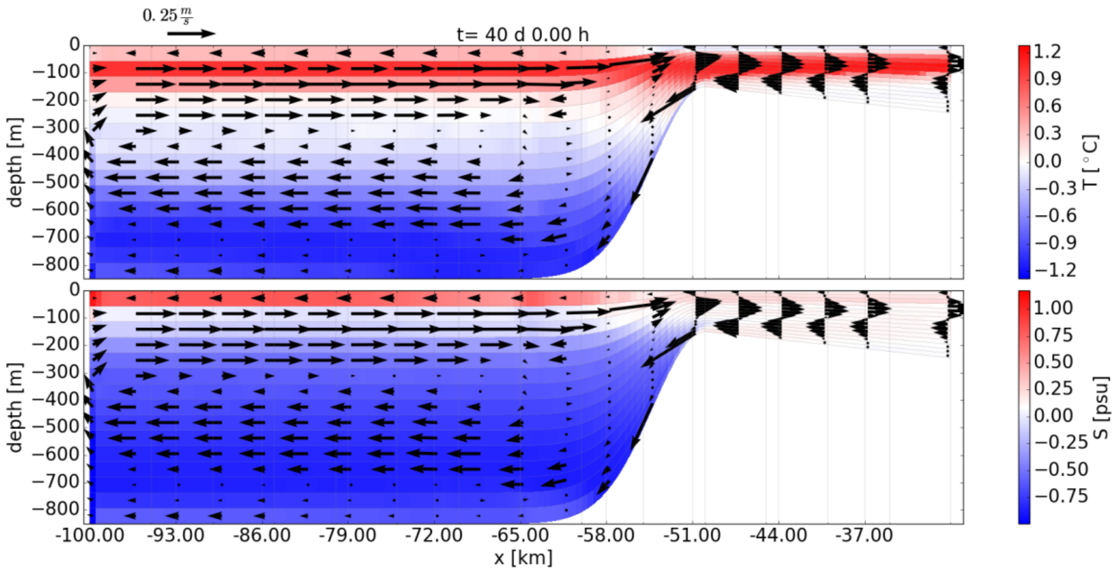

Figure 6: Temperature and salinity anomalies compared to initial state after 40 days. Subglacial discharge is 75 m³/s, a sill with its centre is situated at x=-50km in 150 m depth.

The project collaborates at IOW explicitly demonstrated that the simple turbulent model of meltwater plume is able to resolve plume velocity well comparable with that from non-hydrostatic models (project objective II). Even more, modified GETM coupled to this turbulent meltwater plume model was used to investigate the impact of different parameters, as the impact of subglacial discharge on submarine melting. Scientific questions as the quantification of the impact of glacier geometries and fjord bathymetry on the fjord circulation and thus the production of fresh water by submarine melting at the mouth of fjords, including impact of different sills height, have been answered (project objectives II and III). It shows that very shallow sills at the mouth of a fjord hamper the influx of warm subsurface water and reduce the submarine melting of the fjord's outlet glaciers. This impact of sill depth is illustrated in Fig. 6. Heat and salt are transported upwards by the buoyant plume and can leave the fjord basin above the sill. The renewing of the basin water by warm and salty shelf bottom water is constrained by sills. Hence, temperature and salinity are decreasing in the basin and thus also the depth averaged melt rate decreases from initial 1.8 m/day to 1.5 m/day within 40 days.

3.3. Large ensembles of climate projections with RCP4.5 and RCP 8.5 (project objectives II, III and IV)

Parts of the text in this subsection are taken, mixed with new text and modified from Calov et al (2018) and Beckmann (2018a).

For our projections, we initialized SICOPOLIS-HYDRO over one glacial cycle with a relaxation procedure described in the previous section. We performed the projection simulations with the hybrid scheme, because it better resolves the velocity field. As forcing, we applied surface temperature, surface mass balance and surface runoff anomalies derived from RCP

4.5 and RCP 8.5 scenarios created by MAR with boundary conditions from simulations with three CMIP5 models (NorESM1, MIROC5 and CanESM2), which represent model uncertainties. For surface temperature, SBM and surface runoff, we included an elevation correction. The sliding parameters, which determine fast flow, are found by an optimization procedure using observed surface velocity. For details, see Calov et al. (2018).

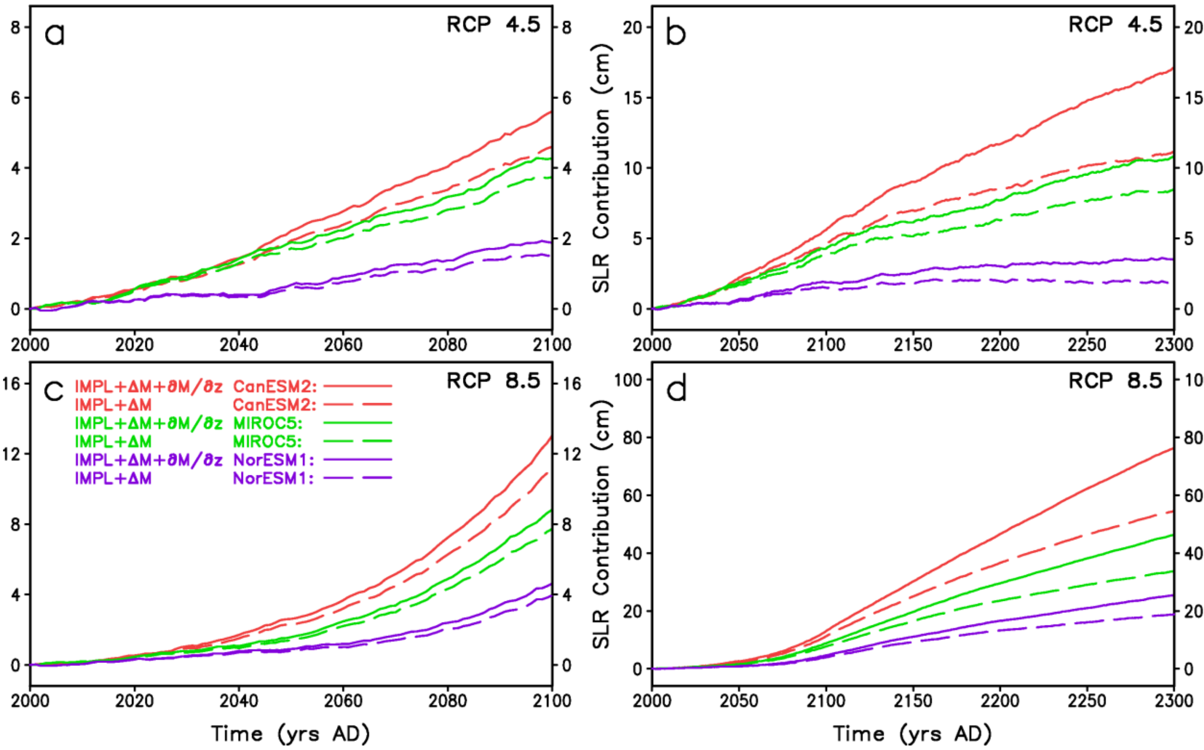

Figure 7: Contribution of the Greenland ice sheet to future sea level rise under MAR forcing for different scenarios. Sea level rise is referenced to the year 2000. RCP 4.5 projections: (a) years 2000–2100 and (b) years 2000–2300. RCP 8.5 projections: (c) years 2000–2100 and (d) years 2000–2300. Colours indicate the different CMIP5 general circulation models utilized by MAR. Different line characteristics specify optimal simulations with (solid) and without (long dashed) elevation correction for the surface mass balance. *All simulations are with hybrid ice dynamics and HYDRO basal hydrology. The figure is taken from Calov et al. (2018) and modified.*

Figure 7 show the resulting time series. Our simulated GrIS sea level contribution for 2100 ranges from 1.9 cm (RCP 4.5, NorESM1) to 13.0 cm (RCP 8.5, CanESM2), see Table 1. The elevation SMB correction is an important factor. Ignoring the elevation SMB correction diminishes simulated 21st-century GrIS sea level contribution between 0.4 and 1.7 cm. Of course, this effect is strongest for the extreme RCP 8.5 scenario together with CanESM2, the CMIP5 model exhibiting the largest SMB anomaly over Greenland.

Certainly much stronger than for the 21st century, the sea level contribution of the GrIS for the year 2300 ranges from 3.5 cm to 76.4 cm. The importance of the elevation SMB feedback clearly increases with the elapsed time of the projections, as the respective curves with this correction on/off diverge more and more from each other. For RCP 8.5 with CanESM2, the relative increase of additional loss in ice volume due to elevation SMB correction nearly triples from 2100 to 2300, from 15% to 40%.

Overall, our simulations show a strong dependence of the GrIS sea level contribution both on the RCP scenarios and on the model used to force MAR. Besides, the impact of the description of ice dynamics on the GrIS sea level rise contribution (not shown explicitly with a figure here) – i. e., whether SIA or hybrid is used – is minor, although the velocities over the catchment areas of the ice streams are better represented in the hybrid model compared to the SIA model (Fig. 4).

Complementary to the projections with the ice sheet model containing treatment of basal hydrology, the team members Beckmann et al. (2018a) used the outlet glacier-plume model to perform year 2100 projections for the contribution of 12 Greenland outlet glaciers to sea level rise under the high end scenario RCP 8.5. The SMB forcing is constructed analogous to Calov et al. (2018) using MAR data for SMB forcing but from the MIROC5 model only. The outlet glacier plume model received its subglacial discharge via offline coupling in two steps.

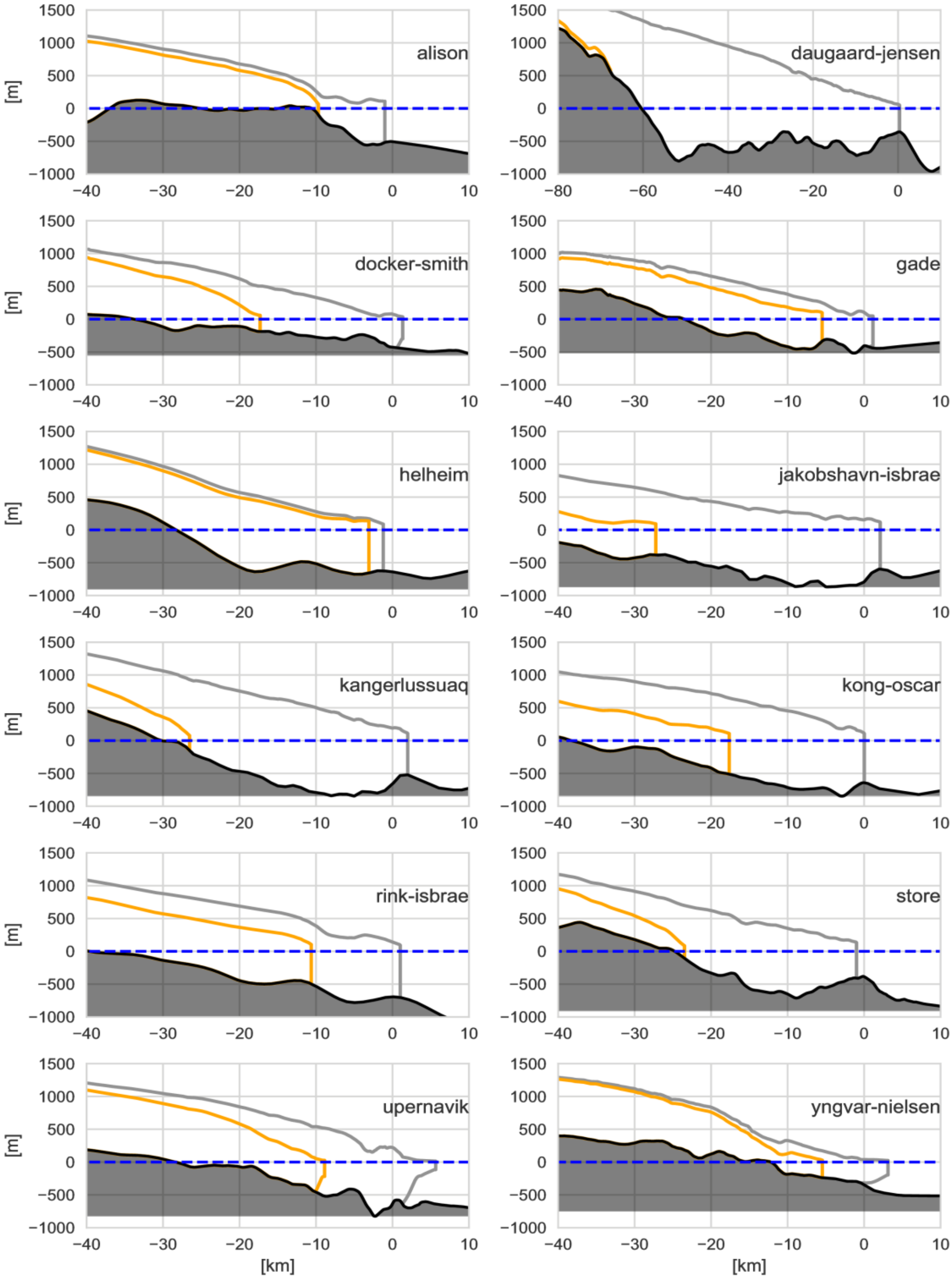

Figure 8: Shape of simulated outlet glacier. Grey lines indicate initial shapes from relaxation to present-day. Orange lines depict shapes from the RCP 8.5 year 2100 projection. Figure adopted from Beckmann et al. (2018a).

First, SICOPOLIS delivers monthly surface runoff and basal runoff. Then the water is routed via HYDRO and distributed via a distance-based algorithm to the 12 outlet glaciers, which are inspected by Beckmann et al. (2018a). Present-day reference for fjord temperature and salinity were taken from AOGCM reanalysis data. To construct minimum and maximum scenarios, ocean-temperature anomalies from several CMIP5 models closest to the considered fjords were taken.

In our simulations, the retreat of individual outlet glaciers under climate change is more or less severe (Fig. 8). This is consistent with the general understanding of the subject matter. After 100 years in RCP 8.5 scenario, some glaciers retreat entirely and become nearly land-terminated (Alison Glacier, Daugaard-Jensen Glacier, Kangerlussuaq Glacier, Store Glacier), while others show a minor change in the position of the grounding line only (Helheim Glacier, Gade Glacier).

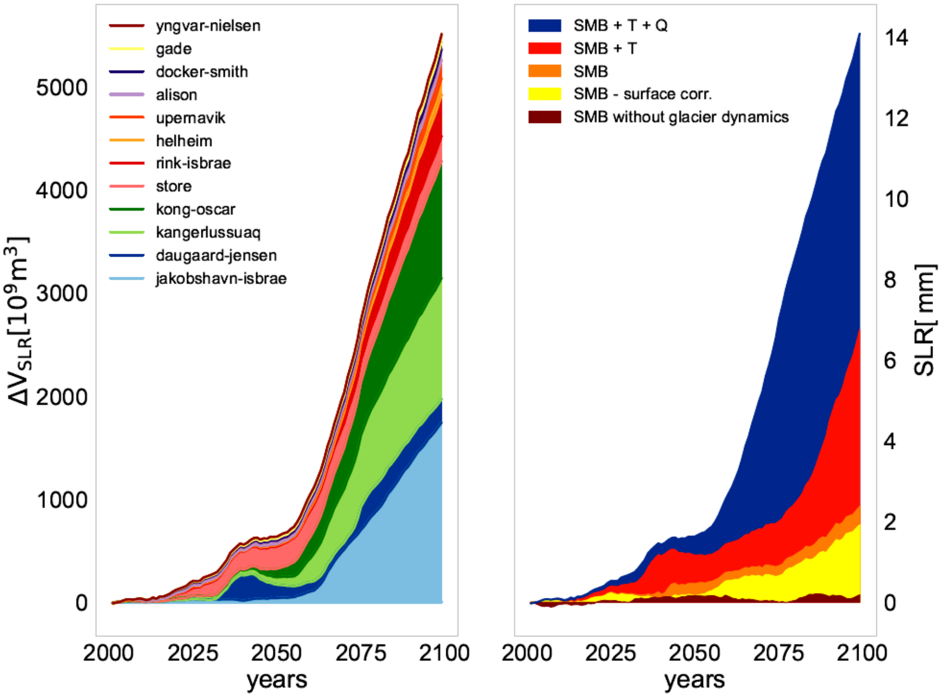

Figure 9: Median of projected sea level rise for 12 Greenland outlet glaciers switching different processes on and off (see inset). Left: contribution of the single outlet glaciers. Right: Cumulative contribution of all 12 outlet glaciers. The figure is taken from Beckmann et al. (2018a).

Figure 9 shows simulated contribution to sea level change of the 12 Greenland outlet glaciers by Beckmann et al. (2018a). Some outlet glaciers contribute little and other ones contribute more to sea level rise. Jakobshavn Isbræ shows the most significant contribution to SLR, due to the big catchment area and large retreat, followed by Kangerlussuaq Glacier due to its full retreat (Fig. 9a). In year 2100, all 12 outlet glaciers contribute 1.4 cm to sea level rise (Fig. 9b). Additionally, it can be seen in Fig 9b that ocean temperature and subglacial discharge play the dominant role over surface mass balance for the retreat of outlet glaciers, while SMB is much less important (project objectives II and III).

With an upscaling method based on matching present-day grounding line discharge to simulated future sea level rise, we estimated a year 2100 contribution to sea level rise for all Greenland outlet glaciers of 5 cm (Beckmann et al., 2018a). This contribution to sea level rise by all outlet glaciers can be added directly to the sea level rise contribution of the Greenland ice sheet for RCP 8.5 simulated by Calov et al. (2018).

Table 1 summarizes the results of our projections (Calov et al., 2018; Beckmann et al., 2018a).

Table 1: Simulated sea level contribution of the Greenland ice sheet and its outlet glaciers (*). For RCP 8.5 with MAR-MIROC5 forcing, we estimated the contribution of the Greenland outlet glaciers too, giving a total of 13.8 cm.

	Year 2100		Year 2300	
MAR GCM	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
NorESM1	1.9	4.6	3.5	25.5
MIROC5	4.3	8.8 (+5*)	10.8	46.3
CanESM2	5.6	13.0	17.1	76.4

4. Statement on economic usability

Our results are of societal value but have not any economic value. Further on, we did not apply for any patent. To our knowledge, there was not any cooperation with industry/business.

5. Cooperation with project partners and their contributions to the project

There was a fruitful and close cooperation between the several project partners, including international partners in Japan and Spain. The most important contributions came from AWI, ILTS and IOW. Over the project term, we had six common meetings in Bremerhaven, Potsdam and Warnemünde. These meetings further stimulated the already close cooperation between the project partners. Additionally, there were several visits of scientists to the partner institutes facilitating exchange of ideas and scientific findings. Very important for the project was the stay of the doctoral student responsible for basal hydrology at AWI. Under the supervision of AWI and together with PIK scientists, he improved an existing simple and developed a new advanced model of the basal hydrological system of ice sheets (HYDRO and CAUS). Likewise, the cooperation with IOW was exceptionally close and they contributed to the project with developments for an estuarine circulation model and simulation of a Greenland fjord with this model. These simulations provided important support for the climate projections performed at PIK. Last not least, ILTS provided PIK with highly competent support in usage of the most recent version of the ice sheet model SICOPOLIS and substantially helped PIK and AWI in coupling SICOPOLIS with the module of basal hydrology HYDRO.

6. Storage and dissemination of data

At PIK, a guideline for storage of data from publications exists explaining the workflow in very detail including a reminder system safeguarding the execution of data storage. The dissemination of our data inside the institute is possible via links in a meta-database to the real data stored.

7. Scientific theses out of the project

Dissertations by Johanna Beckmann (cumulative, successful, 4 papers, 2 of them first author papers) and Sebastian Beyer (cumulative, successful, 6 papers, 1 of them first author papers).

8. Publications out of the Project

Appeared

Beckmann, J., Perrette, Beyer, S., M., Calov, R., Willeit, M., and Ganopolski, A., Modeling the response of Greenland outlet glaciers to global warming using a coupled flowline-plume model, The Cryosphere Discuss, doi:10.5194/tc-2018-89, 2018a.

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Upcoming manuscript

Humbert, A., Neckel, N., Binder, T., and Beyer, S., Supraglacial lake drainage forming englacial channels at 79°N Glacier, Greenland.

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