低温科学 75 （2017） 117-129
doi: 10.14943/lowtemsci. 75. 117

Projecting the response of the Greenland ice sheet to future climate change with the ice sheet model SICOPOLIS

Ralf Greve[1]*, Reinhard Calov[2], Ute C. Herzfeld[3]

Received 13 January 2017, accepted 16 January 2017

Numerical modelling has become established as an important tool for understanding ice sheet dynamics in general, and in particular for assessing the contribution of the Greenland and Antarctic ice sheets to future sea level change under global warming conditions. In this paper, we review related work carried out with the ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets). As part of a group of eight models, it was applied to a set of standardised experiments for the Greenland ice sheet defined by the SeaRISE (Sea-level Response to Ice Sheet Evolution) initiative. A main finding of SeaRISE was that, if climate change continues unabatedly, the ice sheet may experience a significant decay over the next centuries. However, the spread of results across different models was very large, mainly because of differences in the applied initialisation methods and surface mass balance schemes. Therefore, the new initiative ISMIP6 (Ice Sheet Modeling Intercomparison Project for CMIP6) was launched. An early sub-project is InitMIP-Greenland, within which we showed that two different initialisations computed with SICOPOLIS lead indeed to large differences in the simulated response to schematic future climate scenarios. Further work within ISMIP6 will thus focus on improved initialisation techniques. Based on this, refined future climate simulations for the Greenland ice sheet, driven by forcings derived from AOGCM (atmosphere-ocean general circulation model) simulations, will be carried out. The goal of ISMIP6 is to provide significantly improved estimates of ice sheet contribution to sea level rise in the coming years.

Keywords: Greenland, ice sheet, climate change, sea level rise, modelling

1. Introduction

Ice sheets are grounded ice masses of sub-continental to continental size (e.g., Molnia, 2004). The two ice sheets on the present-day Earth are those of Greenland and Antarctica. Most of the terrestrial freshwater reserves are stored in these two ice sheets, amounting to ～ 65 m of sea level equivalent (Antarctica ～ 58 m, Greenland ～ 7.4 m; Vaughan et al., 2013).

Like the smaller ice caps and glaciers, ice sheets show gravity-driven creep flow ("glacial flow"), sustained by the underlying land. This leads to thinning and horizontal spreading, which is essentially compensated by snow accumulation in the higher (interior) areas and melting and calving in the lower (marginal) areas (Fig. 1). Any imbalance of this dynamic equilibrium leads to either growing or shrinking ice masses.

The Greenland ice sheet is significantly warmer than the Antarctic ice sheet. Therefore, the regions close to the ice margin experience a considerable amount

*Corresponding author
e-mail：greve@lowtem.hokudai.ac.jp
1）Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan
2）Potsdam Institute for Climate Impact Research, Potsdam, Germany
3）Department of Electrical, Computer and Energy Engineering, University of Colorado, Boulder, USA

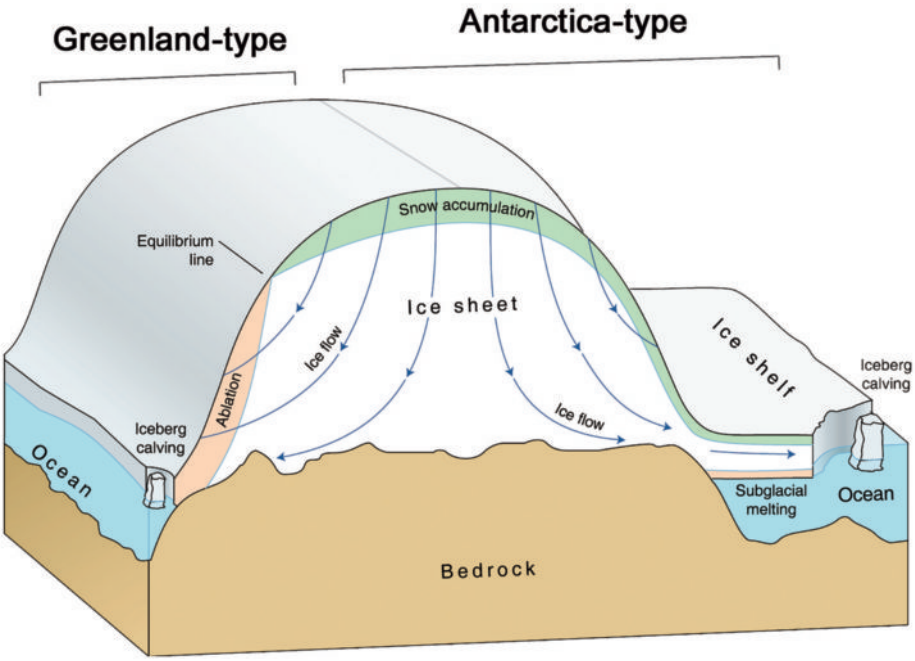

Figure 1 : Main processes that govern the evolution and dynamics of the Greenland and Antarctic ice sheet. Modified from lima.nasa.gov/antarctica/.

of surface melting (ablation) during the summer season, so that the mass loss of the Greenland ice sheet is divided roughly equally between melting and calving (left part of Fig. 1; van den Broeke et al., 2009). In contrast, for the much colder Antarctic ice sheet surface melting is virtually non-existing, and it loses mass mainly through basal melting under its attached, floating ice shelves and calving at the fronts of the ice shelves (right part of Fig. 1; Rignot et al., 2013).

Observations indicate that both the Greenland and Antarctic ice sheets have already shown strong, and accelerating, reactions on global warming (Shepherd et al., 2012; Hanna et al., 2013; Enderlin et al., 2014; Khan et al., 2015). The average rate of ice loss from the Greenland ice sheet has increased substantially from 34 $\pm$40 Gt a^{-1} over the period 1992–2001 to 215$\pm$59 Gt a^{-1} for 2002–2011 (IPCC, 2013a) and 341$\pm$22 Gt a^{-1} for 2011–2014 (Helm et al., 2014), and the average rate of ice loss from the Antarctic ice sheet has increased from 30$\pm$67 Gt a^{-1} over the period 1992–2001 to 147$\pm$75 Gt a^{-1} for 2002–2011 (IPCC, 2013a) and 116$\pm$76 Gt a^{-1} for 2011–2014 (Helm et al., 2014). According to the most recent figures for 2011–2014 (Helm et al., 2014), which were determined by CryoSat-2 altimetry, Greenland contributes nearly 75% to the combined mass loss of the two ice sheets.

Modelling the response of the Greenland and Antarctic ice sheets to anthropogenic climate change has been undertaken for more than two decades. Among the older studies are, e.g., Huybrechts and Oerlemans (1990), Huybrechts et al. (1991), de Wolde et al. (1997), Greve (2000) and Ridley et al. (2005). More recently, this has become a fairly hot topic in climate science because, in the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC), it was explicitly stated that *"Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude"* (IPCC, 2007). The scientific community responded by launching two major ice sheet modelling initiatives, namely SeaRISE (Sea-level Response to Ice Sheet Evolution; tinyurl.com/srise-umt) and Ice2sea (www.ice2sea.eu). Both projects are meanwhile completed and provided valuable input for the Fifth Assessment Report (AR5) of the IPCC (IPCC, 2013b, and references therein). Efforts towards further improved assessments of the expected contribution from the Greenland and Antarctic ice sheets to sea level rise are continued within the ongoing ISMIP6 project (Ice Sheet Modeling

Intercomparison Project for CMIP6; Nowicki et al., 2016). In this paper, we focus on the Greenland ice sheet and review the contributions to SeaRISE and ISMIP6 with the ice sheet model SICOPOLIS.

2. Ice sheet model SICOPOLIS

SICOPOLIS (SImulation COde for POLythermal Ice Sheets; www.sicopolis.net) is a dynamic/thermodynamic ice sheet model that was originally created by Greve (1995, 1997) in a version for the Greenland ice sheet. Since then, SICOPOLIS has been developed continuously and applied to problems of past, present and future glaciation of Greenland (e. g., Robinson et al., 2012), Antarctica (e. g., Kusahara et al., 2015), the entire northern hemisphere, the polar ice caps of the planet Mars and others. A list of the > 100 peer-reviewed papers that use or describe SICOPOLIS can be found at www.sicopolis.net/publ.

The model simulates the large-scale dynamics and thermodynamics (ice extent, thickness, velocity, temperature, water content and age) of ice sheets three-dimensionally and as a function of time. It is based on the shallow ice approximation for grounded ice (Hutter, 1983; Morland, 1984) and the shallow shelf approximation for floating ice (Morland, 1987; MacAyeal, 1989). Recently, hybrid shallow-ice/shelfy-stream dynamics has been added as an option for ice streams (Bernales et al., 2017). The rheology is that of an incompressible, heat-conducting, power-law fluid (Glen's flow law; e.g., Greve and Blatter, 2009). Isostatic depression and rebound of the lithosphere due to changing ice load is modelled by either the local-lithosphere-relaxing-asthenosphere (LLRA) or the elastic-lithosphere-relaxing-asthenosphere (ELRA) approach with an isostatic time lag (Le Meur and Huybrechts, 1996). External forcing is specified by (1) the air temperature at the ice surface, (2) the surface mass balance (precipitation minus runoff), (3) the sea level surrounding the ice sheet (that defines the land area available for glaciation), and (4) the geothermal heat flux prescribed at the bottom of the lithospheric thermal boundary layer.

A particular feature of SICOPOLIS is its very detailed treatment of ice thermodynamics. A variety of different thermodynamics solvers are available, namely the polythermal two-layer method, two versions of the one-layer enthalpy method, the cold-ice method and the isothermal method (Greve and Blatter, 2016). The polythermal and enthalpy methods account in a physically adequate way for the possible co-existence of cold ice (with a temperature below the pressure-melting point) and temperate ice (with a temperature at the pressure-melting point) in the ice body, a condition that is referred to as "polythermal". It is hereby assumed that cold ice makes up the largest part of the ice volume, while temperate ice exists as thin layers overlying a temperate base. In the temperate ice layers, the water content is computed, and its reducing effect on the ice viscosity is taken into account.

SICOPOLIS is coded in Fortran and uses finite difference discretisation techniques on a staggered Arakawa C grid, the velocity components being taken between grid points (Arakawa and Lamb, 1977). For the simulations of the Greenland ice sheet discussed here, all computations are carried out in a stereographic plane (standard parallel at 71°N, central meridian at 39°W), spanned by the Cartesian coordinates x and y. The distortions due to the stereographic projection are corrected by appropriate metric coefficients. Floating ice is ignored, and only the shallow ice approximation is used. A sketch of the model is shown in Fig. 2.

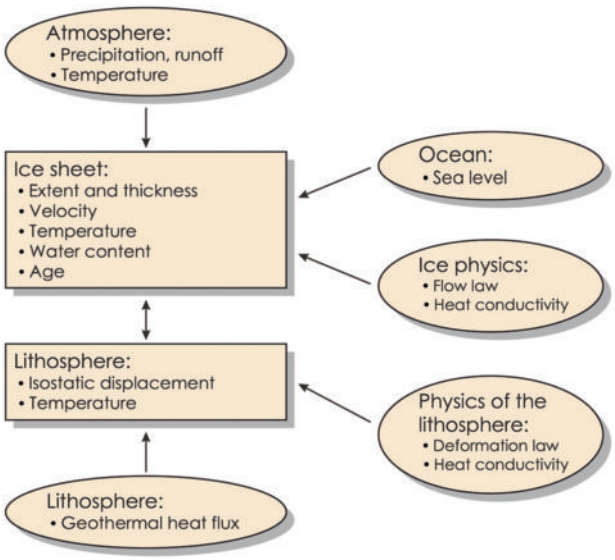

Figure 2 : Sketch of the ice sheet model SICOPOLIS. The rectangular boxes denote prognostic model components, while the ovals indicate required model input (boundary conditions etc.).

3. SeaRISE-Greenland

Sea-level Response to Ice Sheet Evolution (SeaRISE) was a community-organised effort to explore the sensitivity of the available ice sheet models to external forcing, and to gain insight into the potential future contribution to sea level from the Greenland and Antarctic ice sheets (Bindschadler et al., 2013; Nowicki et al., 2013a, b). The main characteristics of SeaRISE were (1) the use of multiple models, (2) standardisation of datasets that describe the physical setting, model initialisation and sensitivity experiments, and (3) application of an 'experiment minus control' method to isolate ice-sheet sensitivity to any environmental-forcing experiment. Results served as input for the Fifth Assessment Report (AR5) of the IPCC (IPCC, 2013b).

3.1 Paleoclimatic spin-up

Here, we only discuss the SeaRISE experiments with SICOPOLIS for the Greenland ice sheet. The strategy for model initialisation (i.e., obtaining a suitable present-day configuration of the Greenland ice sheet that can serve as initial condition for the future climate experiments) was to carry out a paleoclimatic spin-up over a full glacial cycle. However, it is difficult to reproduce the observed geometry by an unconstrained, freely evolving simulation without heavy tuning (e. g., Greve et al., 2011). For this reason, we carried out the spin-up simulation in four steps, each run using the result of the previous run as the initial condition (Greve and Herzfeld, 2013):

1. An initial relaxation run with freely evolving ice topography over 100 years, starting from the present-day geometry and isothermal conditions at −10℃ everywhere, in order to avoid spurious noise in the computed velocity field. The ice sheet is not allowed to extend beyond its present-day margin. The surface temperature and the sea level are those of today; the surface mass balance and basal sliding are set to zero.
2. A steady-state run from 250 ka BP (before present) until 125 ka BP, with the entire topography (surface, bed, ice margin) kept fixed over time. The surface temperature is that of 125 ka BP; the surface mass balance is unspecified (due to the fixed topography). The purpose of this run is to bring internal and basal temperatures to near equilibrium for the climate conditions at 125 ka BP.
3. A transient run from 125 ka BP until 100 years BP; with the entire topography kept fixed over time in order to enforce a good fit between the simulated and observed present-day topographies. The surface temperature varies over time, reflecting the sequence of the Eemian interglacial, the Weichselian glacial and the Holocene; the surface mass balance is unspecified.
4. A short transient run from 100 years BP until the present, with evolving ice topography in order to avoid transition shocks at the beginning of the subsequent future climate experiments. The climatic forcing (surface temperature, surface mass balance) and the sea level are kept steady at today's conditions, and the ice sheet is not allowed to extend beyond its present-day margin.

The horizontal resolution is 10 km prior to 5 ka BP and 5 km from 5 ka BP until today. For further details of the set-up cf. Greve and Herzfeld (2013).

3.2 Future climate experiments

The future climate experiments discussed here are a subset of the suite defined by SeaRISE for the Greenland ice sheet (Bindschadler et al., 2013):

- CTL — constant climate control run; beginning at present (more precisely, the year 2004, corresponding to $t=0$) and running for 500 years, holding the climate steady to the present climate.
- C2 — 1.5 × A1B climate forcing [mean annual temperature, mean July temperature and precipitation anomalies derived from an ensemble average from 18 of the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC AR4) models, run under the A1B emission scenario; see Fig. 2 and accompanying text by Bindschadler et al. (2013)] until 2098, then held steady.
- S1 — constant climate forcing, 2 × basal sliding.
- M2 — constant climate forcing, 20 m w.e. a^{-1} ocean-induced marginal melting (applied at grounded ice cells that have a base below the sea level and are adjacent to ocean).
- R8 — combination experiment approximating

IPCC's RCP (Representative Concentration Pathway) 8.5 scenario; 1.5×A1B climate forcing (extrapolated beyond 2098 over the entire 500 years) plus 1.5×basal sliding plus ocean-induced marginal melting increasing over time to a maximum of 70 m w.e. a^{-1} (for details of this set-up and its rationale see Fig. 14 and accompanying text by Bindschadler et al. (2013)).

The reason for the selection of C2, S1 and M2 is that they are closest to the settings of the combination experiment R8. The horizontal resolution is 5 km for all experiments. For further details see Greve and Herzfeld (2013).

3.3 Results

The results of the paleoclimatic spin-up run (Section 3.1) for the present are shown in Figs. 3 and 4. Comparison of the simulated (Fig. 3a) and observed (Fig. 3b; data by Joughin et al., 2010, 2016) surface velocities reveals that the general pattern with the low-velocity (<10 m a^{-1}) 'backbone', the general acceleration towards the coast and the organisation into drainage systems is reproduced well. As it was discussed in detail by Greve and Herzfeld (2013), on a more local scale, the Jakobshavn Ice Stream, Helheim and Kangerdlugssuaq Glaciers are also reproduced reasonably well despite the applied shallow ice dynamics. In contrast, the North-East Greenland Ice Stream (NEGIS) and the Petermann Glacier are only weakly pronounced in the simulation.

Owing to the fixed-topography constraint during most of the spin-up run, the simulated and observed ice thickness distributions (Fig. 4) agree very well, the misfit being generally small (<100 m). However, some areas stick out, and one of them is the NEGIS area, where simulated ice thicknesses are too large as a consequence of the underpredicted drainage towards the coast. The same holds for the area of Petermann Glacier in the northwest. In contrast, along the south-eastern ice margin simulated ice thicknesses are often too small, which may be due to over-predicted ice flow or to inaccuracies in the surface mass balance. Most of the rapid topographic adjustments that lead to these local misfits arise early during the short transient run over 100 years at the end of the spin-up sequence (step 4; see Section 3.1). After these 100 years, the ice-sheet geometry has largely stabilised, and no spurious rapid adjustments occur in the future climate runs.

Figure 5 depicts the simulated evolution of the volume V of the Greenland ice sheet (panel a) and the volume relative to CTL (panel b) for the five different future climate experiments (Section 3.2). The control run CTL shows a small, but notable drift towards a

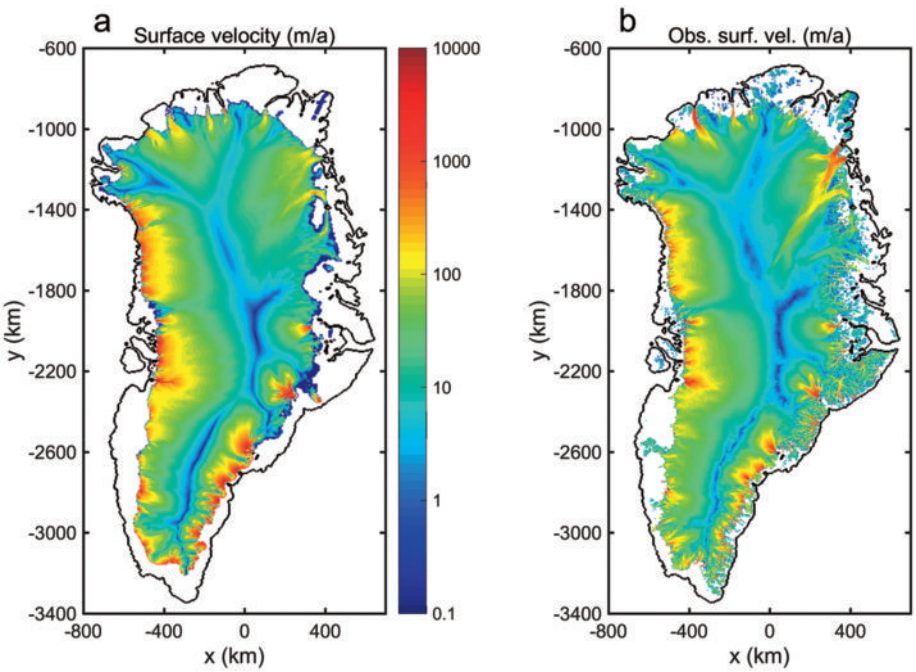

Figure 3 : SeaRISE paleoclimatic spin-up. (a) Simulated present-day surface velocity. (b) Observed present-day surface velocity (Joughin et al., 2010, 2016).

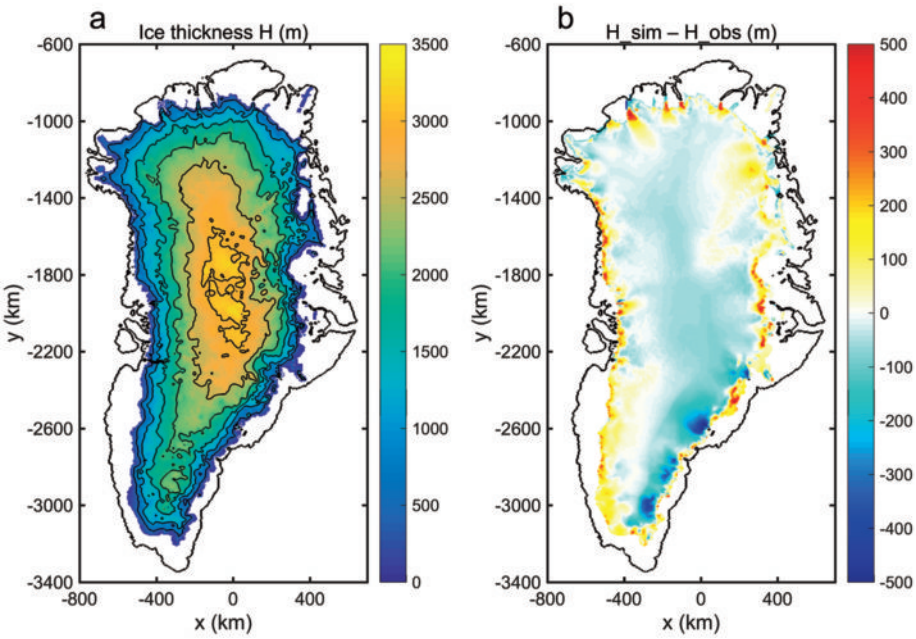

Figure 4 : SeaRISE paleoclimatic spin-up. (a) Simulated present-day ice thickness. (b) Difference of simulated and observed present-day ice thickness (the latter is the difference of the surface topography by Bamber (2001) and the "JakHelKanPet" bed topography by Herzfeld et al. (2011, 2012)).

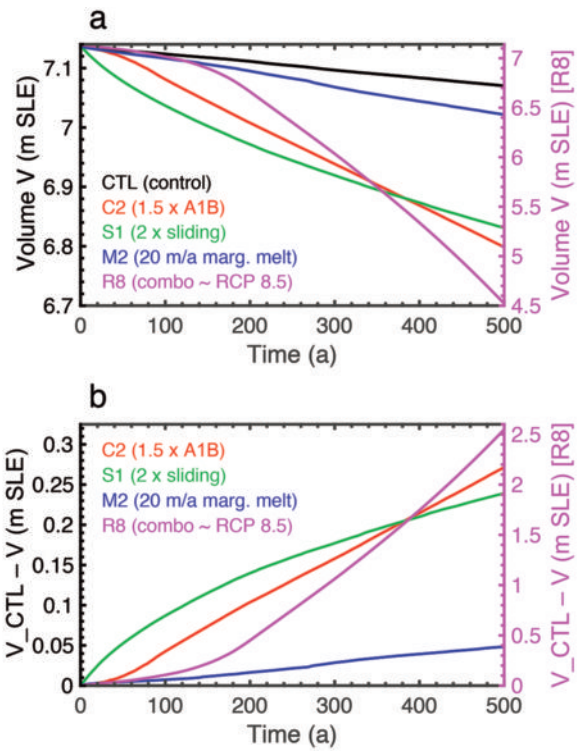

Figure 5 : SeaRISE future climate runs. (a) Ice volumes for experiments CTL (control), C2 (1.5×A1B climate forcing until 2098, then held steady), S1 (2×basal sliding), M2 (20 m w.e. a^{-1} ocean-induced marginal melting and R8 (combination experiment approximating an IPCC RCP 8.5 scenario). (b) Ice volume differences (CTL minus experiment) for C2, S1, M2 and R8. All volumes are given in metres of sea level equivalent (m SLE). Note the two different y-axes (left for CTL, C2, S1, M2; right for R8).

smaller ice volume (positive contribution to sea level, on average ~ 0.13 mm a^{-1} during the 500 model years), which is still a reaction to the release of the fixed-topography constraint 100 years before the end of the spin-up sequence. However, all other experiments produce a stronger ice volume decrease than CTL. Of the three sensitivity experiments (C2, S1, M2), S1 (2× basal sliding) has by far the strongest initial reaction with an experiment-minus-control sea-level contribution ($V_{CTL}-V$, panel b) of ~ 1.3 mm a^{-1} during the first 10 years (but then steadily decreasing). Run C2 (1.5× A1B climate forcing) shows a much weaker, but increasing initial reaction, and approximately stabilises at an average experiment-minus-control sea-level contribution of ~ 0.57 mm a^{-1} from 100 years on until the end of the simulation, ultimately outperforming the impact of run S1. Run M2 (20 m a^{-1} marginal melting) produces the weakest reaction of the sensitivity experiments because the contact of the Greenland ice sheet with the ocean is not that pronounced on the large scale (this is radically different for the Antarctic ice sheet).

As mentioned above, the experiment R8 was designed in order to simulate roughly the response of the Greenland ice sheet to the RCP 8.5 greenhouse gas concentration scenario (a rather pessimistic, 'business-

Table 1：Simulated sea-level contribution of the Greenland ice sheet for SeaRISE experiment R8 after 100, 200 and 500 years model time. "Min", "Mean" and "Max" denote the minimal, mean and maximal values across the participating models (Bindschadler et al., 2013). In addition, the SICOPOLIS results are shown.

	Min	Mean	Max	SICOPOLIS
100 a	0.045 m	0.223 m	0.663 m	0.101 m
200 a	0.096 m	0.532 m	0.889 m	0.450 m
500 a	0.181 m	2.016 m	4.097 m	2.549 m

as-usual' scenario for which it is assumed that emissions continue to rise throughout the 21st century) via a combination of surface climate forcing, enhanced basal sliding and increased ocean-induced marginal melting. The response of the ice sheet to this experiment is very strong and accelerating with time: the experiment-minus-control cumulative sea-level contribution is ～0.10 m after 100 years, ～0.45 m after 200 years and ～2.5 m after 500 years. This means that, after 500 years, approximately one third of the entire ice sheet has disintegrated.

The SeaRISE-Greenland experiments were carried out by a total of eight different ice sheet models, of which five (including SICOPOLIS) completed the R8 experiment with all three forcings as specified above (Bindschadler et al., 2013). An important finding of this multiple-model approach is that the spread of results is very large. For the R8 experiment, the difference of simulated sea-level contributions is as large as an order of magnitude (Table 1). Saito et al. (2016) investigated this problem further and found that the two largest sources for the spread of results are (1) differences in the initialisation methods and (2) differences in the surface mass balance schemes.

4. ISMIP6 InitMIP-Greenland

4.1 ISMIP6

The Ice Sheet Modeling Intercomparison Project for CMIP6 (ISMIP6, www.climate-cryosphere.org/activities/targeted/ismip6) is the successor of the completed SeaRISE and Ice2sea initiatives, and the primary activity within the Coupled Model Intercomparison Project Phase 6 (CMIP6) focusing on the Greenland and Antarctic ice sheets. ISMIP6 was established in autumn 2014, and was endorsed by CMIP6 in mid-2015. A crucial approach is to integrate ISMIP6 in CMIP6. In the past, sea-level projections made by the glaciological community have been lagging behind the projections considered by the wider climate modelling community. For instance, for the IPCC AR5, the SeaRISE and Ice2sea ice sheet modelling initiatives predominantly worked with the old AR4 scenarios, while the CMIP5 community already used the new Representative Concentration Pathways (RCP) scenarios. By linking ISMIP6 to CMIP6, this long-standing disadvantage will be overcome because the latest climate change scenarios simulated by AOGCMs within CMIP6 will be available without delay as drivers for ice sheet modelling studies. This will allow to improve both sea level projections due to changes in the cryosphere and our understanding of the ice sheets in a changing climate. These goals map into the "Changes in Cryosphere" Grand Challenge relevant to Climate and Cryosphere (CliC) and the World Climate Research Program (WCRP) (www.climate-cryosphere.org/activities/grand-challenges). ISMIP6 is described in further detail by Nowicki et al. (2016).

4.2 InitMIP-Greenland experiments

Earlier large-scale Greenland ice sheet experiments, e.g., those run for the SeaRISE initiative, have shown that ice sheet initialisation has a large effect on future sea-level projections and gives rise to important uncertainties (Saito et al., 2016). In order to compare and evaluate the initialisation methods used in the ice sheet modelling community and estimate the uncertainty associated with initialisation, the ice sheet model initialisation experiments for Greenland (InitMIP-Greenland) were devised as an early sub-project within ISMIP6 (H. Goelzer, personal communication, 2016). InitMIP-Greenland comprises three experiments:

- init — Initialisation of the Greenland ice sheet to present day. Modellers can use the method of their choice to achieve this (typically either assimilation methods or paleoclimatic spin-up methods). Further, the exact meaning of "present day" is at the modeller's discretion.
- ctrl — Control run 100 years into the future, starting from the final state of run init and holding the climate steady to the present-day state.

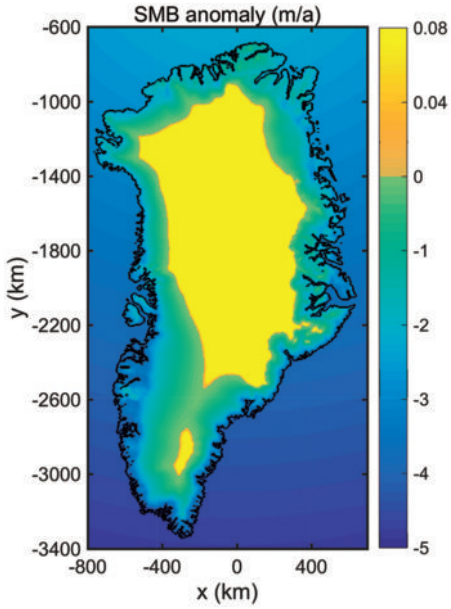

Figure 6 : Schematic surface mass balance anomaly used for the InitMIP-Greenland experiment asmb after 40 years model time (in metres of ice equivalent per year) (H. Goelzer, personal communication, 2016).

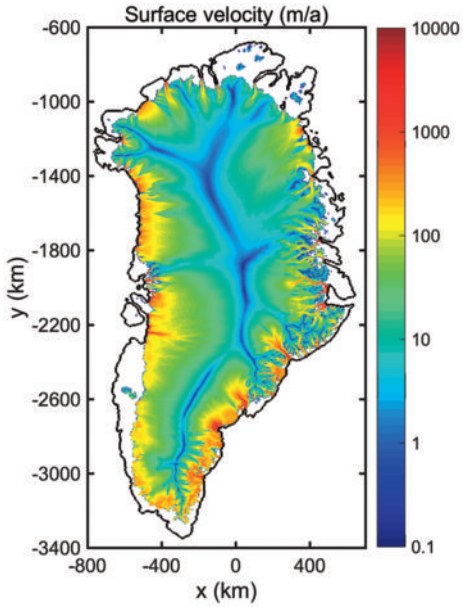

Figure 7 : InitMIP-Greenland paleoclimatic spin-up #2 with freely evolving topography. Simulated present-day surface velocity (for the observed counterpart see Fig. 3b).

- asmb — Run 100 years into the future, starting from the final state of run init with a prescribed, schematic surface mass balance (SMB) anomaly. The SMB anomaly starts from zero, increases step-wise every full year over the first 40 years and remains steady thereafter (Fig. 6).

We contribute to InitMIP-Greenland with the ice sheet model SICOPOLIS and two different spin-up techniques for the run init:

- Spin-up #1 — a SeaRISE-legacy spin-up with essentially fixed topography (as described in Section 3.1).
- Spin-up #2 — a new spin-up over 135 ka with freely evolving topography.

For both cases, we used the recently developed melting-CTS enthalpy method ("ENTM"; Greve and Blatter, 2016) as the solver for ice sheet thermodynamics. Our reference year ("present day") is 1990. New methods applied for spin-up #2 are monthly-mean (rather than mean annual) input data for the present-day precipitation (Robinson et al., 2010), a sub-grid-scale ice discharge parameterisation (Calov et al., 2015) and an iterative correction of the present-day precipitation based on the misfit between the simulated and observed present-day ice thickness. Details of this procedure will be published elsewhere. The horizontal resolution for spin-up #1 is the same as for SeaRISE (10 km prior to 5 ka BP, 5 km from 5 ka BP until today), and for spin-up #2 it is 10 km prior to 9 ka BP and 5 km from 9 ka BP until today. The two future climate scenarios ctrl and asmb are run with freely evolving ice topography for either spin-up method, and the horizontal resolution is 5 km.

4.3 Results

The present-day surface velocity and ice thickness produced by spin-up #1 are almost identical to those obtained by the original SeaRISE spin-up (Figs. 3 and 4) and thus not shown again. The surface velocity produced by spin-up #2 is shown in Fig. 7. While there are some differences in detail, it shares the same main features with the result of spin-up #1: the low-velocity 'backbone', the general acceleration towards the coast, the organisation into drainage systems and most of the major ice streams and outlet glaciers agree well with the observed pattern (Fig. 3b). The Petermann Glacier is even reproduced better by spin-up #2 than by spin-up #1, while the problem with the generally too slow flow in the area of the NEGIS remains.

The agreement between simulated and observed ice topography is naturally better for the fixed-topography case #1 (Fig. 4) than for the freely evolving case #2 (Fig. 8). As for the interior ice sheet simulated by spin-up #2, thicknesses are generally too large in the south-

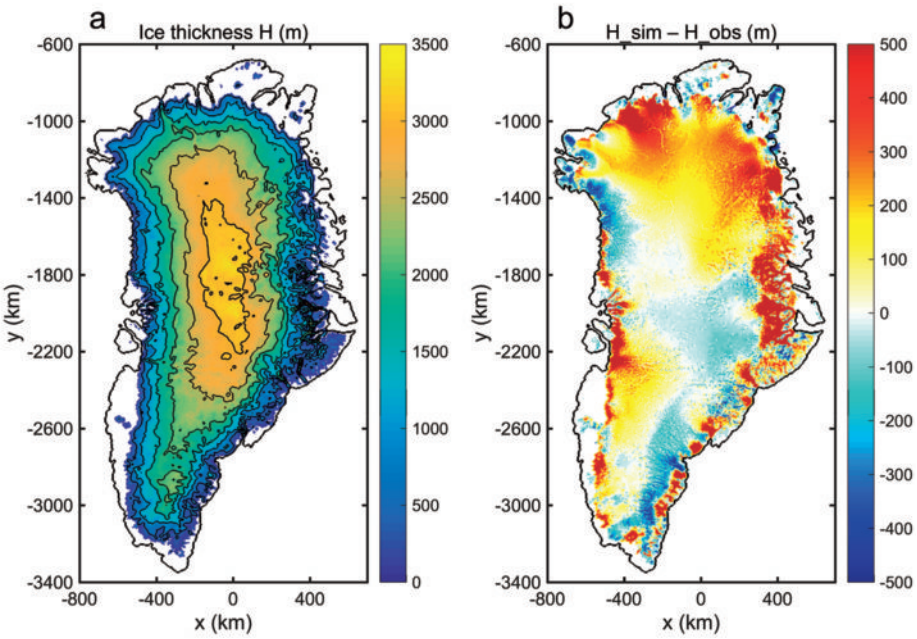

Figure 8 : InitMIP-Greenland paleoclimatic spin-up #2 with freely evolving topography. (a) Simulated present-day ice thickness. (b) Difference of simulated and observed present-day ice thickness (the latter is by Bamber et al. (2013)).

west, north and north-east, while they are too small in the south-east, centre and north-west. Near the ice margin, a number of areas exhibit distinctly overpredicted ice thicknesses, and they often coincide with areas of fast ice flow. The latter is likely mainly due to the employed shallow ice dynamics that does not describe the dynamics of ice streams adequately. The reason for the pattern of disagreement in the interior is more difficult to assess as lacking accuracy of several input data or boundary conditions (surface mass balance, basal sliding, geothermal heat flux) may contribute.

Total ice volumes and areas for the two spin-ups are shown in Table 2 along with their observational counterparts. In line with the discussion above, the volume produced by spin-up #1 matches the observed volume very closely, while the volume produced by spin-up #2 is ～ 8% too large. The ice-sheet area simulated by spin-up #2 is also larger than for spin-up #1; however, in contrast to the ice volume, the result of spin-up #2 is closer to the observation than that of spin-up #1. This is so because the SeaRISE-legacy fixed-topography spin-up #1 is based on older topographic data (surface topography by Bamber (2001), bed topography by Herzfeld et al. (2011, 2012)) that lead to a smaller ice-covered area than the newer data by Bamber et al. (2013).

For the two future climate scenarios ctrl (constant-climate control run) and asmb (schematic SMB anomaly), Fig. 9 depicts the sea-level contribution (initial volume V_{init} minus actual volume V, expressed in sea-level equivalents) of the Greenland ice sheet. As discussed above (Section 3.3), for spin-up #1, ctrl shows a notable drift towards a smaller ice volume (positive sea-level contribution) due to the release of the fixed-topography constraint 100 years before the end of the spin-up. In contrast, for spin-up #2, such a transition shock does not occur, so that the drift is very small. The response of the ice sheet to the asmb forcing is, in absolute terms, ～ 50% larger for spin-up #2 than for spin-up #1, and relative to the respective control run even ～ 85% larger. This demonstrates impressively that, even with the same ice sheet model, different initialisation methods can lead to a major spread of results of future climate

Table 2 : Simulated volume and area of the present-day Greenland ice sheet for InitMIP-Greenland. The simulations are the fixed-topography spin-up #1 and the freely-evolving-topography spin-up #2 carried out with SICOPOLIS (see main text for details). Observational data are also shown (volume by Bamber et al. (2013), area by Kargel et al. (2012)).

	Volume (km^3)	Area (km^2)
Spin-up #1	2.92×10^6	1.66×10^6
Spin-up #2	3.21×10^6	1.86×10^6
Observed	2.96×10^6	1.80×10^6

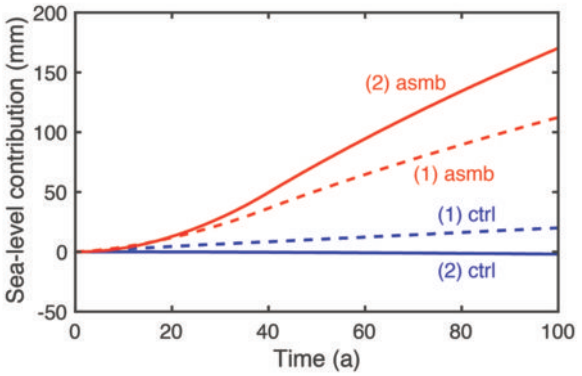

Figure 9 : InitMIP-Greenland future climate runs. Sea-level contribution (due to ice volume change) of the Greenland ice sheet for the runs ctrl (control) and asmb (schematic surface mass balance anomaly). (1) Initialisation by the fixed-topography spin-up #1, (2) initialisation by the freely-evolving-topography spin-up #2.

experiments.

5. Summary and outlook

Climate change constitutes a major challenge for humankind. One of the most severe consequences of climate change is sea level rise, currently (1993–2010) occurring at a global mean rate of 3.2 ± 0.4 mm a^{-1} (IPCC, 2013a), for which the two main contributors are the melting of land ice masses (ice sheets and glaciers) and the thermal expansion of ocean water. The largest potential for future sea level rise lies in the ice sheets of Antarctica and Greenland with their combined volume of ~ 65 m of sea level equivalent.

Numerical modelling has become an important tool for assessing the response of ice sheets to climate change and thus their contribution to sea level rise. In this paper, we focused on the Greenland ice sheet and reviewed related work conducted with the ice sheet model SICOPOLIS. Within the SeaRISE initiative, SICOPOLIS was part of a group of eight models that were applied to a set of standardised experiments for the Greenland ice sheet. These experiments comprised sensitivity studies to changes in the surface climate, basal sliding and marginal (ocean-induced) melting as well as a combination experiment approximating IPCC's 'business-as-usual' RCP 8.5 scenario. Results of the latter showed that there is potential for a significant decay of the Greenland ice sheet over the next centuries if climate change progresses unabatedly. However, the spread of results across the different models was very large, clearly indicating the need for further efforts in this direction.

Therefore, as a post-AR5 initiative, the scientific community devised ISMIP6, which is still in an early stage. A first sub-project is InitMIP-Greenland, in which the influence of model initialisation on schematic future climate simulations is investigated. Results obtained with SICOPOLIS for two different initialisation methods, namely (1) a spin-up with essentially fixed topography, and (2) a spin-up with freely evolving topography (both run over a full glacial-interglacial cycle) showed that the influence of these different spin-ups on the evolution of the ice sheet in the future is indeed very pronounced. Within the ongoing research project "ProGrIS" (Projecting discharge from the Greenland Ice Sheet using climatic forcings derived from atmosphere-ocean models; Grant-in-Aid for Scientific Research A, provided by the Japan Society for the Promotion of Science (JSPS)), we will therefore continue our efforts towards improving the quality of the spin-up for the Greenland ice sheet with the models SICOPOLIS and IcIES (the latter operated by F. Saito and A. Abe-Ouchi; e.g., Abe-Ouchi et al., 2013). Based on this, we will project the total discharge from the Greenland ice sheet, and thus its contribution to sea level rise, with the models SICOPOLIS and IcIES. In close cooperation with the ISMIP6 community, forcings for the atmospheric and oceanic climate over and surrounding the Greenland ice sheet will be derived from the suite of CMIP6 AOGCM (atmosphere-ocean general circulation model) simulations. These combined efforts will hopefully lead to significantly improved estimates of ice sheet contribution to sea level rise in the coming years.

6. Code and data availability

The ice sheet model SICOPOLIS is available as free and open-source software (under the GNU General Public License) via www.sicopolis.net. The data produced by SICOPOLIS for this study can be obtained by contacting the corresponding author.

Acknowledgements

We thank all organisers and steering committee members of the SeaRISE and ISMIP6 initiatives, in particular Robert A. (Bob) Bindschadler, Sophie Nowicki and Heiko Goelzer, for their efforts in managing these projects. Further, we thank Ayako Abe-Ouchi and Fuyuki Saito for continued, fruitful exchange on ice sheet modelling issues, and the numerous colleagues who have contributed to the development of the ice sheet model SICOPOLIS over the last ～ 20 years. Shin Sugiyama kindly proofread the manuscript.

Ralf Greve was supported by Grants-in-Aid for Scientific Research A (Nos. 22244058, 25241005 and 16H02224) of the Japan Society for the Promotion of Science (JSPS), and by the Green Network of Excellence (GRENE) Arctic Climate Change Research and Arctic Challenge for Sustainability (ArCS) projects of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). Reinhard Calov was supported by Leibniz Society grant SAW-2014-PIK-1 GreenRise. Support for research of Ute Herzfeld through NASA Cryospheric Sciences awards NNX11AP39G and NNX16AP71G and U.S. National Science Foundation Geography and Spatial Sciences Awards 1553133 and 1553134 (BCS 1504533) is thankfully acknowledged.

References

Abe-Ouchi, A., F. Saito, K. Kawamura, M. E. Raymo, J. Okuno, K. Takahashi, and H. Blatter (2013) Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume. *Nature,* **500** (7461), 190–193.

Arakawa, A., and V. R. Lamb (1977) Computational design of the basic dynamical processes of the UCLA general circulation model. In: J. Chang (ed.), *Methods in Computational Physics Vol.17,* pp.173–265. Academic Press, New York, NY, USA.

Bamber, J. L. (2001) Greenland 5 km DEM, ice thickness, and bedrock elevation grids, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, Colorado, USA. doi: 10.5067/01A10Z9BM7KP.

Bamber, J. L., J. A. Griggs, R. T. W. L. Hurkmans, J. A. Dowdeswell, S. P. Gogineni, I. Howat, J. Mouginot, J. Paden, S. Palmer, E. Rignot, and D. Steinhage (2013) A new bed elevation dataset for Greenland. *Cryosphere,* **7** (2), 499–510.

Bernales, J., I. Rogozhina, R. Greve, and M. Thomas (2017) Comparison of hybrid schemes for the combination of shallow approximations in numerical simulations of the Antarctic Ice Sheet. *Cryosphere,* **11** (1), 247–265.

Bindschadler, R. A., S. Nowicki, A. Abe-Ouchi, A. Aschwanden, H. Choi, J. Fastook, G. Granzow, R. Greve, G. Gutowski, U. C. Herzfeld, C. Jackson, J. Johnson, C. Khroulev, A. Levermann, W. H. Lipscomb, M. A. Martin, M. Morlighem, B. R. Parizek, D. Pollard, S. F. Price, D. Ren, F. Saito, T. Sato, H. Seddik, H. Seroussi, K. Takahashi, R. Walker, and W. L. Wang (2013) Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project). *J. Glaciol.,* **59** (214), 195–224.

Calov, R., A. Robinson, M. Perrette, and A. Ganopolski (2015) Simulating the Greenland ice sheet under present-day and palaeo constraints including a new discharge parameterization. *Cryosphere,* **9** (1), 179–196.

De Wolde, J. R., P. Huybrechts, J. Oerlemans, and R. S. W. van den Wal (1997) Projections of global mean sea level rise calculated with a 2D energy-balance climate model and dynamic ice sheet models. *Tellus,* **49A**, 486–502.

Enderlin, E. M., I. M. Howat, S. Jeong, M.-J. Noh, J. H. van Angelen, and M. R. van den Broeke (2014) An improved mass budget for the Greenland ice sheet. *Geophys. Res. Lett.,* **41** (3), 866–872.

Greve, R. (1995) *Thermomechanisches Verhalten polythermer Eisschilde - Theorie, Analytik, Numerik.* Doctoral thesis, Department of Mechanics, Darmstadt University of Technology, Germany. Berichte aus der Geowissenschaft, Shaker Verlag, Aachen, Germany.

Greve, R. (1997) Application of a polythermal three-dimensional ice sheet model to the Greenland ice sheet: Response to steady-state and transient climate scenarios. *J. Climate,* **10** (5), 901–918.

Greve, R. (2000) On the response of the Greenland ice sheet to greenhouse climate change. *Clim. Change,* **46** (3), 289–303.

Greve, R., and H. Blatter (2009) *Dynamics of Ice Sheets and Glaciers.* Springer, Berlin etc., Germany.

Greve, R., and H. Blatter (2016) Comparison of thermodynamics solvers in the polythermal ice sheet model SICOPOLIS. *Polar Sci.,* **10** (1), 11–23.

Greve, R., and U. C. Herzfeld (2013) Resolution of ice streams and outlet glaciers in large-scale simulations of the Greenland ice sheet. *Ann. Glaciol.,* **54** (63), 209–220.

Greve, R., F. Saito, and A. Abe-Ouchi (2011) Initial results of the SeaRISE numerical experiments with the models SICOPOLIS and IcIES for the Greenland ice sheet. *Ann. Glaciol.,* **52** (58), 23–30.

Hanna, E., F. J. Navarro, F. Pattyn, C. M. Domingues, X. Fettweis, E. R. Ivins, R. J. Nicholls, C. Ritz, B. Smith, S. Tulaczyk, P. L. Whitehouse, and H. J. Zwally (2013) Ice-sheet mass balance and climate change. *Nature,* **498** (7452),

51–59.

Helm, V., A. Humbert, and H. Miller (2014) Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *Cryosphere,* **8** (4), 1539–1559.

Herzfeld, U. C., B. F. Wallin, C. J. Leuschen, and J. Plummer (2011) An algorithm for generalizing topography to grids while preserving subscale morphologic characteristics - creating a glacier bed DEM for Jakobshavn trough as low-resolution input for dynamic ice-sheet models. *Comput. Geosci.,* **37** (11), 1793–1801.

Herzfeld, U. C., J. Fastook, R. Greve, B. McDonald, B. F. Wallin, and P. A. Chen (2012) On the influence of outlet glaciers in Greenland bed topography on results from dynamic ice sheet models. *Ann. Glaciol.,* **53** (60), 281–293.

Hutter, K. (1983) *Theoretical Glaciology; Material Science of Ice and the Mechanics of Glaciers and Ice Sheets.* D. Reidel Publishing Company, Dordrecht, The Netherlands.

Huybrechts, P., and J. Oerlemans (1990) Response of the Antarctic ice sheet to future greenhouse warming. *Clim. Dynam.,* **5** (2), 93–102.

Huybrechts, P., A. Letreguilly, and N. Reeh (1991) The Greenland ice sheet and greenhouse warming. *Palaeo3,* **89**, 399–412.

IPCC (2007) Summary for Policymakers. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.), *Climate Change 2007: The Physical Science Basis,* pp.1–18. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013a) Summary for Policymakers. In: T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), *Climate Change 2013: The Physical Science Basis,* pp.3–29. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013b) *Climate Change 2013: The Physical Science Basis* (eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Joughin, I., B. Smith, I. Howat, T. Scambos, and T. Moon (2010) Greenland flow variability from ice-sheet-wide velocity mapping. *J. Glaciol.,* **56** (197), 415–430.

Joughin, I., B. Smith, I. Howat, and T. Scambos (2016) MEaSUREs multi-year Greenland ice sheet velocity mosaic, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, Colorado, USA. doi: 10.5067/QUA5Q9SVMSJG.

Kargel, J. S., A. P. Ahlstrøm, R. B. Alley, J. L. Bamber, T. J. Benham, J. E. Box, C. Chen, P. Christoffersen, M. Citterio, J. G. Cogley, H. Jiskoot, G. J. Leonard, P. Morin, T. Scambos, T. Sheldon, and I. Willis (2012) Greenland's shrinking ice cover: "fast times" but not that fast. *Cryosphere,* **6** (3), 533–537.

Khan, S. A., A. Aschwanden, A. A. Bjørk, J. Wahr, K. K. Kjeldsen, and K. H. Kjær (2015) Greenland ice sheet mass balance: a review. *Rep. Prog. Phys.,* **78**, 046801.

Kusahara, K., T. Sato, A. Oka, T. Obase, R. Greve, A. Abe-Ouchi, and H. Hasumi (2015) Modelling the Antarctic marine cryosphere at the Last Glacial Maximum. *Ann. Glaciol.,* **56** (69), 425–435.

Le Meur, E., and P. Huybrechts (1996) A comparison of different ways of dealing with isostasy: examples from modelling the Antarctic ice sheet during the last glacial cycle. *Ann. Glaciol.,* **23**, 309–317.

MacAyeal, D. R. (1989) Large-scale ice flow over a viscous basal sediment: theory and application to ice stream B, Antarctica. *J. Geophys. Res.,* **94** (B4), 4071–4087.

Molnia, B. F. (2004) *Glossary of Glacier Terminology: A Glossary Providing the Vocabulary Necessary to Understand the Modern Glacier Environment.* USGS Open-File Report 2004–1216.

Morland, L. W. (1984) Thermomechanical balances of ice sheet flows. *Geophys. Astrophys. Fluid Dyn.,* **29**, 237–266.

Morland, L. W. (1987) Unconfined ice-shelf flow. In: Van der Veen, C. J. and J. Oerlemans (eds.), *Dynamics of the West Antarctic Ice Sheet.* D. Reidel Publishing Company, Dordrecht, The Netherlands, 99–116.

Nowicki, S., R. A. Bindschadler, A. Abe-Ouchi, A. Aschwanden, E. Bueler, H. Choi, J. Fastook, G. Granzow, R. Greve, G. Gutowski, U. C. Herzfeld, C. Jackson, J. Johnson, C. Khroulev, E. Larour, A. Levermann, W. H. Lipscomb, M. A. Martin, M. Morlighem, B. R. Parizek, D. Pollard, S. F. Price, D. Ren, E. Rignot, F. Saito, T. Sato, H. Seddik, H. Seroussi, K. Takahashi, R. Walker, and W. L. Wang (2013a) Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project I: Antarctica. *J. Geophys. Res. Earth Surf.,* **118** (2), 1002–1024.

Nowicki, S., R. A. Bindschadler, A. Abe-Ouchi, A. Aschwanden, E. Bueler, H. Choi, J. Fastook, G. Granzow, R. Greve, G. Gutowski, U. C. Herzfeld, C. Jackson, J. Johnson, C. Khroulev, E. Larour, A. Levermann, W. H. Lipscomb, M. A. Martin, M. Morlighem, B. R. Parizek, D. Pollard, S. F. Price, D. Ren, E. Rignot, F. Saito, T. Sato, H. Seddik, H. Seroussi, K. Takahashi, R. Walker, and W. L. Wang (2013b) Insights into spatial sensitivities of ice mass response to environmental change from the SeaRISE ice sheet modeling project II: Greenland. *J. Geophys. Res. Earth Surf.,* **118** (2), 1025–1044.

Nowicki, S. M. J., A. Payne, E. Larour, H. Seroussi, H. Goelzer, W. Lipscomb, J. Gregory, A. Abe-Ouchi, and A. Shepherd (2016) Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. *Geosci. Model Dev.,* **9** (12), 4521–4545.

Ridley, J. K., P. Huybrechts, J. M. Gregory, and J. A. Lowe (2005) Elimination of the Greenland ice sheet in a high CO_2

climate. *J. Climate,* **18**, 3409–3427.

Rignot, E., S. Jacobs, J. Mouginot, and B. Scheuchl (2013) Ice-shelf melting around Antarctica. *Science,* **341** (6143), 266–270.

Robinson, A., R. Calov, and A. Ganopolski (2010) An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change. *Cryosphere,* **4** (2), 129–144.

Robinson, A., R. Calov, and A. Ganopolski (2012) Multistability and critical thresholds of the Greenland ice sheet. *Nat. Clim. Change,* **2** (6), 429–432.

Saito, F., A. Abe-Ouchi, K. Takahashi, and H. Blatter (2016) SeaRISE experiments revisited: potential sources of spread in multi-model projections of the Greenland ice sheet. *Cryosphere,* **10** (1), 43–63.

Shepherd, A., E. R. Ivins, G. A, V. R. Barletta, M. J. Bentley, S. Bettadpur, K. H. Briggs, D. H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M. A. King, J. T. M. Lenaerts, J. Li, S. R. M. Ligtenberg, A. Luckman, S. B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mouginot, A. Muir, J. P. Nicolas, J. Paden, A. J. Payne, H. Pritchard, E. Rignot, H. Rott, L. S. Sørensen, T. A. Scambos, B. Scheuchl, E. J. O. Schrama, B. Smith, A. V. Sundal, J. H. van Angelen, W. J. van de Berg, M. R. van den Broeke, D. G. Vaughan, I. Velicogna, J. Wahr, P. L. Whitehouse, D. J. Wingham, D. Yi, D. Young, and H. J. Zwally (2012) A reconciled estimate of ice-sheet mass balance. *Science,* **338** (6111), 1183–1189.

Van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W. J. van de Berg, E. van Meijgaard, I. Velicogna, and B. Wouters (2009) Partitioning recent Greenland mass loss. *Science,* **326** (5955), 984–986.

Vaughan, D. G., J. C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang (2013) Observations: Cryosphere. In: T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (eds.), *Climate Change 2013: The Physical Science Basis,* pp.317–382. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.