Spatial Sensitivities of the Antarctic Ice Sheet to Environmental Changes (The SeaRISE Project).

Sophie Nowicki¹, Robert A. Bindschadler¹, Ayako Abe-Ouchi², Andy Aschwanden³, Ed Bueler³, Hyeungu Choi⁴, Jim Fastook⁵, Glen Granzow⁶, Ralf Greve⁷, Gail Gutowski⁸, Ute Herzfeld⁹, Charles Jackson⁸, Jesse Johnson⁶, Constantine Khroulev³, Eric Larour¹⁰, Anders Levermann¹¹, William H. Lipscomb¹², Maria A. Martin¹¹, Mathieu Morlighem¹³, Byron R. Parizek¹⁴, David Pollard¹⁵, Stephen F. Price¹², Diandong Ren¹⁶, Eric Rignot¹⁰,¹³, Fuyuki Saito¹⁷, Tatsuru Sato⁷, Hakime Seddik⁷, Helene Seroussi¹⁰, Kunio Takahashi¹⁷, Ryan Walker¹⁵, and Wei Li Wang¹

1: Code 615, NASA Goddard Space Flight Center, Greenbelt MD 20771 USA
2: Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Chiba 277-8564, Japan;
3: Geophysical Institute, University of Alaska, Fairbanks, AK, USA
4: Sigma Space Corporation, Lanham, MD 20706 USA
5: Computer Science/Quaternary Institute, University of Maine, Orono, ME 04469 USA
6: College of Arts and Sciences, The University of Montana, Missoula, MT. 59812 USA
7: Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan
8: Institute for Geophysics, The University of Texas at Austin, Austin, TX 78758-4445 USA
9: Department of Electrical, Computer and Energy Engineering and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO
   80309-0449 USA
10: Jet Propulsion Laboratory - California Institute of Technology, 4800 Oak Grove Drive MS 300-331, Pasadena, CA 91109-8099, USA
11: Potsdam Institute for Climate Research, 14473 Potsdam, Germany
12: Los Alamos National Laboratory, Los Alamos, NM 87545 USA
13: Department of Earth System Science, University of California, Irvine, Irvine, CA
   92697-3100, USA
14: Mathematics and Geoscience, Penn State DuBois, College Place, DuBois, PA 15801 USA
15: Earth and Environmental Systems Institute, Pennsylvania State University, University Park PA 16802 USA
16: Department of Physics, Curtin University of Technology, Perth, Australia 1985
17: Japan Agency for Marine-Earth Science and Technology, Research Institute for Global Change, 3173-25 Showamachi, Kanazawa, Yokohama, Kanagawa 236-0001, Japan
Abstract.

Atmospheric, oceanic, and subglacial forcing scenarios from the Sea-level Response to Ice Sheet Evolution (SeaRISE) project are applied to six three-dimensional thermomechanical ice-sheet models to assess Antarctic ice sheet sensitivity over a 500-year timescale and to inform future modeling and field studies. Results indicate: i) growth with warming, except within low-latitude basins (where inland thickening is outpaced by marginal thinning); ii) mass loss with enhanced sliding (with basins dominated by high driving stresses affected more than basins with low-surface-slope streaming ice); and iii) mass loss with enhanced ice-shelf melting (with changes in West Antarctica dominating the signal due to its marine setting and extensive ice shelves; cf. minimal impact in the Terre Adelie, George V, Oates, and Victoria Land region of East Antarctica). Ice loss due to dynamic changes associated with enhanced sliding and/or sub-shelf melting exceed the gain due to increased precipitation. Furthermore, differences in results between and within basins as well as the controlling impact of sub-shelf melting on ice dynamics highlight the need for improved understanding of basal conditions, grounding-zone processes, ocean-ice interactions, and the numerical representation of all three.

1. Introduction.

Antarctica contains 70% of the world’s fresh water, which represents a potential 56.6 m of sea level rise [IPCC, 2007] if all its ice were to melt. Over the past decades, rapid and
dramatic changes have been observed in Antarctica: spectacular collapses of several ice
shelves in the Antarctic Peninsula [Scambos et al., 2004, 2009] and the acceleration of
massive outlet glaciers such as Pine Island Glacier in the Amundsen Sea Embayment
[Rignot, 2008]. Seven out of twelve ice shelves on the Antarctic Peninsula have
significantly retreated or been almost entirely lost and 87% of the 244 marine glacier
fronts have retreated during the past 60 years [Cook et al., 2005]. These observed
changes, thought to have been triggered by ocean warming and atmospheric changes
[Pritchard et al., 2012], suggest that this ice sheet is far more vulnerable to climate
change than initially anticipated [IPCC, 2007].

Modeling of the Antarctic ice sheet remains a technical and scientific challenge given the
size of the continent, the numerous physical processes that need to be accounted for and
are not always well understood, and the lack of observational data. Climate models face
similar challenges, yet the possible range of climate response to various future scenarios
can still be examined through the analysis of results from multiple models [IPCC, 2007].
In particular, when multiple models are subjected to a set of common experiments similar
trends, as well as discrepancies, emerge from ensemble analysis [Gates et al., 1999;
Knutti et al., 2010].

The Sea-level Response to Ice Sheet Evolution effort (SeaRISE) seeks to investigate the
sensitivity and the potential future response of the Antarctic and Greenland ice sheets.
SeaRISE’s strategy is to employ multiple models of ice sheet flow initialized by a
common dataset to mitigate model-to-model differences, and forced externally by a set of
climate scenarios. As a primary goal is to involve as many ice sheet models as possible, the experiments were designed to be simple enough so that any model that was willing to contribute to SeaRISE could participate. The experiments investigate the response to three distinct forcings that are known to influence ice flow: i) atmospheric forcing, modeled via changes in surface mass balance and temperature, ii) oceanic forcing, modeled via changes in subshelf melt rate, and iii) increased lubrication at the base of the ice sheet, modeled via enhanced basal sliding. For each forcing type, three different amplifications were investigated. Combinations of atmospheric, oceanic, and sliding forcings were also explored, including a final SeaRISE experiment that attempts to model a realistic future climate scenario.

The philosophy behind the SeaRISE project, the datasets, experiments and participating models are explained in Bindschadler et al. [submitted]. The datasets for the Antarctic ice sheet includes of mean annual surface temperature [Comiso, 2000], accumulation from assimilated observation [Arthern et al., 2006] or climate models [van de Berg et al., 2006], two basal heat fluxes [Shapiro and Ritzwoller, 2004; Fox Maule et al., 2005], along with surface elevation, basal topography and ice thickness from ALBMAP v1 [LeBrocq et al., 2010. The six state of the art ice sheet models taking part in the Antarctic suite of experiments are AIF [Wang et al., 2012], ISSM [Morlighem et al., 2010, Seroussi et al., 2011, Larour et al., 2012], PennState3D [Pollard and DeConto, 2009, 2012], Potsdam [Winkelmann et al., 2011; Martin et al., 2011], SICOPOLIS [Greve, 1997; Sato and Greve, 2012], and UMISM [Fastook, 1990, 1993; Fastook and Hughes, 1990; Fastook and Prentice, 1994]. These models incorporate different sets of physical
processes, ice flow approximation and spatial resolution, as well as different methods to solve the resulting equations [Bindschadler et al., submitted, Table 2 and Appendix A]. In addition, SeaRISE includes a regional investigation of selected ice streams with the higher-order flowband model PennState2D [Parizek et al., under review]. Bindschadler et al. [submitted] analyze the temporal response of the Antarctic and Greenland ice sheet volume, and hence sea-level contribution, for the various experiments. The response of the Antarctic ice sheet to the climatic set of experiments leads to an ensemble mean growth. In contrast, the response to the enhanced basal sliding and oceanic forcing results in an ice sheet wide mass loss over the entire duration of the 500 years simulations.

In this paper, we analyze the spatial response of the ice sheet models to the first suite of experiments at particular times (100, 200 and 500 years), and demonstrate that the thickness responses of the Antarctic ice sheet to the climate, oceanic and basal flow enhancements are different. The spatial response to the final experiment and associated sea-level finger prints [e.g. Mitrovica et al., 2011] is the focus of a different study [Nowicki et al., in preparation]. The analysis of the simple forcings presented in this paper implies that the observed thickness changes in the current ice sheet can potentially be attributed to the atmosphere, ocean or to sliding processes via similar sensitivity analysis. The paper first presents the ice sheet models participating in the SeaRISE Antarctic experiments via a discussion, in section 2, of the initial conditions they used. A regional analysis of the change in ice sheet volume that results from the first set of SeaRISE experiments is then presented in section 3. The actual patterns of thickness
change resulting for the four types of experiments are analyzed in sections 4-7, before summarizing and discussing conclusions in section 8.

2. SeaRISE’s initial configurations.

The six whole ice sheet models taking part in the SeaRISE suite of Antarctic experiments obtain their starting configuration with either interglacial spinup or by tuning methods/data assimilation. Interglacial spinup involves running a model through one or more interglacial cycles, while tuning methods use present day observations to invert for the flow variables that cannot be measured, such as basal sliding or ice rigidity. Results of the different initialization procedures are illustrated in Figure 1, where the starting configuration for each model is compared to the observed surface elevation of the ALBMAP v1 dataset [LeBrocq et al., 2010]. The models that initialize by tuning methods, namely AIF and ISSM shown in Figure 1 A-B respectively, are by nature a close match to the present day configurations. AIF iterates the governing equations keeping the observed geometry and climate forcing fixed, and tunes the enhancement factor to match the balance velocities provided by SeaRISE [Wang et al., 2012]. ISSM infers the basal friction [Morlighem et al., 2010, Larour et al., 2012a] to best match the InSAR derived surface velocities [Rignot et al., 2011], and computes a thermomechanical steady-state to ensure compatibility between temperature and velocities. For both models, large deviations from the observed surface elevations are predominantly confined to the Transantarctic Mountains, where the noise is a result of multiple interpolations between the initial dataset, the model mesh and the output grid. The fixed 40 km horizontal grid of
AIF also leads to noise in the periphery of the ice sheet, an effect that is less severe with ISSM due to its anisotropic mesh that allows for a 2-3 km resolution over the fast ice streams, and a coarser resolution in the interior.

Different methods for spinup exist, and as a result the initial configurations for PennState3D, Potsdam, SICOPOLIS and UMISM differ. PennState3D spins up over the last 5 million years, with paleo variations for the surface mass balance and temperature based on deep sea core $\delta^{18}O$ and earth orbit [Pollard and DeConto, 2009]. The resulting ice shelves are in some places larger than the present day, for example the Filchner-Ronne and Amery. PennState3D overestimates the surface elevation over mountain regions, such as the Transantarctic Mountains and in the Peninsula, and over regions of strong flow that feed the Filchner or Denman ice shelves for example. Potsdam’s spinup is a two step procedure that initially seeks thermal equilibrium by letting the temperature evolve for 200 kyr keeping the geometry fixed, followed by a 150 kyr geometric relaxation period with constant climate when the surface is allowed to evolve [Martin et al., 2011; Winkelmann et al., 2011]. As in the PennState3D model, large positive deviations occur with Potsdam over mountain regions and areas of fast flow that feed ice shelves, in particular the Peninsula, the catchment basin of the Pine Island and Thwaites Glaciers, or the basins that drain into the Ronne-Filchner and Ross Ice Shelves. In contrast, the Potsdam model underestimates the ice thickness along the ice divides of the East Antarctic ice sheet. SICOPOLIS’s initial configuration is in closer agreement with the present day observed ice sheet due to a spinup that after an initial relaxation run with freely evolving ice topography over 100 years, keeps the topography fixed over time.
The fixed-topography spinup is carried out over 125 kyr with steady surface temperature, followed by a 125 kyr run with variable surface temperature derived from the Vostok δD record converted to temperature with the relation by Petit et al. [1999]. The thickness anomalies for SICOPOLIS are generally less than 200 m, with increasing thickness deviations along the periphery of the ice sheet. The 30 kyr spinup for UMISM is driven by ice core proxy temperatures and does not involve any constraint on the ice sheet geometry. As a result, UMISM’s grounding line or ice front position for most of the West Antarctic ice sheet lies further inland than the observed configuration. A more extensive glaciation results over the Peninsula, and in some eastern regions such as Wilhelm II or Queen Mary Land. UMISM overestimates the ice thickness in the catchment basin that feeds the Amery and Denman ice shelves, and like PennState3D and Potsdam, the region inland from the Transantarctic Mountains.

Although there are differences between initial and observed surface elevations, the models taking part in SeaRISE capture the magnitude and spatial variability of the Antarctic ice sheet thickness, as illustrated in the Taylor diagram [Taylor, 2001] in Figure 2. The diagram compares the modeled ice surface elevations over grounded ice to the observed configuration using three statistics: the standard deviation (which corresponds to the radial distance from the origin), the correlation (which is equal to the cosine of the polar angle) and the root mean square (RMS) pattern difference (which is the distance from the observation point in the diagram) between the modeled and observed fields. Both the STD and RMS have been normalized by the STD of the observed surface elevation [LeBrocq et al., 2010]. Ice shelves are excluded in this analysis since two
models, AIF and UMISM, do not model ice shelves. Figure 2 thus characterizes the statistical relationship between the modeled fields and the observations, and demonstrates how closely the modeled fields resemble the observations. Models that match the observations will lie close to the observation on the Taylor diagram as they have a high correlation, a low RMS, and amplitude of variations that is similar to the observation.

As expected from Figure 1, the models that initialize via tuning methods on a fixed geometry fall near the observation, with ISSM and SICOPOLIS being the closest match to the observations. AIF has a slightly poorer correlation (0.9956) and higher standard deviation (1.02), due to a larger mismatch over mountain ranges and at the ice sheet boundary. The patterns of variation in surface elevation of UMISM are of the same amplitude as the present day ice sheet as its standard deviation is similar to the observation, but the correlation of 0.964 indicates that the positions of the ice sheet margins, valleys and ice divides in the modeled surface elevation is slightly different from the observations. In contrast, PennState3D has a better correlation than UMISM, but the amplitude of the variations is greater than the present day ice sheet. Potsdam lies the furthest away from the observations, indicating that its surface elevation is the most different from the present day ice sheet, but the statistics are still in good agreement with the observations (correlation of 0.9261 and standard deviation of 0.88), indicating that the majority of the modeled surface elevation does not deviate too far from the observations. Thus, although the models that carry out long interglacial spinups have an initial geometry that differs from the observations as seen from the difference maps (Figure 1), the Taylor diagram indicates that all the models taking part in SeaRISE do capture the
3. Basin Sensitivity to SeaRISE experiments

SeaRISE explores the response of the ice sheets to a set of external forcings chosen to capture a warmer atmospheric climate, enhanced basal lubrication and warmer oceanic conditions. The atmospheric forcings consist of imposing anomalies in surface temperature and surface mass balance based upon the A1B scenario [T. Bracegirdle, pers. comm., 2009]. SeaRISE considered three amplifications of the anomalies: 1xA1B, 1.5xA1B, and 2xA1B (referred to here as C1, C2, and C3). The enhanced sliding experiments amplified the basal velocity by factors of 2, 2.5, and 3 (referred to here as S1, S2, and S3). The oceanic forcings, M1, M2, M3 increases subshelf melt rates by 2, 20 and 200 m/year respectively. This first suite of experiments imposes single forcings, but the effect of multiple forcings was also explored with the combination experiments C1S1, C1M2, and C1S2M2. In addition to the experiments described above, models performed a control simulation (CC) by holding the climate constant, in order to assess and mitigate the effect of different initialization procedures.

The response of the Antarctic ice sheet to the SeaRISE forcings after 100 simulated years at the continental and regional scales are shown in Table 1, Figure 3 and Appendix 1. The analysis considers eight regions: 1) QMD: the basins of the East Antarctic ice sheet, which includes Queen Maud, Enderby and Kemp Lands; 2) AMR: the catchment area of
the Amery ice shelf; 3) WLK, which comprise Princess Elizabeth, Wilhelm II, Queen Mary and Wilkes Lands; 4) VCT: the basins formed by Terre Adelie, George V, Oates, and Victoria Lands; 5) ROS: the basins feeding the Ross ice shelf; 6) AMD: the basins flowing into the Amundsen Sea; 7) PEN: the Peninsula; and 8) WDL: the basins flowing into the Ronne-Filchner Ice Shelf and the Weddell Sea. In each of these regions, the change in volume above flotation ($\Delta VAF$) is calculated via the difference,

$$\Delta VAF = VAF_{exp} - VAF_{cc}, \quad (1)$$

where the $VAF$ values for the experiment and control, $VAF_{exp}$ and $VAF_{cc}$, respectively were obtained from post-processing of the SeaRISE submissions.

As discussed in section 2, tuning methods result in an initial configuration that closely matches the observed state of the ice sheet. There is no guarantee, however, that simulations of the future evolution of the ice sheet from these models will be more realistic than for models that initialize through the interglacial spinup methods, as assimilation or tuning methods can force ice sheet models into a state that is far from equilibrium, resulting in unnatural transients once prognostic modeling occurs [Seroussi et al., 2011]. This effect is seen in the control runs, where the volumes above flotation of AIF, ISSM and SICOPOLIS grow by 9.31, 25.55 and 34.17 cm sea level equivalent (sle) respectively, after 100 years of prognostic simulation under a constant climate (Table 1). In contrast, the spinups used by PennState3D, Potsdam and UMISM result in ice sheet geometries that differ from the current ice sheet (Figure 2 and Table 1), but these models
have reached an equilibrium so that prognostic simulations under constant climate leads
to a smaller drift in volume above flotation of order 1-2 cm sle after 100 years. It is
assumed that the initialization procedures affect the experiments and control simulation
in a similar manner, so that these unwanted adjustments can be removed by taking the
difference between the experiment and control simulations. This assumption is supported
by the fact that most ice sheet models are dominated by a linear behavior [Bindschadler
et al. submitted].

Bindschadler et al. [submitted] describe the continent wide response of the Antarctica ice
sheet to the SeaRISE experiments and point out that that for the atmospheric forcing
experiments (C1, C2, and C3) some models predict a gain in ice mass while others
predict a mass loss at year 100. Even models that predict similar overall mass changes
can have regional differences. For example, overall AIF and Potsdam gained a
comparable amount of mass with the C1 experiment, and experienced a growth
comparable to PennState3D for the C2 and C3 forcings, yet their regional $\Delta V AF$ are not
all equal. Another example (with similar overall mass change but regional differences) is
SICOPOLIS and UMISM in the C2 experiment. As with the overall response, responses
of the individual models within each region may not even agree as to whether there is
mass gained or lost. For example, in the QMD, AMD, and PEN regions, AIF, PennState3D and Potsdam gained mass, while SICOPOLIS and UMISM lost mass. With
the exception of SICOPOLIS, all models experience an increase in $V AF$ over the ROS
region. Despite SICOPOLIS's predictions of mass loss in the above regions, it does not
predict a loss everywhere; gain is predicted over the WLK basin that is comparable to
AIF, PennState3D and Potsdam. Other mass gains that are consistent in their magnitude include AIF, PennState3D and Potsdam in the catchment basin of the Amery Ice Shelf (AMR) and the Ross Sea (ROS).

For the sliding experiments, AIF, Potsdam and UMISM yield similar ice sheet wide mass loss to the S1 forcing, but again the individual regional responses differ. AIF and UMISM experience a comparable $\Delta VAF$ with S1 in the catchment basin of the Amery Ice Shelf, and in the basin flowing into the Amundsen Sea, but Potsdam’s ice loss is smaller in the Amery region and larger in the Amundsen Sea. In the Peninsula, AIF and Potsdam responses to S1 are similar and greater than UMISM, while it is Potsdam and UMISM that have an homologous response in the WLK and ROS regions. Although ISSM and SICOPOLIS have a comparable ice sheet wide mass loss for the S2 forcing, the mass loss from the two models are never similar at the basin scale, with ISSM resulting in a greater mass loss compared to SICOPOLIS in all regions apart from the QMD, WLK, and ROS regions. AIF and Potsdam also result in a comparable ice sheet wide $\Delta VAF$ with S2, but the only region where the $\Delta VAF$ is similar is in the Peninsula. Turning to the response to the S3 forcing, Antarctic wide $\Delta VAF$ of similar magnitude arises from PennState3D and UMISM, but the regional analysis reveals an unexpected behavior: PennState3D and UMISM have the most distinct responses. PennState3D is generally one of the least responsive to the S3 forcing, and UMISM the most sensitive to this forcing, with large growth in the VCT and ROS regions that is mitigated by the decline over the remaining of the ice sheet. The end result is that both PennState3D and UMISM predict a similar modest mass loss.
With all models, when the response to the C1 forcing leads to a mass gain, the effect of
the C2 and C3 experiments is an amplified mass gain. When the C1 forcing results in a
mass loss, however, the response to the amplified forcing differs. ISSM and PennState3D
experience a reduced mass loss, UMISM an increased mass loss, while SICOPOLIS
either gains or loses mass. The response to the amplified basal sliding forcings is more
uniform: enhanced sliding results in a negative $\Delta VAF$, except for UMISM and
SICOPOLIS, which can both experience a growth in the ROS and VCT basins for
UMISM. Increased basal melt rate leads to a decline of the ice sheet volume, apart from
Potsdam, which can grow due to a numerically caused grounding line “lock-in” that
arises from a reduction in the ice velocities once the ice shelves are removed completely
(section 6).

The combination experiments can be used to explore whether the ice sheet response to
multiple forcings that are applied simultaneously is similar to the sum of the individual
responses, or whether they result in a stronger/weaker response indicating positive or
negative feedbacks. Figure 3D shows the ratio of the change in $VAF$ resulting from the
combination forcing to the sum of the individual forcings, for all three combination
experiments (C1M1, C1S1 and C1M1S2). A ratio of unity implies that the individual
responses can be added together to infer the response from multiple forcings, while a
ratio that is greater/smaller than unity suggests that the combination forcing
amplifies/decreases the signal. A positive ratio indicates that the combination scenario is
correlated to the sum of the individual responses. A negative ratio implies that the
combination leads to growth while the individual forcings result in a decay, or vice versa. Figure 3D suggests that the ratio is close to unity for ISSM and UMISM for all regions and experiments, and for most models in general.

Figure 3D does include instances where the ratio (of the response to a combination of forcings to the sum of the responses to the associated individual responses) differs significantly from one. In the QMD region, for example, ratios are -4 for AIF/C1M1, 1.45 for AIF/C1S1M2, 4 for PennState3D/C1S1, 1.4 for SICOPOLIS/C1M1, and 1.84 for SICOPOLIS/C1S1M2. Each non-unity ratio is due to one of two distinct situations. In the first situation, seen in the case of the C1S1 and C1M1 forcings, the individual changes in \( VAF \) have similar magnitude but opposite sign, due to growth with C1 and decays with S1 or M1 (Figure 3A-C, or Appendix 1). In this situation, the large ratio is the result of the denominator being close to zero. The numerator of the ratio is also close to zero, so the response to the combination of forcings is not substantially different from the sum of the responses to the associated individual forcings. Examples include AIF/C1M1 and PennState3D/C1S1, as \( \frac{VAF_{C1M1}}{VAF_{C1}+VAF_{M1}} = 0.0003/(0.0033-0.0034) \) for AIF and \( \frac{VAF_{C1S1}}{VAF_{C1}+VAF_{S1}} = 0.0006/(0.0023-0.0021) \) for PennState3D.

The second situation resulting in a non-unity ratio in Figure 3D is when the combination forcings result in a stronger response than the sum of the individual forcings. Here the large ratio is evidence of a nonlinearity as intended. Examples include \( \frac{VAF_{C1S1M2}}{VAF_{C1}+VAF_{S1}+VAF_{M2}} = -0.1196/(0.0033-0.0307-0.0548) \) for AIF, and for SICOPOLIS \( \frac{VAF_{C1M1}}{VAF_{C1}+VAF_{M1}} = -0.007/(0.0001-0.0051) \), or
The regional analysis does not however elucidate whether the change in $VAF$ are caused by a change in ice thickness that is uniform throughout or localized within a region, or whether these responses are associated with a grounding line retreat resulting in an ice sheet that covers a smaller area, for example. To gain insight into the source of the regional $\Delta VAF$ necessitates an investigation of the spatial change in ice thickness. We now focus our analysis on the spatial patterns of thickness change for the C1, S1, M2, and the C1S1M2 sensitivity experiments.

4. The spatial response to the C1 experiment.

The spatial change in volume above flotation at a given year is explored by computing the difference in ice sheet thickness between an experiment and the control simulation for each model. The individual model responses are then combined to form ensemble statistics: maps of the mean response and standard deviation. As the experiments might lead to a change in areal coverage of the ice sheet compared to the control run, the
ensemble statistics are computed on any 10 x 10 km SeaRISE grid that contains nonzero
ice sheet thickness in either experiment or control simulation. In recognition that the
ensemble mean approach hides the actual response of the individual models, and that
there is no guarantee that the ensemble is more likely than any single realization [Giorgi,
2005], we also show the response of the most and least sensitive models.

The atmospheric sensitivity experiment imposes anomalies in surface temperature and
surface mass balance, computed from the A1B response of 18 climate models that
participated in AR4 [T. Bracegirdle, pers. comm., 2009]. These forcings only varied for
the first 94 years of the 500 years simulation periods, and were kept fixed at the 94th year
value thereafter. The C1 experiment, which imposes the A1B anomalies without any
amplification, leads to an ensemble thinning over the margins of the ice sheet, and a
thickening over the steep coastal slopes (Figure 4A). Exceptions to the coastal growth
include George V Land in VCT, the region between the Dronning Maud Land and
Enderby Land in the QMD, and the Amundsen Sea sector. Isolated large thinning occurs
over regions of high flow, such as Byrd Glacier in the Transantarctic Mountains or in
WDL over the Stancomb-Wills Glacier. Localized growth is seen in Kemp Land and
Mertz and Ninnis Glaciers located in the QMD and VCT regions. The dominant pattern
of thinning occurs throughout the basins that drain into the Amundsen Sea (Thwaites in
particular; where after 100 years, a slight growth from CC to C1 is predicted by
PennState2D due to the enhanced accumulation [Parizek et al., in review]), and over the
Peninsula. These two regions resulted in the largest mass loss in Figure 3, but the map
illustrates that some growth does occur over many ice streams on the northeastern side of
the Peninsula. Conversely, the regions experiencing the largest growth, namely ROS and WLK, are two regions that experience a small interior growth over a large area, which more than compensates the peripheral thinning. The low standard deviation in Figure 4B indicates a consistency in individual model behavior over most of the ice sheet. High values of standard deviations are predominantly confined to the Peninsula and over isolated “hot spots” of fast flow, reflecting the spread in models’ responses in these faster flowing regions.

After 100 years of simulations, SICOPOLIS has lost more ice than the other models, while AIF produces the largest gain of mass (Table 1). Their respective changes in VAF of -3.27 and 2.44 cm s\(^{-1}\) arise from distinct responses in ice sheet thicknesses, as illustrated in Figure 4C-D. Both models exhibit thinning along the grounding line of the Amery Ice Shelf, and the ensemble mean broad scale response over the steep coastal slopes, but with distinct spatial magnitudes and spatial extents. In particular, SICOPOLIS’s response displays a high spatial variability over the periphery of the ice sheet that is often absent with AIF. For example, in QMD SICOPOLIS’s localized growth balances the localized thinning to result in a negligible change in $VAF$ (Figure 3). SICOPOLIS’s localized thinning over the grounding line of the Ronne-Filchner Ice Shelves (WDL) and over the Siple Coast (ROS) outweighs the interior growth. The largest mass loss of SICOPOLIS occurs in the Amundsen Sea sector, and can be attributed to the thinning over the Thwaites and Pine Island Glaciers in AMD that do not appear in AIF.
The different responses from AIF and SICOPOLIS can be in part traced back to the surface mass balance (SMB) used by these two models. The surface forcings, shown in Figures 4E and 4G, differ between the two models for two reasons: distinct initial conditions and 100 year SMB anomalies. AIF applies an initial accumulation that is based on a regional climate model [van de Berg et al., 2006], while SICOPOLIS prescribes an accumulation that is derived from assimilated data [Arthern et al., 2006]. Both datasets have similar characteristics: high accumulation in coastal regions and low accumulation in the interior of the continent. Differences in the two datasets are mainly over the Peninsula, the western tip of Ellsworth Land (AMD), and along the Wilkes Land coast, where the accumulation from the climate model is greater than the assimilated dataset. In addition, the negative SMB along the grounding line of the Amery Ice Shelf is only present in the climate model dataset used by AIF. The future precipitation and temperature anomalies are the same for both models, as they originate from the A1B climate model anomalies provided by SeaRISE, but the ablation is calculated by the models’ respective positive degree day (PDD) schemes. The different PDD schemes lead to future SMB anomalies at 100 years, displayed in Figure 4F and H, that differ predominantly over the grounding lines. The use of different initial SMBs should not dominate the ice sheet response, as both control and experiment impose that field. Indeed, the pattern of thickness change resulting from the difference between experiment and control simulation is highly correlated to the 100 year SMB anomaly. SICOPOLIS’s thinning over the Amery Ice Shelf can indeed be largely attributed to the negative anomaly, even though the imposed SMB field is positive in this region.
5. The spatial response to the S1 experiment.

The S1 experiment investigates the response of the ice sheet due to enhancing basal lubrication by a factor of two. The suite of basal sliding experiments results in the most consistent model-to-model response, with an ice sheet wide mass loss for all models after 100 years in the simulations. The regional analysis in section 3 indicates a negative change in $VAF$ for most regions, but also suggests that growth could occur. The ensemble behavior, shown in Figure 5A, is dominated by negligible change over the interior of the ice sheet, a thinning over the ice streams, and isolated thickening along the periphery of the ice sheet. In particular, the positive change in $VAF$ resulting from UMISM in the region that drains into the Ross Ice Shelf, and in the VCT region (Figure 3), can now be attributed to peripheral growth downstream of the Transantarctic Mountains, and along the coast of Oates Land, two regions that are mostly ice-free rock. The standard deviation for the ensemble is low throughout most of the deep interior, with the spread in model responses occurring over the ice streams, reflecting the large differences in modeled initial velocities over the fast ice streams.

The two extreme responses for this experiment are from SICOPOLIS and PennState3D, with a change in $VAF$ of -27.7 and -7.59 cm sle respectively. SICOPOLIS’s thinning occurs predominantly over the fast-flowing ice streams of the eastern periphery of the Antarctic ice sheet, Thwaites Glacier, and Stancomb-Wills Glacier. However, not every ice stream experiences a thinning: Pine Island Glacier and the ice streams feeding the Ross and the Ronne-Filchner Ice Shelves are examples. When thinning results from the
enhanced sliding experiment, the maximum thinning occurs immediately upstream of the 
grounding line, and reduces further inland. As illustrated with Thwaites Glacier, the 
thickness change at the grounding line is smaller than for the remainder of the ice stream 
and inland growth can occur. The response of PennState3D is different in its location and 
pattern: maximum thinning occurs at the terminus of the large ice streams of the Siple 
Coast, Thwaites and Pine Island Glaciers, and the ice streams flowing into the Ronne-
Filchner Ice Shelves. Furthermore, PennState3D’s thinning does not extend as far inland 
as SICOPOLIS’s. The Amery region also experiences thinning upstream of the grounding 
line with PennState3D, but the increase in ice discharge leads to a grounding line 
advance. This S1 upstream thinning and grounding line advance is also predicted on 
Thwaites by PennState2D [Parizek et al., in review].

Further insight into the source of SICOPOLIS’s and PennState3D’s distinct responses is 
gained by looking at the basal velocities for the control and experiments (Figures 5 E,H). 
First, the spatial extent of the regions of fast flow is different in the control simulations: 
the base of PennState3D’s ice streams are long, narrow, well defined channels. In 
contrast, SICOPOLIS’s sliding occurs over most of the catchment area of the Siple Coast 
and the Amundsen Sea sector, for example. Second, the modeled location and number of 
ice streams around Antarctica differ. In VCT, for example, the tributaries of Cook, Ninnis 
and Metz are the only regions of fast flow for PennState3D, whereas SICOPOLIS 
contains more ice streams in this region. Third, the magnitude of the basal velocities is 
generally larger at the ice stream onset, and slower at the grounding lines, with 
SICOPOLIS compared to PennState3D.
As a result, the applied forcings are not the same. The enhanced sliding of PennState3D is confined to regions that were already fast flowing. With SICOPOLIS, sliding intensifies over a larger area and further inland; the result is that many small ice streams to merge and form faster and wider ice streams. With both models, thinning occurs in regions of enhanced flow, as long as high basal velocities occur at the grounding line of the ice stream. SICOPOLIS’s low basal velocities in the vicinity of the grounding zone of the Amery Ice Shelf prevent the increased ice flux from the upstream enhanced flow from discharging into the ice shelf and result in a thickening of the ice sheet upstream from the grounding line. The contrasting responses from the adjacent Pine Island and Thwaites Glaciers in SICOPOLIS (thickening versus thinning) are again due to whether the enhanced ice flow can reach the grounding line, which is the case for Thwaites, but not for Pine Island Glacier due to the lower velocities at the terminus.

6. The spatial response to the M2 experiment.

The spatial response to the melting suite of experiments is illustrated with the M2 scenario that imposes melt rates of 20 m/year beneath all floating ice. With this melt rate, the least sensitive model is SICOPOLIS (-31.46 cm sle), followed by Potsdam (-40.15 cm sle), AIF (-61.4 cm sle), PennState3D (-84.11 cm sle) and UMISM (-100.82 cm sle). This order changes for the other melting scenarios, however, as indicated in Table 1. The ensemble mean response (Figure 6A) features a thinning of the periphery of the ice sheet in regions where the ice meets the ocean. The thinning is largest over the ice streams that
feed the large Ronne-Filchner, Ross and Amery Ice Shelves, along with Pine Island and Thwaites Glaciers. These regions have in common that their bedrock lie below sea level. The response in the Amundsen Sea Sector (AMD), with large thinning of the interior which lessens towards the coast, results from a diversity in modeled responses. This diversity can be seen in Figure 3C, and result in a high standard deviation (not shown). Insight into the response to the M2 experiment therefore requires an analysis of the thickness change for all models that ran the experiment.

The complex thickness change of the ensemble mean is due to a combination of factors. First is the implementation of the experiment. UMISM and AIF do not include ice shelves (Figure 1), so the melt rate is applied at the grounding line. AIF restricts the melting to the grounding line of its ice streams, while UMISM imposes melting at every grid cell where the ice sheet shares a boundary with the ocean. The remaining models impose the melt rates uniformly beneath the ice shelves. Second is the treatment of the grounding line migration: all models apply the flotation condition, but PennState3D includes in addition the Schoof ice flux parameterization [Schoof, 2007a, 2007b; Pollard and DeConto, 2009], while UMISM imposes a Weertman-style spreading rate [Weertman, 1957]. Third is the grid size that varies greatly between the models [see Table 2 and Appendix A of Bindschadler et al., submitted], which is known to greatly affect the grounding line response of 2D models [Vieli and Payne, 2005; Durand et al., 2009a; Goldberg et al., 2009; Parizek et al., 2010; Pattyn et al., 2012]. Fourth is the different initial configurations of the ice sheet (including grounding line positions and thicknesses as seen in Figure 1), so from the start the ice sheet considered in some models
are more sensitive to the prescribed forcings than others. Fifth is the approximation used for modeling the dynamics of ice flow, and in particular the stress transfer between ice shelves and ice sheets. The grounding line retreat of the models is thus not homogeneous.

Together, these factors shed light on the change of $VAF$ for the different regions and models. UMISM erodes a vast portion of its periphery, making it the largest contributor of ice loss. Its comparable change in $VAF$ for the QMD and WLK regions is due to a coastline of similar extent for these two regions. Where the melting is prescribed over the same grounding lines, both AIF and UMISM respond in a similar fashion: the grounding line retreats and inland thinning occurs. The negligible change in $VAF$ over the VCT basin is due to either no forcing being applied (AIF), or to growth balancing the thinning (PennState3D and SICOPOLIS). The growth of the Potsdam model in the VCT basin, however, exceeds the thinning occurring over Cook Glacier, resulting in a net positive change in $VAF$ for this region. The grounding line of PennState3D retreats further inland into the deep basins of the West Antarctic ice sheet than any other model, resulting in the largest change in $VAF$ for these regions.

The extreme melt rate of 20 m/year can lead to the rapid desintegration and complete removal of small ice shelves, which results in a thickening upstream of the grounding lines of small, narrow, ice streams. The complete melting of the small ice shelves results in a “grounding line lock-in”, and a reduction in the computed ice velocities (Figure 6 G,H). This behavior occurs in regions where the control velocities has large gradient in the direction transverse to the flow. The approximation used for the ice dynamics which
does not resolve all the stresses, and the coarse resolution of the ice sheet models compared to the scale of the ice streams are likely causes for this thickening. On the other hand, observations of surface elevation change from ICESat (Ice Cloud and land Elevation Satellite) over the 2003-2007 time period [Pritchard et al. 2009], do indicate thickening over slow-flowing areas adjacent to thinning, narrow, fast-flowing outlet glaciers (for example, in Oates Land in VCT), with the thinning attributed to the ocean. Thus, it is possible that the modeled thickening is not a numerical artifact.

7. The spatial response to the C1S1M2 experiment.

The spatial response for the combination experiments after 100 years is illustrated with the C1S1M2 forcing, which imposes simultaneously the A1B climate anomalies (C1), a sliding amplification by a factor of two (S1), and a melt rate of 20 m/year under floating ice (M2). The ensemble mean response shown in Figure 7A is characterized by a thinning of the ice streams feeding the ice shelves. This thinning can extend into the interior of some catchment areas. The ratio of the difference in thickness from the combination to the sum of the individual forcings, $\Delta H_{\text{C1S1M2}}/(\Delta H_{\text{C1}}+\Delta H_{\text{S1}}+\Delta H_{\text{M2}})$ in Figure 7B, is close to unity over a large fraction of the ice sheet, indicating that the sum of the responses from the individual forcings is a good approximation to the response from the simultaneous forcings, as discussed in Bindschadler et al. [submitted]. Large deviations from unity occur predominantly in the interior of the ice sheet at the boundary of areas wherein the change in thickness is small. Here the large ratios result from small denominators as discussed in section 3. In contrast, the large deviations in the deep
catchment basin of Pine Island and Thwaites Glaciers are due to a thinning seen in the combination experiment that is not captured by the sum of the individual responses. For example, coupled ice-ocean feedback simulated with PennState2D prevent a 50 km S1 advance of Thwaites Glacier [Parizek et al., in review].

UMISM was the most sensitive model in the M2 experiment and is also the most responsive to the C1S1M2 experiment. The change in VAF from this combination experiment is -117.10 cm sle, compared to -1.83, -18.78, -100.82 cm sle for the C1, S1 and M2 forcings respectively. The thickness response to the combination experiment (Figure 7C) resembles the superposition of the individual response to the three distinct forcings (Figures 6F, 7E-F), a behavior expected from section 3, since the ratio of the change in VAF for UMISM was close to unity for all regions. At each location, the thickness response of the combination experiment resembles that of the dominant basal melting forcing, with the pattern of thickness change either amplified or attenuated depending on the relative magnitude of the other two sliding and climate forcings. In particular, the melting of the peripheral ice leads to a grounding line retreat that is comparable to the M2 response. The associated thinning upstream from the grounding line, however, propagates further inland to reach regions that were sensitive to the S1 forcing, as demonstrated for example with the Amery Ice Shelf. Regions that were little affected by the M2 forcing become vulnerable with the combination experiment: the glaciers flowing through the Transantarctic Mountains experience a thinning with C1S1M2 that is characteristic of the S1 forcing.
The model that leads to the smallest change in $VAF$ (-58.54 cm sle) with C1S1M2 is Potsdam, which experienced a growth of 2.25 cm sle with C1, and mass losses of 18.93 cm sle with S1 and -40.15 cm sle with M2. As with UMISM, the thickness response to the C1S1M2 forcing can be decomposed into responses that are characteristic of the individual forcings. The growth of Potsdam on the western flank of the Transantarctic Mountains is mainly due to the C1 forcing, and to the M2 experiment for Byrd Glacier. The latter growth does not extend as far inland as for the M2 forcing due to the thinning associated with the S1 experiment. The S1 thinning dominates over the responses of the M2 and C1 experiments in the Amundsen Sea sector and in WLK, for example. In contrast, the thinning patterns of the tributaries of the Amery Ice Shelf or the Siple Coast are characteristic of the M2 experiment. The different grounding line responses on the Siple Coast, however, illustrates that the response to the C1S1M2 experiment can differ from the superposition of the individual forcings due to feedbacks that arise from the simultaneous forcings, and explains in part the slight differences in the change in $VAF$ between the C1S1M2 and the sum of the individual forcings.

8. Discussion and conclusions

SeaRISE investigated the sensitivity of the current generation of ice sheet models to external forcings that altered in turn the atmospheric conditions, the basal lubrication beneath the grounded ice sheet, and the basal melting under floating ice, as well as different combinations of these three factors. Differences in modeled response of the Greenland [Nowicki et al., submitted] and Antarctic ice sheets to similar SeaRISE
forcings highlight the glaciological significance of their unique environmental and geographic settings. The ensemble change in $VAF$ is distinct for these forcings: the Antarctic ice sheet grows with the warmer atmospheric conditions (cf. the Greenland ice sheet, where surface ablation and runoff already account for ~50% of its annual mass loss [Huybrechts and de Wolde, 1999; Church et al., 2001], shrinks), while it loses mass with the dynamic forcings (as does Greenland, but with regional signatures indicative of the much smaller embayments, the far less pervasive marine instability, and the higher accumulation rates that limit the inland extent of thermally activated sliding). The magnitude of volume change is correlated with the applied forcing, and increases with the amplified experiments. The Antarctic Ice Sheet volume change from the three enhanced sliding experiments (-18.84, -24.09, and -29.10 cm sle) falls within the range of the two smallest melting forcings (-7.06 and -63.59 cm sle), implying that intermediate melt rates would have resulted in a volume change that is comparable to the sliding experiments.

The regional analysis of the change in $VAF$ after 100 years for the Antarctic Ice Sheet, revealed that distinct regional responses emerge from the four types of sensitivity experiments, despite the diversity in individual model sensitivity. For example, the mean $\Delta VAF$ for the VCT basin, suggests that this region gains the most mass as a result of the C1M1 forcing, but that it also leads to the greatest mass loss in the suite of enhanced sliding experiments. Similarly, the basins feeding the Ross Ice Shelf exhibit the maximum growth from the C1 and C3 forcings, the least decline from the S3 experiment, but the most negative response from the M1 and C1M1 forcings. The most sensitive response and mass loss from the experiments C1, C2, C3, and C1S1, occur over the
basins flowing into the Amundsen Sea, while it is the basins flowing into the Ronne-Filchner Ice Shelves that lead to the largest decline in VAF from the M2, M3 and C1S1M2 experiments. The regional change in VAF analysis therefore demonstrates that Antarctica is not affected by the forcings in a uniform manner: each basin has its own behavior. Some basins are more sensitive to changes in atmospheric conditions, while others mainly respond to oceanic or basal forcings.

The spatial analysis demonstrates that the thickness response displays different characteristics for each type of experiment. The atmospheric forcing results in a thinning that is concentrated at the grounding line of the ice sheet, and a growth over the steep coastal slopes. The thickness change after 100 years is highly correlated with the pattern of surface mass balance anomaly. This suite of experiments results in the most uniform response from the models, as indicated by the low standard deviations. The 100 years timescale is too short to assess the evolving dynamical impact of the atmospheric forcing, which becomes apparent over longer time-scales. Note, for example that after 200 years and 500 years (Figure 8 A and E), the thinning over Thwaites is amplified and over the grounding line of the Amery Ice Shelf has propagated inland. The dominant response, namely the interior growth due to the accumulation, is still highly correlated with the surface mass balance anomaly.

The thickness change resulting from the enhanced basal sliding is characterized by a thinning over the regions of fast flow due to the increased ice discharge. The thinning decreases towards the interior, but propagates inland with time (Figure 8 B and F), such
that after 500 years the interior of the ice sheet also lowers. The model-to-model
differences are predominantly due to the spatial distribution, coverage and magnitude of
the basal velocities. The basal conditions beneath the ice mass are presently poorly
known yet have controlling effect on ice flow [e.g. Larour et al., 2012b; Parizek et al., in
review]. Models have to infer important properties such as basal rheology and
bathymetry, as well as the spatial distributions of both the resistance to basal sliding and
the frozen-sliding regions. Thus, reducing the spread in models’ responses, and hence
uncertainty, requires an improved determination of the basal conditions from remote
sensed observations and field campaigns. In addition, it is questionable whether ice
stream dynamics can fully be captured by the coarse grid often used by the current ice
sheet models.

The oceanic forcing leads to a grounding line retreat and associated draw-down upstream
of the grounding line. The thinning does not extend as far inland as the thinning due to
the enhanced sliding. The oceanic suite of experiments results in the most diverse
response due to the differing implementations of the forcing (melting beneath the ice
shelf versus at the grounding line) and treatments of the grounding line migration.
PennState3D imposes two conditions: hydrostatic equilibrium and grounding line flux
condition based on Schoof [2007a, 2007b], which allows the grounding line to retreat
into the deep interior of the West Antarctic ice sheet, illustrating the potential of marine
ice sheet instability leading to collapse of the ice sheet in this region. In contrast, the
models that prescribe a grounding line migration based on only the flotation condition do
not retreat as far inland. Grounding line migration thus continues to be a challenge for ice
sheet models, and it is hoped that intercomparison exercises that focus on grounding line migration, such as MISMIP and MISMIP3d [Pattyn et al., 2012], in conjunction with theoretical and numerical studies on the physics of grounding lines [e.g. Schoof 2007a, 2007b, 2011; Nowicki and Wingham, 2008; Alley et al., 2007; Durand et al., 2009b; Parizek and Walker, 2010] and field campaigns such as Mayer and Huybrechts [1999], Anandakrishnan et al. [2003, 2007], or Peters et al. [2005], will reduce the spread in modeled responses. The forecast of grounding line evolution also requires a detailed knowledge of the bedrock topography [Durand et al., 2011; Parizek et al., under review], which can only be resolved by intensive surveys of the grounding zones of the Antarctic ice sheet.

The simultaneous application of atmospheric, oceanic and enhanced sliding forcings leads to a response that is a mixture of the signatures from the individual experiment. The peripheral thinning due to the oceanic forcing can now reach interior regions that were sensitive to the enhanced sliding experiment (Figure 7 and Figure 8D and H). In the interior, the increased accumulation outweighs the surface draw-down from the enhanced basal slipperiness, so the thickness increases with time. The sum of the responses to the individual forcings captures the spatial signature of the response to the simultaneous forcings, indicating that this first order approximation is a valid estimator of the simultaneous response. The summing approach allows the identification of the source of the thickness change (ocean, atmosphere or sliding), and could therefore become a new tool for the understanding of the observed complex response of the present day ice sheet.
Appendix 1: Regional change in volume above flotation at 100 years.

This Appendix contains the change in volume above flotation used in Table 1 and Figure 3. The analysis considers eight regions: 1) QMD: the basins of the East Antarctic ice sheet, which includes Queen Maud, Enderby and Kemp Lands; 2) AMR: the catchment area of the Amery ice shelf; 3) WLK, which comprise Princess Elizabeth, Wilhelm II, Queen Mary and Wilkes Lands; 4) VCT: the basins formed by Terre Adelie, George V, Oates, and Victoria Lands; 5) ROS: the basins feeding the Ross ice shelf; 6) AMD: the basins flowing into the Amundsen Sea; 7) PEN: the Peninsula; and 8) WDL: the basins flowing into the Ronne-Filchner Ice Shelf and the Weddell Sea. In each of these regions, the change in volume above flotation ($\Delta V_{AF}$) is calculated via the difference, $\Delta V_{AF} = V_{AF}^{exp} - V_{AF}^{cc}$, where the $V_{AF}$ values for the experiment and control, $V_{AF}^{exp}$ and $V_{AF}^{cc}$, respectively were obtained from post-processing of the SeaRISE submissions. The $V_{AF}$ is computed from $V_{AF} = A (H-Z(\rho_w/\rho_i))$ where $A$ is the 10 x 10 km grid cell area, $H$ is the ice thickness, $Z$ is the depth of the bedrock, and $\rho_w$ and $\rho_i$ are the densities of seawater and ice, respectively.
Acknowledgements

A project of this magnitude and scope required extensive support from many persons not listed as authors. Data sets, both published and in pre-publication forms, were contributed by A. LeBrocq, H. Pritchard, B. Csatho (dh/dt), T. Bracegirdle, CReSIS and NASA’s IceBridge mission and posted on the University of Montana CISM web site to be available to all SeaRISE modelers. This web site also served as a discussion forum for SeaRISE during its early stages of model initialization and experiment design. The Los Alamos National Laboratory also offered use of a web site that became the repository of all communication files (telecom notes and meeting presentations of SeaRISE).

Participation in SeaRISE remained voluntary and, in most cases, came without financial support. Thus participants had to leverage off of existing funding activities with objectives that overlapped with SeaRISE goals.

R. Greve, H. Seddik and T. Sato were supported by a Grant-in-Aid for Scientific Research A (No. 22244058) from the Japan Society for the Promotion of Science (JSPS).

U. Herzfeld was supported by a NASA Cryospheric Sciences Award (NNX11AP39G).

M. A. Martin was supported by the German Federal Ministry of Education and Research (BMBF).

B. Parizek was supported by the U.S. National Science Foundation under grants 0531211, 0758274, 0909335, and the Center for Remote Sensing of Ice Sheets (CReSIS) 0424589 and by NASA under grants NNX-09-AV94G and NNX-10-AI04G.

D. Pollard was supported by the US National Science Foundation under grants ANT-0424589, 1043018, 25-0550-0001, and OCE-1202632.
S. F. Price and W.H. Lipscomb were supported by the U.S. Department of Energy (DOE) Office of Science Office of Biological and Environmental Research. Simulations were conducted at The National Energy Research Scientific Computing Center (supported by DOE’s Office of Science under Contract No. DE-AC02-05CH11231) using time awarded through DOE’s ASCR Leadership Computing Challenge allocation to the project “Projections of Ice Sheet Evolution Using Advanced Ice and Ocean Models”. Model development and simulations were also conducted at the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, supported by DOE’s Office of Science under Contract No. DE-AC05-00OR22725. CISM development and simulations relied on additional support by K.J. Evans, P.H. Worley and J.A. Nichols (all of Oak Ridge National Laboratory) and A.G. Salinger (Sandia National Laboratories).

H Seroussi and M. Morlighem are supported by the NASA Cryospheric Sciences Program and Modeling Analysis and Prediction Program, and a contract with the Jet Propulsion Laboratory Research Technology and Development Program. H Seroussi was also supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Oak Ridge Associated Universities through a contract with NASA Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center. E. Larour and E. Rignot further enabled their participation on SeaRISE.

R. Walker was supported by NSF through grants 0909335 and CReSIS 0424589, by NASA under grants NNX-09-AV94G and NNX-10-AI04G, and by the Gary Comer Science and Education Foundation.
W. Wang was supported by the NASA Cryospheric Science program (Grant 281945.02.53.02.19).

Finally, S. Nowicki and R. Bindschadler wish to gratefully acknowledge the unwavering encouragement and financial support from the NASA Cryospheric Science program for the core funding enabling SeaRISE to reach a successful conclusion.
References


Durand, O. Gagliardini, R. Gladstone, D. Goldberg, G.H. Gudmundsson, V. Lee, F.M.
Marine Ice Sheet Model Intercomparison Project, MISMIP. *The Cryosphere*, 6, 573-588,
doi:10.5194/tc-6-573-2012.


Petit, J.R., and coauthors, 1999. Climate and atmospheric history of the past 420,000
years from the Vostok ice core, Antarctica. *Nature*, 399, 429-436.

dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, 461,
971-975, doi:10.1038/nature08471.


Figure captions

Figure 1: The anomaly in ice surface elevation at the start of the SeaRISE experiments: simulated minus modern-day Antarctica. Simulated grounding lines (green lines) and drainage divides (black lines) are shown for the eight regions discussed in the text. Clockwise from the North: 1. QMD, 2. AMR, 3. WLK, 4. VCT, 5. ROS, 6. AMD, 7. PEN, and 8. WDL.

Figure 2: Variability of the modeled initial surface elevation relative to the observed Antarctic ice sheet. The radial distance is proportional to the standard deviation, the angular position corresponds to the correlation, and the distance between the SeaRISE models (points A-F) and observation (Obs) represents the RMS. The standard deviation and RMS difference have been normalized by the observed standard deviation. Models plotted: AIF (A), ISSM (B), PennState3D (C), Potsdam (D), SICOPOLIS (E), and UMISM (F).

Figure 3: The change (experiment minus control) in the volume above flotation for eight regions of the Antarctic ice sheet after 100 simulated years. A) Atmospheric forcings (C1 in blue, C2 in red, C3 in black). B) Enhanced sliding forcings (S1 in blue, S2 in red, S3 in black). C) Oceanic forcings (M1 in blue, M2 in red, M3 in black). D) Ratio of $\Delta VAF$ from the combination experiment to sum of the individual forcings: $\Delta VAF_{CIM1}/(\Delta VAF_{C1}+\Delta VAF_{M1})$ in blue, $\Delta VAF_{CIMJ}/(\Delta VAF_{C1}+\Delta VAF_{S1})$ in red, and $\Delta VAF_{CISM2}/$
$(\Delta VAF_{C1} + \Delta VAF_{S1} + \Delta VAF_{M2})$ in black. In some cases the $\Delta VAF$ exceeds the vertical axis, but the $\Delta VAF$ for all models are given in Appendix 1.

Figure 4: The ensemble mean thickness change from the control (A) and standard deviation (B) resulting from the C1 experiment after 100 simulated years, along with the thickness contribution from the most negative (SICOPOLIS, C) and positive (AIF, D) change in $VAF$. Surface mass balance (E, G) and surface mass balance anomaly (F, H) for these models at 100 years.

Figure 5: The ensemble mean thickness change from the control (A) and standard deviation (B) resulting from the S1 experiment after 100 simulated years, along with the thickness contribution from the maximum (SICOPOLIS, C) and minimum (PennState3D, D) models. The basal velocities from the control and S1 experiments for SICOPOLIS (E, F) and PennState3D (G, H) at 100 years.

Figure 6: The ensemble mean thickness change from the control (A) resulting from the M2 experiment at 100 years, along with the thickness contribution from AIF (B), PennState3D (C), Potsdam (D), SICOPOLIS (E) and UMISM (F). Grounding lines at time 0 years and 100 years are shown in black and green lines respectively. Surface velocity in Wilkes Land from the control (G) and velocity anomaly M2 minus CC (H) for PennState3D, Potsdam, and SICOPOLIS.

Figure 7: The ensemble mean thickness change from the control resulting from the C1S1M2 experiment after 100 years (A), along with the ratio of thickness change (B).
The thickness contribution from the maximum (UMISM) and minimum (Potsdam) models for the C1S1M2 forcing (C, D), the C1 forcing (E, G), and the S1 forcing (F, H). The grounding line for the M2 experiment at 100 years is shown in green.

Figure 8: The ensemble mean thickness change from the control at 200 and 500 years resulting from the C1 experiment (A, E), the S1 forcing (B, F), the M2 experiment (C, G), and the C1S1M2 forcing (D, H).
Table 1: Initial volume above flotation and associated change after 100 years for the SeaRISE sensitivity experiments. Units are in centimeter sea-level equivalent (cm sle). X indicates no submission from the model.

<table>
<thead>
<tr>
<th></th>
<th>AIF</th>
<th>ISSM</th>
<th>PennState3D</th>
<th>Potsdam</th>
<th>SICOPOLIS</th>
<th>UMISM</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>5532</td>
<td>5512</td>
<td>5752</td>
<td>5941</td>
<td>5521</td>
<td>5929</td>
<td>5698</td>
</tr>
<tr>
<td>CC-Initial</td>
<td>9.31</td>
<td>25.55</td>
<td>2.00</td>
<td>-1.06</td>
<td>34.17</td>
<td>1.31</td>
<td>11.88</td>
</tr>
<tr>
<td>C1-CC</td>
<td>2.45</td>
<td>X</td>
<td>1.09</td>
<td>2.25</td>
<td>-3.26</td>
<td>-1.83</td>
<td>0.14</td>
</tr>
<tr>
<td>C2-CC</td>
<td>3.63</td>
<td>X</td>
<td>3.75</td>
<td>3.43</td>
<td>-2.40</td>
<td>-2.72</td>
<td>1.14</td>
</tr>
<tr>
<td>C3-CC</td>
<td>4.62</td>
<td>X</td>
<td>4.37</td>
<td>4.77</td>
<td>-2.54</td>
<td>-3.71</td>
<td>1.50</td>
</tr>
<tr>
<td>S1-CC</td>
<td>-18.09</td>
<td>-21.94</td>
<td>-7.59</td>
<td>-18.93</td>
<td>-27.70</td>
<td>-18.78</td>
<td>-18.84</td>
</tr>
<tr>
<td>S2-CC</td>
<td>-25.94</td>
<td>-31.83</td>
<td>-10.28</td>
<td>-25.70</td>
<td>-33.09</td>
<td>-17.74</td>
<td>-24.09</td>
</tr>
<tr>
<td>S3-CC</td>
<td>-33.43</td>
<td>-41.24</td>
<td>-12.87</td>
<td>-30.61</td>
<td>-44.40</td>
<td>-12.03</td>
<td>-29.10</td>
</tr>
<tr>
<td>M1-CC</td>
<td>-4.27</td>
<td>X</td>
<td>-12.25</td>
<td>-2.99</td>
<td>-7.88</td>
<td>-7.93</td>
<td>-7.06</td>
</tr>
<tr>
<td>M2-CC</td>
<td>-61.40</td>
<td>X</td>
<td>-84.11</td>
<td>-40.15</td>
<td>-31.46</td>
<td>-100.82</td>
<td>-63.59</td>
</tr>
<tr>
<td>M3-CC</td>
<td>-297.58</td>
<td>X</td>
<td>-119.10</td>
<td>23.10</td>
<td>-57.30</td>
<td>-898.81</td>
<td>-269.94</td>
</tr>
<tr>
<td>C1M1-CC</td>
<td>-1.75</td>
<td>X</td>
<td>-9.46</td>
<td>-0.62</td>
<td>-8.99</td>
<td>-9.88</td>
<td>-6.14</td>
</tr>
<tr>
<td>C1S1-CC</td>
<td>-15.64</td>
<td>X</td>
<td>-5.73</td>
<td>-16.11</td>
<td>-25.33</td>
<td>-20.78</td>
<td>-16.72</td>
</tr>
<tr>
<td>C1S1M2-CC</td>
<td>-92.04</td>
<td>X</td>
<td>-92.42</td>
<td>-58.54</td>
<td>-93.90</td>
<td>-117.10</td>
<td>-90.80</td>
</tr>
</tbody>
</table>
Table A1: Change in volume above flotation in cm sle at 100 years for the atmospheric forcings over 8 basins of the Antarctic ice sheet.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Alf</th>
<th>ISSM</th>
<th>PennState3D</th>
<th>Potsdam C1-CC</th>
<th>SICOPOLIS</th>
<th>UMISM</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>QMD</td>
<td>0.3286</td>
<td>X</td>
<td>0.2268</td>
<td>0.3719</td>
<td>0.0082</td>
<td>-0.5283</td>
<td>0.0814</td>
</tr>
<tr>
<td>AMR</td>
<td>0.1804</td>
<td>X</td>
<td>0.1285</td>
<td>0.1433</td>
<td>-0.0692</td>
<td>0.0395</td>
<td>0.0845</td>
</tr>
<tr>
<td>WLK</td>
<td>0.7240</td>
<td>X</td>
<td>0.6524</td>
<td>0.6820</td>
<td>0.8550</td>
<td>-0.6499</td>
<td>0.4527</td>
</tr>
<tr>
<td>VCT</td>
<td>0.0316</td>
<td>X</td>
<td>0.0222</td>
<td>0.0610</td>
<td>-0.4208</td>
<td>0.1320</td>
<td>-0.0348</td>
</tr>
<tr>
<td>ROS</td>
<td>0.4843</td>
<td>X</td>
<td>0.4739</td>
<td>0.4925</td>
<td>-0.2936</td>
<td>0.2775</td>
<td>0.2869</td>
</tr>
<tr>
<td>AMD</td>
<td>0.0643</td>
<td>X</td>
<td>0.0294</td>
<td>0.1856</td>
<td>-1.5838</td>
<td>-0.3716</td>
<td>-0.3352</td>
</tr>
<tr>
<td>PEN</td>
<td>0.1940</td>
<td>X</td>
<td>0.1795</td>
<td>0.2944</td>
<td>-0.9088</td>
<td>-1.3521</td>
<td>-0.3186</td>
</tr>
<tr>
<td>WDL</td>
<td>0.4831</td>
<td>X</td>
<td>-0.6284</td>
<td>0.2286</td>
<td>-0.8688</td>
<td>0.3724</td>
<td>-0.0826</td>
</tr>
<tr>
<td>QMD</td>
<td>0.4883</td>
<td>X</td>
<td>0.3887</td>
<td>0.8211</td>
<td>-0.2088</td>
<td>-0.7996</td>
<td>0.1379</td>
</tr>
<tr>
<td>AMR</td>
<td>0.2520</td>
<td>X</td>
<td>0.2397</td>
<td>0.2644</td>
<td>-0.0939</td>
<td>0.0568</td>
<td>0.1438</td>
</tr>
<tr>
<td>WLK</td>
<td>1.0922</td>
<td>X</td>
<td>0.8970</td>
<td>1.0403</td>
<td>1.3072</td>
<td>-0.9711</td>
<td>0.6731</td>
</tr>
<tr>
<td>VCT</td>
<td>0.0378</td>
<td>X</td>
<td>0.0133</td>
<td>0.2461</td>
<td>-0.3838</td>
<td>0.2004</td>
<td>0.0228</td>
</tr>
<tr>
<td>ROS</td>
<td>0.6978</td>
<td>X</td>
<td>0.6971</td>
<td>0.8414</td>
<td>-0.1905</td>
<td>0.4181</td>
<td>0.4928</td>
</tr>
<tr>
<td>AMD</td>
<td>0.0839</td>
<td>X</td>
<td>0.2362</td>
<td>0.0371</td>
<td>-1.2793</td>
<td>-0.5548</td>
<td>-0.2954</td>
</tr>
<tr>
<td>PEN</td>
<td>0.2858</td>
<td>X</td>
<td>0.2791</td>
<td>0.3406</td>
<td>-0.8820</td>
<td>-2.0283</td>
<td>-0.4009</td>
</tr>
<tr>
<td>WDL</td>
<td>0.7186</td>
<td>X</td>
<td>1.0035</td>
<td>0.6793</td>
<td>-0.6872</td>
<td>0.5473</td>
<td>0.4523</td>
</tr>
<tr>
<td>QMD</td>
<td>0.6183</td>
<td>X</td>
<td>0.4366</td>
<td>0.7957</td>
<td>-0.3838</td>
<td>-1.0662</td>
<td>0.0801</td>
</tr>
<tr>
<td>AMR</td>
<td>0.3064</td>
<td>X</td>
<td>0.2965</td>
<td>0.3015</td>
<td>-0.1285</td>
<td>0.0766</td>
<td>0.1705</td>
</tr>
<tr>
<td>WLK</td>
<td>1.4505</td>
<td>X</td>
<td>1.1095</td>
<td>1.3764</td>
<td>1.5197</td>
<td>-1.2973</td>
<td>0.8317</td>
</tr>
<tr>
<td>VCT</td>
<td>0.0282</td>
<td>X</td>
<td>0.0272</td>
<td>0.0771</td>
<td>-0.4579</td>
<td>0.2711</td>
<td>-0.0109</td>
</tr>
<tr>
<td>ROS</td>
<td>0.8394</td>
<td>X</td>
<td>0.9595</td>
<td>0.9012</td>
<td>-0.1268</td>
<td>0.5587</td>
<td>0.6264</td>
</tr>
<tr>
<td>AMD</td>
<td>0.0931</td>
<td>X</td>
<td>0.1506</td>
<td>0.0692</td>
<td>-1.4139</td>
<td>-0.7398</td>
<td>-0.3682</td>
</tr>
<tr>
<td>PEN</td>
<td>0.3710</td>
<td>X</td>
<td>0.4049</td>
<td>0.5573</td>
<td>-0.9519</td>
<td>-2.7155</td>
<td>-0.4668</td>
</tr>
<tr>
<td>WDL</td>
<td>0.9279</td>
<td>X</td>
<td>0.9948</td>
<td>0.4549</td>
<td>-0.6511</td>
<td>0.7218</td>
<td>0.4897</td>
</tr>
</tbody>
</table>
Table A2: Change in volume above flotation in cm s\(^{-1}\) at 100 years for the enhanced basal sliding forcings over 8 basins of the Antarctic ice sheet.

<table>
<thead>
<tr>
<th>Basin</th>
<th>AIF</th>
<th>ISSM</th>
<th>PennState3D</th>
<th>Potsdam</th>
<th>SICOPOLIS</th>
<th>UMISM</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S1-CC</td>
</tr>
<tr>
<td>QMD</td>
<td>-3.0727</td>
<td>-2.1883</td>
<td>-0.2140</td>
<td>-0.6796</td>
<td>-4.4701</td>
<td>-2.1041</td>
<td>-2.2881</td>
</tr>
<tr>
<td>AMR</td>
<td>-1.1762</td>
<td>-0.9983</td>
<td>-0.6573</td>
<td>-0.6622</td>
<td>-0.6375</td>
<td>-1.0675</td>
<td>-0.8665</td>
</tr>
<tr>
<td>WLK</td>
<td>-2.8145</td>
<td>-3.7362</td>
<td>-0.6103</td>
<td>-4.8951</td>
<td>-8.0333</td>
<td>-5.0137</td>
<td>-4.1839</td>
</tr>
<tr>
<td>VCT</td>
<td>-1.2859</td>
<td>-1.9874</td>
<td>-0.4085</td>
<td>-1.9872</td>
<td>-5.7093</td>
<td>0.1880</td>
<td>-1.8650</td>
</tr>
<tr>
<td>ROS</td>
<td>-0.7878</td>
<td>-1.8382</td>
<td>-1.4018</td>
<td>-1.5506</td>
<td>-0.8950</td>
<td>-1.7655</td>
<td>-1.3731</td>
</tr>
<tr>
<td>AMD</td>
<td>-2.3700</td>
<td>-5.4759</td>
<td>-1.0864</td>
<td>-2.8699</td>
<td>-4.3185</td>
<td>-2.4134</td>
<td>3.0890</td>
</tr>
<tr>
<td>PEN</td>
<td>-2.0915</td>
<td>-1.8473</td>
<td>-0.3076</td>
<td>-1.9175</td>
<td>-1.2921</td>
<td>-1.1037</td>
<td>-1.4266</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S2-CC</td>
</tr>
<tr>
<td>QMD</td>
<td>-4.4602</td>
<td>-3.2244</td>
<td>-0.3168</td>
<td>-2.1525</td>
<td>-5.3389</td>
<td>-3.2440</td>
<td>3.1228</td>
</tr>
<tr>
<td>AMR</td>
<td>-1.7124</td>
<td>-1.4727</td>
<td>-0.7537</td>
<td>-0.8179</td>
<td>-0.4670</td>
<td>-1.5320</td>
<td>-1.1260</td>
</tr>
<tr>
<td>WLK</td>
<td>-4.1637</td>
<td>-5.5104</td>
<td>-0.7413</td>
<td>-6.9288</td>
<td>-13.707</td>
<td>-7.3217</td>
<td>-6.3954</td>
</tr>
<tr>
<td>VCT</td>
<td>-1.8901</td>
<td>-2.9007</td>
<td>-0.5617</td>
<td>-2.4416</td>
<td>-7.1297</td>
<td>9.0716</td>
<td>-0.9754</td>
</tr>
<tr>
<td>ROS</td>
<td>-1.1152</td>
<td>-2.6620</td>
<td>-1.4606</td>
<td>-2.0292</td>
<td>0.1250</td>
<td>-1.5313</td>
<td>-1.4456</td>
</tr>
<tr>
<td>PEN</td>
<td>-2.8365</td>
<td>-2.5991</td>
<td>-0.4766</td>
<td>-2.6369</td>
<td>-0.3384</td>
<td>-1.3211</td>
<td>-1.7014</td>
</tr>
<tr>
<td>WDL</td>
<td>-6.3804</td>
<td>-5.6379</td>
<td>-4.5724</td>
<td>-3.4271</td>
<td>-1.5721</td>
<td>-7.1682</td>
<td>-4.7930</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S3-CC</td>
</tr>
<tr>
<td>QMD</td>
<td>-5.7738</td>
<td>-4.2334</td>
<td>-0.4183</td>
<td>-2.4500</td>
<td>-7.0180</td>
<td>-4.2815</td>
<td>-4.0292</td>
</tr>
<tr>
<td>AMR</td>
<td>-2.2338</td>
<td>-1.9373</td>
<td>-1.0205</td>
<td>-1.0205</td>
<td>-0.7215</td>
<td>-2.2264</td>
<td>-1.5267</td>
</tr>
<tr>
<td>VCT</td>
<td>-2.5133</td>
<td>-3.7765</td>
<td>-0.6304</td>
<td>-2.8731</td>
<td>-9.2710</td>
<td>12.0769</td>
<td>-1.1646</td>
</tr>
<tr>
<td>ROS</td>
<td>-1.4329</td>
<td>-3.4471</td>
<td>-2.3739</td>
<td>-2.7381</td>
<td>0.1488</td>
<td>6.5556</td>
<td>-0.5480</td>
</tr>
<tr>
<td>AMD</td>
<td>-4.2732</td>
<td>-10.063</td>
<td>-1.9001</td>
<td>-4.3086</td>
<td>-6.4353</td>
<td>-2.8991</td>
<td>-4.9798</td>
</tr>
<tr>
<td>PEN</td>
<td>-3.5007</td>
<td>-3.2711</td>
<td>-0.4113</td>
<td>-3.3431</td>
<td>-0.3363</td>
<td>-1.1377</td>
<td>-2.0000</td>
</tr>
</tbody>
</table>
Table A3: Change in volume above flotation in cm sle at 100 years for the oceanic forcings over 8 basins of the Antarctic ice sheet.

<table>
<thead>
<tr>
<th>Basin</th>
<th>AIF</th>
<th>ISSM</th>
<th>PennState3D</th>
<th>Potsdam</th>
<th>SICOPOLIS</th>
<th>UMISM</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>M1-CC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QMD</td>
<td>-0.3351</td>
<td>X</td>
<td>-0.1787</td>
<td>0.9595</td>
<td>-0.5051</td>
<td>-1.9388</td>
<td>-0.3996</td>
</tr>
<tr>
<td>AMR</td>
<td>-0.1359</td>
<td>X</td>
<td>-0.4300</td>
<td>-0.4473</td>
<td>-0.3212</td>
<td>-0.1260</td>
<td>-0.2921</td>
</tr>
<tr>
<td>WLK</td>
<td>-0.0642</td>
<td>X</td>
<td>0.0198</td>
<td>0.0469</td>
<td>0.8426</td>
<td>-1.4876</td>
<td>-0.1285</td>
</tr>
<tr>
<td>VCT</td>
<td>-0.0025</td>
<td>X</td>
<td>-0.1539</td>
<td>0.3193</td>
<td>-0.2478</td>
<td>-1.0074</td>
<td>-0.2185</td>
</tr>
<tr>
<td>ROS</td>
<td>-1.6674</td>
<td>X</td>
<td>-5.1682</td>
<td>-3.4481</td>
<td>-1.3578</td>
<td>-0.7556</td>
<td>-2.4794</td>
</tr>
<tr>
<td>AMD</td>
<td>-0.2375</td>
<td>X</td>
<td>-1.6483</td>
<td>-0.2488</td>
<td>-2.0512</td>
<td>-1.0431</td>
<td>-0.9463</td>
</tr>
<tr>
<td>PEN</td>
<td>-0.1550</td>
<td>X</td>
<td>-0.1994</td>
<td>-0.1050</td>
<td>-1.9062</td>
<td>-1.1469</td>
<td>-0.6605</td>
</tr>
<tr>
<td>WDL</td>
<td>-1.6798</td>
<td>X</td>
<td>-4.5067</td>
<td>-1.4255</td>
<td>-2.3596</td>
<td>-1.3996</td>
<td>-2.2742</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M2-CC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QMD</td>
<td>-5.4793</td>
<td>X</td>
<td>-1.4110</td>
<td>3.1303</td>
<td>-4.6099</td>
<td>-21.107</td>
<td>-5.8953</td>
</tr>
<tr>
<td>AMR</td>
<td>-2.5402</td>
<td>X</td>
<td>-5.8168</td>
<td>-3.4224</td>
<td>-2.9553</td>
<td>-1.9422</td>
<td>-3.3354</td>
</tr>
<tr>
<td>WLK</td>
<td>-0.5757</td>
<td>X</td>
<td>-1.0971</td>
<td>0.1804</td>
<td>-0.6178</td>
<td>-20.972</td>
<td>-4.6164</td>
</tr>
<tr>
<td>VCT</td>
<td>-0.0568</td>
<td>X</td>
<td>0.0788</td>
<td>1.6361</td>
<td>-0.3462</td>
<td>-11.085</td>
<td>-1.9545</td>
</tr>
<tr>
<td>AMD</td>
<td>-0.7298</td>
<td>X</td>
<td>-20.253</td>
<td>1.0267</td>
<td>-5.8489</td>
<td>-11.161</td>
<td>-7.3933</td>
</tr>
<tr>
<td>PEN</td>
<td>-0.4793</td>
<td>X</td>
<td>-0.4265</td>
<td>-0.2727</td>
<td>-2.7289</td>
<td>-13.885</td>
<td>-3.5585</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M3-CC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WLK</td>
<td>-1.1317</td>
<td>X</td>
<td>-2.9603</td>
<td>5.4857</td>
<td>-8.0086</td>
<td>-169.79</td>
<td>-35.282</td>
</tr>
<tr>
<td>VCT</td>
<td>-0.1754</td>
<td>X</td>
<td>0.1994</td>
<td>3.0075</td>
<td>-3.8281</td>
<td>-92.379</td>
<td>-18.635</td>
</tr>
<tr>
<td>ROS</td>
<td>-133.59</td>
<td>X</td>
<td>-42.820</td>
<td>4.6915</td>
<td>-4.7562</td>
<td>-123.96</td>
<td>-60.087</td>
</tr>
<tr>
<td>AMD</td>
<td>-58.319</td>
<td>X</td>
<td>-40.504</td>
<td>8.1598</td>
<td>-7.3677</td>
<td>-114.16</td>
<td>-42.439</td>
</tr>
<tr>
<td>PEN</td>
<td>-0.7318</td>
<td>X</td>
<td>-0.4832</td>
<td>1.0576</td>
<td>-3.6583</td>
<td>-75.468</td>
<td>-15.857</td>
</tr>
<tr>
<td>WDL</td>
<td>-88.959</td>
<td>X</td>
<td>-22.865</td>
<td>1.3531</td>
<td>-20.381</td>
<td>-140.18</td>
<td>-54.206</td>
</tr>
</tbody>
</table>

53
Table A4: Change in volume above flotation in cm s**le** at 100 years for the combination forcings over 8 basins of the Antarctic ice sheet.

<table>
<thead>
<tr>
<th>Basin</th>
<th>AIF</th>
<th>ISSM</th>
<th>PennState3D</th>
<th>Potsdam</th>
<th>SICOPOLIS</th>
<th>UMISM</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1M1-CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QMD</td>
<td>0.0267</td>
<td>X</td>
<td>0.0208</td>
<td>1.2246</td>
<td>-0.6998</td>
<td>-2.4997</td>
<td>-0.3855</td>
</tr>
<tr>
<td>AMR</td>
<td>0.0420</td>
<td>X</td>
<td>-0.2768</td>
<td>-0.3484</td>
<td>-0.3682</td>
<td>-0.0890</td>
<td>-0.2081</td>
</tr>
<tr>
<td>WLK</td>
<td>0.6647</td>
<td>X</td>
<td>0.5634</td>
<td>0.7512</td>
<td>0.6944</td>
<td>-2.1473</td>
<td>0.1053</td>
</tr>
<tr>
<td>VCT</td>
<td>0.0269</td>
<td>X</td>
<td>-0.1139</td>
<td>0.2293</td>
<td>-0.3924</td>
<td>-0.8750</td>
<td>-0.2251</td>
</tr>
<tr>
<td>ROS</td>
<td>-1.1755</td>
<td>X</td>
<td>-4.7105</td>
<td>-2.880</td>
<td>-1.1710</td>
<td>-0.4814</td>
<td>-2.0837</td>
</tr>
<tr>
<td>AMD</td>
<td>-0.1594</td>
<td>X</td>
<td>-1.6356</td>
<td>0.0714</td>
<td>-2.1701</td>
<td>-1.4270</td>
<td>-1.0641</td>
</tr>
<tr>
<td>PEN</td>
<td>0.0416</td>
<td>X</td>
<td>0.0308</td>
<td>0.3802</td>
<td>-2.3725</td>
<td>-2.5230</td>
<td>-0.8886</td>
</tr>
<tr>
<td>WDL</td>
<td>-1.2029</td>
<td>X</td>
<td>-3.3450</td>
<td>-1.1001</td>
<td>-2.5301</td>
<td>-1.0339</td>
<td>-1.8424</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1S1-CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QMD</td>
<td>-2.7446</td>
<td>X</td>
<td>0.0551</td>
<td>-0.7932</td>
<td>-4.3883</td>
<td>-2.5820</td>
<td>-2.0906</td>
</tr>
<tr>
<td>AMR</td>
<td>-0.9983</td>
<td>X</td>
<td>-0.5288</td>
<td>-0.4596</td>
<td>-0.5510</td>
<td>-1.0279</td>
<td>-0.7131</td>
</tr>
<tr>
<td>WLK</td>
<td>-2.0732</td>
<td>X</td>
<td>-0.0914</td>
<td>-4.0772</td>
<td>-6.8546</td>
<td>-5.5771</td>
<td>-3.7347</td>
</tr>
<tr>
<td>VCT</td>
<td>-1.2405</td>
<td>X</td>
<td>-0.3931</td>
<td>-2.0502</td>
<td>-5.7333</td>
<td>0.3348</td>
<td>-1.8165</td>
</tr>
<tr>
<td>ROS</td>
<td>-0.3084</td>
<td>X</td>
<td>-0.7497</td>
<td>-1.1656</td>
<td>-0.3319</td>
<td>-1.5908</td>
<td>-0.8293</td>
</tr>
<tr>
<td>AMD</td>
<td>-2.3119</td>
<td>X</td>
<td>-1.1108</td>
<td>-3.0002</td>
<td>-4.4648</td>
<td>-2.9048</td>
<td>-2.7585</td>
</tr>
<tr>
<td>PEN</td>
<td>-1.9465</td>
<td>X</td>
<td>-0.1103</td>
<td>-1.7119</td>
<td>-1.1040</td>
<td>-2.4105</td>
<td>-1.4566</td>
</tr>
<tr>
<td>WDL</td>
<td>-3.9700</td>
<td>X</td>
<td>-2.7999</td>
<td>-2.1051</td>
<td>-1.9346</td>
<td>-4.6935</td>
<td>-3.1006</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C1S1M2-CC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QMD</td>
<td>-11.961</td>
<td>X</td>
<td>-1.3138</td>
<td>1.4584</td>
<td>-16.750</td>
<td>-22.711</td>
<td>-10.255</td>
</tr>
<tr>
<td>AMR</td>
<td>-4.0031</td>
<td>X</td>
<td>-5.1719</td>
<td>-4.2353</td>
<td>-5.6043</td>
<td>-2.7206</td>
<td>-4.3470</td>
</tr>
<tr>
<td>VCT</td>
<td>-1.6778</td>
<td>X</td>
<td>-0.1606</td>
<td>-0.8041</td>
<td>-5.4531</td>
<td>-11.904</td>
<td>-4.0000</td>
</tr>
<tr>
<td>ROS</td>
<td>-25.823</td>
<td>X</td>
<td>-37.739</td>
<td>-5.7654</td>
<td>-9.7042</td>
<td>-10.653</td>
<td>-17.937</td>
</tr>
<tr>
<td>PEN</td>
<td>-2.7469</td>
<td>X</td>
<td>-0.3680</td>
<td>-2.4308</td>
<td>-5.7686</td>
<td>-15.578</td>
<td>-5.3789</td>
</tr>
</tbody>
</table>
Figures

Figure 1: The anomaly in ice surface elevation at the start of the SeaRISE experiments: simulated minus modern-day Antarctica. Simulated grounding lines (green lines) and drainage divides (black lines) are shown for the eight regions discussed in the text. Clockwise from the North: 1. QMD, 2. AMR, 3. WLK, 4. VCT, 5. ROS, 6. AMD, 7. PEN, and 8. WDL.
Figure 2: Variability of the modeled initial surface elevation relative to the observed Antarctic ice sheet. The radial distance is proportional to the standard deviation, the angular position corresponds to the correlation, and the distance between the SeaRISE models (points A-F) and observation (Obs) represents the RMS. The standard deviation and RMS difference have been normalized by the observed standard deviation. Models plotted: AIF (A), ISSM (B), PennState3D (C), Potsdam (D), SICOPOLIS (E), and UMISM (F).
Figure 3: The change (experiment minus control) in the volume above flotation for eight regions of the Antarctic ice sheet after 100 simulated years. A) Atmospheric forcings (C1 in blue, C2 in red, C3 in black). B) Enhanced sliding forcings (S1 in blue, S2 in red, S3 in black). C) Oceanic forcings (M1 in blue, M2 in red, M3 in black). D) Ratio of $\Delta VAF$ from the combination experiment to sum of the individual forcings: $\Delta VAF_{CIM1}/(\Delta VAF_{C1}+\Delta VAF_{M1})$ in blue, $\Delta VAF_{CIS1}/(\Delta VAF_{C1}+\Delta VAF_{S1})$ in red, and $\Delta VAF_{CISIM2}/(\Delta VAF_{C1}+\Delta VAF_{S1}+\Delta VAF_{M2})$ in black. In some cases the $\Delta VAF$ exceeds the vertical axis, but the $\Delta VAF$ for all models are given in Appendix 1.
Figure 4: The ensemble mean thickness change from the control (A) and standard deviation (B) resulting from the C1 experiment after 100 simulated years, along with the thickness contribution from the most negative (SICOPOLIS, C) and positive (AIF, D) change in VAF. Surface mass balance (E, G) and surface mass balance anomaly (F, H) for these models at 100 years.
Figure 5: The ensemble mean thickness change from the control (A) and standard deviation (B) resulting from the S1 experiment after 100 simulated years, along with the thickness contribution from the maximum (SICOPOLIS, C) and minimum (PennState3D, D) models. The basal velocities from the control and S1 experiments for SICOPOLIS (E, F) and PennState3D (G, H) at 100 years.
Figure 6: The ensemble mean thickness change from the control (A) resulting from the M2 experiment at 100 years, along with the thickness contribution from AIF (B), PennState3D (C), Potsdam (D), SICOPOLIS (E) and UMISM (F). Grounding lines at time 0 years and 100 years are shown in black and green lines respectively. Surface velocity in Wilkes Land from the control (G) and velocity anomaly M2 minus CC (H) for PennState3D, Potsdam, and SICOPOLIS.
Figure 7: The ensemble mean thickness change from the control resulting from the C1S1M2 experiment after 100 years (A), along with the ratio of thickness change (B). The thickness contribution from the maximum (UMISM) and minimum (Potsdam) models for the C1S1M2 forcing (C, D), the C1 forcing (E, G), and the S1 forcing (F, H). The grounding line for the M2 experiment at 100 years is shown in green.
Figure 8: The ensemble mean thickness change from the control at 200 and 500 years resulting from the C1 experiment (A, E), the S1 forcing (B, F), the M2 experiment (C, G), and the C1S1M2 forcing (D, H).