

Antarctic projections
uncertainties

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This discussion paper is/has been under review for the journal The Cryosphere (TC).
Please refer to the corresponding final paper in TC if available.

Reducing uncertainties in projections of Antarctic ice mass loss

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Received: 23 March 2015 – Accepted: 25 March 2015 – Published: 29 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Climate model projections are often aggregated into multi-model averages of all models participating in an Intercomparison Project, such as the Coupled Model Intercomparison Project (CMIP). A first initiative of the ice-sheet modeling community, SeaRISE, to provide multi-model average projections of polar ice sheets' contribution to sea-level rise recently emerged. SeaRISE Antarctic numerical experiments aggregate results from all models willing to participate without any selection of the models regarding the processes implemented in. Here, using the experimental set-up proposed in SeaRISE we confirm that the representation of grounding line dynamics is essential to infer future Antarctic mass change. We further illustrate the significant impact on the ensemble mean and deviation of adding one model with a known bias in its ability of modeling grounding line dynamics. We show that this biased model can hardly be discriminated from the ensemble only based on its estimation of volume change. However, tools are available to test parts of the response of marine ice sheet models to perturbations of climatic and/or oceanic origin (MISMIP, MISMIP3d). Based on recent projections of the Pine Island Glacier mass loss, we further show that excluding ice sheet models that do not pass the MISMIP benchmarks decreases by an order of magnitude the mean contribution and standard deviation of the multi-model ensemble projection for that particular drainage basin.

1 Introduction

During the last two decades the contribution of the Antarctic ice sheet to sea level rise (SLR) has steadily increased. At the beginning of the 1990s, the amount of snow falling over the ice sheet was more or less balanced by the total coastal discharge. Today, the ice sheet loses mass at a rate of $\approx 80 \text{ Gt yr}^{-1}$, equivalent to $\approx 0.2 \text{ mm yr}^{-1}$ of the global eustatic SLR (Shepherd et al., 2012). Proximal geological evidences show that the Western part of the Antarctic ice sheet may have collapsed during warm periods of the

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9, 2625–2654, 2015

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Antarctic projections
uncertainties**

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



late Pleistocene (Scherer et al., 1998). Such collapses have probably been driven by an unstable retreat of the marine based regions (i.e., underlying bedrock below sea level) characterized by a retrograde bed slope. The underlying process, named marine ice sheet instability (MISI), is supported by theoretical (Weertman, 1974; Schoof, 2007a) and numerical results (Durand et al., 2009; Pattyn et al., 2012). Once MISI initiated, it could lead to a collapse of the contemporary West Antarctic ice sheet and have the potential to rise sea level by ≈ 3.3 m (Bamber et al., 2009), leading to a drastic impact on human societies (Nicholls and Cazenave, 2010). However, conditions for the initiation of such a collapse, and rate of retreat remains poorly known (Church et al., 2013). The potential for MISI underscores the urgent need for reliable projections of Antarctic mass balance in order to conceive efficient regional and global adaptation strategies.

Current projections for mean sea level rise in 2100 range from 0.28 to 0.98 m depending on the Representative Concentration Pathways (RCP) scenario, and the contribution of ice sheets represent about a third of the total projected SLR (Church et al., 2013). However, this likely range excludes the possibility of a collapse of West Antarctica. Since the latest IPCC Assessment Report (AR5), new modelling initiatives tend to show that both Pine Island and Thwaites Glaciers may have initiated MISI (Favier et al., 2014; Joughin et al., 2014). Significant progress in the ability of marine ice sheet models to reproduce observed dynamical changes in coastal regions led to these novel results (Gillet-Chaulet and Durand, 2010). Still, ice sheet models have not reached the level of development that models, simulating other components of the climate system, have reached. Antarctic and Greenland ice-sheet model ensembles, in particular, remain in their infancy. Only one attempt has been produced so far, namely the SeaRISE initiative, which has been extensively reported in three pivotal papers by Bindschadler et al. (2013) and Nowicki et al. (2013a, b). Results of all participating models were aggregated into unweighed model averages to produce SLR projections. However, the confidence in related projections remains low because of the unproven ability of many participating models to cope with coastal dynamics (Church et al., 2013).

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Parallel to the SeaRISE initiative, specific model intercomparison exercises (MISMIP and MISMIP3d¹) have been designed to improve our understanding of grounding line dynamics (i.e., dynamics of the limit between the grounded ice sheet and the downstream floating ice shelf). These initiatives led to formulating requirements regarding physics and numerical approaches to adequately simulate the flow of coastal outlet glaciers in contact with the ocean (Pattyn et al., 2012, 2013). In this respect, Favier et al. (2014) proposed a multi-model intercomparison to evaluate the response of Pine Island Glacier (PIG) to changes at the grounding line, based on models meeting these MISMIP and MISMIP3d requirements.

In this paper, we assess the origin of uncertainty in recent ice sheet model projections of Antarctic sea-level contribution for PIG, based on SeaRISE and results due to Favier et al. (2014), Seroussi et al. (2014), and Joughin et al. (2010), guided by MISMIP and MISMIP3d. We will further evaluate the potential bias introduced by models limited by marine ice-sheet physics and reassess SLR projections for Pine Island Glacier based on MISMIP-tested models. We clearly demonstrate the effect of abandoning the “one-model-one-vote” approach (Knutti, 2010). A brief inventory of the physics implemented in common ice sheet models is presented in Sect. 2. In Sect. 3, we compare the SeaRISE sample with a Simplified Ice Sheet Model (SISM) and demonstrate that a proper representation of grounding line dynamics is quintessential in reducing uncertainties. Finally, a global ensemble analysis for PIG basin is presented.

2 Ice sheet models inventory/variety

2.1 Stokes equations and approximations

The basic problem in ice sheet modeling is to solve the gravity-driven flow of an incompressible and nonlinear viscous ice mass, further extended with a constitutive equation

¹MISMIP: Marine Ice Sheet Model Intercomparison Project.

relating stresses to strain rates, i.e.,

$$\boldsymbol{\tau}_{ij} = 2\eta D_{ij}, \quad (1)$$

where $\boldsymbol{\tau}$ is the deviatoric stress tensor and D_{ij} are the components of the strain rate tensor. The effective viscosity η is then expressed as

$$\eta = \frac{1}{2} A^{-1/n} D_e^{(1-n)/n}, \quad (2)$$

where D_e is the strain-rate invariant. Models use a temperature-dependent coefficient A , and set $n = 3$, according to Glen's flow law. The velocity (and pressure field) of an ice body is computed by solving the Stokes problem,

$$\text{div} \boldsymbol{u} = 0, \quad (3)$$

$$\text{div} \boldsymbol{\tau} - \text{grad} p + \rho_i \boldsymbol{g} = 0, \quad (4)$$

where p is the isotropic pressure and \boldsymbol{g} the gravitational acceleration.

Apart from the boundary conditions, which are discussed below, this model represents the most complete mathematical description of ice sheet dynamics and is commonly called a full-Stokes model. Owing to the considerable computational effort, approximations to these equations are often used, such as higher-order, shallow-shelf and shallow-ice approximations. These approximations involve dropping terms from the momentum balance equations as well as simplifying the strain rate definitions and boundary conditions. Higher-order Blatter–Pattyn type models consider the hydrostatic approximation in the vertical direction by neglecting vertical resistive stresses (Blatter, 1995; Pattyn, 2003). A particular case of this type of models is a depth-integrated hybrid model, combining both membrane and vertical shear stress and of comparable accuracy to the Blatter–Pattyn model (Schoof and Hindmarsh, 2010; Cornford et al., 2013). Vertical shearing terms are included in the calculation of the effective viscosity, but the force balance is simplified. A further approximation, known as the shallow-shelf approximation (SSA), is obtained by neglecting vertical shear (Morland, 1987; MacAyeal, 1989).

**Antarctic projections
uncertainties**

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



However, the earliest and most common approximation in large scale ice dynamics simulations is the shallow-ice approximation (SIA). This approximation incorporates only vertical shear stress gradients opposing the gravitation drive, which is valid for an ice mass with a small aspect ratio (i.e., thickness scale much smaller than length scale) in combination with a significant traction at the bedrock. Its main advantage is that all stress and velocity components are locally determined. The approximation is not valid for key areas such as ice divides and grounding lines (Hutter, 1983; Baral et al., 2001), since it excludes membrane stress transfer across the grounding line (Pattyn et al., 2012). The fact that SIA is not valid at grounding lines is remedied by some models through use of grounding line flux or grounding line migration parametrizations based on solutions obtained using matched asymptotics (Schoof, 2007b, 2011).

2.2 Boundary conditions

We will not list all boundary conditions of thermomechanically-coupled ice sheet models, but focus on those that are of importance for the migration of grounding lines. These pertain to the initialization of the ice sheet and conditions at the contact of the ice sheet with the ocean boundary.

2.2.1 Initialization

Initialization of ice sheet models to reproduce the current ice sheet state is commonly done through long-term paleo simulations (paleo spin-up). This has the advantage of establishing a reasonable temperature regime within the ice column (Rogozhina et al., 2011). However, reproducing current ice sheet geometry and velocities remains of limited accuracy. To circumvent this pitfall, inverse methods have recently been introduced. Basal drag (or ice viscosity) is inferred by minimizing the misfit between observed and modelled surface velocity (e.g., Morlighem et al., 2010; Gillet-Chaulet et al., 2012) or observed surface elevation (Pollard and DeConto, 2012b). For thermomechanical-

coupled simulations, a steady-state temperature field is used (Pattyn, 2010), which nevertheless has a limiting impact on short-term projections (Seroussi et al., 2013).

2.2.2 The marine boundary

It has long been hypothesized that grounding line migration may invoke unstable behaviour when the ice sheet rests on a retrograde bed slope below sea level (Weertman, 1974), leading to a potential collapse of marine-based areas (Mercer, 1978). However, despite major developments in numerical ice sheet modeling, the majority of state-of-the-art models in the 1990s and 2000s did not exhibit significant grounding-line retreat when ocean forcing (through ice shelf melting) was applied. The response of Antarctic ice sheet models to a warmer climate led to a higher volume due to atmospheric precipitation increase, but not to a mass loss due to inland grounding-line migration. (Huybrechts and de Wolde, 1999; Ritz et al., 2001; Houghton et al., 2001; Solomon et al., 2007). The incapacity of numerical ice-sheet models to cope with grounding-line migration has been seriously challenged by remote sensing observations at the end of the 1990s showing grounding line retreat and substantial mass loss in the Amundsen Sea sector (e.g., Rignot, 1998), but models were still unable to cope with such rapid changes when IPCC AR4 was released (Solomon et al., 2007).

A verification of ice sheet models became feasible due to a boundary layer theory developed by Schoof (2007a), who showed that in the absence of lateral buttressing, grounding line positions are unique and stable on a downward sloping bedrock. The theory also confirmed the MISI hypothesis in the case of a retrograde bed (unstable grounding line positions). Two model intercomparison exercises have subsequently been organized to verify whether numerical ice sheet models produce results in agreement with the boundary layer theory (MISMIP, MISMIP3d; Pattyn et al., 2012, 2013). It further allowed to identify requirements for numerical models to cope with grounding line migration. Basic conclusions of both intercomparisons are that in order to resolve grounding lines the inclusion of membrane stresses across the grounding line is required at a sufficiently small grid size (< 500 m), even when a subgrid interpolation of

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the grounding line (< 5 km) is preferred. An exception is the use of a grounding line parametrization based on the boundary layer theory due to Schoof, which has been successfully implemented in a series of models (Pollard and DeConto, 2012a; Thoma et al., 2014). This works well for coarse spatial resolutions, but the short term transient response remains questionable when compared to other approaches (Drouet et al., 2013), especially since the theory has been developed for the steady-state case.

In a more recent paper, Pattyn and Durand (2013) further scrutinized the results from the ice2sea MISMIP3d intercomparison to demonstrate that a clear distinction in the response to marine forcing could be related to the complexity of the model physics. The study shows that a least a higher order or a combination of SIA and SSA approximations (all these approaches being further denoted L1Lx in what follows) seem necessary to accurately simulate the flow across the grounding line, as the presence of vertical shearing in the force budget softens the effective viscosity at the grounding line, leading to a faster response on short time scales. The result is clearly different for SSA models that are stiffer at the grounding line and seem to overestimate the contribution to SLR. This has also been confirmed by a model intercomparison of Pine Island Glacier (Favier et al., 2014).

2.3 Description of SISM (Simplified Ice Sheet Model)

To demonstrate the importance of the proper inclusion of a marine boundary in large-scale ice sheet models, we developed a simple (but in terms of marine conditions – wrong) ice sheet model. The Simplified Ice Sheet Model (SISM) is a numerical ice sheet model based on the physics inherent to well-known ice sheet models (e.g. Huybrechts, 1990; Fastook and Holmlund, 1994; Saito and Abe-Ouchi, 2004). It is a two-dimensional vertically-integrated model, solving the Stokes equations according to SIA. The time-dependent evolution of the ice sheet is based on mass conservation. Ice rheology obeys a Glen flow law (with exponent $n = 3$) and ice is considered isothermal (thermomechanical coupling has been neglected compared to the previously-cited models). Basal sliding is introduced according to a Weertman-type sliding law, similar

to other models that are analysed in this paper. Climate forcing is not applied, and present-day climate is parametrized, i.e. surface mass balance (accumulation) is an exponential function of temperature and surface temperature a linear function of elevation (Pattyn et al., 2006). The model is solved on a regular grid with a grid spacing of 15 km. Note that models with a similar degree of complexity in the description of ice flow have been included in the SeaRISE multi-model ensemble (Bindschadler et al., 2013).

Grounding line dynamics are not explicitly included in SISIM. However, melting at the grounding line is introduced by subtracting the amount of basal melt from the surface mass balance at the last grounded grid point. Ice thickness becomes zero when the ice thickness in that grid point – determined from ice advected from upstream and the local mass balance – becomes zero (or negative). Therefore, grounding line retreat is purely due to melting and not by any physical process operating at the grounding line. Hence, a marine ice sheet instability (retreat of the grounding line on a retrograde slope in absence of melt perturbation and significant buttressing) is not simulated with this simplified model (Pattyn et al., 2012).

Using SISIM, we perform a number of the Antarctic SeaRISE experiments and investigate the impact of including a model with a known bias on the ensemble projection. The model was simply initialized by running it forward in time for 100 and 1000 years, respectively, starting from BEDMAP2 data of bedrock and surface topography (Fretwell et al., 2013). For these spinups, mass balance was kept constant in time. This leads to differences in surface elevation up to 800 m on the ice sheet margins whereas total volume is only affected by 0.1 %.

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Sea-level projections

3.1 SeaRISE and PIG model ensembles: approaches

The SeaRISE initiative led to the first attempt to evaluate multi-ice sheet models ensembles. At the time the experiments were designed, circa 2008, SeaRISE's primary goal was to investigate the sensitivity of ice sheet models to external forcing. Its base-line hypothesis presumed that there was no "best" ice sheet model around and ensemble modelling would potentially lead to a better understanding of ice sheet models (Bindschadler et al., 2013). Six models participated in the SeaRISE modelling of the Antarctic ice sheet, with a large variety of approximations to the Stokes equations and different treatments with respect to implementing grounding line dynamics (see Table 1). More details on the physics and numerics of SeaRISE models can be found in Bindschadler et al. (2013).

The SeaRISE experiments all start from an initial present-day ice sheet, which is built up using either a paleo spin-up or assimilation methods. Perturbations in boundary conditions are then imposed for 500 years and compared to a control run to remove the long term drift. Climate forcing experiments refer to the ensemble mean AR4 A1B changes in temperature and precipitation being imposed for 94 years and being held at the year-94 values for the remainder of the 500 year runs. An amplification factor of 1, 1.5 and 2, respectively, is applied in order to increase the climate effect (experiments C1, C2 and C3, respectively). Subsequently, basal sliding perturbations are implemented through a uniform increase of basal sliding (amplified by a factor 2, 2.5 and 3, respectively, for experiments S1, S2 and S3, respectively) and the sensitivity of Antarctic ice shelves to sub-ice shelf melt was performed through applying a uniform melt rate at the base of floating ice (2, 20 and 200 myr^{-1} , experiments M1, M2 and M3, respectively). These sensitivity experiments (or combinations of them) were further used to evaluate the dynamic contribution of Antarctica to sea level rise for the XXIst century under the various RCP scenarios (Bindschadler et al., 2013; Levermann et al., 2014), with estimated median contributions ranging from 0.07 m for the low-

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



emission RCP-2.6 scenario and 0.09 m for the strongest RCP-8.5 (Levermann et al., 2014). While the reliability of such projections has been questioned (Church et al., 2013), this has not been further evaluated and discussed so far.

While SeaRISE focussed on modeling the whole Antarctic ice sheet, a number of studies have simulated the effect of ice shelf melting at the basin scale. In particular, Pine Island Glacier (Joughin et al., 2010; Favier et al., 2014; Seroussi et al., 2014) or Thwaites Glacier (Joughin et al., 2014) since both basins have shown considerable contemporary grounding line retreat and thinning (Rignot et al., 2014). Joughin et al. (2010) present a first comprehensive modelling of Pine Island Glacier (PIG) based on a SSA model and using assimilation methods for initialization. Although this particular model did not participate in any MISIMIP intercomparison, its physics (SSA) and spatial resolution around the grounding line (down to 140 m) makes it compliant with MISIMIP recommendations.

Favier et al. (2014) propose a model intercomparison of PIG based on three models of varying complexity, i.e., a SSA, a higher-order and a full-Stokes model. Those three models also took part in the ice2sea MISIMIP3d intercomparison (Pattyn et al., 2013) and produced verified results at the spatial resolution used in the PIG intercomparison. Their approach consists of computing an initial state as close as possible to the current geometry and surface velocities using assimilation methods. Melting and calving perturbations are further applied. They show that the response of PIG is mainly driven by the bedrock topography rather than the type and the amplitude of the perturbation and further conclude that PIG is probably already engaged in a MISI. The study finally estimates the contribution of PIG to SLR over the next 20 years ranging from 3.5 to 10 mm. Finally, Seroussi et al. (2014) use a higher-order model over PIG to simulate its dynamical response to marine forcing over the next 50 years using a higher-order model, with spatial resolutions down to 500 m at the grounding line. This particular model did not perform the MISIMIP experiments, but as with the Joughin et al. (2014) model, physics and numerical implementation are conform to MISIMIP and MISIMIP3d recommendations.

Antarctic projections
uncertainties

G. Durand and F. Pattyn

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



All models presented above will be compared below for the PIG basin. However, we start the analysis with an evaluation of the importance of marine processes on ice sheet response on a pan-Antarctic level.

3.2 Grounding line migration in the SeaRISE ensemble

Figure 1 displays the contribution to SLR after 200 years as a function of the change in grounded area. It clearly highlights the fact that large contributions to SLR always go along with significant changes in the extension of the grounded ice sheet. In other words, having models able to cope with grounding line dynamics is a prerequisite before establishing projections of upper bound dynamic contribution of the Antarctic ice sheet to SLR. The evolution of the grounded area as a response of SeaRISE experiment M3 is presented in Fig. 2. Despite the drastic and unrealistic perturbation (200 m yr^{-1} melt rate, designed to approximate a sudden collapse of all ice shelves), the response of the participating models varies widely, from a limited grounding line retreat to almost a complete collapse of all the marine sectors within a period of 200 years. Moreover, amongst the models presenting a significant retreat, the impacted regions are different with significant differences in grounding-line retreat rates.

Large differences in model response are essentially due to two factors: models that correctly implement melting under the ice shelves will fail to produce a significant retreat if the grounding line area is not properly sampled (spatial resolution below 500 m), when using a physical approximation based on SSA, or lacking a parameterization of grounding line dynamics based on the boundary layer theory due to Schoof (2007a). This failure has been clearly illustrated by Vieli and Payne (2005) and Docquier et al. (2011). On the other hand, models that implement melting at the grounding line, i.e., the last grounded grid point, melt grounded ice away, thereby mimicking grounding line retreat. The result is unphysical in both implementation (since melting occurs under the ice shelves) and reaction (spatial resolution and/or physical model are unappropriate). The SISIM model illustrates this perfectly, as grounding line retreat in this model is not due to ice-dynamical processes at the grounding line, but due to ice being melted away

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



at the grounded line. The retreat rates produced by this model are within the range produced by SeaRISE, due to the fact that several models within SeaRISE implement grounding line melt in a similar fashion.

3.3 Impact of SISM on the SeaRISE ensemble

5 Since the number of models participating in the Antarctic SeaRISE experiments is rather limited, we may expect that adding a model (e.g. SISM) to the sample will significantly impact on the ensemble mean projections, thereby questioning its relevance. Its effect is illustrated in Fig. 3 and Table 2.

10 Compared to other models, the contribution to SLR with SISM is close to the SeaRISE ensemble mean for sliding experiments and is amongst the largest for melting perturbations, but it is not a striking outlier. As a reminder, SISM is based on simple model physics, isothermal and has a parameterized surface mass balance, not evolving according to any RCP scenario. Taking SISM into account in the ensemble unweighed mean leads to two distinct impacts. When considering melt perturbation, adding SISM to the ensemble increases both the mean and SD of the ensemble projections. The increase in mean is substantial, up to 20 % for experiments M2. We can anticipate that adding a biased model which would present a limited capacity of grounding line retreat would lead to a decrease of the ensemble mean contribution to SLR together with an increase in the related SD, as the sample size increases. The particular case of sliding experiments is instructive: the projected contribution of SISM is fortuitously close to the SeaRISE ensemble mean. Including the SISM in the ensemble mean projections slightly affects the mean but also decreases the SD. Ironically, in the particular situation where a biased model projection is coincidentally close to the ensemble mean, introducing such a model may be wrongly interpreted as improving the confidence in the ensemble projection.

25 The SeaRISE experiments were rerun with SISM, starting from a different spinup (100 year instead of 1000 year; Fig. 3). Despite significant differences (several hundred of meter in ice thickness in coastal areas) between both geometries, the prognostic

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



runs are hardly affected in terms of SLR contribution over the next 200 years. This indicates that choosing the initial state uniquely based on correspondances between modeled and actual geometry is certainly a too weak constraint.

3.4 Ensemble analysis on PIG

In view of the small SeaRISE sample, we extended the sample with recent regional studies (basin-scale), focused on Pine Island Glacier (Joughin et al., 2010; Favier et al., 2014; Seroussi et al., 2014). Since the most significant changes in grounding line position and mass balance are currently observed over PIG (Mouginot et al., 2014), this drainage basin appears to be the most appropriate region to evaluate the impact of model physics/numerics on SLR projections. Amongst these studies, Favier et al. (2014) argue that PIG is already experiencing MISI and forthcoming mass change projected by models is relatively similar irrespective of the perturbation amplitude, even for an almost complete collapse of the current ice shelf. This implies that a qualitative comparison with SeaRISE experiments is feasible, despite the difference in melt perturbations between the various studies.

Figure 4 presents the evolution of the cumulated contribution of PIG drainage basin to SLR for the period 2000–2050 according to the SeaRISE M3 experiment and according to Joughin et al. (2010); Favier et al. (2014) and Seroussi et al. (2014). As mentioned above, estimations from SeaRISE range from a very limited retreat of the grounded line (e.g., Fig. 2a) and relatively low contribution to SLR (below 5 mm cumulated in 2050) to an extremely high discharge of 3 mm yr^{-1} and a collapse of the entire drainage basin within a century (e.g., Fig. 2d). As expected, SISIM is amongst the models predicting the highest contribution for PIG, but this model result stays within the envelope of the whole sample range.

A striking feature of Fig. 4 is that all projections due to Joughin et al. (2010), Favier et al. (2014) and Seroussi et al. (2014) occupy a limited range compared to the full range of the SeaRISE sample, with SLR contribution between 2.3 and 18.8 mm by 2040, compared to 2.8 and 146.4 mm respectively.

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



4 Discussion

Most models in the SeaRISE sample have a coarse spatial grid size (> 10 km, see Table 1), which – despite the physical approximations – do not sample grounding line dynamics as stipulated in the MISMIP intercomparison (Pattyn et al., 2012, 2013).

5 Only one model uses the parametrization based on the boundary layer theory due to Schoof (2007a), and has been tested against MISMIP, exhibiting a behaviour similar to models that do capture grounding line dynamics at high spatial resolution. While such parametrized models are probably less reliable for transient effects, they capture the essence of grounding line migration and stability (Pattyn and Durand, 2013). The
10 basin-scale simulations for PIG are performed with models that capture grounding-line dynamics at the spatial resolution required and with appropriate physics. Most models did participate in the MISMIP intercomparison at the spatial resolution used in the PIG analysis.

Models that capture grounding line dynamics are within the dark grey envelope in
15 Fig. 4 (associated mean of 8.6 mm and SD of 4.9 mm in 2040), compared to the light-grey envelope that represents the SeaRISE sample (mean of 50.1 mm and SD of 67.5 mm in 2040). Not only do the MISMIP-verified models occupy a smaller range than the full sample but a distinction between the physical representation of each of the models tends to appear. It is not expected that a model according to Full Stokes
20 would show the same results as a SSA model, since the physical model is different. Such a distinction clearly appears for models that capture grounding-line migration as was already shown in Pattyn and Durand (2013) based on an ideal ice-sheet geometry. SSA models do react faster to a perturbation, because they are stiffer at the grounding line (i.e., the viscosity of the grounding line is higher). Hybrid and higher-order models
25 (and in the limit full Stokes models) produce a slower response, as the viscosity at the grounding line is lower due to the inclusion of vertical shearing in the stress tensor. Such differentiation is not captured whenever the spatial resolution at the grounding line is too coarse and obliterates the effects due to the physical model. Examining

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Antarctic projections
uncertainties**

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



MISMIP-verified models, results computed by Seroussi et al. (2014) with a higher order model are in agreement with the estimation computed with the higher order model used in Favier et al. (2014), despite differences in setup and perturbation. Only the estimations produced by Joughin et al. (2010) with a SSA model are different to the response of the SSA model in Favier et al. (2014). Finally, the model based on the parametrized approach has the highest contribution to SLR of the sample of models that capture grounding line migration. Although this comparison remains qualitative because boundary conditions and perturbations differ from one modeling experiment to the other, this finding is in line with the results of MISMIPs, which tends to demonstrate that an application to a “real” case seems to endorse the conclusions of “idealized”-case simulations.

It is peculiar to note that the models due to Favier et al. (2014) exhibit marine ice instability (and presumably also the case for Joughin et al., 2010 and Seroussi et al., 2014) and their response is to a large extent indifferent to the amplitude of the perturbation applied. Yet, their contribution to SLR on the time scales considered is smaller than the majority of the models that were used in SeaRISE that did not capture any MISI. This poses serious questions as to whether the inherent complexity of an ice sheet model (thermomechanics, sliding, surface mass balance) is decisive in the process of representing ice sheet response to marine forcing. This issue will definitely become important when ice sheet models will be fully coupled to ocean models at a spatial resolution that should comply with both systems. Furthermore, the coupling could exhibit a series of other feedbacks between the rate of sub-shelf melting and changes in the sub-shelf cavity shape, which are currently unknown.

5 Conclusions

The SeaRISE initiative has been the first multi ice sheet model ensemble projection to evaluate the future contribution of Antarctica to SLR. Results of all participating model results were taken into account, irrespective of the inherent difference in complexity be-

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tween the models. A similar approach is used in AOGCMs community (Knutti, 2010). However, it is probably simpler to evaluate the ability of ice sheet models to perform adequately when compared to AOGCMs as fewer key processes are at play. In any case, and whatever the component of the modeled climate component, first order processes must be taken into account (Knutti, 2010). As an example, it sounds particularly inappropriate to use an atmospheric model unable to compute a radiation balance to make any projections of mean surface temperature. Similarly, to compute projections of Antarctic contribution to SLR, ice flow models have to be evaluated on their ability of incorporating grounding line dynamics. If this process is not implemented within a model, any of its projections pertaining to coastal regions is unreliable, even on decadal time scale. Furthermore, solely based on the evolution of the modeled ice sheet, it may be hard to discriminate whether the projection is reasonable or not. Indeed, ad-hoc parametrizations can force any model to retreat, but the lack of physics makes any projection of the retreat and contribution to SLR untrustworthy. Owing to the small number of ice sheet models, including such a biased model have strong effect on the mean, as well as on the dispersion of the results.

Benchmarks to evaluate the ability of models to cope with grounding line dynamics have been recently developed and others will emerge (MISMIP+). Ice sheet models should be evaluated using these benchmarks before being applied on actual cases. Such an approach has been followed by Favier et al. (2014) on PIG. Taking into account only a selection of models with appropriate physics and numerics to compute grounding line dynamics very significantly reduces the spread of the projected contribution to SLR, reinforcing our confidence in the possible evolution of the glacier. Initiatives to produce new multi-ensemble models will undoubtedly be launched in the near future. Their ability to decrease uncertainties will strongly depend on whether inappropriate models (i.e. unvalidated grounding line dynamics) will be included or not.

Acknowledgements. This study was funded by the French National Research Agency (ANR) under the SUMER (Blanc SIMI 6) 2012 project referenced as ANR-12-BS06-0018. This re-

search is also a contribution to the Belgian Federal Research Project “IceCon” (Constraining Antarctic ice mass change) BELSPO, contract number SD/CA/06A.

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Antarctic projections
uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic projections
uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Antarctic projections
uncertainties**

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I ◀

▶ I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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5

TCD

9, 2625–2654, 2015

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic projections
uncertainties

G. Durand and F. Pattyn

Table 2. Mean and SD of global sea-level increase (cm) projected by the SeaRISE models extended with SISM (described in Sect. 2.3) or SeaRISE models alone (in brackets) for each experiment at 100 and 200 years. For reference, a loss of $4.0469 \times 10^{14} \text{ m}^3$ of ice above flotation equates 1 m rise in mean global sea level. Note that similar number are presented in Bindschadler et al. (2013) but a different sea-level conversion factor was used ($4.0 \times 10^{14} \text{ m}^3$ equivalent to 1 m mean sea level).

	100 Mean	SD	200 Mean	SD
S1	18.1 (18.1)	6.2 (6.8)	31.4 (31.6)	11.3 (12.4)
S2	23.5 (23.1)	8.2 (8.8)	40.4 (39.9)	14.5 (15.9)
S3	28.9 (28.0)	13.0 (14.0)	50.6 (49.6)	20.7 (22.4)
M1	7.62 (6.8)	4.1 (4.0)	15.7 (15.1)	7.9 (8.6)
M2	80.0 (68.5)	36.6 (26.1)	144.3 (130.4)	53.4 (46.0)
M3	413.8 (343.5)	343.7 (332.7)	657.7 (538.5)	525.4 (488.4)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I ◀

▶ I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



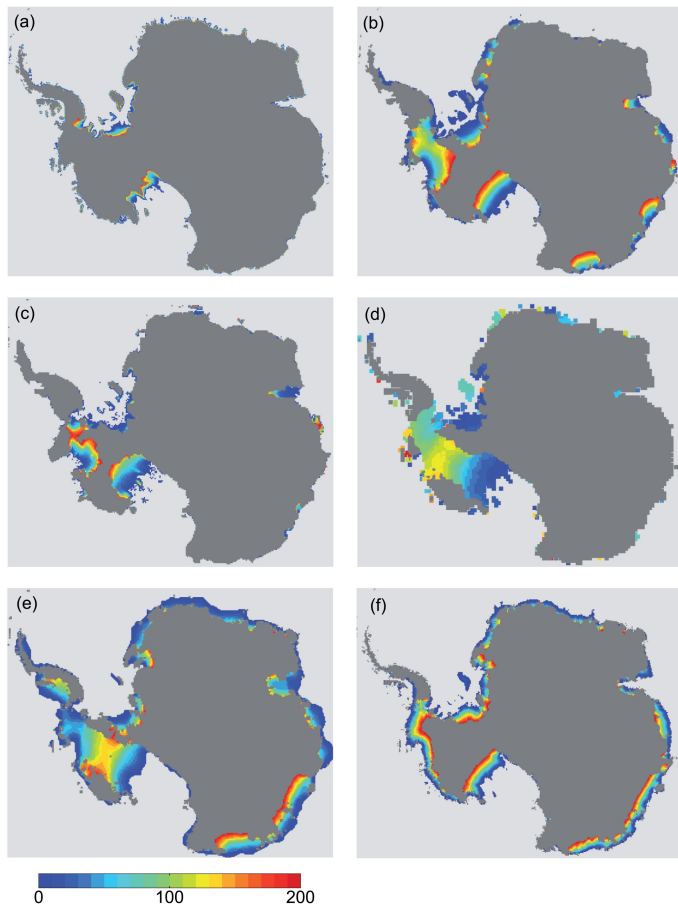


Figure 2. Evolution of the Antarctic grounded area as computed by the five models which participated to SeaRISE experiment M3 (a to e) and similar results obtained by SIM (f). Colors corresponds to the time of ungrounding.

Antarctic projections uncertainties

G. Durand and F. Pattyn

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Antarctic projections
uncertainties

G. Durand and F. Pattyn

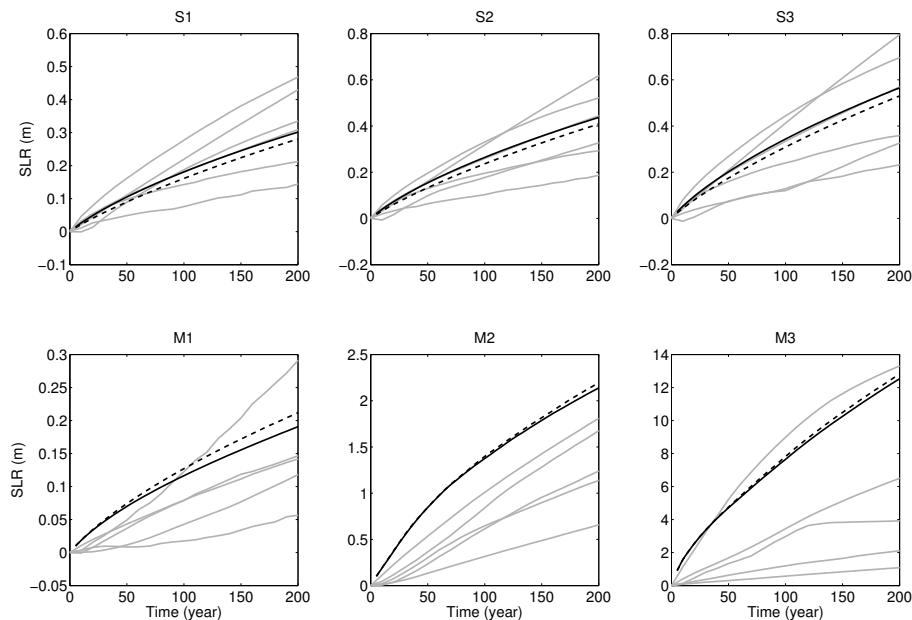


Figure 3. Evolution of the contribution to SLR for all the models participating to SeaRISE experiments S1, S2, S3, M1, M2 and M3 (grey lines). SLR contribution computed by SISIM for similar perturbations are presented in black, after a 1000 and 100 years spins-up (continuous and dashed line respectively).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

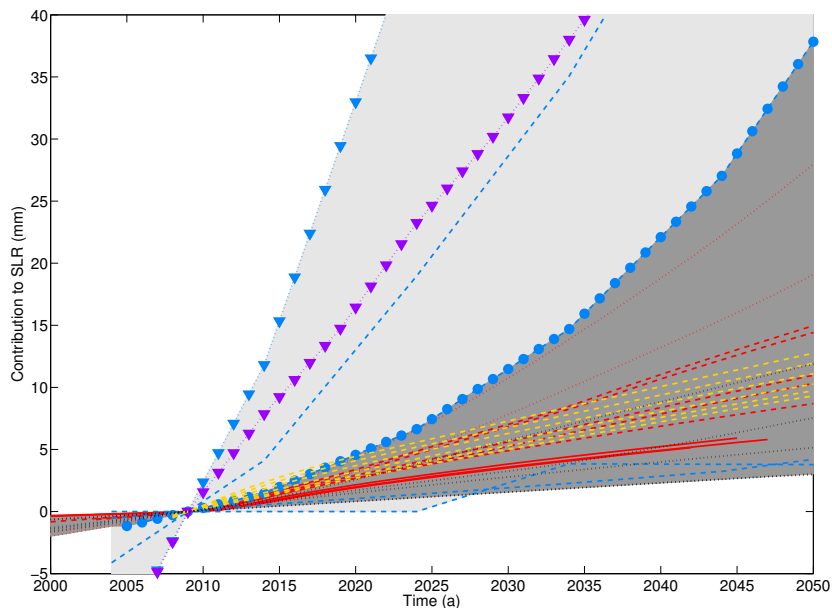


Figure 4. Evolution of the cumulated contribution of Pine Island Glacier to SLR until 2050 as computed by models participating to SeaRISE experiment M3 (blue lines), SISM for the SeaRISE M3 forcing (purple line), together with estimations from Joughin et al. (2010) (black lines), Favier et al. (2014) (red lines) and Seroussi et al. (2014) (orange lines) for the same region. Models are ordered according to their complexity: SIA (dotted lines with triangles), SSA (dotted lines), heuristic approach (dashed lines with circles), L1Lx (dashed line) and full-Stokes (continuous). Starting time of SeaRISE experiments is 2004 (Bindschadler et al., 2013). Starting times of experiments computed by Joughin et al. (2010) and Seroussi et al. (2014) correspond to the acquisition year of the surface velocities used for inversion, respectively 1996 and 2008. As detailed in Favier et al. (2014), the starting time of their experiments corresponds to the last grounding line measurements available, i.e. completed in 2011 (Park et al., 2013). Cumulated contribution has been offset to zero in 2009.

Antarctic projections
uncertainties

G. Durand and F. Pattyn

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

