

Why marine ice sheet model predictions may diverge in estimating future sea level rise

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[1] Despite major recent efforts, marine ice sheet models aiming at predicting future mass loss from ice sheets still suffer from uncertainties with respect to grounding line migration. A recent model intercomparison provided tools to test how models treat grounding line dynamics in a three-dimensional setting. Here we use these tools to address to what extent differences in mass loss occur according to the approximation to the Stokes equations, describing marine ice sheet flow, used. We find that models that neglect components of vertical shearing in the force budget wrongly estimate ice sheet mass loss by $\pm 50\%$ over century time scales when compared to models that solve the full Stokes system of equations. Models that only include horizontal stresses also misrepresent velocities and ice shelf geometry, suggesting that interactions between the grounded ice sheet and the ocean will also be modeled incorrectly. Based on these findings, we strongly advise the use of high-order models to compute reliable projections of ice sheet contribution to sea level rise. **Citation:** Pattyn, F., and G. Durand (2013), Why marine ice sheet model predictions may diverge in estimating future sea level rise, *Geophys. Res. Lett.*, *40*, 4316–4320, doi:10.1002/grl.50824.

1. Introduction

[2] There is a general consensus on the current imbalance of the Greenland and Antarctica ice sheets, both contributing on average 0.6 mm yr^{-1} since 1992 to the rate of global sea level rise (SLR) [Shepherd *et al.*, 2012]. One of the biggest unknowns in estimating the future contribution of ice sheets to global sea level change is the stability of the West Antarctic Ice Sheet (WAIS). Large portions of the bedrock beneath the WAIS (and some marine sections of the East Antarctic ice sheet as well) lie below sea level and deepen toward the interior of the ice sheet [Fretwell *et al.*, 2013]. These so-called “marine ice sheets” resting on reverse bed slopes have the potential to retreat in an unstable and catastrophic manner [Schoof, 2007], possibly leading to a collapse of the WAIS [Mercer, 1978; Bamber *et al.*, 2009]. The grounding line (GL), which marks the upstream limit of floating ice shelves, controls the dynamics of a marine ice

sheet and its mass balance. Properly capturing the GL position and its evolution through time as a response of a given perturbation is crucial for any ice sheet model attempting to establish reliable projections of future ice sheet contribution to SLR [Gillet-Chaulet and Durand, 2010].

[3] Limitations to the ability of models to adequately capture GL dynamics were clearly identified almost a decade ago [Vieli, 2005]. No consensus on the response of GLs to various perturbations was established until a boundary layer (BL) theory was developed [Schoof, 2007], which confirmed the long standing marine ice sheet instability hypothesis [Weertman, 1974] for an ice sheet without lateral restrictions on a retrograde bed slope. BL theory allowed for the first marine ice sheet model intercomparison exercise (MISMIP) [Pattyn *et al.*, 2012], which demonstrated that (i) models that do not resolve extensional stresses fail to comply with BL theory and (ii) spatial discretization is a crucial consideration with resolution below one kilometer necessary to properly capture GL migration. However, the GL is by nature a 2-D horizontal feature (in the map plane), which complicates conclusions drawn from a flow line geometry. As a result, the exercise has recently been extended to a 3-D geometry (MISMIP3d) [Pattyn *et al.*, 2013].

[4] In the advent of the Fifth IPCC Assessment Report (AR5), numerous ice flow models of various complexity are used to establish ice sheet mass balance projections [e.g., Winkelmann *et al.*, 2012; Bindshadler *et al.*, 2013; Gillet-Chaulet *et al.*, 2012], most often without a proper evaluation of the ability to correctly treat GL evolution. This limitation must be removed by future IPCC assessments. To date, a comprehensive study of the impact of ice sheet model complexity on ice sheet discharge is lacking. A global evaluation of GL migration in plan view models was presented by Pattyn *et al.* [2013]. Here we further scrutinize these results to establish the specific response of various types of ice sheet models commonly used in the literature today. We focus on model outputs that are relevant to model predictions of future SLR, such as surface elevation change and ice mass flux. We deliberately refrained from taking into account other uncertainties in ice sheet modeling, which are perhaps equally important, such as uncertainties in boundary conditions (e.g., ice melt by the ocean, basal sliding), uncertainties in ice sheet geometry (ice thickness, bed depth below sea level, grounding line position), etc., and which are discussed in more detail by Bindshadler *et al.* [2013]. Here we demonstrate that the uncertainty related to GL migration in response to changes in boundary conditions can be greatly reduced.

2. Approximations to the Stokes Flow

[5] A full Stokes model represents the most complete mathematical description of marine ice sheet dynamics.

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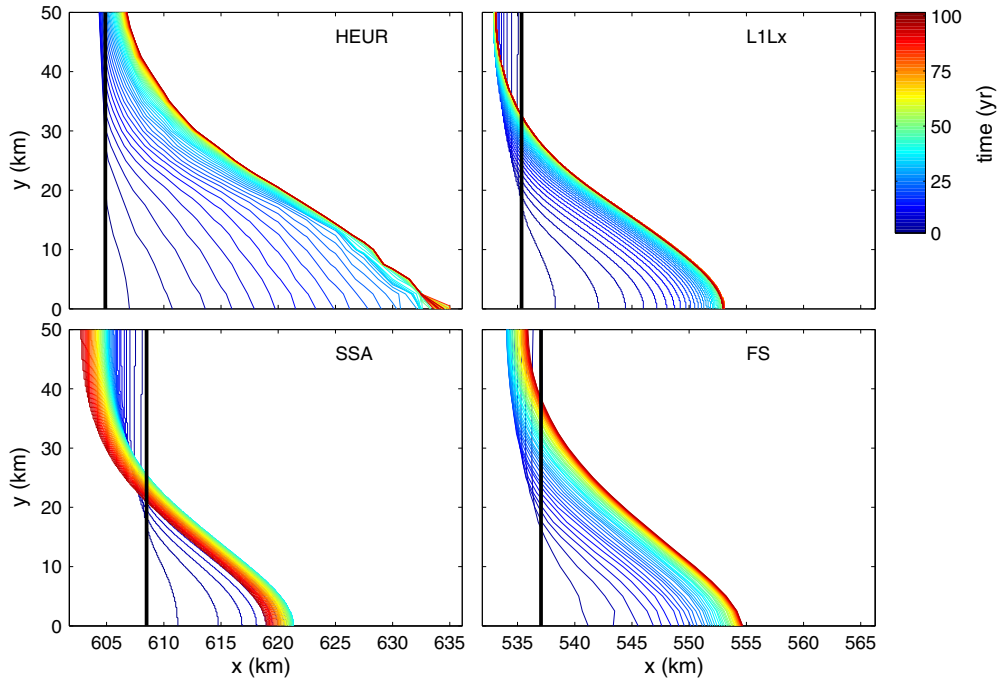


Figure 1. Plan view of the evolution of the GL position according to approximation to the Stokes flow equations, i.e., heuristic (*Heur*), shallow shelf (*SSA*), high-order (*L1Lx*), and full Stokes (*FS*) models. The x axis is along the flow direction, and distance is given from the ice divide ($x = 0$ km); the symmetry axis is centered at $y = 0$ km; the lateral boundary at $y = 50$ km. One model result per category is shown. GL at $t = 0$ is shown as a thick black vertical line. Color coding corresponds to the time evolution.

Several approximations to the Stokes flow momentum balance exist, ranging from the shallow ice approximation (SIA), which assumes that all resistance to flow is provided by shear-stress gradients in the vertical, to so-called “high-order” models that combine both vertical shear with horizontal stress gradients, to full Stokes models that solve the full equations of motion without neglecting any terms [Hindmarsh, 2004; Gillet-Chaulet *et al.*, 2012; Larour *et al.*, 2012; Pattyn *et al.*, 2013]. Four types of models are identified within the MISIP3d group, i.e., models that treat the GL via a heuristic rule based on the BL theory by Schoof [2007] (*Heur*), ice stream models based on the shallow-shelf approximation and that only include horizontal stress gradients (*SSA*), models that include vertical shearing on top of horizontal stress gradients (*L1Lx*), and full Stokes models (*FS*). SIA models can safely be excluded from this list as they omit horizontal stress gradients, which are a prerequisite for treating GL migration accurately [Pattyn *et al.*, 2012, 2013]. Details and references on the model approximations as well as the selection procedure for the model results analyzed below, are given in the supporting information.

3. Experimental Setup

[6] The initial experimental setup is a simple bed shape with a constant downward slope in x and without lateral variations in y , given by $b(x, y) = -100 - x$, where b (m) is the bed elevation (positive above sea level) and x is given in kilometers. This domain stretches from 0 to 800 km in x and from 0 to +50 km in y (where 0 is a symmetry axis and +50 km is the lateral boundary). An ice sheet is grown by applying a constant accumulation rate (0.5 m yr^{-1}) and the appropriate boundary conditions until a steady state is reached.

Starting from this steady state initial condition, a 75% decrease in basal friction (Gaussian-shaped perturbation) is applied, centered at the GL and the symmetry axis for a period of 100 years. This leads to an advance of the GL and ice mass transfer from the grounded ice sheet to the floating ice shelf. For further details on the boundary conditions and the perturbation experiment, readers are referred to the supporting information and Pattyn *et al.* [2013].

4. Results and Discussion

[7] Figure 1 shows the evolution of the GL during the 100 years of the experiment described in section 3. In response to enhanced sliding (as a consequence of reduced basal friction), all models exhibit a GL advance along the glacier centerline, leading to a curved GL in map view. As previously pointed out in Pattyn *et al.* [2013], models solely based on horizontal stress gradients, such as *SSA* and *Heur*, predict a steady state GL position that is farther downstream compared to *FS* or *L1Lx*, which include some form of vertical shearing. More interestingly, *SSA* models react much faster to the given perturbation and reach their maximum position after about 30 years, compared to models that include vertical shearing (80 years). This is particularly the case for *Heur* models; their GL migration is not only faster than that of all other models but also farther downstream, exhibiting a maximum GL advance of 30 km compared to 20 km for the other approximations.

[8] Enhanced sliding not only leads to an obvious acceleration of the grounded ice sheet in the vicinity of the sliding perturbation, but this signal is also advected into the ice shelf. The average grounded ice acceleration over 100 years for *FS* and *L1Lx* is remarkably similar, leading to an average

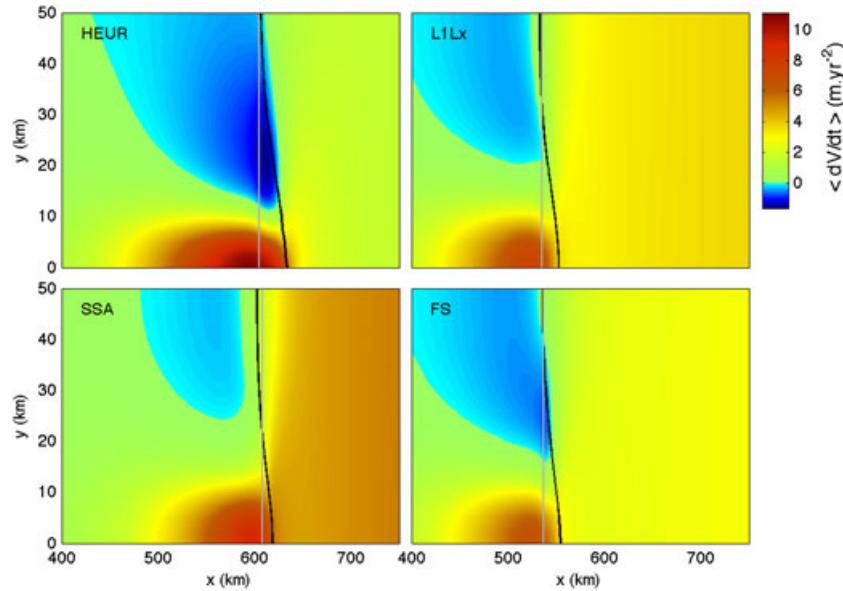


Figure 2. Plan view of the mean acceleration over 100 years for each model category as specified in the panels (see Figure 1 for definition of axes). Positions of the GL at $t = 0$ and $t = 100$ years are shown with a gray and black line, respectively. The same models as in Figure 1 are shown.

acceleration of the ice shelf of about 3 m yr^{-2} . Both *Heur* and *SSA* models exhibit a different behavior, with a higher acceleration of 4 m yr^{-2} for *SSA* models and 2 m yr^{-2} for *Heur* models. The heuristic rule in *Heur* models due to *Pollard and DeConto* [2009] imposes the BL flux either at the last grounded or the first floating grid point, which suddenly changes the ice shelf velocity (as the upstream flux is a boundary condition for the ice shelf). Moreover, the BL theory is valid for steady state GL fluxes and does not apply to transient states. Both factors make it difficult to evaluate whether the smaller shelf acceleration is therefore real or a numerical artifact. Due to the lack of vertical shearing

in *SSA* models, the effective viscosity in the grounding zone is increased, making the ice stiffer in the grounding zone and probably its reaction time faster compared to full Stokes models. This difference leads to a $\pm 50\%$ deviation from *FS* and *L1Lx*, and its consequences will be discussed further below.

[9] Response of the various classes of models in terms of mean rate of thickness change is shown in Figure 3. As expected, all models show a thinning of the upstream grounded ice sheet. Also, in response to the sliding perturbation, the ice shelf thickens substantially in the region where GL advance takes place. Due to the larger displacement

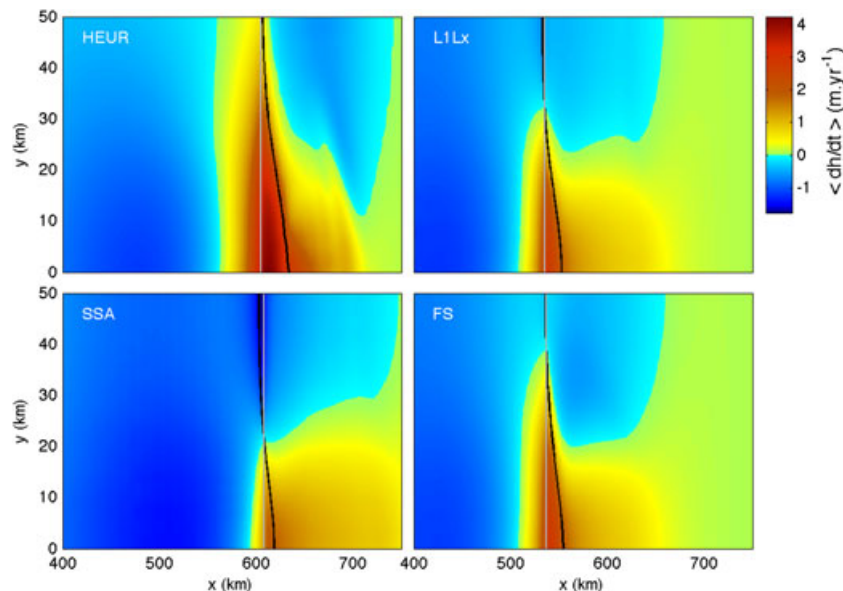


Figure 3. Plan view of the mean rate of elevation change over 100 years for each model category as specified in the panels (see Figure 1 for definition of axes). Positions of the GL at $t = 0$ and $t = 100$ years are shown with a gray and black line, respectively. The same models as in Figure 1 are shown.

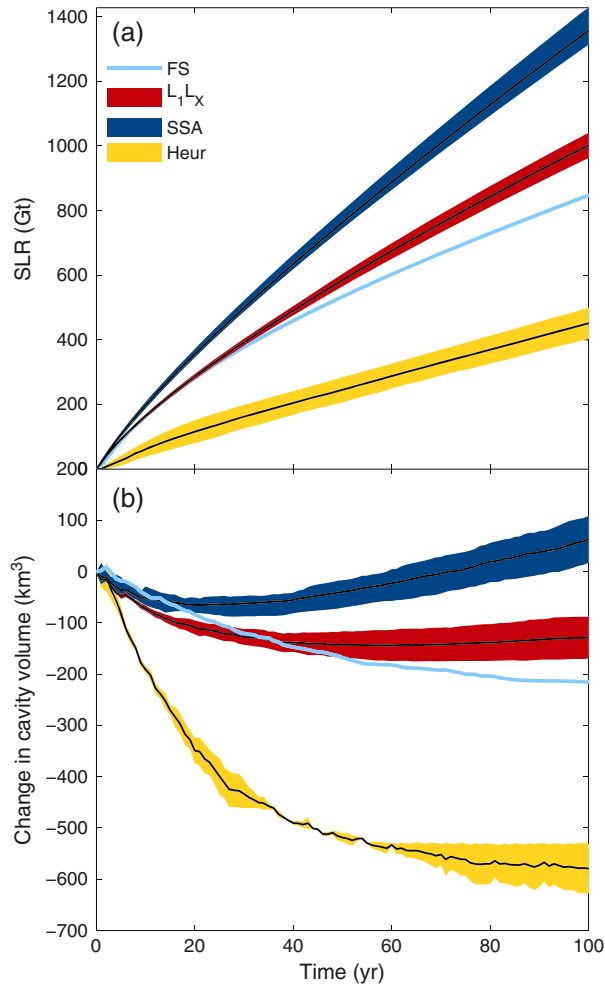


Figure 4. (a) Evolution of the SLR contribution according to each model category. Mean values are presented as solid lines. The envelope presents the minimum and maximum contributions for each category: *Heur* (yellow), *SSA* (dark blue), *L_LL_x* (red), and *FS* (light blue). Note that only one *FS* model computed the experiment so that no envelope could be calculated. (b) Evolution of the change in cavity volume underneath the ice shelf.

of the GL (Figure 1), *Heur* models overestimate thinning upstream of the initial GL as well as thickening downstream, compared to the other model approximations.

[10] The simulated changes in ice sheet geometry during the simulation would impact sea level. The contribution to SLR for each class of models is shown in Figure 4, displaying the temporal evolution of the volume above flotation. In general, the closer the models come to solving the full set of Stokes equations, the slower the grounded ice sheet response and the smaller its contribution to SLR [Drouet *et al.*, 2013]. Therefore, *SSA* models overestimate the contribution to SLR by 40% compared to *FS* for the time scale considered. In contrast, the larger ice thickness increase at the GL in *Heur* models is largely balanced by a substantial advance of the GL. As a consequence, *Heur* models present the lowest contribution to SLR during the simulation with an underestimation of about 50% when compared to the *FS* estimation. Both *FS* and *L_LL_x* models show

similar results, with a 10% overestimation of SLR by *L_LL_x* after 100 years.

[11] Current retreat of Antarctic outlet glaciers is attributed to the loss of buttressing exerted by ice shelves on the grounded ice sheet, with shelf loss caused by enhanced melting underneath ice shelves [Rignot and Jacobs, 2002; Jenkins *et al.*, 2010; Rignot *et al.*, 2013]. The amount of buttressing exerted by an ice shelf results from a combination of its geometry and velocity [Gagliardini *et al.*, 2010], so that the ice/ocean coupled system will behave differently if the cavity shape is different. As mentioned previously, both *SSA* and *Heur* approximations lead to changes in the geometry and flow field that are distinctly different from those given by the high-order approximations *L_LL_x* and *FS* (Figures 2 and 3). Therefore, the response of the ice shelf to melting, in terms of thinning and buttressing, will act differently on the ice sheet for the *SSA* and *Heur* approximations. Moreover, the rate of submarine melting is largely connected to the geometry of the ice shelf cavity [Walker and Holland, 2007; Holland *et al.*, 2008], which in turn is determined not only by basal melting but also by changes in thickness and flow field that control the ice advected into the ice shelf and the resulting cavity shape. The extension and height of the ocean cavity below the ice shelf are distinctly different according to both *Heur* and *SSA* models compared to high-order models (summarized as the change in cavity volume for each class of model in Figure 4). These differences will lead to varying patterns of basal melt rates on decadal time scales [Goldberg *et al.*, 2012a, 2012b].

5. Conclusion

[12] We compared the evolution of velocity and geometry of an idealized marine ice sheet as computed by ice sheet models of different levels of complexity. The numerical results presented are compiled from the basal lubrication experiment P75 of the MISMIP3d intercomparison [Pattyn *et al.*, 2013]. However, the interpretation and conclusions drawn here are not specific to that experiment.

[13] The evidence presented illustrates that the choice of the approximation to Stokes equations is crucial for consistent short-term (10–100 years) predictions of ice sheet behavior. Uncertainties with respect to model complexity, as discussed in Bindenschadler *et al.* [2013], could potentially be greatly reduced in the future by focusing on models that inherently produce consistent results in the controlled experiments, like those presented here.

[14] We now have the tools to evaluate model response in controlled experiments [Pattyn *et al.*, 2013], without uncertainties in boundary conditions or forcing parameters. We could therefore properly investigate the impact of the use of different Stokes approximations. Results show that although the BL theory (based on the *SSA*) is correct in capturing the essence of GL dynamics in compliance with theory [Weertman, 1974], the *SSA* approximation is too simple to capture changes in ice sheet mass and SLR contribution over decadal and centennial time scales. Horizontal stress gradients are essential in predicting GL migration, but vertical shearing at the GL is as important, as it lowers the effective viscosity, which influences ice sheet mass change, geometry, and flow fields of the grounding zone and the ice shelf. We, therefore, suspect that Blatter/Pattyn-type high-order model results would lie between the result of *L_LL_x* and *FS*

models, although none of these models participated in the intercomparison. Nevertheless, solving the complete Stokes system seems not a prerequisite; the inclusion of vertical shearing in the grounding zone according to other high-order approximations leads to comparable results as with a full Stokes model.

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