Impact of bedrock description on modeling ice sheet dynamics

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[1] Recent glaciological surveys have revealed a significant increase of ice discharge from polar ice caps into the ocean. In parallel, ice flow models have been greatly improved to better reproduce current changes and forecast the future behavior of ice sheets. For these models, surface topography and bedrock elevation are crucial input parameters that largely control the dynamics and the ensuing overall mass balance of the ice sheet. For obvious reasons of inaccessibility, only sparse and uneven bedrock elevation data is available. This raw data is processed to produce Digital Elevation Models (DEMs) on a regular 5 km grid. These DEMs are used to constrain the basal boundary conditions of all ice sheet models. Here, by using a full-Stokes finite element code, we examine the sensitivity of an ice flow model to the accuracy of the bedrock description. In the context of short-term ice sheet forecast, we show that in coastal regions, the bedrock elevation should be known at a resolution of the order of one kilometer. Conversely, a crude description of the bedrock in the interior of the continent does not affect modeling of the ice outflow into the ocean. These findings clearly indicate that coastal regions should be prioritized during future geophysical surveys. They also indicate that a paradigm shift is required to change the current design of DEMs describing the bedrock below the ice sheets: they must give users the opportunity to incorporate high-resolution bedrock elevation data in regions of interest. **Citation:** Durand, G., O. Gagliardini, L. Favier, T. Zwinger, and E. le Meur (2011), Impact of bedrock description on modeling ice sheet dynamics, *Geophys. Res. Lett.*, *38*, L20501, doi:10.1029/2011GL048892.

1. Introduction

[2] Greenland and Antarctic mass loss was identified about a decade ago [*Rignot and Thomas*, 2002; *Rignot and Kanagaratnam*, 2006; *Shepherd and Wingham*, 2007], and discharge rates may have continuously grown since that time [*Rignot et al.*, 2011; *Zwally and Giovinetto*, 2011]. The impact of the current changes of both ice sheets is the main uncertainty in the estimation of the forthcoming sea level rise [*Intergovernmental Panel on Climate Change*, 2007]. Contrary to Greenland, surface melting rarely takes place in Antarctica, so that grounded ice turns into floating ice-shelves when reaching the ocean. Moreover, a large part of the Antarctic grounded ice rests over a bedrock that lies well below sea level [*Lythe et al.*, 2001]. An ice sheet in such a configuration, i.e., a marine ice sheet, has very particular dynamics due to changes in location of the grounding line (i.e., the limit between grounded ice and floating ice) which mainly control the ice sheet volume. Modeling grounding line dynamics has been an important problem for ice sheet modelers over the last decades, and model results were, until recently, inconsistent as no consensus was emerging on how the grounding line should react to changes in boundary conditions [*Vieli and Payne*, 2005]. However, recent theoretical progress [*Schoof*, 2007] and independent numerical simulations [*Nowicki and Wingham*, 2008; *Durand et al.*, 2009a], have confirmed the old standing marine ice sheet instability (MISI) hypothesis first proposed by *Weertman* [1974]: marine terminated outlet glaciers do present an intrinsic instability when they rest over a seaward up-sloping bedrock. In other words, once the grounding line initiates a landward retreat toward greater depths, the outflow is increased and leads to a further retreat. This kind of bedrock topography is far from being exceptional and characterizes most outlet glaciers that are currently out of balance (e.g., Pine Island in West Antarctica, see Figure 1).

[3] As a result, that an extensive knowledge of the bedrock elevation is a crucial requirement for the correct modeling of ice sheet dynamics. A DEM of Antarctica with a 5 km resolution was compiled by *Lythe et al.* [2001] and since then it has been notably improved by *Le Brocq et al.* [2010] who incorporated new measurements in the Amundsen sea sector [*Holt et al.*, 2006; *Vaughan et al.*, 2006]. However, because the bedrock not directly accessible, the Antarctic bedrock elevation is still only partially known and will remain so in the near predictable future. In the global context of sea level rise, we aim (i) to measure the impact of bedrock data on the modeled ice response, (ii) to determine where to focus future bedrock measurement campaigns, and (iii) to define the optimum bedrock resolution. We do this using the full-Stokes Elmer/Ice model using a range of bedrock boundary conditions detailed in Section 2. The low sensitivity of ice outflow to bedrock description in the interior of the continent is demonstrated in Section 3, and the important role of kilometric scale roughness is highlighted in Section 4. Section 5 presents the conclusions of our study.

2. Model and Methods

[4] We consider a gravity-driven flow of isothermal, incompressible and non-linearly viscous ice. Most ice sheet models use shallow layer approximations, i.e., they neglect some components in the stress tensor, and therefore fail to reproduce outlet glaciers behavior where all stress components compete equally. Here, we assume no approximation of the Stokes equation, and have paid particular attention to the resolution of the contact problem between ice and bedrock at the grounding line [*Durand et al.*, 2009a]. It has been clearly established that mesh refinement in the transition zone between the grounded and floating parts of the ice sheet is a critical component [*Schoof*, 2007; *Durand et al.*, 2009a]. This

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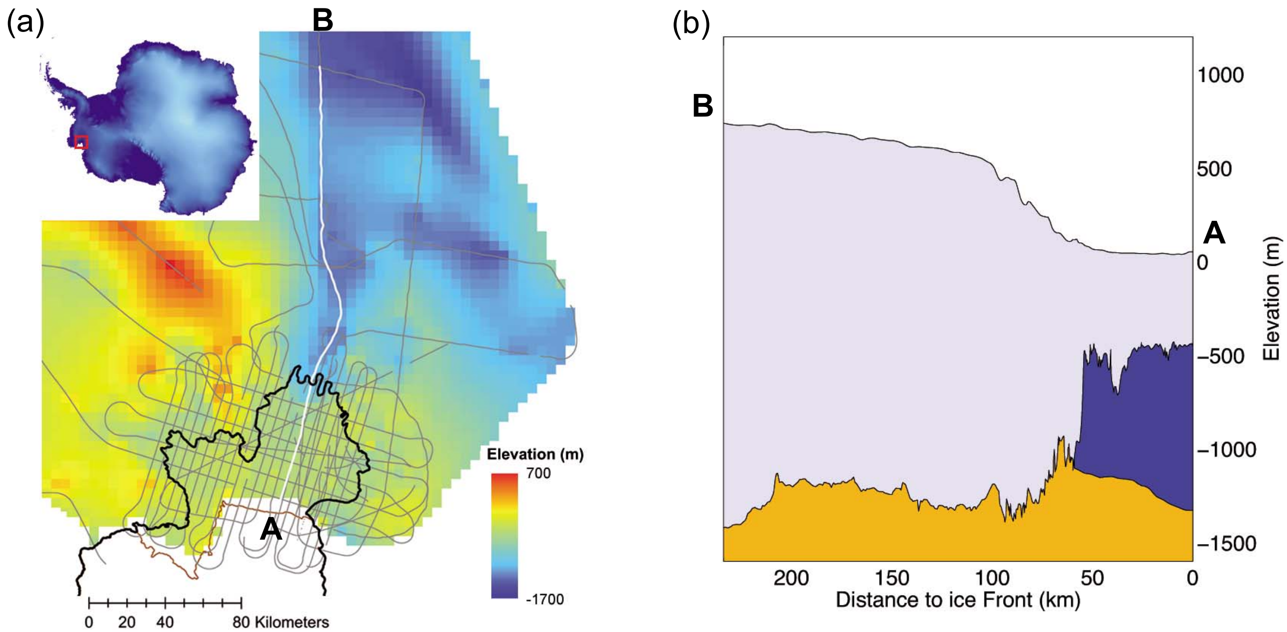

Figure 1. Bedrock elevation of the Pine Island Glacier (PIG), Antarctica. (a) 5 km-DEM of the lower ice surface of the PIG computed using natural neighbors interpolation. Ice thickness was measured in 2009 by the Center for Remote Sensing of Ice Sheets (CReSIS) team along the flight lines shown with grey lines. Sub surface elevation at each measurement position was deduced from the upper surface elevation [*Bamber et al.*, 2009]. The coastline defined by *Bohlander and Scambos* [2007] is shown with a red line. An overdeepened trough can be clearly seen upstream of the grounding line (black line). (b) Cross-section along the flight line (white) in Figure 1a that clearly shows a MISI configuration (see text for details).

has some strong implications in terms of computing resources when using a full Stokes model, and prevents from having numerous long-term simulations as in the approach presented here. We therefore restrict our analysis to a vertical two-dimensional plane flow with ice flowing along the x–direction (x = 0 at the dome); the z–axis is the vertical upward pointing axis. The ice flow is computed by solving the Stokes problem with a non-linear rheology, coupled with (i) the evolution of ice/air and ice/water free surfaces and (ii) the position of the grounding line x_G. It is implemented within the finite element code Elmer/Ice [*Gagliardini and Zwinger*, 2008; *Durand et al.*, 2009a, 2009b; *Gagliardini et al.*, 2010]. More details on the model and numerics can be found in the auxiliary material and are given by *Durand et al.* [2009a].[1]

[5] Our approach is to first build an initial steady geometry over a given bedrock configuration (details on the bedrock geometry are given below for each experiment). A topographic perturbation is introduced at $t = 0$ and the ice surface is allowed to relax. We then examine the impact of the perturbation in terms of change in the volume of ice above flotation (VAF), i.e., the volume of ice which contributes to the sea level budget during relaxation. A VAF increase corresponds to a growth of the ice sheet and therefore a negative contribution to sea level. There is, of course, no geological reason to justify such abrupt changes in the bedrock elevation, this however allows to test the sensitivity of the model to bedrock description.

3. Sensitivity Analysis

[6] The first set of experiments addresses the sensitivity of the model to both the characteristic size and position of an area of increased or decreased elevation. A steady state geometry is first computed on a linear downsloping bed ($b(x) = -x/1000$) with an initial steady grounding line position x_g = 512.8 km and a 100 km-long ice shelf (flow parameters used in this study can be found in the auxiliary material). At $t = 0$ a triangular shape bedrock perturbation is added, with a constant length of the base set to 100 km and a height that ranges between $-0.99 \times h$ and $0.99 \times h$, where h is the local ice thickness at the perturbation center. The ice surface is then allowed to relax to a steady geometry (see Figure 2). Areas of increased elevation hold back the upstream flow, which leads to greater surface elevation in the central part of the ice sheet (see Figures 2a and 2d, label A). The higher the elevation, the lower the ice discharge and, therefore, the larger the increase in the VAF. Similarly, an increased elevation close to the coast impacts a large portion of the ice sheet and therefore induces a large increase in the VAF.

[7] Conversely, introducing a trough in the bedrock has two distinct effects. First, large troughs located in the inner part of the continent have a limited impact upon the ice sheet volume. As an example, a 2000-m deep and 100-km span trough, will only induce a 2% decrease in the VAF when located 200 km from the grounding line (see Figures 2b and 2d, label B). Second, if the initial grounding line is over the depression, then depending on the slope, a MISI configuration can be reached leading to a grounding line retreat and finally to a dramatic decrease of the VAF. In opposition with all the previous cases, rather than the depth, it is the breadth of the trough that essentially drives the VAF variations (see Figure 2d, label C). A longer up-sloping region will result in a longer retreat of the grounding line and therefore to a larger decrease in the VAF. This is illustrated in Figure 2c where a trench with a maximal depth of 100 m extending

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048892.

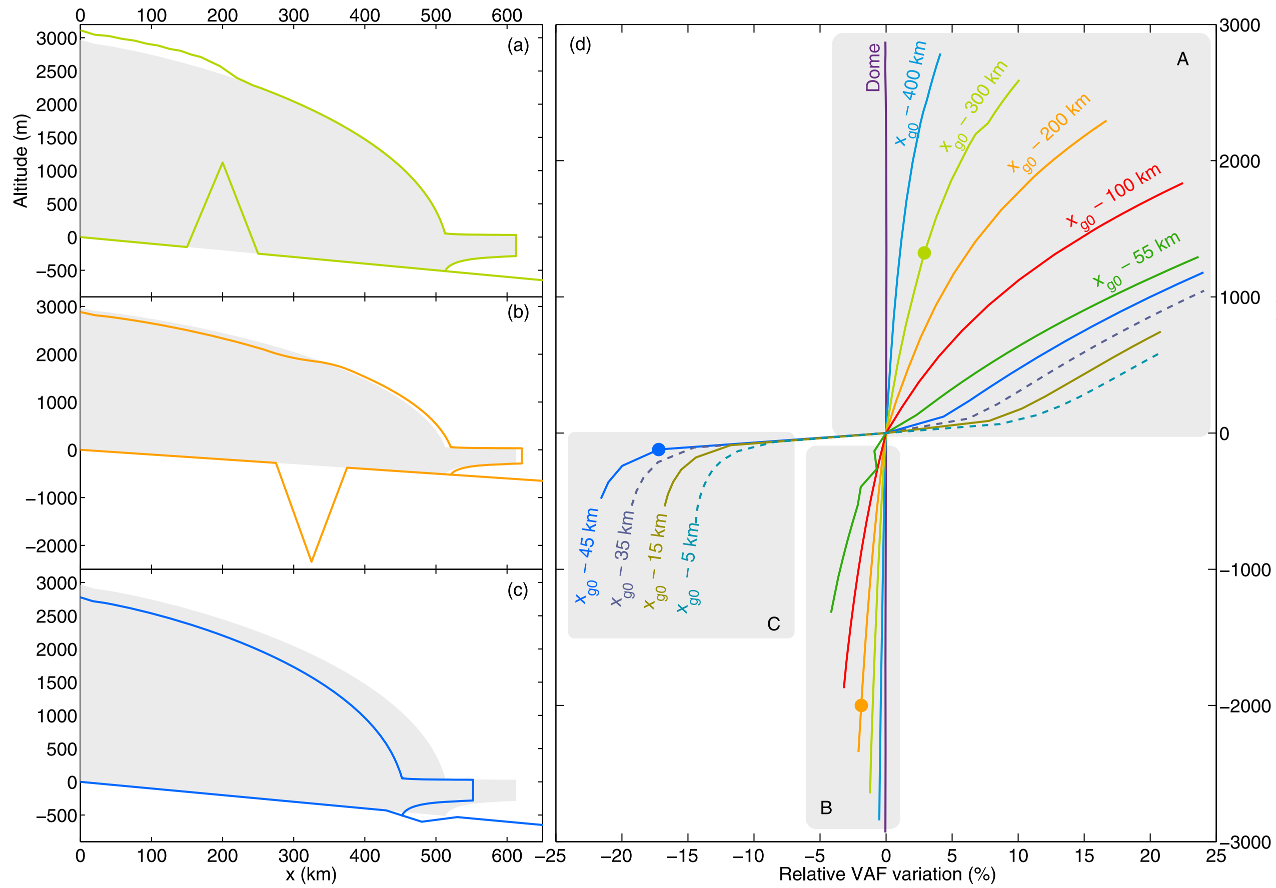

Figure 2. Sensitivity of the ice flow model to the size and position of an elevation perturbation. The initial steady geometry is shown by the shaded area in Figures 2a–2c. (a) Steady surface geometry (green) obtained with a 1500-m high and 100-km span perturbation located 300 km inland from the initial grounding line x_{g0}. (b) Steady surface geometry (orange) obtained with a 2000-m deep and 100-km span perturbation located 200 km inland from x_{g0}. (c) Steady surface geometry (blue) obtained with a 100-m deep and 100-km span trough located 45 km inland from the initial grounding line. (d) Relative variations of the Volume of ice Above Floatation (VAF) versus the amplitude of the relief perturbation at various distances behind the initial grounding line position, x_{g0} (dome (purple), respectively 400 km (light blue), 300 km (light green), 200 km (orange), 100 km (red), 55 km (green), 45 km (blue), 35 km (grey), 15 km (dark green), 5 km inland (turquoise)). Steady surfaces that correspond to the green, orange and blue dots are presented in Figures 2a–2c, respectively. Groups of similar behavior are shown with shaded areas and labeled A, B and C (see text for details).

over 90 km upstream of the initial position of the grounding line induces a 17% decrease in the VAF (see Figure 2c and blue dot in Figure 2d). These experiments clearly suggest that accurate knowledge of the bedrock elevation in central regions of the ice sheet is less of an issue when investigating its short term contribution to sea level. This is because a wrong description of the bed of inland areas only produces surface adjustments and weak related mass exchange with the ocean. Conversely, accurate knowledge of the bed elevation seems crucial in the vicinity of the grounding line. Indeed, if the description of the bed is too crude, it induces important dynamical changes, i.e., significant migrations of the grounding line and large ensuing mass exchanges with the ocean.

4. Optimal Resolution of the Bedrock Description in Coastal Regions

[8] In our second set of experiments, we attempt to estimate the resolution of the bedrock that would be required to avoid spurious dynamical effects in coastal regions. Rather than focussing on a specific glacier, we choose to run our simulations on a synthetic bedrock geometry that reproduces typical large-scale overdeepening (compare, for example, profiles of Figures 1 and 3). This makes it possible to simplify the problem (e.g., temperature, convergence/divergence of the flow, and basal friction are not taken into account) and to focus on the MISI mechanism. For this purpose, a high resolution (200 m) bedrock is generated. A roughness signal z_r with a 200-m resolution is superimposed on an elevation general trend z_{trend} so that the final elevation is defined by $b = b_{trend} + b_r$. b_r is computed using a classic iterative random midpoint displacement algorithm with a prescribed fractal dimension of 1.3 [*Russ*, 1994]. The choice of the fractal dimension used (between 1.1 and 1.5) does not affect notably the results. b_{trend} imposes an increasing bed elevation from the inland central part toward the edges of the continent as generally observed below marine ice sheets:

$$b_{trend} = \begin{cases} -1100 + x, & x \leq 450\text{km} \\ -650 - 5 \times (x - 450), & x > 450\text{km} \end{cases}$$

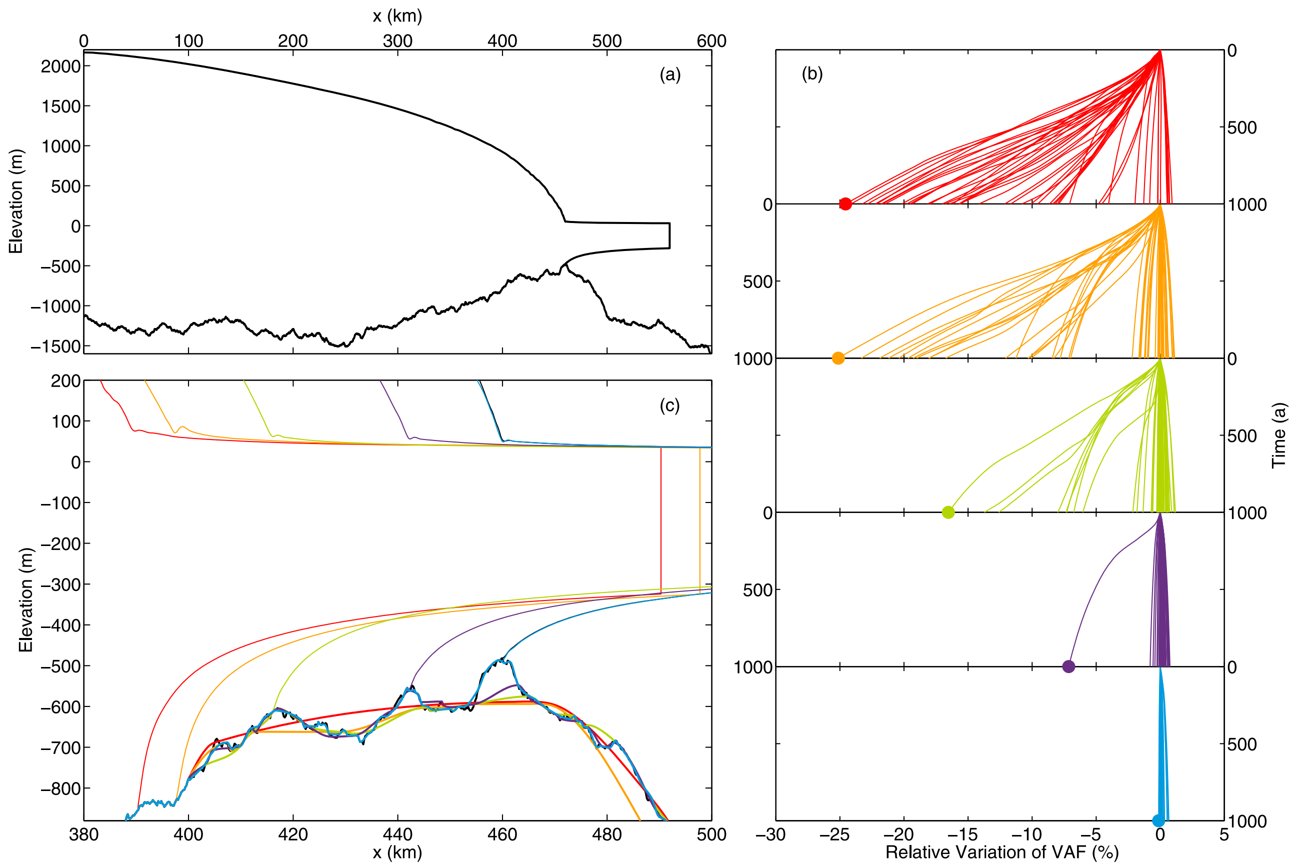

Figure 3. Sensitivity of the ice flow model to small scale roughness in coastal regions. (a) Initial steady state on a synthetic fractal bedrock (see Methods for details). Note the overdeepening similar to that observed beneath Pine Island Glacier (see Figure 1b). (b) Evolution of the Volume of ice Above Flotation (VAF) versus time after perturbations of the bedrock using various under-sampling resolutions (see text for details): 20 km (red), 10 km (orange), 6 km (green), 2 km (purple) and 1 km (light blue). (c) The surfaces corresponding to the largest VAF decreases after a 1000 years of relaxation for any given resolution (as shown by the dots in Figure 3b with a similar color coding).

where x is in kilometers and b_{trend} in meters. Then, we grow an initial steady state ice sheet upon it obtaining an initial steady position $x_g = 459.8$ km (flow parameters are presented in the auxiliary material). Between $x = 400$ km and $x = 500$ km, n_p points are randomly selected and a cubic spline interpolation is done between the selected elevations. n_p, here set to 4, 9, 24 and 49 corresponds to mean under-sampling intervals of 20, 10, 4, 2 and 1 km respectively. For every given mean sampling interval, 50 under-sampled beds are generated. At $t = 0$ the bedrock profile is changed to an under-sampled and interpolated one. Surfaces are then allowed to relax over 1000 years. This procedure mimics the computing of a DEM with various resolutions and makes it possible to quantify the sensitivity of the model to the bedrock description. A good enough representation of the bedrock should only slightly perturb the initial steady state and should result in only weak variations of the VAF.

[9] Figure 3 clearly shows that sampling intervals of over 1 km induce smoothing that may locally reverse the slope, giving rise to a MISI favorable configuration (see for instance the difference between the light blue and red curves in Figure 3c). This instability is physical but, in the present case, only results from the misrepresentation of the bedrock. Only 24% of the simulations made with a 20 km mean sampling distance reach a new equilibrium close to the initial one (i.e., ±2% VAF variation). For the 76% remaining simulations, a grounding line retreat is initiated and continues over a thousand years, leading to a decrease of up to 25% in the VAF within this period of time. Decreasing the mean sampling interval progressively reduces the occurrence of MISI configurations. With a 5-km mean sampling rate, a distance similar to the resolution currently used in bedrock DEMs, still 16% of the simulations lead to an erroneously unstable configuration. Finally, the mean sampling rate has to be decreased down to 1 km to definitively avoid the occurrence of MISI. These numerical experiments suggest that the current spatial coverage of many outlet glaciers is far too sparse (see Figure 1), but also that current bedrock DEMs [*Lythe et al.*, 2001; *Le Brocq et al.*, 2010] are of insufficient resolution in coastal regions where small-scale reliefs that may stabilize the ice sheet are not incorporated.

[10] In the near future, it is unrealistic to expect geophysical surveys of all the outlet glaciers of the Antarctic ice sheet to be completed with an increased flight-line density. However, the choice of a proper interpolation method may circumvent this pitfall by mitigating the unrealistic ice dynamics obtained when bedrock data is too scarce [*Seroussi et al.*, 2011]. Starting from the bedrock interpolation that gives the largest VAF decrease in the previous experiments, we added a small-scale roughness with statistical properties similar to those of

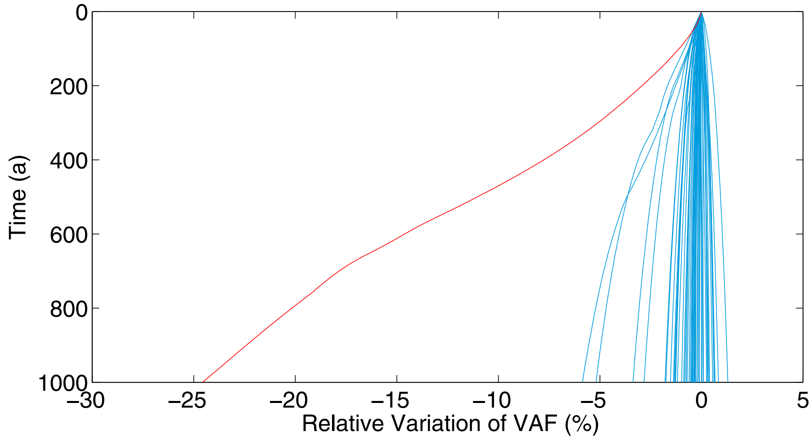

Figure 4. Sensitivity of the ice flow model to the reintroduction of a synthetic roughness on a too smoothed bedrock profile. Relative variation of the VAF during a 1000-year relaxation of an ice sheet resting over a smoothed bedrock (red line) as presented in Figure 3b (illustrated by a red dot) with the largest VAF decrease for the poorest resolution. 50 bedrocks were further computed by adding small scale roughness on this smoothed bed (see Methods for details); resulting relative variations of the VAF during a 1000-year relaxation period are presented in light blue.

the initial bedrock. A modeling procedure similar to the one used before is performed, i.e., 50 simulations with an abrupt change at $t = 0$ from the initial bedrock to a smoothed and re-roughed one, followed by surface relaxation during the following 1000 years. Figure 4 shows that adding roughness to an unrealistic over-smoothed bedrock clearly improves the dynamical response of the modeled ice sheet: 90% of the simulations reach a new steady state with less than ±2% of VAF variation. Despite a large scale MISI configuration, by introducing roughness to the bedrock, small scale topographic hills offer downsloping portions of bedrock that stabilize the ice sheet. This last set of experiments indicates that adding roughness to a smoothed DEM could be a good way to test the sensitivity of models to our description of the bedrock and therefore could give an estimate of related uncertainties on sea level contribution.

5. Conclusion

[11] The main finding of our study is that higher resolution in bedrock representations over outlet glaciers are needed in order to improve the modeling of ice sheet dynamics. However, our study does not incorporate lateral effects induced by real 3D geometry. As an example, buttressing effects are suspected to delay the unstable grounding line retreat or even to stabilize the ice sheet but their exact impact on the dynamics is still unclear and under debate [*Goldberg et al.*, 2009; *Katz and Worster*, 2011]. Currently, there is no model capable of fully accounting for three-dimensional effects in coastal areas. It is therefore difficult to extend our 2D results in terms of realistic geometries. Nevertheless, our conclusion on the low impact of a rough description of inland bedrock elevation is most probably robust. As for the coastal areas, strong topographical features such as narrow valleys draining the coastal ice cannot be correctly described with a 5-km grid which unavoidably smooths out these topographic structures and ensuing 3D effects. Therefore, our main finding, that is improved resolution in bedrock representations over outlet glaciers is needed, remains pertinent.

[12] In summary, the 5-km resolution that DEMs currently propose are largely accurate enough to describe inland regions; however, the resolution should be improved to a kilometric scale for coastal outlet glaciers. Because refined mesh models are required for tracking grounding lines [*Schoof*, 2007; *Durand et al.*, 2009a], and to model outlet glacier dynamics [*Morlighem et al.*, 2010; *Gillet-Chaulet and Durand*, 2010],the basal topography needs to be complementary. We propose that fixed-grid DEMs are a large potential source of error in models and that elevations defined in an unstructured mesh are needed in response. This should offer more detail near the grounding line, but not necessarily in the inland portions of the ice sheet. This paradigm shift can only be facilitated via high-density surveying in coastal areas.

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