Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics

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[1] Increase in ice-shelf melting is generally presumed to have triggered recent coastal ice-sheet thinning. Using a full-Stokes finite element model which includes a proper description of the grounding line dynamics, we investigate the impact of melting below ice shelves. We argue that the influence of ice-shelf melting on the ice-sheet dynamics induces a complex response, and the first naive view that melting inevitably leads to loss of grounded ice is erroneous. We demonstrate that melting acts directly on the magnitude of the buttressing force by modifying both the area experiencing lateral resistance and the ice-shelf velocity, indicating that the decrease of back stress imposed by the ice-shelf is the prevailing cause of inland dynamical thinning. We further show that feedback from melting and buttressing forces can lead to nontrivial results, as an increase in the average melt rate may lead to inland ice thickening and grounding line advance. **Citation:** Gagliardini, O., G. Durand, T. Zwinger, R. C. A. Hindmarsh, and E. Le Meur (2010), Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics, *Geophys. Res. Lett.*, *37*, L14501, doi:10.1029/2010GL043334.

1. Introduction

[2] Ice-sheets are an important component of the climatic system, affecting atmospheric and oceanic circulation and controlling a major part of eustatic sea level change. In the current context of global warming and consequent sea-level rise, contribution from continental ice discharge from both Greenland and Antarctica has grown dramatically this last decade [*Velicogna*, 2009]. However, ice loss as a result of enhanced flow in coastal regions is currently poorly understood, and the corresponding potential contribution to sea-level rise in the twenty-first century remains speculative. In particular, enhanced coastal discharge is worrying for regions where the bedrock lies below sea level (i.e. marine ice-sheets) because the retreat of ice-streams may initiate large scale collapse [*Schoof*, 2007].

[3] Ocean warming, and subsequent melting of floating ice-sheet parts, is frequently invoked as a trigger of the observed enhanced dynamical thinning of inland grounded ice [*Payne et al.*, 2004; *Shepherd et al.*, 2004; *Bindschadler*, 2006; *Holland et al.*, 2008]. The main and striking argument usually given in support of this is the simultaneity of the observed acceleration of different outlet glaciers. However, very few ice flow modeling attempts have been undertaken in order to corroborate this hypothesis and to go beyond speculation towards a comprehensive understanding of the underlying processes [*Pattyn et al.*, 2006; *Walker et al.*, 2008, 2009]. This is at least partly due to the long standing problem of finding a consistent approach to model the grounding line evolution (i.e., the evolution of the line that marks the limit between grounded and floating ice). Since the basal conditions of inland grounded ice and downstream floating ice tongues differ greatly, two distinct modes of deformation dominate these regions, respectively horizontal shearing and longitudinal extension. Therefore, depending on the region being considered, different approximations of Stokes equations are used by large scale ice-sheet models, with important coupling issues within the transition zone, where both deformation mechanisms are of the same magnitude. However, recent results indicate that even depth-integrated models can produce consistent results if implemented numerically in a careful way [*Schoof*, 2007; *Durand et al.*, 2009; *Goldberg et al.*, 2009].

[4] In this study, we use a finite element model which solves the full Stokes equations (i.e quasi-static flow equations with all terms) to investigate the impact of melting below ice-shelves on the dynamics of the grounding line and corresponding impact on the evolution of the volume of the ice-sheet. The governing equations for the model and numerical details have been described by *Durand et al.* [2009] and are listed in the auxiliary material.[4] The new features introduced for this study, i.e. basal melting and back-force from floating ice, are detailed in Section 2. In Section 3, we demonstrate that buttressing forces exerted by the ice-shelf turn out to be the dominant process when sub-ice-shelf melting occurs. However, the combination of both lateral resistance from side walls of the ice-shelf with basal-melting may lead to nontrivial behavior of marine ice-sheet dynamics; in particular, an increase in the average melt rate can produce a gain of ice-sheet volume. This is illustrated in Section 4, while Section 5 contains a concluding discussion.

2. Description of the Model

[5] The model is presented in detail in the auxiliary material and here we focus on the implementation of melting and buttressing. Briefly, using the finite element model Elmer/Ice, we solve the full-Stokes equations for an ice-stream and associated ice-shelf in plane flow, the grounding line position at each time being fully determined by solving the contact problem between the ice and the bedrock. In all the applications, the length of the ice-shelf L_{shelf} is set constant,

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Table 1. Definition of All the Presented Simulations

Experiment	$\overline{a}_{b\perp}$ [m a^{-1}]	β	K	Figure[a]
1- initial	0.0	-	0	Figure S1, Dark Brown
1-a	0.5	1.10	0	Figure S1, Brown
1-b	1.0	1.10	0	Figure S1, Orange
1-c	1.5	1.10	0	Figure S1, Light Orange
2- initial	0.0	-	>0	Figure 1, Red
2-a	1.0	1.50	>0	Figure 1, Orange
2-b	1.0	1.25	>0	Figure 1, Yellow
2-c	1.0	1.10	>0	Figure 1, Green
3- initial = 2-c	1.0	1.10	>0	Figure 1, Green
3-a	1.1	1.50	>0	Figure 1, Light Blue
3-b	1.2	1.50	>0	Figure 1, Blue
3-c	1.6	1.50	>0	Figure 1, Dark Blue

[a]Figure S1 can be found in Text S2.

assuming implicitly that calving of icebergs always occurs at the same distance from the grounding line.

[6] In this work, we extend a previously applied model [*Durand et al.*, 2008, 2009] by including basal melting below the ice-shelf and lateral resistance on the ice-shelf sides. The basal melting is given as a normal flux $a_{b\perp}$ such that the vertical flux is $a_b = a_{b\perp}\,[1 + (\partial_x z_b)^2]^{1/2}$ in the bottom surface equation (S6). Parameterization of the melt rate $a_{b\perp}(x)$ follows the position dependent distribution proposed by *Walker et al.* [2008]:

$$a_{b\perp}(x) = \frac{\overline{a}_{b\perp}}{N}\left(1 - \frac{x - x_G}{L_{\rm shelf}}\right)^2 \left(\frac{x - x_G}{L_{\rm shelf}}\right)^{\beta-1}, \qquad (1)$$

where $x_G \le x \le x_G + L_{\rm shelf}$ and N is a normalization factor defined such that $\overline{a}_{b\perp} = L_{\rm shelf}^{-1}\int_{x_G}^{x_G+L_{\rm shelf}} a_{b\perp}\,dx$ stands for the average melt rate. The melt distribution exponent β controls the shape of the melting distribution and its influence is discussed in detail below. Smaller β concentrates the melting towards the grounding line. This simplified parameterization reflects the tendency of basal melting to be close to zero at the grounding line, intense just downstream of the grounding line, and to decrease very rapidly seaward, as observed [*Rignot and Jacobs*, 2002] or modeled using physically-based ice-ocean models [*Walker and Holland*, 2007; *Payne et al.*, 2007].

[7] Typically, lateral resistance on ice-shelf sides is either modeled by introducing a back-force at the front of the ice-shelf [*Dupont and Alley*, 2005; *Walker et al.*, 2008] or by adding some basal friction below the ice-shelf [*Van der Veen and Whillans*, 1996; *Pattyn et al.*, 2006]. In both cases, the added resistance does not depend on the area of the ice-shelf/bay interface, and in the latter case artificially introduces shear deformation in the ice-shelf when using a full-Stokes model. In our approach, the lateral resistance is accounted for over the whole area of the ice-shelf/bay interface by adding a body force $\boldsymbol{f}$ in the momentum balance equation (S4), such that

$$\boldsymbol{f} = -K|\boldsymbol{u}|^{m_{lr}-1}\boldsymbol{u}\,, \qquad (2)$$

where K and m_{lr} are the lateral resistance coefficient and exponent, respectively. In the following applications, K is set to 0 for the grounded part ($x \le x_G$). On the ice-shelf, $K > 0$, parameterizes the non-linear resistance from the contact between the ice-shelf and the bay walls. In our approach, the resulting total back force is not constant but depends on the ice-shelf velocity field and the horizontal and vertical dimensions of the ice-shelf. To simplify analysis of the results, the length of the ice-shelf $L_{\rm shelf}$ is set constant. Expression (2) for the lateral resistance force can be inferred from analytical solutions obtained for the flow of a very long flat weak-bedded ice-shelf. Such derivations, presented in the auxiliary material, allow us to relate K to the ice-shelf width and the rheological parameters of the ice. In the following applications, when buttressing applies, K is chosen according to (S19) assuming an ice-shelf width of approximately 100 km. The value of all the parameters entering the equations are given in Table S1.

3. Grounding Line Retreats Caused by Decreased Ice-Shelf Buttressing

[8] All the simulations discussed below are summarized in Table 1. We first simulate the effect of sub ice-shelf melting beneath an unconfined ice-shelf, *i.e.* the lateral resistance body force $\boldsymbol{f}$ is set to 0 in the momentum balance equation (S4). An initial steady state is first obtained with zero melting prescribed, then three simulations are run with the melt distribution exponent β = 1.1 and three different average melt rates of $\overline{a}_{b\perp}$ = 0.5 (Exp1-a), 1.0 (Exp1-b) and 1.5 m a^{-1} (Exp1-c). The geometry is allowed to evolve under these new conditions until a steady state is achieved. The corresponding geometries, surface velocities and prescribed melt distributions are plotted in Figure S1 of Text S2 in the auxiliary material.

[9] The ice-shelf thins dramatically if melting is prescribed, and obviously, the larger the melt rate is, the thinner the ice-shelf becomes. However, no retreat of the grounding line is observed and changes in the grounded ice volume are insignificant in this case where no back-force is included. Further increase of the melt rate would lead to disappearance of the ice-shelf, but no movement of the grounding line would precede the break off. This confirms previous results obtained by *Pattyn et al.* [2006]. Furthermore, a larger perturbation of the model parameters (for example viscosity, basal slipperiness, snow accumulation or sea level) than for the case of no-melting has to be applied to initiate any displacement of the grounding line. This is illustrated in Figure S2 of the Text S2 in the auxiliary material, where the response of the grounding line to a 25% decrease of the flow rate factor A is shown for both cases with and without sub ice-shelf melting. The latter results indicate that in case of a two-dimensional flow line model of a marine ice-shelf with no buttressing, melting at the ice-sea interface has a *stabilizing* effect on the grounding line. It is uncertain whether this stabilizing effect, obtained here with a full-Stokes model, could be reproduced by depth-integrated models which do not capture the physics very close to the grounding line. Stabilizing the ice-sheet as a consequence of melting is in clear contradiction to what is expected from observations, as the usual explanation for the observed outlet glaciers acceleration and thinning lies in the effect of a warming ocean below the ice-shelf [*Payne et al.*, 2004; *Shepherd et al.*, 2004; *Bindschadler*, 2006; *Holland et al.*, 2008]. The absence of buttressing forces is certainly the cause for this stabilizing effect as demonstrated below.

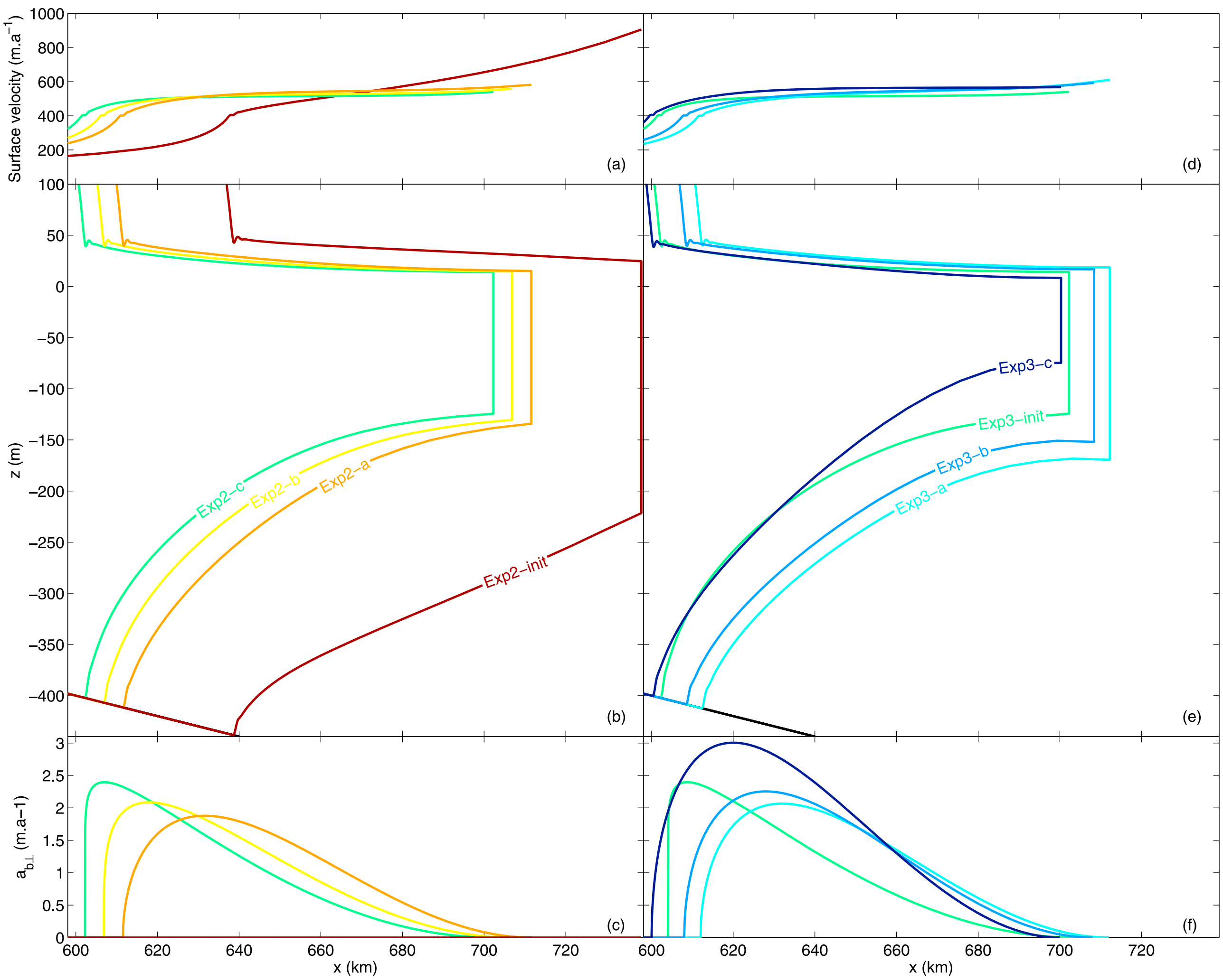

Figure 1. Surface velocity, geometry and corresponding sub ice-shelf melt distribution for the steady ice-shelf with lateral friction and different melt distribution. **Exp2**: (a–c), steady state solutions obtained without melting (red curve) and for different melting distributions $\beta = 1.5$ (orange), $\beta = 1.25$ (yellow), $\beta = 1.1$ (green) with the same average basal melt rate $\overline{a}_{b\perp} = 1.0$ m a^{-1}; **Exp3** (d–e), starting from the solution for $\overline{a}_{b\perp} = 1.0$ m a^{-1} and $\beta = 1.1$ (green curve), steady state solutions obtained after a change of the shape of the melting rate distribution ($\beta = 1.5$) and an increase of the average melt rate to $\overline{a}_{b\perp} = 1.1$ m a^{-1} (light blue), $\overline{a}_{b\perp} = 1.2$ m a^{-1} (blue) and $\overline{a}_{b\perp} = 1.6$ m a^{-1} (dark blue).

[10] We now introduce, in the second set of simulations, lateral resistance by setting K to non-zero in the momentum balance equation (S4). In the case of no melting ($\overline{a}_{b\perp} = 0$), starting from a steady state geometry obtained with no lateral resistance, the inclusion of lateral resistance ($K > 0$) leads to a significant thickening of the ice-shelf and a substantial advance of the grounding line of about 120 km (see for comparison the steady surfaces Exp1-ini in Figure S1 of Text S2 and Exp2-ini in Figure 1). Starting from this latter steady state, three different melt rate distributions are prescribed. All of them have identical average melt rates of $\overline{a}_{b\perp} = 1.0$ m a^{-1}, but the melting is increasingly concentrated towards the grounding line by setting $\beta = 1.5$ (Exp2-a), 1.25 (Exp2-b) and = 1.1 (Exp2-c). Corresponding ice-shelf surface velocities and geometry for the steady state solutions are plotted in Figure 1. Clearly visible is the significant grounding line retreat as the melting becomes more concentrated towards the grounding line as outlined by *Schoof* [2007]. This also confirms the conclusion of previous modeling work done by *Walker et al.* [2008]. Note that some other simulations indicate an increased sensitivity with respect to the melting distribution in case of larger buttressing forces (data not shown).

[11] It is obvious from Figure 1 that melting influences the shape of the ice-shelf and thus apparently decreases its volume and in consequence - being a body force - also the buttressing effect. This decrease in ice-shelf volume, and the associated decrease in the total buttressing force, explains the grounding line retreats observed for these simulations. However, as sub ice-shelf melting also has a strong feedback on the velocity field within the ice-shelf, and because the lateral resistance depends on the local velocity, the integrated buttressing force depends also on the ice-shelf velocities. As shown in Figure 1a, the mean surface velocity decreases as the melt rate distribution is more concentrated towards the grounding line. Compared with the ice-shelf area decrease, it can induce a reverse effect on the resulting buttressing force owing to the dependence of the lateral resistance law

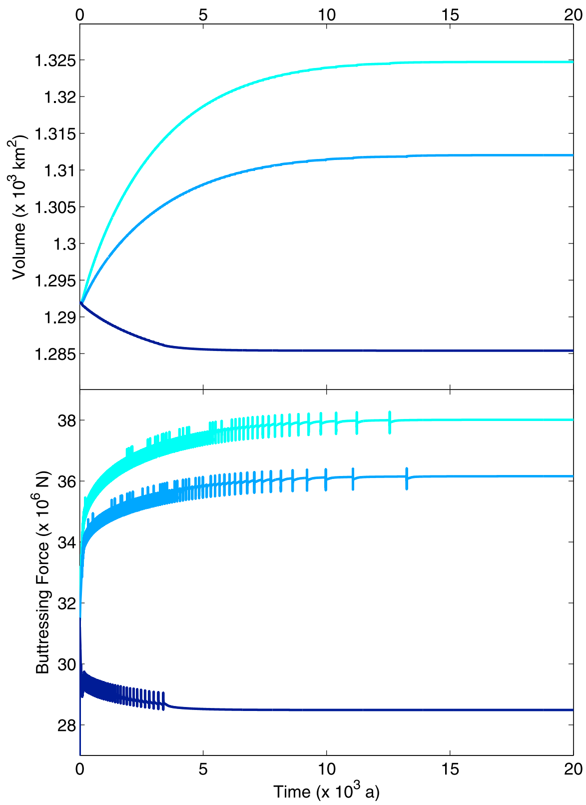

Figure 2. **Exp3**: Evolution of the grounded ice-sheet volume and the total buttressing force versus time. Starting from the solution for $\overline{a}_{b\perp}$ = 1.0 m a^{-1} and β = 1.1 (green curve in Figure 1), the curves represent the transient solutions obtained after a change in the melting rate distribution (β = 1.5) and an increase of the average melt rate to $\overline{a}_{b\perp}$ = 1.1 m a^{-1} (light blue), $\overline{a}_{b\perp}$ = 1.2 m a^{-1} (blue) and $\overline{a}_{b\perp}$ = 1.6 m a^{-1} (dark blue). Steady state geometry and surface velocities obtained after 20 × 10^3 years and corresponding melting rate distributions are presented in Figure 1d–1e.

on velocity, and therefore have a non-trivial consequence on grounding line dynamics.

4. Enhanced Melting May Lead to Grounding Line Advance

[12] Motivated by the previous remark, we now try to answer the question: is it possible to obtain a higher volume and a grounding line advance despite higher average melt rates? Starting from the steady state obtained with a buttressed ice-shelf ($K > 0$) with sub ice-shelf melting distribution defined by $\overline{a}_{b\perp}$ = 1.0 m a^{-1} and β = 1.1 (Exp2-c in Figure 1), a third set of simulations is run with increasing average melt rates from $\overline{a}_{b\perp}$ = 1.1 (Exp3-a), 1.2 (Exp3-b) to 1.6 m a^{-1} (Exp3-a), but assuming less concentrated melting near the grounding line (*i.e.*, setting β = 1.5 instead of 1.1). Geometries were allowed to evolve to new steady states, and the corresponding surface velocities, surface geometries and applied melt distributions are plotted in Figure 1d–1f. The time evolution of the grounded ice-sheet volume and the total buttressing force are plotted in Figure 2. Note that increasing the average melt rate does not necessarily lead to a grounding line retreat if the shape of the melt distribution is simultaneously affected. For Exp3-a and Exp3-b, even if the average melt rate is higher, a change in the melt distribution has the effect of increasing the velocity field just downstream of the grounding line, and consequently results in an increase of the total buttressing force. In the present set of simulations, a 60% increase in the average basal melt rate has to be applied in order to initiate a decrease of the buttressing forces that is followed by a retreat of the grounding line and a significant decrease in the ice-sheet volume (Exp3-c). This clearly illustrates the nontrivial consequences for marine ice-sheet dynamics that can arise from the complex interactions between melting and lateral resistance.

5. Conclusions

[13] Using a full-Stokes model, we have confirmed recent results obtained with other models which use approximations to the Stokes equations [*Pattyn et al.*, 2006; *Walker et al.*, 2008]. The grounding line retreat that follows melting below the ice-shelf arises from the decrease in buttressing forces. The basic view that, as a consequence of melting, the sea may progressively encroach on grounded ice is too simplistic and in certain cases wrong. Following on from this initial result, studying the effect of melting in a plane strain problem with no lateral resistance may lead to unrealistic results. Certainly, for basic studies of the processes and qualitative results, lateral resistance forces have to be taken into account to parameterize the back force induced by the friction of the ice-shelf on its embayment.

[14] We have also confirmed that the distribution of melting is a key parameter in determining forces at the grounding line and needs accurate prescription to properly investigate marine ice-sheet dynamics.Prescribing an average melt rate everywhere under the ice-shelf is not satisfactory. We also show that interactions between melting and change in lateral resistance are far from being trivial. As an illustration, we showed in Section 4 that an increase in the global melting may actually lead to a grounding line advance and growth of the grounded ice-sheet providing that at the same time, the melting is less concentrated near the grounding line.

[15] From a broader perspective, this work has demonstrated the limits of two-dimensional flow line modeling of ice-shelves and, consequently has some important implications for future marine ice-sheet models. To make reliable predictions of grounded ice mass loss, the glaciological community need: (*i*) robust three-dimensional models which self-consistently solve the problem of grounding line dynamics and (*ii*) a realistic consideration of lateral friction at the side of the ice-shelf and below ice-rises. From both modeling and measurements, we will further need (*iii*) a high-resolution knowledge of the mass exchange between the ocean and the ice-shelf, including its spatial distribution below the ice-shelf. For this latter point, accurate modeling of sub ice-shelf melting requires coupling of an ice-sheet model and an ocean model, and a full description of ice-ocean interactions with their complete physics. If we fail to make major advances on the previously mentioned points, prediction of ice-sheet contribution to sea-level rise will remain mainly speculative.

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