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Mechanical effect of mélange-induced buttressing on embayment-terminating glacier dynamics

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Abstract

Embayment terminating glaciers interact dynamically with seasonal sea ice and icebergs, a mixture we refer to as *mélange*. For certain glaciers, *mélange* prevents calved bergs from rotating away from the front, thus allowing the ice front to advance into the embayment. Here we demonstrate that *mélange* can, if rigid enough, provide sufficient buttressing to reduce the calving rate, while leaving the ice-front velocity largely unaffected. The net result is additional ice-front advance.

Observations indicate a seasonal advance/retreat cycle has occurred at Jakobshavn Isbræ since the 1950s. We model an idealized Jakobshavn Isbræ-like scenario and find that *mélange* may be responsible for a seasonal ice-front advance of up to 0.6 km. These results come from a model that incorporates *mélange* into the interior of the domain, includes relevant stresses, and models drag via a kinematic boundary condition. A weakening or loss of *mélange* due to increasing temperatures would lead to further mass loss from glaciers such as Jakobshavn Isbræ.

1 Introduction

Ice-sheet outlet glaciers and ice streams may have short response times to environmental forcings (Rignot et al., 2004; Scambos et al., 2004; Zwally et al., 2002) and the associated response has long term implications for changes in ice volume and ice dynamics (Price et al., 2011; Dupont and Alley, 2005; Parizek and Alley, 2004). At the margins, some marine terminating outlet glaciers are buttressed by a seasonal iceberg/sea-ice mixture, here referred to as *mélange*, that can prevent calved bergs from rotating away from the front (Amundson et al., 2010). The ice front then advances into the embayment, in the form of calved unrotated bergs (Joughin et al., 2008; Reeh et al., 2001; Howat et al., 2010). The newly formed ice shelf generates lateral-drag induced buttressing capable of slowing glacial flow (Dupont and Alley, 2005; Joughin et al., 2012). Here we show, in addition to this mechanism for advance, that *mélange*

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can mechanically suppress the rate of calving, leading to additional advance and associated reduction in velocity.

Seasonal calving and ice-front advance are documented at a number of Greenland outlet glaciers including Kangerlussuaq, Helheim, and Jakobshavn Isbræ (Luckman et al., 2006; Joughin et al., 2008). Here we choose Jakobshavn Isbræ (hereafter referred to as JI) as a case study owing to its importance in overall Greenland mass budget and extensive observational record. Historically, a seasonal advance and retreat of ~2.5 km, with associated winter reduction in calving rate, has occurred at JI from the 1950s to 1990s (Sohn et al., 1998; Csatho et al., 2008). Observations show that for the 2004–2007 period, the winter advance coincided with periods when mélange behaved rigidly, the ice front only retreating when the mélange experienced internal deformation or broke apart in spring (Joughin et al., 2008). Reeh et al. (2001) asserted that mélange suppresses calving rates but has a negligible impact on the overall force-balance at the ice front. We argue that calving rate primarily depends on the longitudinal strain rate in the vicinity of the ice front (Alley et al., 2008; Benn et al., 2007), and that the presence of a rigid mélange is capable of mechanically suppressing that strain rate enough to reduce the calving rate, while leaving velocity largely unaffected.

This work seeks an upper-bound on the potential mechanical impact mélange-induced buttressing can have on the calving rate for an idealized Jakobshavn-Isbræ-like (JI-like) system. We choose geometric and rheologic parameters based on observations, however, the idealized nature of this model makes direct comparison to this particular physical location only suggestive. Our results indicate mélange growth may be an important mechanism contributing to the ~5 km ice-front advance for a JI-like system. These results have two immediate implications. The first is that mélange may allow for glacier advance under a cooling climate. Second, warming temperatures may yield less, and perhaps weaker, mélange, resulting in less calving-rate suppression, and consequently an increase in volume loss for glaciers such as JI.

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2 Model description

We use the MacAyeal/Morland equations to model the stress equilibrium of a combined ice-shelf/mélange system (MacAyeal, 1989). The equations are solved using the finite element method with linear basis functions across triangular elements via the MATLABTM PDE toolbox. The primary variable solved for is the depth-integrated velocity $\mathbf{u} = [u, v]$, from which other variables, such as strain rates, can be calculated.

Our model formulation is novel in that it is the first time, to our knowledge, that mélange has been incorporated within the interior of the domain, thus allowing for a more natural treatment of drag-induced buttressing. We do this by treating the mélange as a continuous medium, of uniform density, thickness, and hardness, analogous to an idealized ice shelf. In reality mélange is a granular medium of bergs encased by sea-ice; our approximation assumes that the bergs are densely packed and that there is no failure along grain boundaries. We model the mélange rheology using Glens flow-law. The weakness of this approach is that we are missing potentially-important bridging stresses, and a different constitutive relation, such as a Coulomb rheology, would be needed to capture shear failure, potentially along grain (or berg) boundaries (Weiss et al., 2007). Beyond the mélange, we treat JI as a floating ice-shelf, rather than a grounded outlet, a simplification which may be justified given that the terminal portion of JI is weakly supported at the bed (Thomas, 2004; Joughin et al., 2012).

The domain is split into two equal sized regions (see Fig. 1), divided by the ice/mélange boundary, or ice front. The MacAyeal-Morland equations are applied continuously across both glacial ice and mélange. A straight line of nodes delineates the ice front. Every node down flow of the ice front is identified as mélange. Linear interpolation from ice-shelf nodes to mélange nodes creates a transition zone (orange triangles in Fig. 1) from ice to mélange that narrows into a cliff-like transition with mesh refinement. For numerical reasons, mélange cannot have zero thickness, thus we use a near-zero value to represent summer mélange-free condition. This very thin mélange

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layer results in ice-front longitudinal strain rates which are less than a few percent below the theoretical values expected in a truly mélange-free state. The stress equilibrium equations are:

$$\partial_x(2vh(2\partial_x u + \partial_y v)) + \partial_y(vh(\partial_y u + \partial_x v)) - \rho gh \partial_x z_s = 0 \quad (1a)$$

$$5 \quad \partial_y(2vh(2\partial_y v + \partial_x u)) + \partial_x(vh(\partial_x v + \partial_y u)) - \rho gh \partial_y z_s = 0 \quad (1b)$$

The depth-integrated equations are appropriate for systems with negligible vertical deformation. Here, ∂_x represents the partial derivative in the x-direction, h is the ice or mélange thickness, ρ is the density of ice or mélange, g is the gravitational constant.

10 Assuming hydrostatic equilibrium, the surface elevation is $z_s = (1 - \rho/\rho_{sw})h$, where ρ_{sw} is the density of sea water.

We use the Glen treatment for ice rheology with flow-law-exponent $n = 3$ (Glen, 1955; Nye, 1957). We assume isothermal ice with a uniform ice-hardness parameter B . The effective viscosity is defined as

$$15 \quad v = \frac{B}{2} \left[(\partial_x u)^2 + (\partial_y v)^2 + \frac{1}{4} (\partial_y u + \partial_x v)^2 + \partial_x u \partial_y v \right]^{\frac{1-n}{2n}} \quad (2)$$

The density and thickness are also uniform within the ice shelf and mélange subdomains. The mélange hardness parameter and density are denoted B_m and ρ_m , respectively.

Four boundary conditions are necessary to solve the stress equilibrium equations. Utilizing symmetry, only the half-width of the ice-shelf is modeled. At the upstream boundary a constant inlet velocity is applied $u(0, 0 < y < W) = [u_o, 0]$ where W is the half-width. At the embayment wall we apply a nonlinear kinematic boundary condition for the x-directed flow $f = \gamma u$ where $\gamma = B_s u^{1/n-1}$ and B_s is a constant side-drag coefficient, u is velocity and $v = 0$. It is this kinematic boundary condition which generates drag, and thus buttressing, at the ice front. This boundary treatment assumes lateral shear is confined to a narrow region near the embayment wall. The centerline boundary

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condition accounts for symmetry of flow and is given by:

$$vh(\partial_y u + \partial_x v) = 0, \quad 0 < x < L, \quad y = W \quad (3)$$

$$v = 0, \quad 0 < x < L, \quad y = W \quad (4)$$

- 5 where the first condition specifies no lateral shear, and the second specifies no lateral flow. For the mélange/ocean boundary the depth-integrated ocean pressure is balanced by the glaciostatic and dynamic components of the depth-integrated mélange pressure. This boundary condition is specified as:

$$2vh(2\partial_x u + \partial_y v) = \frac{\rho g h^2}{2} \left(1 - \frac{\rho_i}{\rho_w}\right), \quad x = L, \quad 0 < y < W \quad (5)$$

$$10 \quad vh(\partial_y u + \partial_x v) = 0, \quad x = L, \quad 0 < y < W \quad (6)$$

- The calving rate is calculated using the Alley et al. (2008) empirically-based calving parameterization appropriate for ice-shelf flow and glacial flow weakly-supported at the bed. The calving rate is effectively linearly-dependent on centerline ice front longitudinal strain rate and is given by:

$$15 \quad \dot{c} = c_a(hW\partial_x u)^{0.98} \quad (7)$$

where c_a is the Alley calving coefficient.

3 Experiments and results

- 20 We seek an upper bound on the impact mélange-induced drag has on glacier dynamics and estimate potential ice-front advance for JI. Here we focus on the velocity and calving rate at the ice front, on the centerline, as indicated in Fig. 1. We begin by choosing parameter values matching observed values and which generate a reasonable velocity

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field. The Alley coefficient is then adjusted to allow the calving rate to match the ice-front velocity for the mélange free state. This simulates a stationary summer ice front. The various parameter values are given in Table 1.

Starting from our stationary ice front under mélange-free conditions, we examine how the ice-front velocity and calving rate change in response to the buttressing produced by mélange of finite thickness. Figure 2 shows the reduction in ice-front longitudinal strain rate ($\partial_x u$) for a range of mélange thicknesses, from zero, to the full ice-shelf thickness. Figure 3 shows the nonlinear character of the calving rate response to mélange thickness, and also shows the much more subdued response in ice-front velocity. In both cases there is a reduction with greater mélange thickness. However, having started with a balance between velocity and calving for the mélange-free state, the preferential reduction in calving rate over velocity upon the introduction of mélange implies an ice-front advance; more ice is arriving than calving would remove.

As indicated in Figs. 2 and 3, if we adopt a conservative and thin mélange thickness of 20 % of ice-shelf thickness we see that velocity is reduced by $\sim 10\%$ while longitudinal strain rate is lowered by more than 40 % with a corresponding suppression in calving rate also exceeding 40 %. By simply subtracting the calving rate from the ice-front velocity and assuming mélange holds rigid through 4 months of winter, this accounts for 0.6 km of ice-front advance. Due to the non-linear response to mélange-induced buttressing, thicker mélange would lead to significantly higher buttressing.

Because of the idealized nature of the model, and because a reasonable velocity field can be arrived at for a variety of parameter values, we examined the sensitivity of the results to changes in several of the parameters. This included the hardness of the mélange (B_m), and the domain (embayment) length L . Increasing the mélange hardness produces a greater buttressing effect for a given mélange thickness, and therefore a greater suppression of calving rate. Similarly, increasing the domain length increases the area over which drag can generate buttressing, and thereby increases the influence of mélange on calving rate. For example, a 10 % increase in either B_m or L yields a 3 % further reduction in calving in the 20 % mélange thickness scenario. Therefore, longer,

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or colder embayments might reasonably be expected to exhibit a stronger response to the presence of mélange. Ultimately, the sensitivity studies indicate that the results are qualitatively robust under multiple sets of parameter values.

4 Conclusions

The recent seasonal ~5 km advance of JI corresponds to a velocity decrease of 1000 ma^{-1} (Joughin et al., 2008). We find that mélange is capable of suppressing longitudinal strain rate while leaving velocity largely unaffected. We find that up to 0.6 km of this advance may be caused by buttressing of calving rate for fairly conservative mélange thickness value. Ultimately the observed advance is due to a combination of suppressed calving rate and calved bergs unable to rotate away from the front (Amundson et al., 2010). In a cooler climate, increased mélange hardness enhances buttressing of calving and allows additional advance. We posit that mélange may be an important mechanism in allowing glaciers to rapidly advance into embayments during periods of glacial growth. In a warming climate the loss or weakening of mélange will end these modes of seasonal ice-front advance, not just at JI, but also at Helheim glacier and Kangerlussuaq glacier where a seasonal advance has also been observed (Luckman et al., 2006). Loss or weakening of mélange may consequently result in increased volume loss for these outlets.

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**Table 1.** Parameter values.

Parameter	JI value
W half width	3 km
L shelf and mélange length	15 km
h	1100 m
ρ_i	917 kg m^{-3}
ρ_m	917 kg m^{-3}
ρ_{sw}	1028 kg m^{-3}
B_i	$1.36 \times 10^8 \text{ Pa s}^{1/3}$
B_m	$1.0245 \times 10^8 \text{ Pa s}^{1/3}$
n	3
g	9.81 m s^{-2}
B_s	1.8×10^6
Inlet velocity	5025 m a^{-1}
c_a	$0.011 \text{ m}^{-0.96} \text{ a}^{0.02}$

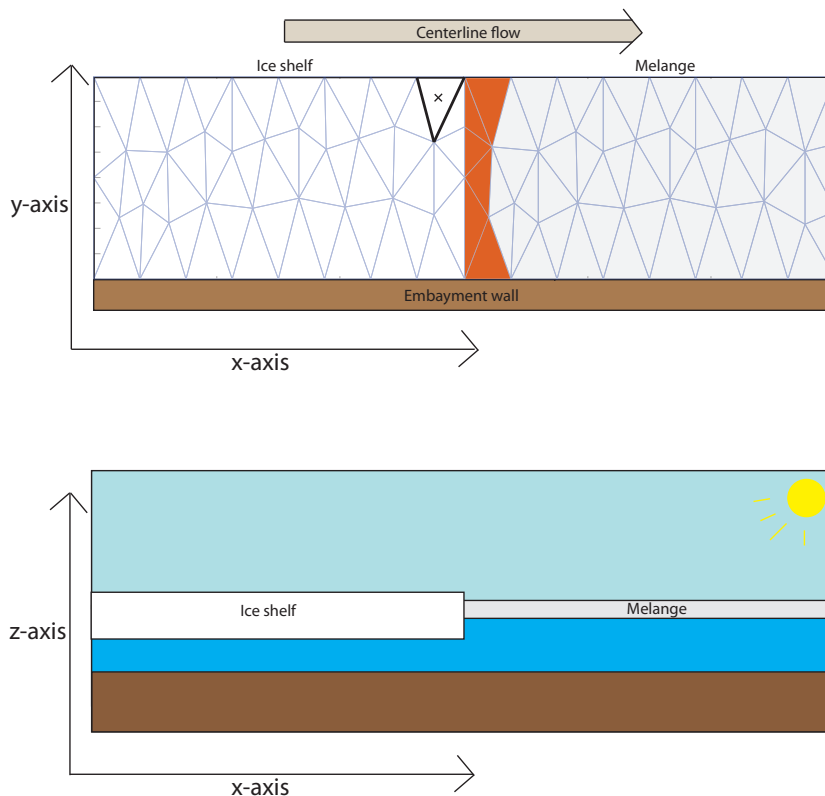


Fig. 1. The top image represents the plan-view schematic of modeled ice-shelf/mélange system with illustrative mesh (actual mesh greatly refined). The vertical line of nodes in the middle of the domain define the ice-shelf/mélange boundary, which we refer to as the ice front. The orange elements represent the transition zone. The “x” indicates where longitudinal strain rate and ice-front velocity are evaluated. The bottom diagram provides perspective for the scenario being modeled.

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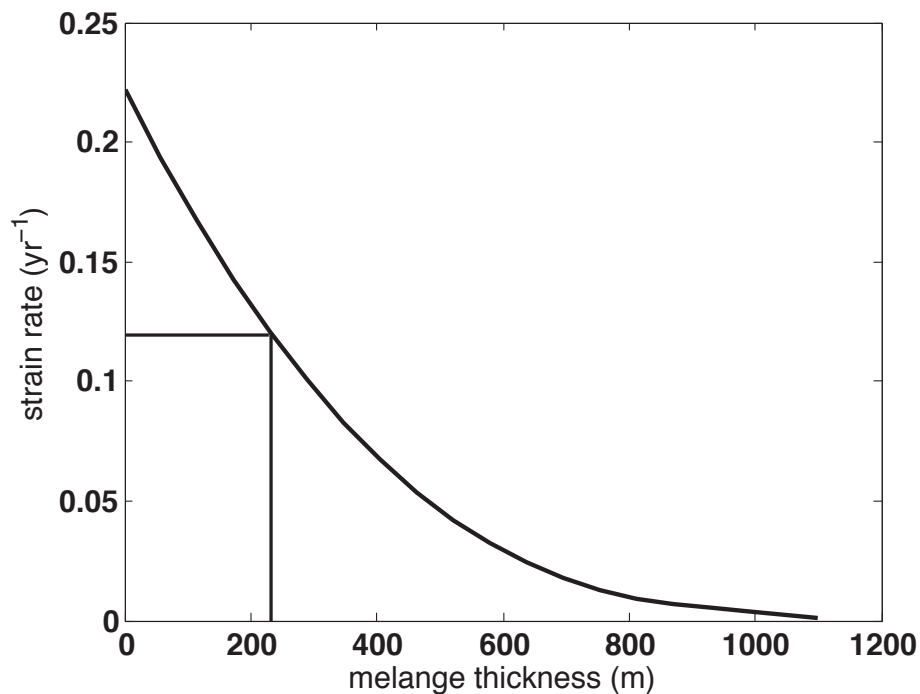


Fig. 2. JI-like scenario longitudinal strain rate for various mélange thicknesses. The 20 % mélange value, noted in the discussion section, is specifically indicated.

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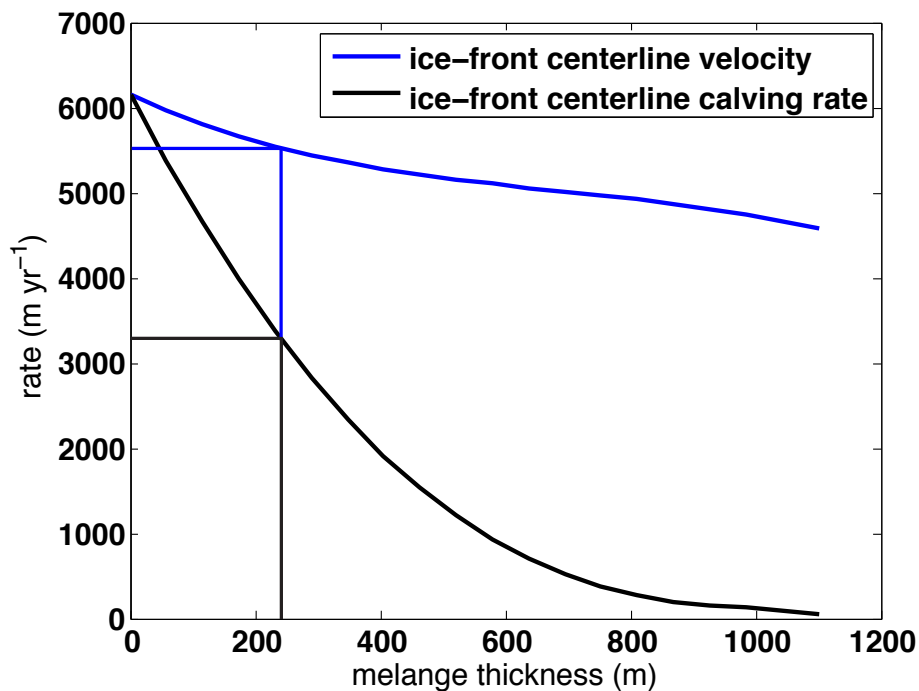


Fig. 3. JI-like scenario velocity and calving rate for a range of mélange thickness. The 20 % mélange values, noted in the discussion section, are specifically indicated.

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