Initial effects of oceanic warming on a coupled ocean-ice shelf-ice stream system

Ryan Walker[1], Todd Dupont[2], David Holland[3], Byron Parizek[4], and Richard Alley[1]
[1]Pennsylvania State University [2]University of California Irvine [3]New York University [4]Penn State DuBois

Introduction

Ice-stream characteristics influence grounding-line response to oceanic warming. Unfortunately, some ice-stream characteristics are difficult to determine. For example, inversions for ice-stream basal drag from surface velocities (Joughin et al., 2004) and laboratory studies of till (Rathbun et al., 2008) both indicate that a wide range of behavior is possible.

Given initially-identical ice shelves subjected to the same oceanic warming, we assess the sensitivity of tributary ice-stream response to the assumed rheology of the bed. Because the pattern of basal melting and freezing beneath an ice shelf may shift as the shelf evolves (Walker and Holland, 2007), and this distribution can strongly affect ice-stream response (Walker et al., 2008), it is desirable to investigate this question with a fully-coupled model of the ocean-ice shelf-ice stream system. Explicit modeling of the ocean allows us to apply the climatic forcing in a natural way, while laying the groundwork for further investigation of future sea-level rise.

Methods

This study uses a combined model that couples the ocean-ice shelf model of Walker and Holland (2007) with the ice shelf-ice stream model of Dupont and Alley (2005), as modified by Walker et al. (2008). The ocean component uses a 2-D vertical overturning streamfunction, while the ice component is a "shelfy-stream" model.

Basal drag for the ice stream is given by

$$\tau_b = \beta^2(x)|u|^{\frac{1}{n}}$$

where $n = \{1, 2, 5, 10\}$ (linear viscous to effectively plastic, Rathbun et al., 2008). By varying the coefficient, we produce ice streams-shelves with identical thickness and velocity profiles, but different bed rheologies.

For each bed rheology, we run the coupled model to equilibrium with the ocean forced by inflowing high-salinity shelf water (HSSW). To investigate sensitivity of the ice stream-ice shelf to ocean temperature, we then apply warming of 0.25, 0.5, and 0.75°C.

Equations

Ocean momentum

$$\left(z_\sigma^{-1}\psi_{\sigma\sigma}\right)_t + \left(z_\sigma^{-1}u\psi_{\sigma\sigma}\right)_x + \left(z_\sigma^{-1}\omega\psi_{\sigma\sigma}\right)_\sigma = \epsilon\frac{g}{\rho_0}\left(z_\sigma\rho_x - z_x\rho_\sigma\right) + \left[z_\sigma\nu_H\left(z_\sigma^{-2}\psi_{\sigma\sigma}\right)_x\right]_x + \left[z_\sigma^{-1}\nu_V\left(z_\sigma^{-2}\psi_{\sigma\sigma}\right)_\sigma\right]_\sigma$$

Ocean tracers

$$(z_\sigma\{S|\theta\})_t + (z_\sigma u\{S|\theta\})_x + (z_\sigma\omega\{S|\theta\})_\sigma = [z_\sigma\kappa_H\{S|\theta\}_x]_x + \left[z_\sigma^{-1}\kappa_V\{S|\theta\}_\sigma\right]_\sigma$$

Ice momentum

$$\partial_x\left(4h\nu\partial_x u - \frac{\rho_i g}{2}h^2\right) = \rho_i g h\partial_x z_b + \frac{h}{L_y}\tau_y(u) + \tau_b(u)$$

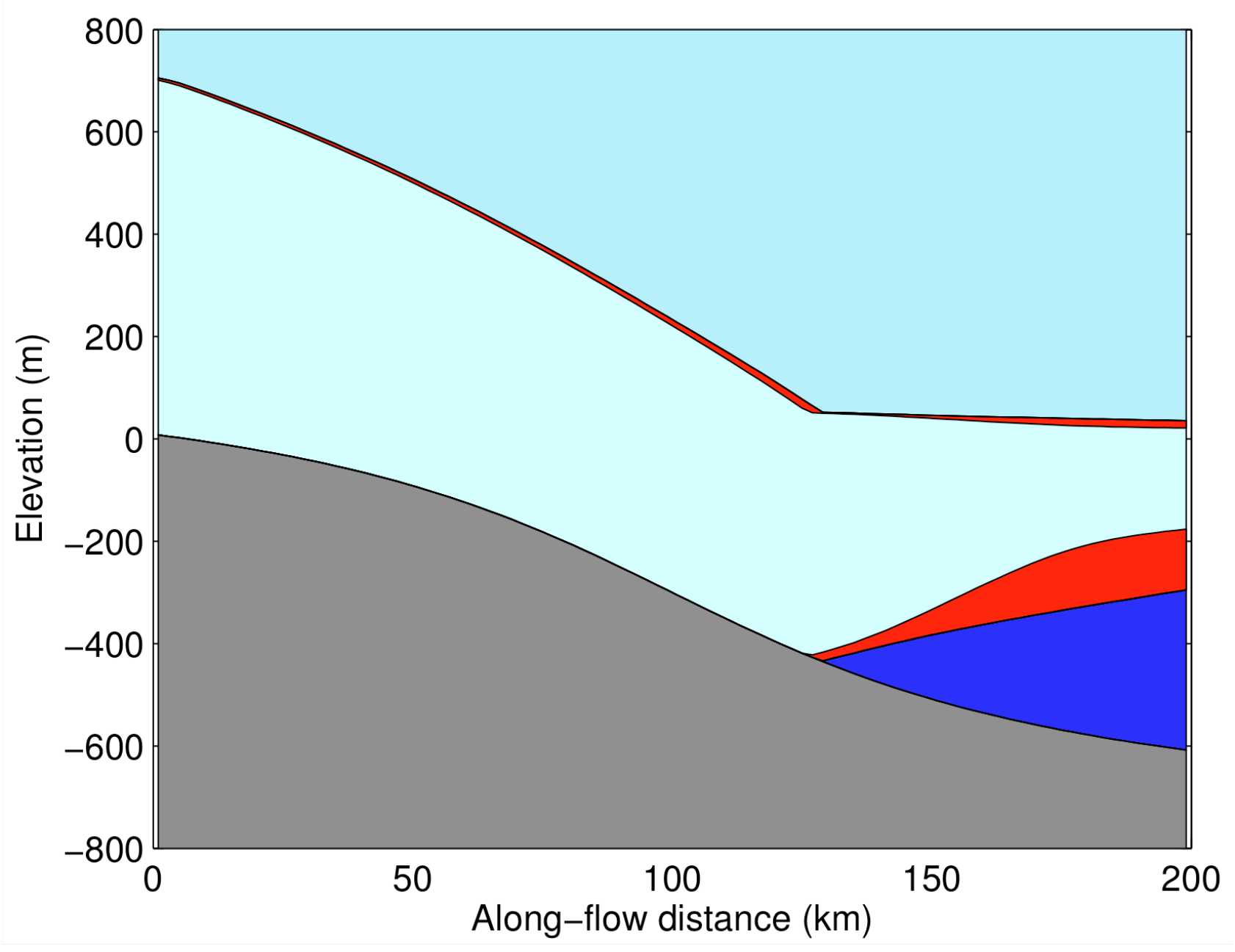
Ice mass balance

$$\partial_t h = -\partial_x(uh) - m$$

Results

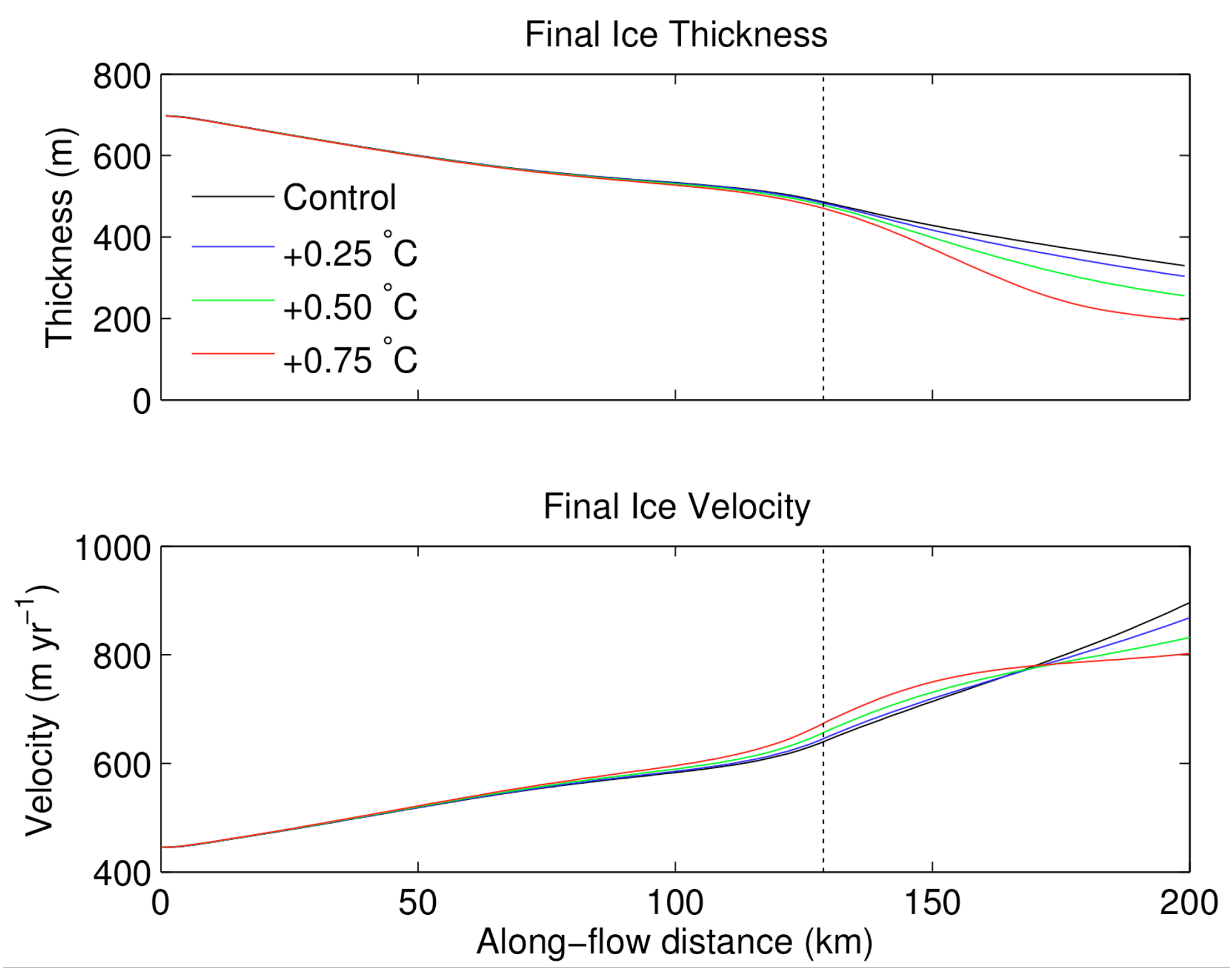
For our linear-bed experiments, we observe significant change to the ice shelf with oceanic warming (4%, 10%, 20% mass loss for 0.25, 0.50, 0.75°C), but due to the seaward-sloping bed and concentration of thinning near the ice front, grounding-line retreat is modest (0.3, 1.1, 2.0 km, resp.).

Model domain, with red areas showing ice loss in maximum-warming experiment.



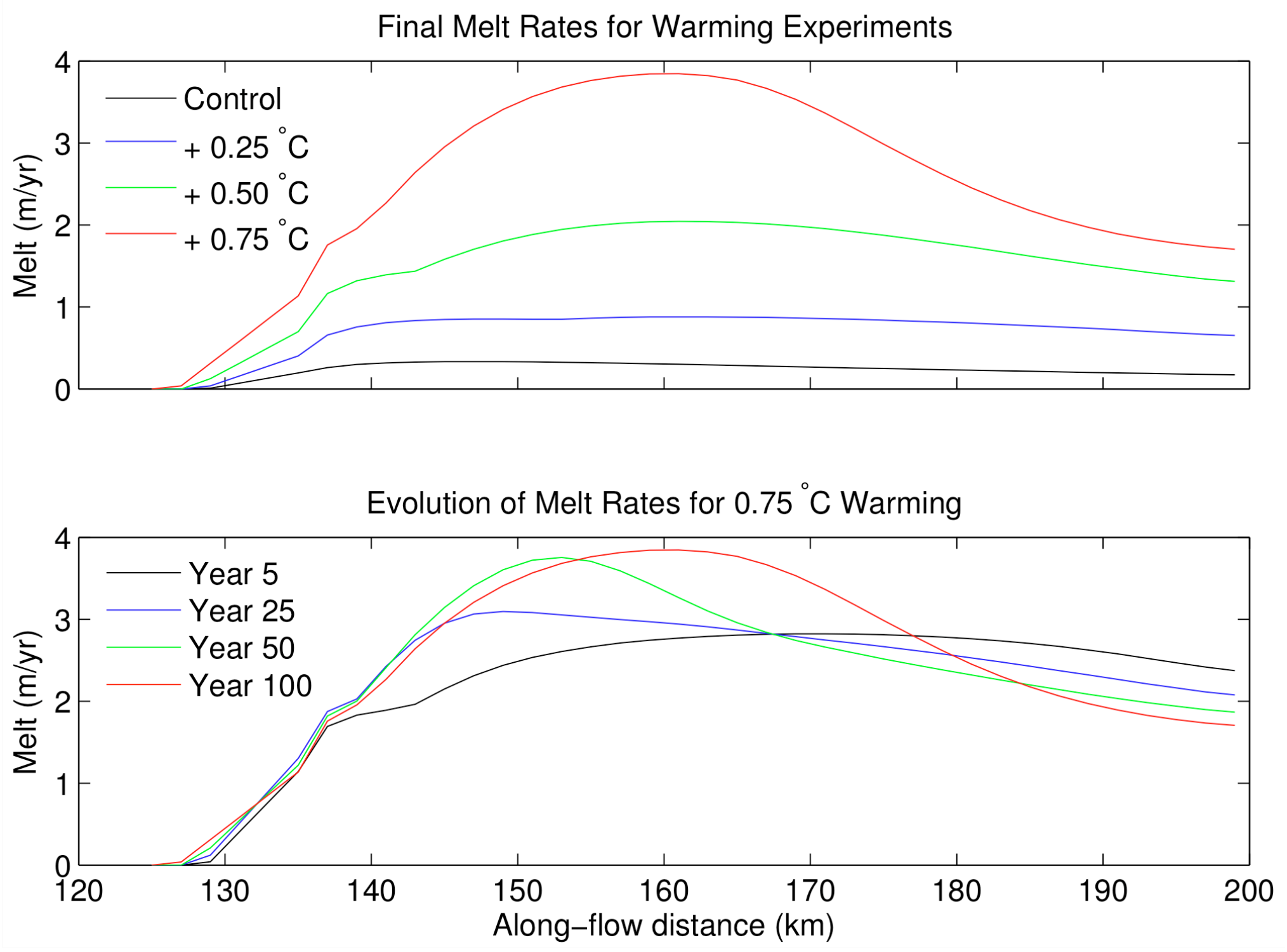
Steepening of the ice shelf near the grounding line combined with thinning near the ice front results in acceleration of the ice stream and inland portion of the shelf and slowing of the seaward portion of the shelf. While the ice stream also thins in response to warming, the acceleration is sufficient to slightly increase the flux across the grounding line and decrease the volume of ice above flotation (1.8% and -1.0%, resp., for 0.75°C).

Effects of oceanic warming on thickness and velocity profiles for linear-bed experiments. Vertical dashed line shows original grounding-line position.



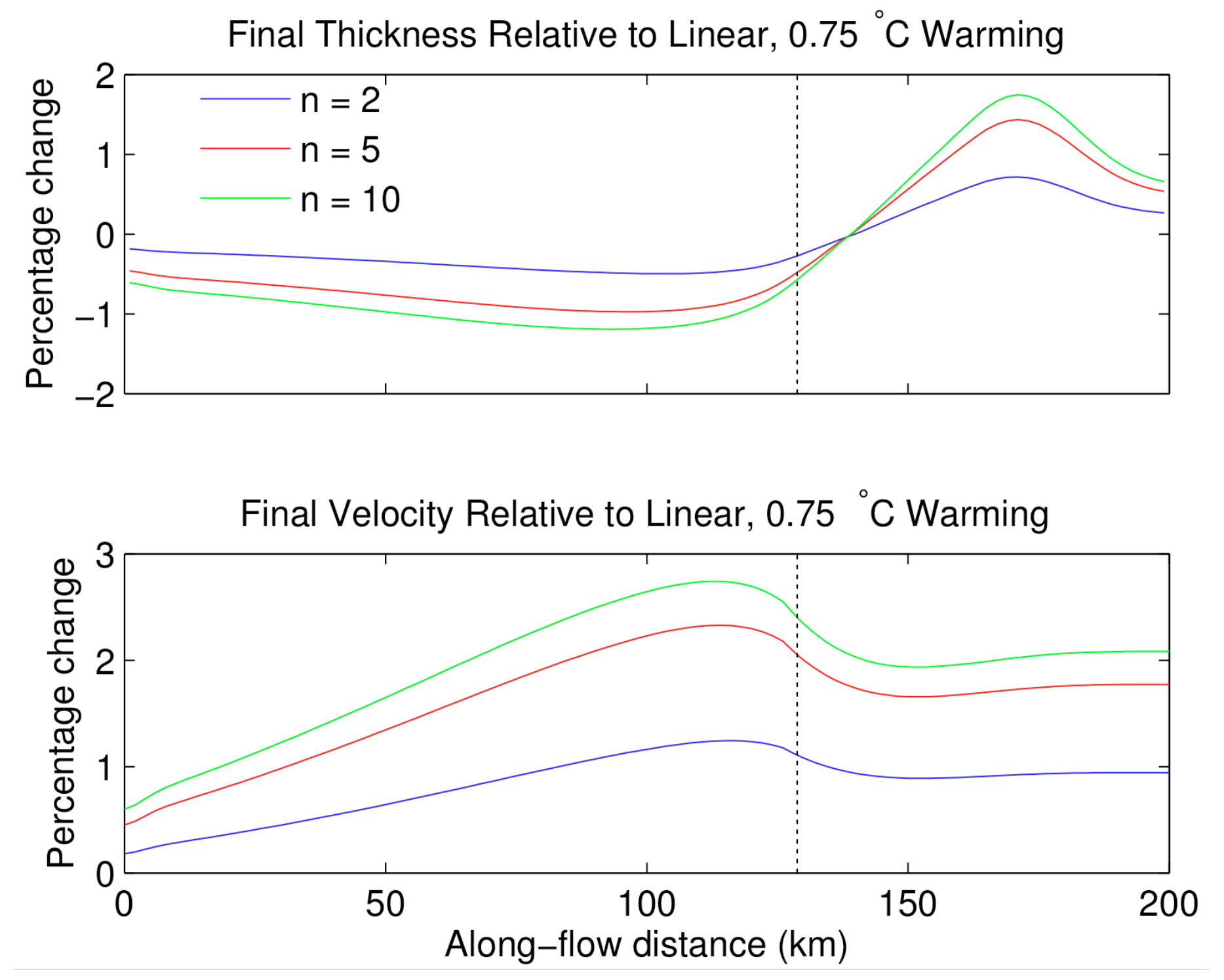
Basal melting increases roughly tenfold with the applied warming. Because the buoyant meltwater plume ascends the shelf base more rapidly in steeper regions, there is a positive feedback between basal slope and basal melting (Walker and Holland, 2007), leading to significant shifts in the distribution of melting as the ice shelf evolves. In particular, the eventual shift of melting away from the grounding line in the warming experiments likely mitigates the resulting grounding-line retreat, as seen in Walker et al. (2008).

Basal melting for linear-bed experiments; melt rates do not vary significantly for nonlinear beds.



The nonlinear-bed experiments show that ice-stream response to ice-shelf melting strengthens with increasing basal exponent *n*. For a given warming, higher *n* gives greater thinning and acceleration of the ice stream, with the net effect of increasing the grounding-line flux and decreasing volume above flotation (3.6% and -2.2%, resp., for *n* = 10 and 0.75°C warming, thus doubling the linear-bed response).

Effects of bed rheology on the response of the ice stream-ice shelf system to oceanic warming of 0.75°C. Changes are shown relative to the final state of the linear-bed experiment with the same warming.



Conclusions

In these experiments, the applied oceanic warming exerts the greatest influence over the evolution of the ice shelf-ice stream, with the seaward-sloping bed limiting the resulting grounding-line retreat even when a significant portion of the ice shelf is melted. However, for the same oceanic warming, there is a noticeable increase in thinning and acceleration of the ice stream, leading to greater flux across the grounding line, as the basal rheology is changed from linear-viscous towards plastic. While results from simplified process models should not be taken as definitive predictions, as factors including three-dimensional ocean circulation and shear-margin weakening are not considered, our experiments agree with the recent observational study of Joughin et al. (2009) in suggesting that the basal flow law of an ice stream can affect both its contribution to sea-level rise and the overall stability of its source ice sheet. In turn, this suggests a need for additional understanding of the flow law of the ice-stream bed. This can be addressed in the field, laboratory, and through remote sensing.

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References

Dupont, T. K., and R. B. Alley, 2005. Assessment of the importance of ice-shelf buttressing to ice-sheet flow. Geophys. Res. Lett., 32, L04503, doi:10.1029/2004GL022024.

Joughin, I., D. R. MacAyeal, and S. Tulaczyk, 2004. Basal shear stress of the Ross ice streams from control method inversions. J. Geophys. Res., 109(B9), B09405.

Joughin, I., S. Tulaczyk, J. L. Bamber, D. Blankenship, J. W. Holt, T. Scambos, and D. G. Vaughan, 2009. Basal conditions for Pine Island and Thwaites Glaciers, West Antarctica, determined using satellite and airborne data. J. Glaciol., 55(190), 245-257.

Rathbun, A. P., C. Marone, R. B. Alley, and S. Anandakrishnan, 2008. Laboratory study of the frictional rheology of sheared till. J. Geophys. Res., 113, F02020, doi:10.1029/2007JF000815.

Walker, R. T., T. K. Dupont, B. R. Parizek, and R. B. Alley, 2008. Effects of basal-melting distribution on the retreat of ice- shelf grounding lines. Geophys. Res. Lett., 35, L17503, doi10.1029/2008GL034947.

Walker, R. T., and D. M. Holland, 2007. A two-dimensional coupled model for ice shelf-ocean interaction. Ocean Modelling, 17, 123-139.

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