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WAIS 2008
(Topic: How my model may help your model)

How ice shelf morphology controls the longitudinal distribution of basal melting

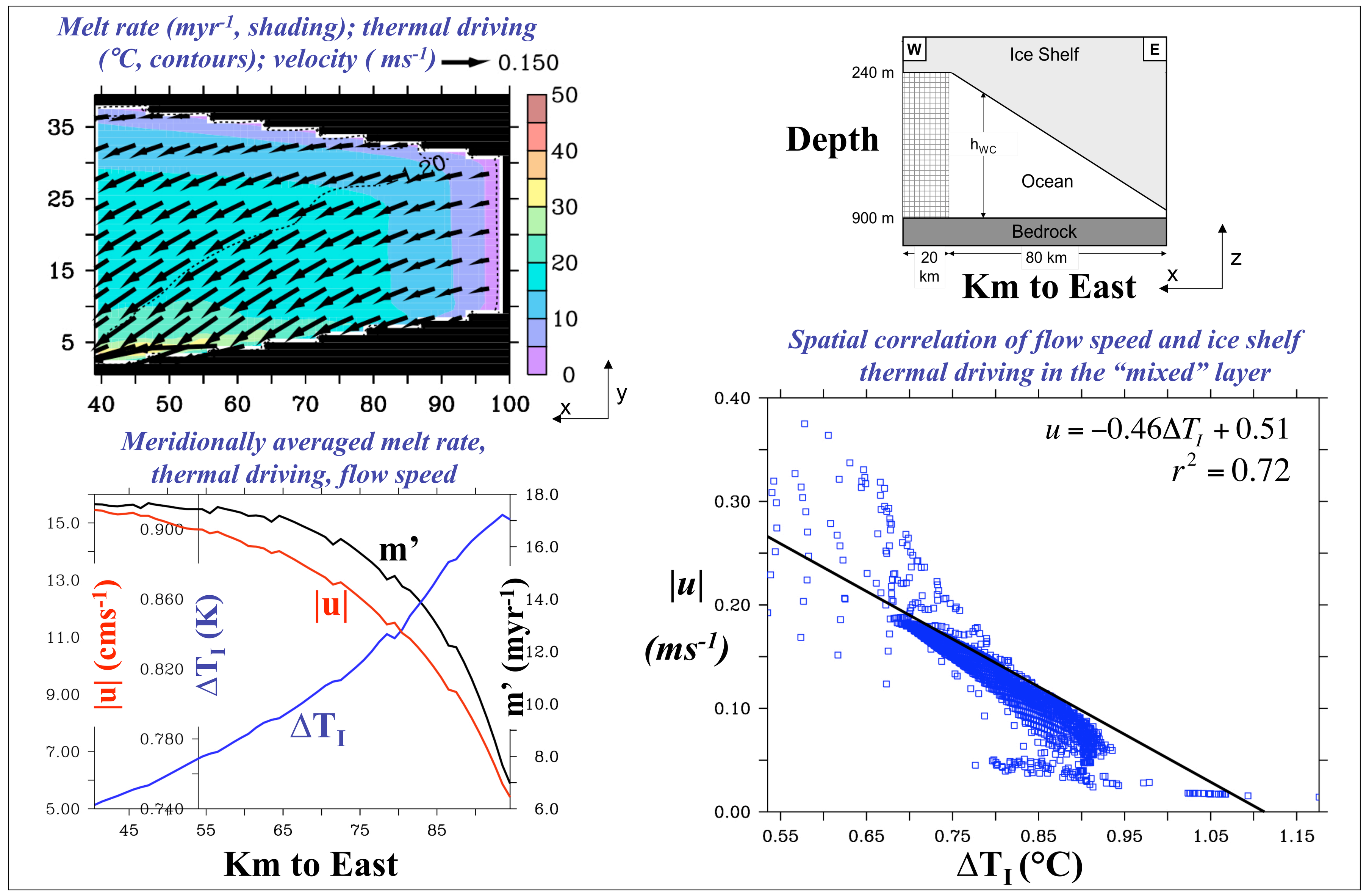
Introduction

Satellite observations indicate that basal melting rates are strongly enhanced near grounding lines (e.g. Joughin and Padman 2003; Rignot and Steffen 2008). Ice-ocean modeling studies retain this pattern even with highly idealized topography and forcing (Holland, Jenkins et al. 2008), suggesting that large-scale ice shelf morphology may underlie longitudinal gradients in melting rate. Walker et al. (2008) have recently demonstrated the dynamic implications of heightened basal melting near the grounding line. Adding a morphology-dependent distribution of basal melting will improve the ability of glaciological models to assess the "basal slope feedback", and the more general role of basal melting in ice shelf stability.

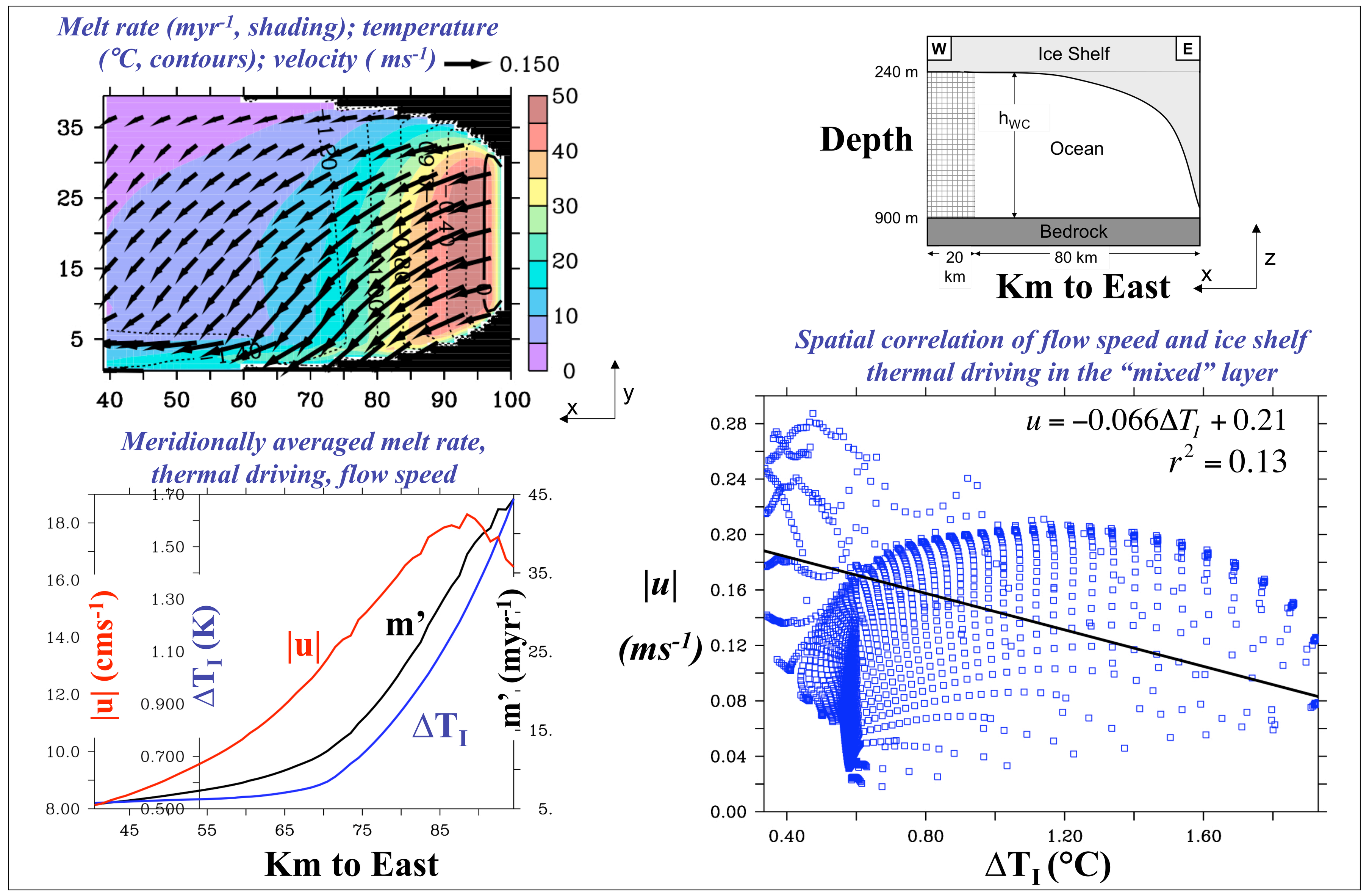
Here, we demonstrate how local slope drives oceanic temperature and velocity under "small", "warm" ice shelves. Melting rates are driven by the product of thermal forcing and flow speed; steep basal slopes increase the spatial correlation of these properties near the ice interface. When constrained by the grounding line ocean temperature, a very simple model provides basal melting distributions similar to those generated by idealized numerical simulations. A deeper understanding of mixed layer turbulence under ice shelves, with contribution from both models and observations, is required to validate the simplifications employed in both of these models.

Numerical results

☆ A uniform slope drives an inverse correlation of velocity and temperature

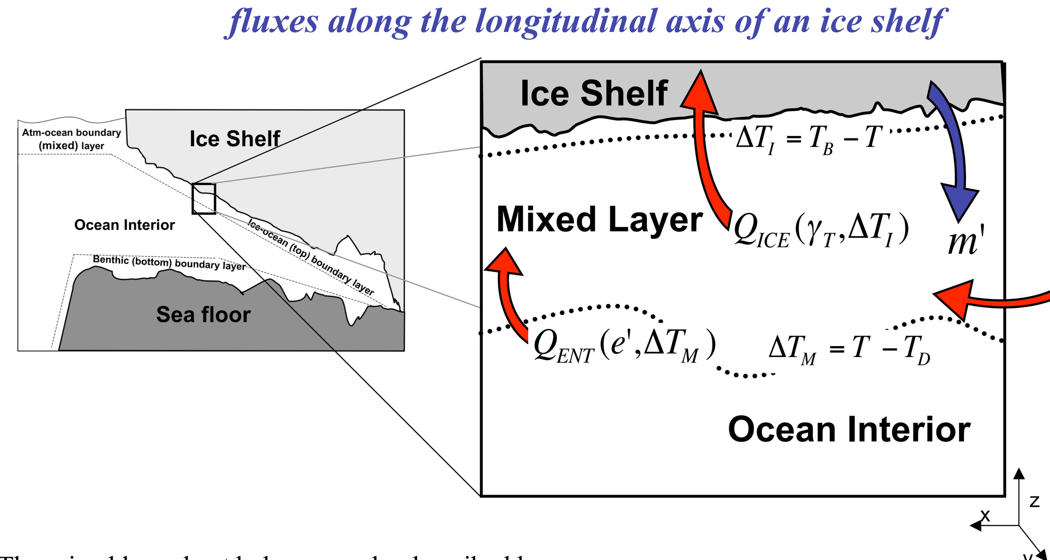


☆ A steep "trunk" drives higher temperature near grounding lines



Can a 1-D local heat balance predict the melting distribution?

Schematic representation of reduced-gravity "mixed" layer heat and mass fluxes along the longitudinal axis of an ice shelf



The mixed layer heat balance can be described by:

$$\mathbf{u} \bullet \nabla(hT) = -e'\Delta T_M + \gamma_T \Delta T_I \quad (1)$$

$\Delta T_M = T - T_D$: the temperature difference across the base of the mixed layer
$\Delta T_I = T_B - T$: the temperature difference across a viscous sub-layer
e': entrainment velocity
γ_T: ice-ocean transfer velocity
u: horizontal velocity
h: mixed layer thickness
T_D: interior temperature
$T_B(P,S)$: local freezing point

In a **local** balance:

$$e'\Delta T_M = \gamma_T \Delta T_I \quad (2)$$

We can approximate $e' = c_E|u|\theta$, $\gamma_T = g_T|u|$ (Jenkins 1991, Holland and Jenkins 1999, Holland et al. 2008).

When ice dissolves into seawater, temperature and salinity gradients are related by (3):

$$\left.\frac{dT}{dS}\right|_{FW} = \frac{L_f}{Sc_{p,w}} + \frac{(T_B - T_{Ice})c_{p,i}}{Sc_{p,w}} + \frac{(T_{ML} - T_B)}{S} \quad (3)$$

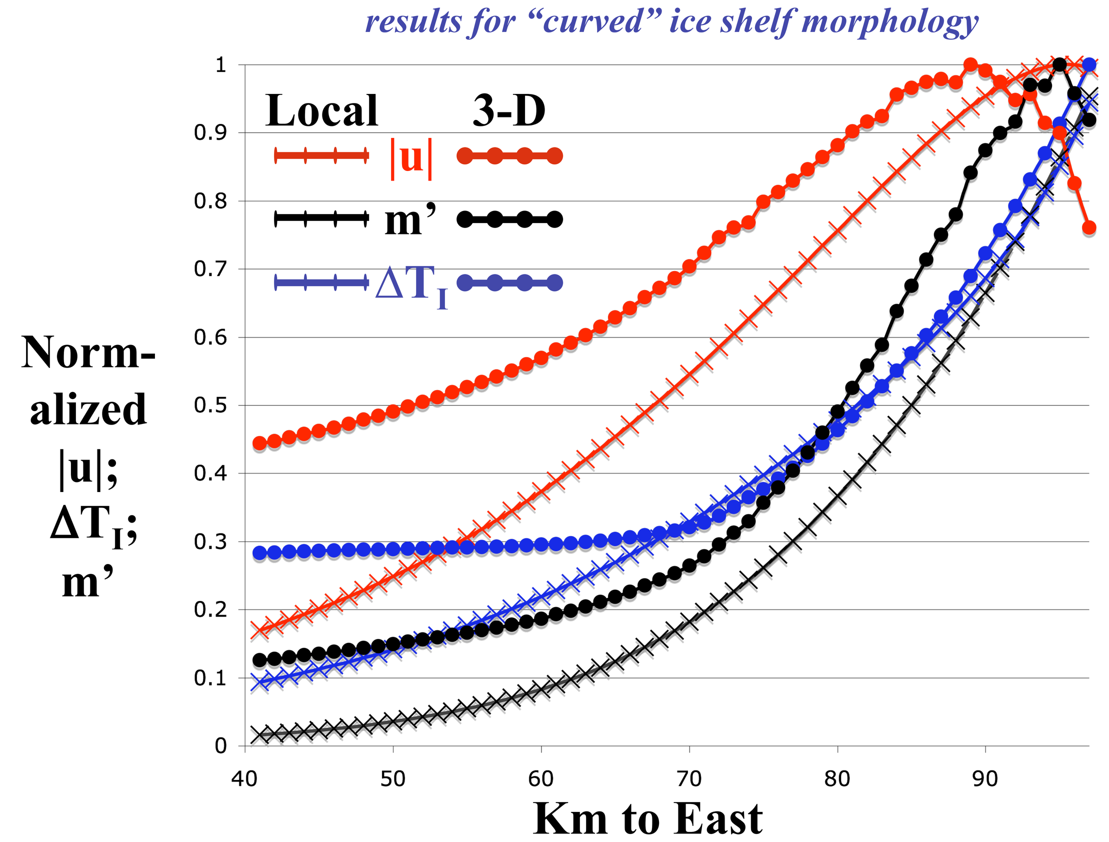
where S is salinity and $c_{p,I}$ is the specific heat of ice. Considering only the first term of (3) (the latent heat flux, ~2.4°C/psu) and a geostrophic momentum balance:

$$u = \frac{g\beta\sin\theta}{f}\left.\frac{dS}{dT}\right|_{FW}\Delta T_M \quad (4)$$

The melt rate is then given by:

$$m' = -\frac{\rho_O}{\rho_I}\frac{c_{p,O}g_T}{L_f}\left(\frac{g\beta\theta}{f}\left.\frac{dS}{dT}\right|_{FW}\right)\Delta T_M \Delta T_I = c_M \theta \Delta T_M \Delta T_I \quad (5)$$

Comparison of local (eq. 2,4,5) and 3-D numerical results for "curved" ice shelf morphology



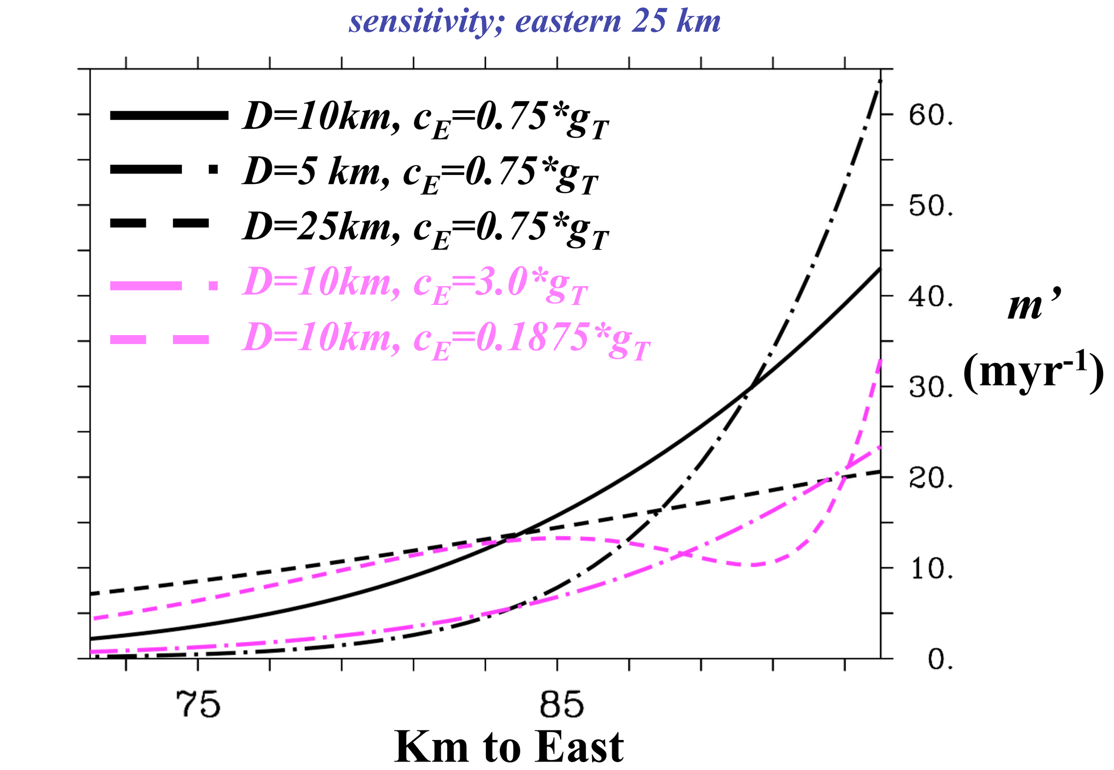
☆ What works?
- ☆Temperature in "thin" regions

☆ What doesn't work?
- ☆Convergence (3-D flow)
- ☆Advection (large h)
- ☆Frictional effects (boundary currents)
- ☆$\Delta T_B \sim \Delta T_I$ (small change in slope)

What does the 1-D model imply for slope-dependent melting?

☆ **The longitudinal melting distribution is sensitive to slope (no oceanic shut-off to the basal slope feedback) and the magnitude of heat flux coefficients**

Local model melt rate slope and entrainment velocity sensitivity; eastern 25 km

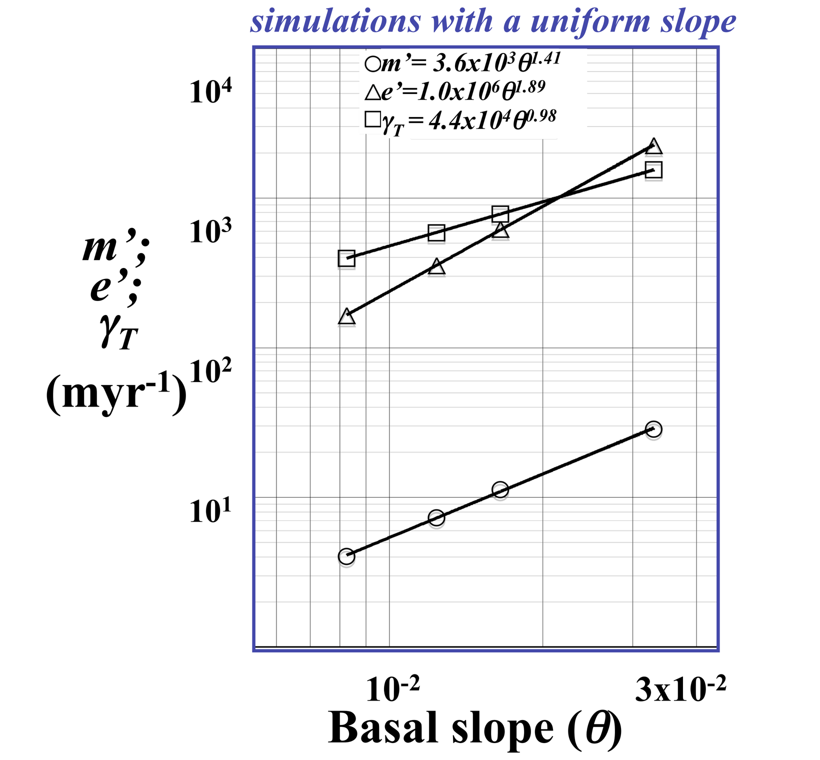


$$\theta(x) = \frac{dB}{dx} = \frac{(z_{GL} - z_{FRONT})}{L_x} e^{-\frac{x}{D}} \quad (6)$$

$$T(x)_{LOCAL} = \frac{c_E\theta T_D + g_T T_B}{c_E\theta + g_T} \quad (7) \qquad T_0^{LOCAL} = T_0^{3-D} = \frac{k\theta_0 T_D + T_B}{k(\theta_0 + 1)} \quad (8)$$

☆ **When $e' \sim O(g_T)$, temperature scales sub-linearly with slope, melting rate scales super-linearly**

Area-averaged m', e', and γ_T from numerical simulations with a uniform slope



Assuming constant T_D and T_B, using (2) and (5),

$$T \sim \frac{e'}{\gamma_T}\left(1 + \frac{e'}{\gamma_T}\right)^{-1}\Delta T_T \quad (9)$$

$$m' \sim \frac{\gamma_T e'}{\gamma_T + e'}\Delta T_T \quad (10)$$

$\Delta T_T = \Delta T_I + \Delta T_M$: local freezing point-interior temperature gradient

Therefore the magnitude of the coefficients determines the sensitivity to slope:

1. If $e' \ll \gamma_T$, $T \sim \theta$, $m' \sim \theta$.
2. If $e' \sim \gamma_T$, $T \sim \theta(1+\theta)^{-1}$, $m' \sim \theta^2(1+\theta)^{-1}$
3. If $e' \gg \gamma_T$, $T \sim C$, $m' \sim \theta^{1}$.

Summary

☆ **The distribution of basal melting is driven by the spatial correlation of flow speed and temperature**
☆ **In a local heat balance, mixed layer temperature and flow speed increase with basal slope**
☆ **A scaling of melt rate with slope depends on ratio of poorly constrained turbulent heat transfer functions**
☆ **Because basal slope varies strongly, even a weak scaling results in strong basal melting gradients**
☆ **A local model works best in strongly forced ice shelves with thin boundary layers**

More questions…

☆ Is a simplified basal melting model useful?
☆ How can we determine the boundary layer dynamics (and thus key input parameters) under ice shelves?
- ☆ Oceanographic measurements -- ice front and under ice
- ☆ Ocean modeling -- intercomparisons, shear parameterizations, sensitivity to tides
- ☆ Glaciologic observations -- localized maps of melting, basal topography

☆ Role of channels and/or crevassing? Stratification?
☆ When and how quickly does ice advection stabilize the basal slope feedback?

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Further Info

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Numerical details

Mixed Layer Parameterizations	
Viscous drag	• Quadratic drag law
Mixed layer TKE	• Inclusion of 20% shear-driven turbulence in TBL;
Ice shelf thermodynamics	• Flow-dependent turbulent thermal exchange velocity (3-eq formulation)
Ice shelf conductivity	• Vertical advective/diffusive heat balance at ice shelf base
Equation of state	• Stand-alone linearized equation to calculate pressure-dependent freezing point (in-situ)
Other configuration details	
Horizontal Resolution	• 1 km
Vertical Resolution	• Interior isopycnal layer + bulk mixed layer (includes buffer layer)
Initialization and Restoring	• "Source" water mass, T_D = -2.0 to 2.0°C, S_D = 34.9 • 10 m thick mixed layer

After Hallberg 2003, Holland; Jenkins 1999, Holland; Jenkins 2001