Lessons from fully coupled ocean-ice shelf process models

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A quick introduction

- Overview of the process model
- A technical challenge: Handling meltwater advection with a moving ice-ocean interface
- A key process: Basal-slope feedback
- A case study: Idealized Filchner Ice Shelf

Overview of the model

- The ocean component is a vertical overturning streamfunction model based on earlier work by Hellmer and Olbers (1989) on thermohaline circulation beneath an ice shelf
- Starting from hydrostatic Boussinesq equations, assume flow primarily transverse to ice front, take curl of remaining momentum equations, and introduce streamfunction ψ
- Convert to a time-dependent terrain-following vertical coordinate σ to more easily accommodate an evolving ice shelf

Ocean equations

Momentum

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

Tracer advection-diffusion

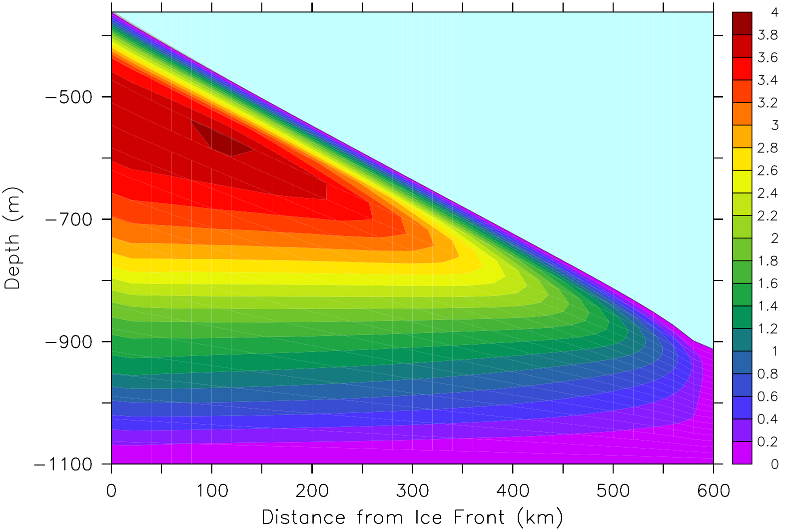
$$\left(z_\sigma S\right)_t + \left(z_\sigma uS\right)_x + \left(z_\sigma\omega S\right)_\sigma = \left[z_\sigma\kappa_H S_x\right]_x + \left[z_\sigma^{-1}\kappa_V S_\sigma\right]_\sigma$$

$\omega \equiv \frac{D}{Dt}\sigma$ is the effective vertical velocity in the new coordinates

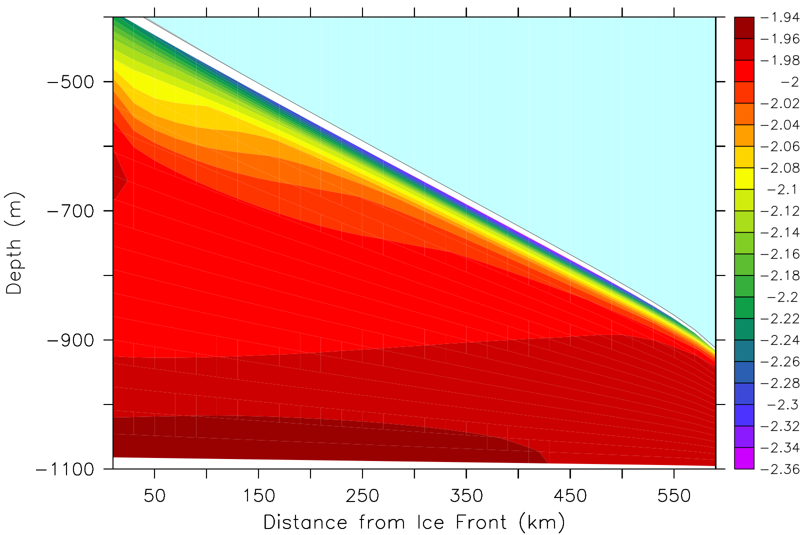
Boundary conditions

- Model is forced by vertical profile of temperature and salinity at ice front
- Zero-gradient condition on streamfunction at ice front boundary
- No normal flow at ice-shelf base, ocean floor, grounding-line boundary
- No-slip at ice-shelf base and ocean floor

Example of model output: Streamfunction



Example of model output: Potential temperature



Coupling with the ice shelf

- Ice shelf is either the Paterson (1994) shelf-only model, or the Dupont and Alley (2005) shelf-stream model
- Both are 1-D, so update shelf mass balance at the ocean time step (and velocity less frequently)
- Thermodynamics at the ice-shelf base are given by the Holland and Jenkins (1999) 3-equation method

$$T_B = aS_B + b + cp_B$$

$$\{c_I m(T_I - T_B)\} + c_W \gamma_T (T_M - T_B) = mL$$

$$\gamma_S (S_M - S_B) = mS_B$$

Handling of meltwater advection into the domain presents challenges...

- In models with a stationary ice-shelf base*, an advective boundary condition would be inconsistent with the modeled velocity field
- Instead, add a diffusive term to RHS of tracer equation:

$$\frac{\partial}{\partial z}\left(\frac{\rho_{ice}}{\rho_0} m\left(S_B - S_M\right)\right) = \frac{\partial}{\partial z}\left(\tilde{m}\left(S_B - S_M\right)\right)$$

- Consider forward time-differencing of this term:

$$S_M^{n+1} = S_M^n + \frac{\delta t}{\delta z}\left(\tilde{m}\left(S_B - S_M^n\right)\right) = \alpha S_B + (1-\alpha) S_M^n$$

where $\alpha = \frac{\tilde{m}\delta t}{\delta z}$ is the meltwater fraction of cell at t^{n+1}

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*Jenkins et al., 2001

...especially with a moving interface

- Our model has a moving interface, so meltwater advection can be handled directly
- This interface is somewhere between a "free surface" and a "rigid lid" (a "deforming rigid lid"?)
- The interface moves (ice thickness changes) for two reasons:
  - Basal melting (affects ocean thermodynamics)
  - Ice dynamics (*does not* affect ocean thermodynamics)
- These contributions must be separated to avoid artificial forcing of the ocean by ice-shelf dynamics

An advective BC for meltwater advection

- Our boundary condition at the ice-shelf base is

$$S\big|_{\sigma=0} = \beta S_B + (1-\beta) S_M$$

where $\beta = \frac{\omega_{melt}}{\omega} = \frac{-z_\sigma^{-1}\tilde{m}}{\omega}$; i.e., we partition the interface velocity

- Substituting into the advection equation and applying forward time-differencing gives

$$S_M^{n+1} = \frac{z_\sigma^n}{z_\sigma^{n+1}} \left[S_M^n - \frac{\delta t \omega}{\delta \sigma} \left(\beta S_B + (1-\beta) S_M^n \right) \right] = \epsilon S_B + (1-\epsilon) S_M^n$$

where $\epsilon = \frac{\delta t \tilde{m}}{\delta \sigma z_\sigma^{n+1}} = \frac{\delta t \tilde{m}}{\delta z^{n+1}}$ is the meltwater fraction at t^{n+1}

- Using mixed-layer values here prevents artificial thermodynamics, and means model conserves salinity and potential temperature rather than salt and heat content

Factors determining magnitude of basal melting

- In the 3-equation formulation of ice-shelf-base thermodynamics, $m \propto \gamma(u)(T_B - T_M)$
- Thus, melting is determined directly by thermal driving and indirectly by ocean velocity beneath the shelf (via turbulent mixing coefficient)
- Driving in the momentum equation of our model is provided by the density gradient

$$\frac{g}{\rho_0}\mathcal{J}(\rho, z) = \frac{g}{\rho_0}\frac{\partial \rho}{\partial x}\frac{\partial z}{\partial \sigma} - \frac{g}{\rho_0}\frac{\partial \rho}{\partial \sigma}\frac{\partial z}{\partial x}$$

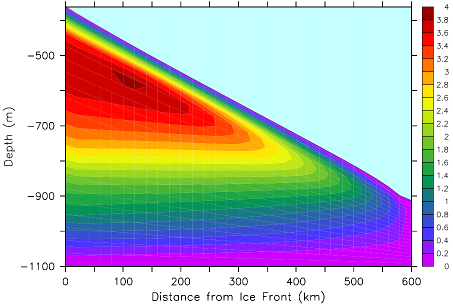
- Note that the last term is a buoyancy times a slope, so velocity tends to increase in steep regions, as would be expected
- It follows that, for equal thermal driving, *basal melting is greatest in areas of steep basal slope*

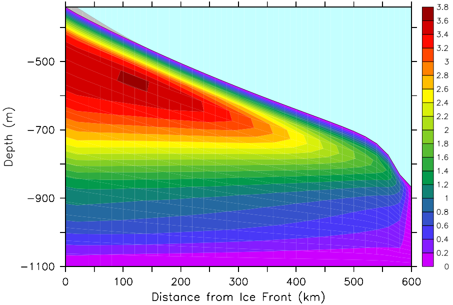
The basal-slope feedback for ice-shelf melting

- When the ice shelf is allowed to evolve, higher melting in areas of steep basal slope tends to further increase the slope
- Because the circulation is buoyancy driven, the ocean accelerates beneath areas of steep basal slope
- This in turn causes increased melting, so there is a positive feedback between slope and melting
- The basal-slope feedback may eventually be halted by ice dynamics, if horizontal ice flux adjusts to balance the melting

Case study: Idealized Filchner

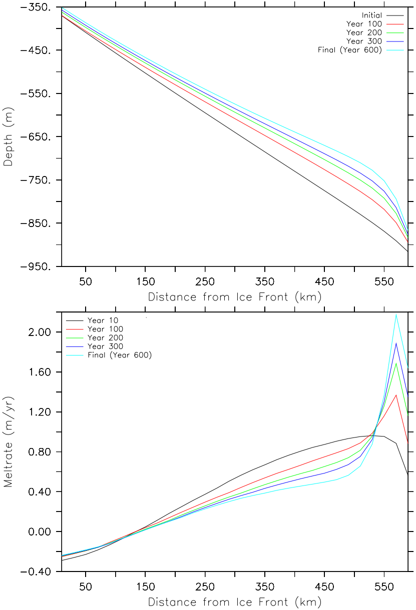
- Ice shelf (Paterson model) initially in steady state without ocean
- Ocean forced by CTD data
- Coupled model run to equilibrium (600+ years)
- Relatively little change to overall circulation, though shelf changes significantly



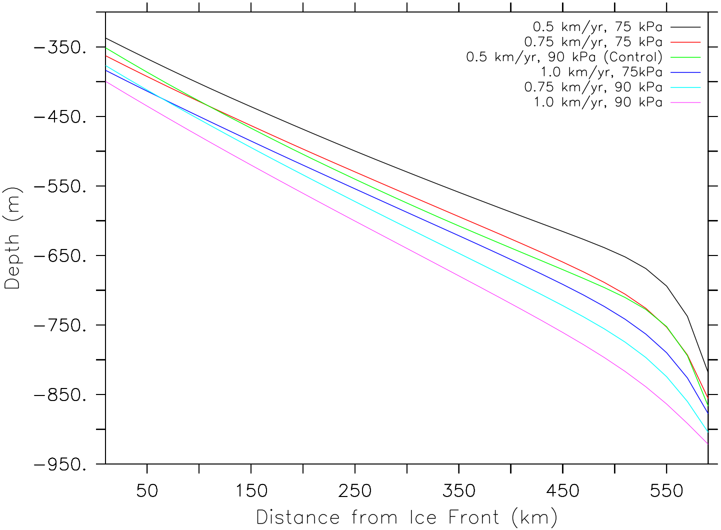


Case study: Basal-slope feedback

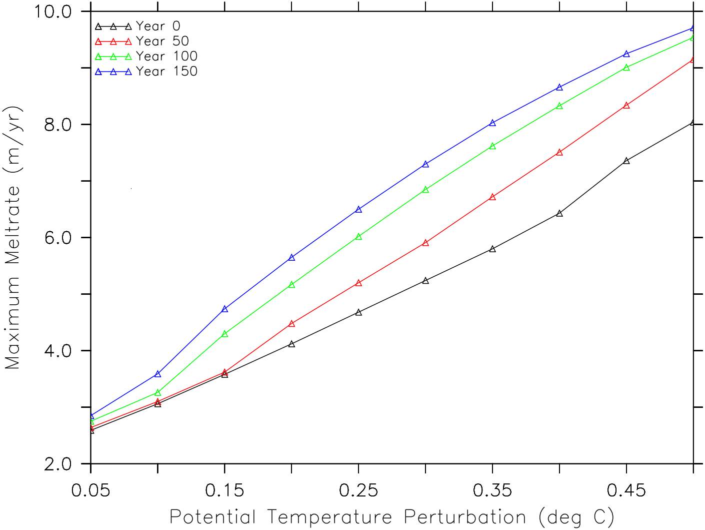
- Deep grounding line and HSSW increase thermal driving at depth
- Basal-slope feedback amplifies effects of thermal driving
- Shelf steepens near grounding line, flattens elsewhere
- Net mass loss of slightly over 10% from original steady state



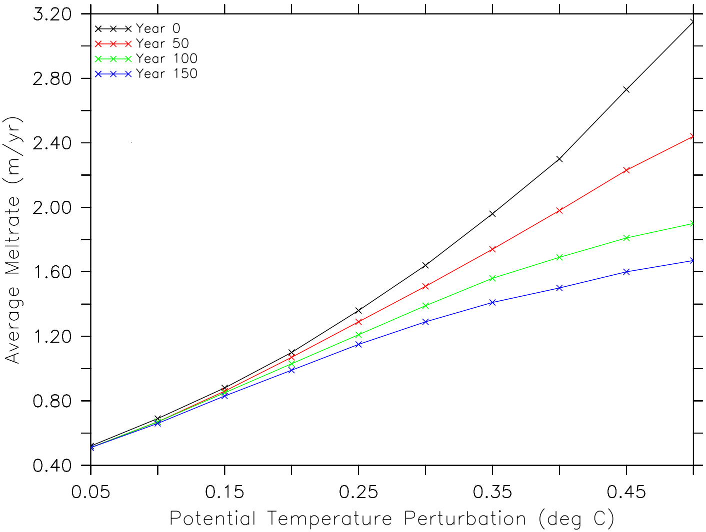
Strength of the feedback depends on lateral drag and ice flux into shelf



Maximum melt rates increase with ocean temperature and time as shelf steepens near grounding line



Mean melt rates increase with temperature but drop over time due to shelf flattening over most of its length



In conclusion, coupling is tricky, but well worth the effort

- Coupling of ice and ocean models presents many technical challenges
- Many open questions remain, including initialization, handling of grounding-line migration by ocean model, and effect of ice-stream acceleration on basal-slope feedback
- Basal-slope feedback is an example of an important process that can only be considered in a coupled model
- We need coupled ice-ocean models to predict sea-level rise