Damaged Goods: Impact of Damage-rheology Coupling on Ice Sheet Evolution

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Joint work with:

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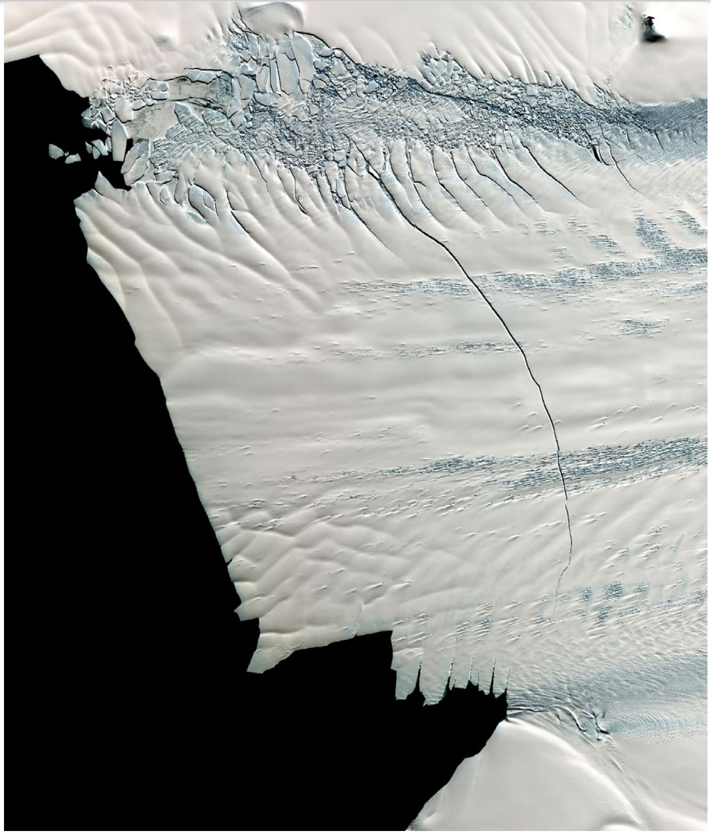
Real ice is messy…

- Models tend to assume "ideal" ice
- But it's also brittle, and that leads to crevasses, fractures, etc.
- Can see that, well, pretty much everywhere…

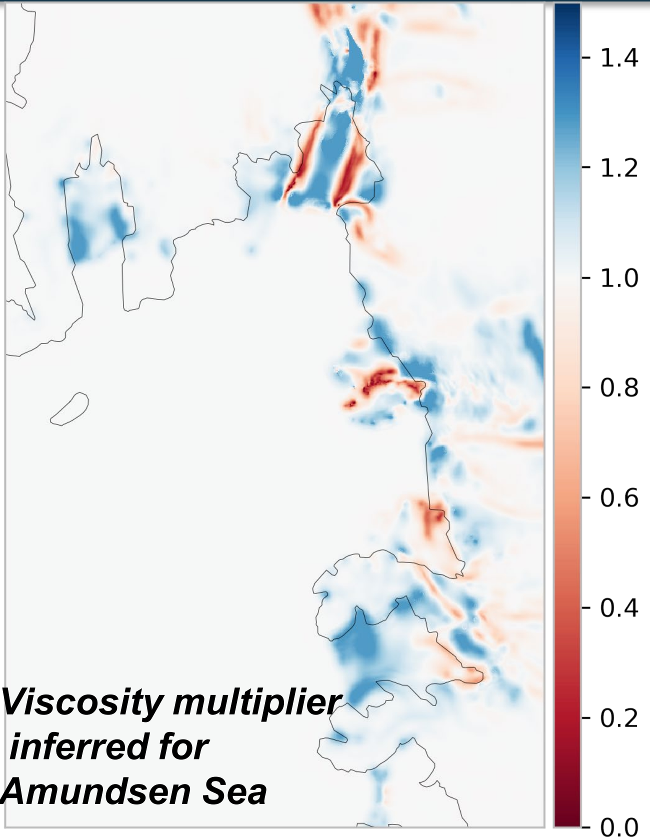
- How does this impact ice dynamics?



"non-ideal" ice in Ice Sheet modeling

- Most ice sheet models are built upon Glen's flow law (shear-thinning rheology)

- However, when we try to match observed velocity fields, we have to adopt some sort of viscosity multiplier, particularly in ice shelves
  - normally looks like regions of reduced ice viscosity
  - Can see "damaged" ice (crevasses, etc)
  - Inversions are great, for *right now…*



Viscosity multiplier inferred for Amundsen Sea

Can we model damage in a large-scale model?

- Following Bassis and Ma (2015), start with the dynamics of a crevasse…
  - Crevasses are transported with the ice flow
  - Ice in ***tension***: crevasses tend to increase
  - Ice in ***compression***: crevasses heal

- Damage: measure of average crevasse penetration
  - **d=0**: No crevasse
  - **d=1**: fully penetrate the ice (leads to calving)
  - (long wavelength limit for perturbations)
- **Goal** – couple with viscosity and evolve

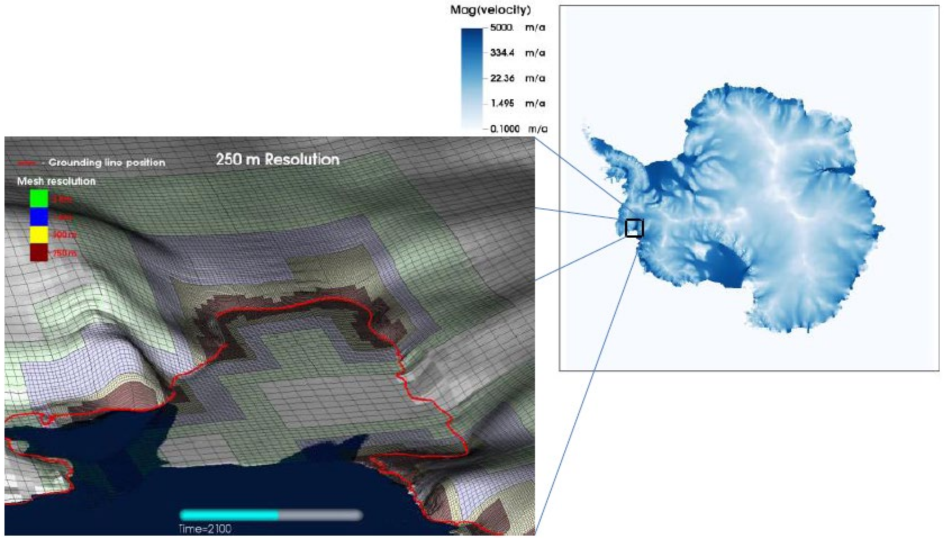
Damage evolution

- Advection with a source term:

$$\frac{\partial d}{\partial t} = \vec{u} \cdot \nabla d + S(\vec{u}, T, t, ??)$$

- Source term:
  – Based on local stress
  – Includes surface mass balance
  – Nye zero-stress minimum crevasse depth

Ice Sheet Models (BISICLES)



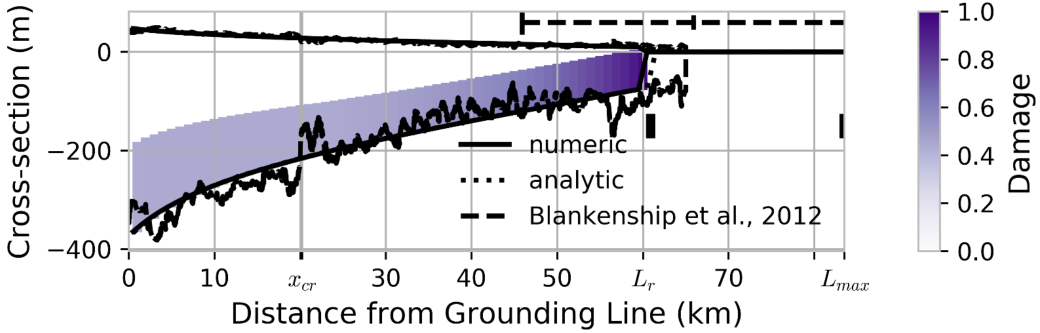
- **Finite volume, vertically integrated (shallow ice-ish: L1L2 approximation)**
- **Solves for velocity given nonlinear constitutive relation**
- **Adaptive Mesh Refinement <1 km resolution needed for Grounding Line**
- **Good for regional and continental scales**

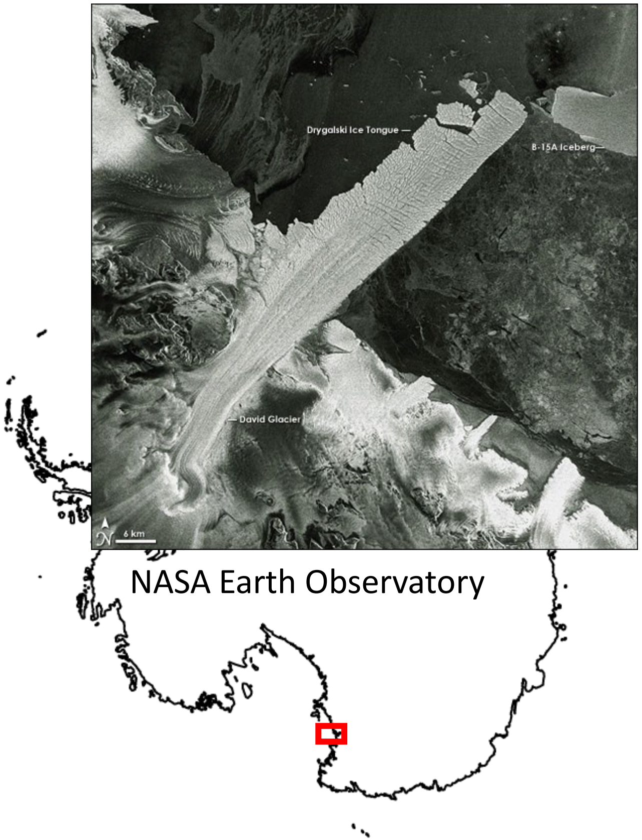
Cornford et al. (2013, 2016)

Experiment 1: Evolve damage (no coupling)

- Start with Nye values as initial condition
- Evolve to steady state
- Can use to predict calving fronts…
- Can validate against “observed” damage
  - (viscosity multipliers
- (Kachuck, et al, 2022)

Fully-Damaged Terminus at Drygalski Ice Tongue



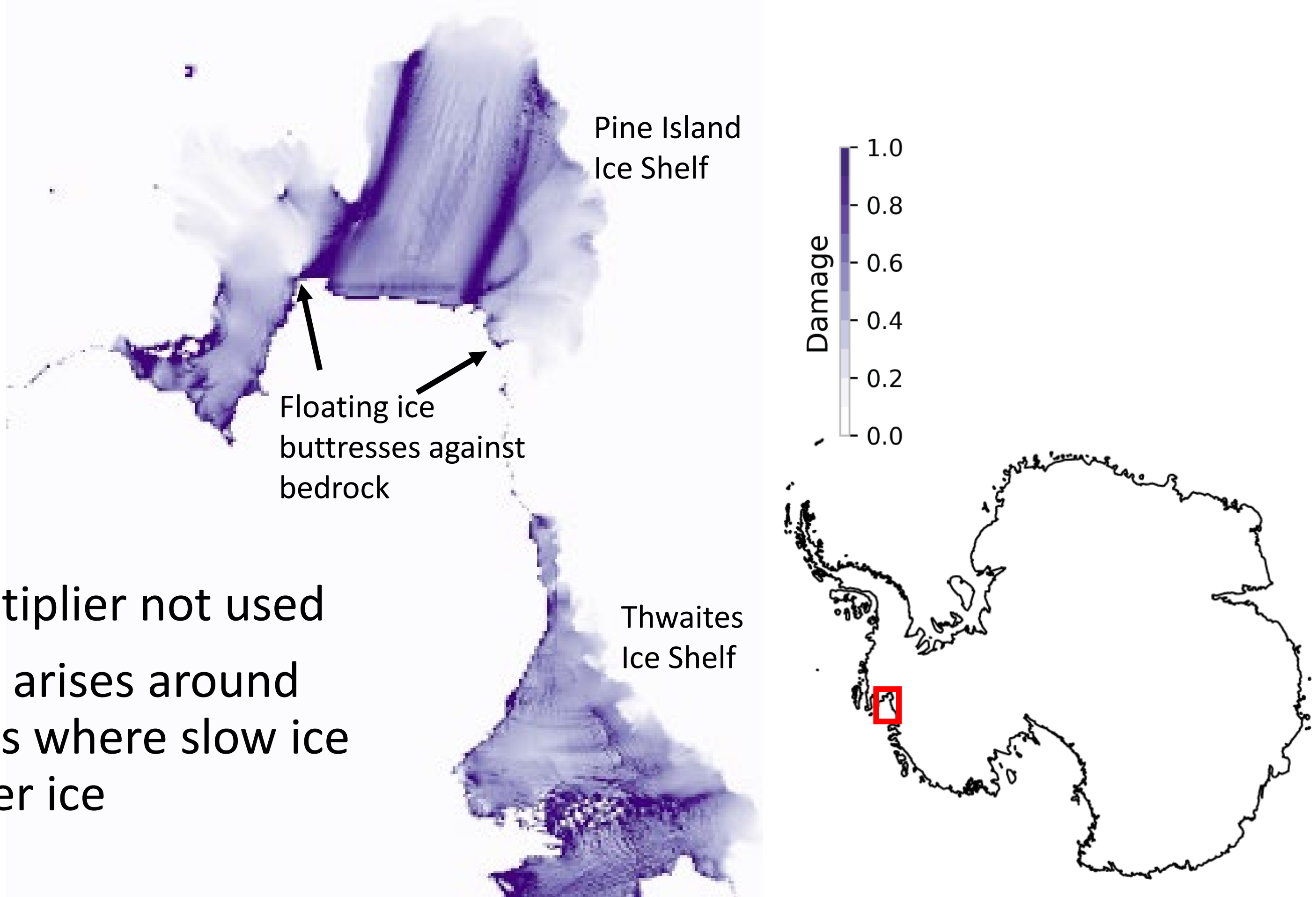


NASA Earth Observatory

- One-dimensional problem, treat ice as broken at damage=1
- Captures length and thickness

Kachuck, et al. (Journal of Glaciology, 2022)

Damage in the Amundsen Sea

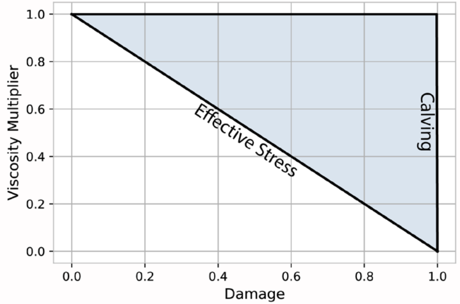


- Viscosity multiplier not used
- High damage arises around shear margins where slow ice contacts faster ice

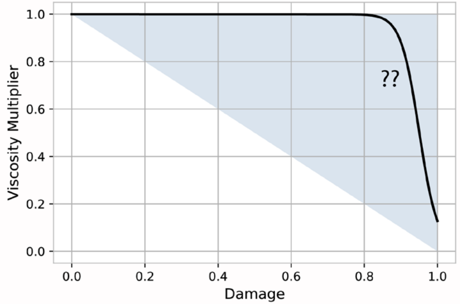
What about coupling?

- Need a coupling function $\phi(d)$ such that

$$\mu_{effective} = \phi(d)\mu_{Glen}$$

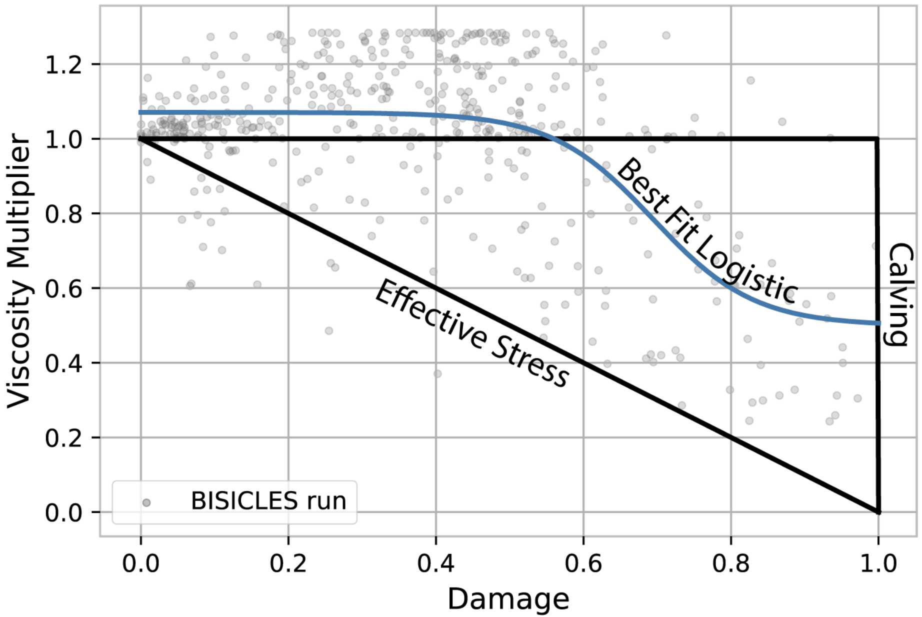


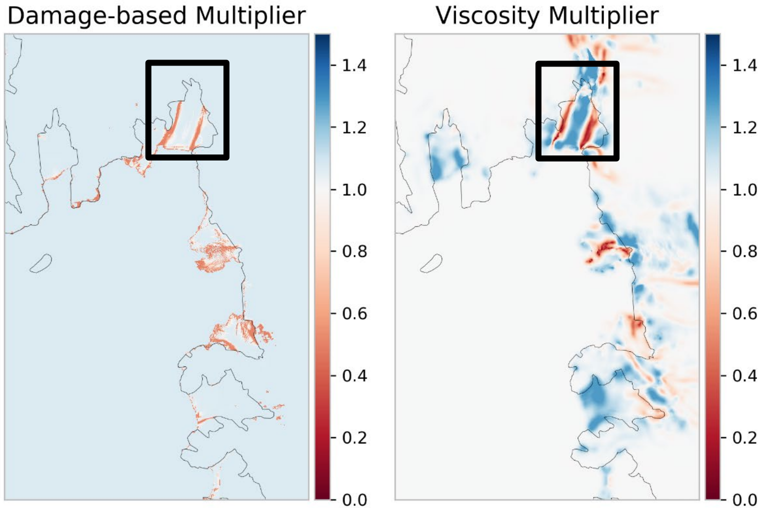
- Experimented with various forms:
  - Linear
  - Hyperbolic tangent
  - Is there a floor? ($\phi(1) > 0$)



- What about calving criteria? ($d > (1 - \epsilon)$)

Replicate the Viscosity Multiplier with Damage



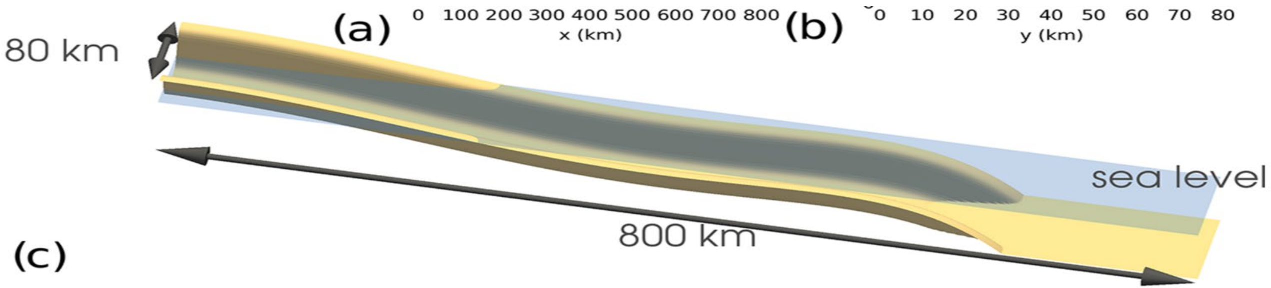


Vertical offset implies an effective temperature about 3 °C colder than input

Small amounts of damage (<0.3) have little effect on bulk rheology

4 parameters instead of ~millions+regularization

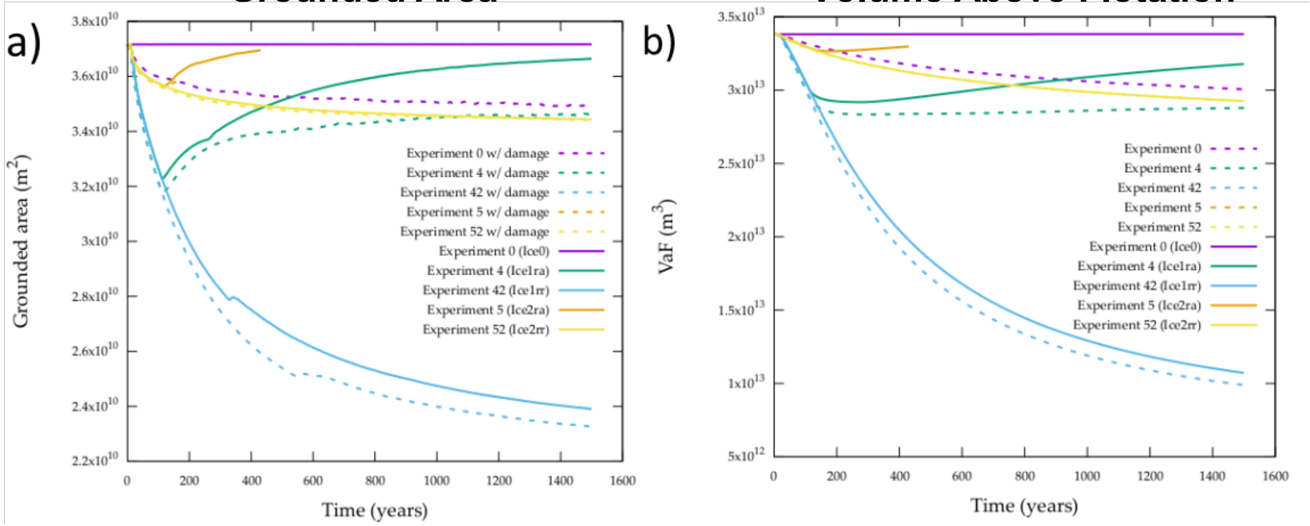
Test case 2: Coupling with MISMIP+ example

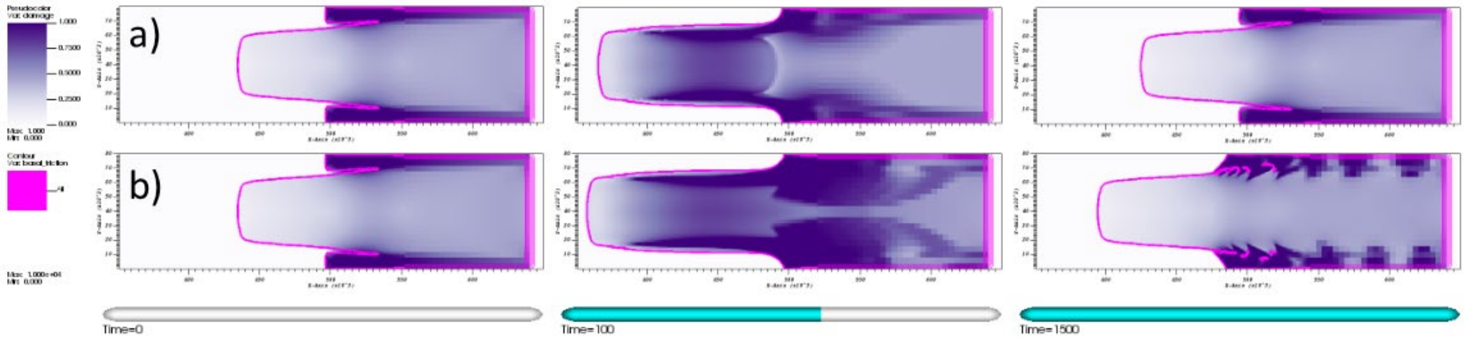


- **MISMIP+**
  - Marine ice sheet in a trough
  - Designed to test buttressing
    - maintain GL on retrograde slope
  - Spin-up to steady-state, then apply basal melt forcing
    - Retreat phase followed by re-advance
  - Warning: not for the (solver) faint of heart…

Impact of damage coupling

Grounded Area | **Volume Above Flotation**





“Caveats”

- **What does damage really represent? (moving from crevasse to some sort of integrated quantity)**

- **Still sorting out coupling details**

Summing up…

- Lots of progress on incorporating ice damage into models
- Still sorting out a bunch of details
  - Still working on best coupling function

- Note: Damage reduces buttressing!

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Thank you!

Extras