

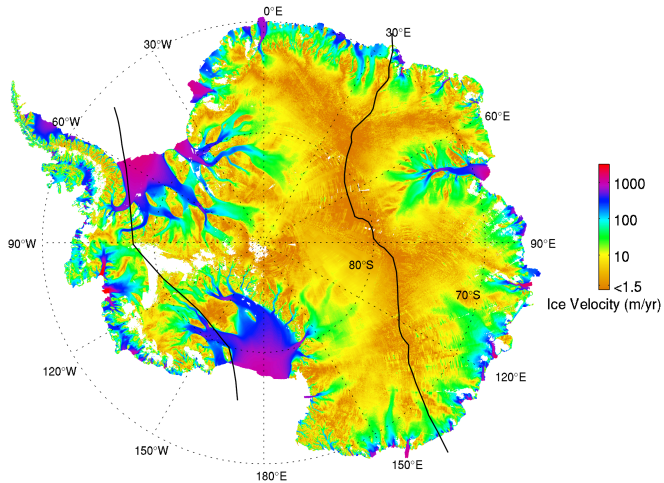
Ice streams: patterning in ice sheets

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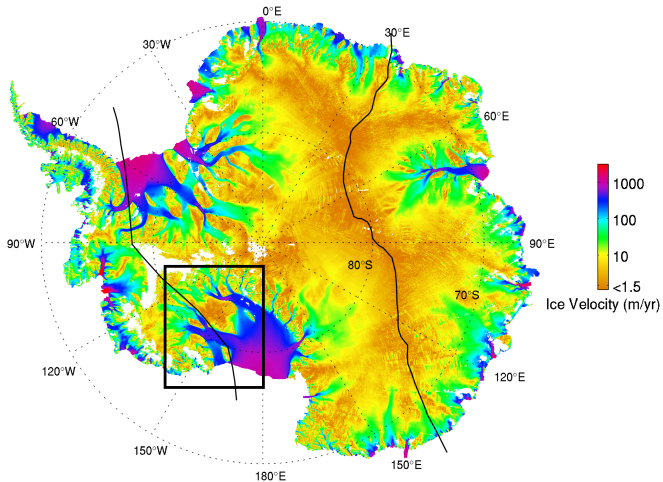
²Atmospheric and Ocean Sciences Program, Princeton University

Ice flow



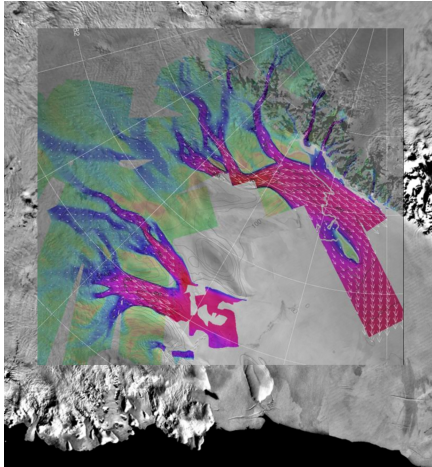
Ice surface speeds

Ice flow



Patterning, unforced by topography?

Ice flow

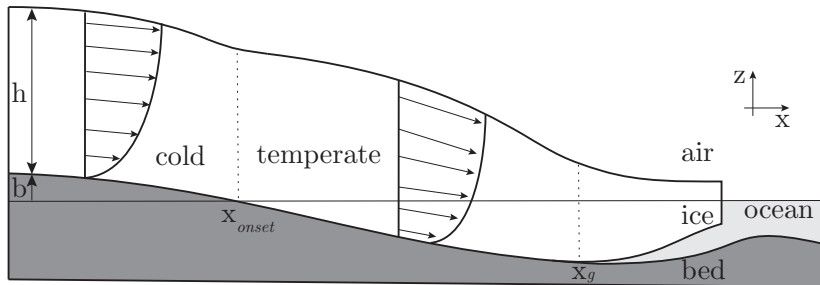


Ice stream onset

What and why?

- We are interested in spontaneous formation of ice streams as a form of pattern formation (or “symmetry breaking”)
- Our focus will be on basal sliding
- Relevant to models that do not rely on holding constant “inverted” basal friction coefficients but allow them to evolve dynamically

The problem: Upstream onset of sliding?



Usual assumption: sliding starts where the bed reaches the melting point

Zoom in on the transition from no slip to sliding

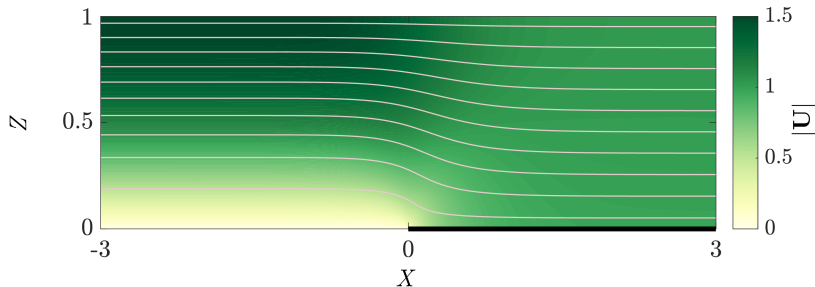
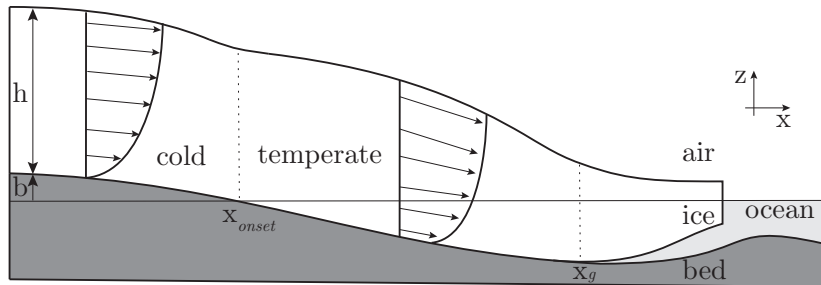


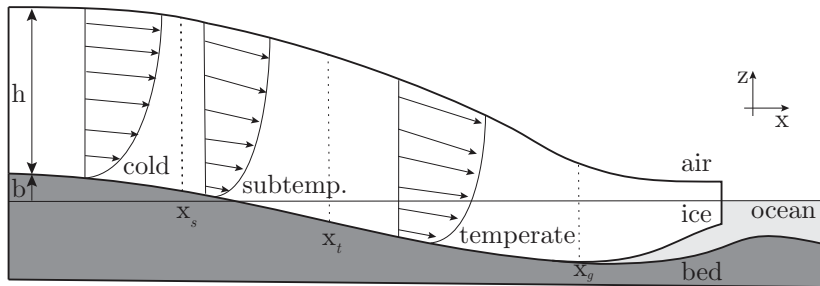
Image shows streamlines with true aspect ratio. A sharp switch in sliding draws cold ice down — refreezing the bed (Mantelli et al, PRSA, 2019)

Gradual onset in sliding?



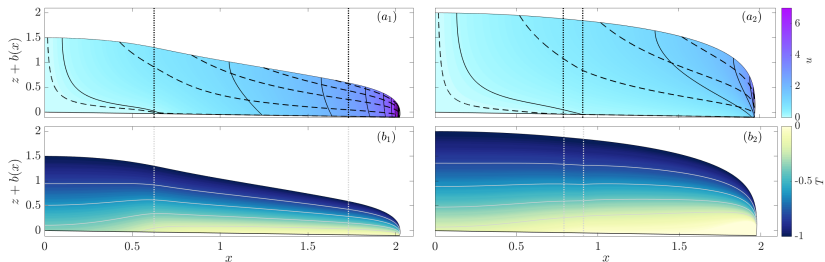
This doesn't work

Gradual transition in sliding



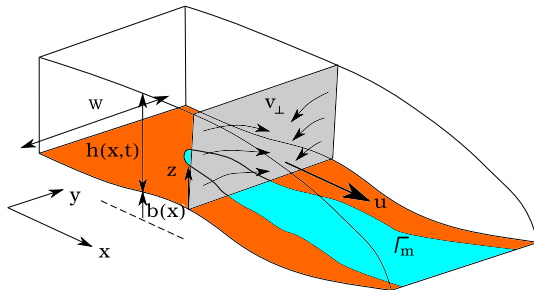
This might, but you have to do it right

Gradual transition in sliding: flowline solutions



Steady state shallow ice model with subtemperate sliding.
Vertical lines indicate region of subtemperate sliding.

Three dimensions? A novel 2.5-dimensional model



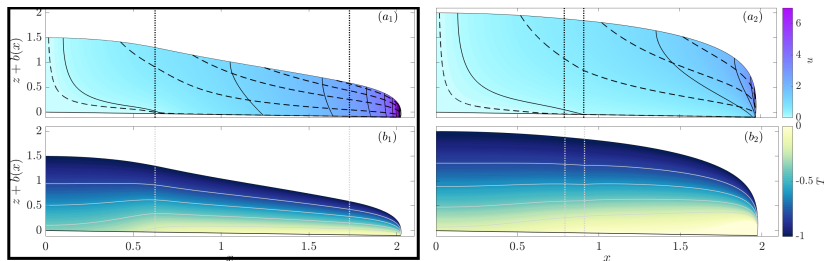
$$\nabla_{\perp} \cdot (\eta \nabla_{\perp} u) = \rho g h (b_x + s_x),$$

$$\nabla_{\perp} \cdot \left\{ \eta \left[\nabla_{\perp} \mathbf{v}_{\perp} + (\nabla_{\perp} \mathbf{v}_{\perp})^T \right] \right\} - \nabla p - \rho \mathbf{g}_{\perp} = \mathbf{0},$$

$$\nabla_{\perp} \cdot \mathbf{v}_{\perp} + u_x = 0, \quad \nabla_{\perp} = (\partial/\partial y, \partial/\partial z).$$

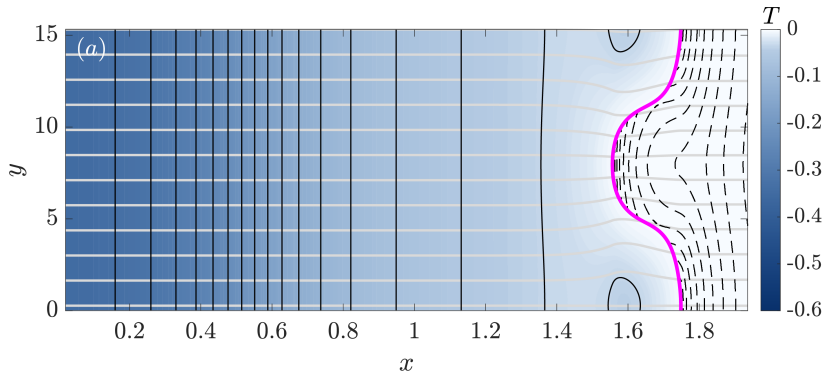
<https://arxiv.org/abs/2011.01996>

Gradual transition in sliding: from 2D to 3D



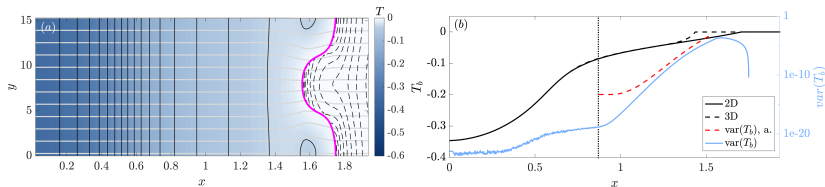
Recompute left-hand solution with slight noise in basal conditions, in 3D. *Unique* solution by forward integration from ice divide

Spatial instability: looking down



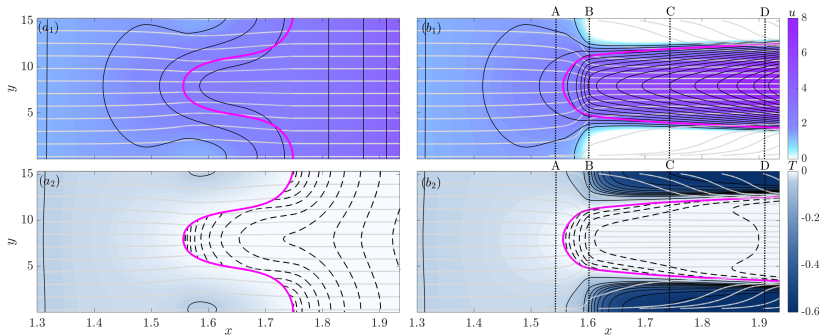
Bed map of temperature, velocity stream lines: patterning in the subtemperate sliding region

Spatial instability: looking down



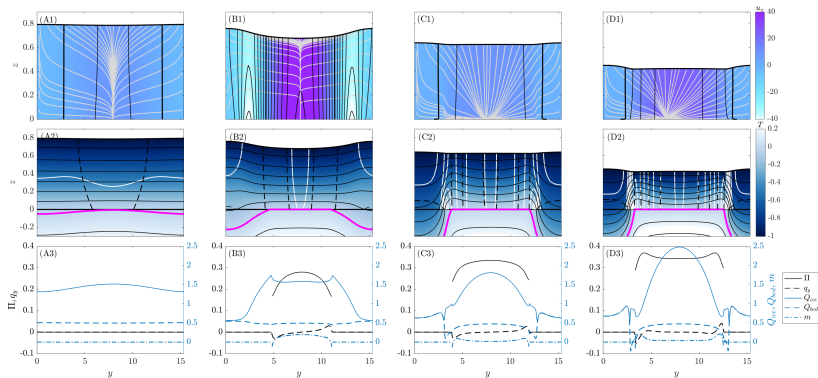
Bed map of temperature, velocity stream lines: patterning in the subtemperate sliding region

Spatial instability: still looking down



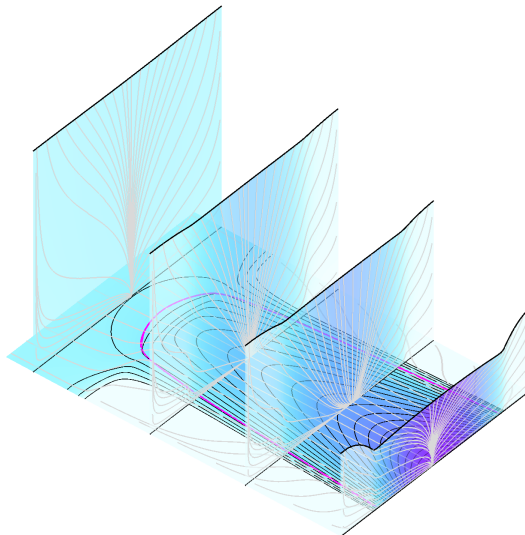
Close-up with different sliding laws: “Weertman”-type power law (no dependence on effective pressure) versus Coulomb friction on right. Solutions are identical up to onset of temperate bed.

Spatial instability: cross-sections



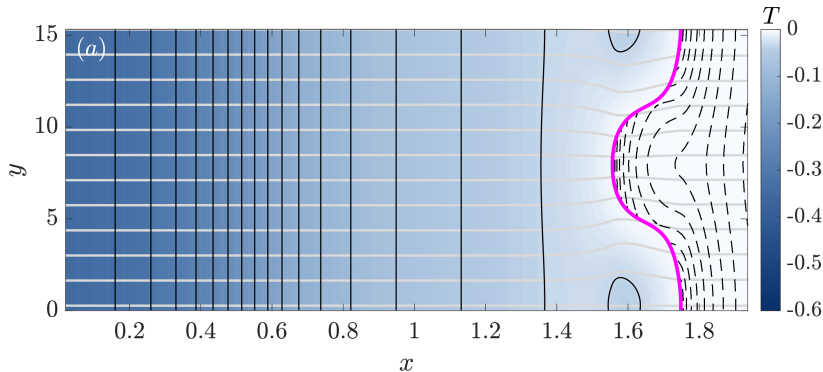
Detailed predictions of flow patterns in cross-section

Spatial instability: cross-sections



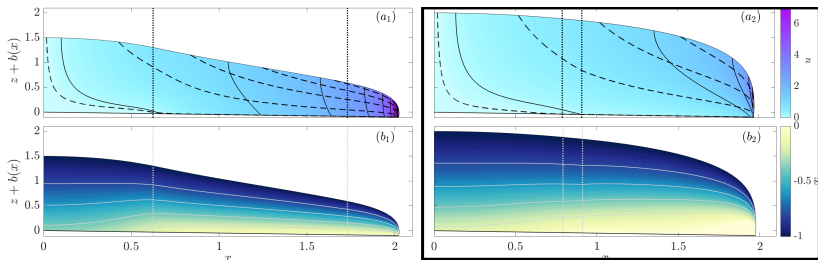
Detailed predictions of flow patterns in cross-section

Spatial instability: recall this



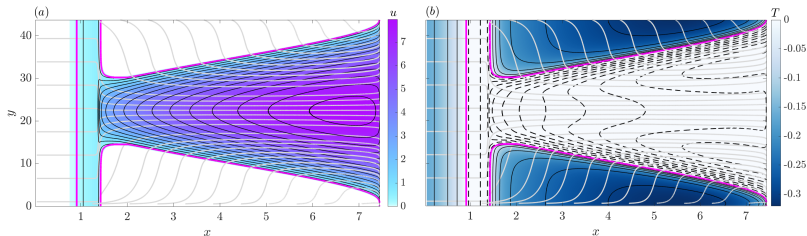
Bed map of temperature, velocity stream lines: patterning in the subtemperate sliding region

The other flowline



Patterns can form in different ways: recompute right-hand solution with noise in 3D.

Spatial instability: looking down again



Pink is boundary of temperate bed, patterning occurs after bed goes temperate

Conclusions

- Solutions are *unique* steady state solutions, for given noisy forcing
- Patterning into streams and frozen-bedded, slow-moving ridges results from bed weakening with increased basal temperature or water pressure
- Can use analytical techniques to determine where patterning first appears

Conclusions

- Model predicts formation of sharp margins
- Bed is partly *subtemperate* in margins
- Effect of englacial dissipation shifted into ice stream by advection
- Maximum basal water supply in evolved ice stream located *between* margin and center line

Conclusions

- A (big) open question is whether these patterns are unstable *in time* — preliminary work suggests we really may need full Stokes models
- Sliding onset in ice sheet models?

More detail: <https://arxiv.org/abs/2011.01996>
in press, PRSA