Sill-Controlled Circulation in Ice Shelf Cavities

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Research Overview

- Goal is to understand the sill-controlled circulation in an idealized ice shelf cavity.
- Posed as a 2-layer lock-exchange problem with boundary interface height forcing.
- We explore the dynamics using analytical uniform PV theory and a numerical model.

Pine Island Glacier

- Topographic sill under Pine Island Glacier modulates inflow of warm Circumpolar Deep Water (CDW) into the shelf cavity (Ref. 1,2,3).
- Warm, salty water in bottom layer flows over sill and is transformed into cold, fresh water as it comes into contact with ice shelf and exits in top layer (Ref. 1,2,3).
- Pine Island Glacier (PIG) is one of the most rapidly retreating glaciers due to warm CDW modulated by topography.

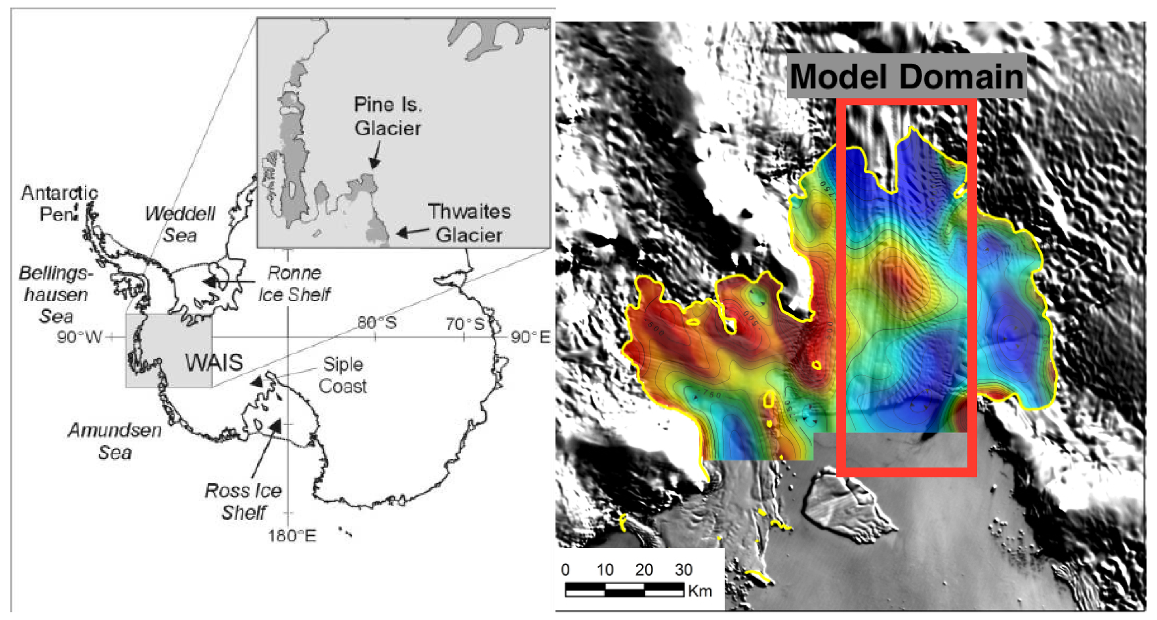

Figure 1: Pine Island Glacier location and geometry. Credit: Rignot et al. 2002 (Ref. 1) and NASA (Ref. 4).

Cavity Parameters

Cavity Size= 50km x 100km x 700m (W x L x H)
Sill Height = 400m
ρ = 1027.47 to 1027.75 kg/m^3
$f = -1.41 \cdot 10^{-4} s^{-1}$
Flow rate $\sim$ 300 mSv
Internal Baroclinic Def. Radius= 5km

Uniform PV theory

Semigeostrophic approx. ($L >> W$) for two layers h_1, h_2 above bottom topography B:

1. $fv_i = \frac{\partial p_i}{\partial x}$
2. $q_i = \frac{f}{H_i} = \frac{f + \frac{\partial v_i}{\partial x}}{h_i}$
3. Solutions: $h_i(x) = A_i e^{k_d x} + B_i e^{-k_d x} + C_i$
$u_i(x) = D_i e^{k_d x} + E_i e^{-k_d x} + F_i x + G_i$

Theoretical Predictions/Limitations

- Uniform PV predicts boundary layer structure that depends on the flow rate.
- For wide channels, theory predicts boundary current separation.
- Numerical solutions show uniform PV does not provide a complete picture i.e. flow has PV gradients instead of boundary layer separation.

Important Result

In the wide channel limit ($L_d << W$), uniform PV is only a reasonable assumption within the lateral boundary layers. An imposed upstream-downstream PV difference necessarily forms a PV gradient in the domain. This carries cross-sill flow via mean or eddy advection and is strongly influenced by sill height.

About the Model

- Back of the Envelope Ocean Model (BEOM) is a numerical shallow water isopycnal model (see ref. 5).
- Simulates rotating basins with a free surface/rigid lid, wetting/drying, and hydrostatic layered stratification.
- Setup includes 2 layers with bottom topography, a rigid lid and upstream/downstream buoyancy forcing.

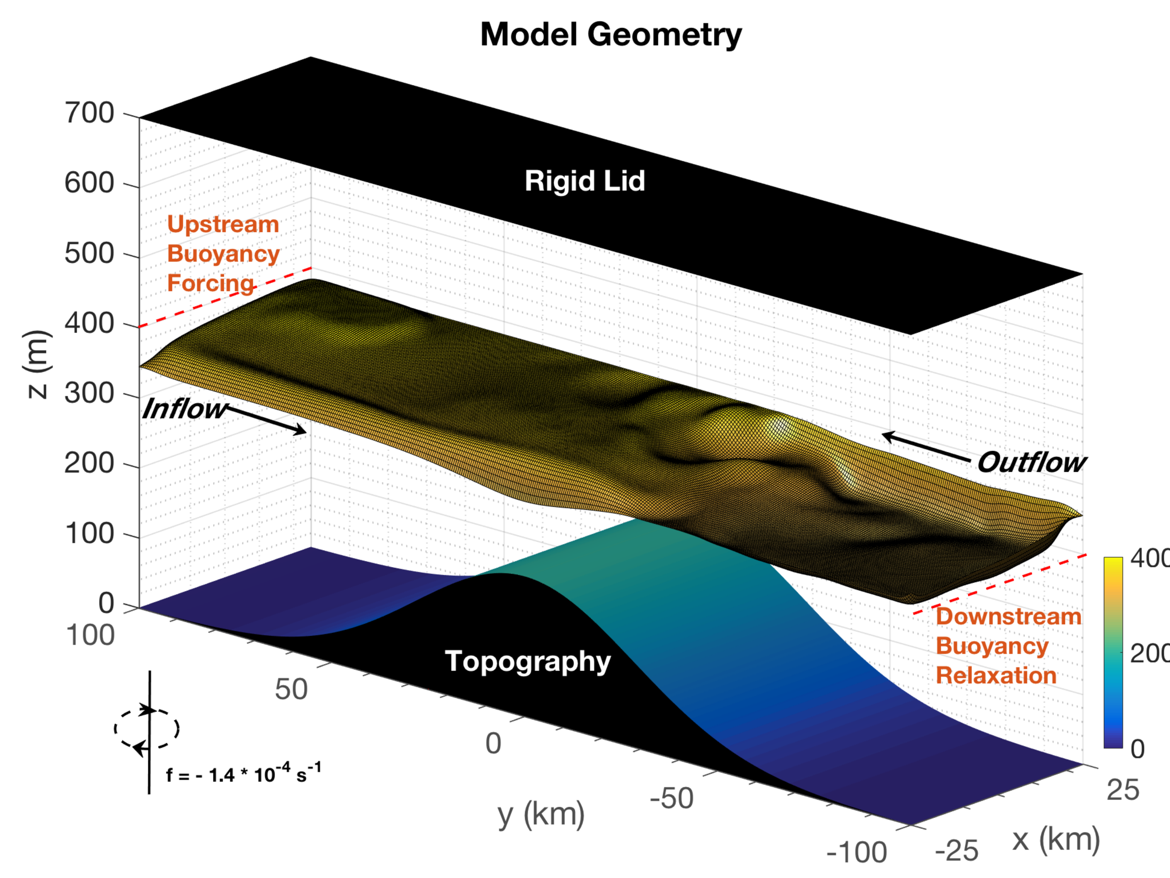

Figure 2: Example of model setup geometry.

Numerical Results

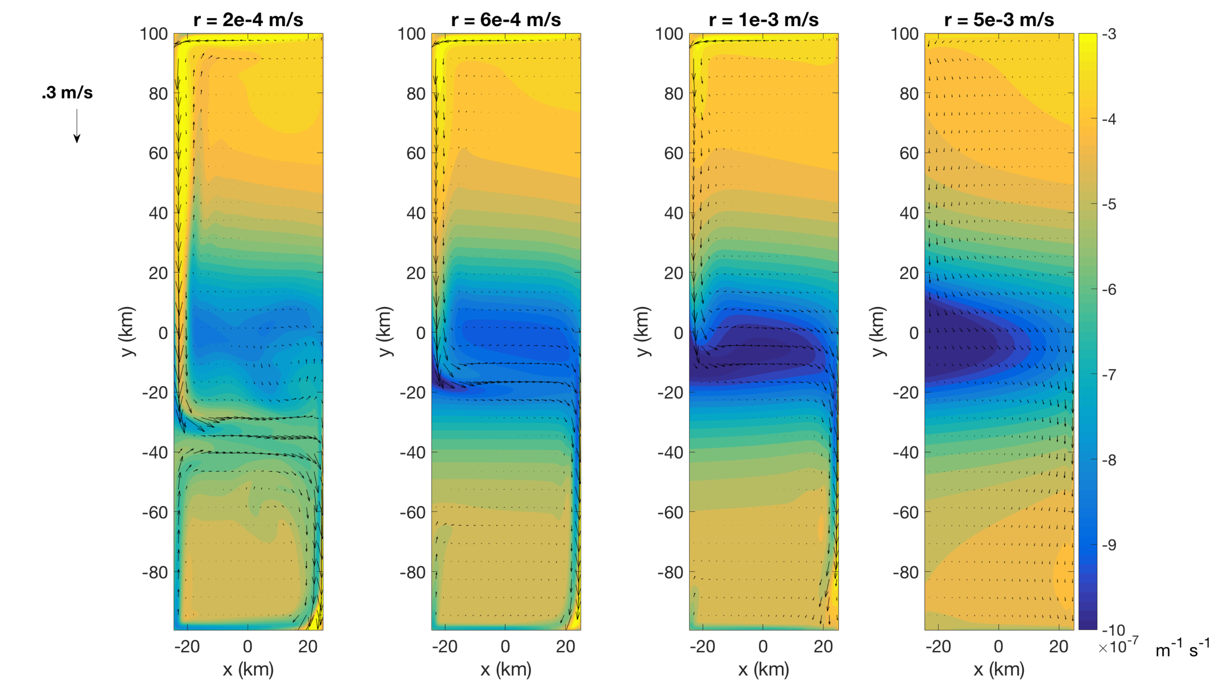

Figure 3: 20 day time-avg. bottom layer PV with velocity quivers for varying drag velocity r (for sill=200m).

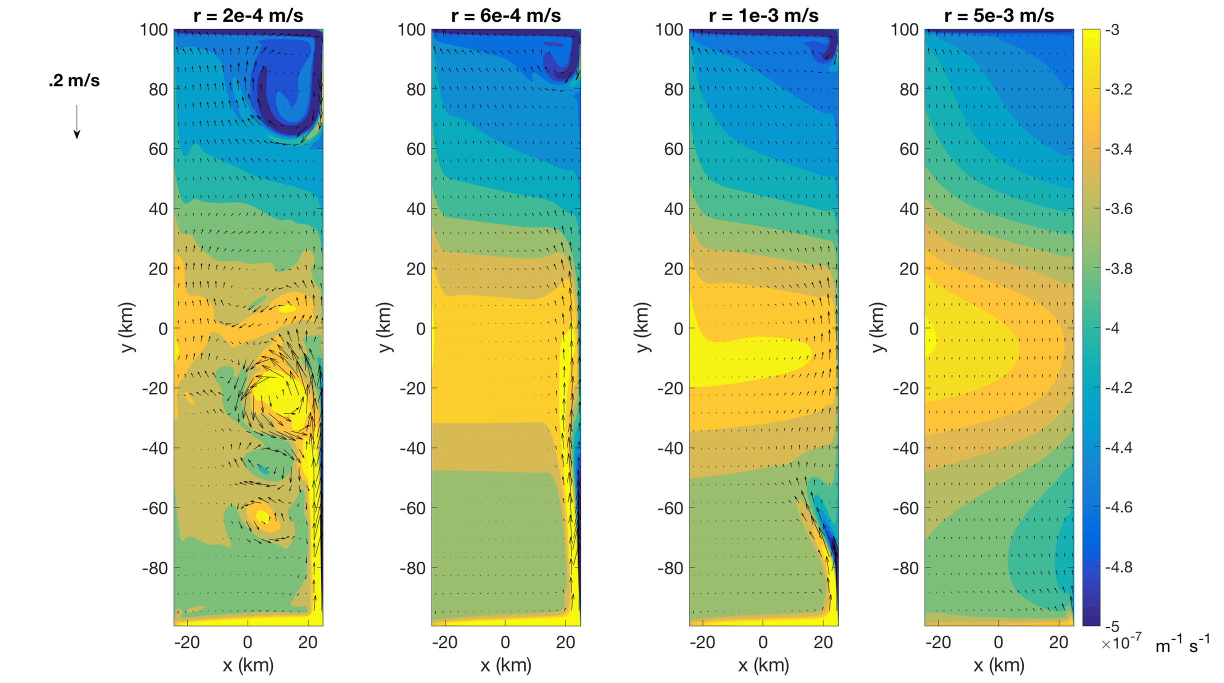

Figure 4: Same as fig. 3 for top layer PV.

- Presence of a sill weakens overall circulation strength and increases baroclinicity.
- Results show lateral boundary eddies contribute significantly to total transport in low drag regime.

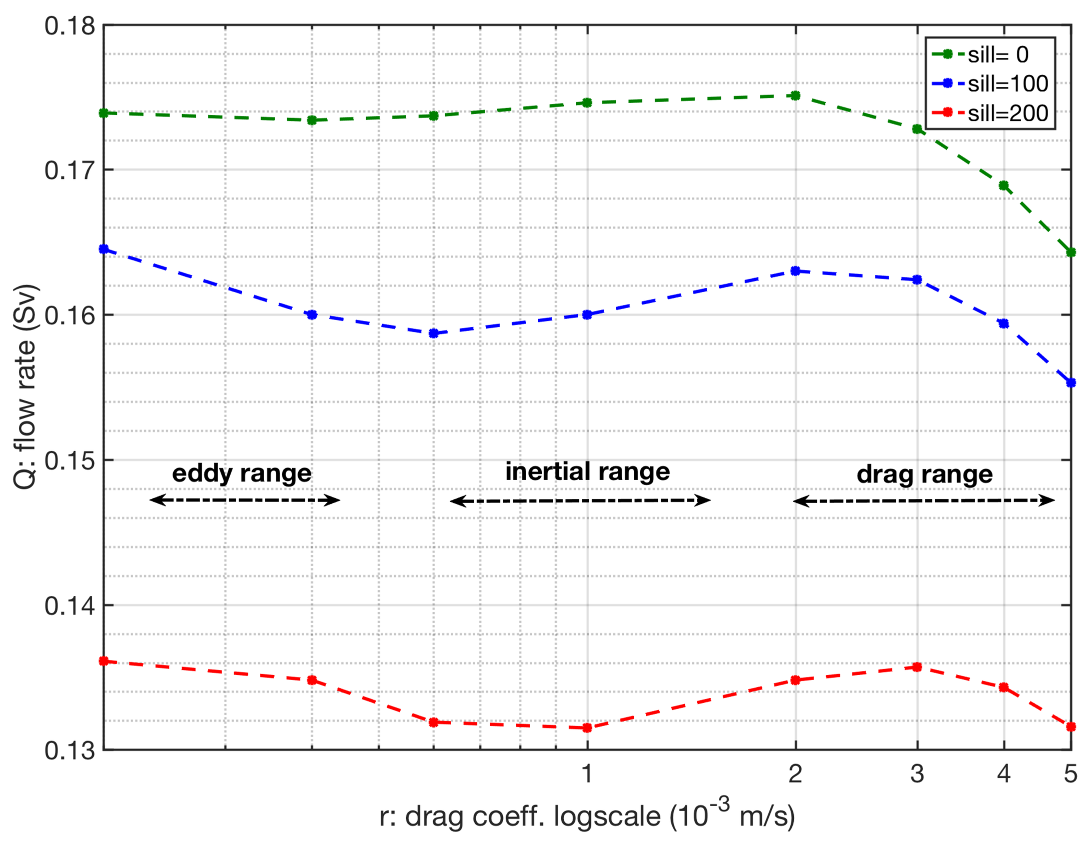

Figure 5: Flow rate vs. drag and sill height.

Summary and Future Work

- A rich range of behavior is observed in 2-layer exchange flows depending on **cavity shape** and **drag**.
- Circulation strength is strongly sill-controlled, but rather insensitive to drag.
- Future work will explore these dynamics in hydraulically-controlled and layer-outcropping regimes.

References

[1] Rignot, E., Vaughan, D.G., Schmeltz, M., Dupont, T., MacAyeal, D. (2002) Acceleration of Pine Island and Thwaites Glaciers, West Antarctica. Annals of Glaciology, 34, 189-194.

[2] Jenkins, A., Dutrieux, P., Jacobs, S., McPhail, S.D., Perrett, J. R., Webb, A.T., White, D. (2010) Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. Nature Geoscience, 3, 468-472.

[3] De Rydt, J., Holland, P.R., Dutrieux, P., Jenkins, A. (2014) Geometric and oceanographic controls on melting beneath Pine Island Glacier. J. Geophys. Res. Oceans, 119, 2420–2438.

[4] NASA. Operation IceBridge campaign bathymetry data, 2009. Retrieved from: www.nasa.gov/mission pages/icebridge/

[5] St-Laurent, Pierre. Back of the Envelope Ocean Model (BEOM). Source code available under copyleft license: http://www.nordet.net/beom.html