Dropping Ice Shelves onto an Ocean Model and Moving Grounding Lines

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Projected Global Mean Sea Level Rise

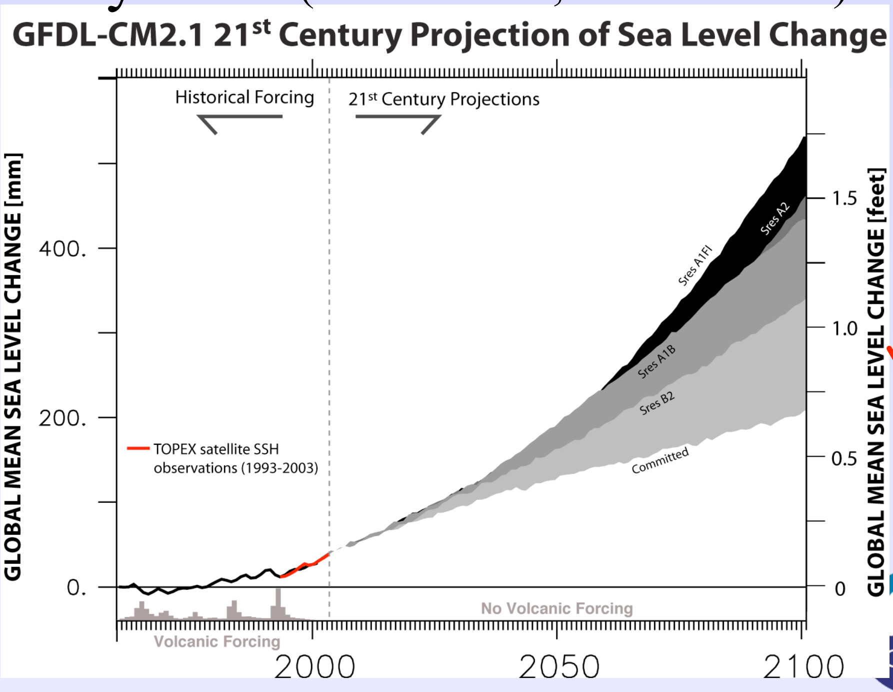
Sources of uncertainty in 2100 global mean sea level projections:

- Forcing scenario (~20 cm range at 2100 for GFDL-CM2.1)
- Ocean heat storage (steric rise) (13 to 32 cm in IPCC AR4)
- Land ice (except ice sheets) (4 to 19 cm in IPCC AR4)
- Ice sheet surface mass balance (-10 to 4 cm in IPCC AR4)
- Dams & land water ±3 cm/century? (Lettenmaier & Milly, Nature Geo. 2009)
- Antarctic & Greenland Ice sheet dynamics changes – ?
  - Plausible range 20 to 110 cm by 2100 (Pfeffer et al., Science 2008)

Reservoir sizes in Sea Level Rise equivalent:

- Mountain glaciers & ice caps – 0.3 m
- Greenland Ice Sheet – 7.3 m
- West Antarctic Ice Sheet (marine) – 5 m
- East Antarctic Ice Sheet (land) – 51.6 m

(Uniform warming of ocean ~0.5 m °C^{-1})



Plausible 1 m ice-sheet dynamics contribution to sea level rise

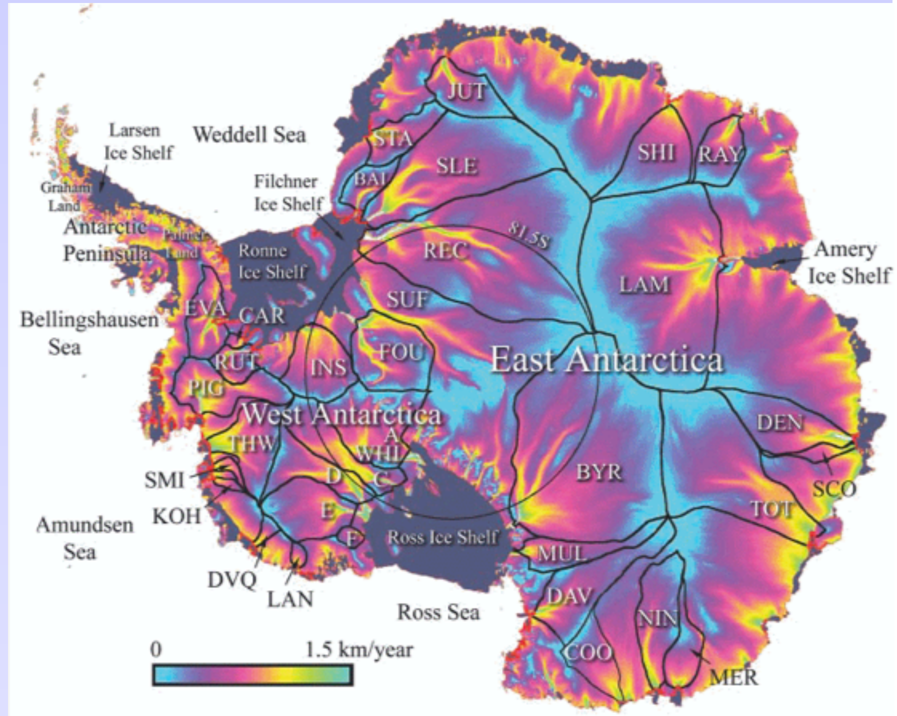
What is needed to model ice-sheet dynamics contributions to global mean sea level rise?

1. Ice sheet dynamics model, including the ability to simulate the rapidly flowing ice streams.

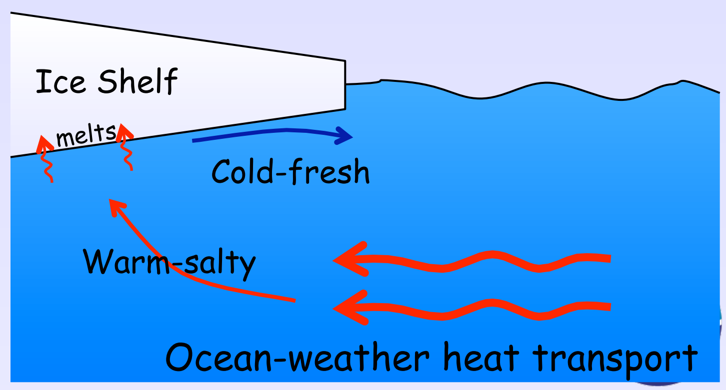
3. Ice shelf model, including calving of ice-bergs and collapse.

4. Model of the ocean circulation in the ice-shelf cavity.

5. Parameterizations or resolution of the eddy- and tidal- delivery of warm ocean water to the ice shelf cavity.

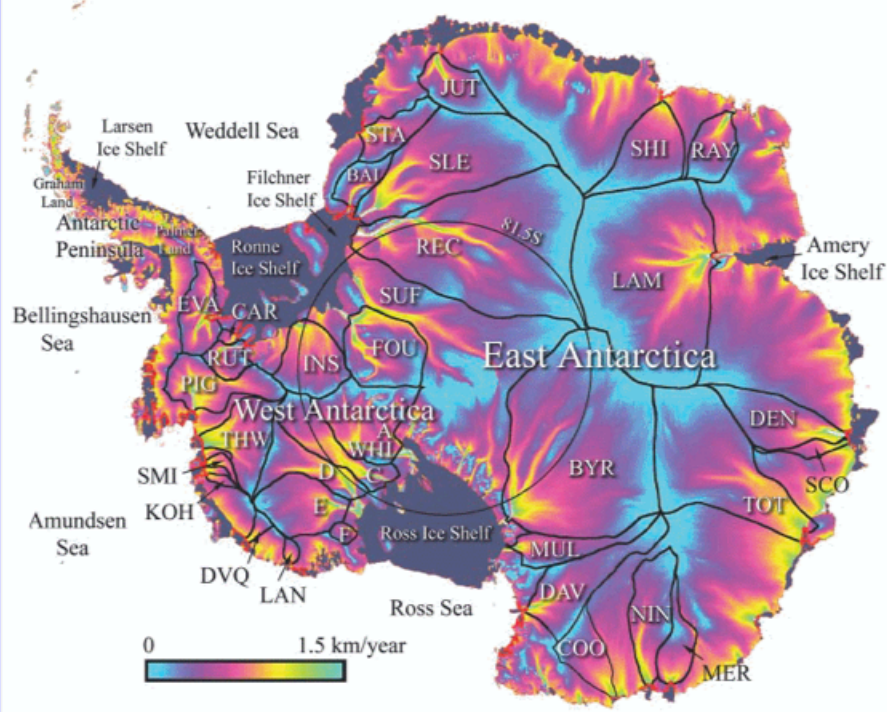


Bamber et al., Science 2000; C. Rapley, British Antarctic Survey



Ocean ice-shelf interaction and sea-level rise.

- Surface melting of ice sheets is thought unlikely to contribute significant sea level rise.
- Ice shelves buttress most ice streams; in cases where these shelves disintegrated, the ice streams have accelerated.
- The grounding line determines where the ice starts to float; its location is set by a balance between ice flow and ocean heat flux driven melting.
- Parameterizations or resolution of the eddy- and tidal- delivery of warm ocean water to the ice shelf cavity may be critical for predicting how shelves evolve.



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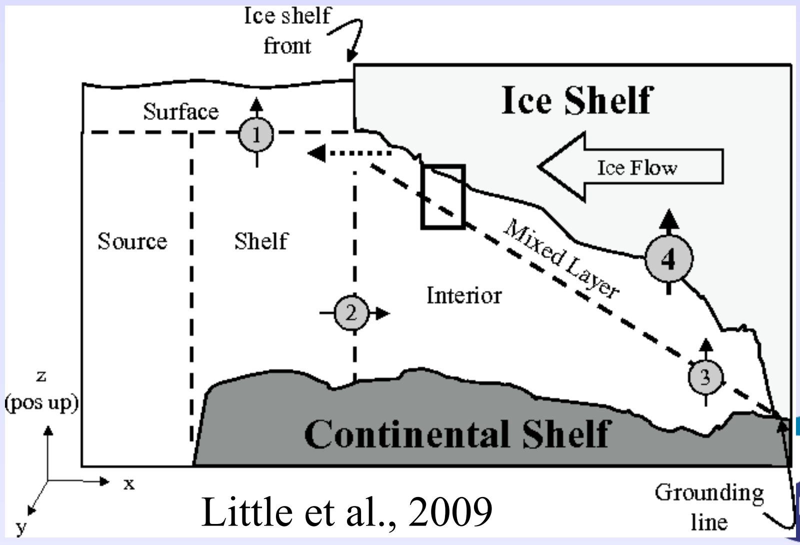


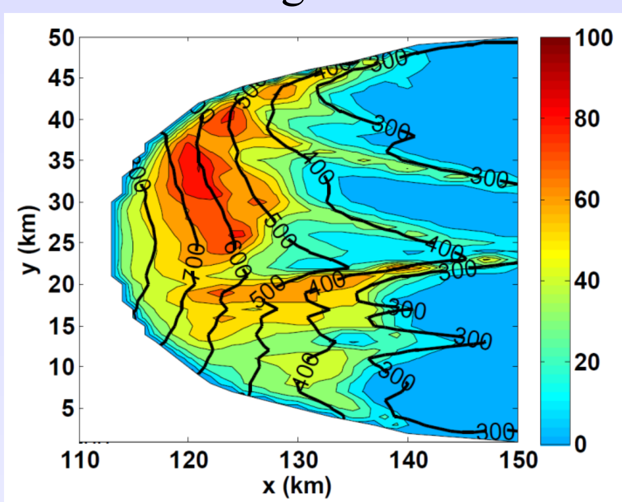
Little et al., 2009

Studies of the effects of ocean dynamics on ice-shelf melting

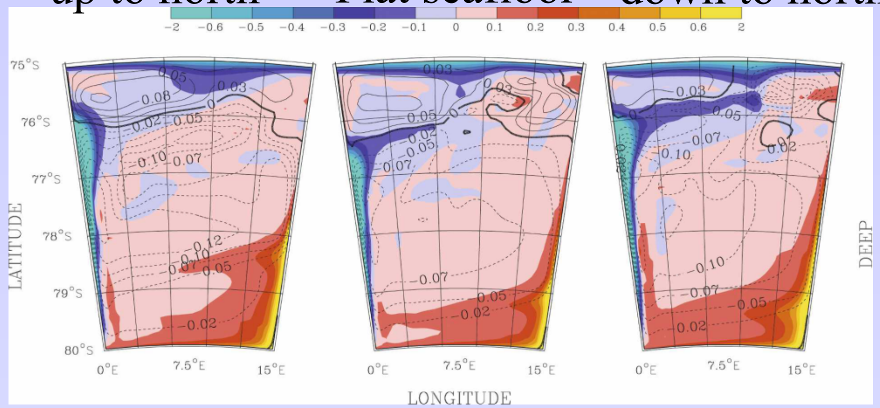
We are actively working to put ice shelves into GOLD-based coupled models.

Studies to date have not used split time-stepping.

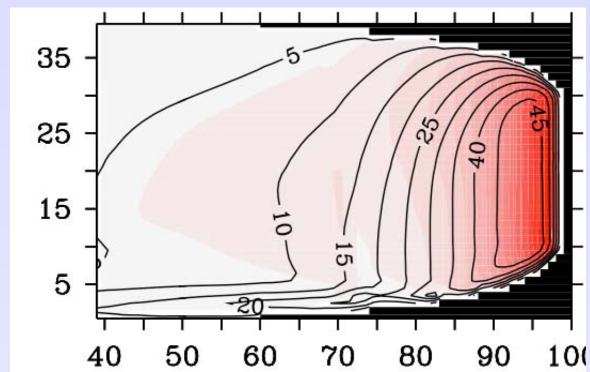
Goldberg, Little, & Sergienko - Melting shapes the shelf-bottom, the shelf-bottom guides the flow and localizes melting. Shelf-structures emerge spontaneously.



Seafloor slopes up to north | Flat seafloor | Seafloor slopes down to north



Little, Gnanadesikan and Hallberg, 2008- melt in large ice shelves concentrated in southeast- regardless of bottom slope.



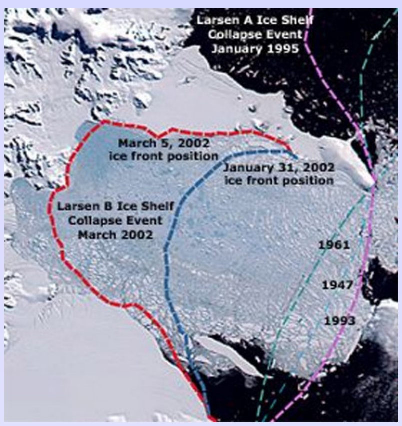
Little, Gnanadesikan and Oppenheimer, 2009- melt rate (contours) strongly controlled by *ice shelf* bottom.

Ice shelves - where water meets ice

• Ice shelves provide buttressing to ice sheets.

• Several shelves Antarctica have collapsed.

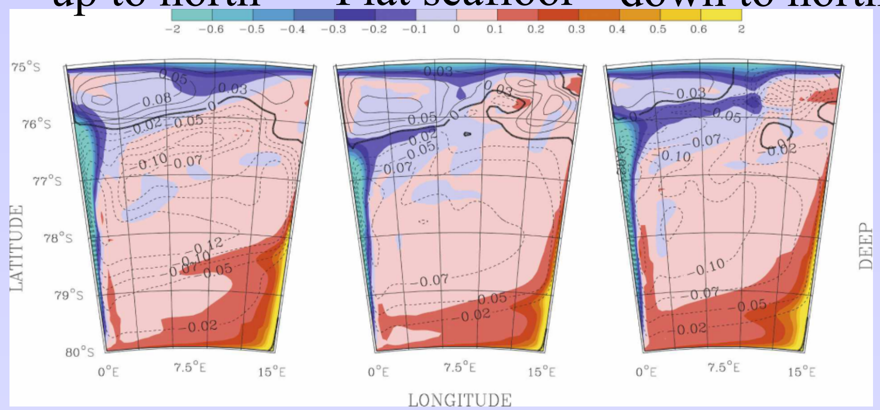
• The resulting acceleration of flow into the ocean is significant!



• Key question: what determines distribution/rate of ice shelf melt?

We are actively working to put ice shelves in GFDL's coupled models.

Seafloor slopes up to north | Flat seafloor | Seafloor slopes down to north



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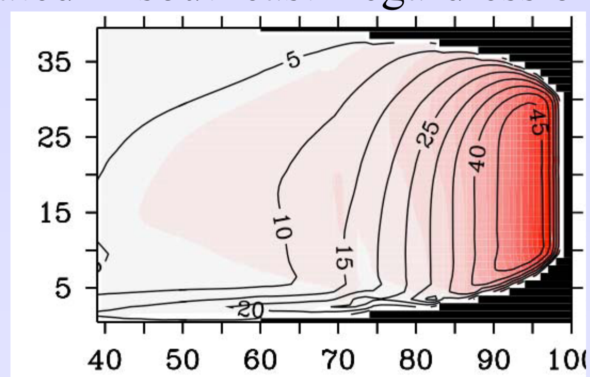


Little, Gnanadesikan and Oppenheimer, 2009- melt rate (contours) strongly controlled by *ice shelf* bottom.

Further work (w. Goldberg/Sergienko) indicating that the melting also shapes the bottom!

Baroclinic-barotropic split time stepping suitable for use with ice shelf cavities

- Transports used as input and output to the barotropic solver. The continuity solver is inverted to determine velocities.

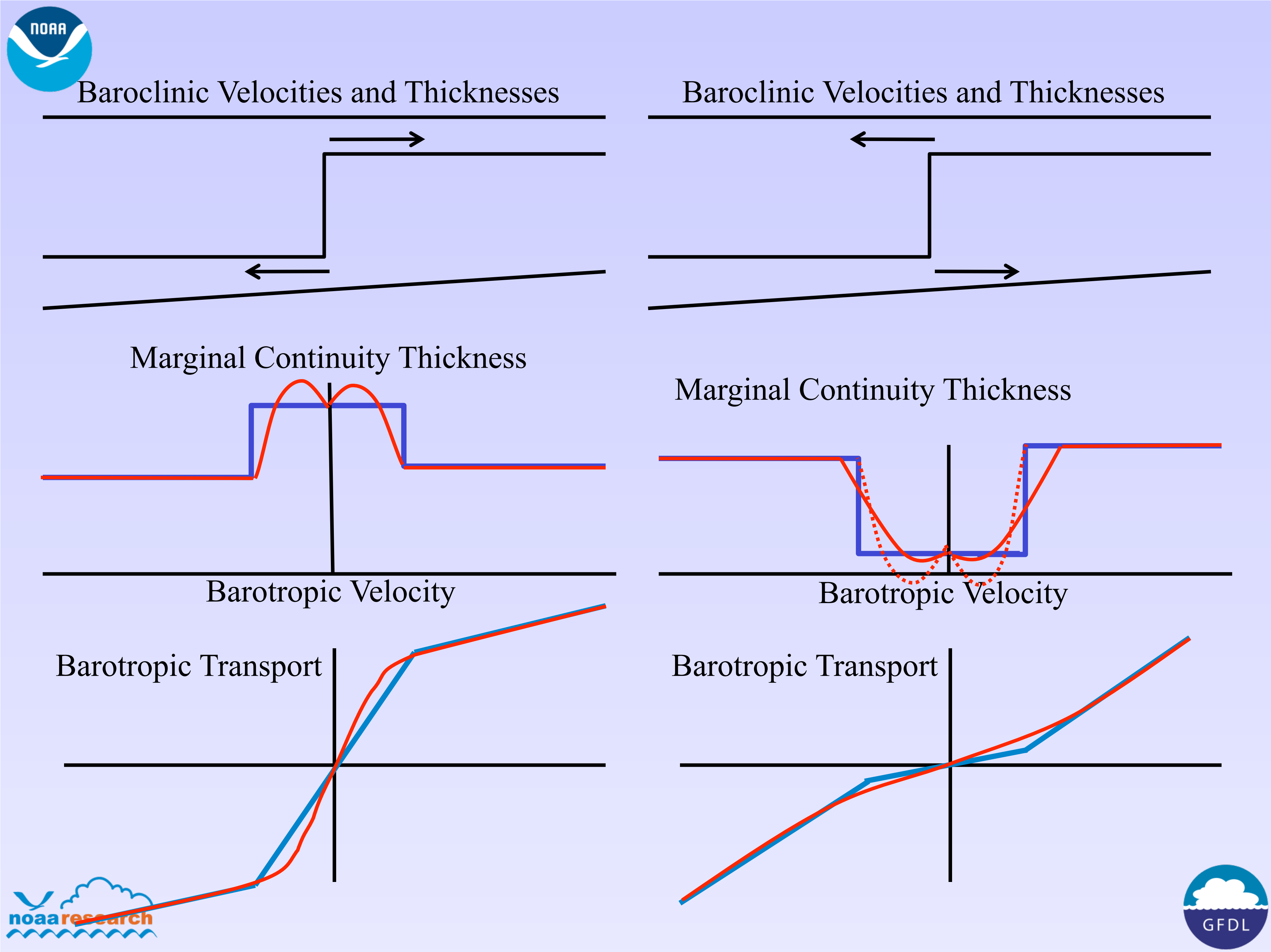
$$\frac{\partial \eta}{\partial t} = \nabla \cdot \overline{U} + M \qquad \overline{U}(\overline{u}) = \frac{1}{\Delta T}\int_0^{\overline{u}\Delta T} H(x)\,dx \qquad \overline{u}^n = \overline{U}^{-1}\left(\sum_k U_k^n\right)$$

$$u_k^{n+1} = \tilde{u}_k^{n+1} + \Delta\overline{u} \qquad \text{Find } \Delta\overline{u} \text{ such that } \sum_k U_k\left(\tilde{u}_k^{n+1} + \Delta\overline{u}\right) = \overline{U}^{n+1}$$

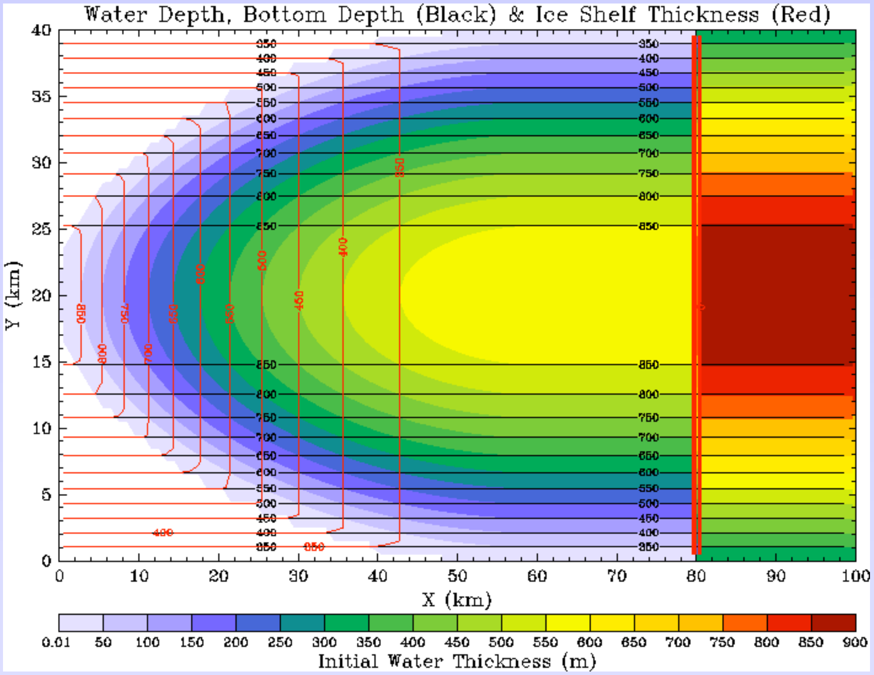
- Barotropic accelerations are treated as anomalies from the baroclinic state.

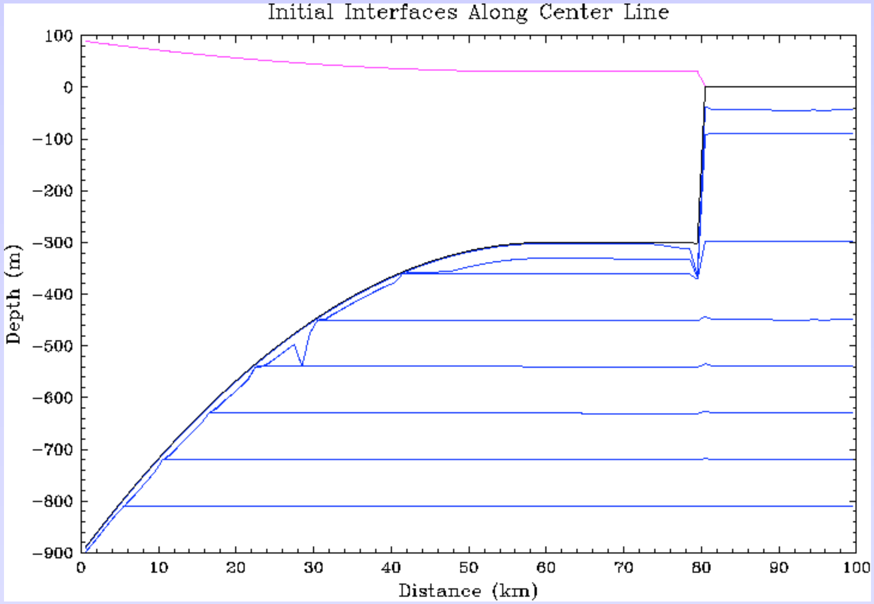
$$\frac{\partial \overline{u}}{\partial t} = -f\hat{k} \times (\overline{u} - \overline{u}_{Cor}) - \nabla g(\eta - \eta_{PF}) - \frac{c_D\left(\left\|u_{Bot}\right\| + \left\|u_{Shelf}\right\|\right)}{\sum_k h_k}(\overline{u} - \overline{u}_{Drag}) + \frac{\sum_k h_k \frac{\partial u_k}{\partial t}}{\sum_k h_k}$$

- Bottom and surface drag laws are treated implicitly.
- The barotropic continuity solver uses flow-dependent thicknesses which approximate the sum of the layer thickness transports.


Baroclinic Velocities and Thicknesses
Baroclinic Velocities and Thicknesses
Marginal Continuity Thickness
Marginal Continuity Thickness
Barotropic Velocity
Barotropic Velocity
Barotropic Transport
Barotropic Transport

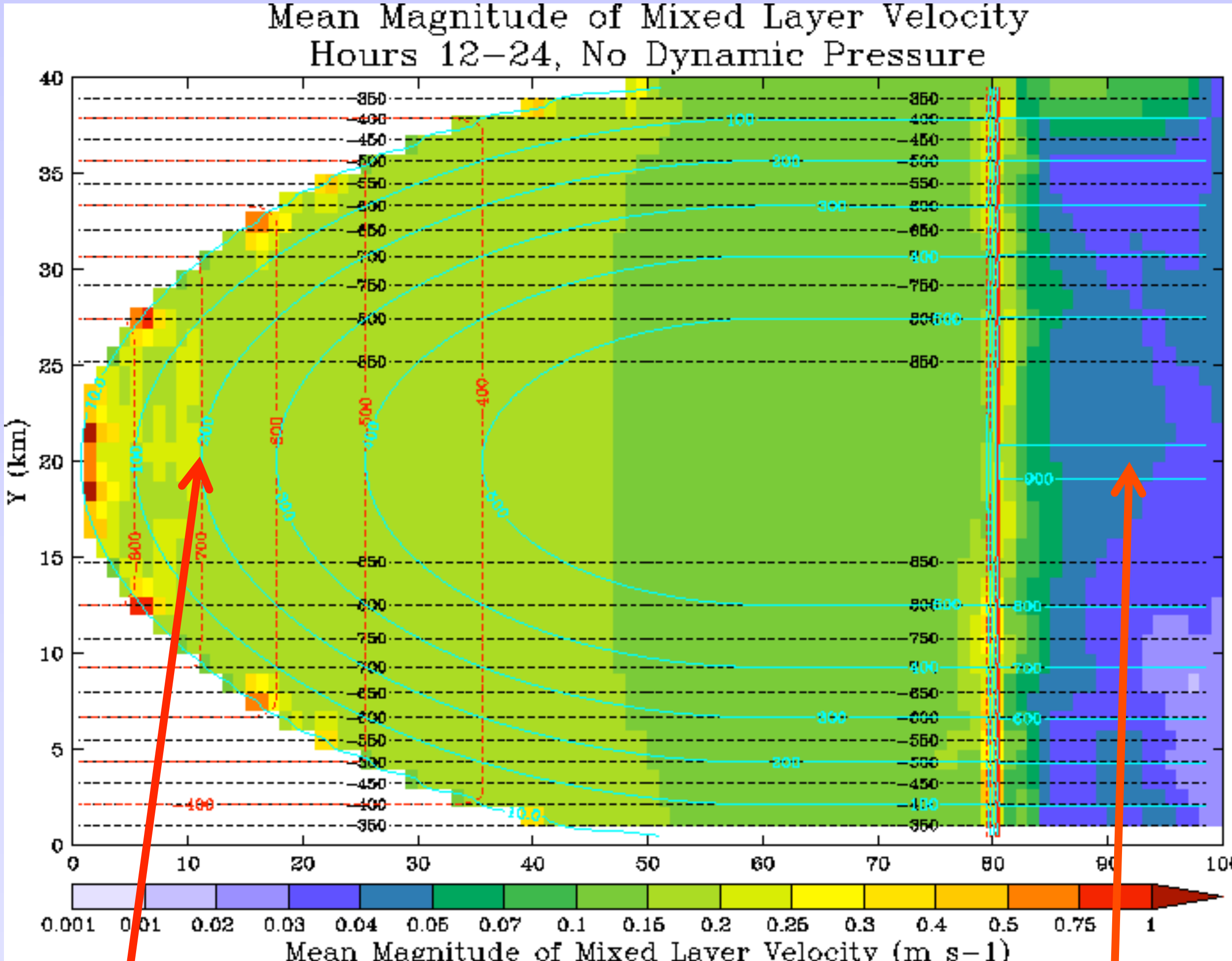
An Ice Shelf Test Case

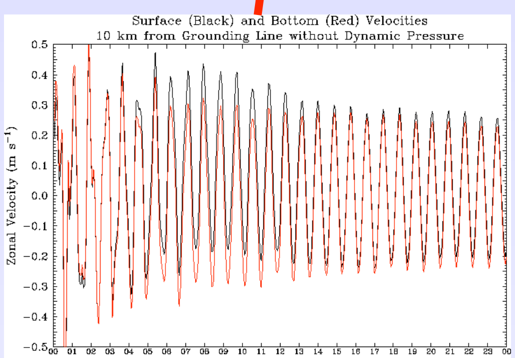


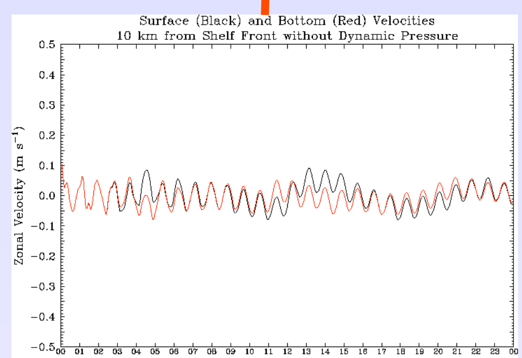


Ice shelf is released from an average of ~0.72 m above its resting position, generating a tsunami.

This tests the circulation response to impeding gravity waves.


Mean Magnitude of Mixed Layer Velocity
Hours 12–24, No Dynamic Pressure
Y (km)
Mean Magnitude of Mixed Layer Velocity (m s−1)
0.001 0.01 0.02 0.03 0.04 0.05 0.07 0.1 0.15 0.2 0.25 0.3 0.4 0.5 0.75 1


Surface (Black) and Bottom (Red) Velocities
10 km from Grounding Line without Dynamic Pressure
Zonal Velocity (m s−1)
JAN 1


Surface (Black) and Bottom (Red) Velocities
10 km from Shelf Front without Dynamic Pressure
Zonal Velocity (m s−1)
JAN 1

So what's wrong with this?

- Ice shelves move with the tides, but do not exhibit breaking gravity waves!
- The short-term pressure at the bottom of an ice shelf is far from hydrostatic. Ice is rigid.
- Ice shelves resist bending.
- Ice is very viscous (viscosity ~10^9-10^{13} m^2 s^{-1})
  - In the ice $\frac{dw}{dt} = -\rho g - \frac{dp}{dz} + \kappa \nabla^2 w + \hat{k} \cdot (\nabla \cdot \tilde{\tau})$
  - Approximate the surface pressure by

$$p_{Sf\,cOcn} = p_{Atm} + \rho_{Ice} H_{Ice} g - \nabla \left(H_{Ice} \kappa \nabla \frac{\partial \eta}{\partial t} \right)$$

or

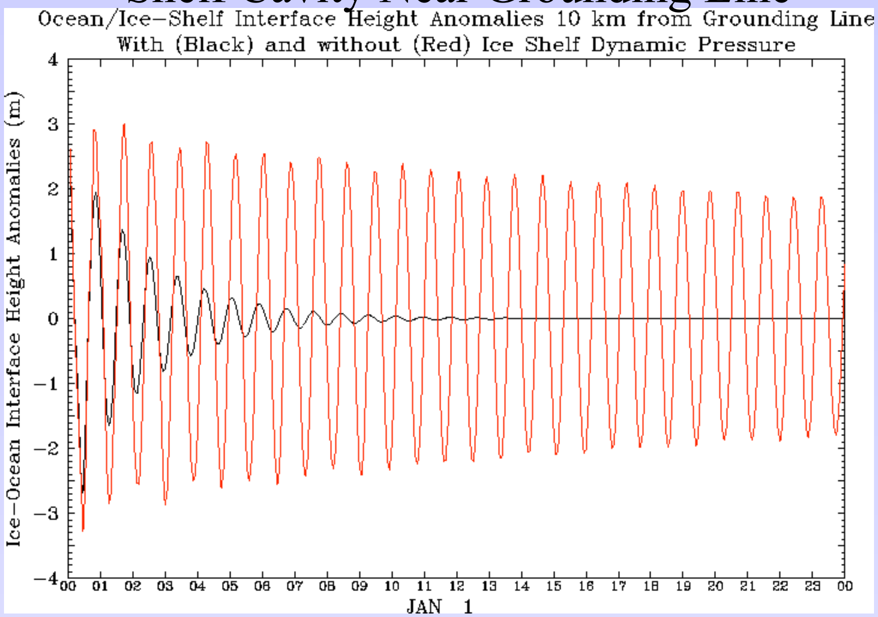
$$p_{Sf\,cOcn} = p_{Atm} + \rho_{Ice} H_{Ice} g + H_{Ice} \lambda \frac{\partial \eta}{\partial t} \qquad \lambda = \kappa / L^2$$

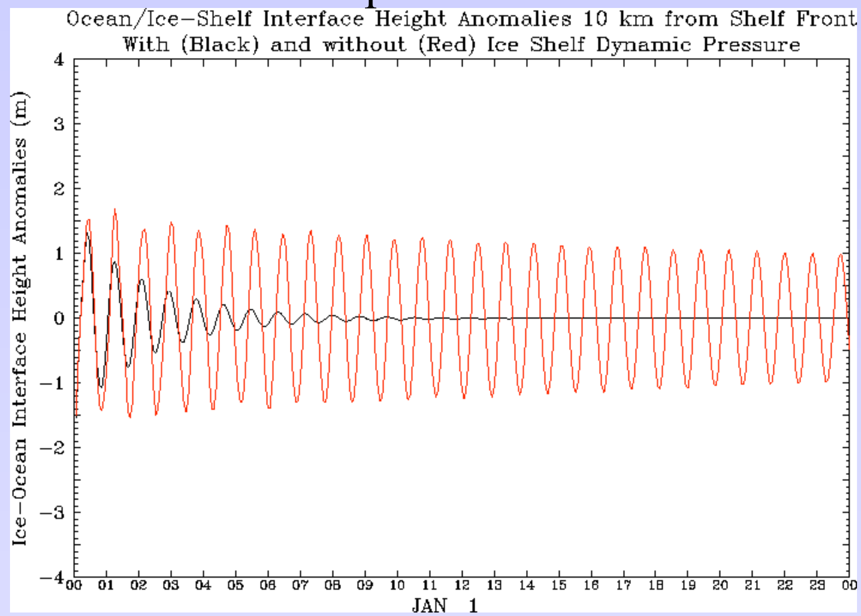
Impacts of Ice Shelf Dynamic Pressure

Shelf Cavity Near Grounding Line

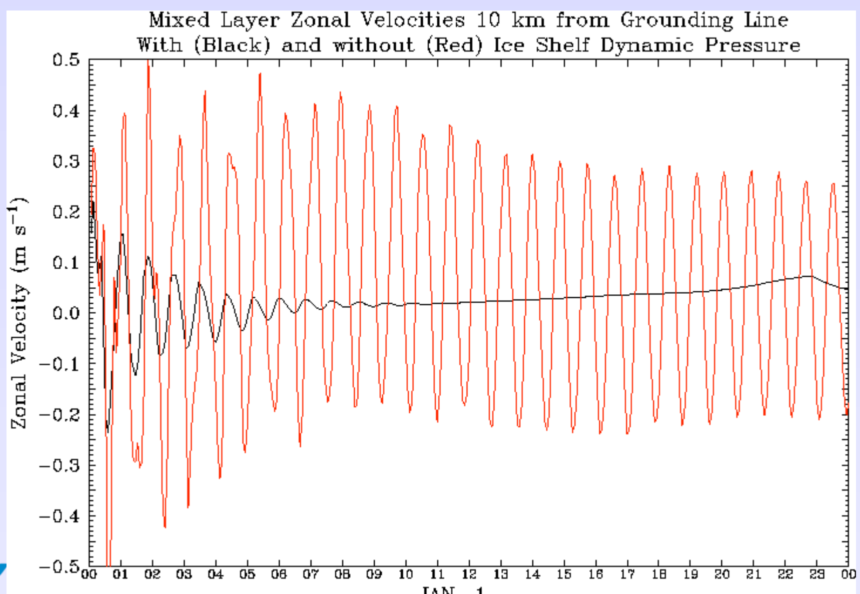
Open Ocean

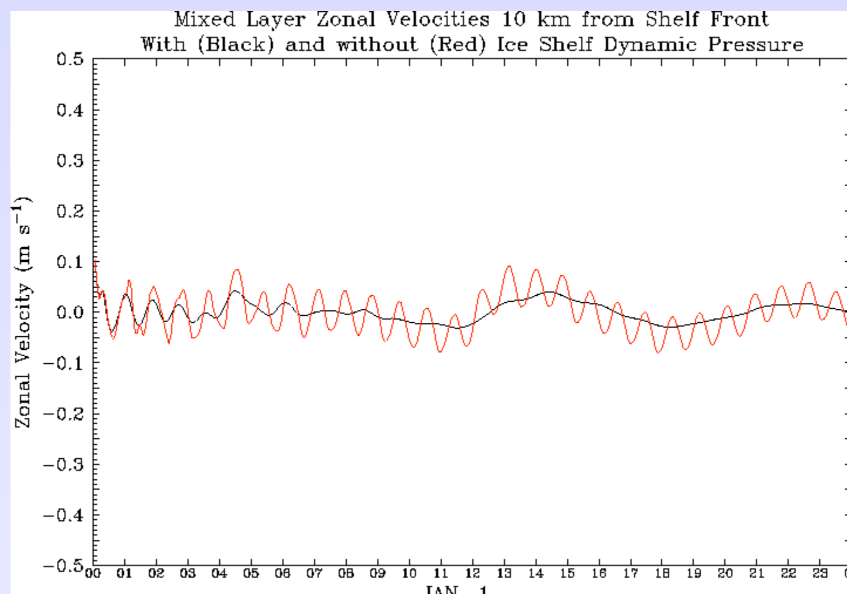
Surface Height Anomalies

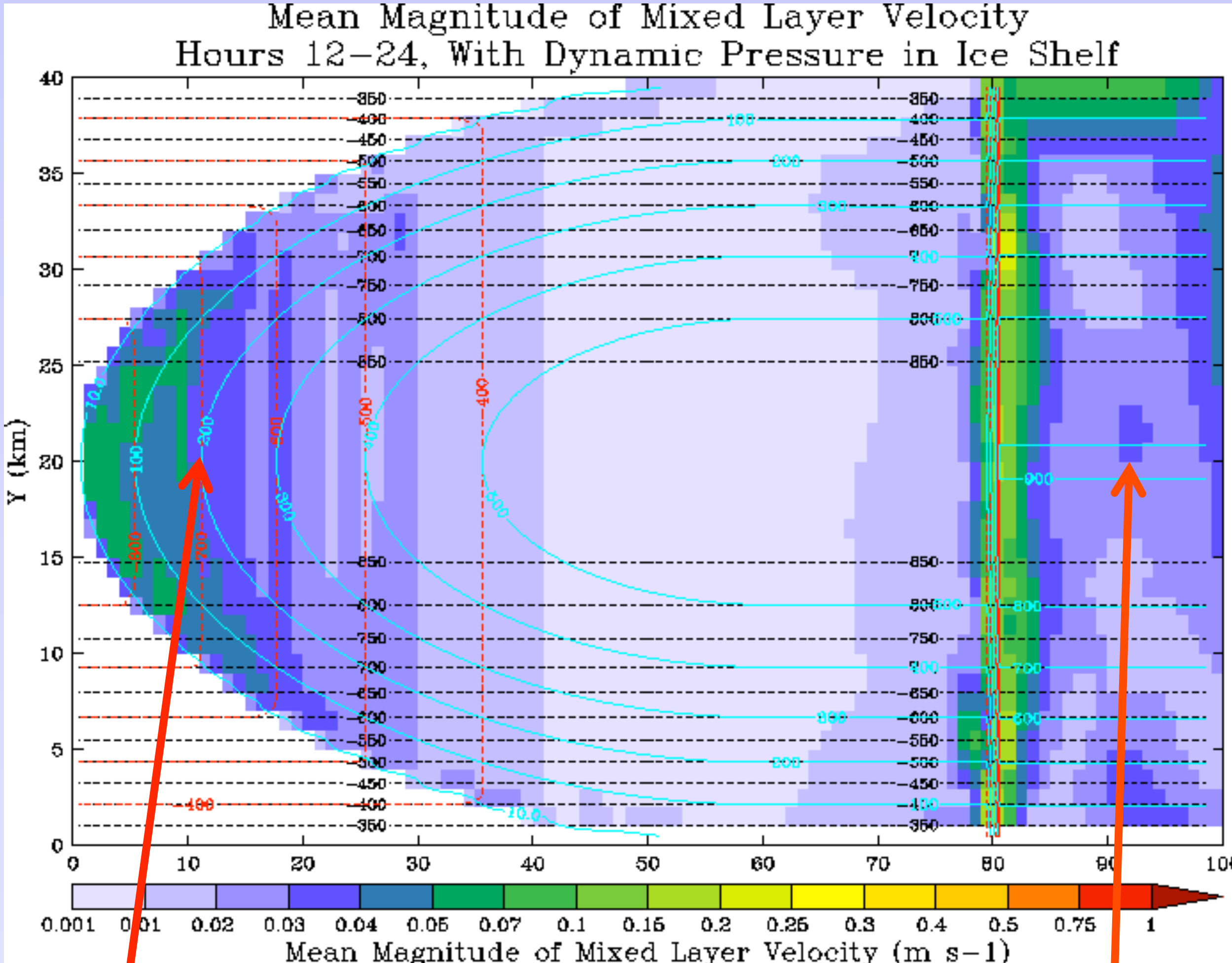


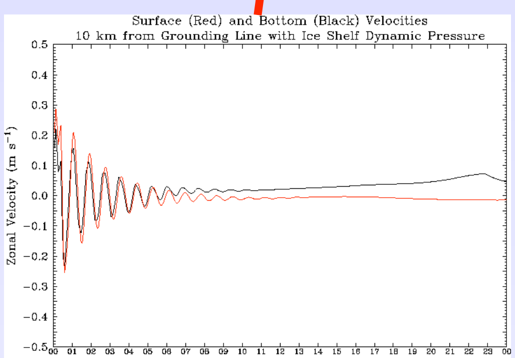


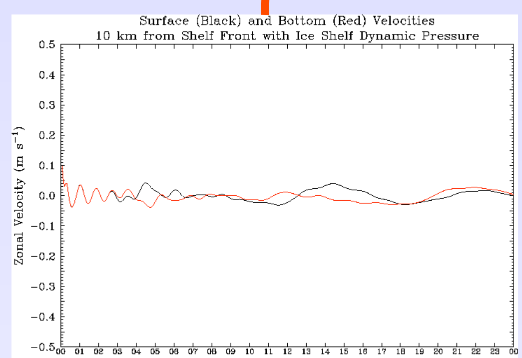
Zonal Mixed Layer Velocity



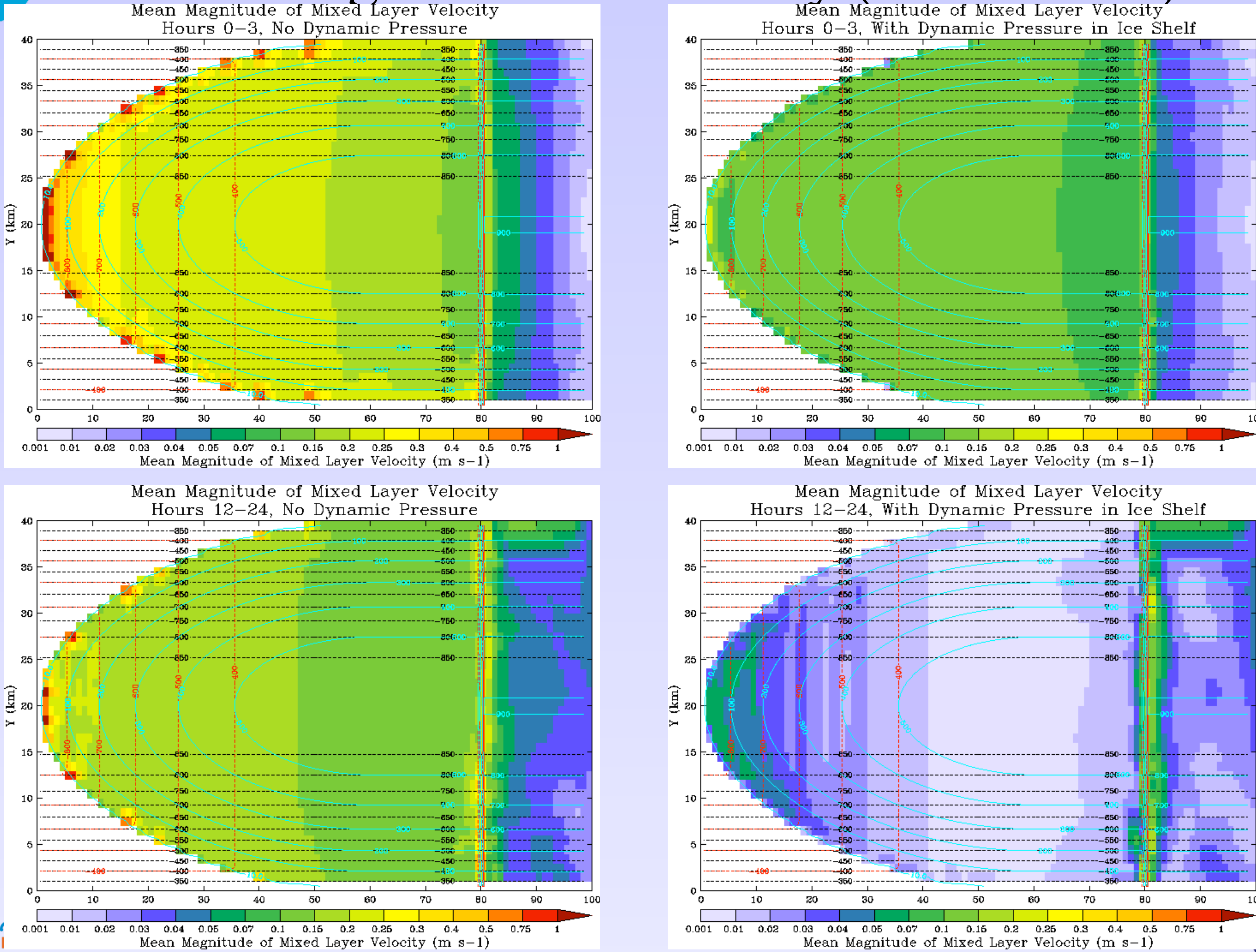



Mean Magnitude of Mixed Layer Velocity
Hours 12–24, With Dynamic Pressure in Ice Shelf
Y (km)
0.001 0.01 0.02 0.03 0.04 0.05 0.07 0.1 0.15 0.2 0.25 0.3 0.4 0.5 0.75 1
Mean Magnitude of Mixed Layer Velocity (m s−1)


Surface (Red) and Bottom (Black) Velocities
10 km from Grounding Line with Ice Shelf Dynamic Pressure
Zonal Velocity (m s−1)
JAN 1


Surface (Black) and Bottom (Red) Velocities
10 km from Shelf Front with Ice Shelf Dynamic Pressure
Zonal Velocity (m s−1)
JAN 1

Mean Magnitude of Velocity (≈Melt Rate)



Driving an Ice Shelf Forward at 3 km /day