Dependence of Pine Island Glacier Ice Shelf Basal Melt Rates on Subgrid-Scale Parameterizations of Mixing

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Abstract

Pine Island Glacier Ice Shelf (PIGIS) is melting rapidly from beneath due to the circulation of relatively warm water under the ice shelf, driven primarily by buoyancy of the meltwater plume. Basal melt rates predicted by ocean models with thermodynamically active ice shelves depend on the representation of environmental characteristics including geometry (grounding line location, ice draft and seabed bathymetry) and ocean hydrographic conditions, and subgrid-scale parameterizations. We developed a relatively high resolution (lateral grid spacing of 0.5 km, 24 terrain following levels) model for the PIGIS vicinity based on the Regional Ocean Modeling System (ROMS). Initial stratification was specified with idealized profiles based on observed hydrographic data seaward of the ice front. Predicted basal melt rate distributions were compared with satellite-derived estimates and stratification beneath PIGIS was compared with Autosub profiles. As in previous studies, we found that the melt rate was strongly dependent on the (specified) depth of the thermocline separating cold surface waters from deep, relatively warm waters, and on the presence of a submarine ridge under the ice shelf that impedes circulation of warm deep water into the back portion of the cavity. Melt rates were sensitive to the model's subgrid-scale parameterizations. The quadratic drag coefficient, which parameterizes roughness of the ice shelf base, had a substantial effect on the melt rate through its role in the three-equation formulation for ice-ocean buoyancy exchange. Turbulent tracer diffusion, which was parameterized by a constant value or various mixed layer models, played an important role in determining stratification in the cavity. Numerical diffusion became significant in some cases. We conclude that flow of warm water into the inner portion of the PIGIS cavity near the deep grounding line is sensitive to poorly constrained mixing parameterizations, both at the ice base and as a mechanism for allowing inflowing ocean heat to cross the sub-ice-shelf sill. Improved understanding of mixing processes is required as the community moves towards fully coupled ocean/ice-sheet models with evolving ice thickness and grounding lines.

Dependence of Pine Island Glacier Ice Shelf Basal Melt Rates on Subgrid-Scale Parameterizations of Mixing

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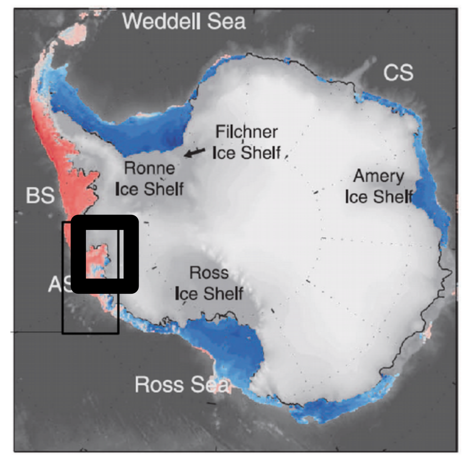
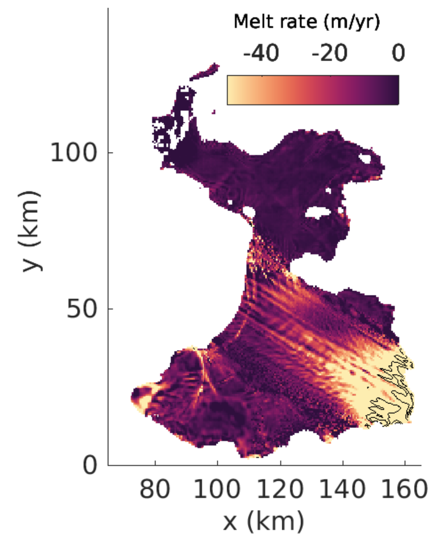
Introduction



The Pine Island Ice Shelf is melting rapidly from beneath due to the circulation of relatively warm water onto the continental shelf. Determining how the melt rate changes due to changing ocean conditions requires a detailed understanding of the mechanisms of heat transfer beneath the ice shelf.

Question

How well can we tune the melt rate in a thermodynamically coupled ocean—ice shelf model to match observationally inferred melt rates?



Observed Pine Island Ice Shelf Melt Rate (Shean et al., 2018, *Cryosphere Discuss.)*

Previous studies have shown that the primary controls on melt rate are:

1) Depth and slope of ice shelf base; presence of channels
2) Bathymetry in cavity
3) Heat content of ocean (thermocline depth, water mass properties)
4) Formulation of buoyancy exchange at the ice/ocean interface

Here we also consider

5) The role of tracer diffusion due to numerical diffusion and mixed layer formulation.

Ocean Model Description

- ROMS with ice shelf
- Ice shelf interacts thermodynamically with ocean (3-equation formulation); no other surface forcing
- 500 m horizontal grid spacing; 24 vertical levels
- Open boundaries allow disturbances to pass out of domain but maintain stratification with nudging

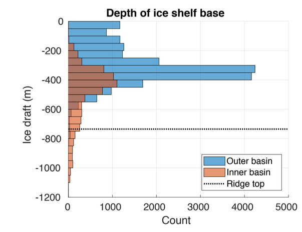
Reference simulation

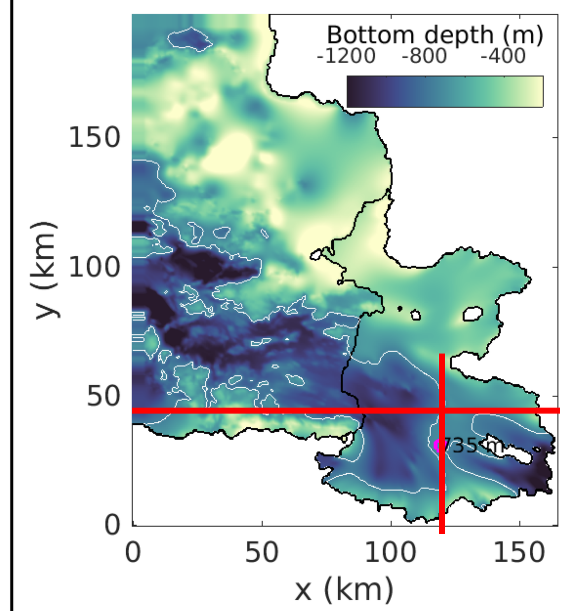
- Third-order tracer advection
- KPP vertical mixing, quadratic drag (cd=2.5e-3), Laplacian horizontal viscosity (A_H=15 m²/s)

Experiments

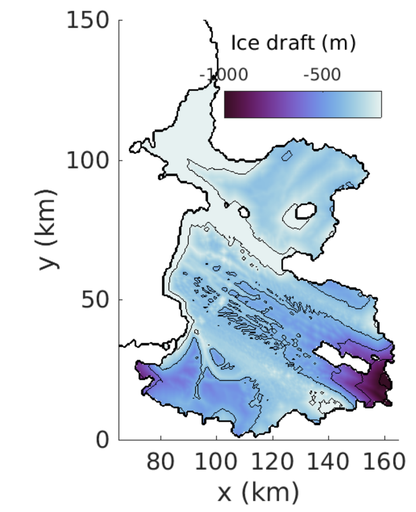
- MPDATA tracer advection
- Mellor-Yamada Level 2.5 mixed layer
- Varying explicit diffusion

Model Domain



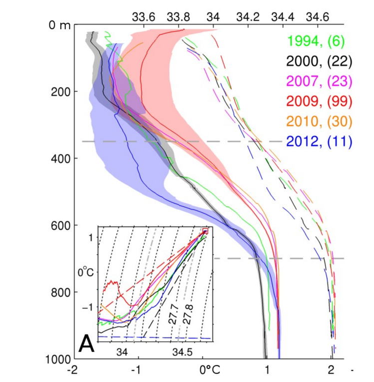


Bathymetry in model domain IBCSO data on continental shelf were blended with sub-ice shelf data (B. Smith, pers. comm.).

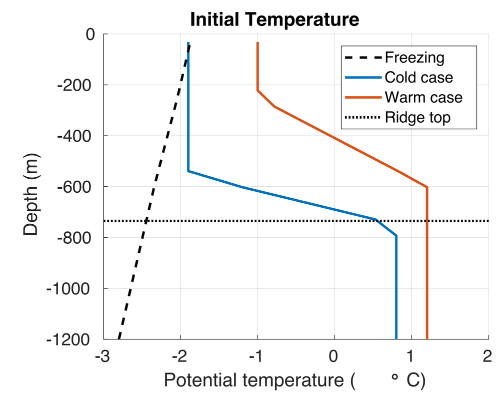


Ice draft for year 2013 derived from WorldView DEMs (Shean et al., 2018 *Cryosphere Discuss.*) .

Hydrography -- Initial Conditions

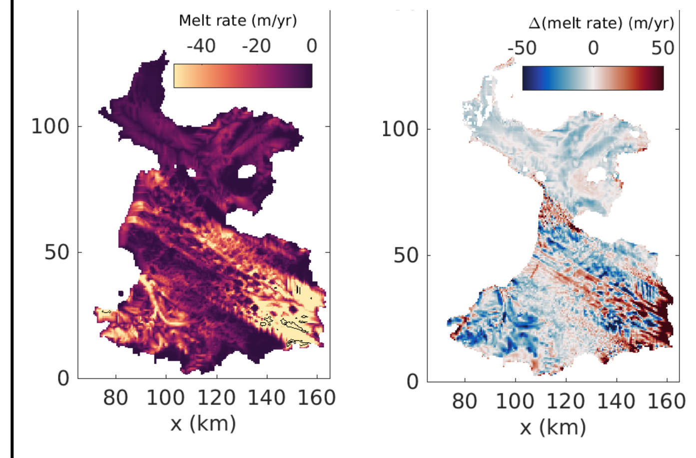


Ensemble of observed temperature and salinity profiles (Dutrieux et al, 2014, *Science*).

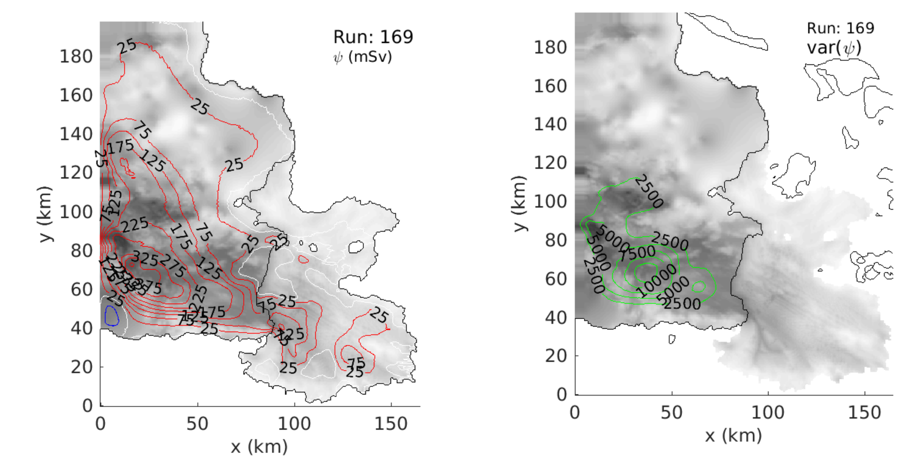


Idealized temperature profiles used in model runs represent extremes. Linear T-S relations are assumed.

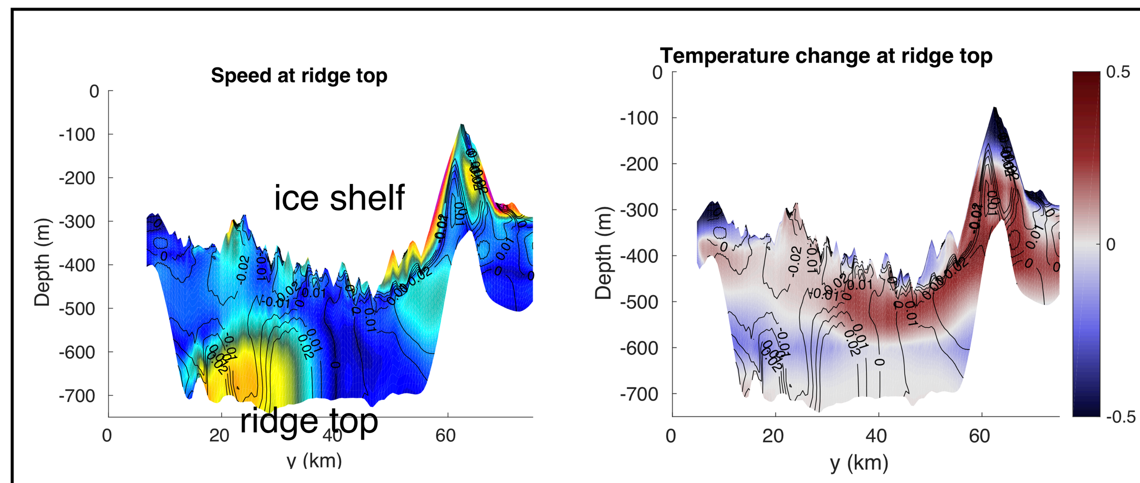
Simulated circulation and melt



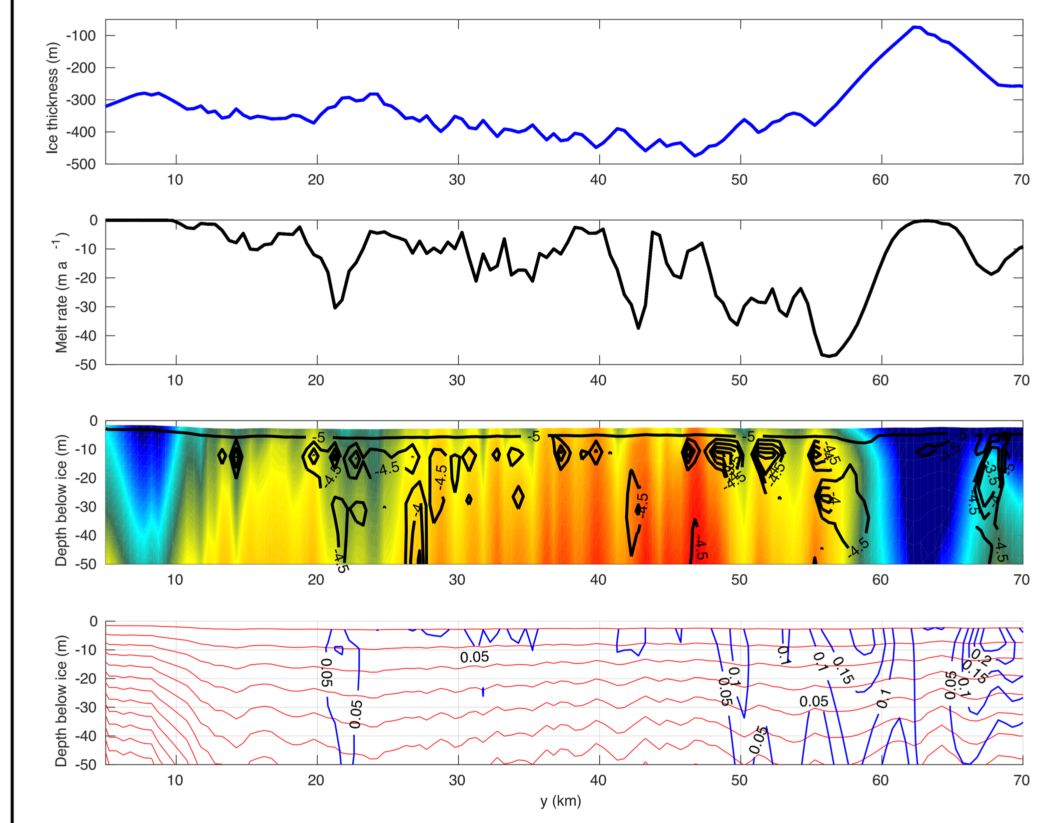
Reference model simulated melt rate (left) and difference from observed (right). Largest discrepancy is near grounding line.



Mean (left) and variance (right) of barotropic stream function. Ridge creates a potential vorticity barrier that isolates barotropic circulation in back cavity.



Flow over the ridge top is baroclinc. A broad, ~200 m thick layer near the bottom flows into the inner cavity at up to 5 cm/s and a ~20 m thick layer beneath the ice flows outward, especially along the sides of channels, at speeds up to 20 cm/s. Zoom of the basal boundary layer shown below..

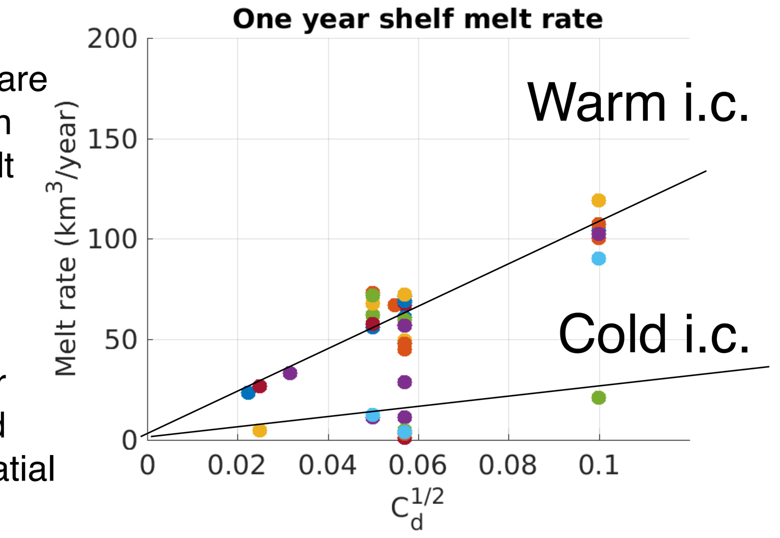


Basal l boundary layer above ridge. (a) depth of ice base (b) melt rate (c) temperature with log10(Akt) contours (d) speed (blue contours) and layer depths (red contours). Vertical resolution of the boundary layer is better than 10 m.

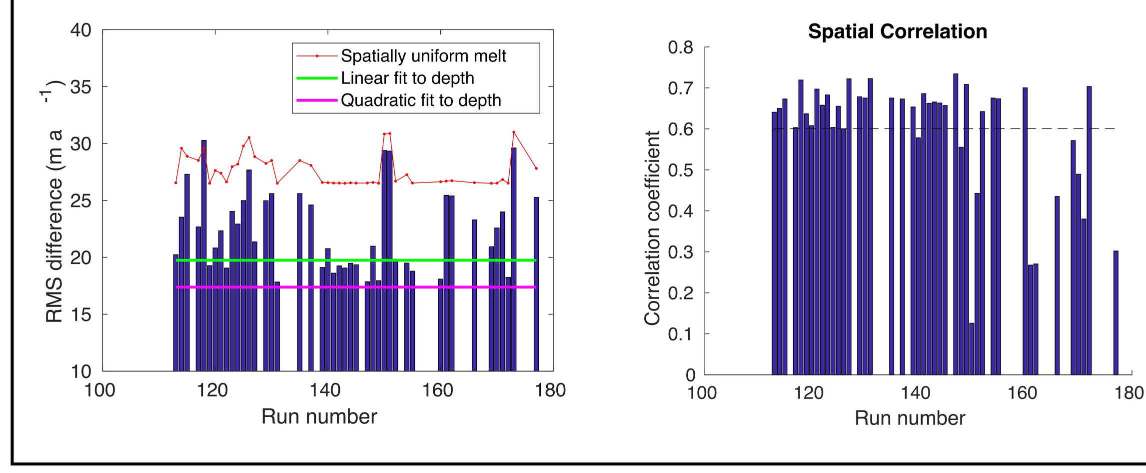
Parameter dependence of melt rate

The depth of the thermocline and the basal drag coefficient are the primary controls on spatially averaged melt rate.

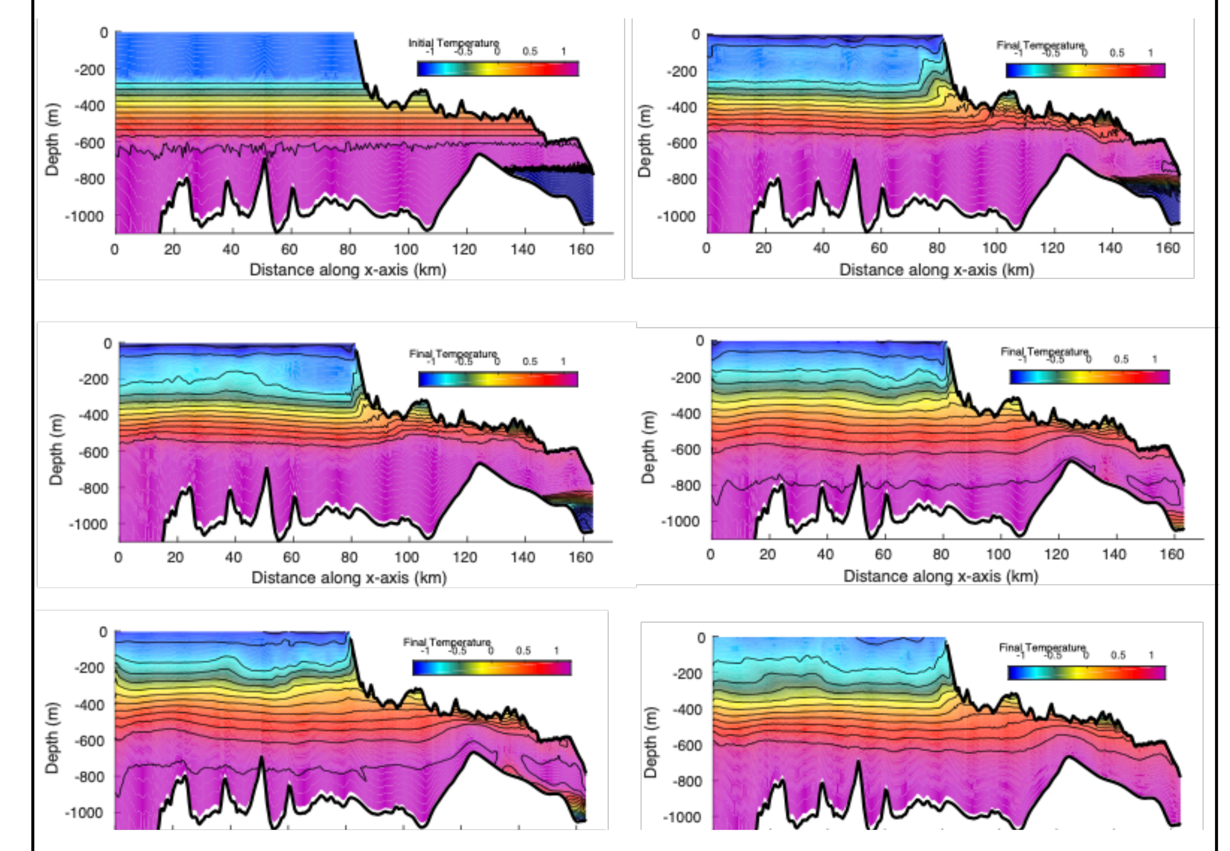
Varying background diffusivity, mixed layer formulation, and tracer advection scheme had some effect on the spatial pattern of melt.



Model simulations produce a melt pattern that is a better r.m.s. fit to observations than assuming a spatially constant value. The best simulations approach the error of an empirical fit that is a quadratic function of ice shelf base depth.

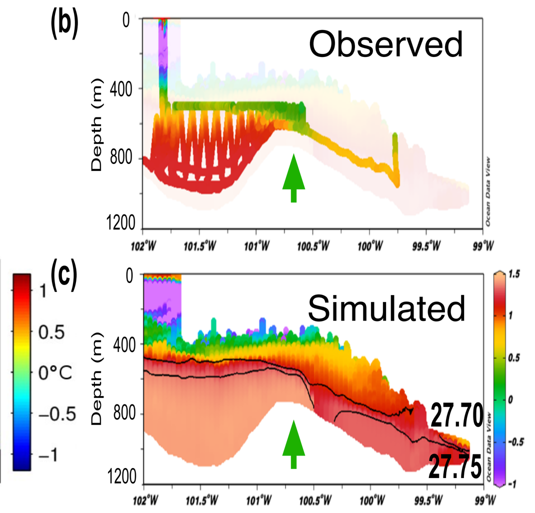


Simulations with similar melt patterns can have notably different stratification due to the differences in tracer diffusion. Observations of hydrography beneath the ice shelf, as done by Autosub, are helpful in selecting the best model configuration

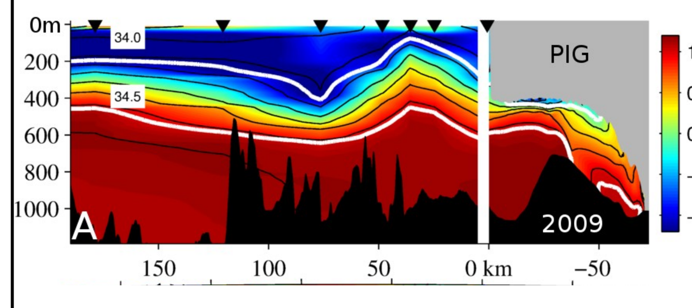


Compared with previous simulations (below), ours lacks melt water in the deepest reaches of the cavity.

Nakayama et al, 2019



Dutrieux et al, 2014



Conclusions

- Choice of drag coefficient and thermocline depth have dominant influence on spatially averaged melt rate.
- Varying other model parameters (tracer advection scheme, turbulence parameterization, background diffusivity) have comparatively little effect.
- Depth and slope of ice shelf base control spatial pattern of melt. Limitations on terrain-following vertical coordinate makes it difficult to represent melt in critical region near grounding line.
- High resolution basal topography has channels that guide outflow. Small scale features are reflected in basal melt.
- Observed melt rates alone are not sufficient to constrain model choices. Additional observations, such as hydrographic observations beneath the shelf, are necessary to select the best fit model.

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