POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Physics of the ocean boundary layer below ice shelves:

the relationship between modeling and observations

Xylar Asay-Davis

OASIIS Workshop, 15 June 2017

Leibniz Association

Potsdam Institute for Climate Impact Research

PIK

More observations like Tim Stanton's, please!

Physics of the ocean boundary layer below ice shelves: the relationship between modeling and observations

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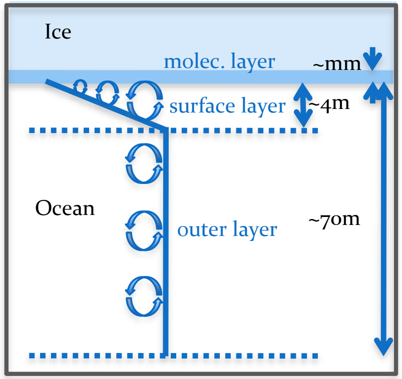
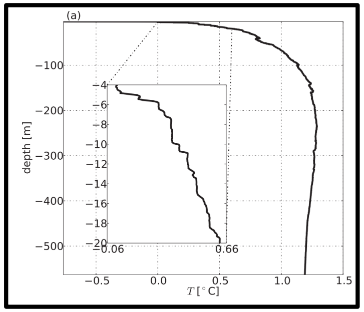
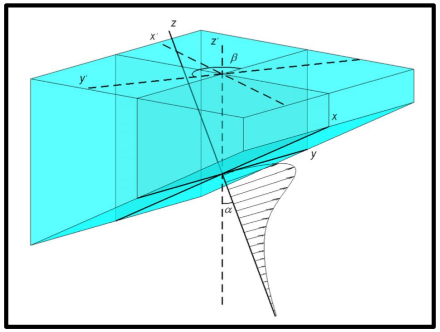
Outline

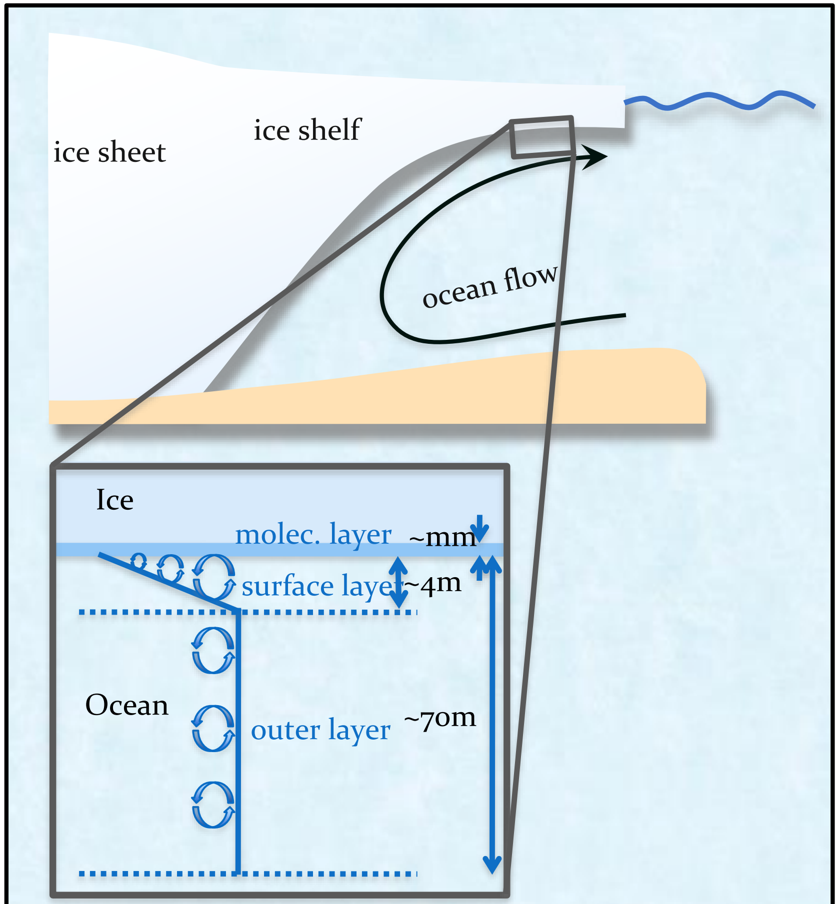
- **Observations and theory behind boundary-layer parameterizations used in ocean models**
- **Observations, theory and modeling suggesting need for new parameterizations**
- **Components of an improved boundary-layer parameterization**
- **New observations needed to better constrain parameterizations**



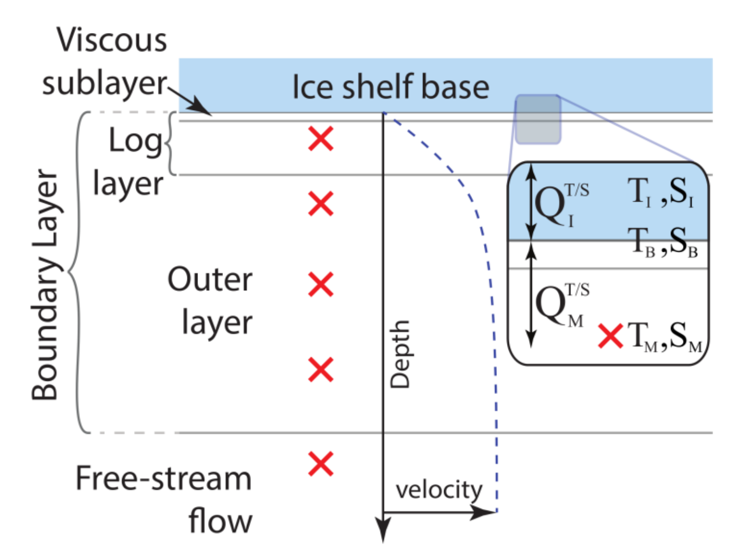




Theory and modeling of the boundary layer (BL)



Thermodynamic boundary layer
(e.g. McPhee et al. 1987)

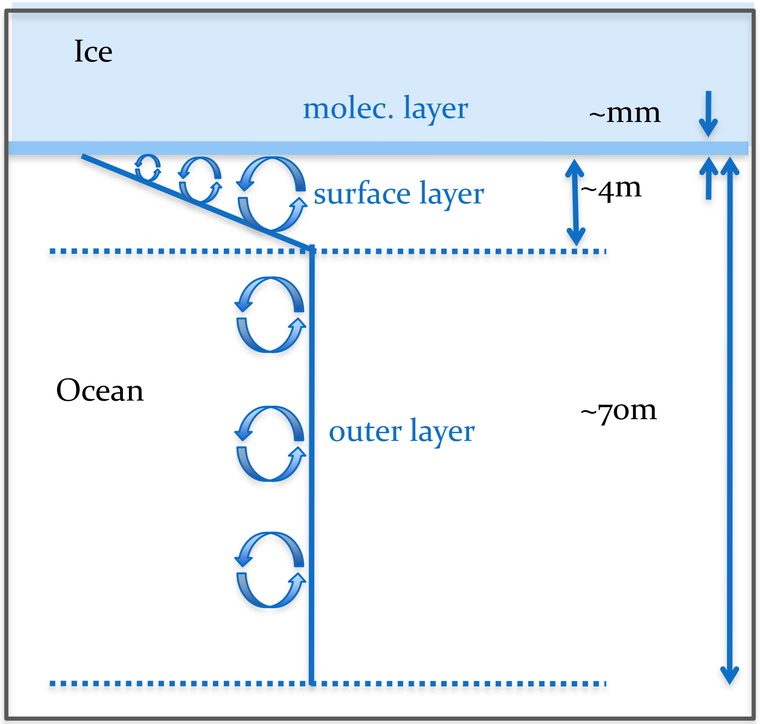


Velocity boundary layer
(Gwyther et al. 2015)

- Surface roughness, molecular diffusivities dominant in surface layer
- Turbulence (therefore eddy viscosity/diffusivities) dominant in outer layer

Theory: McPhee et al. 1987

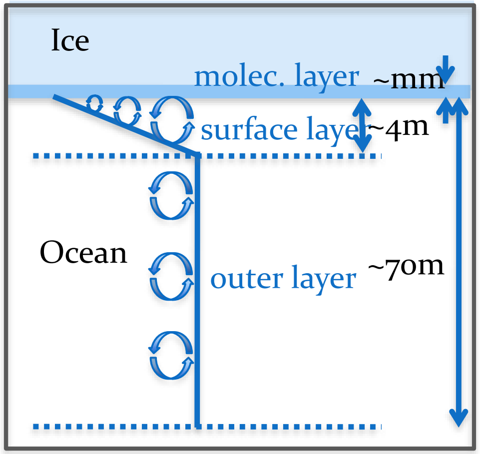
- **Applied to sea ice (not ice shelves)**
- **1D vertical model**



McPhee, M. G., Maykut, G. A., & Morison, J. H. (1987). Dynamics and Thermodynamics of the Ice/Upper Ocean System in the Marginal Ice Zone of the Greenland Sea. Journal of Geophysical Research, 92(C7), 7017–7031.

Theory: McPhee et al. 1987

- **Constant heat, salt flux through BL**



$$\langle w'T'\rangle_0 = wQ_L = -K_h \frac{\partial T}{\partial z} \quad (1)$$

$$\langle w'S'\rangle_0 = w(S_w - S_i) = -K_S \frac{\partial S}{\partial z} \quad (2)$$

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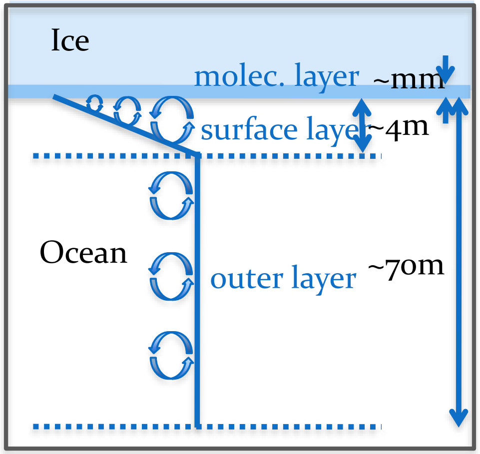

- **Constant heat, salt flux through BL**
- **Diffusivities $K_h(z)$ and $K_s(z)$ vary with space:**
  - **Weak, molec. diffusion in molec. Layer**
  - **Transition to turbulence in surface layer**
  - **Fully turbulent mixing in outer layer**

$$\langle w'T' \rangle_0 = wQ_L = -K_h \frac{\partial T}{\partial z} \qquad (1)$$

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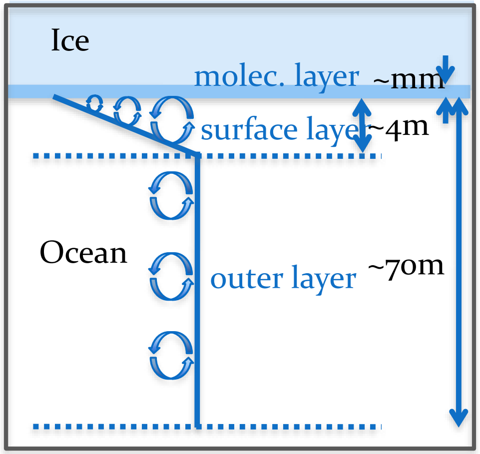
Theory: McPhee et al. 1987

- **Vertically integrate to get 2 of the 3 boundary conditions**
- **3rd boundary condition is freezing point**



$$\rho_i a_b L_i = \rho_i c_i \kappa_i \frac{\partial T_i}{\partial z}\Big|_b - \rho_w c_w u_* \Gamma_T [T_f(S_b, P_b) - T_w],$$

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"Three equations" using notation from Jenkins et al. (2010)

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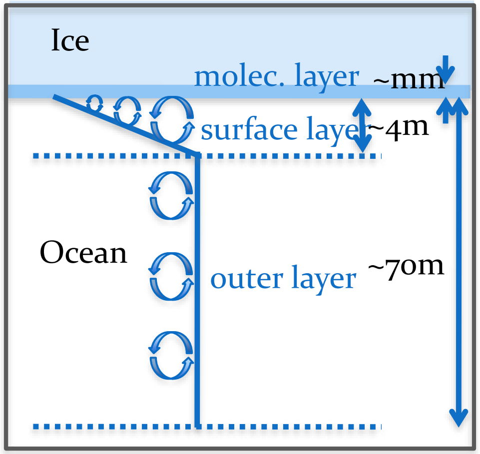
- **3rd boundary condition is freezing point**
- **Heat and salt transfer coeffs. $\Gamma_T(z_w)$ and $\Gamma_S(z_w)$**
  - **Parameterize transfer across BL**
  - **Functions of $K_h(z)$ and $K_s(z)$**
  - **Asymptote to constants as $z_w \rightarrow \infty$**
- **Similarly for drag coeff. $C_D(z_w)$**



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"Three equations" using notation from Jenkins et al. (2010)

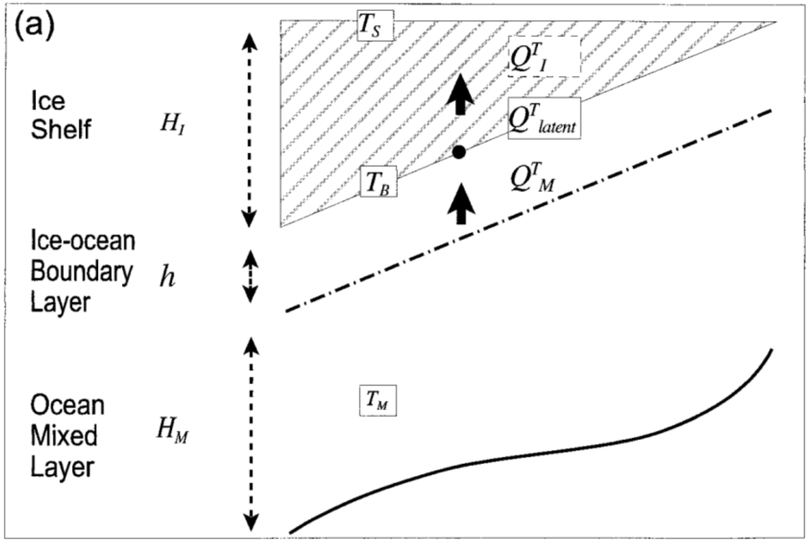
$$u_*^2 = C_d U^2,$$

Quadratic drag law using notation from Jenkins et al. (2010)

McPhee, M. G., Maykut, G. A., & Morison, J. H. (1987). Dynamics and Thermodynamics of the Ice/Upper Ocean System in the Marginal Ice Zone of the Greenland Sea. Journal of Geophysical Research, 92(C7), 7017–7031.

Modeling: Holland and Jenkins (1999)

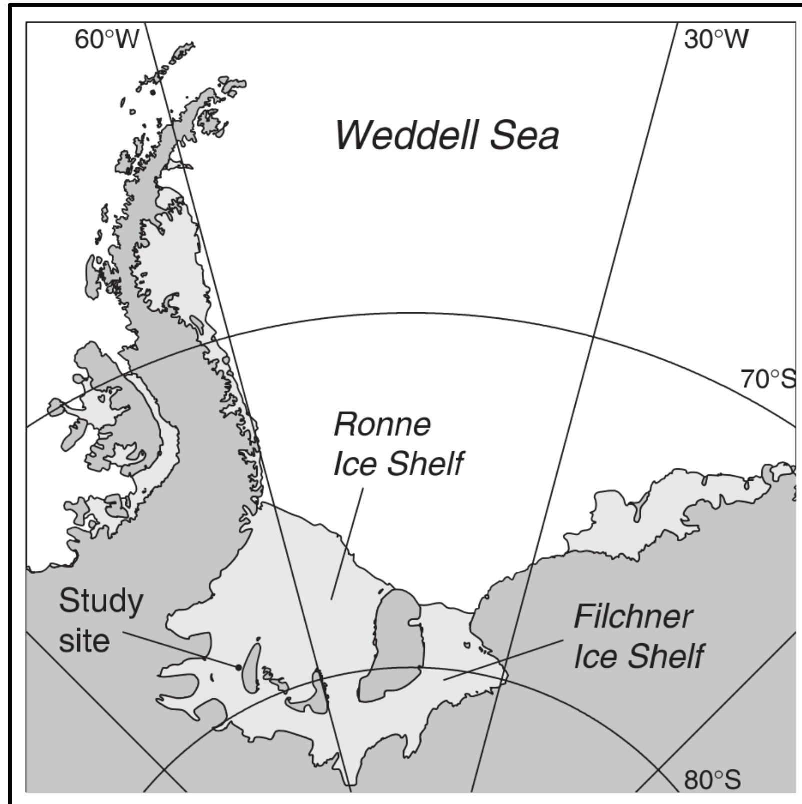
- **Applied McPhee et al. (1987) to ice shelves**
- **Currently most common BL parameterization in ocean models with ice-shelf cavities**



Holland, D. M., & Jenkins, A. (1999). Modeling Thermodynamic Ice–Ocean Interactions at the Base of an Ice Shelf. Journal of Physical Oceanography, 29(8), 1787–1800.

Observations: Nicholls et al. (1997); Corr et al. (2002)

- **"Site 3" on Ronne Ice Shelf**



Nicholls et al. (1997). New oceanographic data from beneath Ronne Ice Shelf, Antarctica. GRL, 24(2), 167.
Corr et al. (2002). Precise measurement of changes in ice-shelf thickness by phase-sensitive radar to determine basal melt rates. GRL, 29(8), 73-1-74–4.

Figures from Jenkins et al. (2010)

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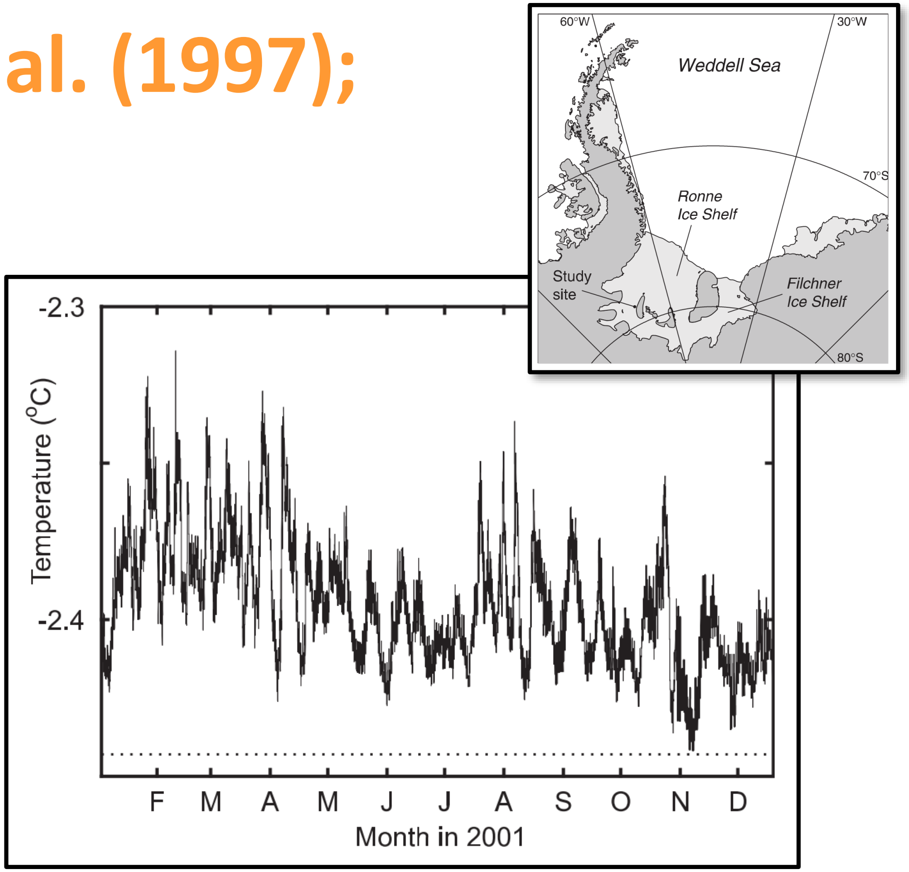
- **“Site 3” on Ronne Ice Shelf**
- **Long CTD time series of T, S and |u| at various depths**



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Figures from Jenkins et al. (2010)

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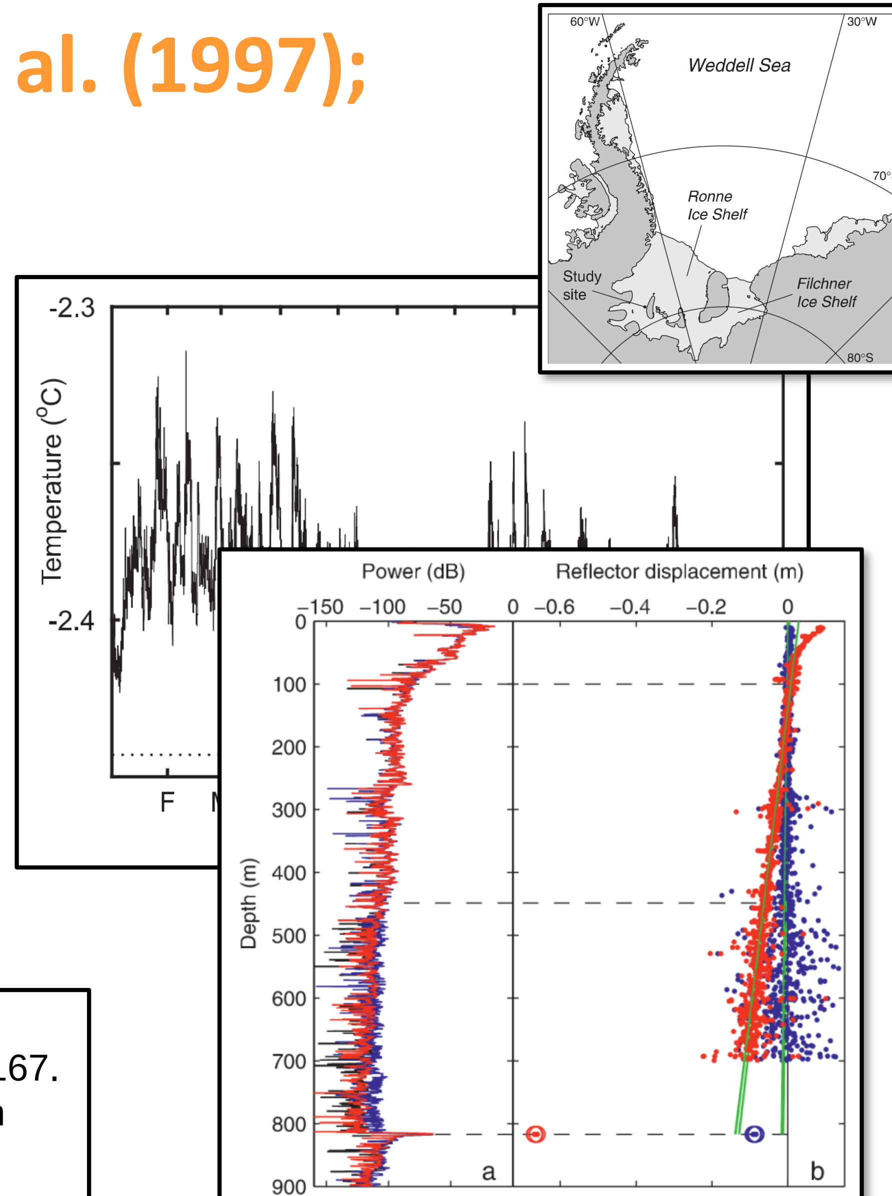
- **“Site 3” on Ronne Ice Shelf**
- **Long CTD time series of T, S and |u| at various depths**
- **Concurrent radar measurements of ice layers**
  - **Inferred mean melt rates**



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Model fit: Jenkins et al. (2010)

- **Found Best-fit parameters for Site 3**

Symbol	Value	Description
$C_d^{1/2}\Gamma_T$	0.0011	Thermal Stanton number
$C_d^{1/2}\Gamma_S$	3.1×10^{-5}	Diffusion Stanton number
$C_d^{1/2}\Gamma_{\{TS\}}$	5.9×10^{-4}	Stanton number
C_d	0.0097	Drag coefficient
Γ_T	0.011	Heat transfer coefficient
Γ_S	3.1×10^{-4}	Salt transfer coefficient
$\Gamma_{\{TS\}}$	0.006	Transfer coefficient

Jenkins, A., Nicholls, K. W., & Corr, H. F. J. (2010). Observation and parameterization of ablation at the base of Ronne Ice Shelf, Antarctica. Journal of Physical Oceanography, 40(10), 2298–2312.

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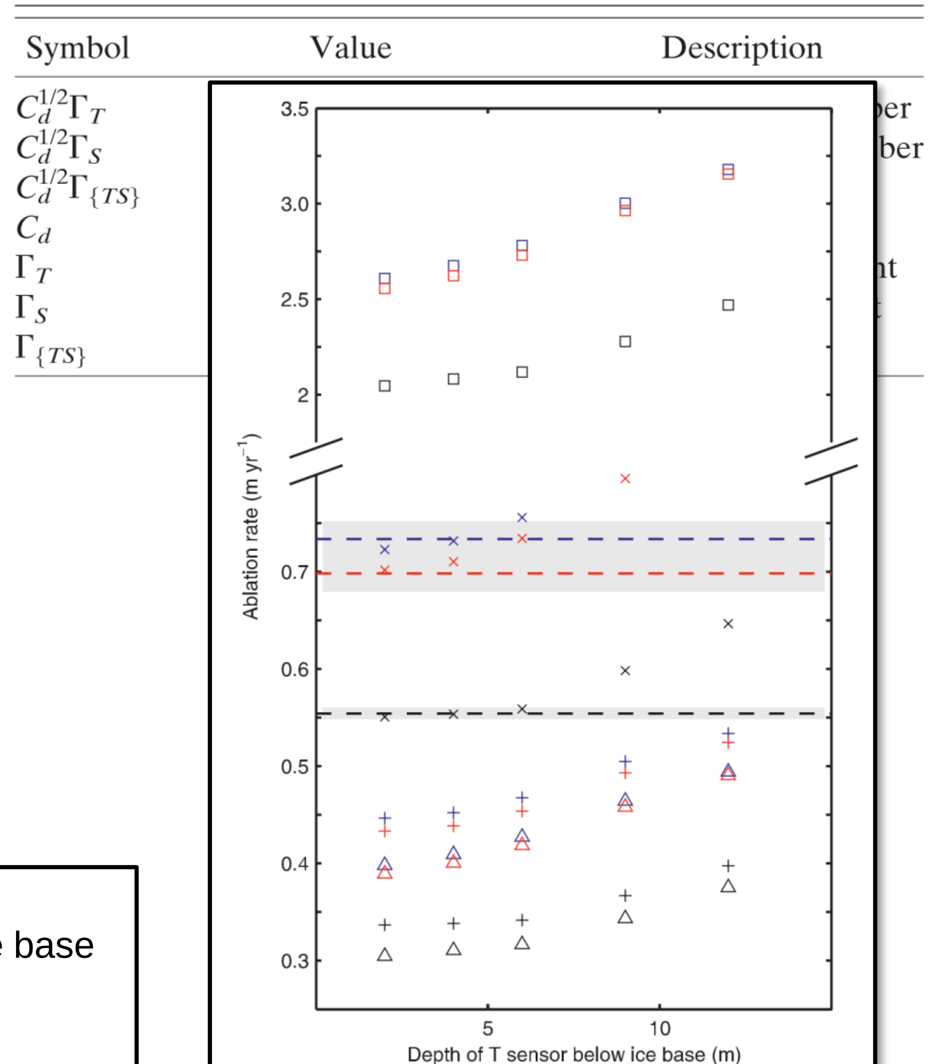
- **Showed McPhee et al. (1987) consistent with Ronne Site 3 observations**



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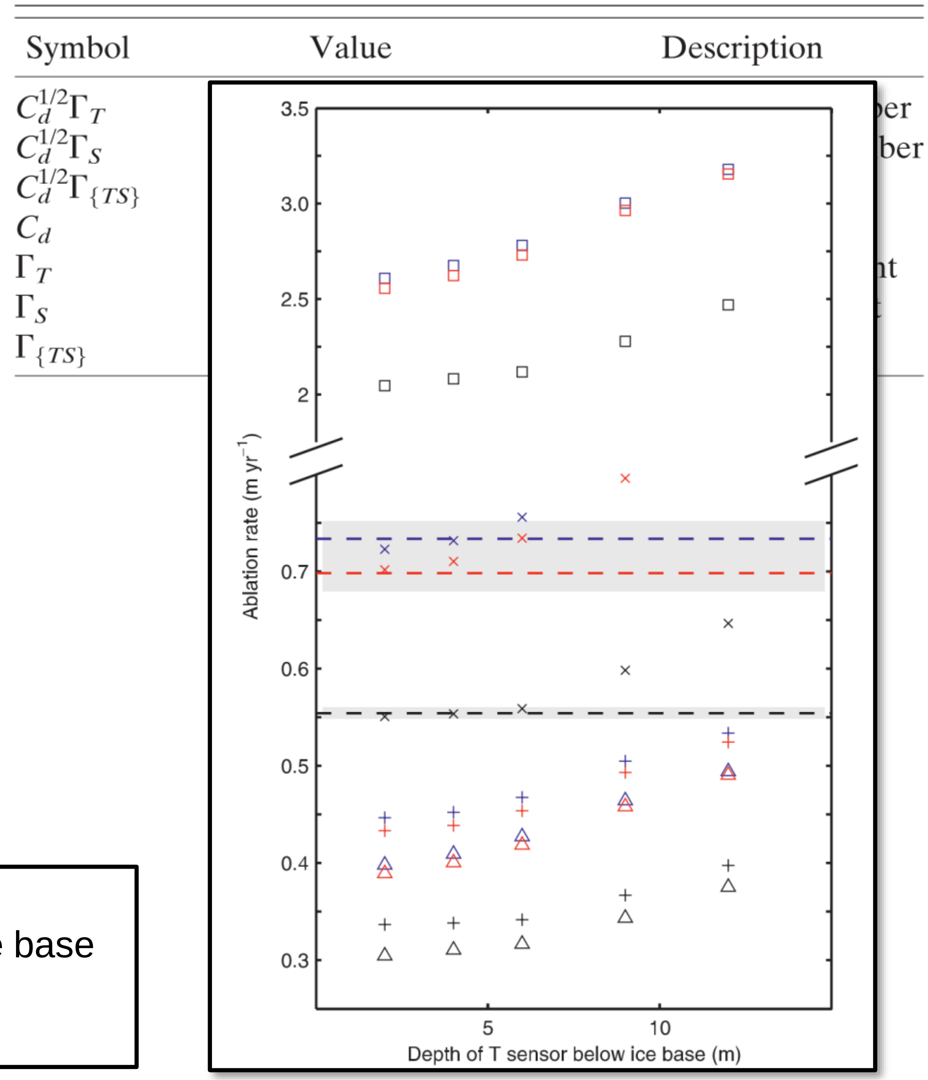
Model fit: Jenkins et al. (2010)

- **Found Best-fit parameters for Site 3**
- **Showed McPhee et al. (1987) consistent with Ronne Site 3 observations**
- **Indicate that best-fit Γ_T, Γ_s and C_D vary with z_w**
  Γ_T, Γ_s - transfer coefficients
  C_D - drag coefficient
  z_w - depth of CTD or grid cell



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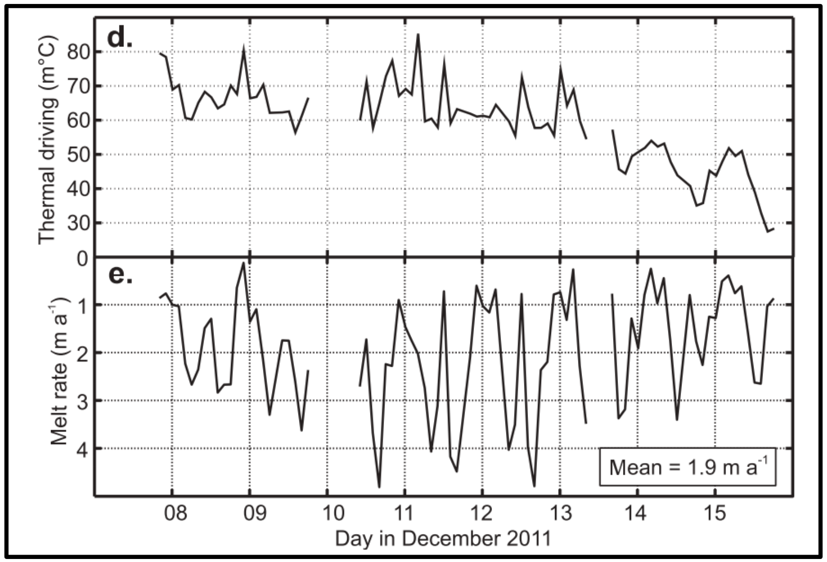
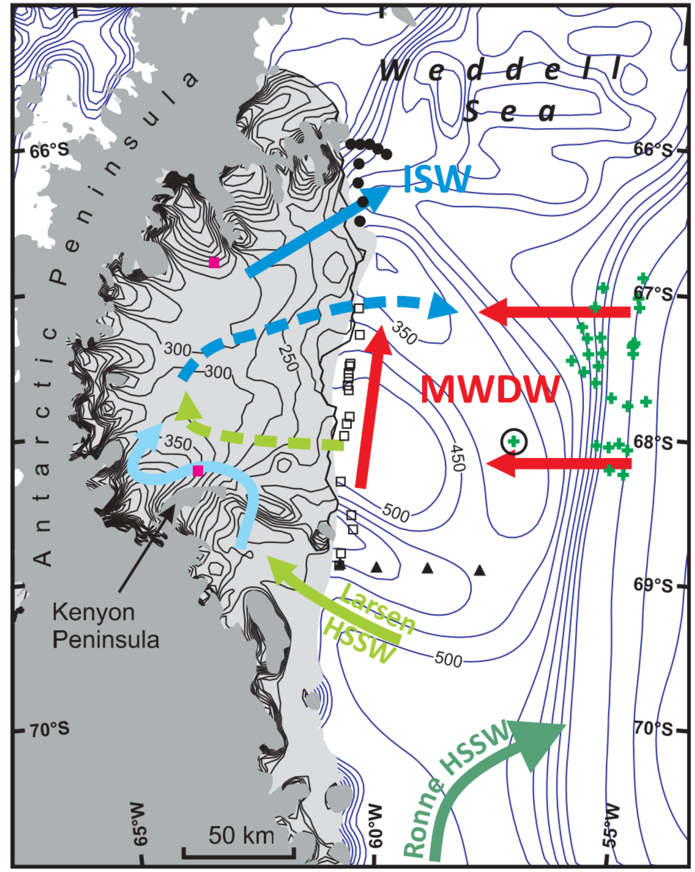
Observations: Nicholls et al. (2012)

- **Larsen C**
- **CTD, ADCP and pRes**
- **Best fit like Jenkins et al. (2010)**

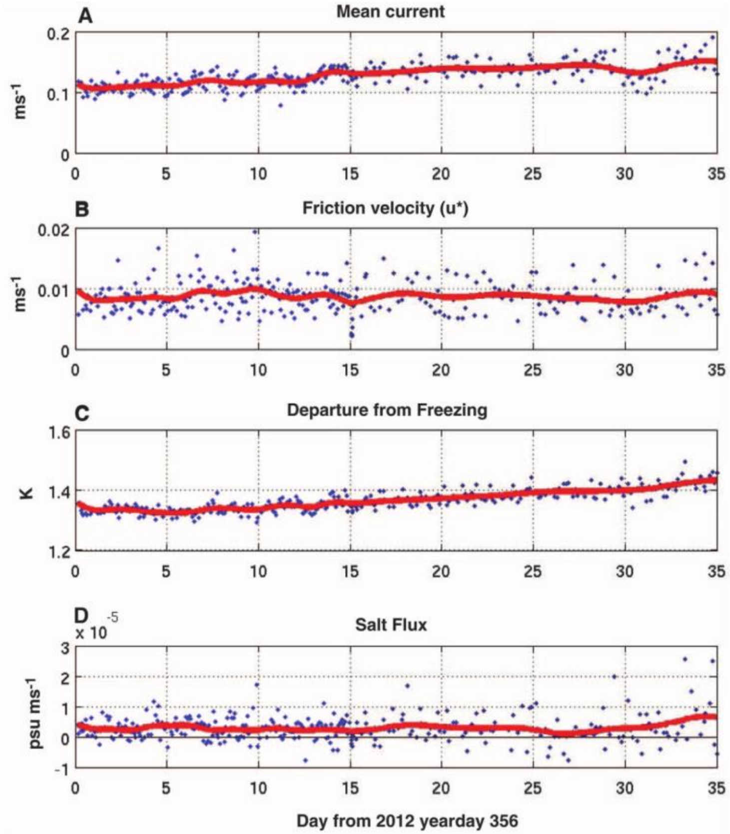




Nicholls et al. (2012). Ocean circulation beneath Larsen C Ice Shelf, Antarctica from in situ observations. Geophysical Research Letters, 39(19), L19608.

Observations: Stanton et al. (2013)

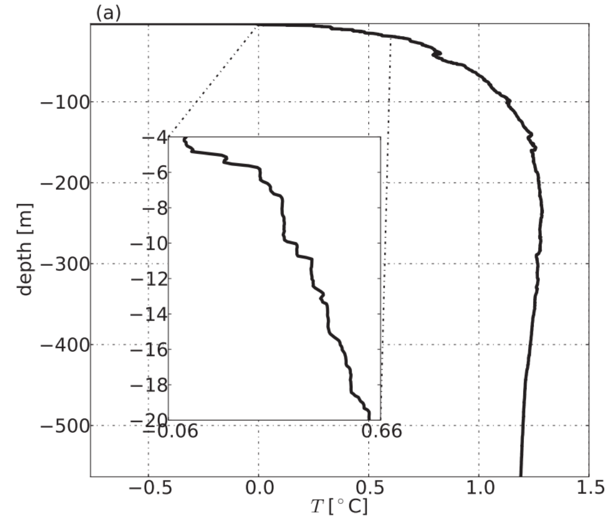
- We heard al about it yesterday
- PIG
- CTD
- 4Hz flux package (u, v, w, T, p, S)
  - Turb. heat, salt and mom. fluxes
- Acoustic backscatter (melt measurements)
- pRes (more melt measurements)
- Comparison with parameterizations in progress



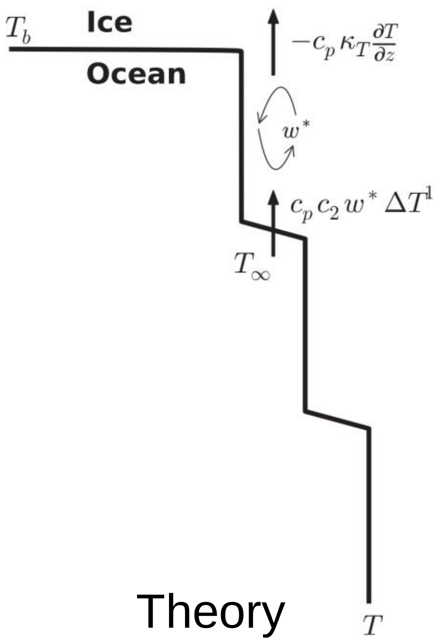
Stanton et al. (2013). Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica. Science (New York, N.Y.), 341(6151), 1236–9.

Theory/Obs: Kimura et al. (2015)

- **Thermal staircase under George VI**
- **Outer layer isn't uniformly turbulent**
- **Instead, diffusive convection**
  - **Double diffusion**
  - **Freshening from melt is stabilizing**
  - **Cooling from melt is destabilizing**
  - **Alternating stable, unstable regions**
- **New parameterizations likely needed**



Observations

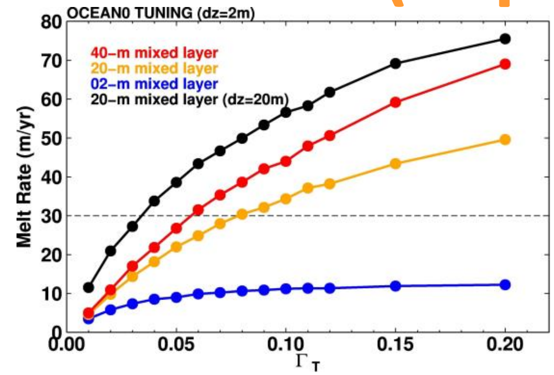


Theory

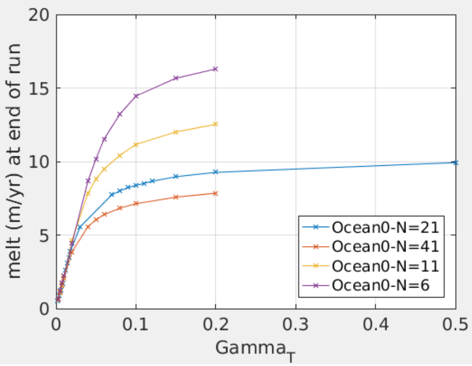
Kimura, S., Nicholls, K. W., & Venables, E. (2015). Estimation of Ice Shelf Melt Rate in the Presence of a Thermohaline Staircase. Journal of Physical Oceanography, 45(1), 133–148.

Model Intercomparison: Gwyther et al. (in prep.)

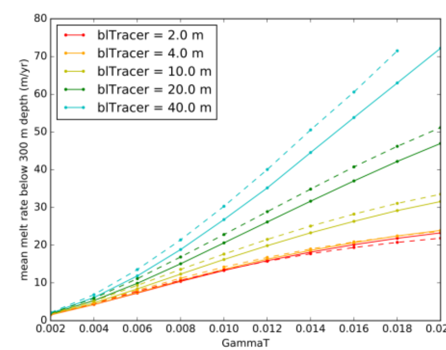
- **Simulations using the ISOMIP+ framework (Asay-Davis et al. 2016)**
- **ROMS and COCO melt rates do not converge with vert. resolution**
- **MPAS-O, POP2x and NEMO melt rates converge only if BL thickness held fixed (arbitrary length scale)**



COCO



ROMS



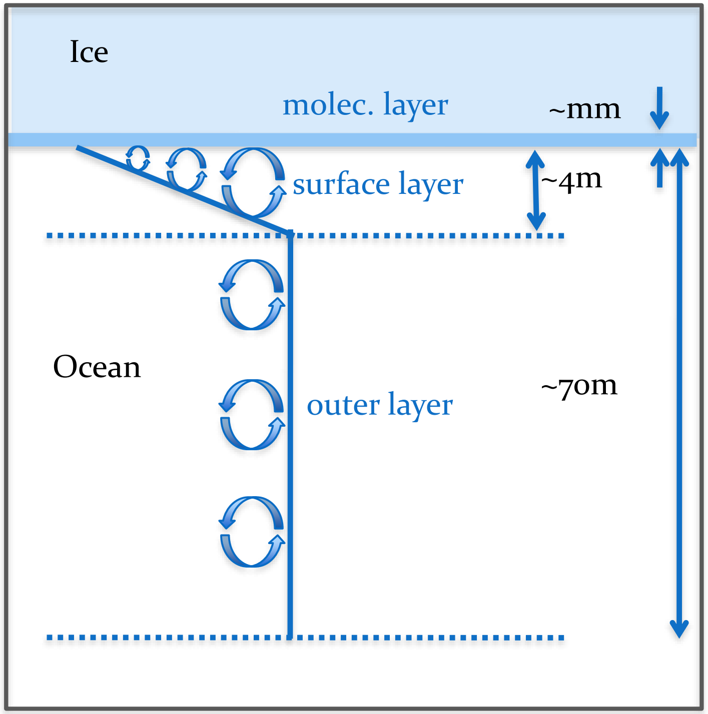
MPAS-O

Gwyther et al. (in prep.) The importance of vertical processes and resolution on basal melt of an ice shelf: a multi-model study within the ISOMIP+ framework.

Asay-Davis et al. (2016). Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: MISMIP v. 3 (MISMIP+), ISOMIP v. 2 (ISOMIP+) and MISOMIP v. 1 (MISOMIP1). Geoscientific Model Development, 9(7), 2471–2497.

Need better BL parameterizations: convergence

- **Ocean models sample T_w, S_w and u_w at depth z_w below ice-ocean interface**



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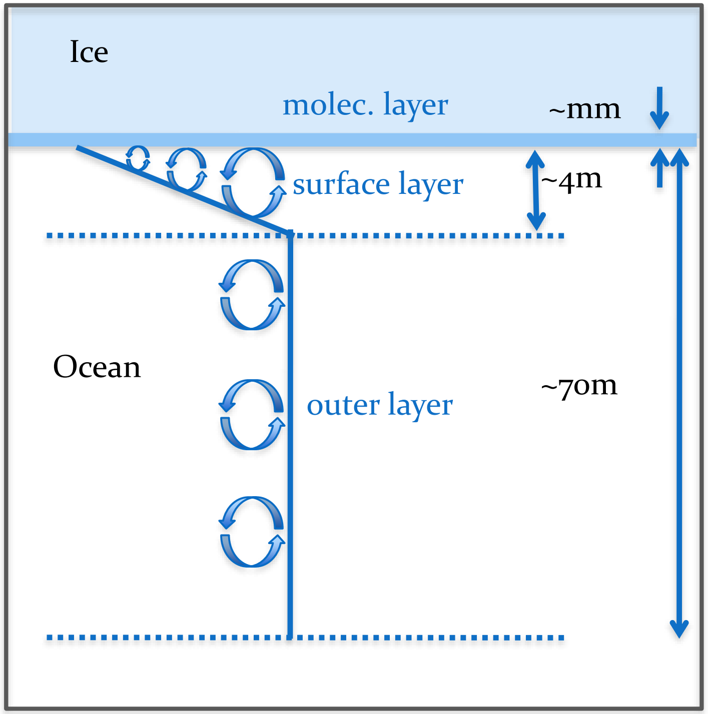

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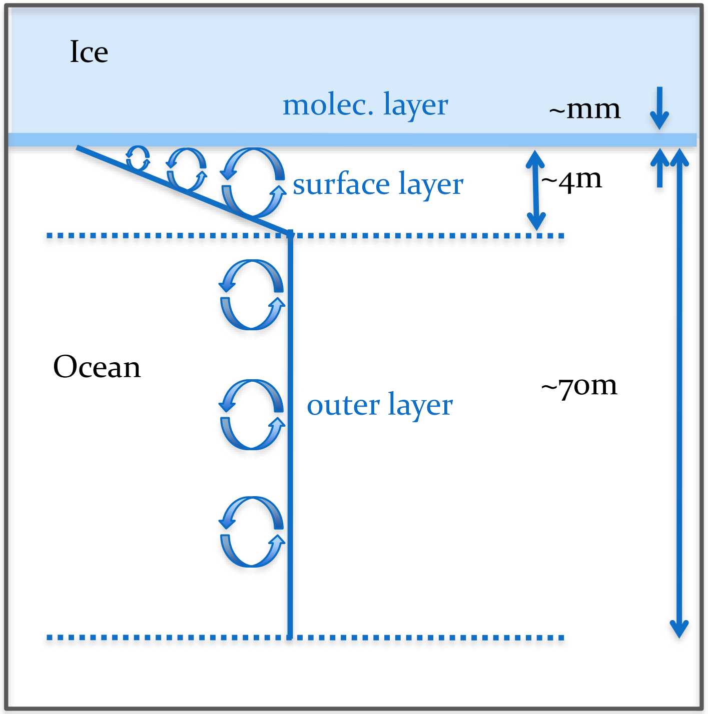

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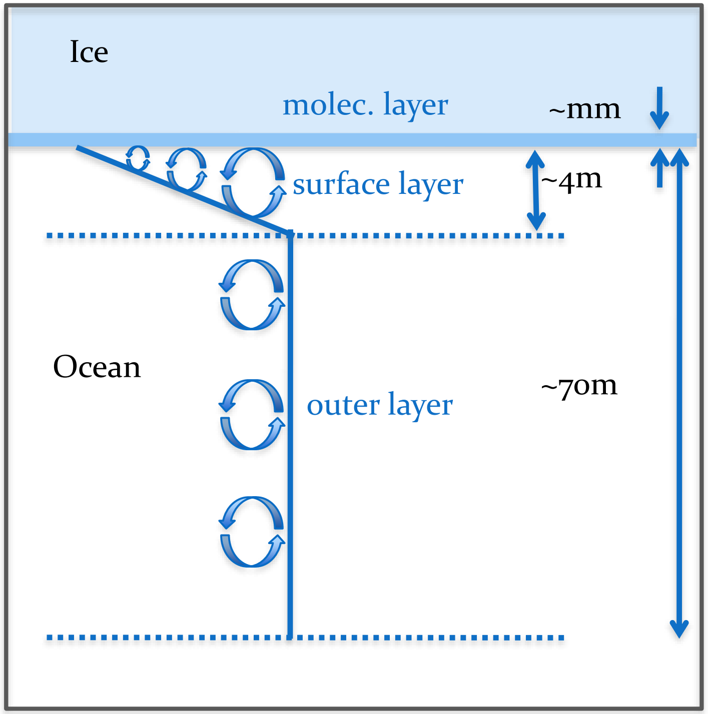
  - Use transfer coeffs. $\Gamma_T(z_w)$ and $\Gamma_S(z_w)$ that depend on $K_h(z)$ and $K_s(z)$
  - Use a z-dependent drag coeff: $u_*^2 = C_D(z_w)|u_w|^2$



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Need better BL parameterizations: buoyancy

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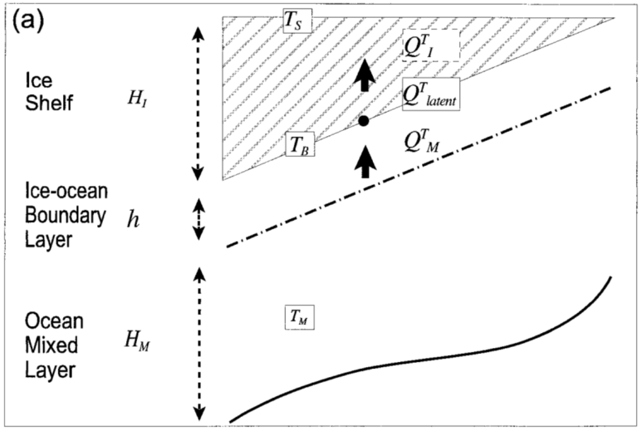
  - **But no buoyancy-driven flow in BL**



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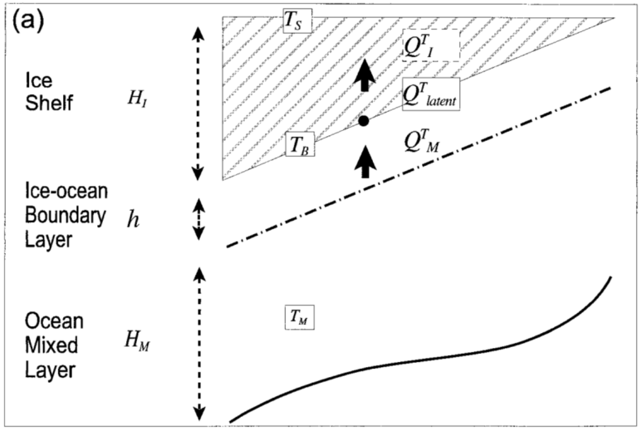
  - **But no buoyancy-driven flow in BL**
- **BL parameterization should include buoyancy-driven boundary current**



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Theory: Jenkins (2016)

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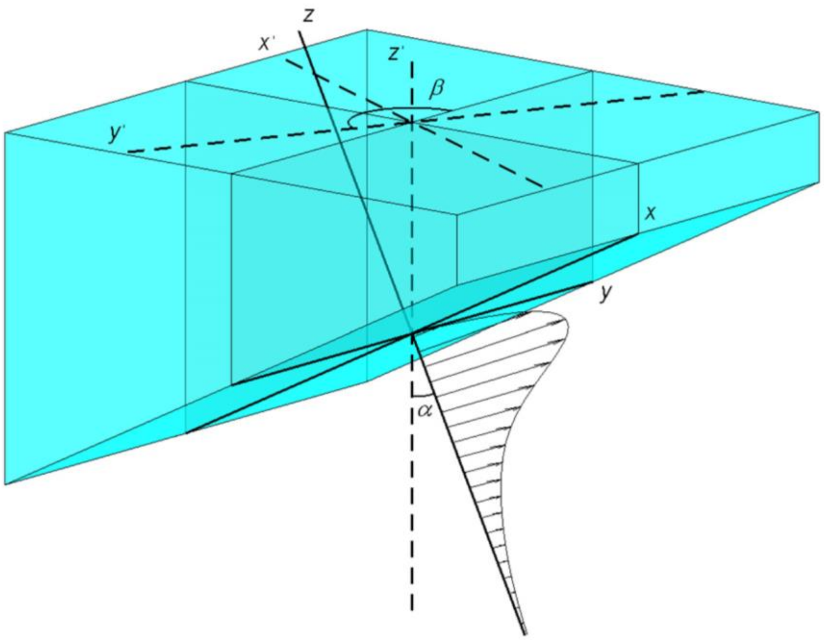

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P I K

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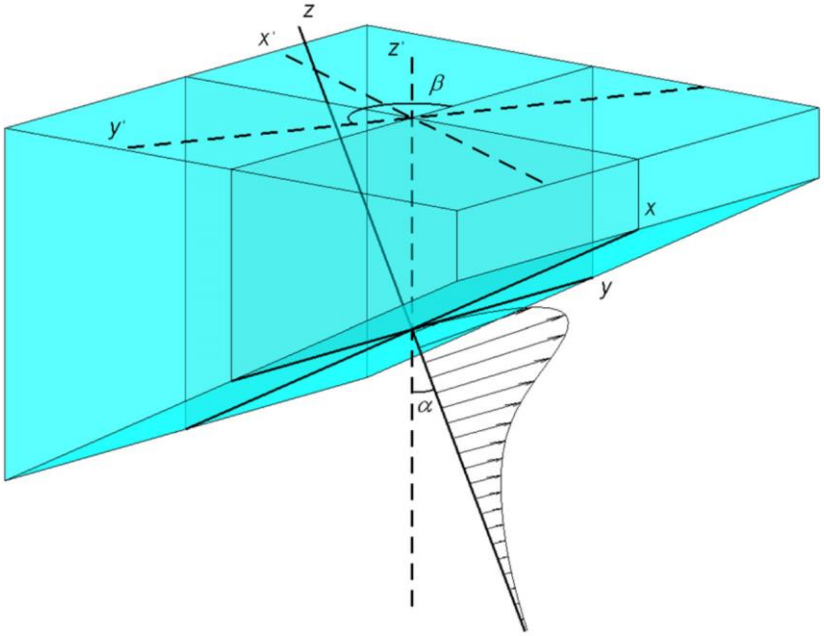
  - **Advection**



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- **Allows along- and across-slope:**
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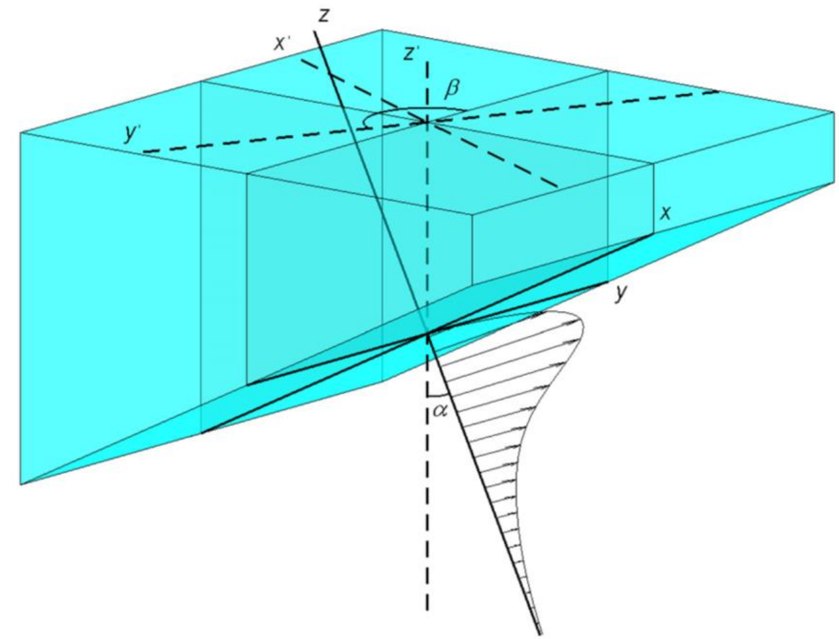
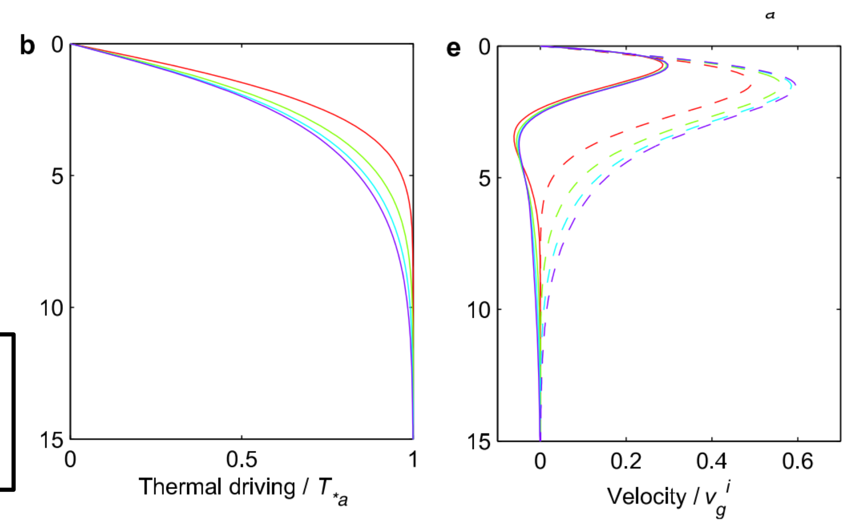
  - **Advection**
- **Boundary current**
  - **Inner Ekman boundary layer**
  - **Outer geostrophic region**

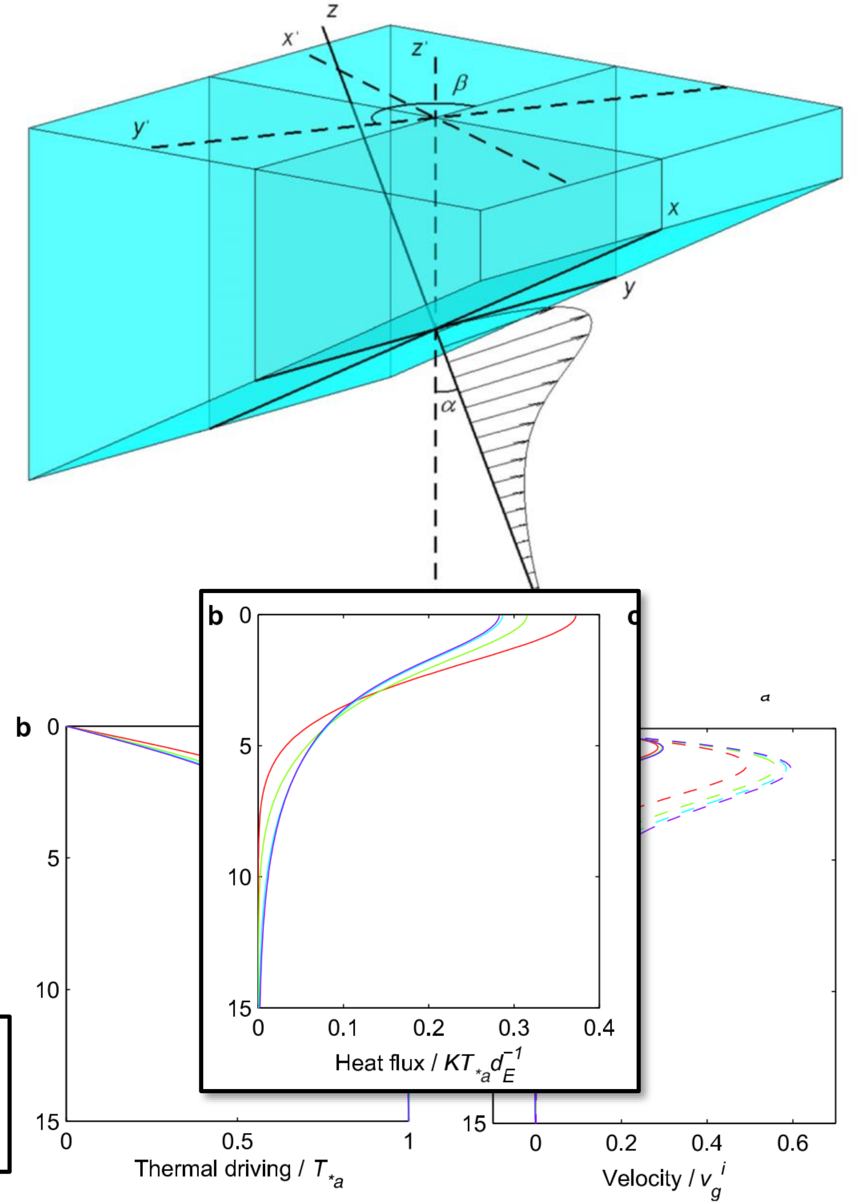




Jenkins, A. (2016). A Simple Model of the Ice Shelf–Ocean Boundary Layer and Current. Journal of Physical Oceanography, 46(6), 1785–1803.

Theory: Jenkins (2016)

- **1D model but not just vert. diffusion**
- **Allows along- and across-slope:**
  - **Gradients (in T, S, u, etc.)**
  - **Advection**
- **Boundary current**
  - **Inner Ekman boundary layer**
  - **Outer geostrophic region**
- **Heat flux not const. in BL**



Jenkins, A. (2016). A Simple Model of the Ice Shelf–Ocean Boundary Layer and Current. Journal of Physical Oceanography, 46(6), 1785–1803.

Promising directions

Theory and Modeling

- **Jenkins (2016), but needs theory for non-const. $K_h(z)$**
- **"Modelling the ice-shelf ocean boundary layer" (Supervised by John Taylor, Paul Holland and Keith Nicholls)**
  - **Very high resolution simulations**
  - **Modeling (not parameterizing) boundary-layer processes**

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  - Modeling (not parameterizing) boundary-layer processes

Observations

- Tim Stanton's observations below PIG
- Planned boreholes under FRIS, Ross, Amery… if properly instrumented
- As an end member (e.g. zero slope), similar obs. under sea ice

Summary

- **BL parameterization in sub-ice-shelf ocean models:**
  - **Derived for sea ice (no buoyant flow)**
  - **Not well constrained**
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Summary

- **BL parameterization in sub-ice-shelf ocean models:**
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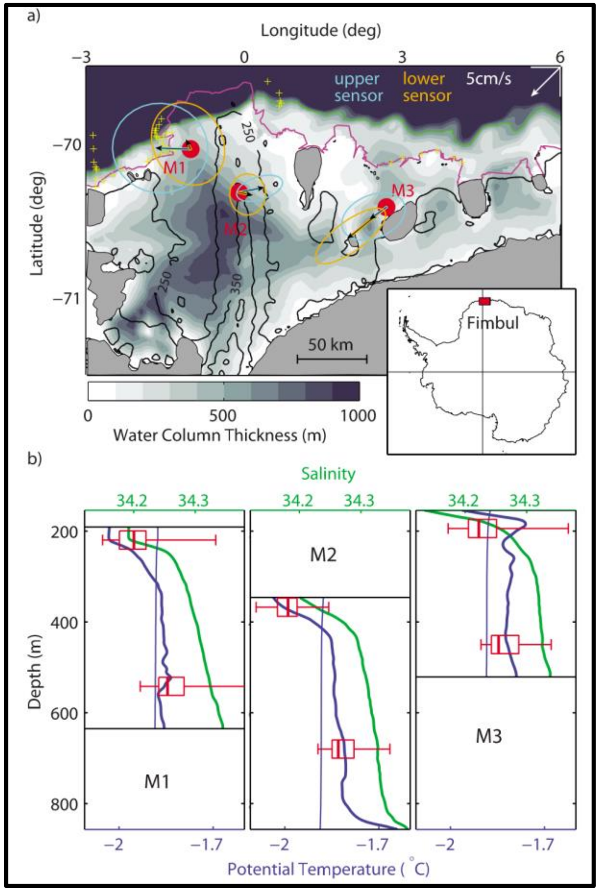
- **Observations needed to:**
  - **Differentiate possible parameterizations**
  - **Constrain parameters**
  - **Span a range of conditions**
    - **Warm, cold cavities**
    - **Melting, freezing (including frazil)**
    - **All 3 modes of melting**

Thank you

Other related observational data sets

- **Not yet used to (in)validate melt parameterizations**
- **Some do not include pRes (or other melt rate) measurements**
- **Hattermann et al. (2012)**
  - **Fimbul Ice Shelf**
  - **CTD (T, S and u)**
  - **no pRes (no independent melt rates)**



Hattermann et al. (2012). Two years of oceanic observations below the Fimbul Ice Shelf, Antarctica. Geophysical Research Letters, 39(12), L12605.

Observations: Herraiz-Borreguero et al. (2013, 2015)

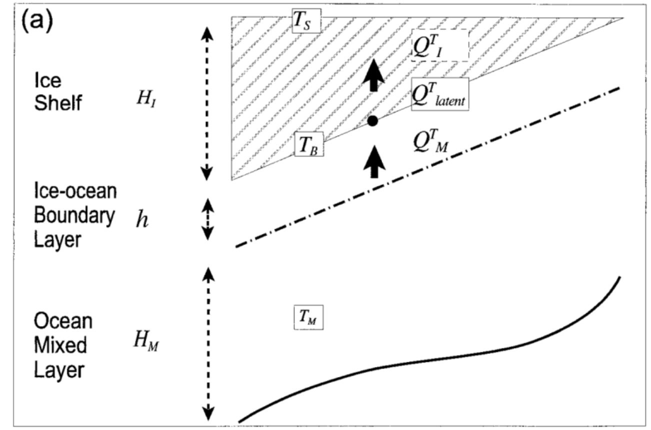
- …among other papers
- Amery Ice Shelf
- CTD, no pRes

Herraiz-Borreguero et al. (2013). Ice shelf/ocean interactions under the Amery Ice Shelf: Seasonal variability and its effect on marine ice formation. Journal of Geophysical Research: Oceans, 118(12), 7117–7131.

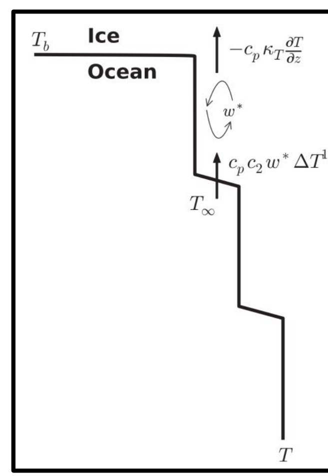
Herraiz-Borreguero et al. (2015). Circulation of modified Circumpolar Deep Water and basal melt beneath the Amery Ice Shelf, East Antarctica. Journal of Geophysical Research: Oceans, 120(4), 3098–3112.

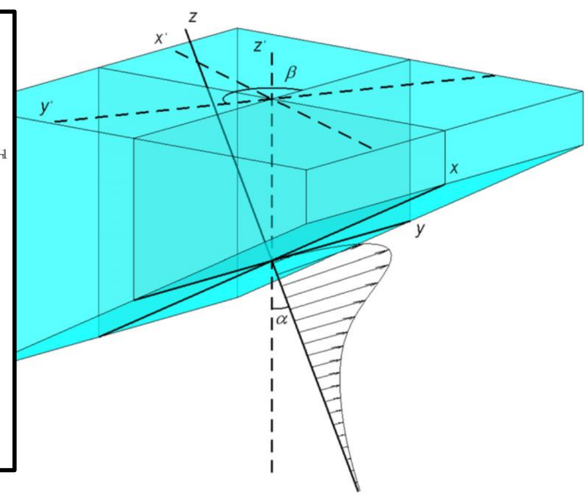
Need better BL parameterizations: buoyancy

- **In current BL params. (McPhee et al. 1987):**
  - **Buoyancy reduces eddies via "stability parameter" η_* (less mixing in BL)**
  - **But no buoyancy-driven flow in BL**
- **BL parameterization should include buoyancy-driven boundary current (Jenkins 2016)**
- **Sometimes may need diffusive convection**



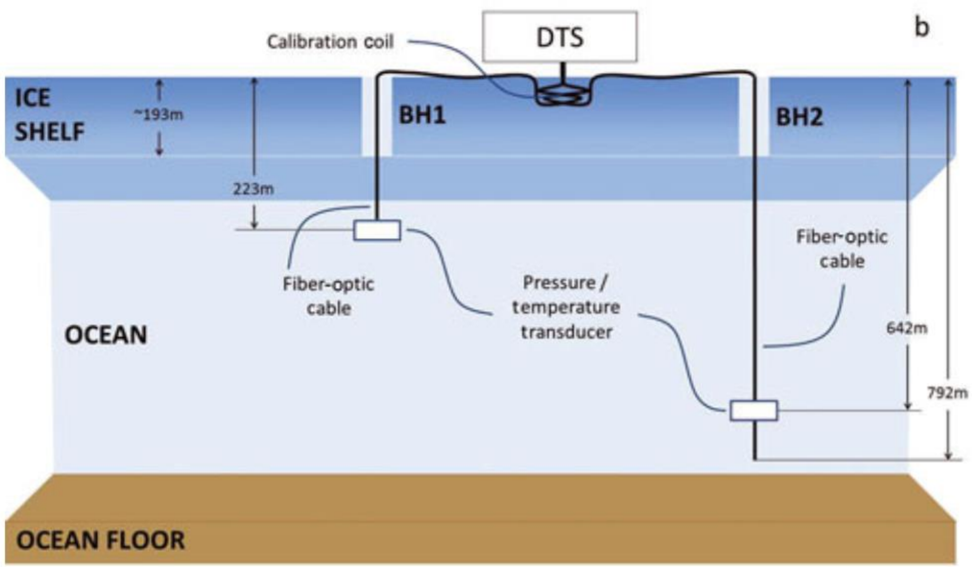
$$\eta_* = \left(1 + \frac{\xi_N u_*}{f L_O R_c}\right)^{-1/2},$$

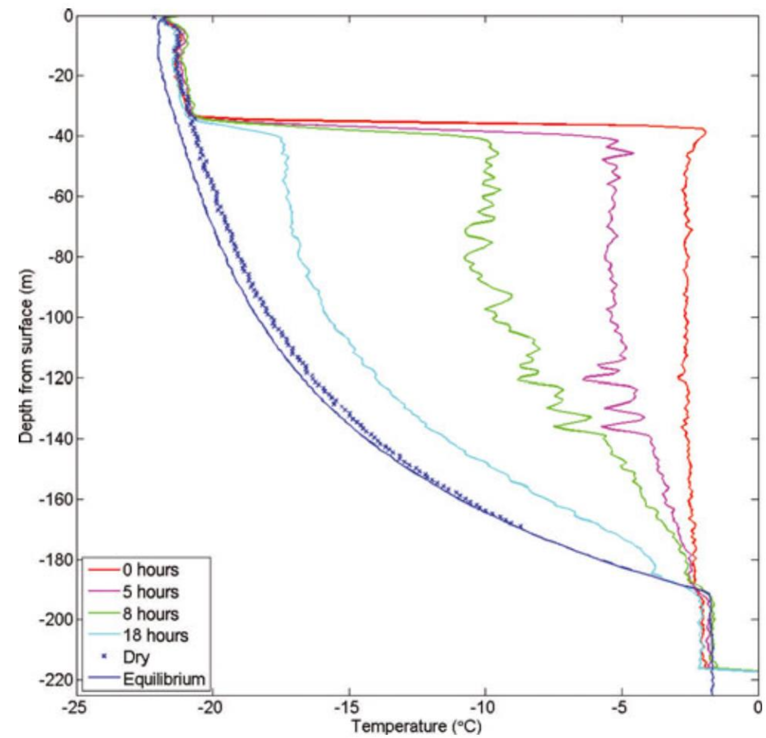




Observations: Tyler et al. (2013)

- **McMurdo Ice Shelf**
- **distributed temperature sensor (DTS)**





Tyler et al. (2013). Using distributed temperature sensors to monitor an Antarctic ice shelf and sub-ice-shelf cavity. Journal of Glaciology, 59(215), 583–591.