Ice-ocean interactions around Antarctica: *shelf circulation, boundary layer turbulence and ice losses*

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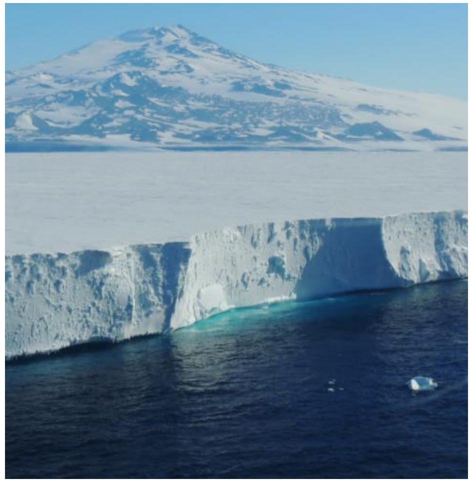
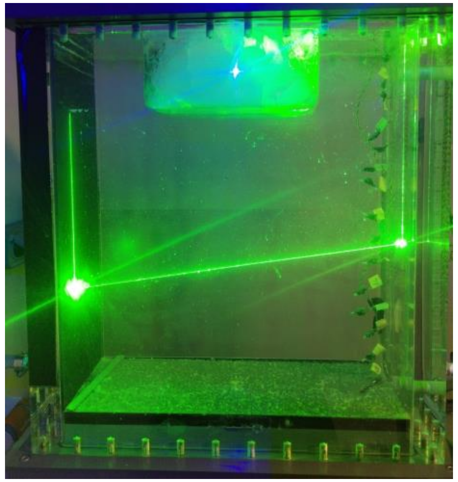
Outline

We want to predict how rapidly the **Antarctic ice sheet is retreating** now (inverse problem) and over the next hundreds of years (forward problem).

1) Ocean circulation around Antarctica
2) Ocean circulation in ice-shelf cavities
3) Turbulent fluxes between ice and ocean
4) Ice topography

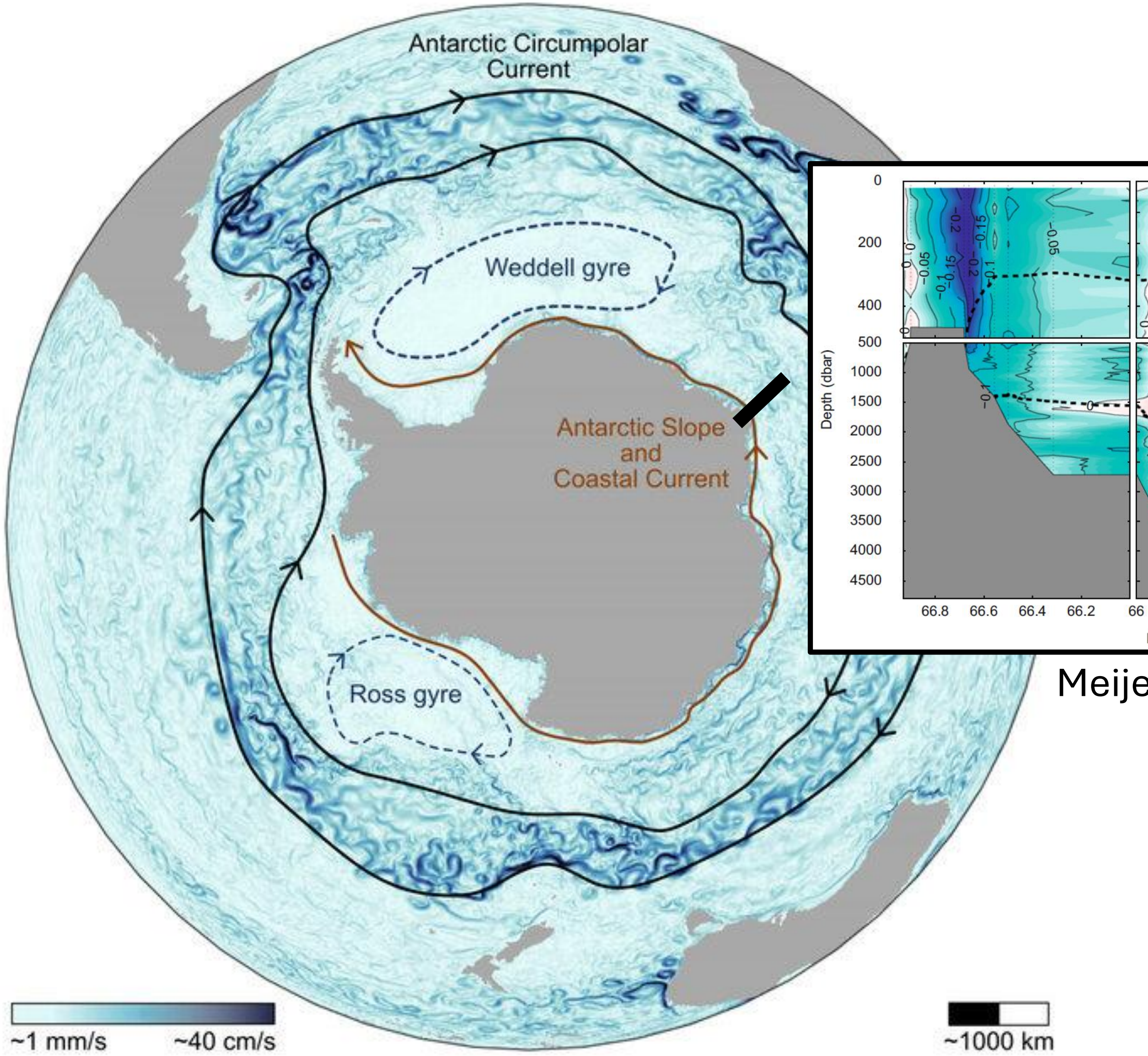





Ocean Circulation around Antarctica

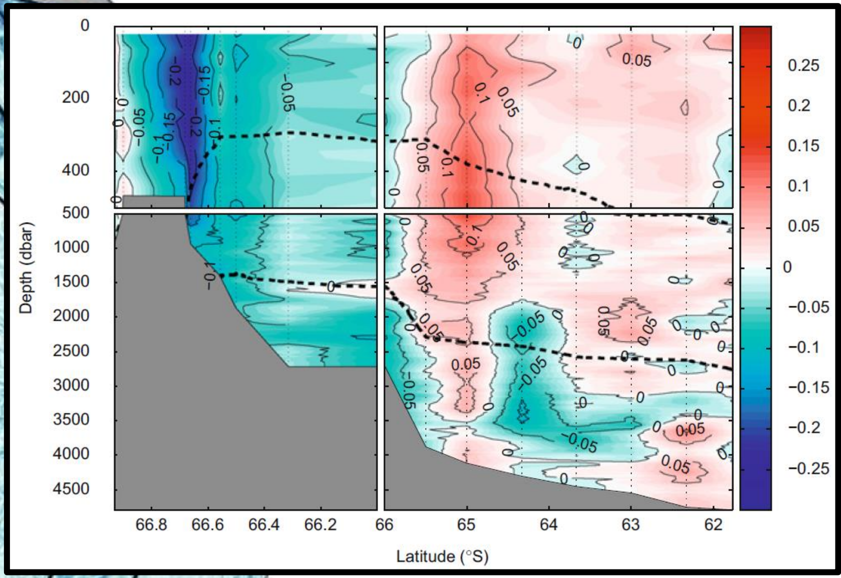
Ocean currents at continental scales

Antarctic Circumpolar Current
- Wind driven (westerlies)
- Zonally unbounded

Antarctic Slope Current
- Wind driven (easterlies)
- Shelf break attached

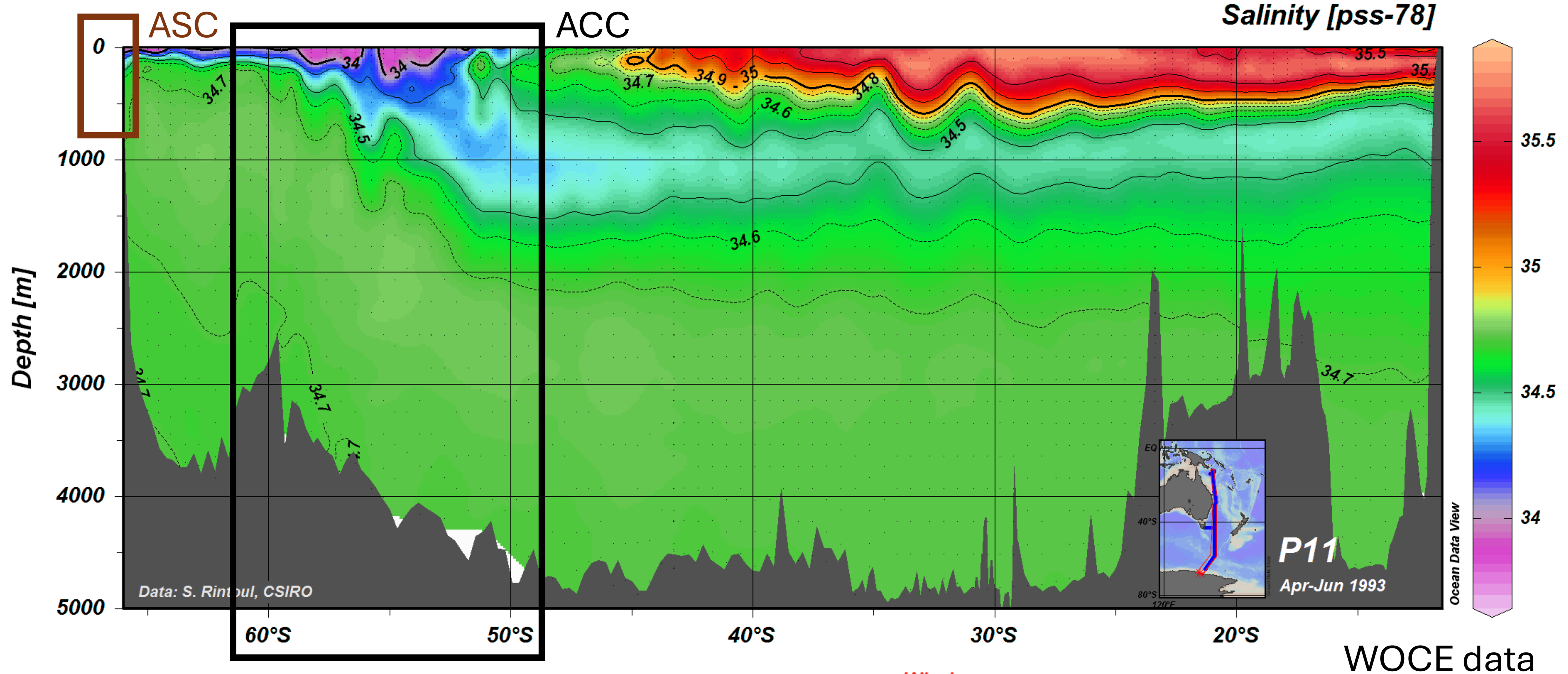


Bennetts 2024



Meijers 2010

Can warm tropical waters reach Antarctica?



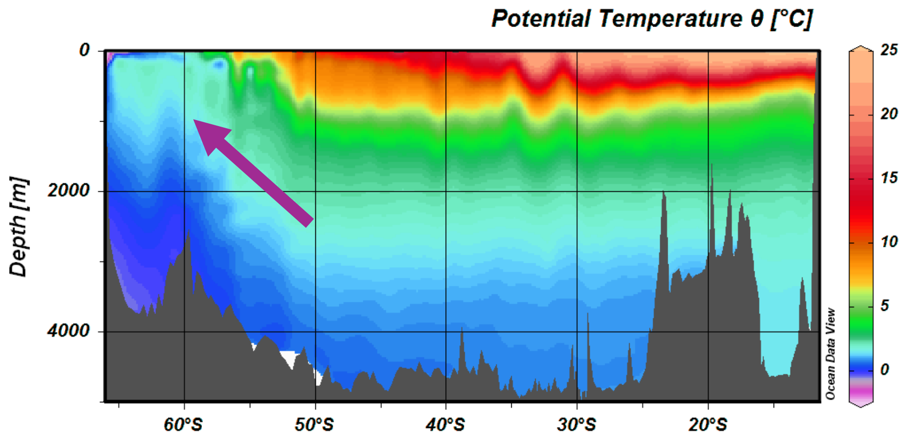
WOCE data

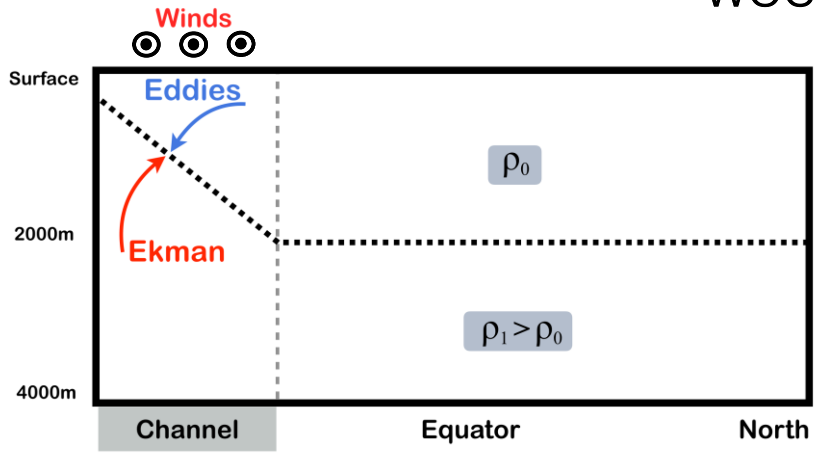
The circumpolar channel thermodynamics modulate

Antarctic waters

↔

open oceans



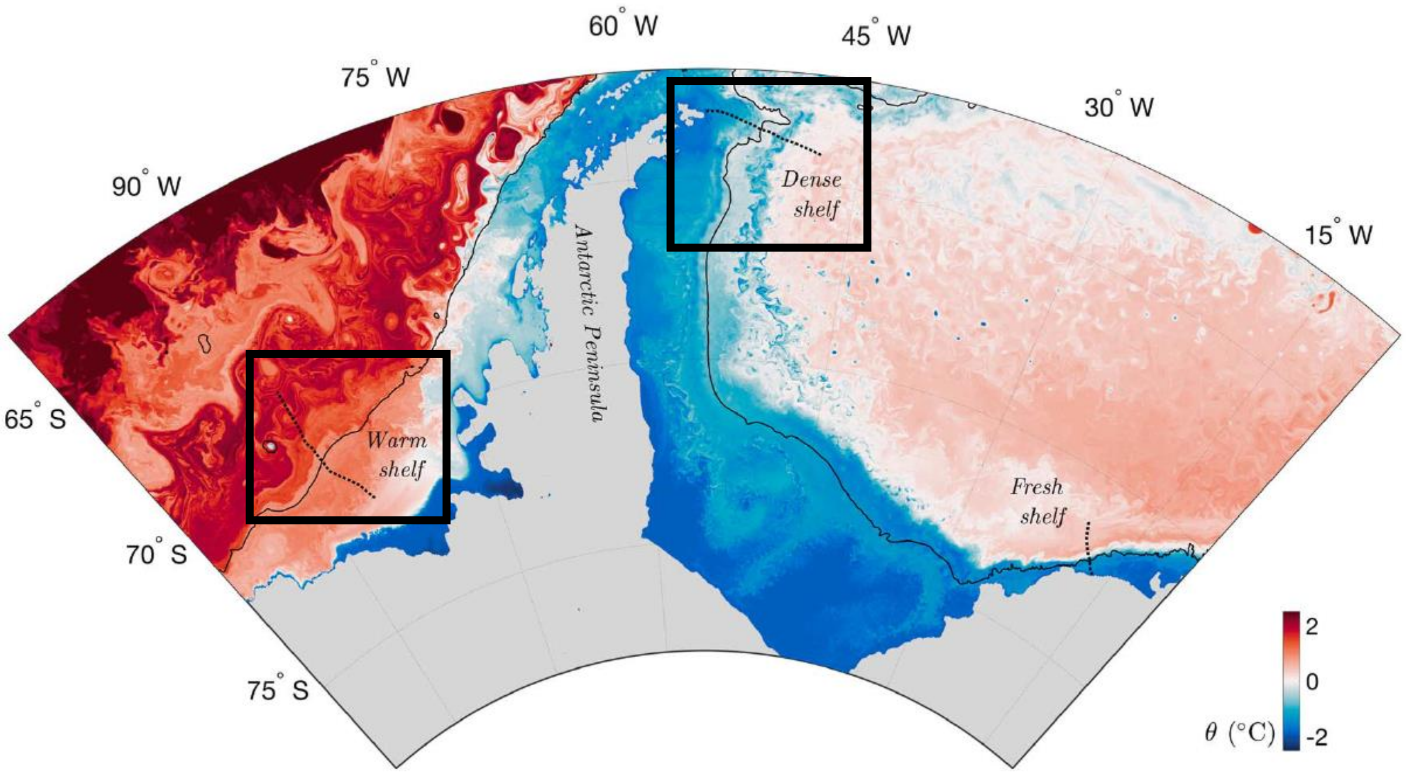


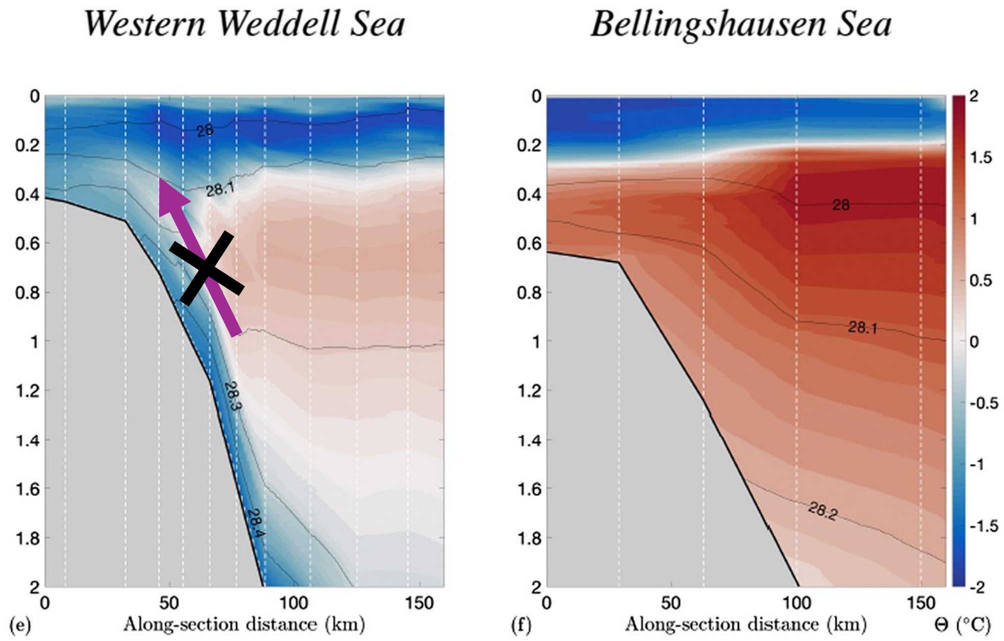
- Winds, eddies and topography all play a role

Nadeau 2024

Temperature heterogeneities on the continental shelf

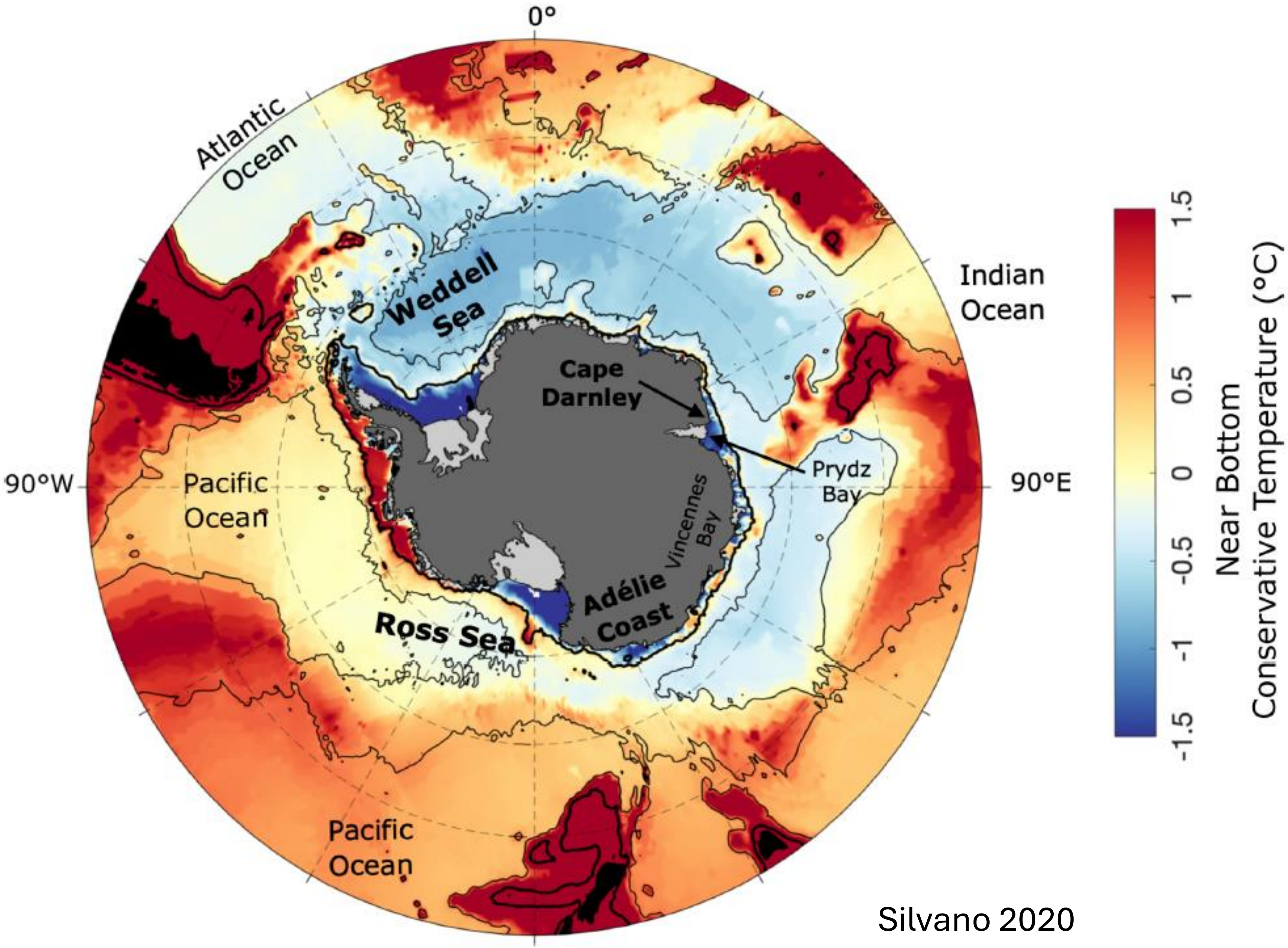
- On-shelf properties vary significantly
- Small-scale eddies control heat fluxes across shelf breaks…





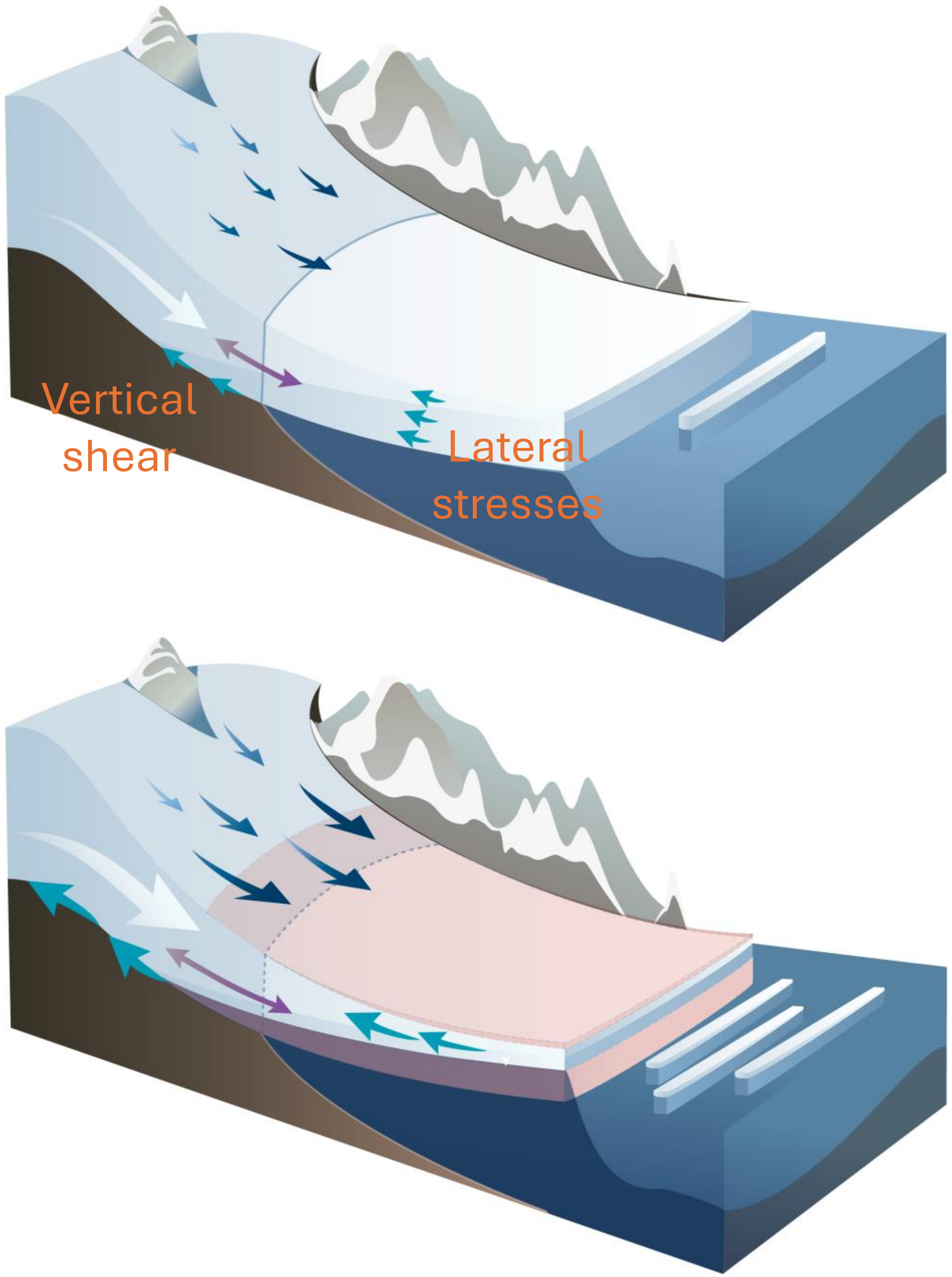
Thompson 2018

Temperature heterogeneities on the continental shelf



Silvano 2020

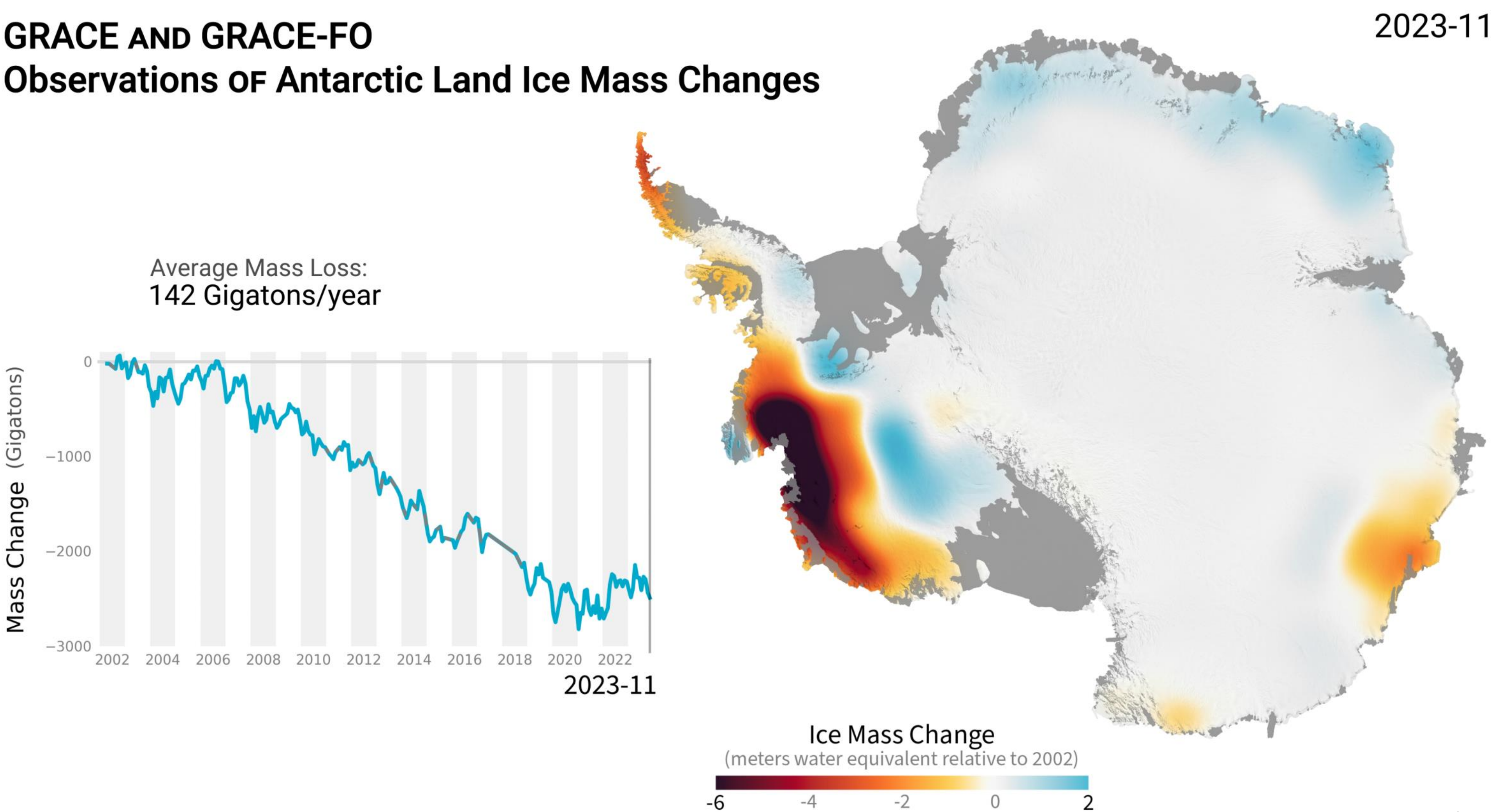
Ocean-driven ice-shelf thinning increases ice losses



- Ice sheets are viscous gravity-driven flows
- Ice shelves (often) provide buttressing against the flows of continental ice upstream depending on the stress budget
- Ice-shelf thinning reduces side friction, enabling faster grounded ice discharge into the ocean

Gudmundsson 2019

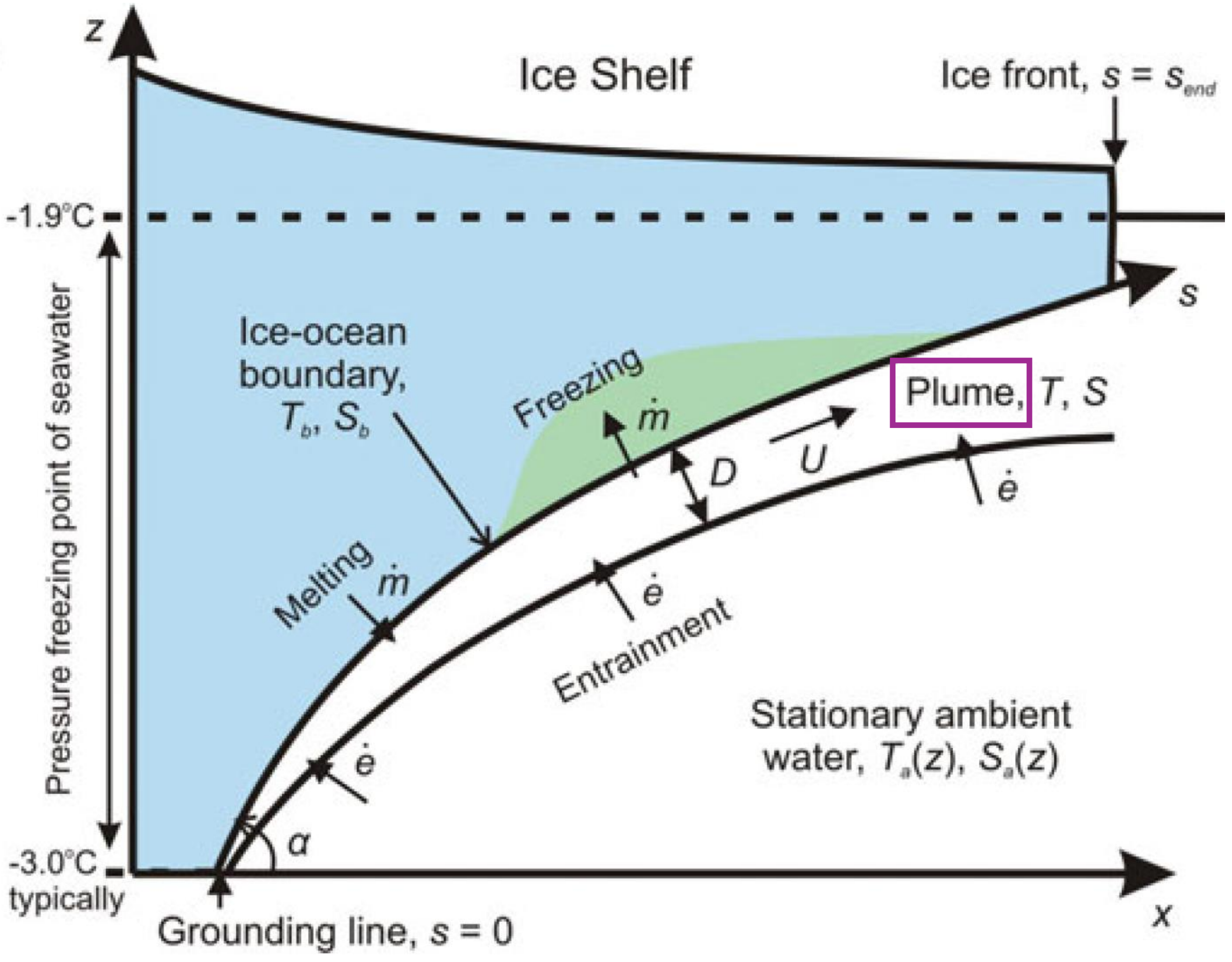
Ice losses globally, with large regional differences



https://svs.gsfc.nasa.gov/31158

Ocean Circulation in Ice-Shelf Cavities

Thermohaline circulation in ice-shelf cavities



Jenkins 2021

- Prevailing idea: meltwater plume in a quiescent ambient

- 1D model for mean plume properties with parameterizations

→ entrainment $\dot{e}(U, \alpha)$

→ melt rate $\dot{m}(U, T, S)$

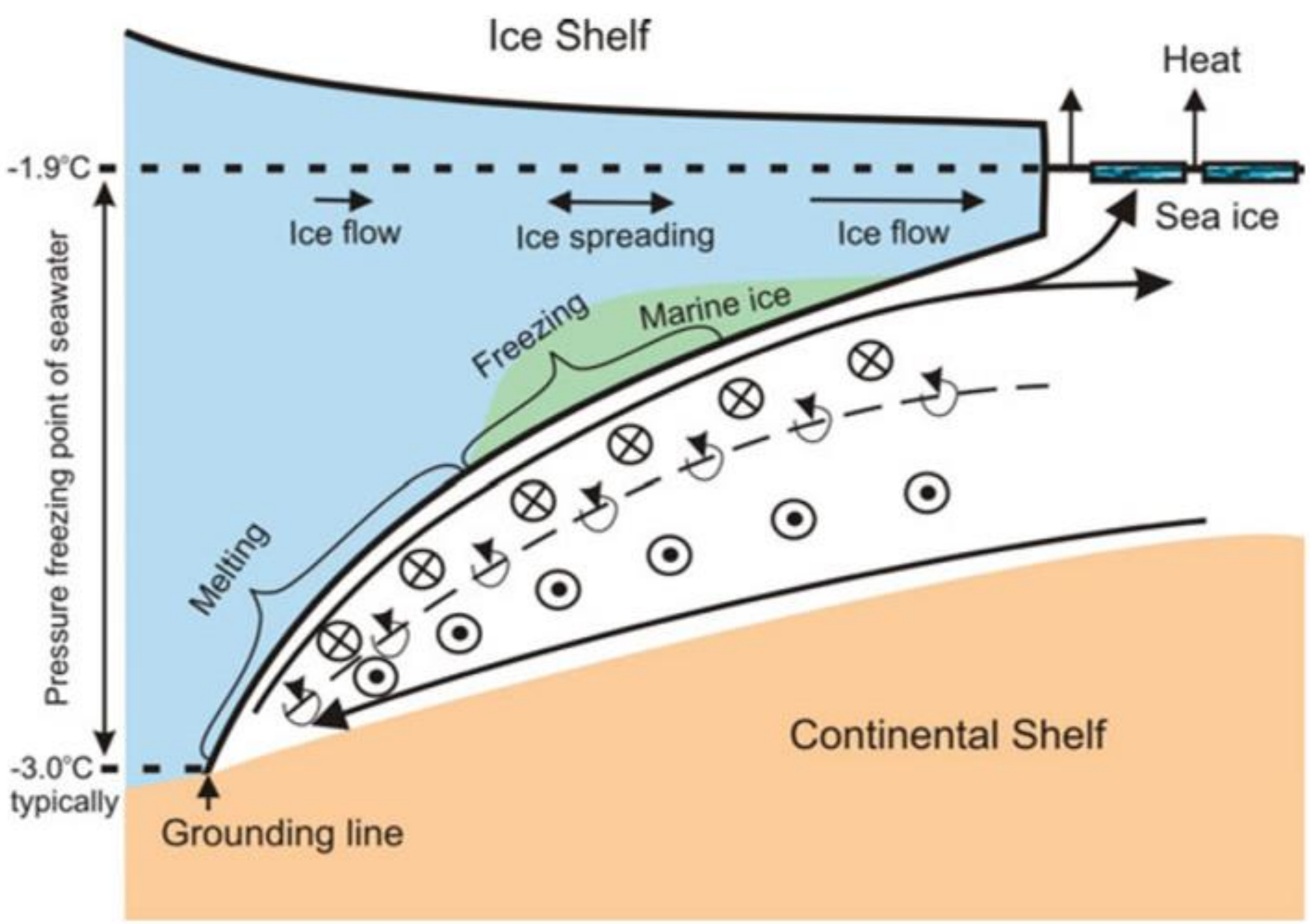
- Key modelling challenges

→ stratified ambient

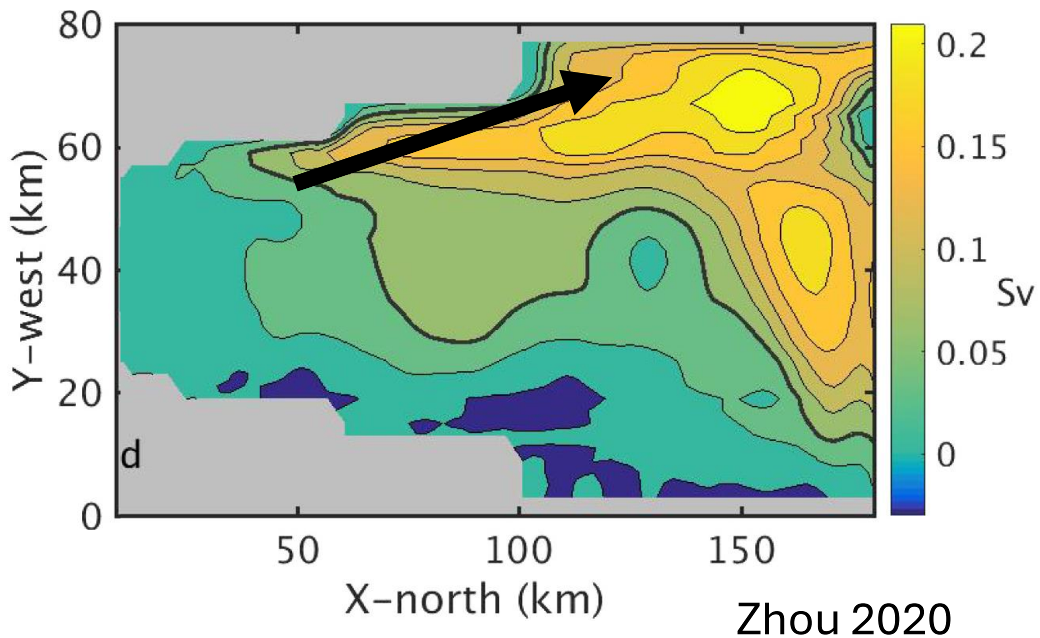
→ subglacial discharge (intense point source of buoyancy)

→ wind-driven intrusions

Rotation and seabed topography make everything complicated



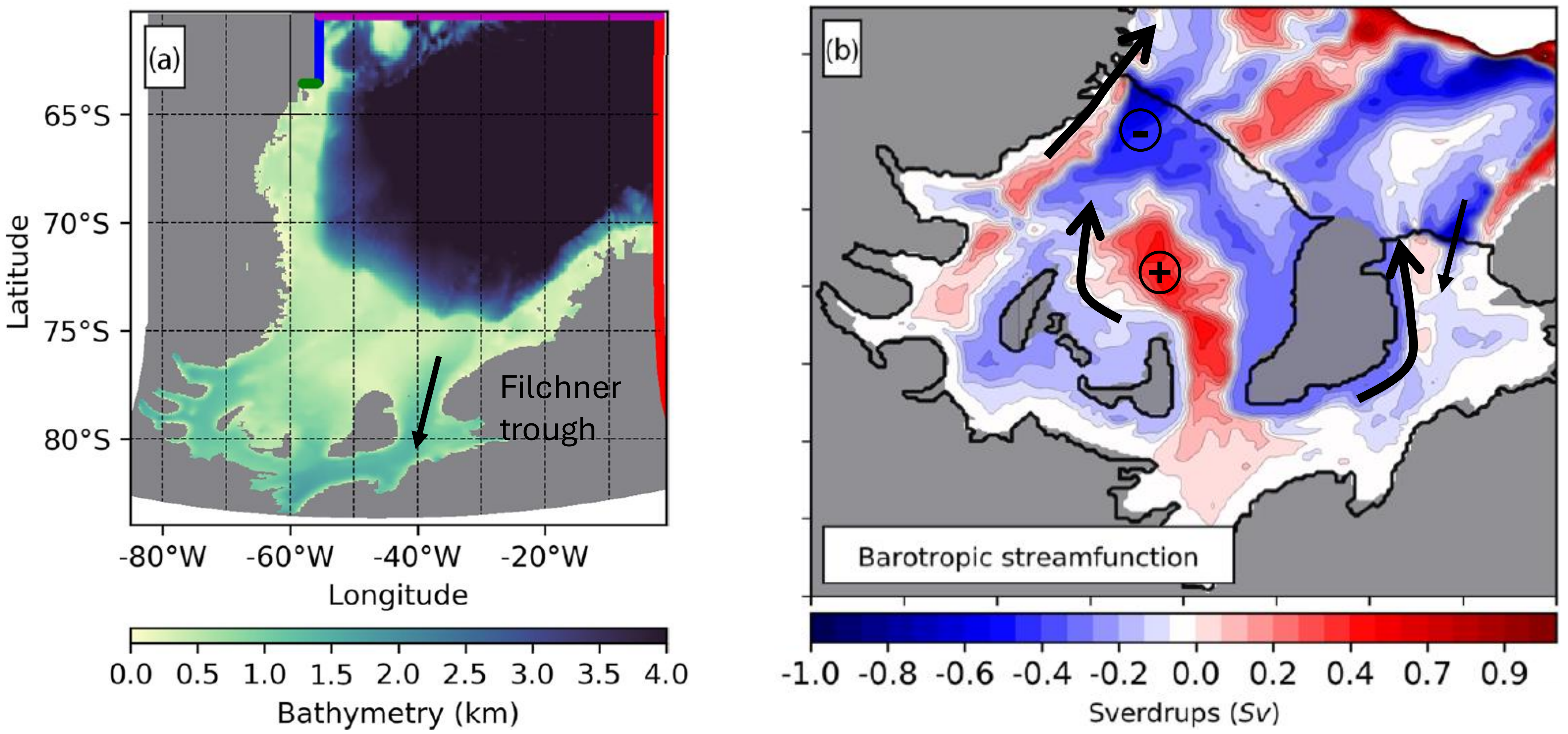
Jenkins 2021



Zhou 2020

- Plumes drive westward flows, turning east at depth (thermal wind balance)
- Meltwater outflows are to the west in closed cavities

Rotation and seabed topography make everything complicated

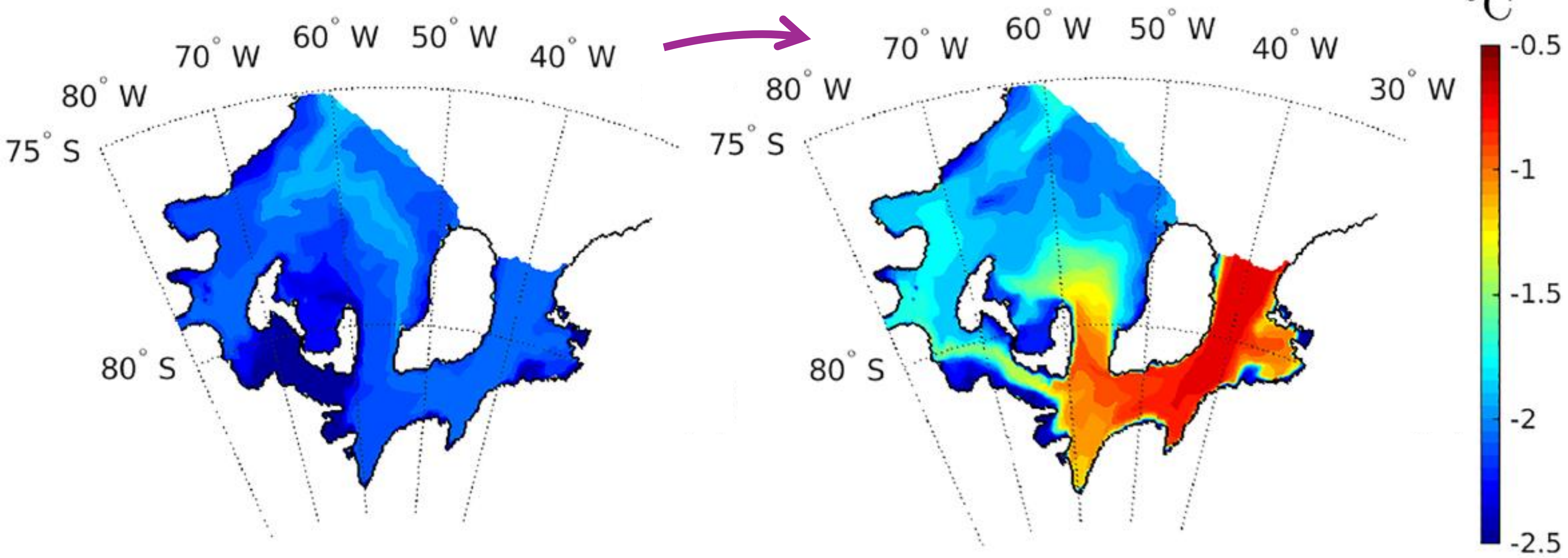


Bull 2021

- Inflows intrude through seabed depressions
- Cyclonic (clockwise) circulation around red patches

Cavities may tip from cold to warm conditions (and vice versa)

Fresher initial state



- initial salinity 34.45 psu → cold time-averaged bottom temperature
- initial salinity 34 psu → warmer state

Hazel 2020

Turbulent Fluxes between Ice and Ocean

Ice-ocean boundary layers

- Diffusive sub layers (mm)

→ *viscosity, diffusion*

- Surface layer (m)

→ *wall/stratified turbulence*

- Outer layer (dam)

→ *stratified turbulence/rotation*

- Fusion point

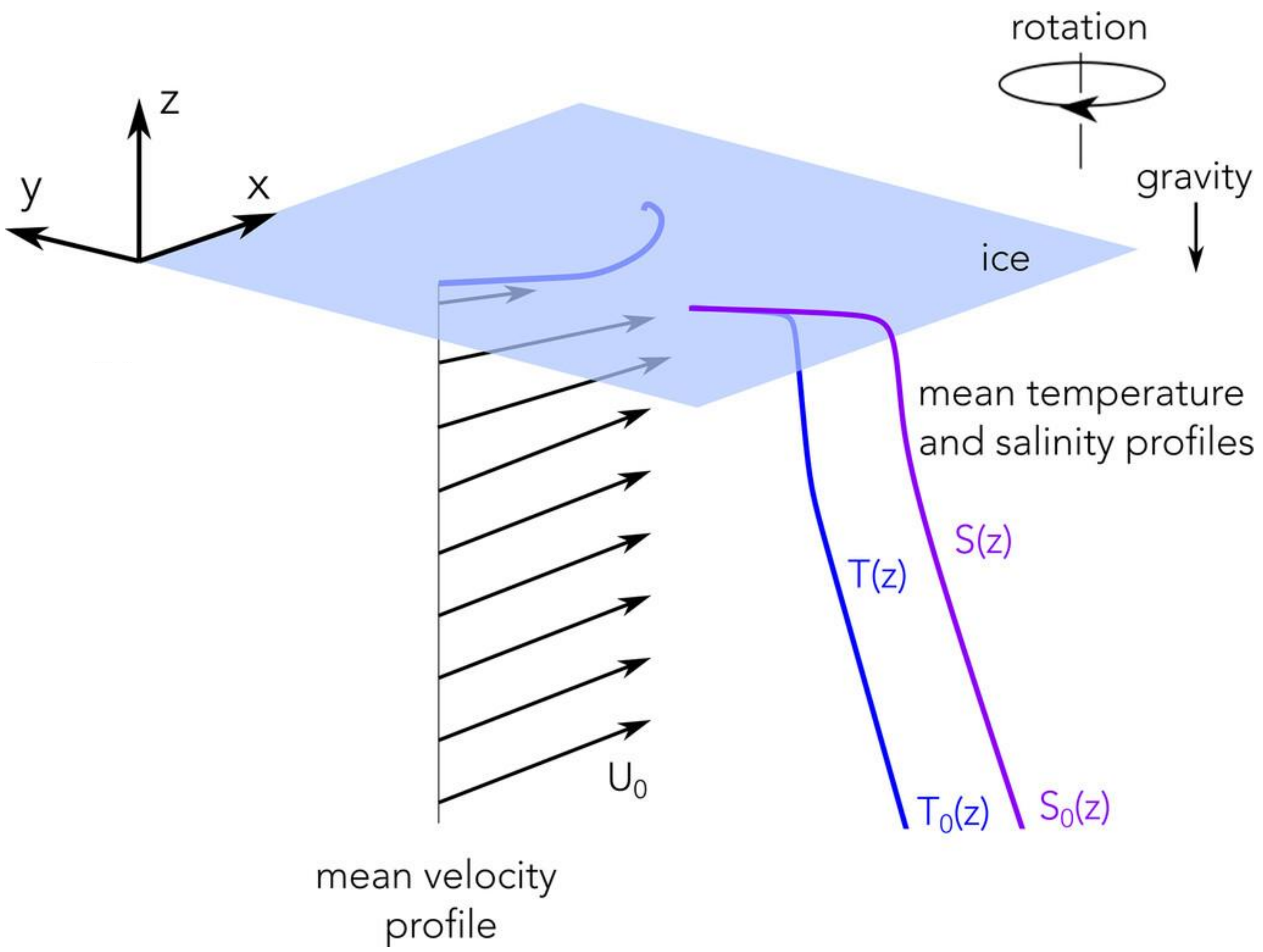
→ $T_b = T_f = \lambda_1 S_b + \lambda_2 + \lambda_3 P_b$

- Heat budget

→ $\dot{m}\rho_i L_i = F_T = -\kappa_T c_w \rho_w \partial_z T_{|b}$

- Salt budget

→ $\dot{m}\rho_i S_b = F_S = -\kappa_S \rho_w \partial_z S_{|b}$



Rosevear 2021

Ice-ocean boundary layer parameterizations

- Ocean models don't resolve the BL

→ we want a **parameterization**

$\dot{m}, F_T, F_S$ in terms of $\boldsymbol{T_0, S_0, \vec{U}_0, slope}$

- 3 equation model assumes

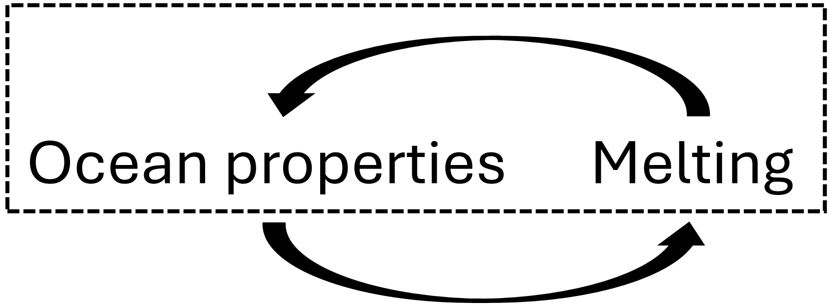
$$F_T = \rho_w c_w \boldsymbol{\Gamma_T C_D^{1/2}} |\vec{U}_0| [T_0 - T_f(S_b)]$$

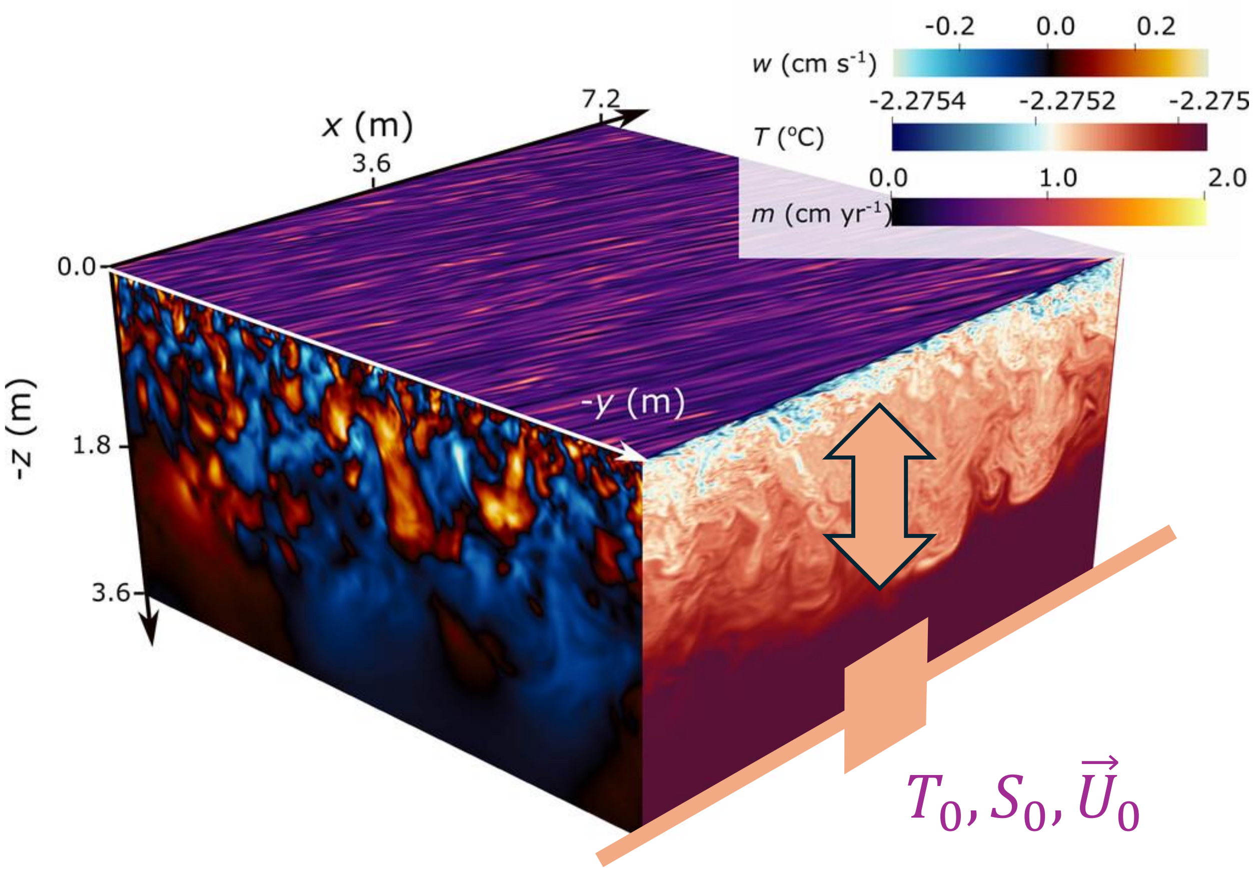
$$F_S = \rho_w \boldsymbol{\Gamma_S C_D^{1/2}} |\vec{U}_0| (S_0 - S_b)$$

- What will it take to improve it?

→ lots of data !

→ some from high-resolution simulations

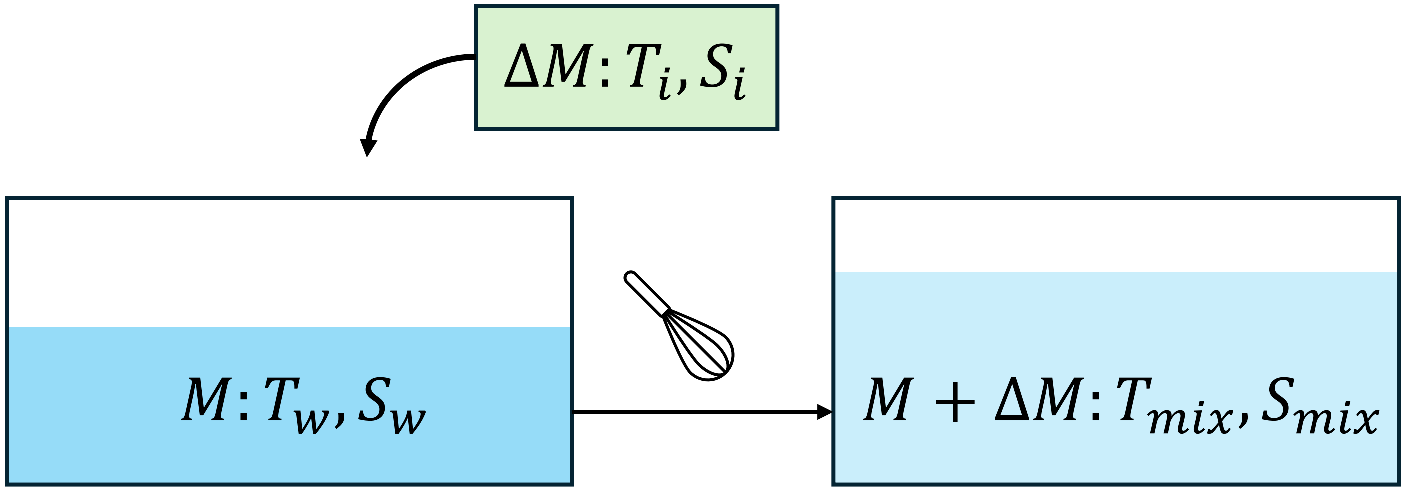




Rosevear 2021

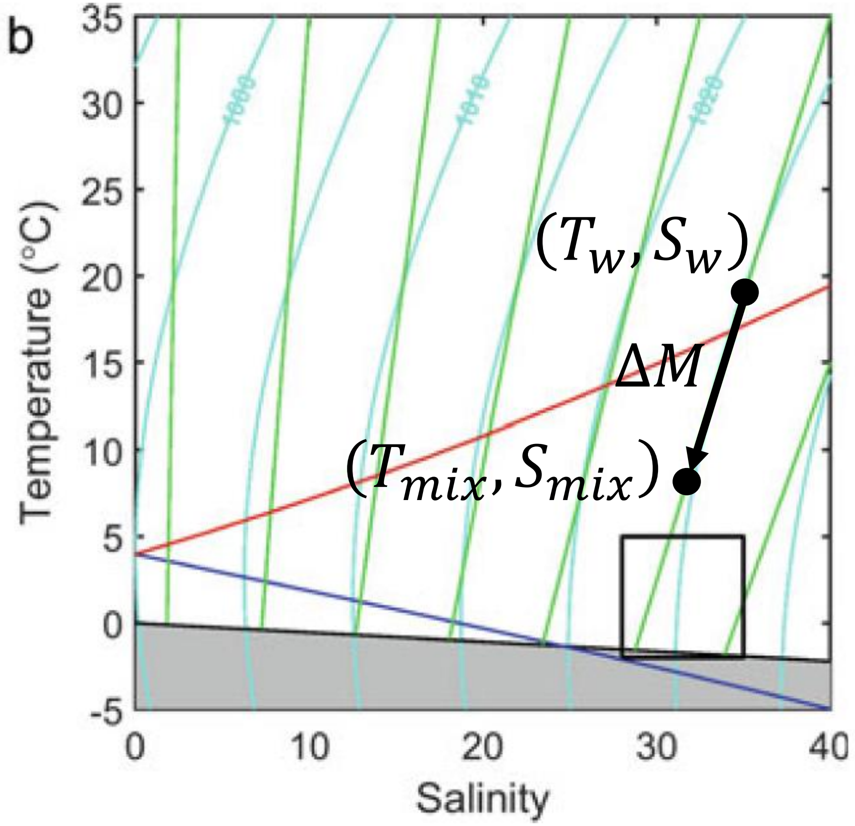
The impact of ice melting on water mass transformation

- Thought experiment in the shear-dominated regime (no stratification)



$$R = \frac{\Delta M}{M + \Delta M}$$

$$T_{mix} = T_w + R\left(T_{i,eff} - T_w\right)$$
$$S_{mix} = S_w + R(S_i - S_w)$$

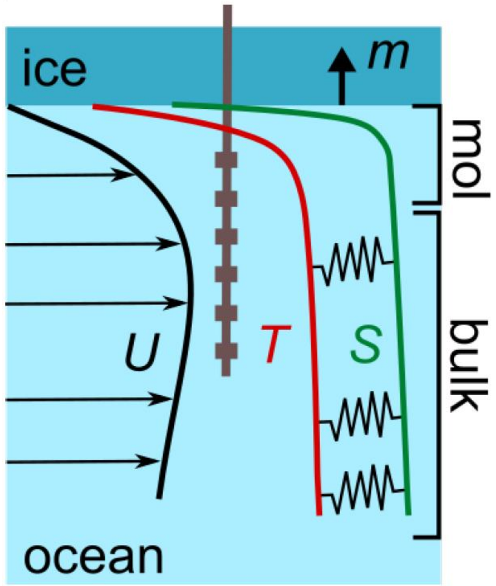


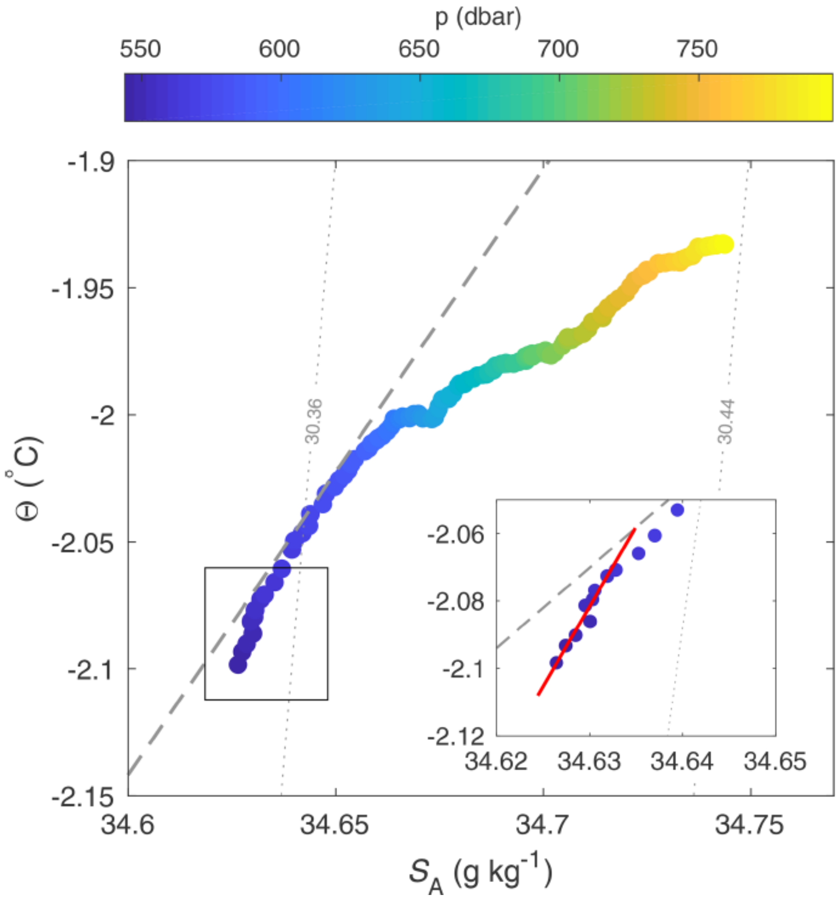
Jenkins 2021

- Seawater properties follow the meltwater mixing line

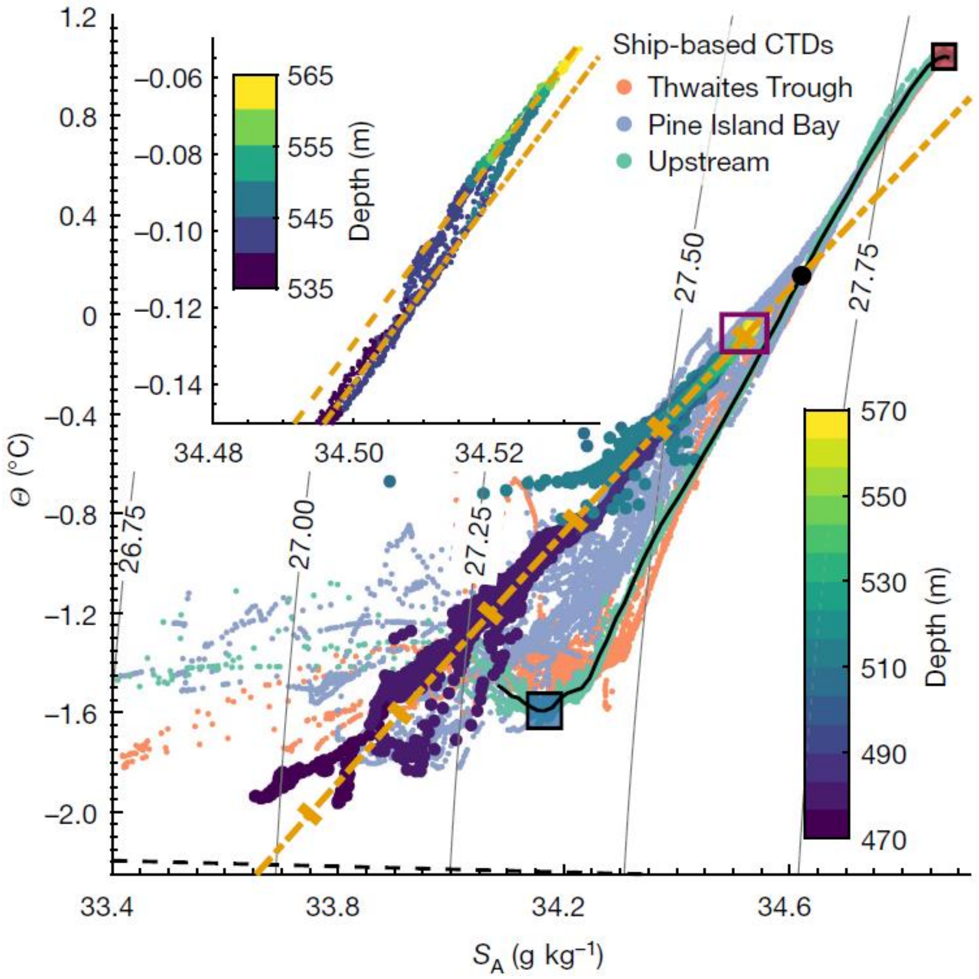
The impact of ice melting on water mass transformation

- Starting from the Navier-Stokes equations, Gade (1979) showed that T and S are linearly correlated in a turbulent BL, in agreement with the meltwater mixing line





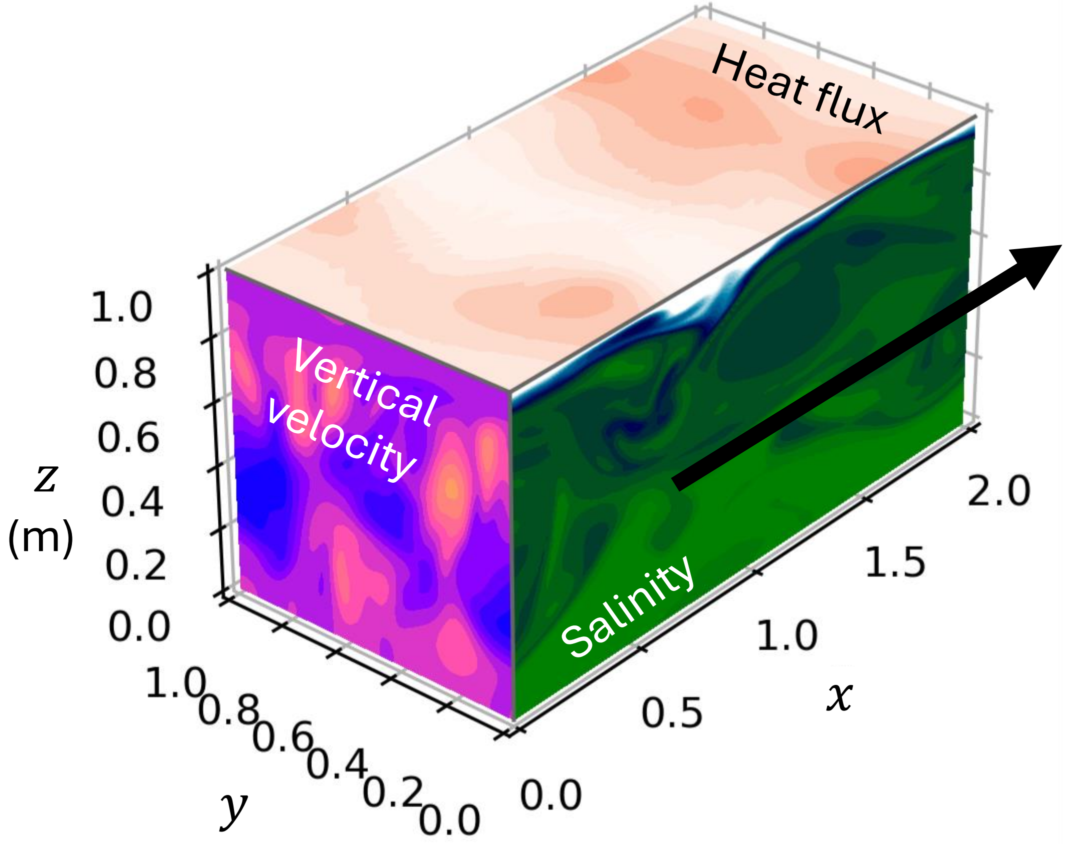
Rosevear 2022 (Amery)



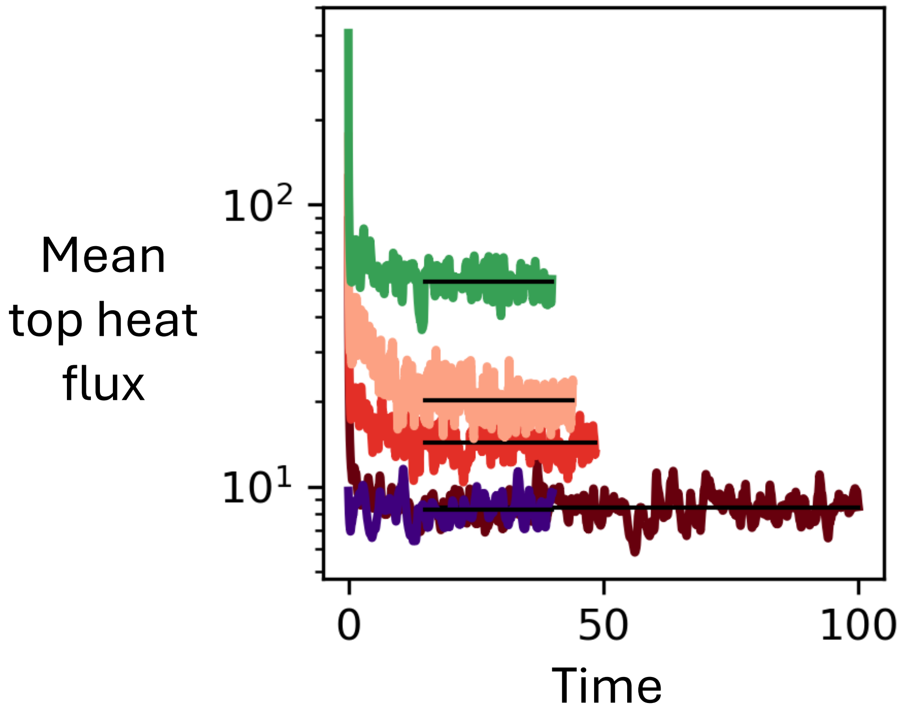
Davis 2023 (Thwaites)

Is the meltwater mixing line observed in simulations?

- The ambient is uniform in space/time and close to freezing → shear dominated
- We use a constant pressure gradient to drive the flow
- The interface is flat and steady
- Horizontally periodic (spectral code; Dedalus)



We run the simulations until we reach a statistical steady state



Simulation setup

- We work with dimensionless variables

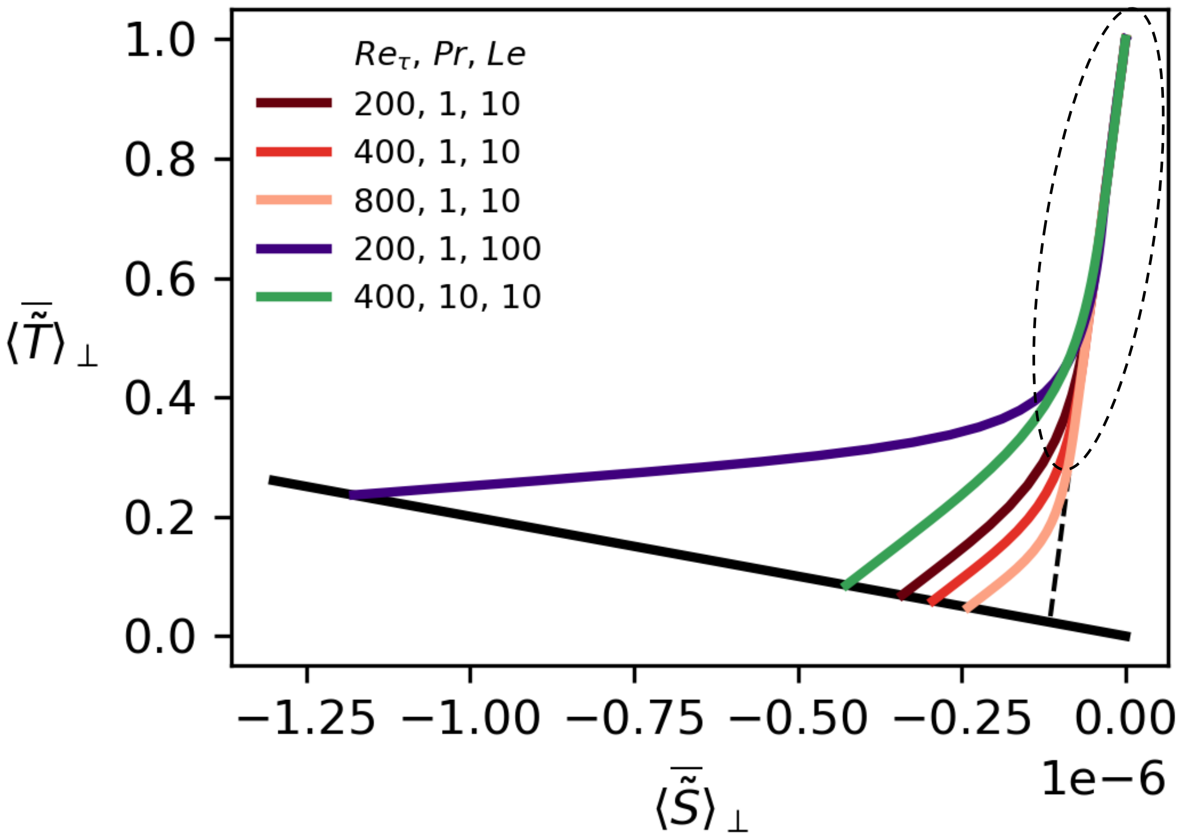
$$\partial_{\tilde{t}} \vec{\tilde{u}} = \cdots + \nabla^2 \vec{\tilde{u}} + \boldsymbol{Re_\tau} \overrightarrow{e_x} + \tilde{\rho}(\tilde{T}, \tilde{S}) \overrightarrow{e_z}$$
$$\partial_{\tilde{t}} \tilde{T} = \cdots + \boldsymbol{Pr^{-1}} \nabla^2 \tilde{T}$$
$$\partial_{\tilde{t}} \tilde{S} = \cdots + \boldsymbol{Pr^{-1}} \boldsymbol{Le^{-1}} \nabla^2 \tilde{S}$$

- **Turbulence parameter** $\equiv$ $\boldsymbol{Re_\tau} = \frac{u_\tau}{\nu H} \in [200{,}800], u_\tau \sim 0.1$ mm/s

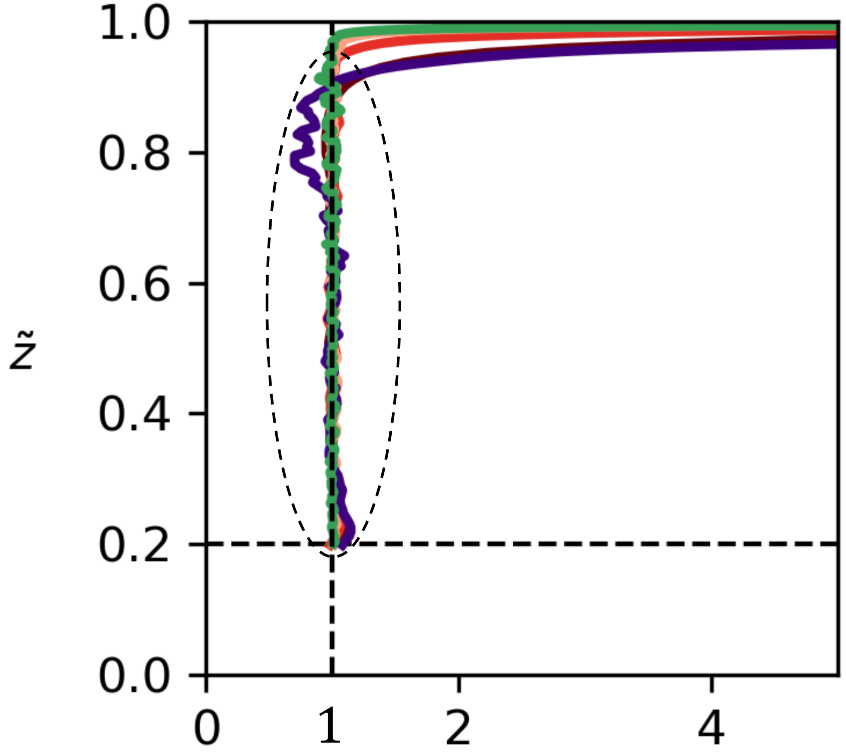
- **Diffusivity parameters** $\equiv$ $\boldsymbol{Pr} = \frac{\nu}{\kappa_T} \in [1{,}10], \boldsymbol{Le} = \frac{\kappa_T}{\kappa_S} \in [1{,}100]$

All simulations exhibit the same meltwater mixing line

$T - S$ diagram



Turbulent diff. ratio



$$Le^{eff} \approx Le^{turb} = \frac{\tilde{\kappa}_T^{turb}}{\tilde{\kappa}_S^{turb}}$$

- We find $\tilde{\kappa}_T^{turb} \approx \tilde{\kappa}_S^{turb}$ (one of Gade's hyp.)

$$\tilde{\kappa}_T^{turb} = \frac{\langle \tilde{w}\tilde{T} \rangle_\perp}{\langle -\partial_{\tilde{z}} \tilde{T} \rangle_\perp}$$

Linear correlations → existence of a reduced model

<u>If T and S are correlated…</u>

The IOBL can be modelled by a **single-scalar model**, called **thermal driving**

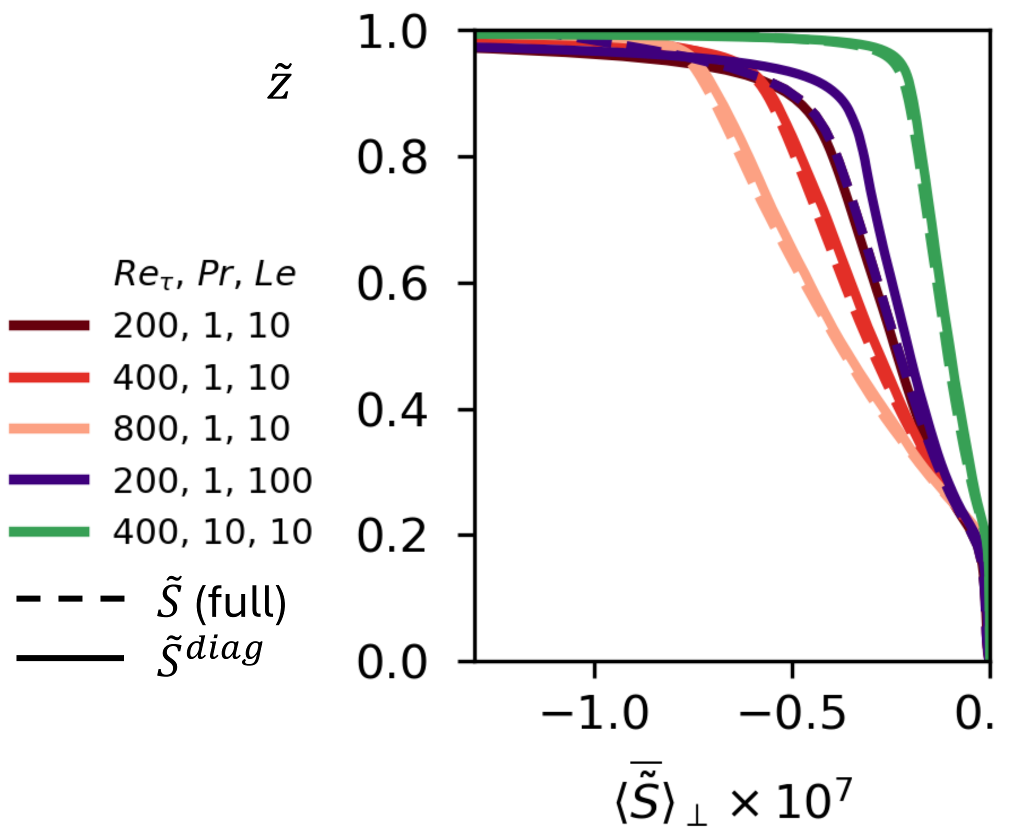
$$\tilde{T}_* = \tilde{T} - \tilde{T}_f(\tilde{S})$$

$$\left.\begin{matrix}\cancel{\partial_{\tilde{t}}\tilde{T}} \\ \cancel{\partial_{\tilde{t}}\tilde{S}}\end{matrix}\right\} \partial_{\tilde{t}}\tilde{T}_* = \cdots + \boldsymbol{Pr_*^{-1}}\nabla^2\tilde{T}_*$$

Then we can diagnose

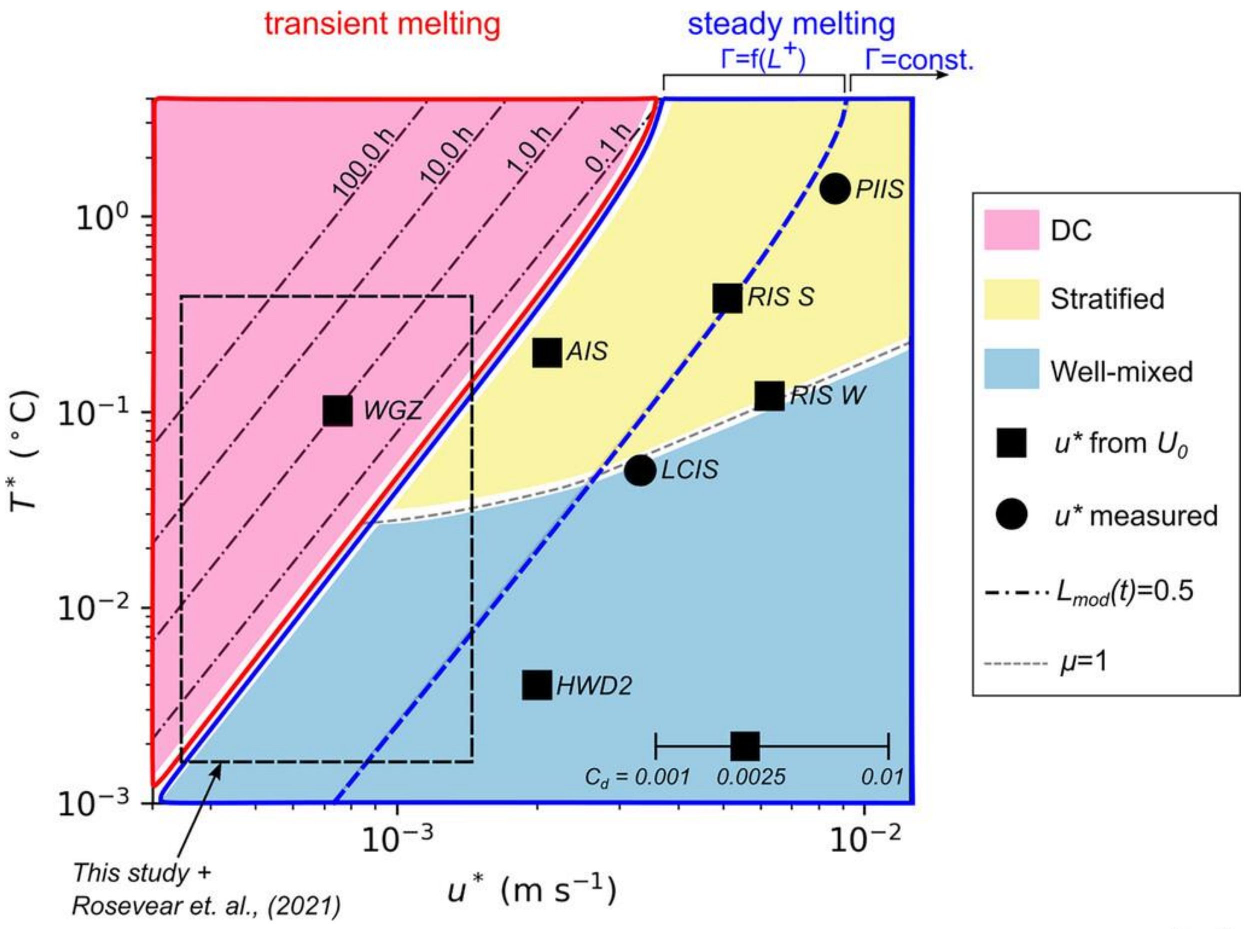
$$\tilde{T}^{diag} \propto \tilde{T}_* \,;\, \tilde{S}^{diag} \propto \tilde{T}_*$$

And all fluxes…



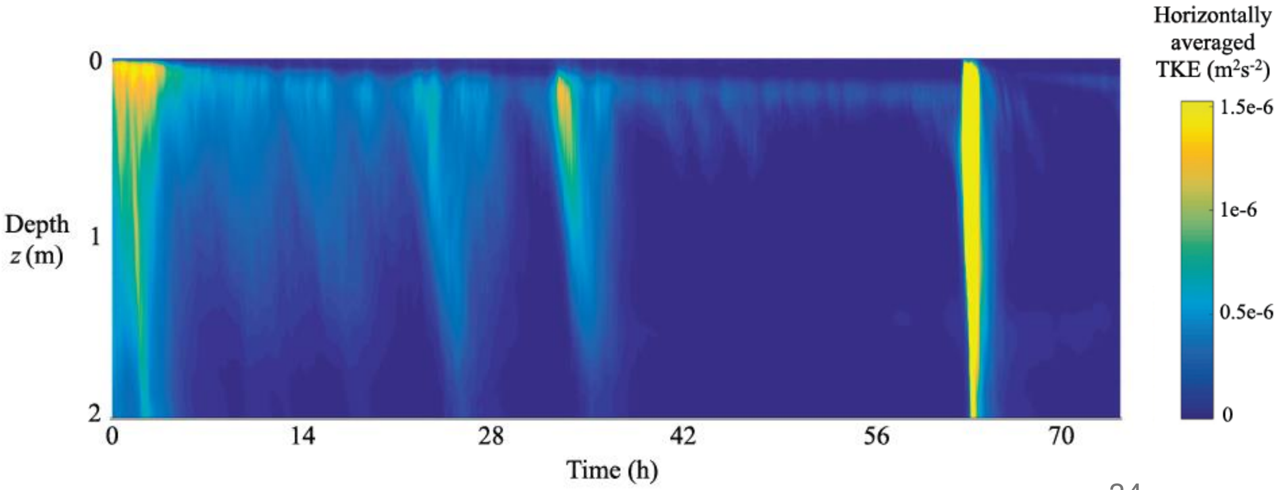
Preprint @ arXiv:2404.09545

Ice-ocean boundary layers come in different flavours



Rosevear 2021

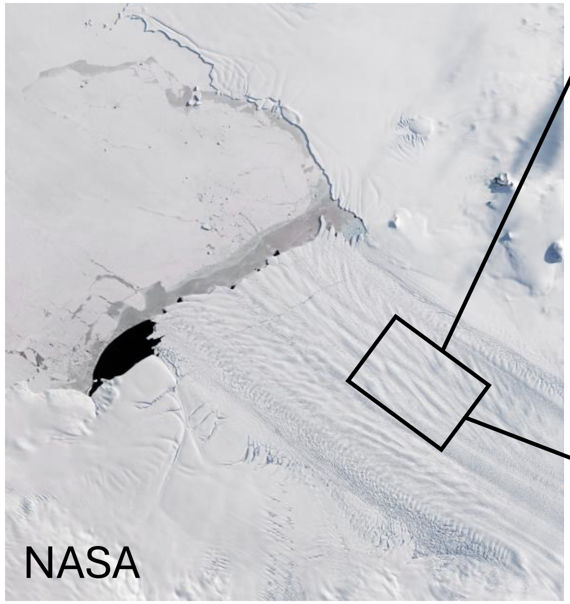
- The 3-equation model works well in the well-mixed regime (passive scalars).
- But fails in the stratified and diffusive convection regimes, because of:
  - anisotropic turb.
  - intermittent turb.
  - differential diffusion

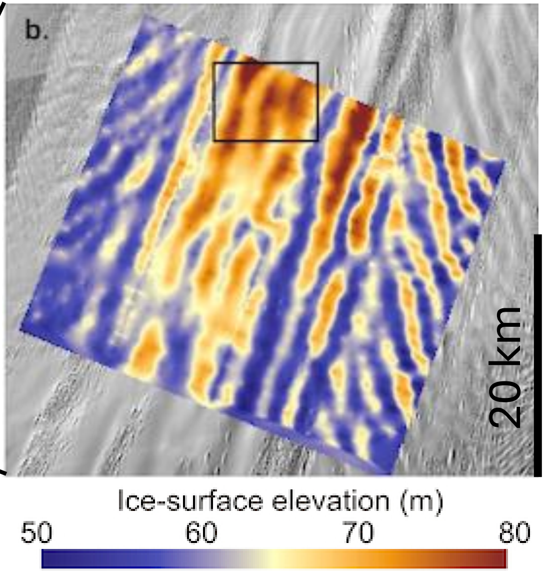


Vreugdenhil 2021

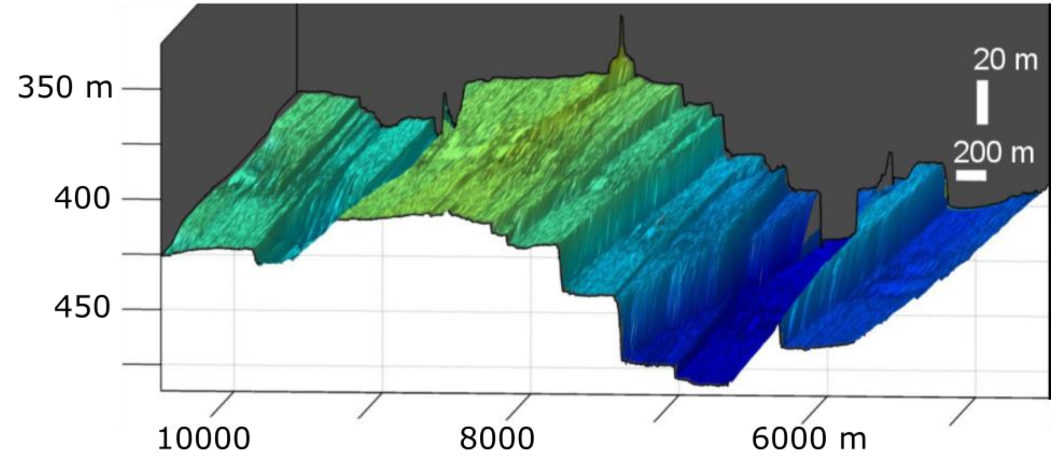
Ice Topography

Multi-scale ice boundary topography

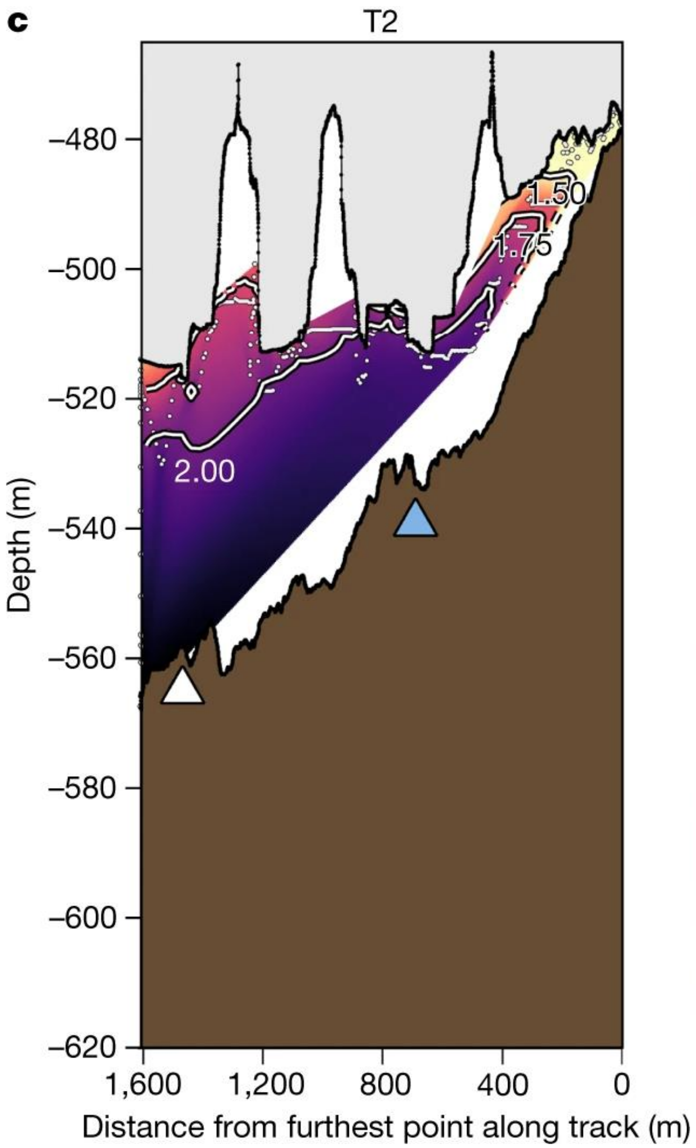




Vaughan 2012

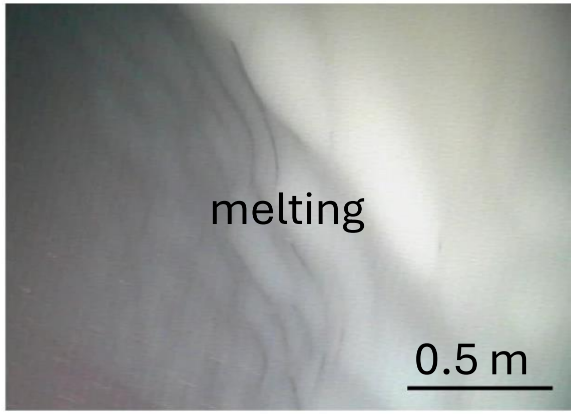


Dutrieux 2014



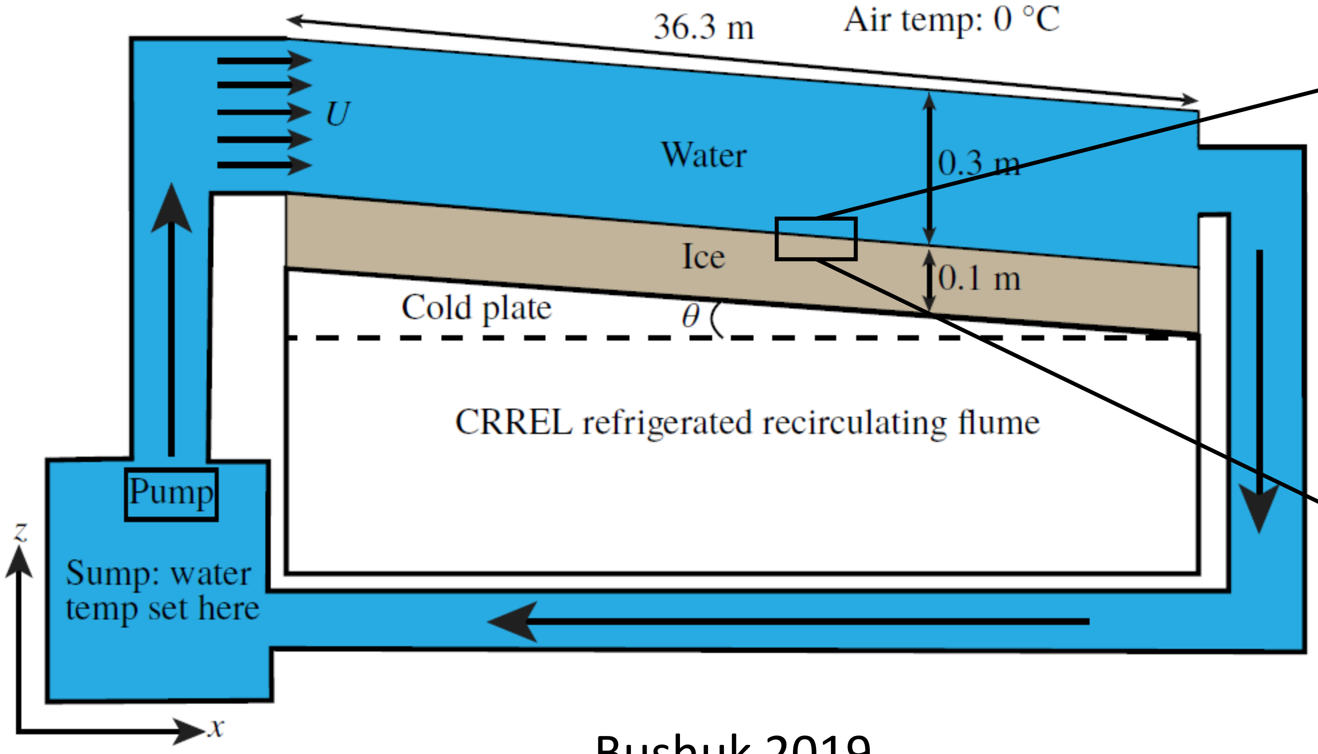
Schmidt 2023

Scallops on the side of a large terrasse

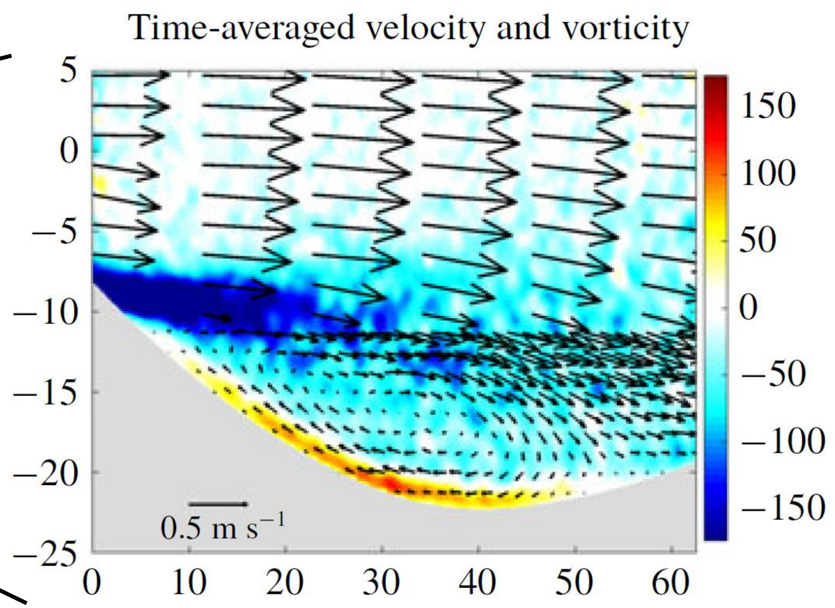


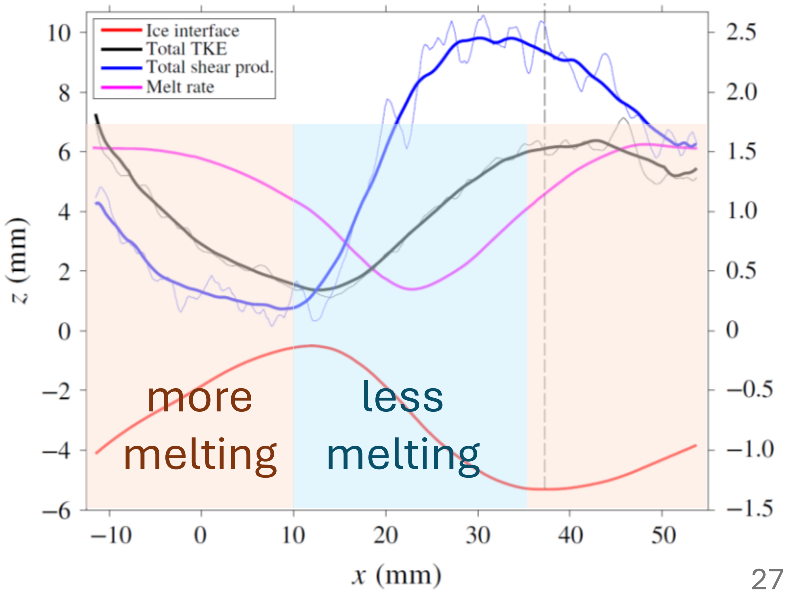
Ridges at the top of a crevasse

Ice scallops as a hallmark of flow-boundary coupling ?



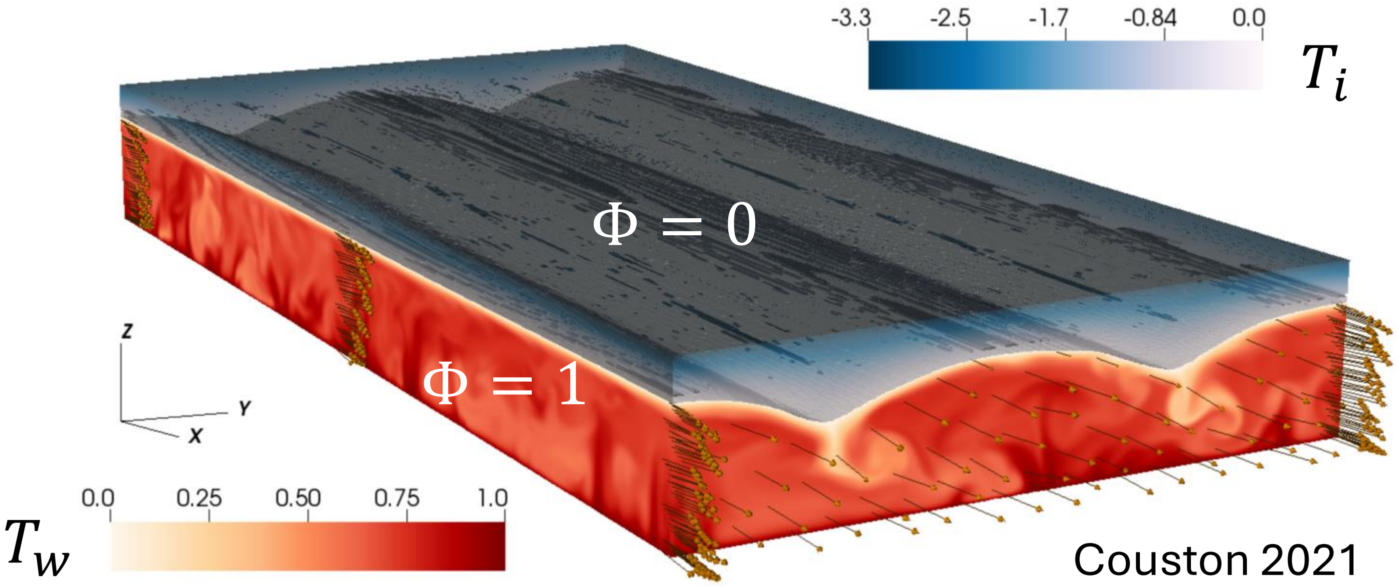
Bushuk 2019





- Scallops developed for $U > 0.6$ m/s ($T \approx 0.6$ °C)
- Time-mean recirculating eddy in scallop trough (PIV) suggests self-reinforcing mechanism
- Considered temperature as a passive scalar
- **Melt rate can double in the presence of scallops**

Simulating turbulence and interface motions simultaneously

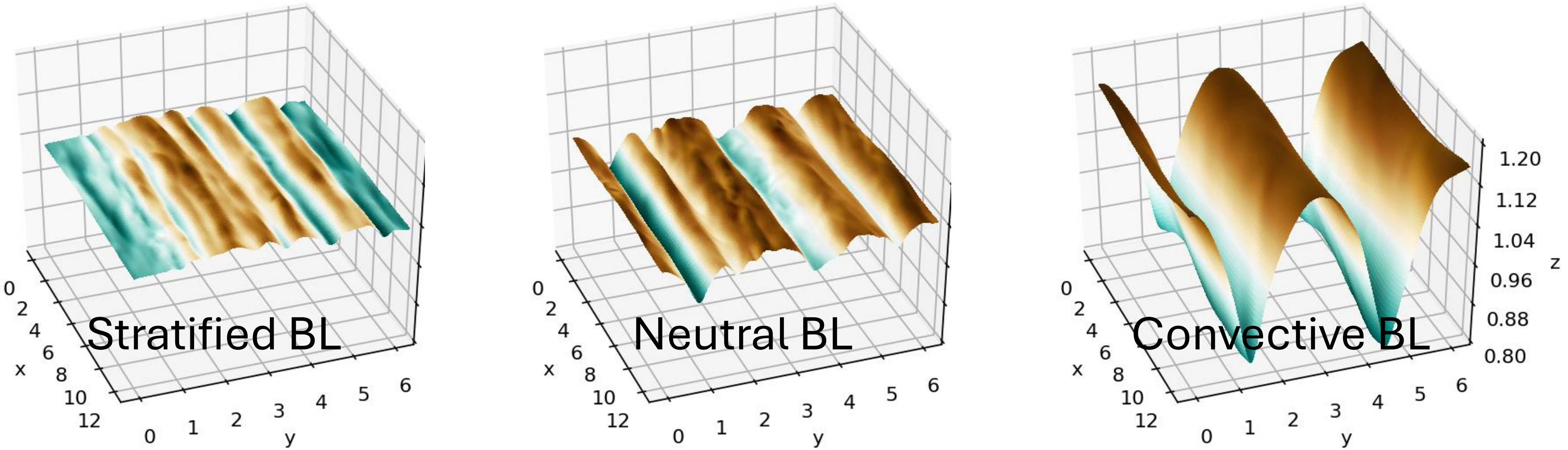


- Φ-Penalized Navier-Stokes equations (phase field)

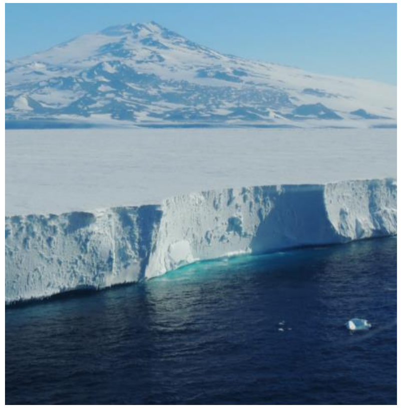
→ *Φ obeys a diffusive equation with latent-heat source/sink*

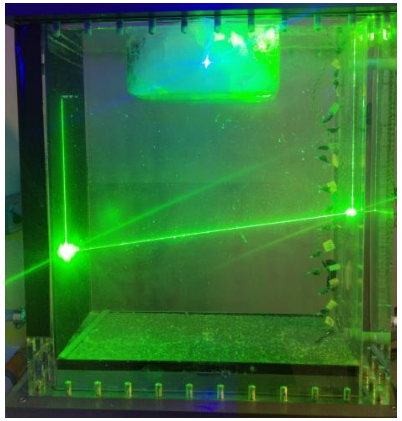
- $Re_\tau = 150, Pr = 1, St = 1, Ri_\tau = 0, \pm 40$

- Far from ocean conditions…



Conclusions



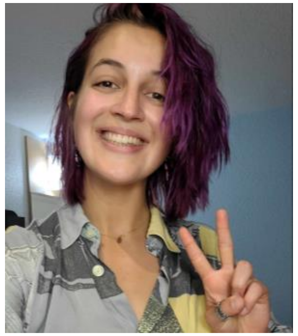


- Ocean simulations must resolve sub mesoscales to correctly capture heat fluxes → Antarctica
- Tipping points may exist, but are most likely sensitive to how we model polynyas, deep convection and ice-shelf melting
- Current ice-ocean boundary layer parameterizations fail in all but the well-mixed regime → can experiments help?
- Most climate models lack interactive ice-shelf cavities, so we must learn how to emulate how they transform water masses → can AI help?

Brivaël Collin

Sofia Allende

Louis Saddier



Julie Limonet

Chinthaka Jacob

ERC opportunities