How quickly does ice melt in seawater?

École de Physique des Houches
New Challenges in Turbulence Research VII

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We don’t know...

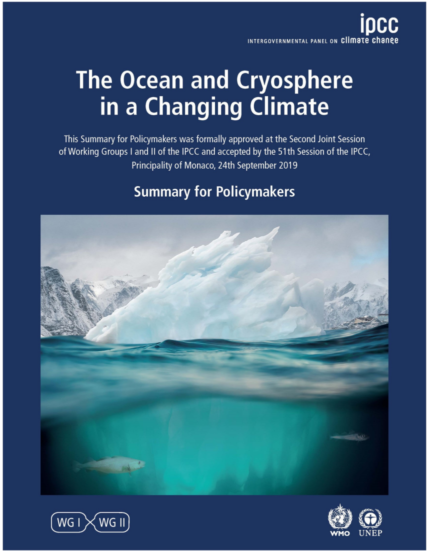
We don't know...

No effective coarse-grained models, i.e. parameterizations of turbulence in ice-ocean boundary layers.

But we know a lot!
And we know (some of) what we don't know and what we don't do.

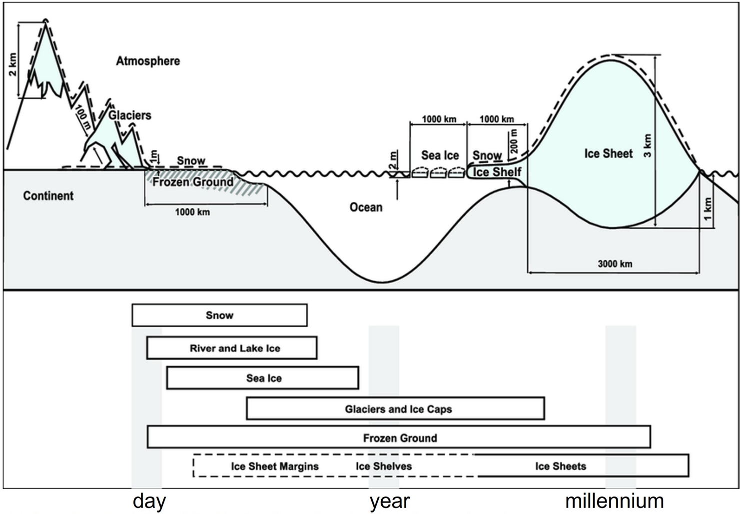
But we know a lot!
And we know (some of) what we don't know and what we don't do.
Ocean codes don't implement state-of-the-art models of stratified turbulent boundary layers.

1. Ice-ocean interactions until the early 2010s
   - Fluxes across the Ice-Shelf-Ocean Boundary Layer (ISOBL)
   - Meltwater plume models
   - Cavity-scale circulation
2. Ice-ocean interactions in the past ∼15 years
   - Melting regimes of horizontal ice boundaries
   - Testing Reynolds mixing analogy with high-resolution simulations
   - Testing plume parameterizations with high-resolution simulations
3. Ice-ocean interactions: some challenges for the future
   - Position-aware parameterizations
   - Subglacial discharge
   - Basal ice topography



- Part of IPCC Sixth Assessment Report (AR6)
- AR1 published in 1990
- First IPCC report examining the state of Earth's farthest corners—from the highest mountains and remote polar regions to the deepest oceans
- It found that even and especially in these places, human-caused climate change is evident
- In fact, it found that the world's ocean and cryosphere have been *taking the heat* for climate change for decades
- Direct impact on sea levels as if water isn't in solid ice, it's in the ocean (or ground)

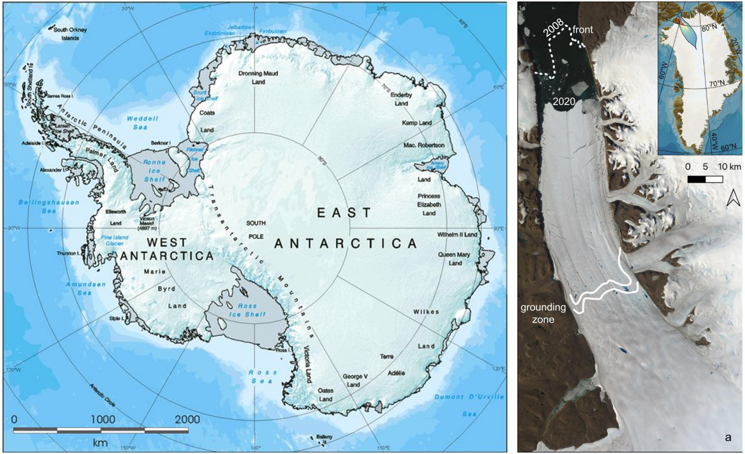
Figure 4.1. Components of the cryosphere and their time scales.



© Lemke & al (2007) *AR4: The Physical Science Basis*.

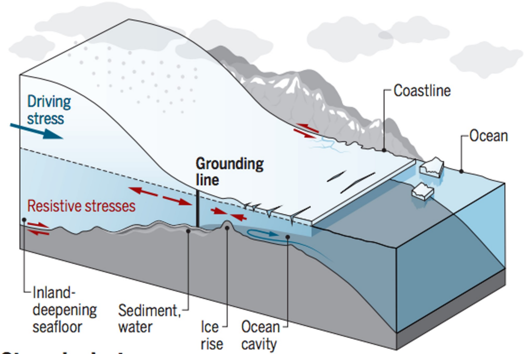
Sea-Level rise Equivalent (SLE)

- Antarctic ice sheet (AIS): 60 m
- Greenland ice sheet (GIS): 7.2 m
- Glaciers & ice caps: 0.4 m
- Frozen grounds (permafrost): 0.1 m
- Sea ice and ice shelves: 0 m



© Left: Abrahamsen (2012) *Oceanographic conditions beneath Fimbul Ice Shelf, Antarctica*. Right: Akesson & al (2022) *Petermann ice shelf may not recover after a future breakup*.

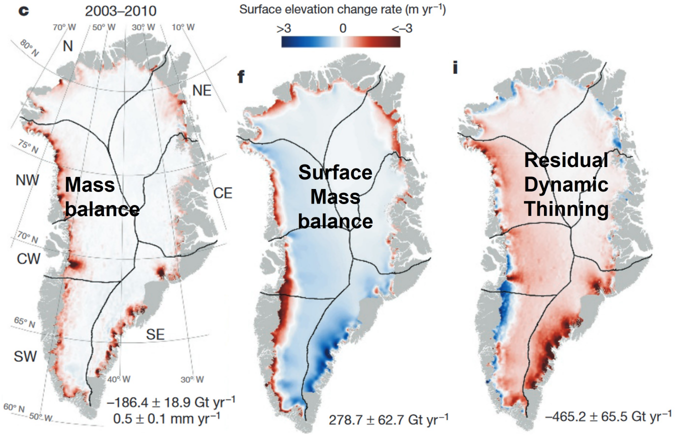
- Ice shelves fringe most of the Antarctic coastline. They add up to equate Greenland's surface area
- Only one extensive ice shelf borders Greenland (but fast retreating), others glaciers referred to as marine terminating



Stress budget
Ice flows in the direction of its surface slope due to gravity. Properties of the ice and materials at the boundaries determine other terms in the stress budget.

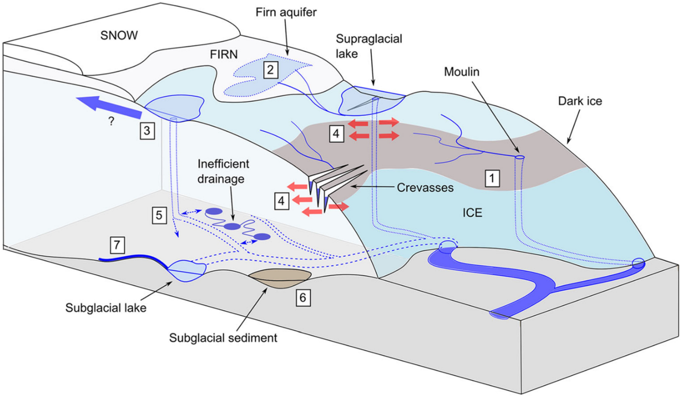
© Left: Hulbe (2017) *Is ice sheet collapse in West Antarctica unstoppable?* Right: D Vaughan ITGC (2020) *Ice front of Thwaites Glacier*.

- Ice shelves can provide buttressing against the flows of continental ice upstream (often, but not always) depending on the stress budget
- Vertical shear becomes ineffective, except near pinning points
- Next in line are extensional stresses (neglected under SIA) and lateral stresses



© Kjeldsen et al (2015) *Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since ad 1900.*

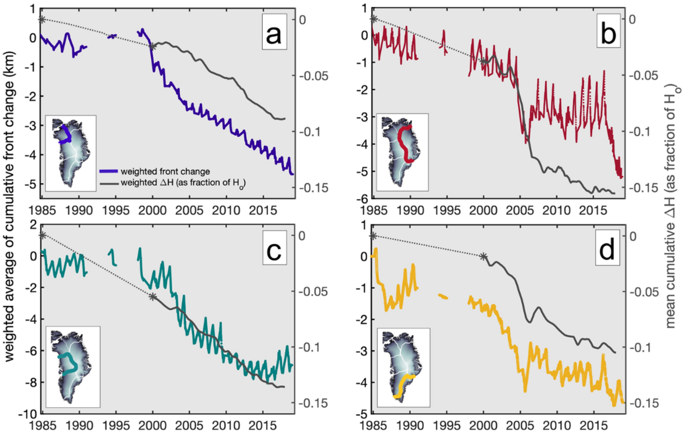
- GIS made of marine-terminating glaciers (little floating ice)
- GIS evolution is primarily driven by dynamic thinning and weak surface mass balance $S > 0$
- Weak SMB possibly linked to changes in atmospheric forcing and circulation



© Nienow et al (2017) *Recent Advances in Our Understanding of the Role of Meltwater in the Greenland Ice Sheet System.*

© EOS, D. Walsh.

- Dynamic thinning can result from supraglacial meltwater infiltrating the ice, lubricating the bed and increasing ice velocity



© King et al (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat.*

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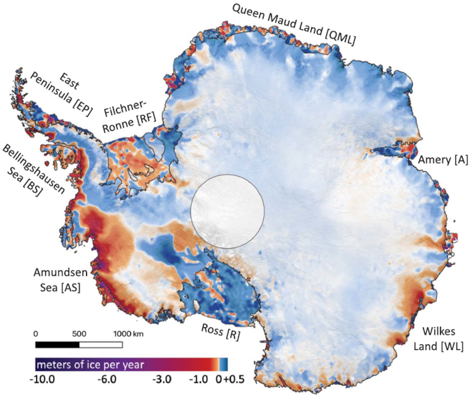
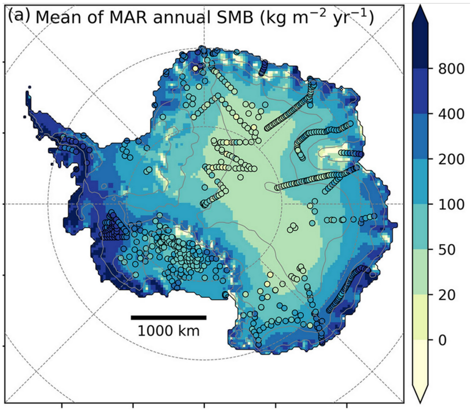
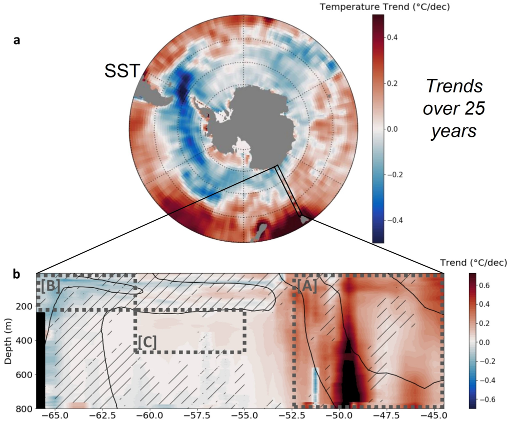
- Dynamic thinning can also result from melt-driven retreat of marine-terminating glacier fronts inland, reducing friction



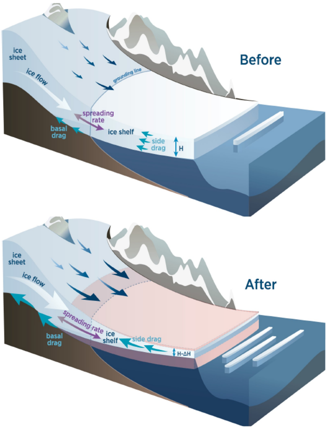


© Left: Smith et al (2020) *Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes*.
Right: Agosta et al (2019) *Estimation of the Antarctic surface mass balance […] (1979–2015) […]*.

- Thinning is dynamic (more so than GIS) as SMB well above 0 ($S > 0$)
- Dynamic thinning linked to warming oceans that melt ice shelves, losing buttressing



Trends over 25 years



© Left: Auger & al (2021) *Southern Ocean in-situ temperature trends over 25 years emerge from interannual variability*.
Right: Gudmundson & al (2019) *Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves*.

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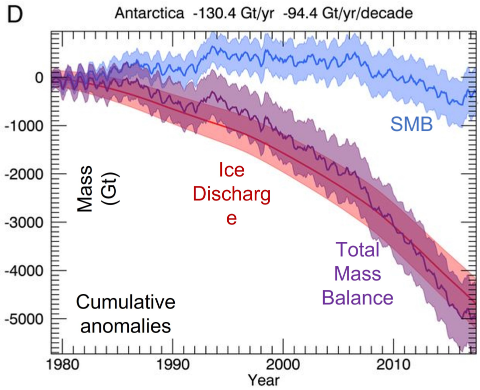
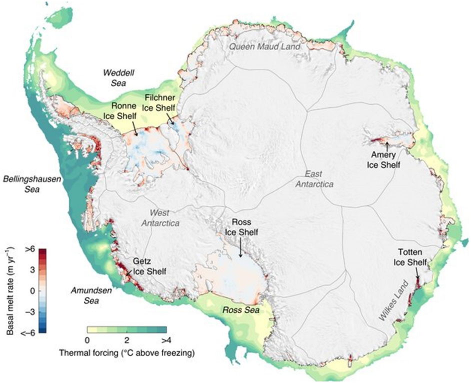
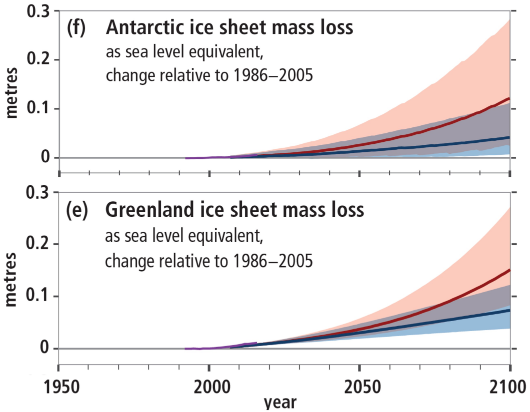




© Left: Rignot & al (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*. Right: Adusumilli & al (2020) *Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves*.

- AIS loss accelerating but with large regional variations



- Both GIS and AIS loss poised to increase through the 21st century

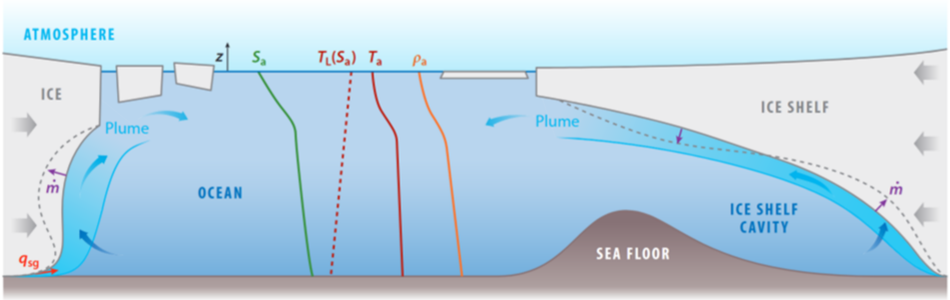


Figure: *Hewitt, I. J. (2020). Subglacial plumes. Annual Review of Fluid Mechanics, 52(1), 145-169.*

- The importance of Ice-Shelf Water (ISW) in Antarctic Bottom Water (ABW) formation was recognized long ago, first from melt-induced cooling (e.g. Sverdrup 1940) and then from salt release through refreezing (e.g. Robin 1970)
- In the 70s and 80s, the first computer models emerged (vertical slices), requiring a parameterization of heat and salt fluxes across an ice-shelf-ocean boundary layer

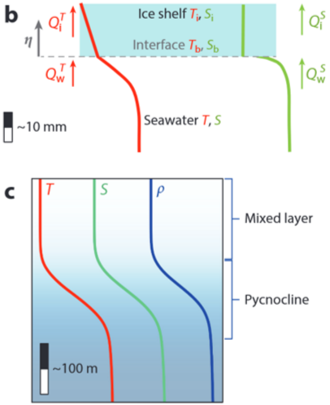
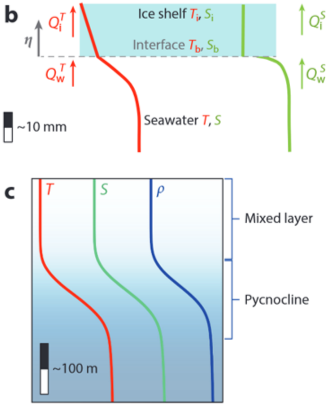


Figure: *Rosevear, M. G., Gayen, B., Vreugdenhil, C. A., & Galton-Fenzi, B. K. (2025). How Does the Ocean Melt Antarctic Ice Shelves?. Annual Review of Marine Science, 17(1), 325-353.*

- Melting occurs when the ocean brings more heat than is conducted through the ice
- Cooling and freshening create a buoyant meltwater layer that shields the ice



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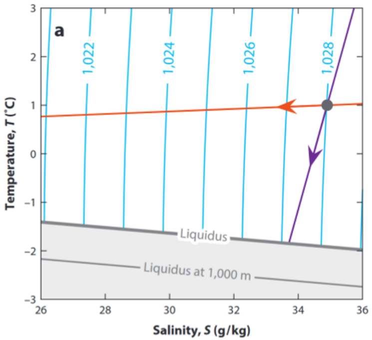

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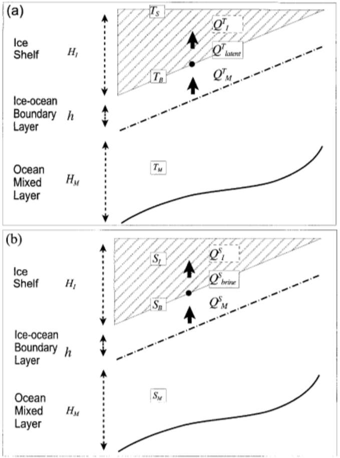
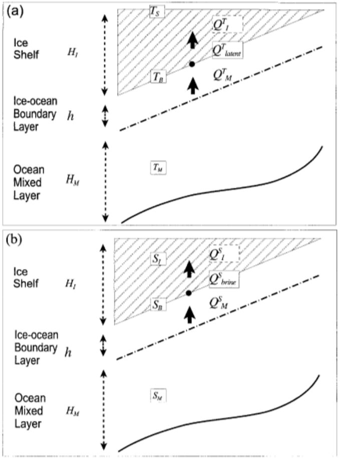


Figure: *Holland, D. M., & Jenkins, A. (1999). Modeling thermodynamic ice–ocean interactions at the base of an ice shelf. Journal of physical oceanography, 29(8), 1787-1800.*

- Holland & Jenkins popularized ISOBL parameterizations in 1999, putting forth three formulations of increasing complexity



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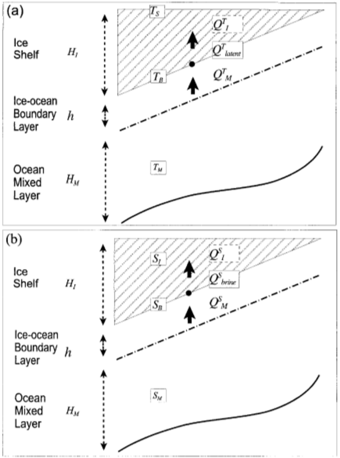
- Holland & Jenkins popularized ISOBL parameterizations in 1999, putting forth three formulations of increasing complexity
- The three-equation model (3EQ), which is the most sophisticated (and used), reads:

$$T_B = aS_B + b + cP_B, \tag{1a}$$

$$\rho_I w_B L_f = Q^T_M = \rho_0 c_{p0} \gamma_T (T_M - T_B), \tag{1b}$$

$$\rho_0 w_B S_B = Q^S_M = \rho_0 \gamma_S (S_M - S_B), \tag{1c}$$



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- The heat and salt exchange velocities $\gamma_{T,S} = Nu_{T,S} \kappa_{T,S}/h$ were (still are), following Kader & Yaglom (1972) and Mc Phee et al. (1987), parameterized as $\boldsymbol{\gamma_{T,S} = u_* \Gamma_{T,S} = U_M \sqrt{C_D} \Gamma_{T,S}}$

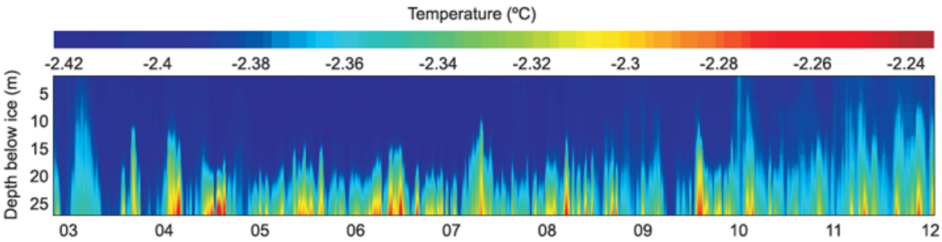
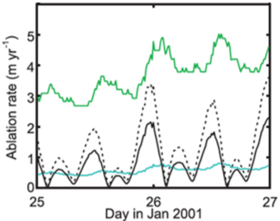
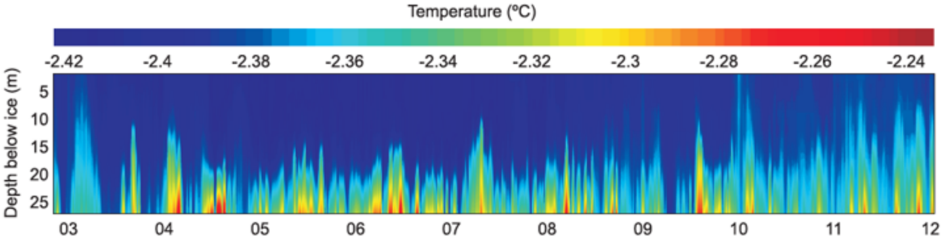


Figure: *Jenkins, A., Nicholls, K. W., & Corr, H. F. (2010). Observation and parameterization of ablation at the base of Ronne Ice Shelf, Antarctica. Journal of Physical Oceanography, 40(10), 2298-2312.*



- Jenkins et al. 2010 tested 3EQ with observation below Ronne Ice Shelf
- A good agreement can be obtained, after careful calibration of the parameters



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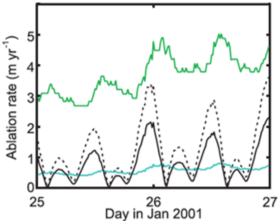
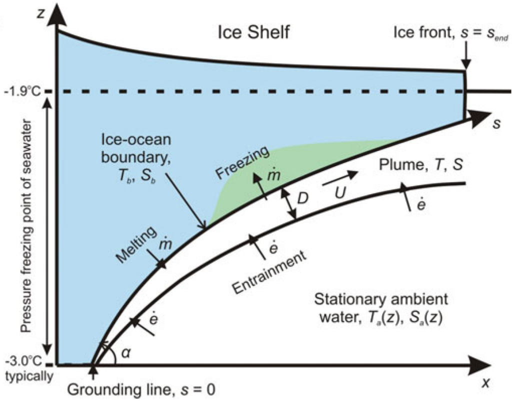


- Jenkins et al. 2010 tested 3EQ with observation below Ronne Ice Shelf
- A good agreement can be obtained, after careful calibration of the parameters
- Some questions arise: what should we use as mixed-layer values? Is the formulation correct, even if best fits generate widely varying



$$\frac{d}{ds}(DU) = \dot{e} + \dot{m}_w,$$

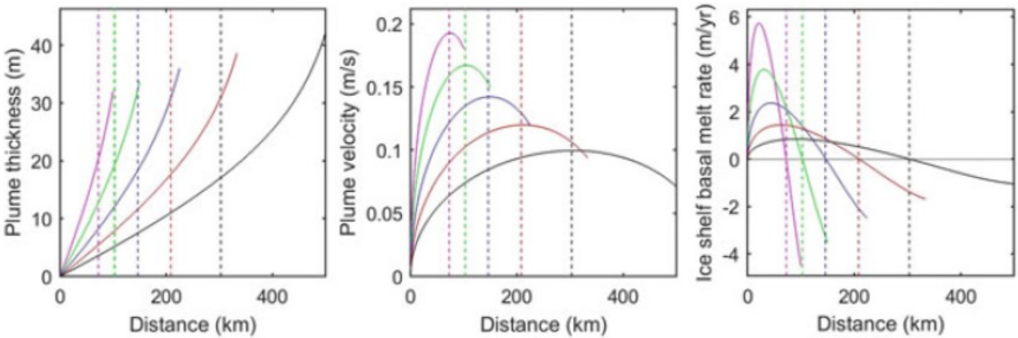
$$\frac{d}{ds}(DU^2) = D\frac{\Delta\rho}{\rho_0} g \sin\alpha - C_d U^2,$$

$$\frac{d}{ds}(DUT) = \dot{e}T_a + \dot{m}_w T_b - C_d^{1/2} U \Gamma_T (T - T_b),$$

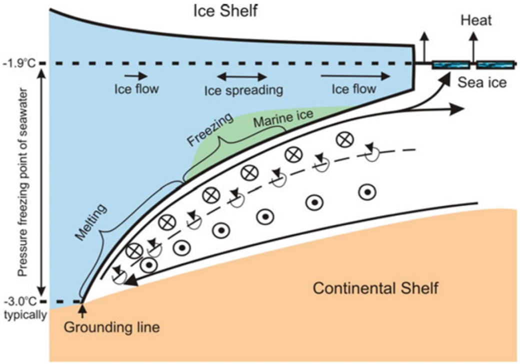
$$\frac{d}{ds}(DUS) = \dot{e}S_a + \dot{m}_w S_b - C_d^{1/2} U \Gamma_S (S - S_b).$$

© Jenkins (2021) *Interaction of ice shelves with the ocean* (in Karthaus Summer School Lecture notes).

- A reduced one-dimensional model for steady meltwater plumes quickly emerged (e.g. Jenkins 2011) as a low-cost substitute for full 3D ocean models
- It integrates 3EQ and an ambient entrainment parameterization as $\dot{e} = E_0 U \sin\alpha$



- The plume monotonically thickens; however, both the melt rate and the velocity reach a maximum
- As the slope increases, the plume thickens, speeds up and the melt rate increases



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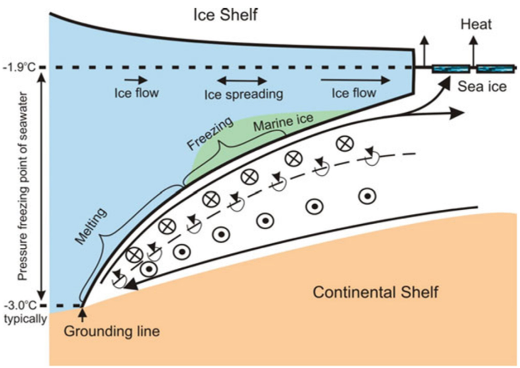
- The cavity-scale circulation is in geostrophic balance ($Ro \ll 1$)

- Thermal wind balance and positive equatorward density gradients $\partial_y \rho > 0$ (saltier to the north) imply westward flows ($u < 0$), to the left of the plume (Coriolis $f < 0$), near the ice ($\partial_z u \propto \partial_y \rho / f < 0$), possibly turning eastward at depth



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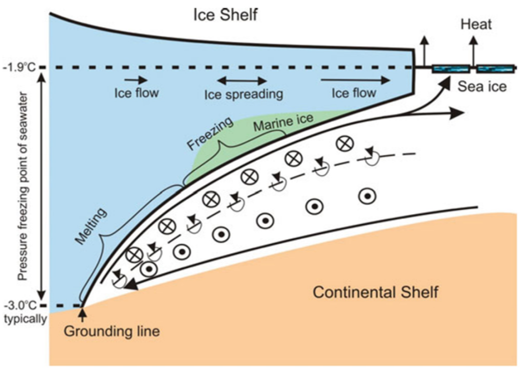

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- Bulk geostrophic flows tend to follow isocontours of ice thickness as they are non divergent ($w = 0$)

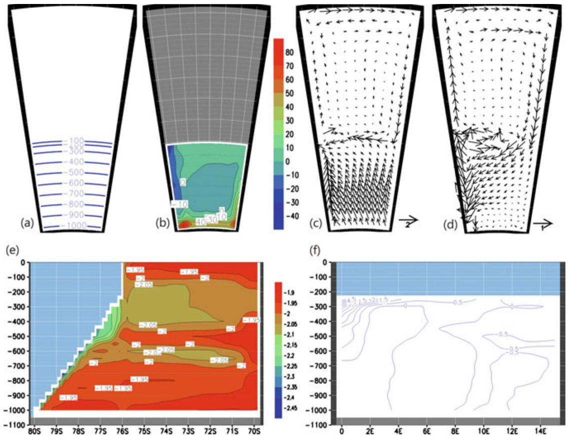

Fig. 5.13 Results from a three-dimensional model of the ocean circulation in an idealised sub-ice-shelf cavity: **a** ice draught (m); **b** basal melt rate (cm yr^{-1}); **c** mixed layer velocity (cm s^{-1}); **d** depth-mean velocity (cm s^{-1}); **e** temperature at the western boundary (°C); **f** velocity normal to the ice front (cm s^{-1})

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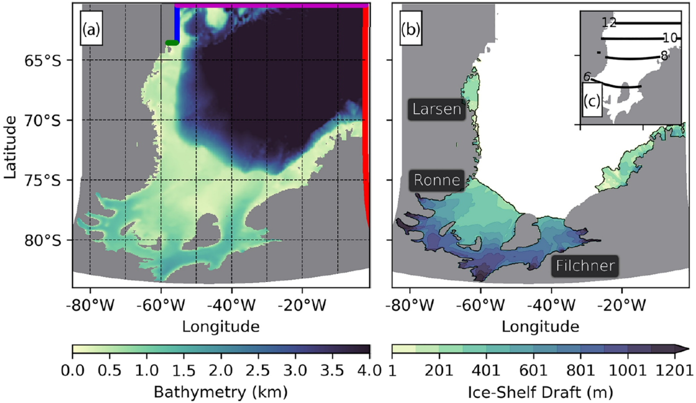
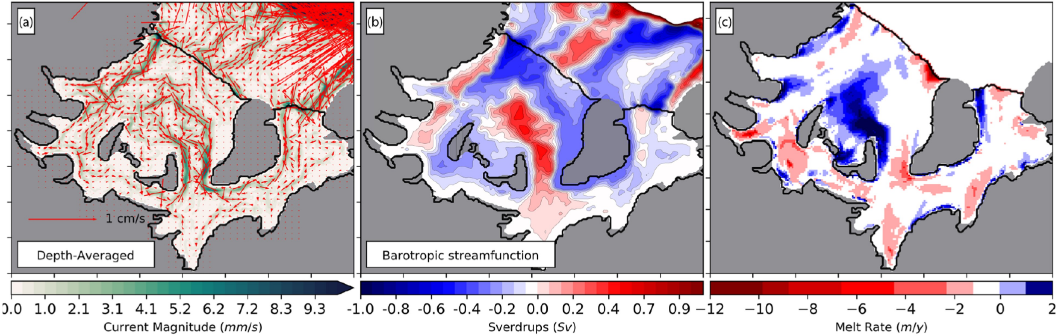
- Exhibits the ice pump mechanism (melting at depth/freezing above maintained by weak overturning)
- Mixed layer velocity to the north and west, as expected
- Depth averaged velocity has non zero zonal component because of boundaries and cyclonic gyres
- Outflow has two distinct tongues of water extruding, one where the plume stops ascending and one due to ambient stratification
- Broad weak inflow to the east and energetic thin outflow to the west



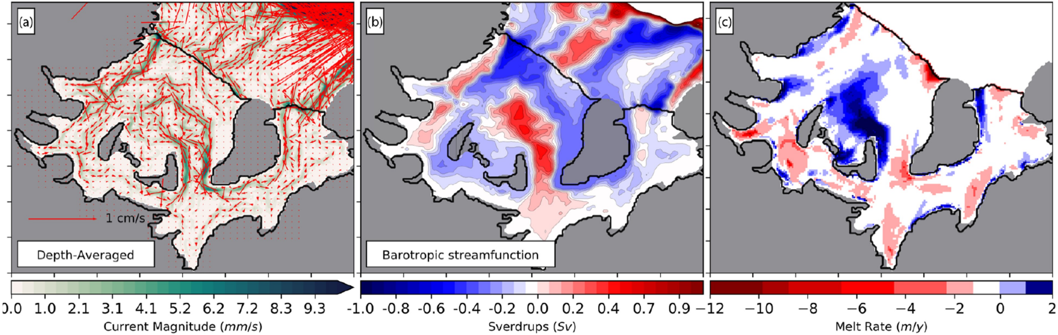
© Bull & al (2021) *Remote control of Filchner-Ronne Ice Shelf*.

- Nucleus for European Modeling of Ocean model (NEMO) of Weddell Sea WED025 (1/4°)
- Japanese Reanalysis for driving oceans (JRA55-do) provides surface forcing conditions
- Boundary conditions forced from global model output with JRA forcing
- Mean melt rate scales linearly with Antarctic slope current salinity and quadratically with temperature



© Bull & al (2021) *Remote control of Filchner-Ronne Ice Shelf*.

- Clockwise/cyclonic (anti-clockwise) around red (blue) patches



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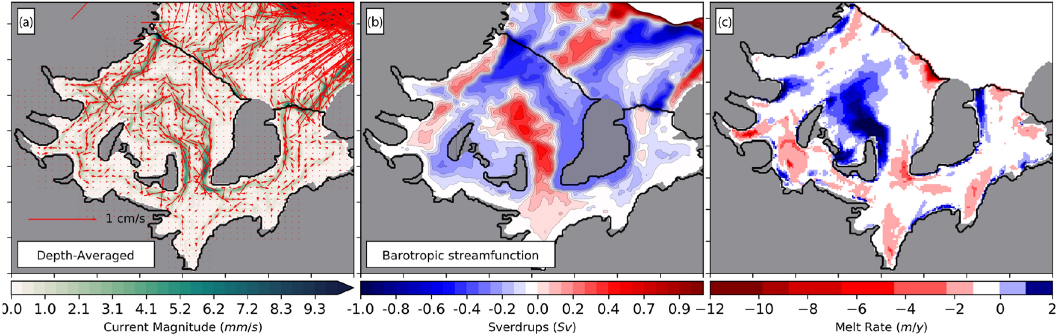
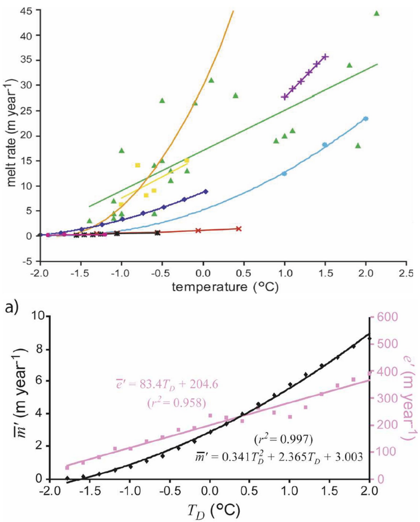
- Clockwise/cyclonic (anti-clockwise) around red (blue) patches
- Outflows to the west of FIS and RIS, near inflows (usually running through bed depressions)



© Bull & al (2021) *Remote control of Filchner-Ronne Ice Shelf*.

- Clockwise/cyclonic (anti-clockwise) around red (blue) patches
- Outflows to the west of FIS and RIS, near inflows (usually running through bed depressions)
- FRIS is a cold cavity, implying large freezing areas



© Holland & al (2008) The Response of Ice Shelf Basal Melting to Variations in Ocean Temperature.

- T^2 dependence faster than the $T^{3/2}$ dependence from the plume model
- The difference comes from the scaling of mixed layer (plume) speed with buoyancy: primitive equation yields a near-geostrophic linear scaling while the plume model has a square root scaling
- In cases where the mixed layer buoyancy is not controlled by the melt rate but by external factors (e.g. subglacial discharge or tidal currents) the melt rate dependence on temperature should be closer to linear (melt-driven plume vs convection-driven melt)

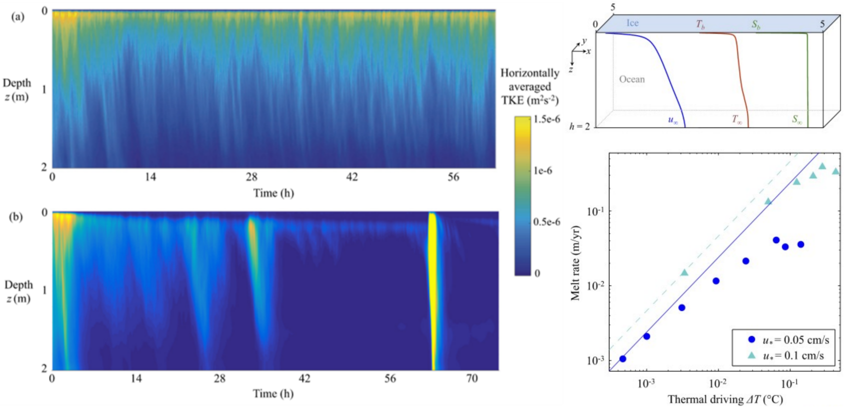


Figure: *Vreugdenhil, C. A., & Taylor, J. R. (2019). Stratification effects in the turbulent boundary layer beneath a melting ice shelf: Insights from resolved large-eddy simulations. Journal of Physical Oceanography, 49(7), 1905-1925.*

- Vreugdenhil et al. (2019) have recently shown that the melt rate of flat interfaces deviates from the linear 3EQ scaling at large thermal driving

- Rosevear et al. (2022) then proposed a 3-regime diagram based on friction velocity u^* and thermal forcing T^*

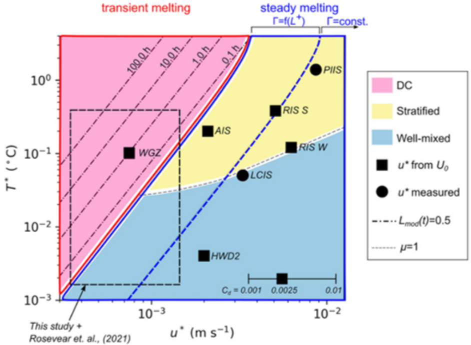
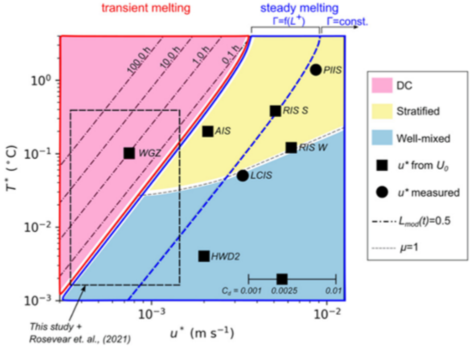


Figure: *Rosevear, M. G., Gayen, B., & Galton-Fenzi, B. K. (2022). Regimes and transitions in the basal melting of Antarctic ice shelves. Journal of Physical Oceanography, 52(10), 2589-2608.*

- Rosevear et al. (2022) then proposed a 3-regime diagram based on friction velocity u^* and thermal forcing T^*



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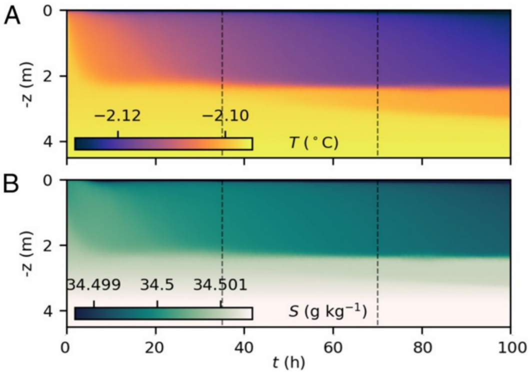
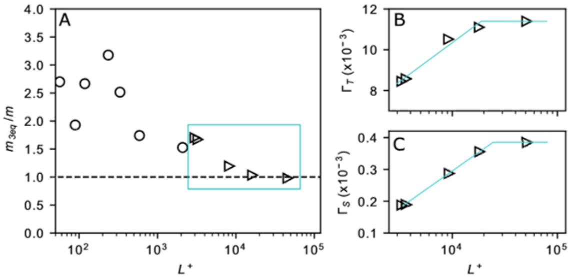
- At low u^* they identified a diffusive-convective regime, which has a permanently cooling and freshening mixed layer (no steady state)



- 3EQ overpredicts melting when the Obukhov length scale

$$L^+ = \frac{L}{\delta^+} = \frac{-u^{*3}}{kB_b}\frac{u^*}{\nu} \leq 5 \times 10^4 \qquad (2)$$

with $k = 0.41$ von Kármán's constant and $B_b > 0$ the surface buoyancy gradient



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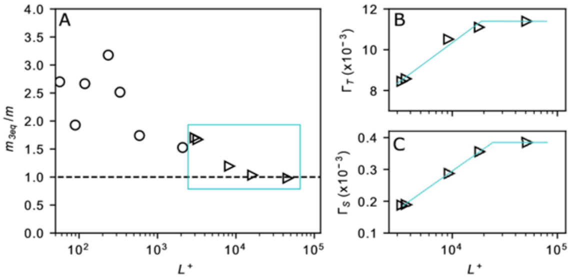
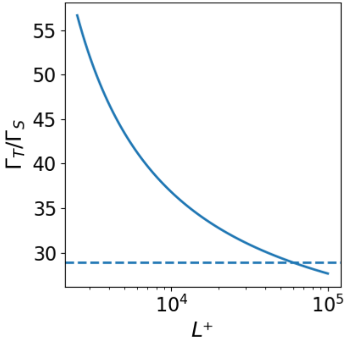




- $Nu_S \downarrow$ faster than $Nu_T \downarrow$ with $L^+ \downarrow$ as temperature anomalies become an important source of TKE in the stratified limit

- A low-salinity layer slowly thickens in diffusive convection
- Fluxes vary with depth as the deep layer becomes decoupled from the interface

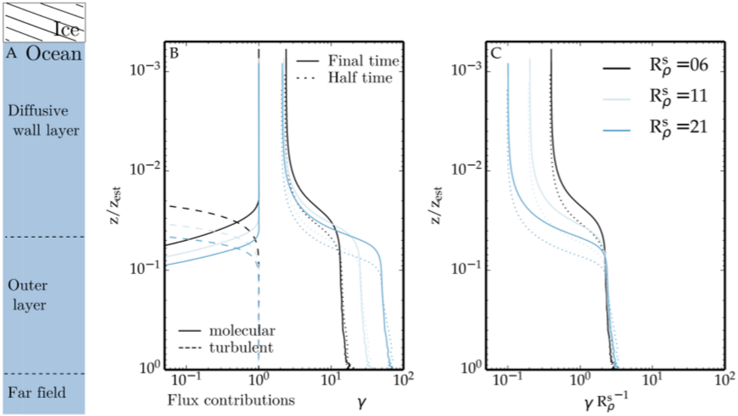


Figure: *Keitzl, T., Mellado, J. P., & Notz, D. (2016). Reconciling estimates of the ratio of heat and salt fluxes at the ice–ocean interface. Journal of Geophysical Research: Oceans, 121(12), 8419-8433.*

What is this??

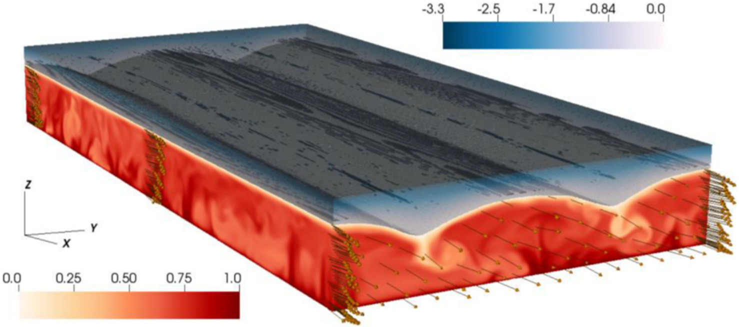
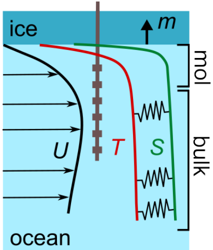


Figure: *Couston, L. A., Hester, E., Favier, B., Taylor, J. R., Holland, P. R., & Jenkins, A. (2021). Topography generation by melting and freezing in a turbulent shear flow. Journal of Fluid Mechanics, 911, A44.*

Postdoctoral work at the British Antarctic Survey...
Relevant to polar ocean environments if...

(Some) Observations support Reynolds mixing analogy

- If $\kappa_T^{turb} = \kappa_S^{turb}$ ...
- Gade (1979) showed that T and S are linearly correlated in a turbulent ice-ocean BL



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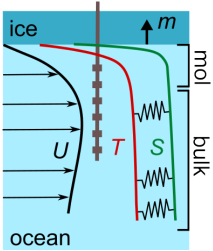

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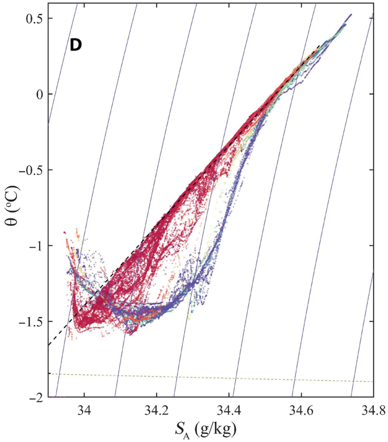

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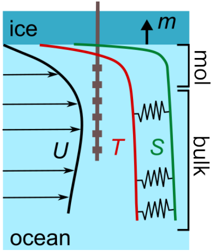

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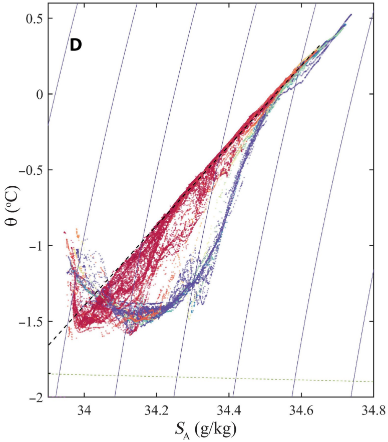

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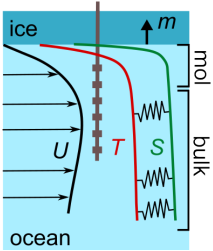
- $\kappa_T^{turb} = \kappa_S^{turb}$ often assumed in ocean models



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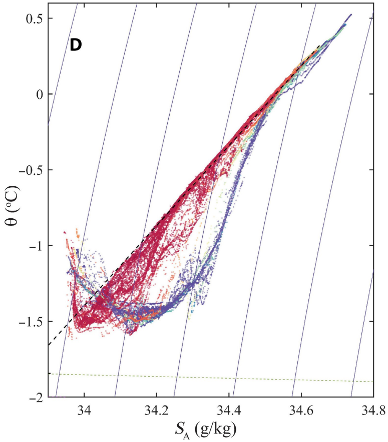

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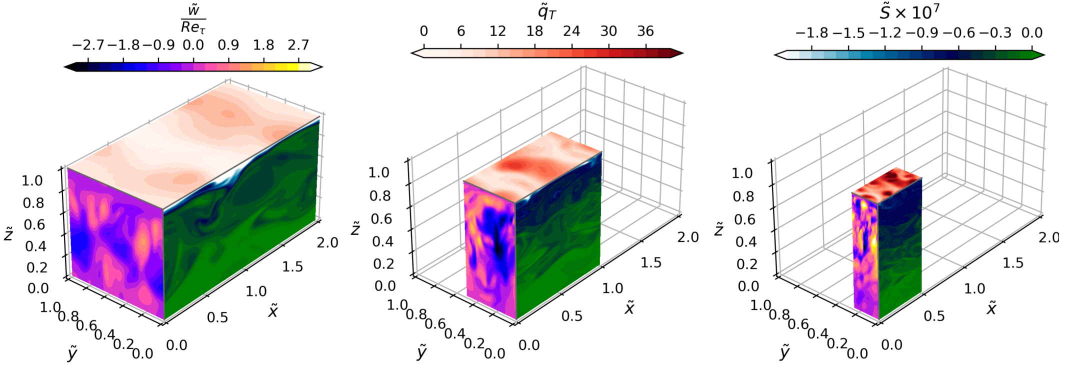
We test Reynolds mixing analogy in DNS of ice-ocean BL

- Uniform close-to-freezing ambient (bottom sponge layer) → shear dominated (pressure driven)
- Fixed horizontal ice boundary (low melt limit)
- Code Dedalus : horizontally periodic + minimal flow unit (smaller C_D)



7D Parameter space

$$\partial_{\tilde{t}}\tilde{\boldsymbol{u}} = Re_\tau^2 \boldsymbol{e_x} - Re_\tau^2 Ri_\tau(\tilde{S} - R_\rho \tilde{T})\boldsymbol{e_z} + ...,$$
$$\partial_{\tilde{t}}\tilde{T} = Pr^{-1}\tilde{\nabla}^2\tilde{T} + ...,$$
$$\partial_{\tilde{t}}\tilde{S} = Sc^{-1}\nabla^2 S + ...,$$
$$\tilde{T} = \gamma\tilde{S}, \quad \partial_{\tilde{z}}\tilde{S} = LeSt^{-1}\left(1+\tilde{S}\right)\partial_{\tilde{z}}\tilde{T}, \quad \tilde{z} = 1$$

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- $Re_\tau = \frac{u_\tau}{\nu H} \in [200, 800] \Rightarrow u_\tau \sim 0.1$ mm/s
- $Pr = \frac{\nu}{\kappa_T} \in [1, 10]$, $Le = \frac{\kappa_T}{\kappa_S} \in [1, 100]$

7D Parameter space

$$\partial_{\tilde t}\tilde{\boldsymbol{u}} = Re_\tau^2 \boldsymbol{e_x} - Re_\tau^2 Ri_\tau(\tilde S - R_\rho \tilde T)\boldsymbol{e_z} + \ldots,$$
$$\partial_{\tilde t}\tilde T = Pr^{-1}\tilde\nabla^2 \tilde T + \ldots,$$
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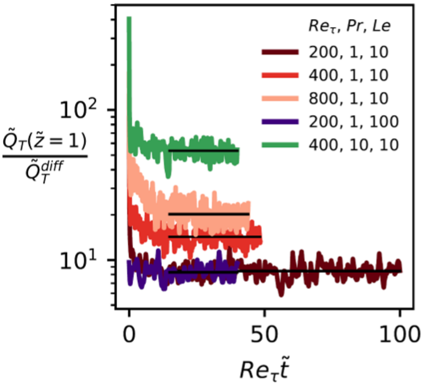
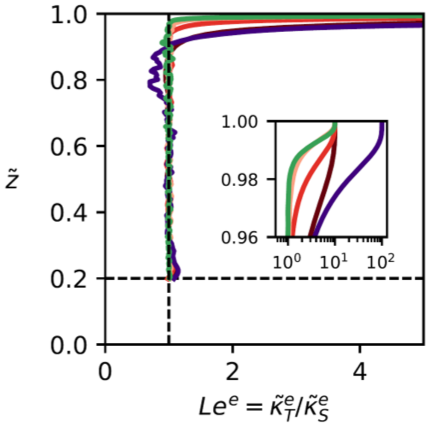


Turbulent diffusivities

- $\tilde{\kappa}_X^e = \tilde{\kappa}_X^{mol} + \tilde{\kappa}_X^{turb}$



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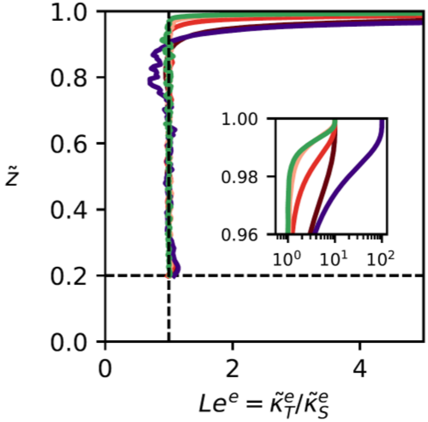
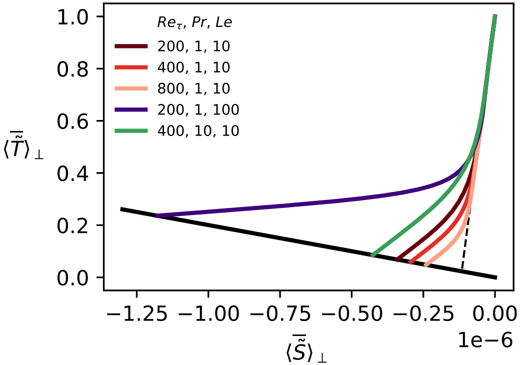


$T - S$ diagram

- Clear overlap with meltwater mixing line in the bulk



Validity of Reynolds mixing analogy supports the existence of a reduced model

- Flux relationship at interface implies constrained transformations of water masses
- And supports the existence of an aggregate coordinate encoding T and S effects

$$\tilde{T}_* = \tilde{T} - \gamma \tilde{S}$$

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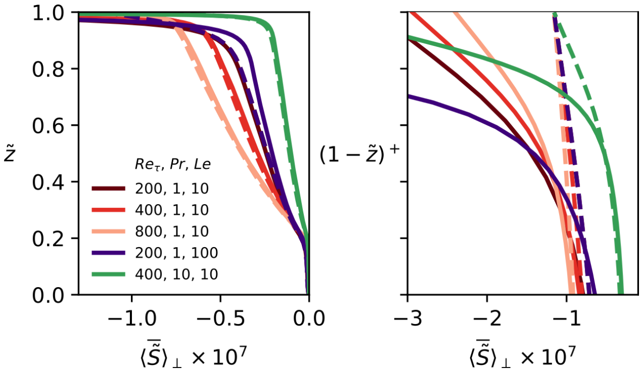
- $\partial_{\tilde{t}} \tilde{T}$, $\partial_{\tilde{t}} \tilde{S} \to \partial_{\tilde{t}} \tilde{T}_*$ $(Pr_* \leq Pr)$
- Using the linear $T - S$ correlation
- $\tilde{T}(\tilde{T}_*)$, $\tilde{S}(\tilde{T}_*)$
- Good agreement in the bulk
- Disagreement in the sublayers



Remarks on the reduced thermal driving model

- Great to spin up the flow and have a 0th-order prediction of the melt rate
- But would require a wall model to capture sublayer properties
- And the impact of interfacial salt deficit on melt rate and flux ratio

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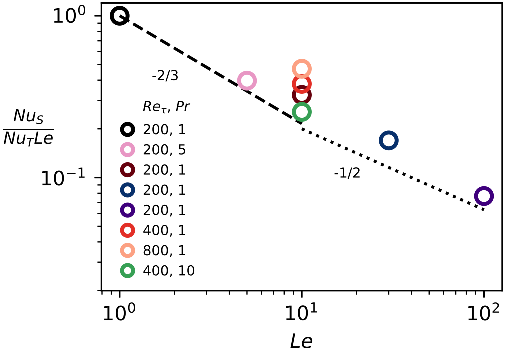
Exchange velocity ratio

$$\frac{\gamma_S}{\gamma_T} = \frac{Nu_S}{Nu_T Le} = \frac{St\left[1-\overline{\tilde{T}}(\tilde{z}=1)\right]}{-\left[1+\overline{\tilde{S}}(\tilde{z}=1)\right]\overline{\tilde{S}}(\tilde{z}=1)} \approx \frac{St}{-\overline{\tilde{S}}(\tilde{z}=1)}$$

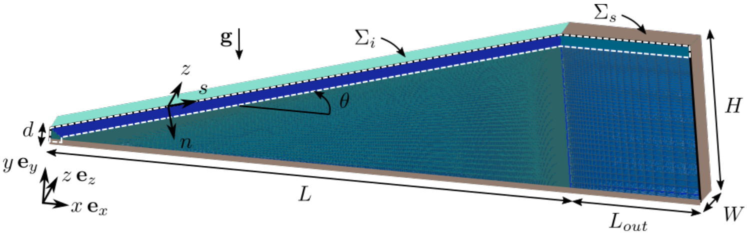


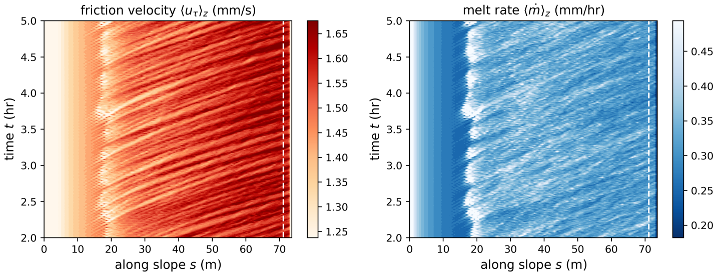
This passive scalar limit still holds lots of secrets... Next steps

- Theoretical derivation of a wall model for the reduced thermal driving set of equations
- When does $Le^e \neq 1$? In the high thermal driving limit?
- Can we relate shifts in $T - S$ observations from the meltwater mixing line to $Le^e \neq 1$?
- Should we turn to laboratory experiments and/or simulations on GPUs to minimize greenhouse gases emissions?
- Other important things ... (reach out if you'd like to know more!)

DNS of plume dynamics (work with Alexandre Tlili)

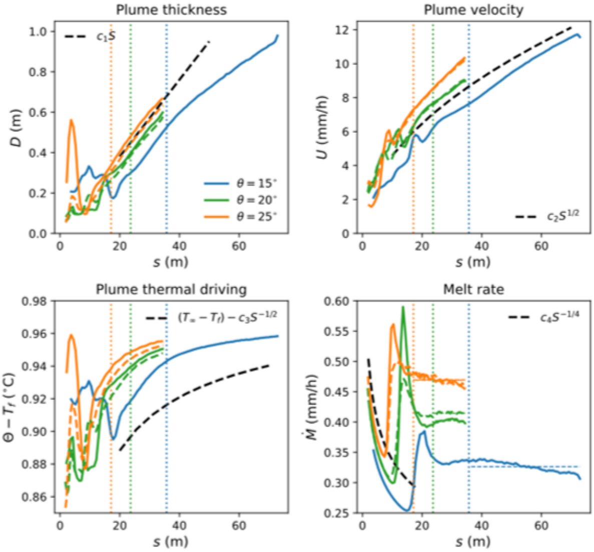
- Code Nek5000
- Melting of tilted ice boundary → plume
- Freshwater with $Pr = 14$
- $\theta = 15^\circ, 20^\circ, 25^\circ$
- $Ra \sim 10^{14}$
- $L \sim 100$ m
- $T_\infty = 1^\circ C$





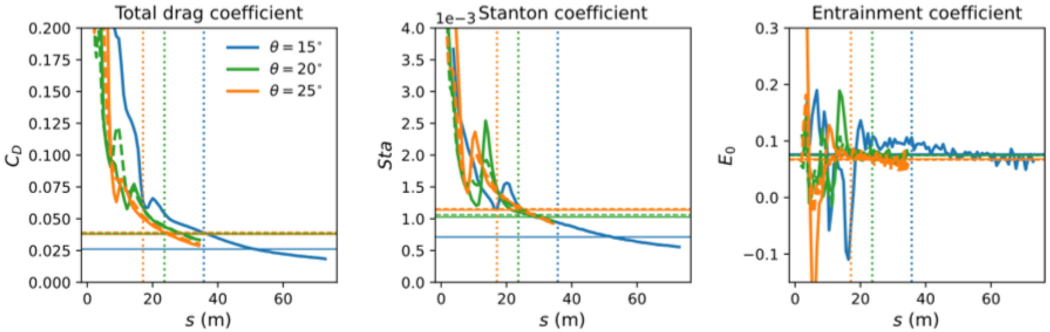
Key plume properties

- Plume thickness $\sim s$ ($\sim s$ expected)
- Plume velocity $\sim s^{1/2}$ ($\sim s^{1/2}$)
- Plume buoyancy $\sim s^{-1/2}$ (~ 1)
- Melt rate slightly decreasing ($\sim s^{1/2}$)



Model parameters

- They are not constants! (save maybe the entrainment coefficient)



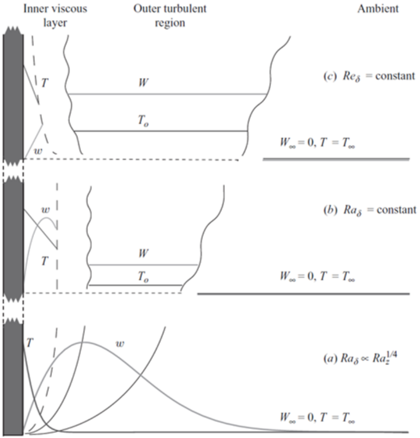
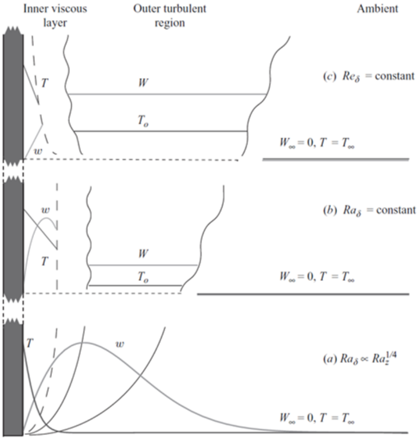


Figure: *Wells, A. J., & Worster, M. G. (2008). A geophysical-scale model of vertical natural convection boundary layers. Journal of Fluid Mechanics, 609, 111-137.*



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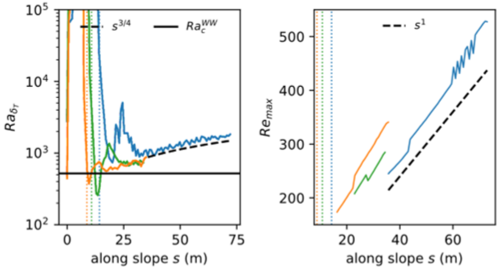
Buoyancy controls the dynamics (not shear)

- A uniform melt rate is inconsistent with 3EQ (underpredicts) ...
- ... but is consistent with vertical convection $Nu \sim Ra_{\mathcal{L}}^{1/3}$



The melt regime matters close to grounding lines

- Laminar-to-buoyancy-driven turbulence at $Ra_c^{vert} \sim 10^{12}$
- Buoyancy-to-shear-driven turbulence at $Ra_t^{vert} \sim 10^{18}$
- $L_c^{fresh} \sim 10\mathrm{m}$, $L_t^{fresh} \sim 1\mathrm{km}$, $L_c^{salt} \sim 4\mathrm{m}$, $L_t^{salt} \sim 400\mathrm{m}$ $(\alpha\Delta_T \leftrightarrow \beta\Delta_S)$
- A better buoyancy-driven melt parameterization would be $\dot{M} \sim \Delta_T^{4/3}$

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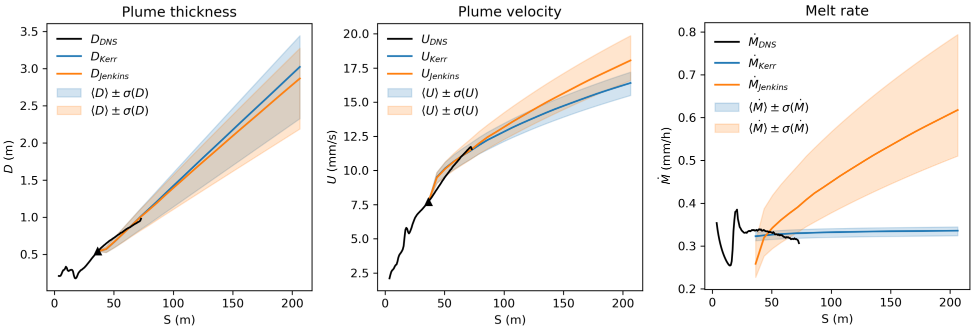

Next steps

- Assessing the impact of boundary slope/stratification, which will require more simulations
- Assessing the impact of thermal driving, which is more subtle than cavity length because of the freshwater EOS nonlinearity
- Assessing the impact of the pressure-dependence of the freezing point
- Applying the results to glaciers terminating in lakes
- Other important things (interested? $\rightarrow$ postdoc opportunity in the near future!)

1. Ice-ocean interactions until the early 2010s
   - Fluxes across the Ice-Shelf-Ocean Boundary Layer (ISOBL)
   - Meltwater plume models
   - Cavity-scale circulation
2. Ice-ocean interactions in the past ∼15 years
   - Melting regimes of horizontal ice boundaries
   - Testing Reynolds mixing analogy with high-resolution simulations
   - Testing plume parameterizations with high-resolution simulations
3. Ice-ocean interactions: some challenges for the future
   - Position-aware parameterizations
   - Subglacial discharge
   - Basal ice topography

Velocity coefficients' dependence with depth

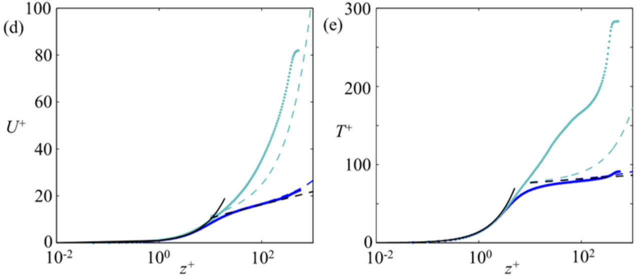

Figure: *Vreugdenhil, C. A., & Taylor, J. R. (2019). Stratification effects in the turbulent boundary layer beneath a melting ice shelf: Insights from resolved large-eddy simulations. Journal of Physical Oceanography, 49(7), 1905-1925.*

- Limited dependence thanks to the log law in the high shear limit
- Boundary roughness matters

Tilted ice boundaries are exposed to melt-driven plumes, but not only

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- Melt-driven plume models underpredict melting by 2 orders of magnitude!

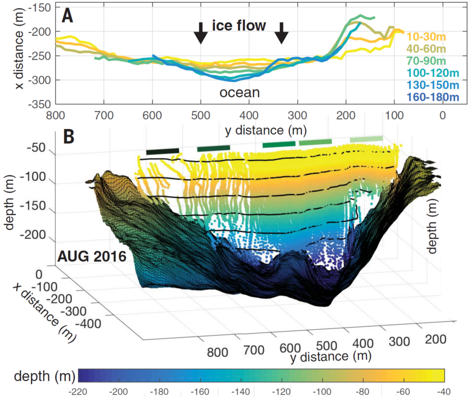


Figure: *Sutherland, D. A., Jackson, R. H., Kienholz, C., Amundson, J. M., Dryer, W. P., Duncan, D., ... & Nash, J. D. (2019). Direct observations of submarine melt and subsurface geometry at a tidewater glacier. Science, 365(6451), 369-374.*

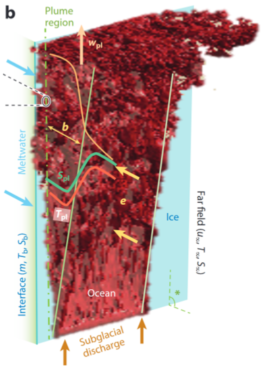
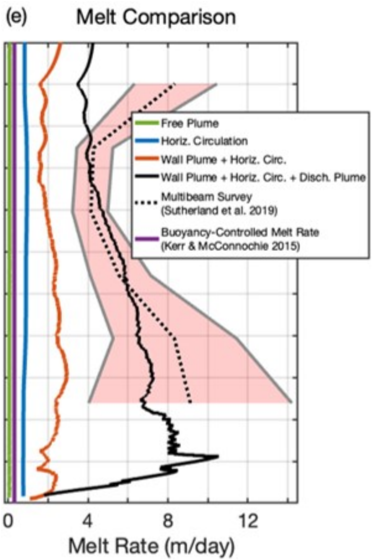


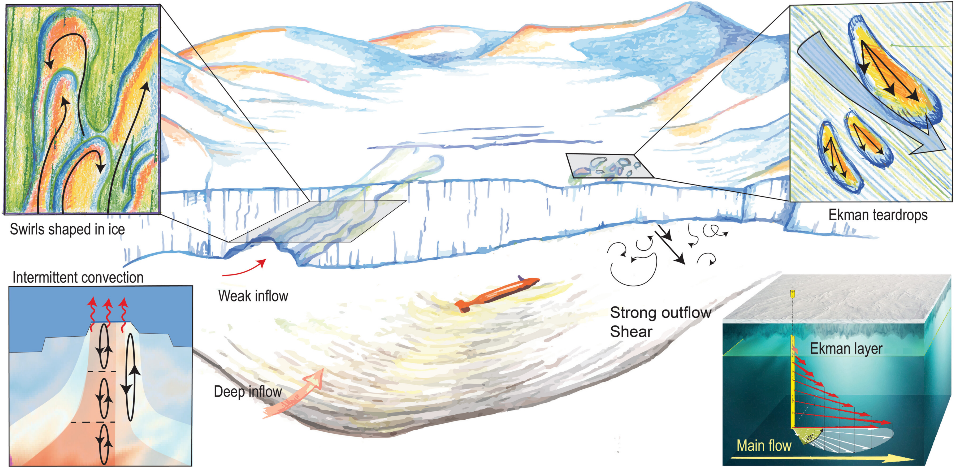
Figure: *Zhao, K. X., Skyllingstad, E. D., & Nash, J. D. (2024). Improved parameterizations of vertical ice-ocean boundary layers and melt rates. Geophysical Research Letters, 51(4), e2023GL105862.*



Many phenomena impact ice melting

- Cross flows can enhance wall-normal fluxes
- Subglacial discharge provides extra buoyancy
- The presence of sediments can enhance melting
- Bubbles trapped in the ice too!

Complex basal ice topography at multiple scales



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Boundary layer turbulence interacts with small-scale topography

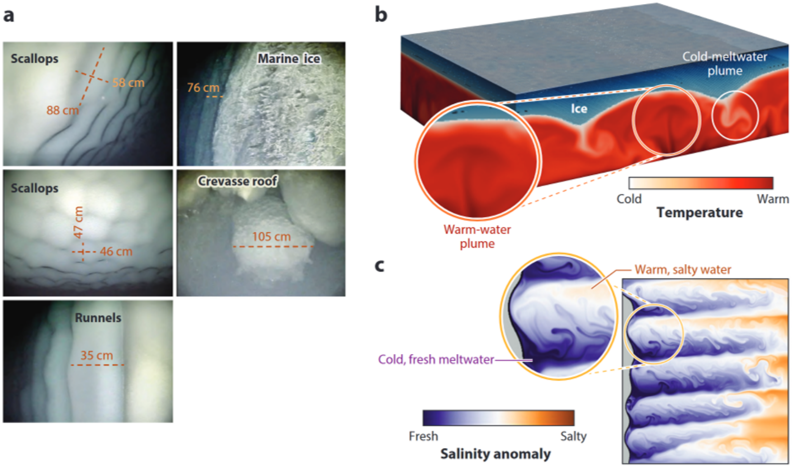
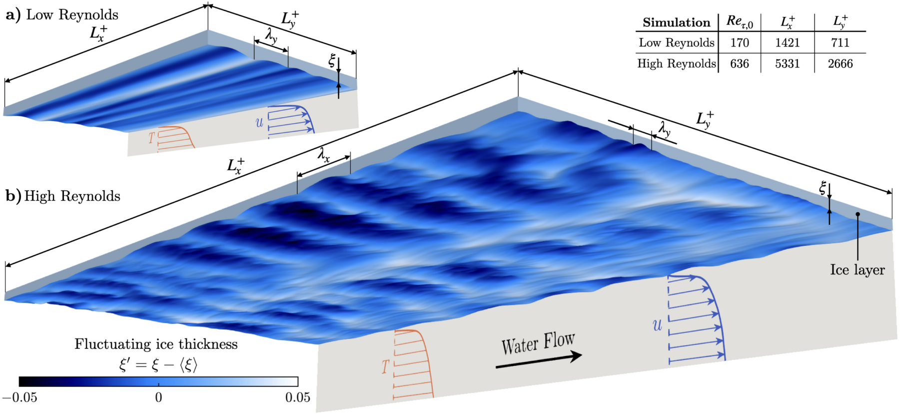


Figure: *Rosevear, M. G., Gayen, B., Vreugdenhil, C. A., & Galton-Fenzi, B. K. (2025). How Does the Ocean Melt Antarctic Ice Shelves?. Annual Review of Marine Science, 17(1), 325-353.*

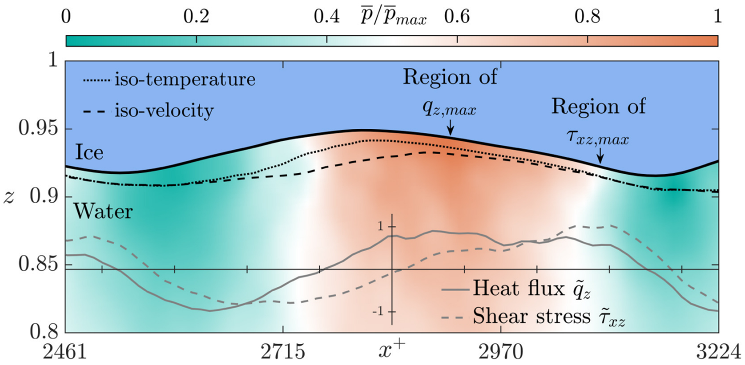
Streamwise wavelength emerge at high Re_τ (and low L_{fus})



Simulation	$Re_{\tau,0}$	L_x^+	L_y^+
Low Reynolds	170	1421	711
High Reynolds	636	5331	2666

Figure: *Perissutti, D., Marchioli, C., & Soldati, A. (2024). Morphodynamics of melting ice over turbulent warm water streams. arXiv preprint arXiv:2406.12116.*

Turbulent flow-topography instability ("passive" scalar)



- Instability driven by $q_{z,max}$ in the trough
- Shear also phase shifted relative to the topography (link with Hanratty's proposed correction to Reynolds stresses along a corrugated boundary)

Some stuff drawn from:

Couston, L. A. (2024). Turbulent ice-ocean boundary layers in the well-mixed regime: insights from direct numerical simulations. Journal of Physical Oceanography.

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So... How quickly does ice melt in seawater?

- Melt rate increases with temperature and nearby turbulence...
- It depends on the position within the cavity (geostrophy or plume dominated?) and distance from the wall of coarse-grained ocean properties
- In idealized situations, there is hope to obtain parameterizations (DNS, lab. exp.)
- How are we going to scale up?
- Empirically... based on our understanding of regime diagrams... (high shear OK)
- But we need a depth-dependent statistical model, possibly stochastic, of ice-ocean boundary layers
- Good parameterizations will still fail pointwise because of time-varying forcing and local hidden processes (freezing, discharge plumes...)
- We should aim for statistical (time) agreement over sub regions