Lecture 2: Ice-shelf–ocean interactions

Polar Dynamics
GFD Week

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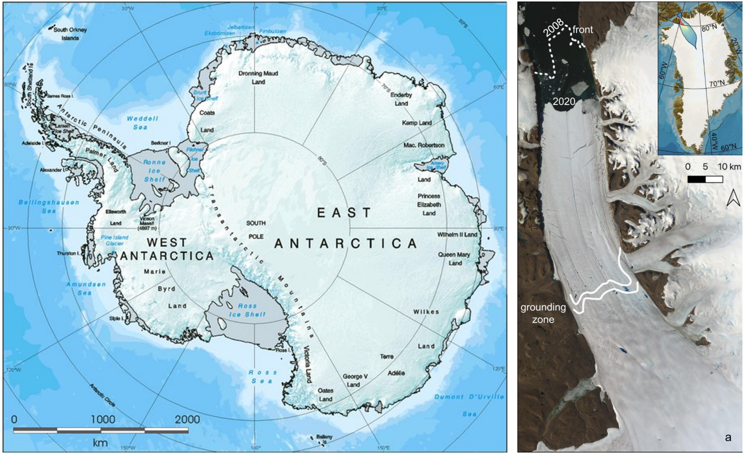
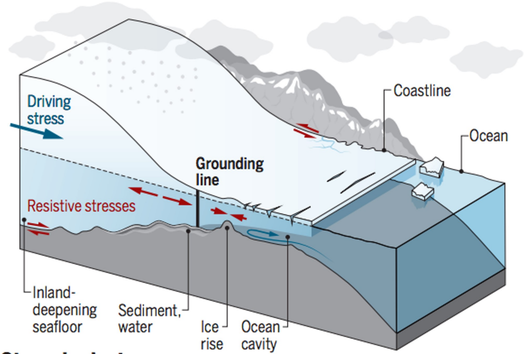


© Left: Abrahamsen (2012) *Oceanographic conditions beneath Fimbul Ice Shelf, Antarctica*. Right: Akesson & al (2022) *Petermann ice shelf may not recover after a future breakup*.

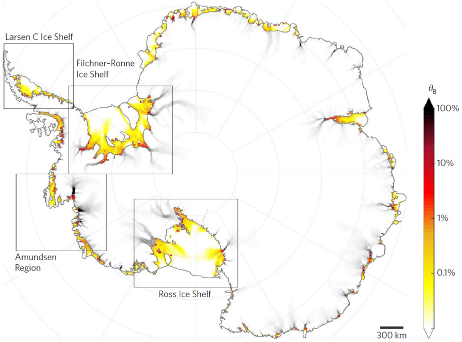
- Ice shelves fringe most of the Antarctic coastline
- Only one extensive ice shelf borders Greenland (but fast retreating), others glaciers referred to as marine terminating

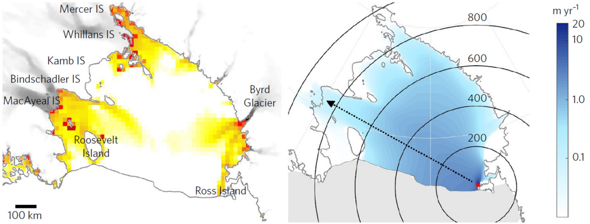


Stress budget
Ice flows in the direction of its surface slope due to gravity. Properties of the ice and materials at the boundaries determine other terms in the stress budget.

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

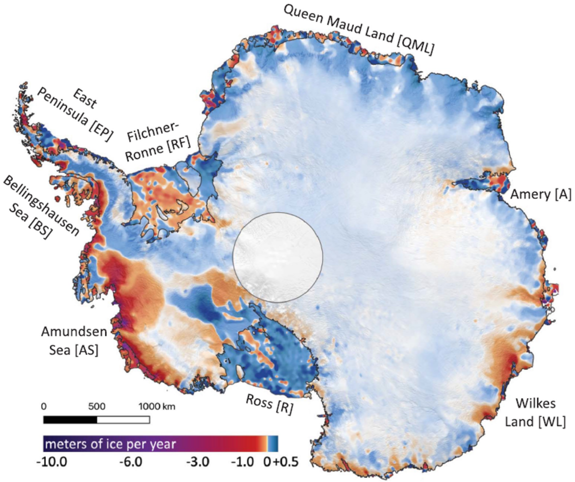
- Ice shelves can provide buttressing against the flows of continental ice upstream (often, but not always) depending on the stress budget
- Vertical shear becomes ineffective, except near pinning points
- Next in line are extensional stresses (neglected under SIA) and lateral stresses





© Reese & al (2018) *The far reach of ice-shelf thinning in Antarctica*.

- Buttressing prowess estimated from (instantaneous) changes in ice discharge across grounding lines induced by 1 m thinning over 20 km $\times$ 20 km square (red)
- Ice fluxes most sensitive to thinning near grounding lines and pinning points
- Ice speed (gray shading for grounded ice) up to 1000 m/y
- Black arrow shows tele-buttressing effect



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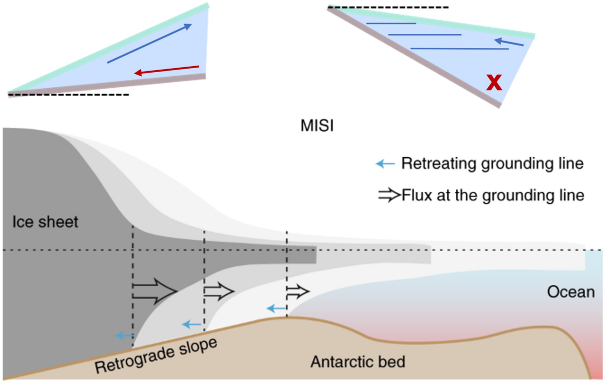
Retrograde slope
unconstrained melt outflow
easy access to GL for CDW

Prograde slope
self-inhibiting stagnant melt
no access



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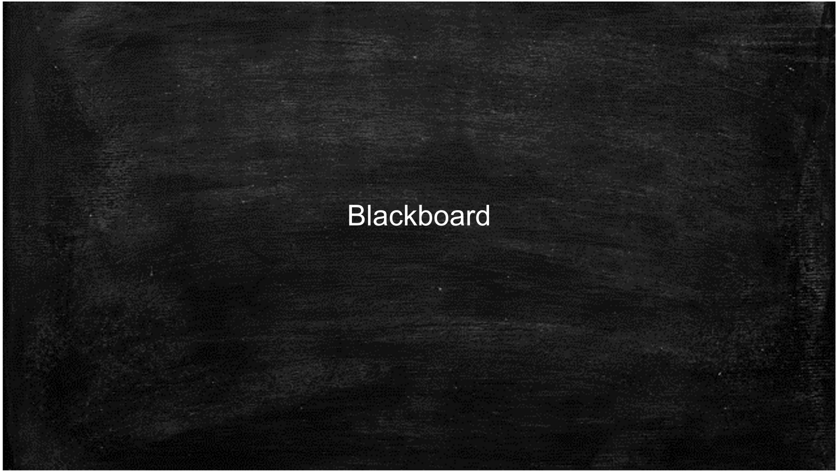
- GL = grounding line; CDW = Circumpolar deep water (offshore)
- Key point is $T_L(p, S_a)$ decreases with p (about 1 C° per km vertical), i.e., retreating GL on retrograde slope
- CDW will melt near-GL areas, which will reduce buttressing, increasingly rapidly on retrograde slopes



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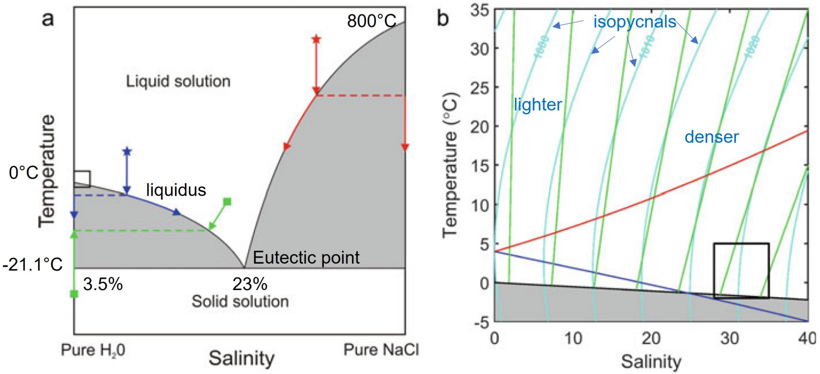
1. Critical components of the climate system
   - Buttressing prowess and recent thinning
   - The Marine Ice Sheet Instability
   - Analytical ice-shelf model
2. Ice-shelf–ocean boundary layer
   - Impact of ice melting on water masses
   - Boundary layer thermodynamics and parameterization
   - Meltwater plumes
3. Sub ice ocean circulation
   - Idealized cavity circulation
   - Realistic cavity circulation
   - Three cavity modes



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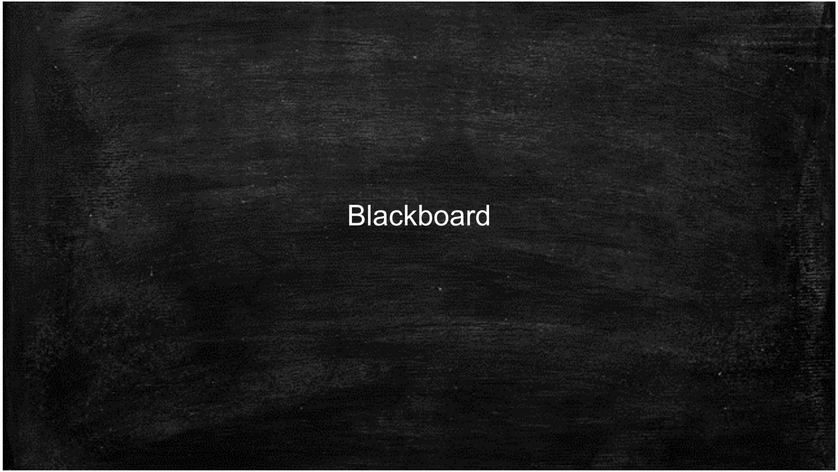
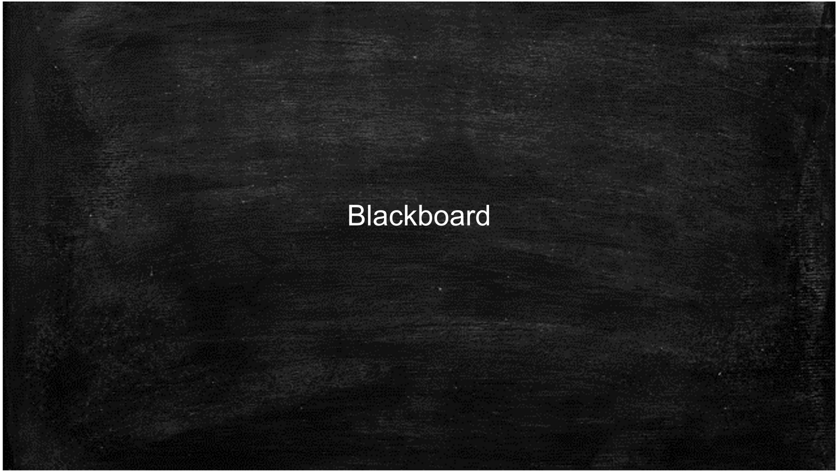
- Cooling seawater (blue/red) will generate a mixture of ideal solid with seawater at liquidus conditions, i.e., $T_b = \lambda_1 S_b + \lambda_2 + \lambda_3 P_b$
- Mixing seawater (green) with ideal ice will generate a mixture of warmer ideal ice with seawater at liquidus conditions


Blackboard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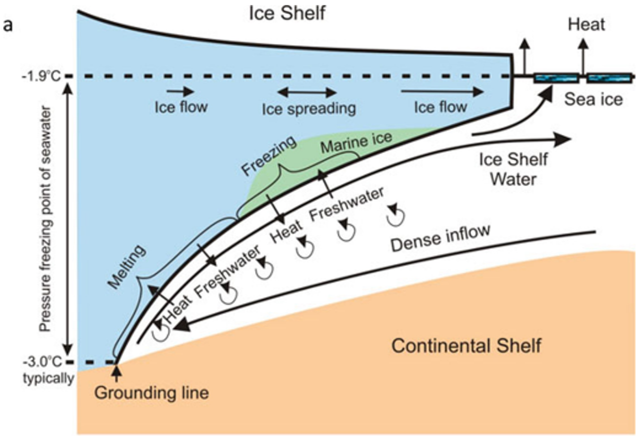

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- Melting by a warm ambient generates buoyant flows along the ice-shelf base
- They can be few meters thick
- They themselves control melt rates
- Such buoyant flows can be energized by subglacial discharge (add. buoyancy source)

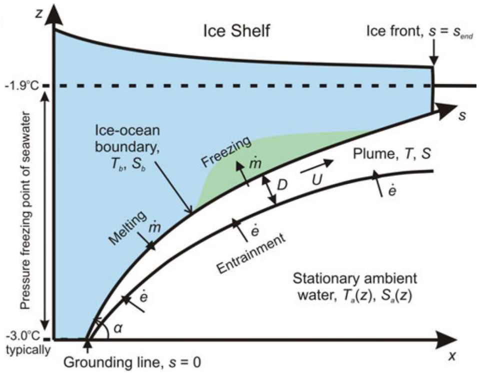
- A state-of-the-art 1D plume model
- This is sometimes used to compute melt rates in models that do not resolve the cavity dynamics

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

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

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

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



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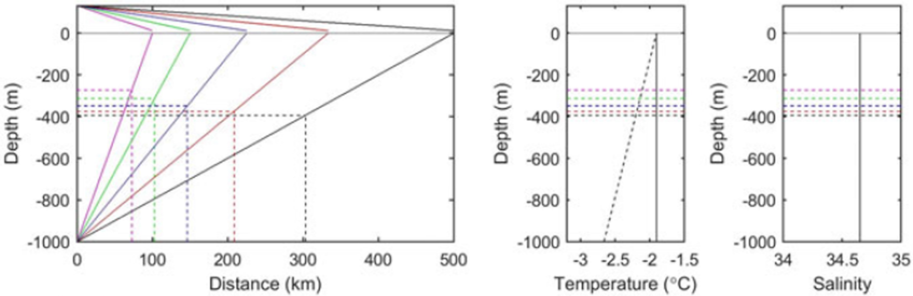

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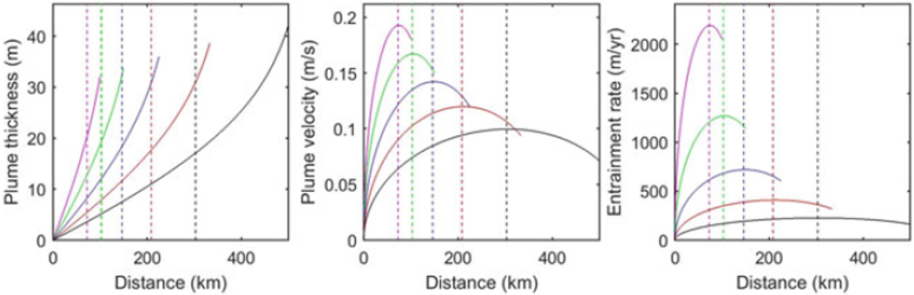
- Homogeneous ambient $T_a = -1.9$ C° and $S_a = 34.6$ psu
- Tilted dashed lines show $T_L(p, S_a)$ (middle) $\Rightarrow$ above freezing everywhere
- Horizontal dashed lines show observed melting/freezing transition (all)



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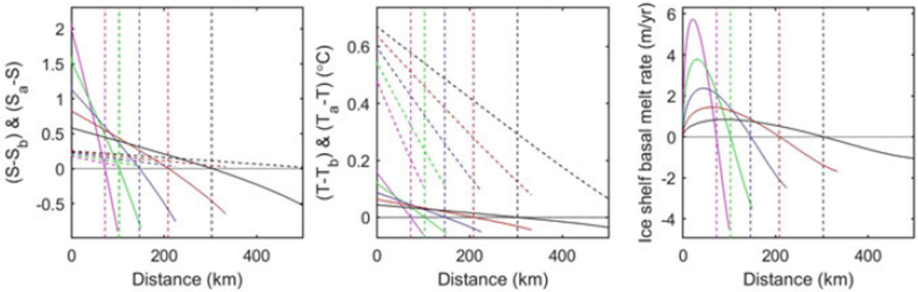
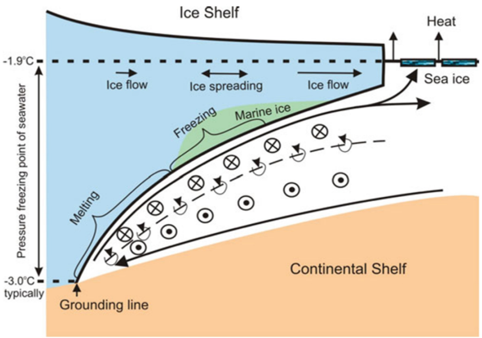
- Faster thickening and flow for steeper slopes
- Velocity maximum coincides with melt/freeze transition since buoyancy is lost upon freezing (salt going up is more important than temperature going up)
- entrainment and velocity are positively coupled (same pattern) as $\dot{e} \Rightarrow$ melting $\Rightarrow$ freshening $\Rightarrow U \Rightarrow \dot{e}$
- slope effect on entrainment is stronger than on velocity as $\dot{e} \propto U \sin\alpha$



- Plume S and T vs base (solid) or ambient (dashed)
- Competition between warming/cooling from entrainment/melting
- Supercooling ensues past the melt/freeze transition as warming from entrainment and freezing is slower than increase of $T_L(P_b, S_b)$
- Melt/freeze transition occurs higher for steeper slopes because entrainment increases with slope (quadratic) more quickly than $\dot{m}_w$ and T_f (linear)
- Melt (max and mean) increases with slope because entrainment is more efficient



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- In a large cavity, the global circulation is expected to be in geostrophic balance (small Rossby number)

- 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
- The deep eastward flow draws in a southward flow by friction within a bottom Ekman layer, closing the circulation
- Bulk geostrophic flows tend to follow isocontours of ice thickness as they are non divergent ($w = 0$)

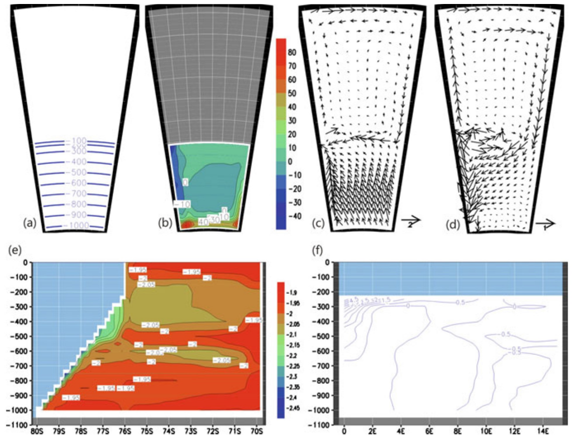

Fig. 5.13 Results from a three-dimensional model of the ocean circulation in an idealised sub-ice-shelf cavity: **a** ice draught (m); **b** basal melt rate (cm yr^{-1}); **c** mixed layer velocity (cm s^{-1}); **d** depth-mean velocity (cm s^{-1}); **e** temperature at the western boundary (°C); **f**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

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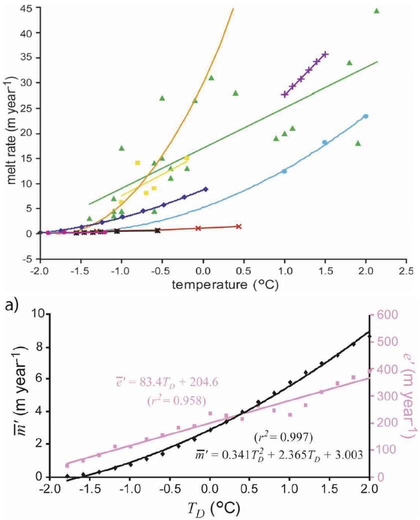
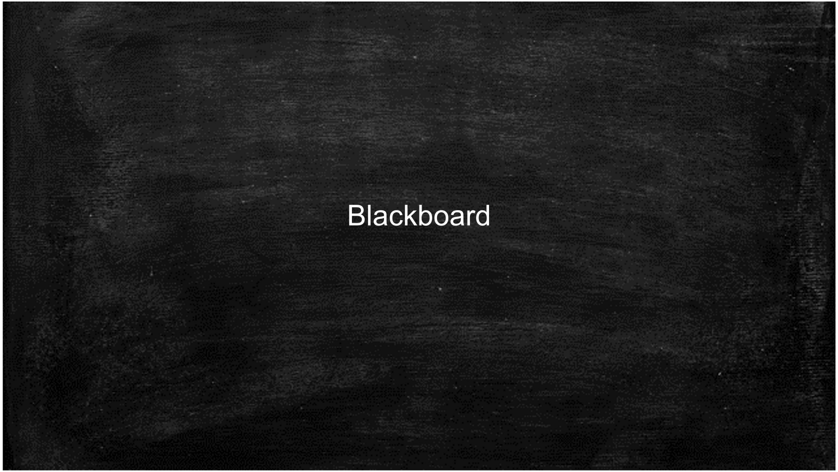
- Exhibits the ice pump mechanism (melting at depth/freezing above maintained by weak overturning)
- Mixed layer velocity to the north and west, as expected
- Depth averaged velocity has non zero zonal component because of boundaries and cyclonic gyres
- Outflow has two distinct tongues of water extruding, 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

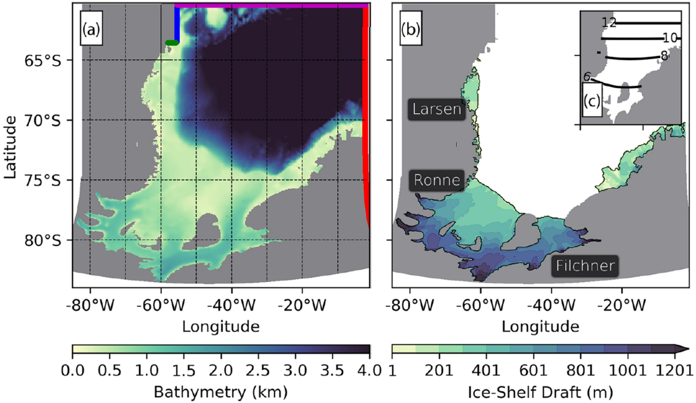


© Holland & al (2008) The Response of Ice Shelf Basal Melting to Variations in Ocean Temperature.

- 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)



Derivation of T-dependence of plume or geostrophic melt rate (Karthaus 2019 p110).



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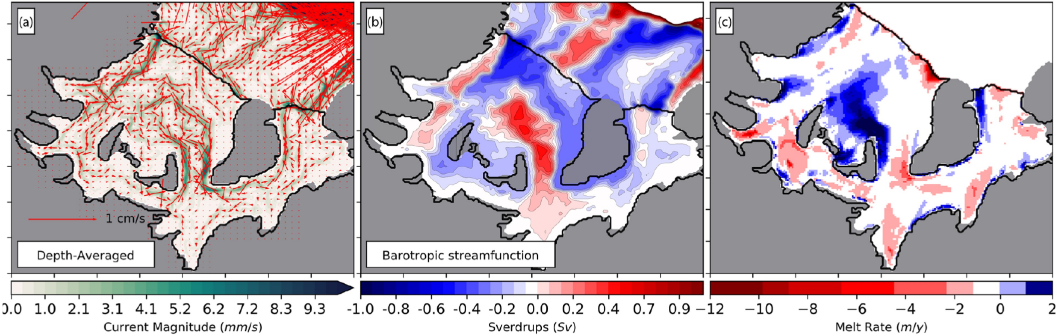
- Nucleus for European Modeling of Ocean model (NEMO) of Weddell Sea WED025 (1/4°)
- Japanese Reanalysis for driving oceans (JRA55-do) provides surface forcing conditions
- Boundary conditions forced from global model output with JRA forcing
- Mean melt rate scales linearly with Antarctic slope current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



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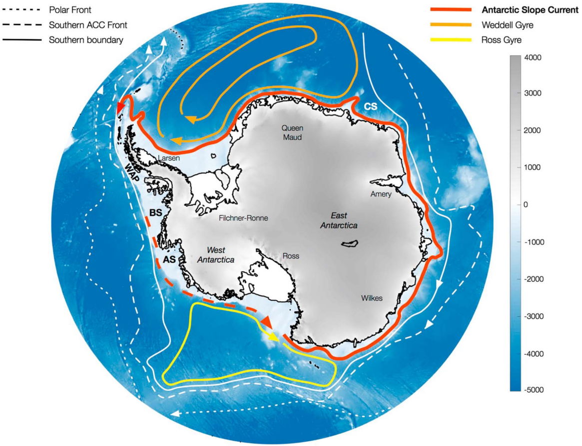
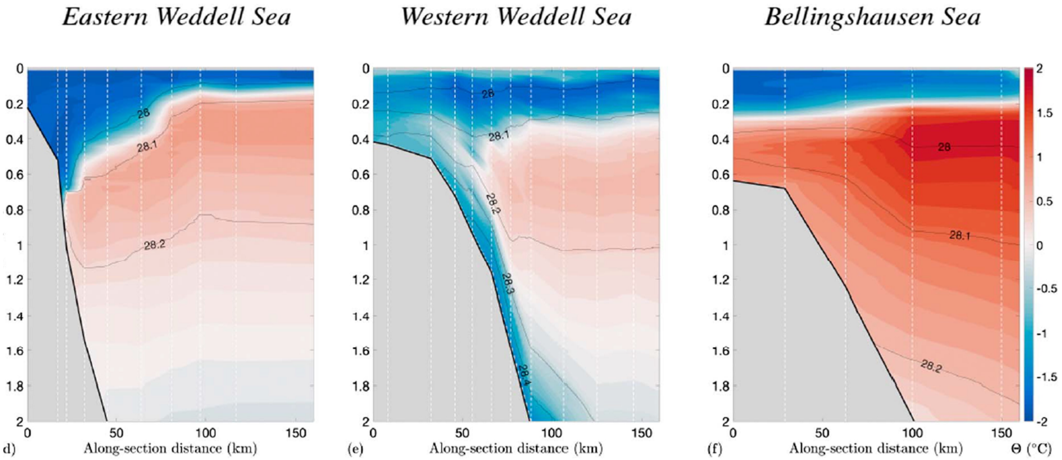
- Clockwise (anti-C) around red (blue) patches
- Outflows to the west of FIS and RIS, near inflows (usually running through bed depressions)
- FRIS is a cold cavity, implying large freezing areas



© Thompson & al (2018) *The Antarctic Slope Current in a Changing Climate*.

- Antarctic Circumpolar Current (ACC) is an easterward flow driven by westerlies and circling Antarctica
- The Antarctic Slope Current is counter to the ACC and overlies the continental slope
- It modulates the inflow of warm offshore water (often referred to as Circumpolar Deep Water or CDW) onto the shelf



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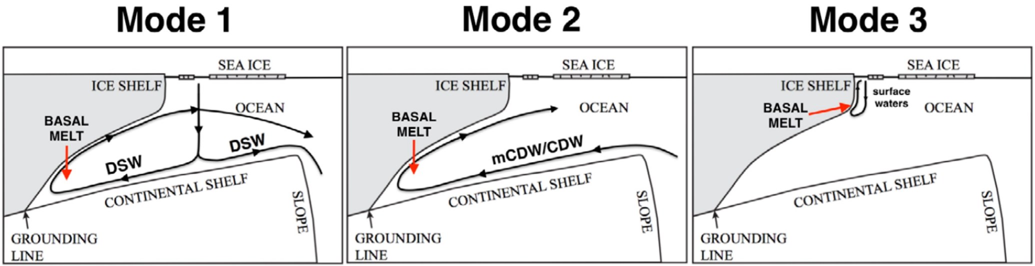

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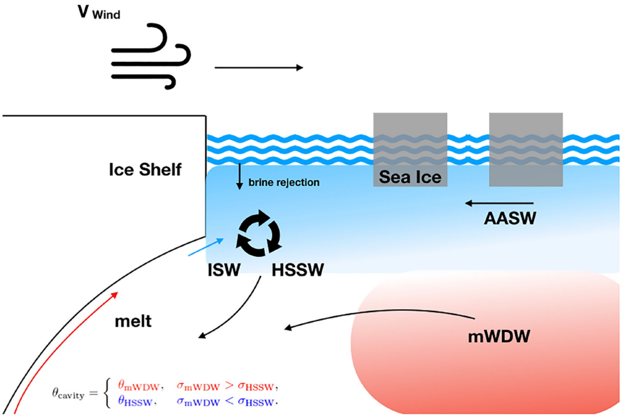
- The type of water filling up the cavity depends on the ASC, CDW properties but also cavity geometry and sea-ice formation, which depends on winds
- Mode 1 is driven by cold Dense Shelf Water (DSW), Mode 2 by warm (modified) Circumpolar Deep Water (mCDW/CDW), and Mode 3 by surface waters
- The outflow from the cavity is a mixture of glacial meltwater with DSW (Mode 1) or mCDW (Mode 2); the mixture is called Ice Shelf Water (ISW) when its temperature is below the surface freezing point



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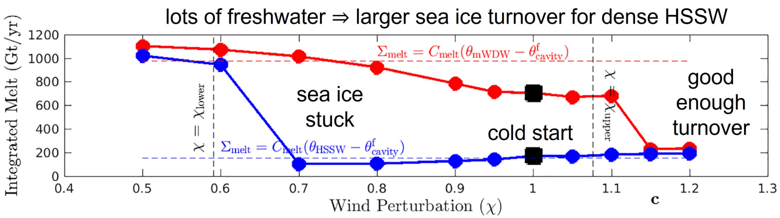
- Ex. of Mode 1-2 bifurcation (wind driven)
- Winds push sea ice
- Open water (polynia) generates new sea ice, enhancing brine rejection and HSSW densification
- mWDW generates more melt, yielding lighter HSSW



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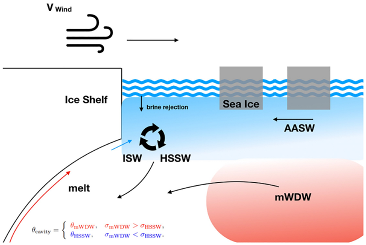

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- Results obtained with a regional ocean model
- Start from high wind/cold ocean conditions (filled with HSSW)
- Hysteresis unravelled from decreasing/increasing winds experiment
- Bifurcation observed only in *some* simulations