Onset of Double Diffusive Convection in the Ice Shelf/Ocean Boundary Layer

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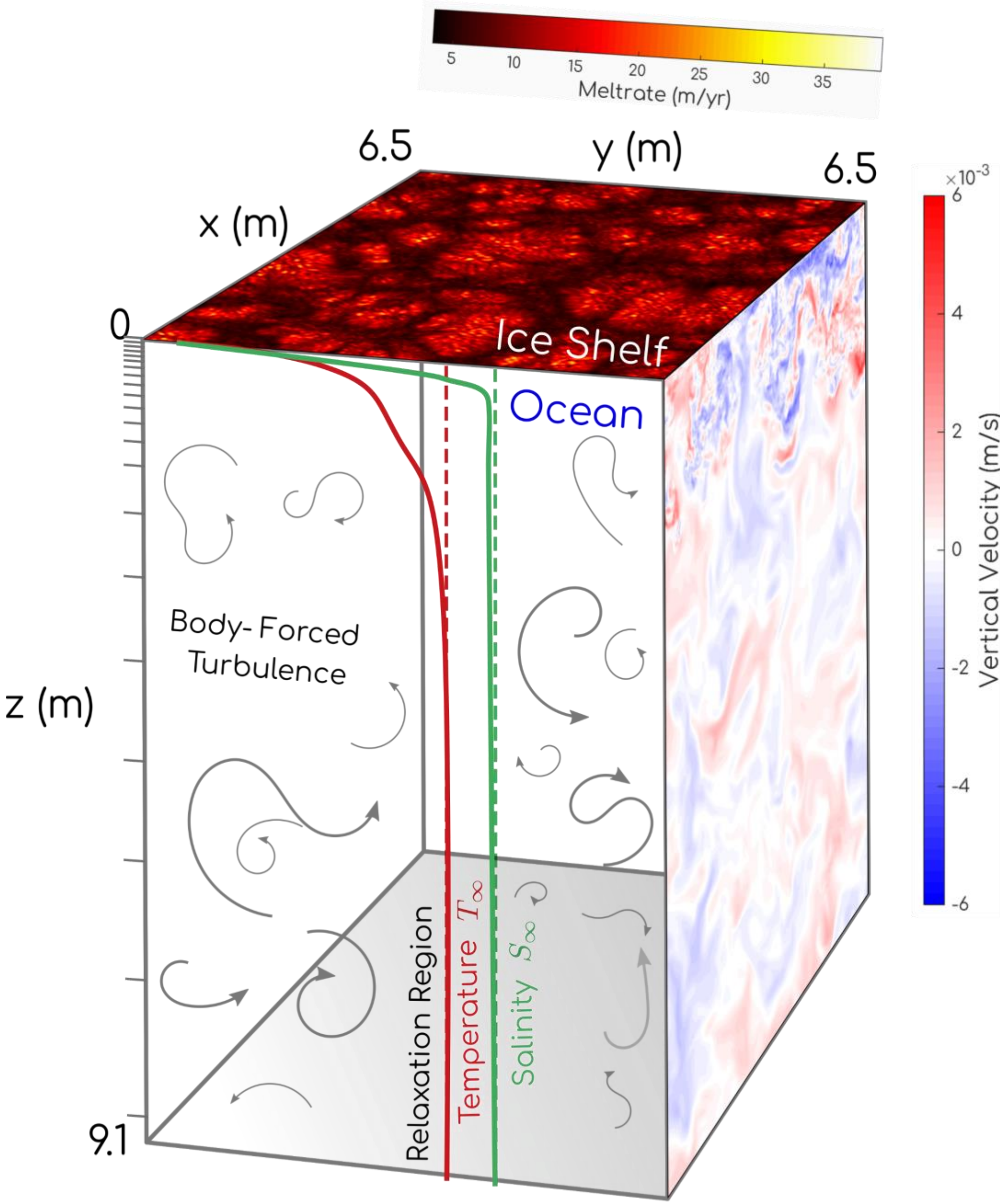
Simulation Schematic



- Observations show double-diffusive behaviour in the ice shelf ocean boundary layer beneath George VI Ice Shelf
- Steady state diffusive convection requires a fresh salinity boundary layer (not observed)
- We consider transient convection in an adjusting melting ice shelf-ocean boundary layer similar to experiments of Martin and Kauffman 1977, but with a turbulent forcing
- Turbulence is forced throughout at prescribed dissipation rate
- Initial condition of constant temperature and salinity and relaxation of scalars in far-field
- Dynamic melting boundary condition (diffusive three equation model)
- Diffusive scalar length scales are resolved near the ice and turbulent velocity length scales are resolved everywhere using grid stretching
- Accurate molecular diffusivities

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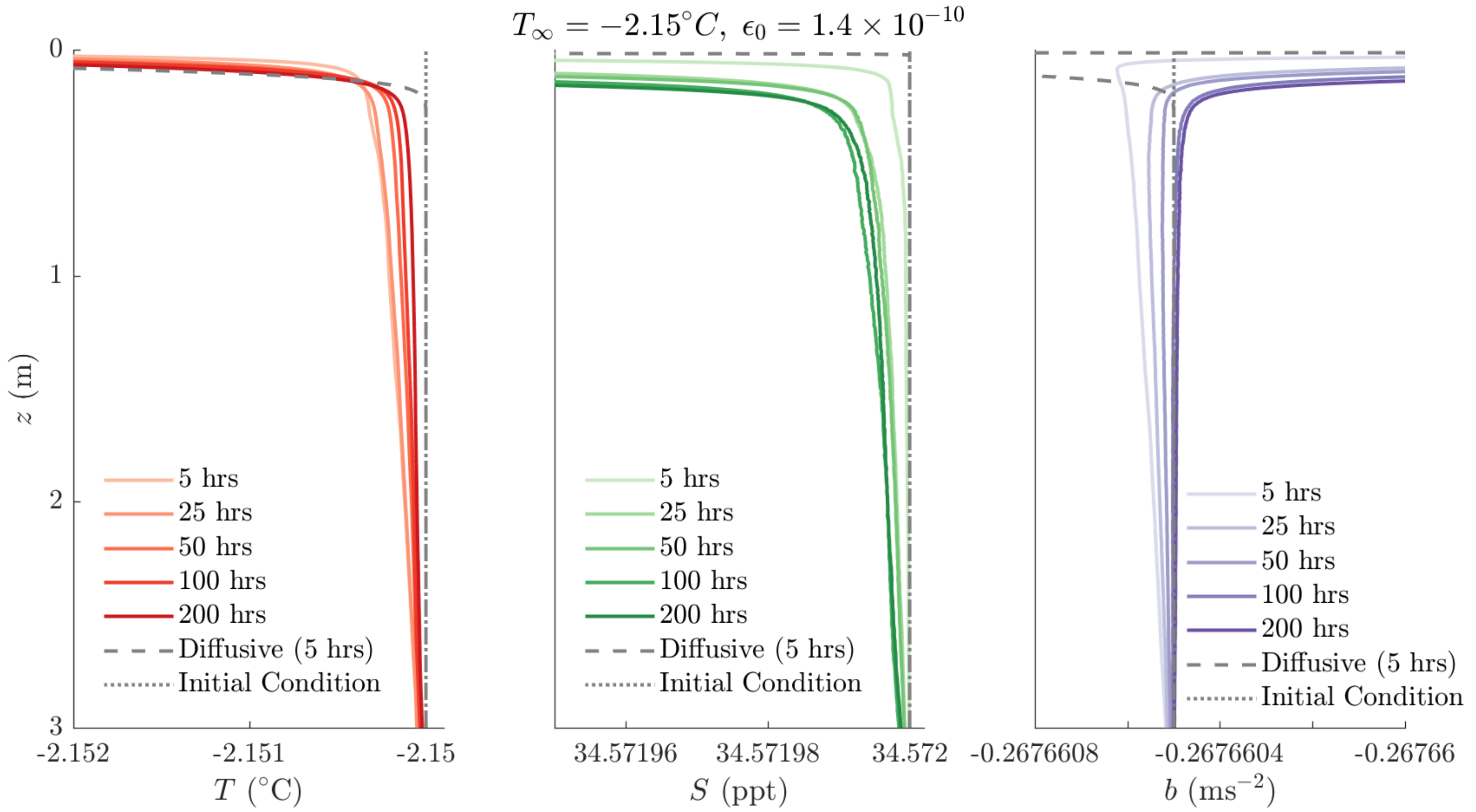
Ice-Ocean Boundary Layer Double Diffusion

Leo Middleton

Simulation Evolution



- Differing molecular diffusivities cause differing profiles for temperature and salinity,
- Salinity is stably stratified but temperature is unstably stratified,
- Density gradient is dominated by salinity close to the ice $R_\rho < 1$
- Further from the ice, temperature dominates, giving a peak in density $R_\rho > 1$

$$R_\rho = \frac{\alpha \frac{\partial T}{\partial z}}{\beta \frac{\partial S}{\partial z}}$$

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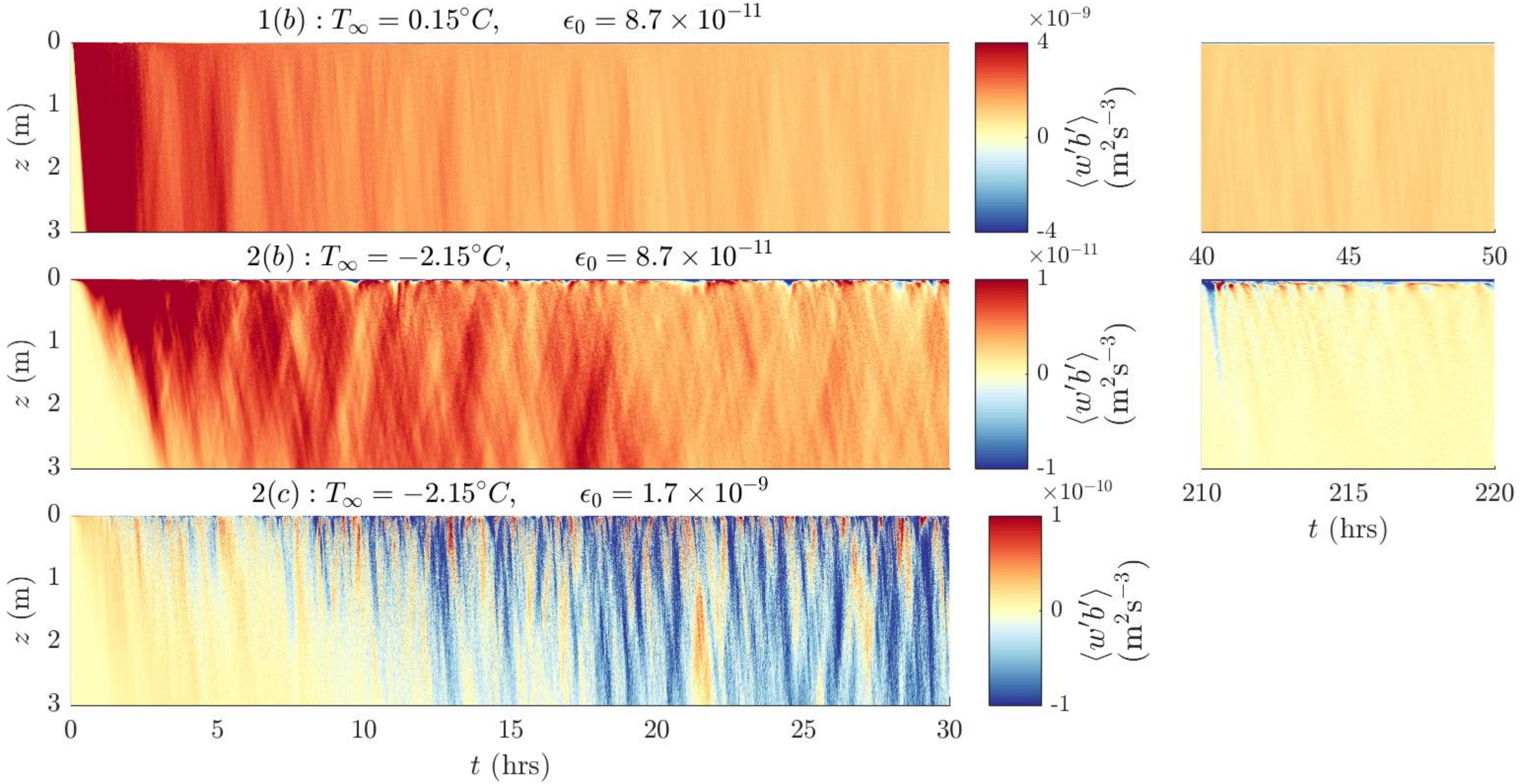
Simulation Evolution



- The turbulent vertical buoyancy flux converts energy between turbulent kinetic energy (TKE) and potential energy
- $\langle w'b' \rangle > 0 \implies$ source of TKE (double-diffusive convection)
- $\langle w'b' \rangle < 0 \implies$ sink of TKE (standard assumption in melting parameterisations
- Cold, low mechanical forcing simulation 2(c) transitions from double-diffusive convection but case 2(b) is still has positive buoyancy flux after 200 hrs

Criterion for Convection

See Middleton and Taylor 2020 JFM for full 3D formulation of this argument

- The evolution equation for buoyancy is
$$\frac{Db}{Dt} = g\alpha\kappa_T\nabla^2 T - g\beta\kappa_S\nabla^2 S = \nabla^2 b_p \text{ for } b_p = g\alpha\kappa_T T - g\beta\kappa_S S$$
- If we take a horizontal average $\implies \frac{\partial\langle b\rangle_{xy}}{\partial t} = \frac{\partial}{\partial z}\left(\langle wb\rangle_{xy} - \frac{\partial\langle b_p\rangle_{xy}}{\partial z}\right)$
- In the buoyancy evolution is in steady state $\langle wb\rangle_{xy} = \frac{\partial\langle b_p\rangle_{xy}}{\partial z} = \kappa_T\frac{\partial\langle b\rangle_{xy}}{\partial z}\frac{R_\rho - \frac{\kappa_S}{\kappa_T}}{R_\rho - 1}$
- So the turbulent buoyancy flux will be up-gradient when $\frac{\kappa_S}{\kappa_T} < R_\rho < 1$
- At the ice base the salinity gradient dominates so $R_\rho < \kappa_S/\kappa_T$ and further away the temperature gradient becomes more important such that $R_\rho > \kappa_S/\kappa_T$
- We measure the turbulence using the buoyancy Reynolds number using the dissipation rate, ϵ the kinematic viscosity ν and the buoyancy frequency N $$Re_b = \frac{\epsilon}{\nu N^2}$$

Convection occurs when the depth at which $R_\rho = \frac{\kappa_S}{\kappa_T}$, is less than the depth at which $Re_b = 1$

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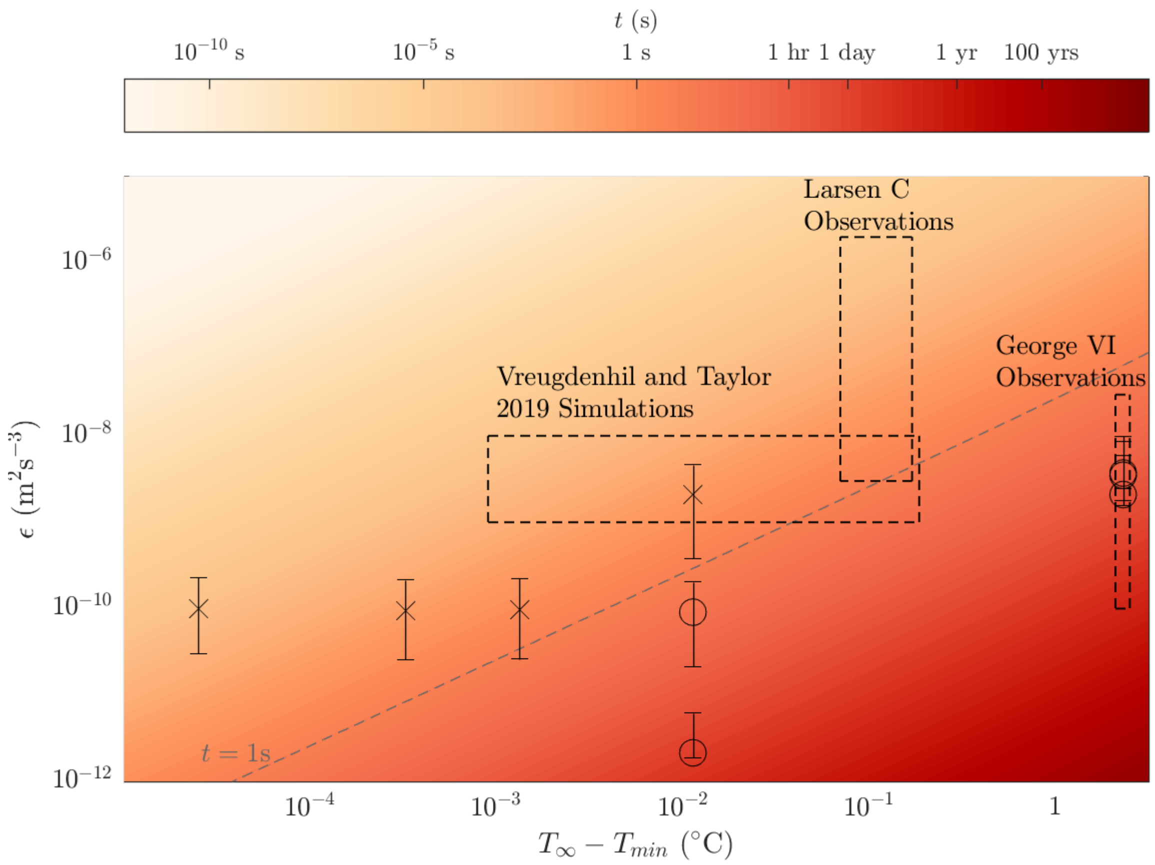
Criterion for Convection



- We can apply our criterion to the diffusive solution from Martin and Kauffman (1977)

$$T = T_\infty + A(T_\infty, S_\infty)\mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa_T t}}\right)$$
$$S = S_\infty + B(T_\infty, S_\infty)\mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa_S t}}\right)$$

- Fixing the far-field salinity we vary the far-field temperature and forced dissipation rate, solving for the time at which the criterion for convection is no longer satisfied. T_{min} denotes the freezing temperature.
- Simulations that consistently convect are denoted with circles and simulations that transition are denoted with crosses
- Observational ranges and previous LES parameter space are shown with dashed boxes
- Transition times are based on diffusion only so will not be accurate, but provide a point of comparison

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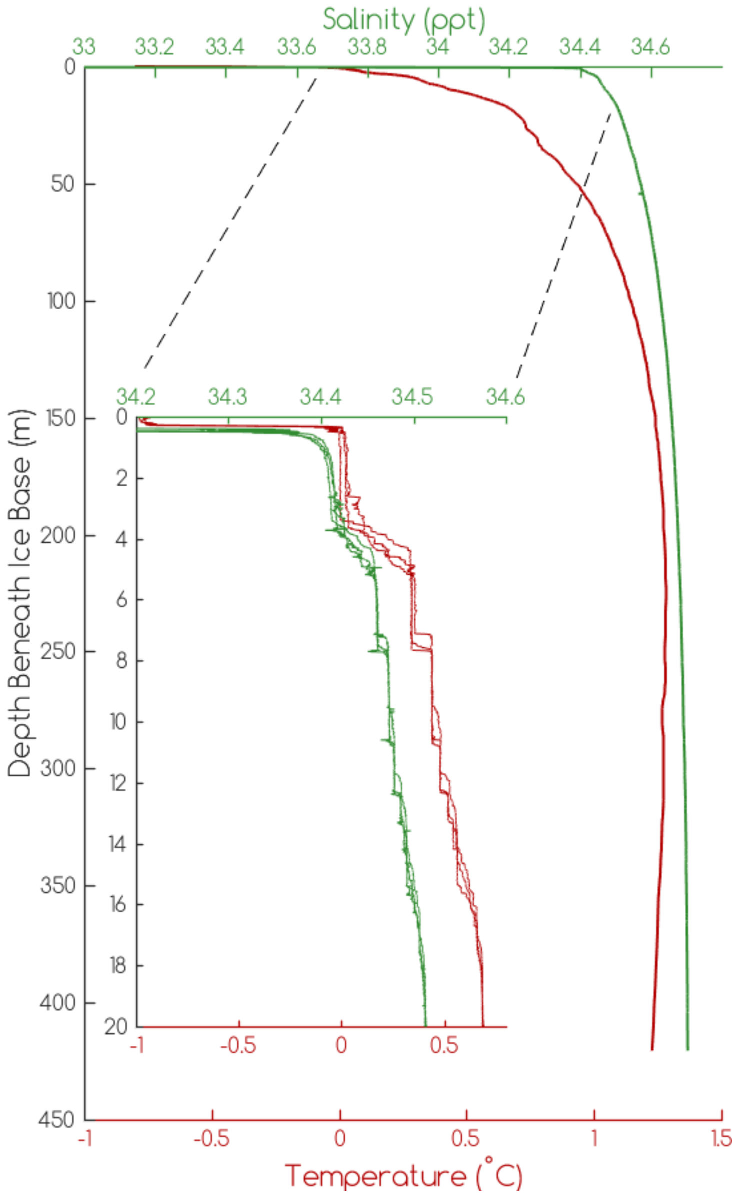
Conclusions

- Double-diffusive convection does not occur in steady state with reasonable boundary salinities
- Transient double-diffusive convection may occur under a growing salinity boundary layer
- If convection does occur it may be long lived and effect the turbulent dissipation rate, as well as the heat and salt transport
- We developed a criterion for under-ice convection requiring profiles of temperature and salinity and a measure of turbulent dissipation rate
- We applied our criterion to a diffusive solution for temperature and salinity, providing a point of comparison for observations.

George VI Observations

- Borehole observations beneath George VI Ice Shelf made in 2012 showed staircase structures in the upper 20m adjacent to the ice,
- These staircases are believed to be double-diffusive in origin, although proving which double-diffusive mechanism is responsible for their formation is hard ,
- Kimura et al. 2015 argued they form due to a double-diffusive convection forced by the ice (as in Martin and Kauffman 1977) as they extend right up to the ice, and the width of staircases decreases further from the ice (as in the experiments of Turner 1969),
- Venables et al. 2012 showed, using microstructure observations, that occasional bursts of turbulence eradicated the staircases beneath George VI before they reformed.



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Steady State

- In steady-state double-diffusive convection, potential energy adds energy to kinetic energy so

$$\langle w'b' \rangle = g\alpha \langle w'T' \rangle - g\beta \langle w'S' \rangle > 0$$

- The turbulent vertical fluxes must be balanced with the diffusive fluxes from the melting ice

$$\langle w'T' \rangle = \kappa_T \frac{\partial T}{\partial z}\bigg|_b \qquad \langle w'S' \rangle = \kappa_S \frac{\partial S}{\partial z}\bigg|_b$$

- which implies the basal density ratio

$$R_\rho^b = \frac{\alpha \frac{\partial T}{\partial z}\big|_b}{\beta \frac{\partial S}{\partial z}\big|_b} > 0$$

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Steady State + Three Equation Model

- The diffusive three equation model for the ice base is

Heat flux balance $$\rho_i L_i m = c_p \rho_w \kappa_T \left.\frac{\partial T}{\partial z}\right|_b,$$

Salt flux Balance $$\rho_i S_b m = \rho_w \kappa_S \left.\frac{\partial S}{\partial z}\right|_b,$$

Liquidus condition $$T_b = \lambda_1 S_b + \lambda_2 + \lambda_3 P,$$

- So for steady-state double diffusive convection

$$S_b < \frac{\alpha L_i}{\beta c_p} \sim 4 \text{ ppt}$$

i.e. we require a fresh salinity sublayer

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