Convection, phase change and solute transport in mushy sea ice

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Motivation

- Sea ice is a mushy layer of ice crystals and brine.
- Dense brine drains during ice formation, whilst some brine is trapped within sea ice
- Observations (Fig. 1) and 1-D simulations suggest that warming sea ice may release some of this brine
- **Our goal: investigate this mechanism** using 2-D numerical simulations

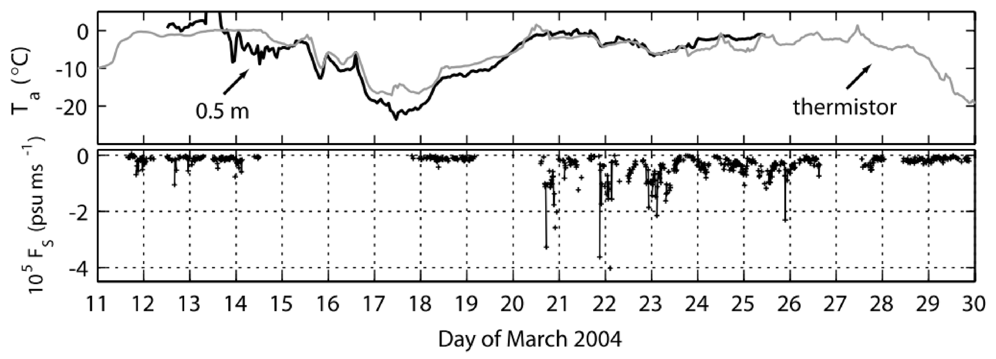

Fig. 1: Observed atmospheric temperature (top) and ice-ocean salt flux (bottom) from warming sea ice [1].

What is a mushy layer?

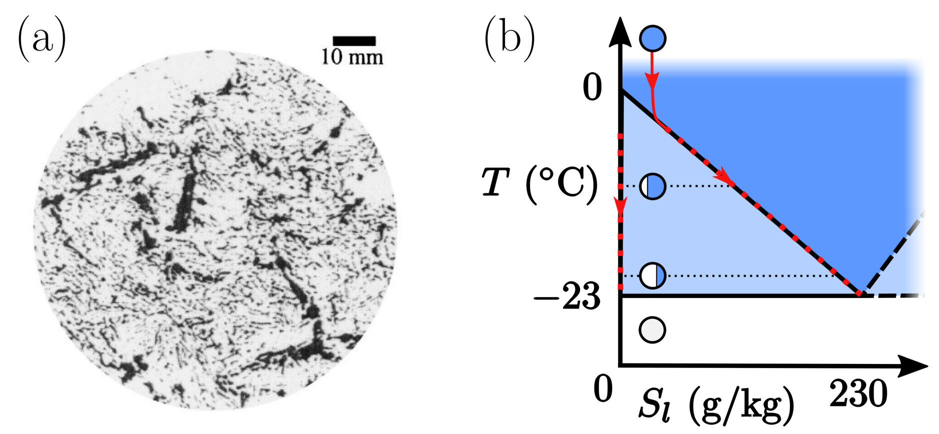

Fig. 2: (a) Sea ice is a porous mixture of solid ice crystals (white) and liquid brine (dark) [2]. (b) Trajectory (→) of a solidifying salt water parcel through the phase diagram. As the temperature T_l decreases, more ice forms and the residual brine salinity S_l increases making the fluid denser, which can drive convection. Using a linear approximation for the liquidus curve, the freezing point is $T_f(S_l) = -0.1 S_l$

Numerical Method

Solve (1)-(4) using Chombo finite volume toolkit:

- Momentum and mass: projection method [3].
- Energy and solute:
  - Advective terms: explicit, 2$^{\text{nd}}$ order unsplit Godunov method.
  - Nonlinear diffusive terms: semi implicit, geometric multigrid.
  - Timestepping: Backward Euler.

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[1] Karolina Widell et al. *Geophysical Research Letters* 33.12 (2006), pp. 1–5. [2] Hajo Eicken et al. *Cold Regions Science and Technology* 31.3 (2000), pp. 207–225. [3] D. F. Martin et al. *Journal of Computational Physics* 227.3 (2008), pp. 1863–1886. [4] M. G. Worster. *Journal of Fluid Mechanics* 224.-1 (1991), p. 335. [5] Michael Le Bars et al. *Journal of Fluid Mechanics* 550.-1 (2006), p. 149.

The experiment

Water of initial salinity $S_0 = 30\,\mathrm{g/kg}$ and temperature -2.9°C is frozen from above in a Hele-Shaw cell (plate separation $d = 0.1$mm). We assume $K_0 = 10^{-10}\,\mathrm{m}^2$, and fix the atmospheric temperature $T_a = -10$°C. After ~ 0.5m of ice growth, we impose different warming scenarios.

Summary

- ...
- ...
- ...

Case 1: Basal warming

Case 2: Atmospheric warming followed by basal warming

Governing Equations for Flow in Porous Mushy Sea Ice

Continuous equations for conservation of momentum (1), mass (2), salt (3) and energy (4) are found by averaging over lengths greater than the pore scale of sea ice [4, 5]. In a narrow Hele-Shaw cell, the momentum equation is well approximated by Darcy's law everywhere.

$$\mathbf{U} = -\frac{K(\chi)}{\eta}\left(\nabla p - \rho_l \mathbf{g}\right), \qquad \nabla \cdot \mathbf{U} = 0, \tag{1, 2}$$

$$\frac{\partial S}{\partial t} + \mathbf{U} \cdot \nabla S_l = \nabla \cdot \chi D_l \nabla S_l, \tag{3}$$

$$\frac{\partial H}{\partial t} + \rho_0\, c_{p,l}\, \mathbf{U} \cdot \nabla T = \nabla \cdot \left[k_l \chi + (1-\chi) k_s\right] \nabla T. \tag{4}$$

$\mathbf{U}$ (Darcy velocity), χ (porosity), p (pressure), T (temperature), S_l (liquid salinity), $S = \chi S_l$ (bulk salinity), $H = \rho_0 \left\{L\chi + \left[\chi c_{p,l} + (1-\chi) c_{p,s}\right] T\right\}$ (enthalpy), $\rho_l = \rho_0 \left[1 - \alpha T + \beta S_l\right]$ (liquid density), $K(\chi)^{-1} = \left(d^2/12\right)^{-1} + \left[K_0 \chi^3/(1-\chi)^2\right]^{-1}$ (permeability), η (viscosity); D_l (salt diffusivity); α, β (thermal/haline expansion); $c_{p,l}, c_{p,s}$ (liquid/solid specific heat); k_l, k_s (liquid/solid heat conductivity); d (Hele-Shaw cell thickness); K_0 (Reference permeability).

Future Work

- Consider forcing from reanalysis data, rather than the idealised scenarios considered here.
- Investigate sensitivity of results to the Hele-Shaw cell gap width.
- Write PhD thesis.