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

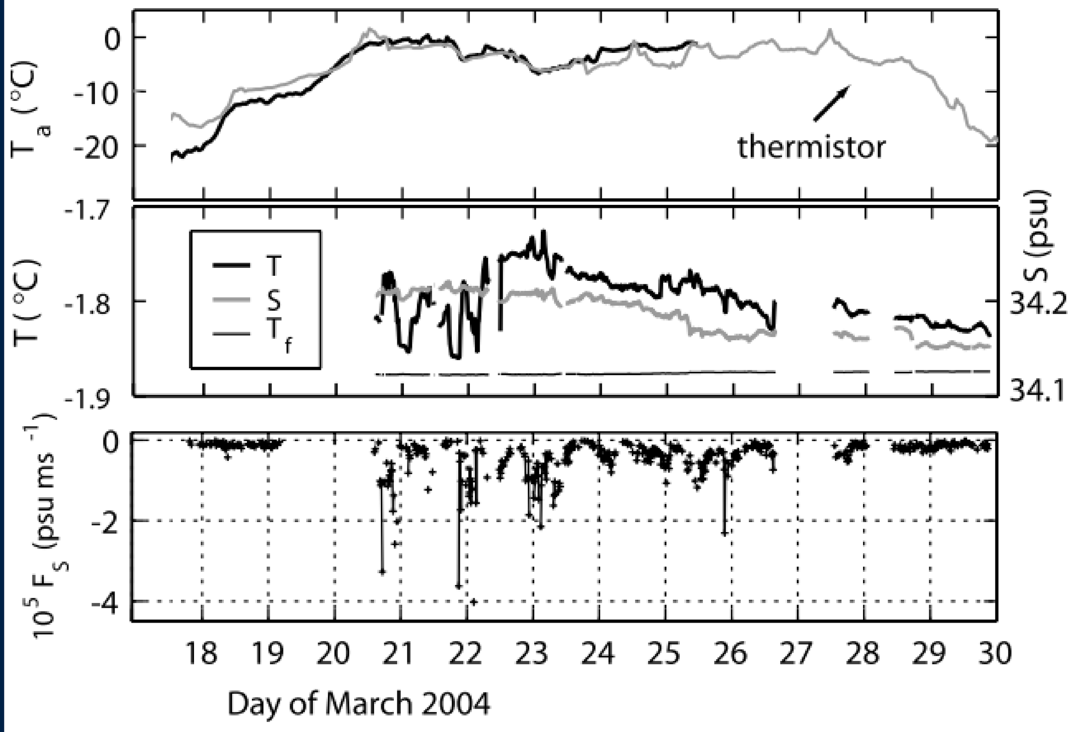


Fig. 1: [1] observed intense salt fluxes F_s below sea ice coincident with changes to the temperature in the atmosphere (T_a) and ocean (T).

What is a mushy layer?

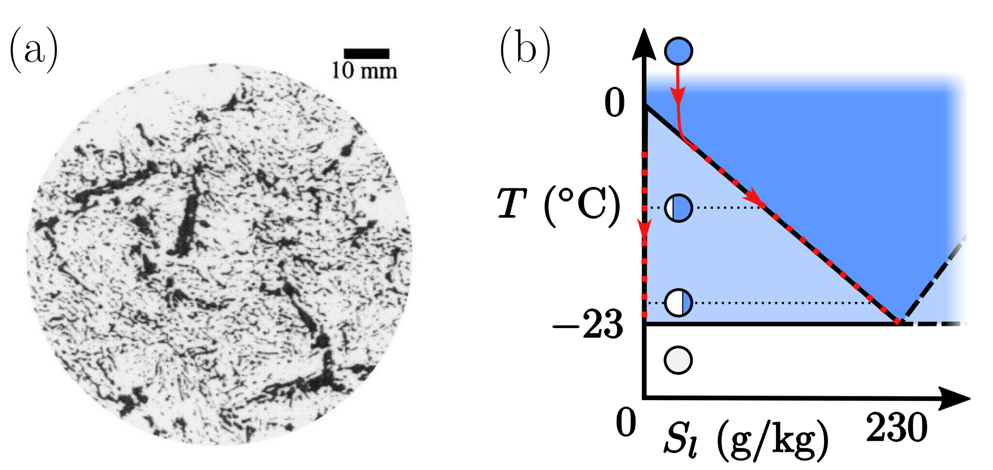


Fig. 2: (a) Sea ice is a porous mixture of solid ice crystals (white) and liquid brine (dark) [2].
(b) Trajectory (→) of a solidifying salt water parcel through the phase diagram. As the temperature T decreases, more ice forms and the residual brine salinity S_l increases making the fluid denser, which 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, 2nd order unsplit Godunov method.
  - Nonlinear diffusive terms: semi implicit, geometric multigrid.
  - Timestepping: Backward Euler.

The experiment:

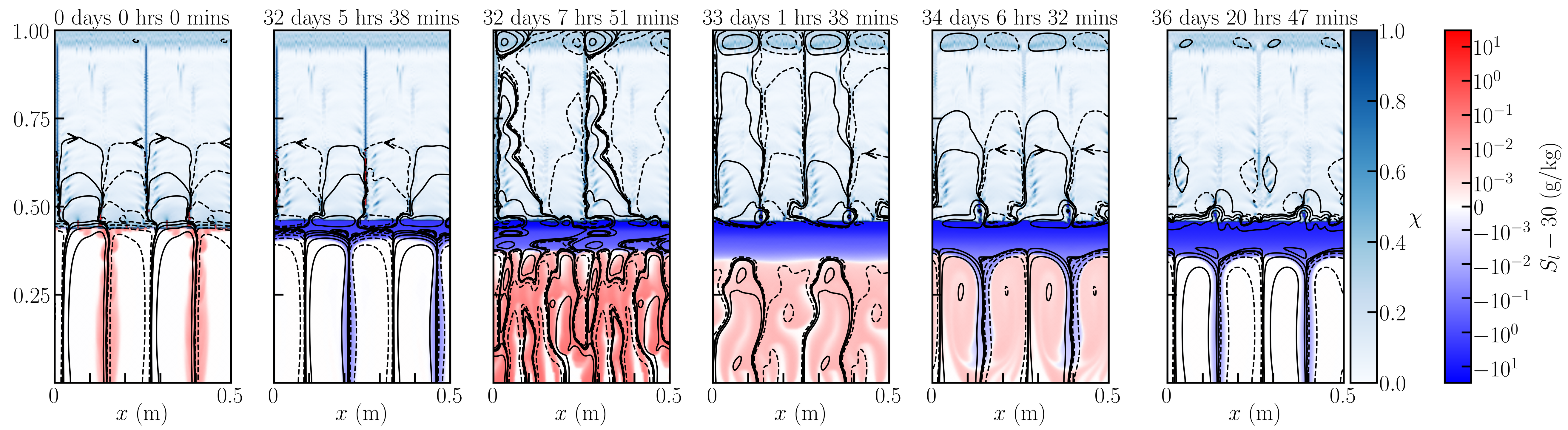
We consider 2-D simulations in a Hele-Shaw cell of width 0.5m, height 1m, and plate separation d. Water of initial salinity $S_0 = 30\,$g/kg and temperature $T_f(S_o) + 0.2$°C is initially frozen from above by applying a fixed atmospheric temperature $T_a = -10$°C. We assume $K_0 = 10^{-9}\,\text{m}^2$, and initially set $d = 0.5$mm to restrict thermal convection in the underlying liquid during growth. After ~ 0.5m of ice growth, we increase d to 2mm and spin up simulations for 2 days before considering different warming scenarios.

Summary

- **We observe significant desalination events from warming sea ice in a 2-D model, with similar magnitude and timing to field observations.**
- **Following basal melting, desalination can be caused by fresh melt water rising through brine channels.**

Full depth desalination

Fig. 7 (→): Porosity χ in the ice, salinity S_l in the underlying liquid, and streamfunction (solid black logarithmically spaced contours: CW, dashed: ACW) during basal melting. Remnant brine channels are visible throughout the ice during initial growth. Subsequently the ocean temperature is increased to $T_o = T_f(S_o) + 1.5$°C and a layer of buoyant water forms due to basal melting, whilst internal melting within the ice gradually increases the porosity. After 32 days a period of strong convection is initiated throughout the ice. Melt water rises through previously active brine channels and sinks through the rest of the ice.



Case 1: Atmospheric warming

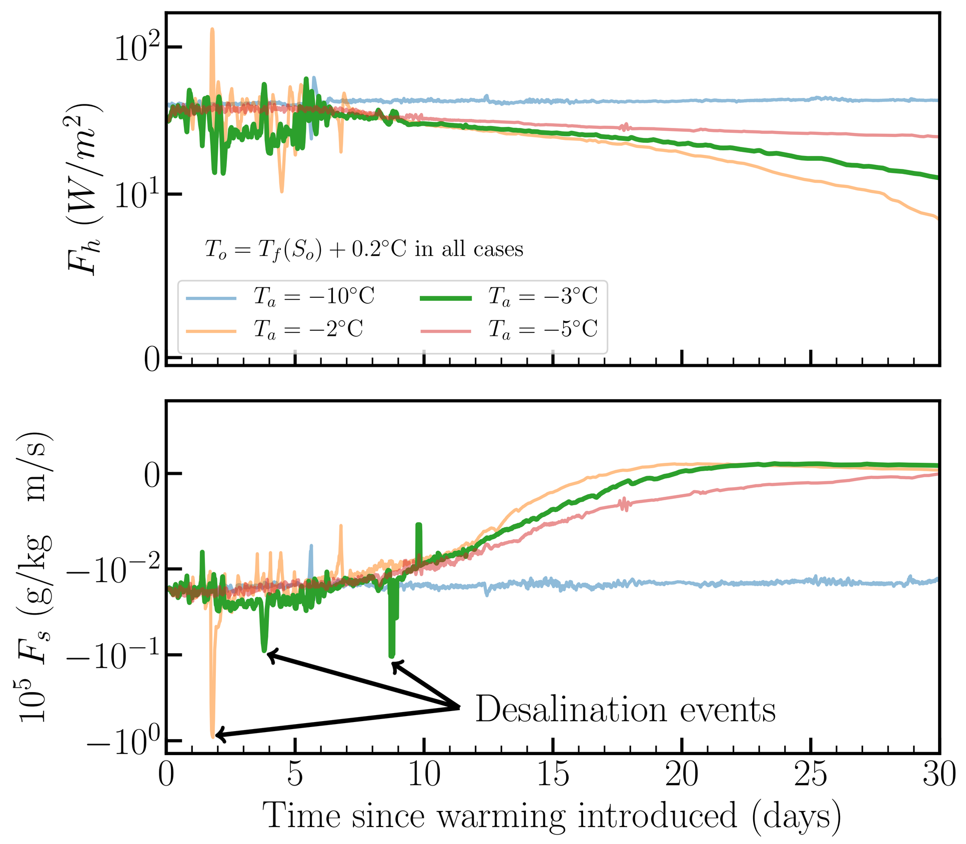


Fig. 3 (↑): Vertical fluxes of heat F_h and salt F_s at $z = 0.3$m in response to increased atmospheric temperature (see legend). Short intense desalination events occur after warming. After ~ 15 days the warming ice stops rejecting significant quantities of salt.

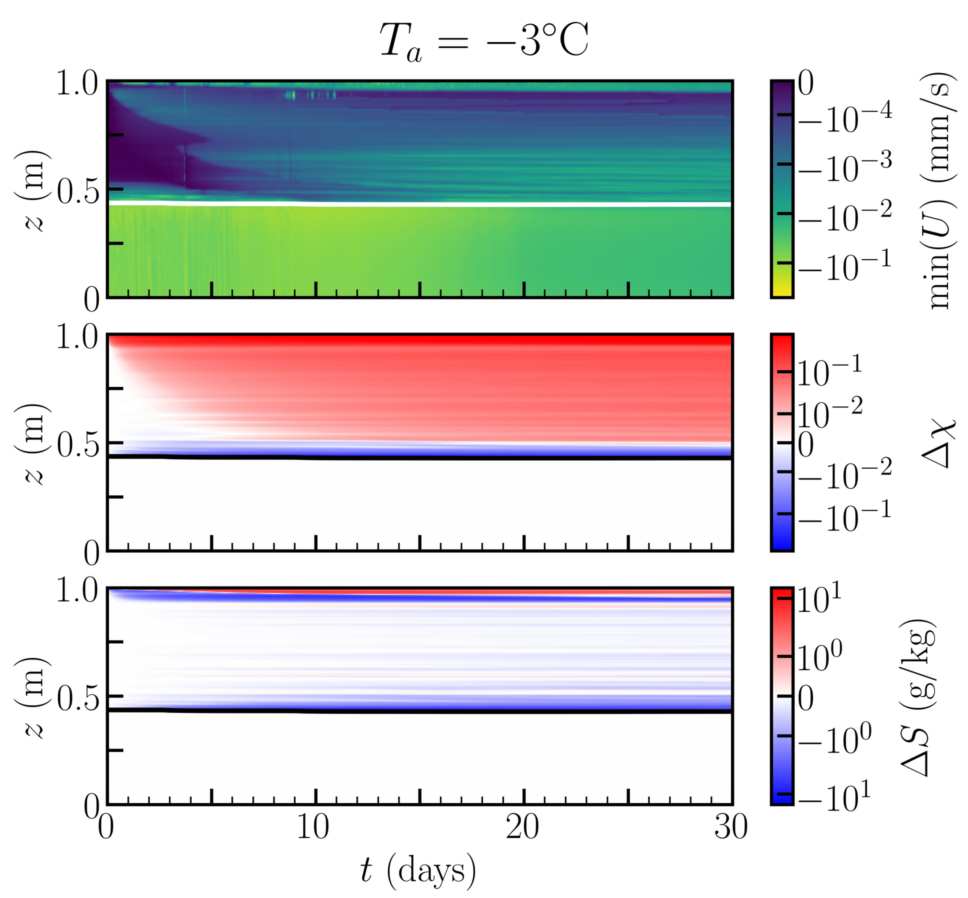


Fig. 4 (↑): Vertical profiles for $T_a = -3$°C. Top panel: minimum vertical velocity, middle panel: change in horizontally-averaged porosity, bottom panel: change in horizontally-averaged bulk salinity. The sea ice interface is indicated by a white line (top panel) or black line (lower panels). Atmospheric warming increases the ice porosity, which allows salt to drain through the entire depth of ice.

Case 2: Basal warming

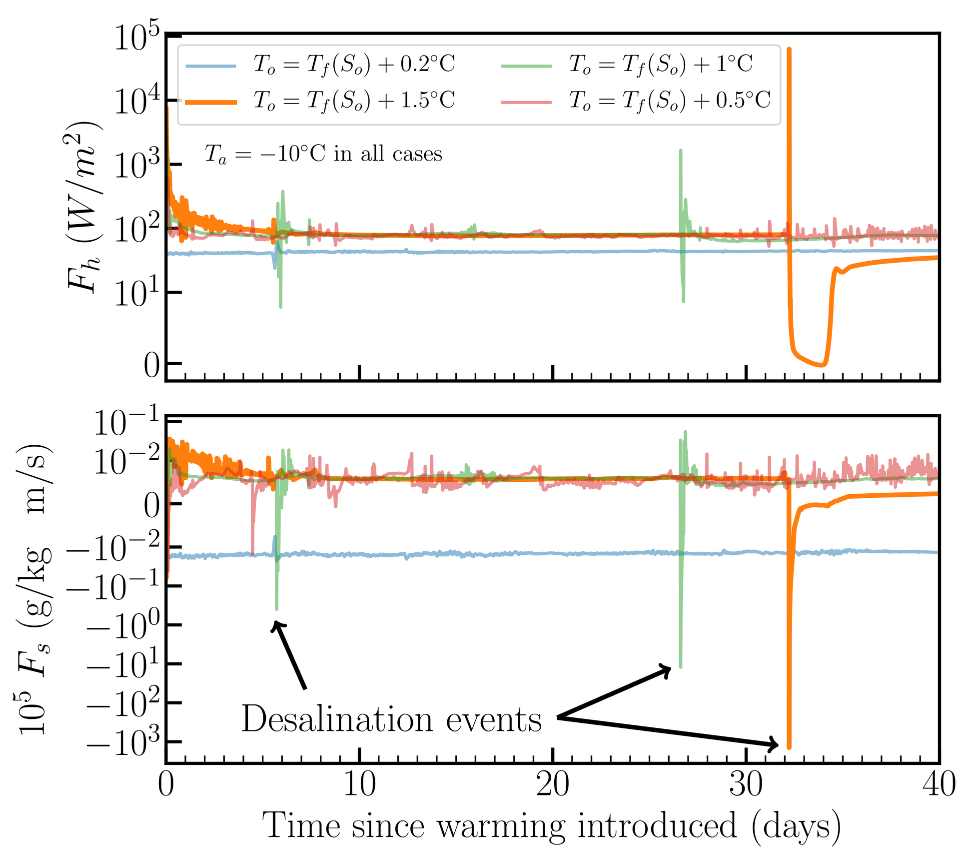


Fig. 5 (↑): Vertical heat F_h and salt F_s fluxes as in Fig. 4 but for simulations with an increased oceanic temperature T_o. Salt fluxes are typically positive due to the downward transport of fresh melt water. However, for $T_o > T_f(S_o) + 0.5$°C we observe short intense bursts of negative salt fluxes.

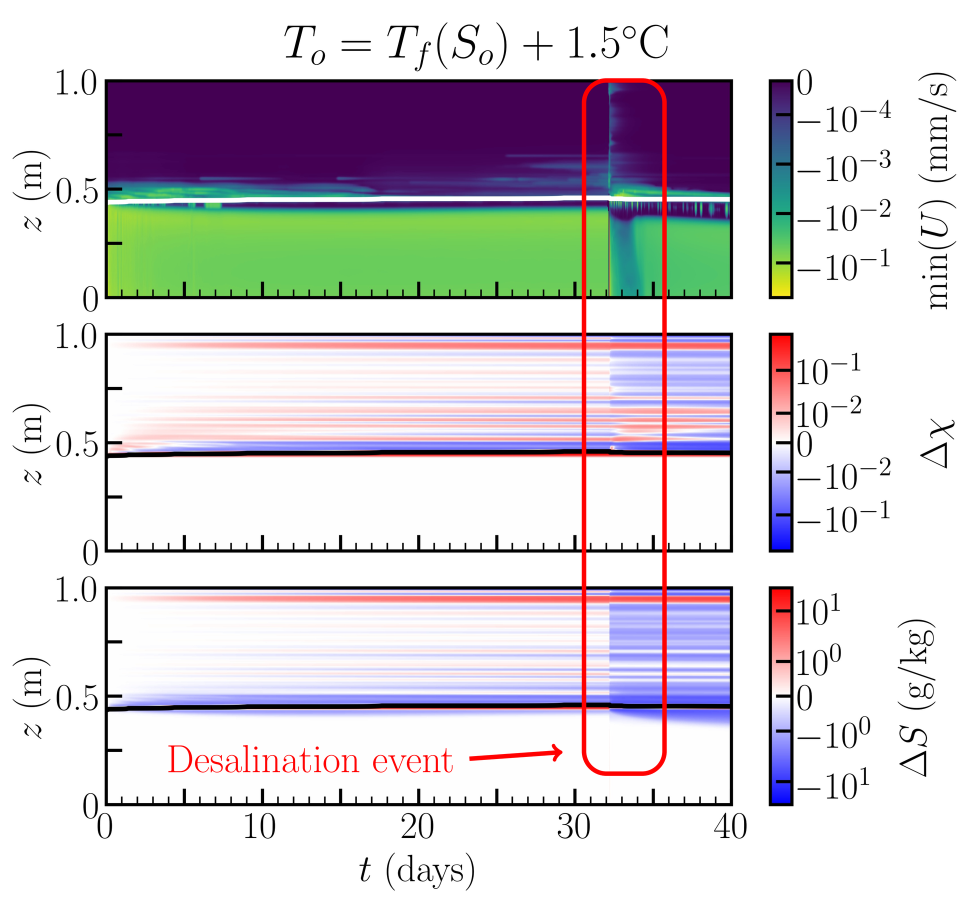


Fig. 6 (↑): Vertical profiles as in Fig. 5, but for oceanic warming with $T_o = T_f(S_o) + 1.5$°C. An increase in porosity permits stronger convection through a deeper layer at the base of the ice. However a convectively stable layer of buoyant melt water forms below the ice, preventing rejected salt from mixing with the underlying ocean except in the case of intense desalination events.

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),
$H = \rho_0 \left\{L\chi + [\chi c_{p,l} + (1-\chi)c_{p,s}]T\right\}$ (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 idealised scenarios.
- Investigate sensitivity of results to the Hele-Shaw cell gap width.

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