3D convection, phase change, and solute transport in mushy sea ice

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Summary:

- Simulated brine drainage via 3-D convection in porous mushy sea ice
- Shallow region near ice-ocean interface is desalinated by many small brine channels
- Full-depth “mega-channels” allow drainage from saline layer near top of ice.
What is a mushy layer?

Dense brine drains convectively from porous mushy sea ice into the ocean.

- What is spatial structure of this flow in 3 dimensions?

**Upper fig.**: Sea ice is a porous mixture of solid ice crystals (white) and liquid brine (dark).


**Lower fig.**: Trajectory ($\rightarrow$) of a solidifying salt water parcel through the phase diagram. As the temperature $T$ decreases, the ice fraction increases and the residual brine salinity $S_I$ increases making the fluid denser, which can drive convection.

Using a linear approximation for the liquidus curve, the freezing point is

$$T_f(S_I) = -0.1S_I.$$
Problem setup

Cold upper boundary
\( T = -10 \degree C \), no normal salt flux, no vertical flow

Initial conditions
\( S = 30 \text{g/kg} \)
\( T = T_{\text{freezing}} (S = 30 \text{g/kg}) + 0.2 \degree C \)
\( U = 0 \)
Plus small random \( O(0.01 \degree C) \) temperature perturbation

Open bottom boundary
Inflow/outflow, with constant pressure
Inflow: \( S = 30 \text{g/kg}, T = T_{\text{freezing}} (S = 30 \text{g/kg}) + 0.2 \degree C \)

Horizontally periodic

Numerically solve mushy-layer equations for porous ice-water matrix (see appendix).
Movie
Contours of:

Ice permeability
-function of ice porosity;
(red lower,
green higher
~ice-ocean interface)

Velocity
(blue lower,
purple higher).

https://drive.google.com/file/d/1JBltmurLZ1zHKXT-Qt-8pmVEHuJlYdKl/view?usp=sharing_eil&ts=5eaef8d6
Results -- *Permeability and Velocity*

Fine channels coarsen, and mega-channel forms as time progresses.
Qualitative similarities with experiments

Contours of bulk salinity (psu)
*Fig 6d from Cottier & Wadhams (1999)*

Array of smaller brine channels

Large “mega-channel”

Brinicle?

Photograph of dye entrainment in sea ice
*Fig 3c from Eide & Martin (1975)*
Results -- *Vertical Salinity Flux*

**Vertical salt flux:**

- **Dark Blue - Strong Downward**
- **Light Blue - Weak downward**
- **Pink - weak upward.**

Salt flux weakens in smaller channels as mega-channel develops.

Increasing time.
After strong initial desalination pulse, salt flux weakens over time
Discussion

- Initially many small brine channels form, then are consolidated into a single “mega-channel”
  - Single channel is robust over a range of domain sizes
- Shallow region near ice-ocean interface is desalinated by an array of many small brine channels
- Full-depth “mega-channels” allow drainage from saline layer near top of ice
- Comparison with observations:
  - Laboratory: Eide and Martin (1975),
  - “Icy fingers of death” -- BBC Earth

Adaptive mesh refinement focuses computational effort where needed to resolve the problem while using lower resolution in less-dynamic regions.

Initial results are promising but more work needed to fine-tune mesh-refinement criteria.

Shaded regions show refinement. Clear is base resolution, green is 2x finer, and purple is 2x even finer (4x base resolution). Over-aggressive refinement in early phases leads to refining the entire domain and slows computation.
Conclusions

- We have simulated brine drainage via 3-dimensional convection in porous mushy sea ice
- Shallow region near ice-ocean interface is desalinated by an array of many small brine channels
- Full-depth “mega-channels” allow drainage from saline layer near top of ice
- Adaptive mesh refinement capability is implemented and is being fine-tuned.

Appendix: Governing Equations

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].

1. \[ \vec{U} = \frac{k_w(\chi)}{\eta}(\nabla p - \rho_l g) \]

2. \[ \nabla \cdot \vec{U} = 0 \]

3. \[ \frac{\partial S}{\partial t} = \vec{U} \cdot \nabla S_l = \nabla \cdot \chi D_l \nabla S_l \]

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

\( \vec{U} \) (Darcy Velocity), \( \chi \) (porosity), \( p \) (pressure), \( T \) (temperature), \( S_l \) (liquid salinity), \( S = \chi S_l \) (bulk salinity), \( \eta \) (viscosity), \( D_l \) (salt diffusivity), \( \alpha, \beta \) (thermal, haline expansion), \( c_{p,l}, c_{p,s} \) (liquid/solid specific heat), \( k_l, k_s \) (liquid, solid heat conductivity), \( K_0 \) (reference permeability)

\[ H = \rho_0 \{L \chi + [\chi c_{p,l} + (1 - \chi) c_{p,s}]T\} \] (enthalpy)

\[ \rho_l = \rho_0 [1 - \alpha T + \beta S_l] \] (liquid density)

\[ K(\chi)^{-1} = (\eta^2/12)^{-1} + [K_0 \chi^3/(1 - \chi)^2]^{-1} \] (permeability)
Appendix: Computational Approach

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.

Reference: