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

Daniel Martin[1], James Parkinson[2], Andrew Wells[2], and Richard Katz[2]

[1]Lawrence Berkeley National Laboratory
[2]University of Oxford

November 22, 2022

Abstract

Sea ice is a porous mushy layer composed of ice crystals and interstitial brine. The dense brine tends to sink through the ice, driving convection. Downwelling at the edge of convective cells leads to the development of narrow, entirely liquid brine channels. The channels provide an efficient pathway for drainage of the cold, saline brine into the underlying ocean. This brine rejection provides an important buoyancy forcing on the ocean, and causes variation of the internal structure and properties of sea ice on seasonal and shorter timescales. This process is inherently multiscale, with simulations requiring resolution from O(mm) brine-channel scales to O(m) mushy-layer dynamic scales. We present new, fully 3-dimensional numerical simulations of ice formation and convective brine rejection that model flow through a reactive porous ice matrix with evolving porosity. To accurately resolve the wide range of dynamical scales, our simulations exploit Adaptive Mesh Refinement using the Chombo framework. This allows us to integrate over several months of ice growth, providing insights into mushy-layer dynamics throughout the winter season. The convective desalination of sea ice promotes increased internal solidification, and we find that convective brine drainage is restricted to a narrow porous layer at the ice-ocean interface. This layer evolves as the ice grows thicker over time. Away from this interface, stagnant sea ice consists of a network of previously active brine channels that retain higher solute concentrations than the surrounding ice. We investigate the response of ice growth and brine drainage to varying atmospheric cooling conditions, and consider the potential implications for ice-ocean brine fluxes, nutrient transport, and sea ice ecology.

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

D.F. Martin (DFMartin@lbl.gov)[1], James Parkinson[2], Andrew Wells[1], Richard F. Katz[1]

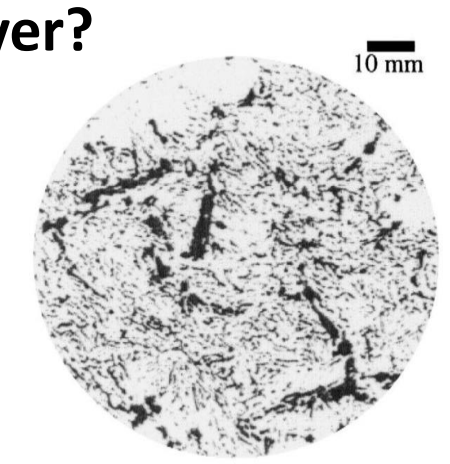
[1]. Lawrence Berkeley National Laboratory, Berkeley, CA, USA [2]. University of Oxford, UK.

Motivation

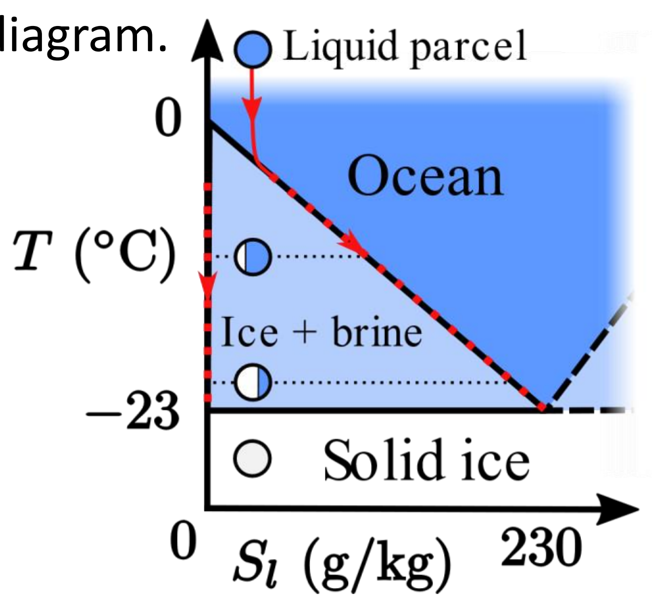
Sea ice is a mushy layer of ice crystals and brine. Dense brine drains during ice formation, while some brine is trapped within sea ice. Observations (Fig. 1) and 1- and 2-D simulations suggest that warming sea ice may release some of this brine. **Our goal:** investigate this mechanism using 3-D numerical simulations

What is a Mushy Layer?

(right) Sea ice is a porous mixture of solid ice crystals (white) and liquid brine (dark) [2].



(lower) Trajectory (→) of a solidifying salt water parcel through the phase diagram. As the temperature T decreases, more ice forms and the residual brine salinity Sl increases making the uid denser, which can drive convection. Using a linear approximation for the liquidus curve, the freezing point is $T_f(S_l) = 0.1 S_l$.



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. $\vec{U} = -\frac{k_W(\chi)}{\eta}(\nabla p - \rho_l \vec{g})$
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), χ (porosity), p (pressure), T (temperature), S_l (liquid salinity), S = χS_l (bulk salinity), 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), K_0 (reference permeability)

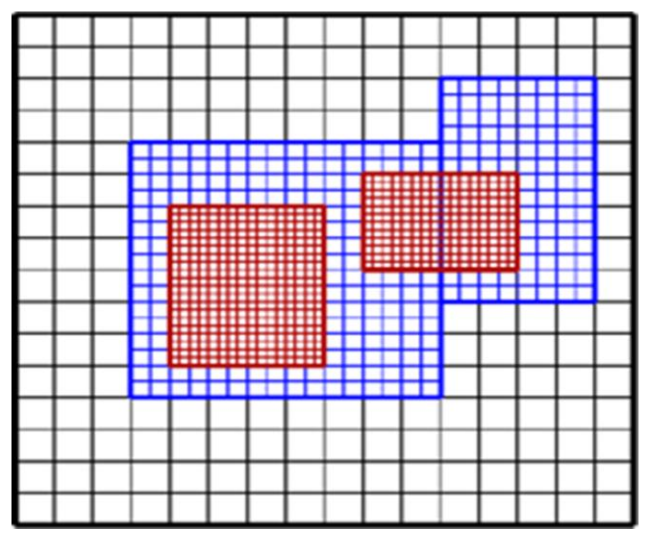
$$H = \rho_0\{L\chi + [\chi c_{p,l} + (1-\chi)c_{p,s}]T\} \text{ (enthalpy)}$$

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

$$K(\chi)^{-1} = (d^2/_{12})^{-1} + [K_0 \chi^3/(1-\chi)^2]^{-1} \text{(permeability)}$$

Adaptive Mesh Refinement

- Fine mesh resolution is required to resolve brine channels, but don't know *a priori* where they will be.
- We use *Block-structured adaptive mesh refinement (AMR), in which we* locally and dynamically refine the computational mesh where needed.
- Our implementation is built apon the Chombo AMR library. (http://chombo.lbl.gov)



ABOVE: Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer than level 0.

Numerical Scheme

- 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: 2nd-order semi-implicit scheme due to Twizell, Gumel, and Arigu (1996).

References

[1] K. Widell et al. Geophysical Research Letters 33.12 (2006), pp. 1{5.
[2] H. 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).
[4] M. G. Worster. Journal of Fluid Mechanics 224.-1 (1991), p. 335.
[5] M. Le Bars et al. Journal of Fluid Mechanics 550.-1 (2006), p. 149.

This work was funded by US DOE, NERC and a travel grant from the Royal Society.

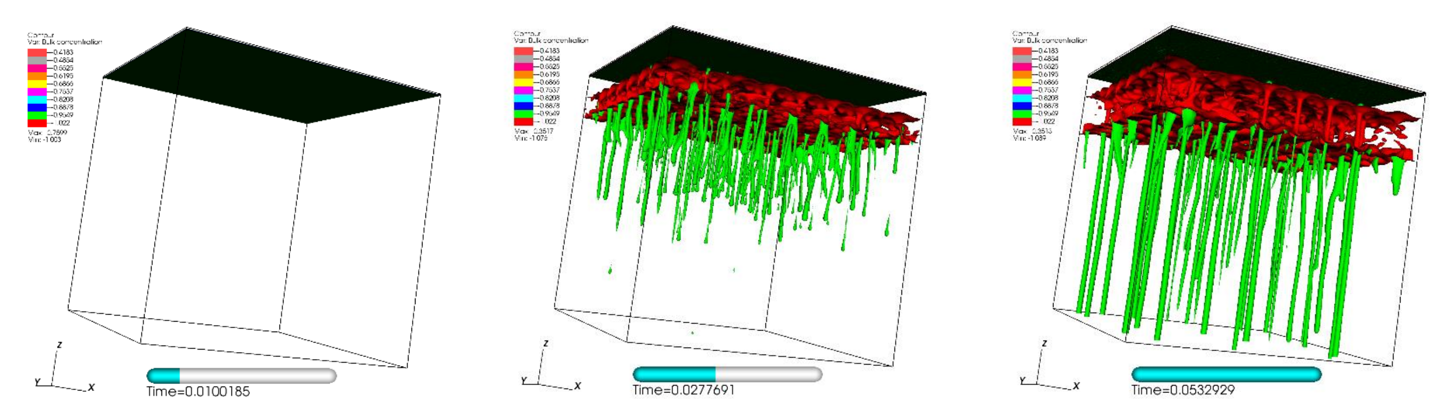
Idealized Experiment

We consider 3-D simulations in a cell of width 0.5m and height 1m. Water of initial salinity S_0 = 30 g/kg and temperature $T_f(S_0)$ + 0.2C is initially frozen from above by applying a fixed atmospheric temperature T_a = -10C.
We assume $K_0 = 10^{-9} m^2$ and model the underlying water as a porous medium with permeability $K_w = 10 K_w$, so we can use Darcy's Law everywhere.

To test the effects of the atmospheric temperature, we also ran the same experiment with varying upper boundary temperatures.

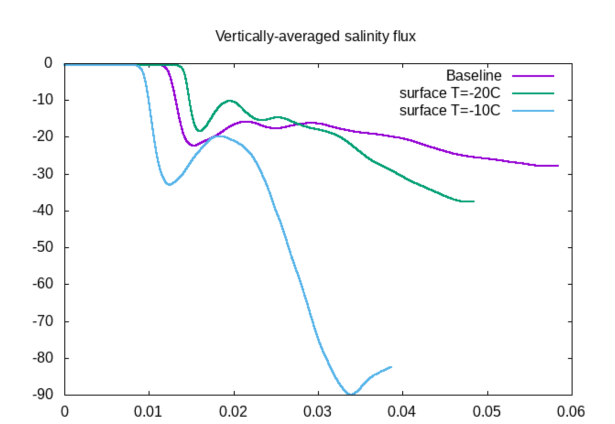
Idealized Experiment Results

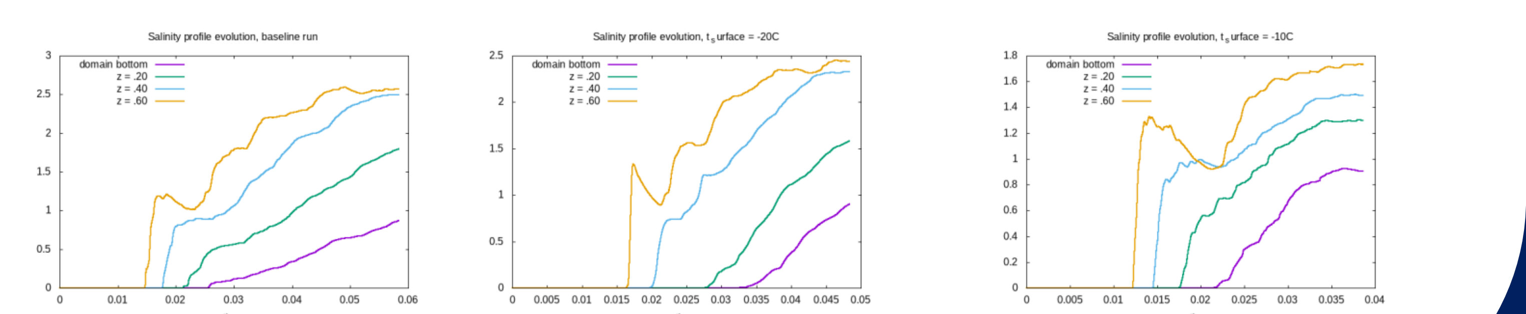
As expected, a mushy layer forms on top and brine channels form as the solution evolves.



(above) Nondimensionalized bulk Concentration isosurfaces after 0, 0.027, and 0.05 (time units are dimensionless and scaled by the diffusive timescale)

Right – Vertically averaged salinity flux over time for each experimental run.





Salinity profile evolution at different vertical depths for (left) baseline experiment, (center) $T_a = -20C$, and (right) $T_a = -20C$.