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

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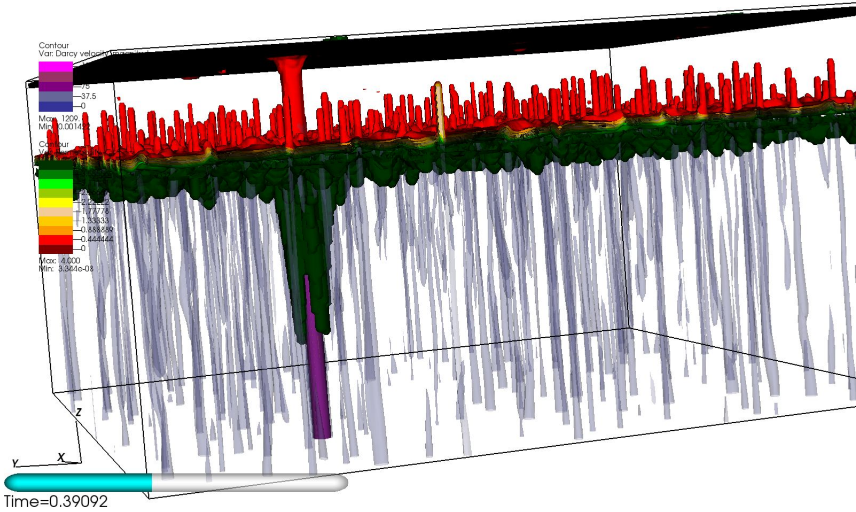
Summary:

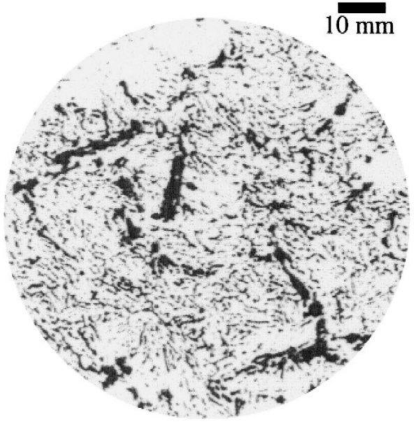
- Simulated brine drainage via 3-D convection in porous mushy sea ice
- Shallow region near ice-ocean interface is desalinated by many small brine channels
- Full-depth "mega-channels" allow drainage from saline layer near top of ice.



What is a mushy layer?

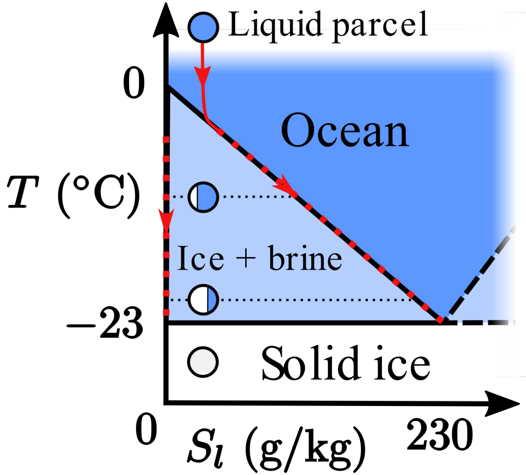
Dense brine drains convectively from porous mushy sea ice into the ocean.

- 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).

H. Eicken et al. Cold Regions Science and Technology 31.3 (2000), pp. 207–225



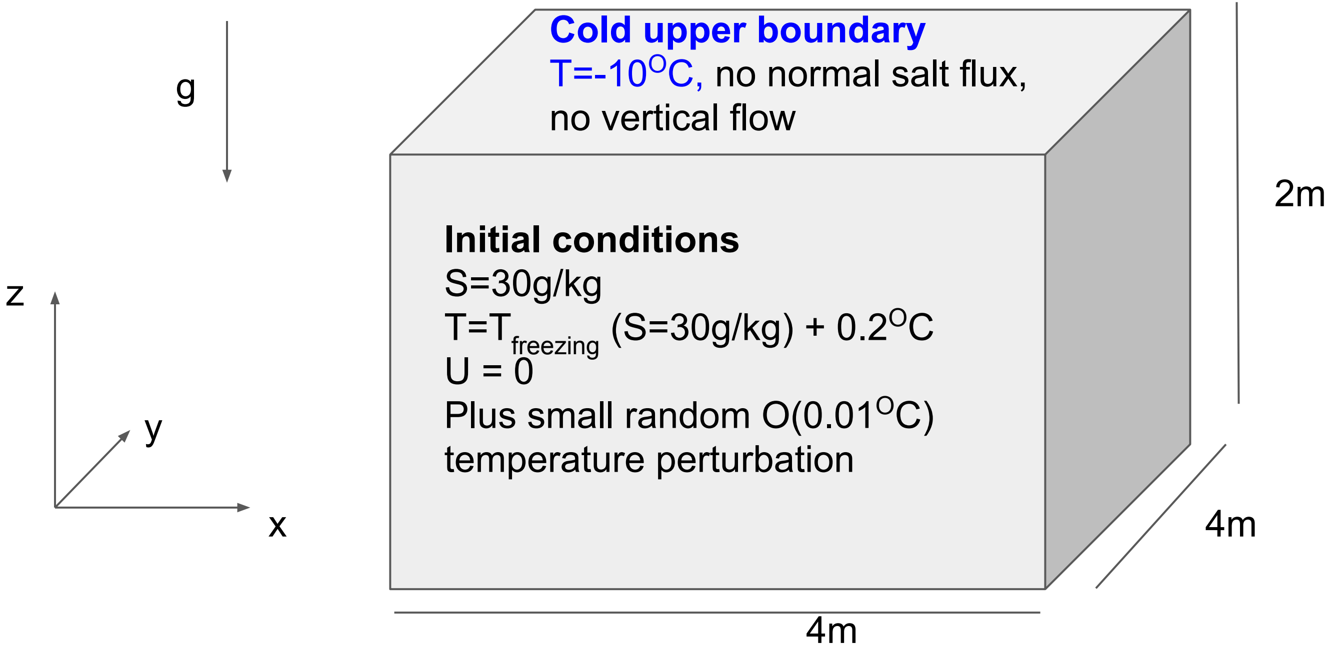
Lower fig.: Trajectory (→) of a solidifying salt water parcel through the phase diagram. As the temperature *T* decreases, the ice fraction increases and the residual brine salinity S_l increases making the fluid denser, which can drive convection.

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

$$T_f(S_l) = -0.1 S_l.$$

Problem setup

Numerically solve mushy-layer *equations* for porous ice-water matrix *(see appendix).*



Cold upper boundary
$T=-10^{O}C$, no normal salt flux,
no vertical flow

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

Horizontally periodic

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

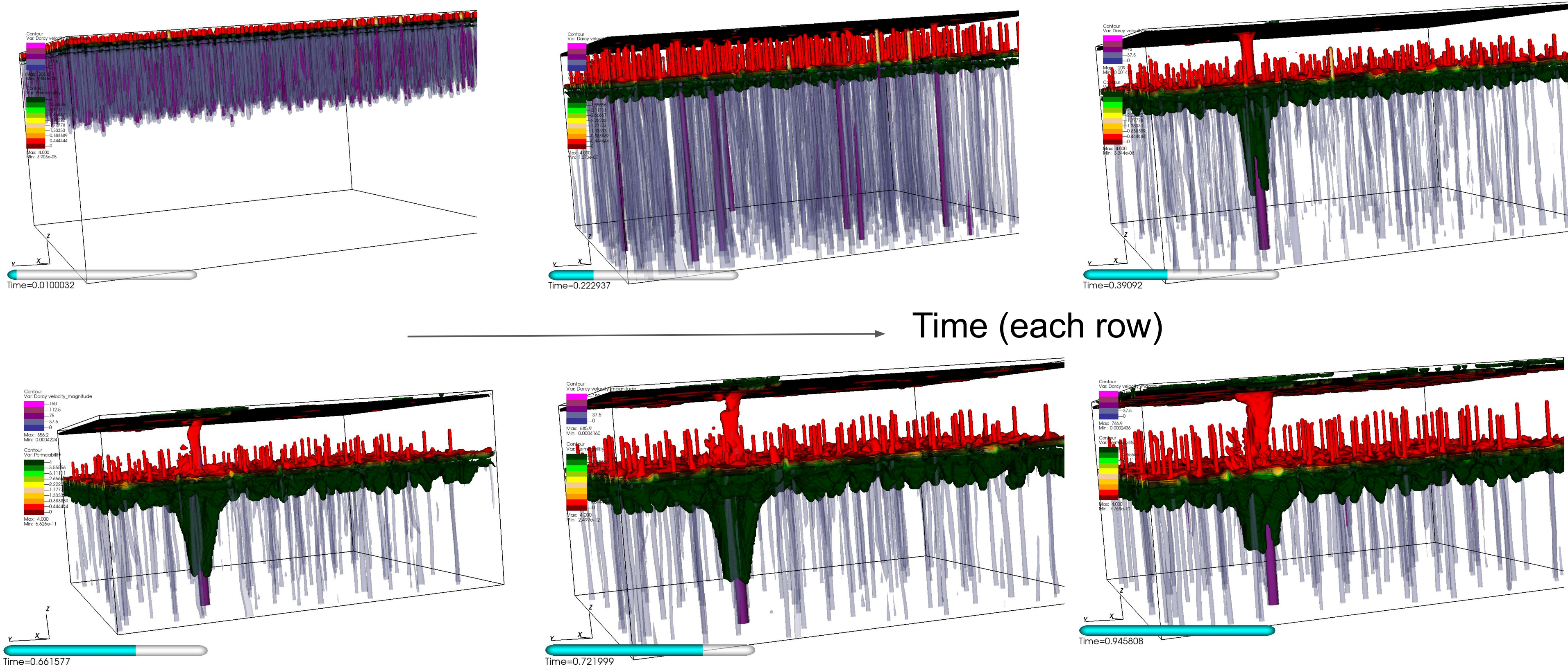
Movie
Contours of:

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-8pmVEHuJIYdKI/view?usp=sharing_eil&ts=5eaef8d6

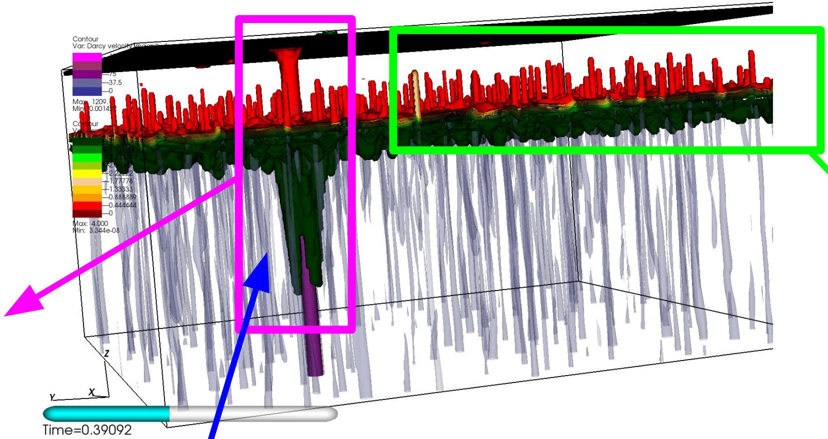
Results -- *Permeability and Velocity*



Time (each row)

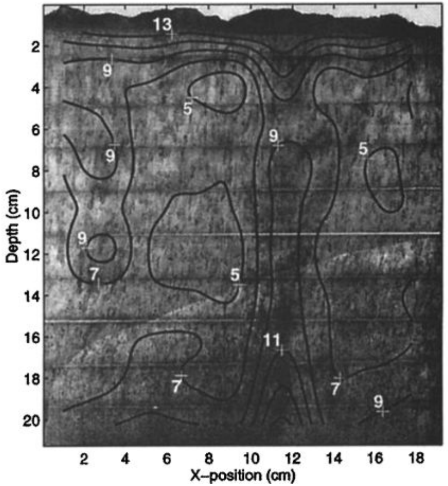
Fine channels coarsen, and mega-channel forms as time progresses.

Qualitative similarities with experiments



Brinicle?

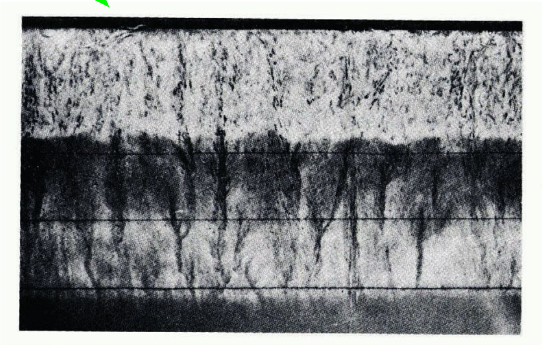
Large “mega-channel”



Contours of bulk salinity (psu)

Fig 6d from Cottier & Wadhams (1999)

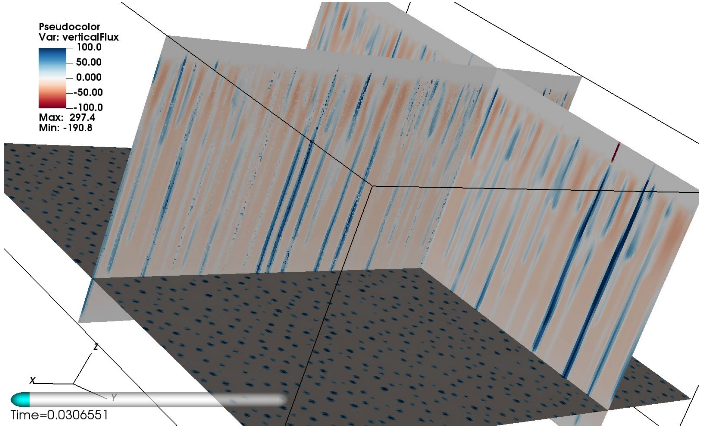
Array of smaller brine channels

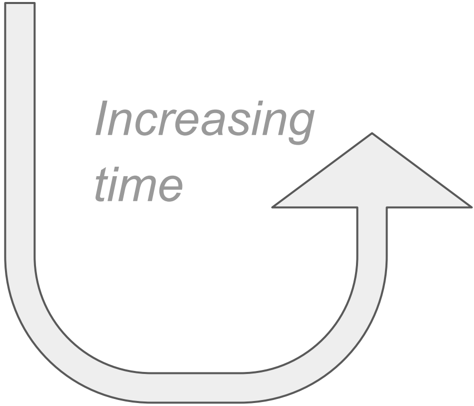


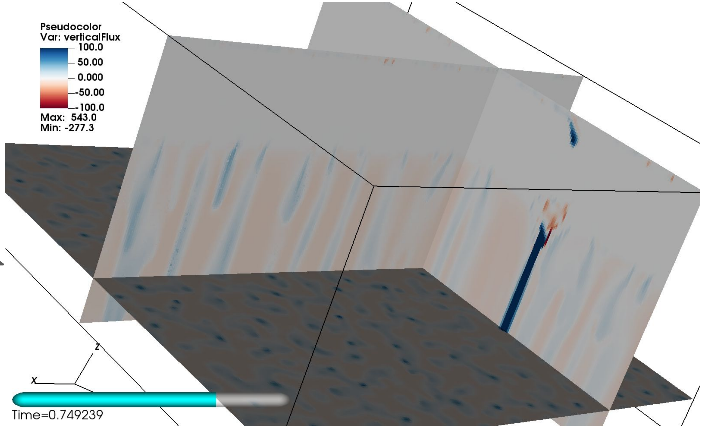
Photograph of dye entrainment in sea ice

Fig 3c from Eide & Martin (1975)

Results -- *Vertical Salinity Flux*





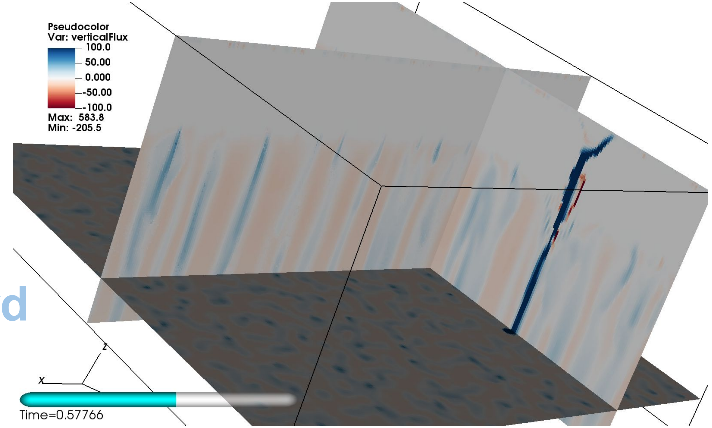


Vertical salt flux:

Dark Blue - Strong Downward

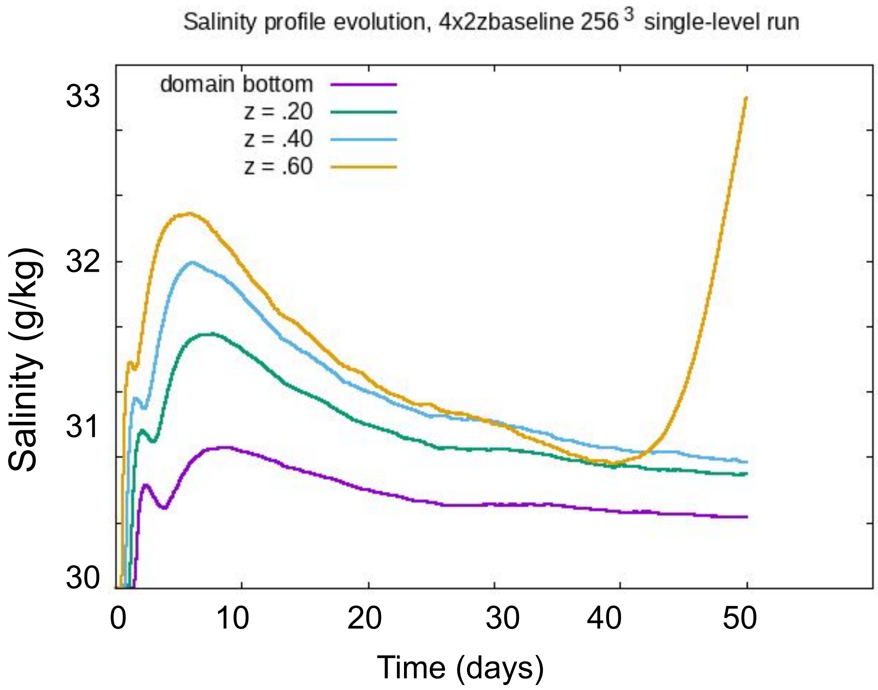
Light Blue - Weak downward

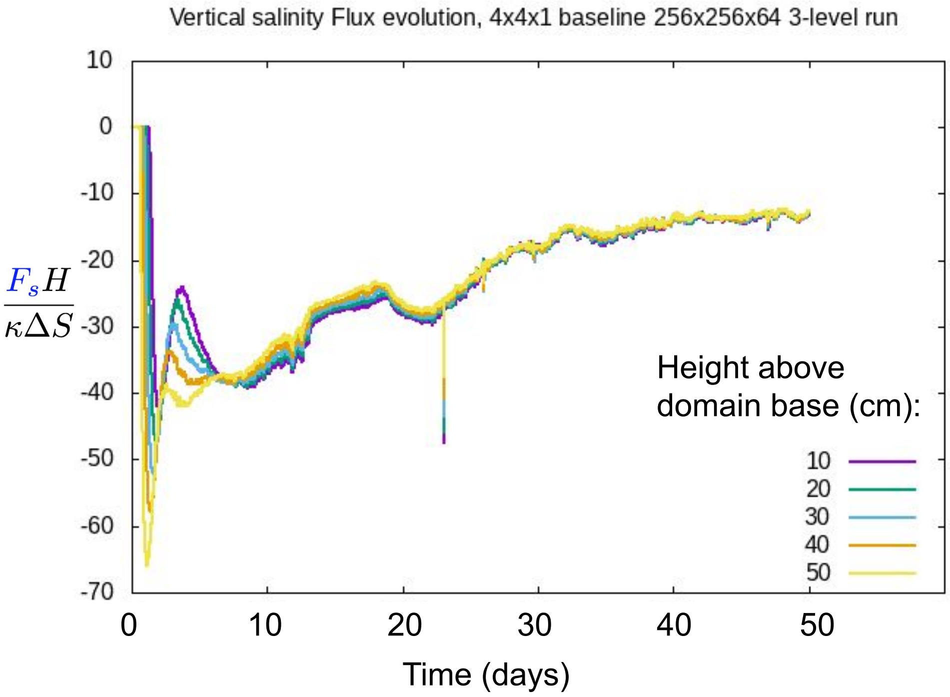
Pink - weak upward.



Salt flux weakens in smaller channels as mega-channel develops

Liquid-region salinity and salt flux


Salinity profile evolution, 4x2zbaseline 256^3 single-level run


Vertical salinity Flux evolution, 4x4x1 baseline 256x256x64 3-level run

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

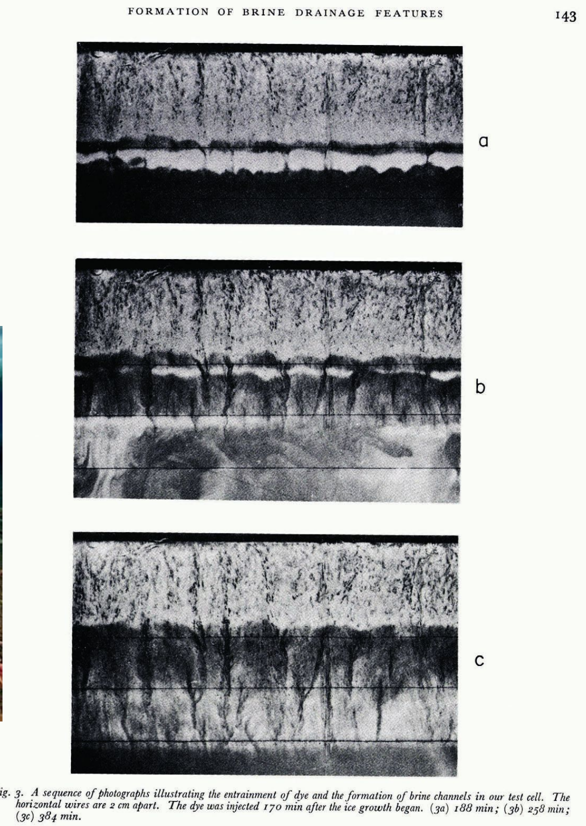


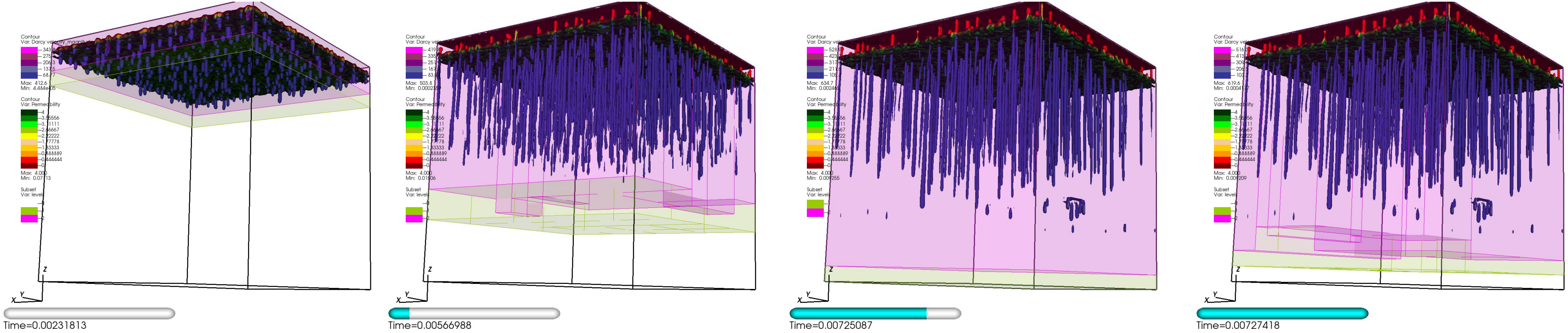
Fig. 3. A sequence of photographs illustrating the entrainment of dye and the formation of brine channels in our test cell. The horizontal wires are 2 cm apart. The dye was injected 170 min after the ice growth began. (3a) 188 min; (3b) 258 min; (3c) 384 min.

http://www.bbc.com/earth/story/20161219-brinicle-finger-of-death

Adaptive mesh refinement

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.

Reference: J.R.G. Parkinson, D.F. Martin, A.J. Wells, R.F. Katz, “Modelling binary alloy solidification with adaptive mesh refinement”, *Journal of Computational Physics: X*, Volume 5, 2020, https://www.sciencedirect.com/science/article/pii/S2590055219300599

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. $\vec{U} = -\frac{k_w(\chi)}{\eta}(\nabla p - \rho_l \vec{g})$
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), $S = \chi S_l$ (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)

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

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

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

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.
  - Timestepping: 2nd order Runge-Kutta method. *Twizell, Gumel, and Arigu (1996).*

Reference:

James R.G. Parkinson, Daniel F. Martin, Andrew J. Wells, Richard F. Katz, “Modelling binary alloy solidification with adaptive mesh refinement”, *Journal of Computational Physics: X*, Volume 5, 2020, https://www.sciencedirect.com/science/article/pii/S2590055219300599