Motivation, part I:

brine movement and phase transition are the foundation for many physical properties of sea ice

→ there’s dynamics in sea ice
Motivation, part II:

RADAR volume backscatter: pore space and brine salinity
Thermal properties: pore space
Mechanical properties: pore space
Albedo of bare ice: pore space
Spring-time albedo (meltponds): permeability
Ocean circulation: fluid dynamics
Nutrients for microalgae: fluid dynamics
Oil entrapment and transport: pore space, fluid dynamics

→ attempt to describe fluid dynamics and the development of salinity, pore space and permeability
at the microscopic scale

Fluid Dynamics

Ice Temperature

Pore Space

can be measured in cm-size samples and smaller

Cole et al. (2004)
continuum approach

*at the macroscopic scale*

(consider volume or mass averages)

can be profiled across the entire sea ice thickness

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Fluid Dynamics

Permeability

Bulk Salinity

Porosity

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Ice Temperature

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Barrow
Feb 9, 2008
 Fluid Dynamics

- Ice Temperature
- Permeability
- Pore Space / Porosity
- Bulk Salinity

only indirect measurements in sea ice (e.g. tracer studies)

→ dynamics in sea ice has to be inferred from what we are able to measure
Glossary – Bulk (Sea Ice) Salinity

1. take a chunk of sea ice (e.g. a cylinder 8 cm diameter, 5 cm thick)
2. melt this sample in a closed container (e.g. over night in the lab)
3. measure the salinity of the meltwater (usually with a conductivity probe)
Glossary – (microscopic) Pore Space and (macroscopic) Porosity

Pore Space (vertical photo)

\[ \text{porosity} = \frac{\text{volume of pores}}{\text{total volume}} \]

Cole et al. (2004)

Light et al. (2003)
Glossary – Permeability

\[ u = -\frac{\Pi}{\mu} \frac{\Delta p}{\Delta x} \]  \hspace{1cm} (Darcy’s law)

\( u \): mean flow rate of a fluid through a porous medium (m/s)

\( \Delta p \): pressure difference (Pa)

\( \Delta x \): thickness of the medium (m)

\( \mu \): dynamic viscosity of the fluid (kg/(m\(^2\) s))

\( \Pi \): permeability of the porous medium (m\(^2\))
Glossary – An intuitive interpretation of permeability

Assume porous medium is a bundle of cylindrical pipes of cross-sectional area $A = \pi R^2$ (other geometries lead to similar results)

$f$: Area fraction of cylinders (= porosity) [0..1]

$$\Pi = f \cdot \frac{A}{8\pi} \quad (\text{from Hagen-Poiseuille equation})$$

A first estimate of the permeability of sea ice:

- close to the ocean: $f=0.3$, $R = 500\ \mu$m
- desalinating ice: $f=0.1$, $R = 50\ \mu$m
- cold, effectively impermeable: $f=0.02$, $R < 5\ \mu$m (assuming that pores are interconnected)

$\Pi < 6\times10^{-14} \text{ m}^2$ \quad $\bar{u} < 3 \text{ cm/day}$

$\Pi = 1\times10^{-8} \text{ m}^2$ \quad $\bar{u} = 5 \text{ cm/s}$

$\Pi = 3\times10^{-11} \text{ m}^2$ \quad $\bar{u} = 1 \text{ cm/min}$

(flux due to flushing through sea ice)

(resolution limit of Light et al. (2003))

(cf. Freitag, 1999)
Snapshots from within the cycle of scientific investigation

Observation: what do we see? – and why?...

→ develop models / assumptions

→ infer other properties with the help of models / assumptions

Need to validate models / assumptions
Classic paper by Malmgren (1927) in the Arctic Ocean.

Seasonal Evolution of Sea Ice Salinity in First-Year Ice

NOTE:
- transport from sea ice to ocean
- redistribution within sea ice

Seawater:
- 33‰
Transport from sea ice to ocean

advection

diffusion

Redistribution in sea ice

advection (note high pressure during brine expulsion)
diffusion

phase transition
Condition for natural convection in sea ice

Driving motion: density differences (rate limited by finite permeability of medium and viscosity of fluid (cf. Darcy))

Retarding motion: thermal diffusivity (in conjunction with phase transition)

“Can perturbations move through the porous medium without being annihilated by diffusion?”

yes, if $R_{a_p}$ exceeds a critical Rayleigh number (value depends on boundary conditions)

Porous medium Rayleigh Number:

$$R_{a_p} = \frac{\Delta \rho \, g \, \Pi \, \Delta z}{\kappa \, \mu}$$

$\Delta \rho$: density difference, $\Delta z$: layer thickness
$\kappa$: thermal diffusivity, $g$: gravitational acceleration
Caveat: more complicated in the presence of under-ice flow with pressure fluctuations (Feltham et al. (2002), Neufeld and Wettlaufer (2008))

**Figure 6.** (a) The concentration of the liquid region and (b) the depth of the mushy layer as functions of time. The concentration initially remains constant indicating that the salt rejected by the growing ice remains trapped within the mushy layer. Once the depth of the mushy layer exceeds a critical value $h_c$, salt is convected out of the mushy layer and causes the concentration of the liquid region to increase. The solid curves are hand-drawn to fit the data.
Where solutes segregate: Studies of convection in sea ice

*Eide and Martin* (1975)

- Convection in lowermost cm of a “2-D” ice sheet
- Density-driven flow out of brine channels of few mm diameter
- Drainage of primary channels and cooling of surrounding ice foster development of feeder channels
Rejected Brine and Brine Plumes

Movie of Wakatsuchi, 1974 / 1983

Shadowgraph

growing sea ice

brine plumes

2 cm

Fluid Dynamics Simulations of Desalination

3 cm x 3 cm domain size

Brine Salinity

Porosity

(show animations)
Desalination process in winter and spring

Notz & Worster (2008)

Desalination:
• initially very fast
• then continuing at a slower rate
• and finally virtually absent (see next slide)
Observed Salinity Profiles in First-Year Sea Ice

Barrow, 2007

Note:
- C-shape during growth
- steady state salinity during growth

late May/June: melt season in Barrow

for Antarctic FY ice see Eicken (1992)
Steady-state (stable) salinity as a function of growth rate

Nakawo & Sinha (1981)

Canadian Arctic
Results from 2D Fluid Dynamics Modeling

Example profile generated at the scale of sea ice thickness

Steady state salinity obtained from multiple runs with varying oceanic heat flux

Simulated ratio between stable salinity $S$ and seawater salinity $S_0$ as a function of growth rate $v$. The solid line follows

$$\frac{S}{S_0} = 0.14 \left( \frac{v}{1.35 \times 10^{-7} \text{ m s}^{-1}} \right)^{0.33}.$$

The stable salinity of growing sea ice can be predicted based on the growth velocity, independent of oceanic heat flux.

- Ice–air interface temperature $-20^\circ\text{C}$
- Oceanic heat flux $F_w = 0 \text{ Wm}^{-2}$

Petrich et al. (2006)
Implications for Nutrient Flux and Under-Ice Biota

Ice—Ocean volume flux $F_v$ as function of growth rate $v$ for different ice—ocean interface properties (triangles, circles, squares).
How to model sea ice desalination "best"?

- ultimately, advection and diffusion and crystal interface kinetics
- however, even 2D ice growth simulations can take days or weeks to run
  → for simplicity of modeling, parameterize processes

Example:
"classic" desalination model of Cox & Weeks (1988):

1. initial segregation (parameterizes the bottom 3 cm)
2. gravity drainage and brine expulsion
3. brine expulsion, only (if porosity < 5%)

however, different approaches investigated these days, e.g.:
* 2D/3D solution of Navier-Stokes eqns in porous media
* 1D parameterization of advection
* Turbulent mixing
Solute segregation

- Cox & Weeks (1975):
  \[ S_{si} = k_{eff} S_w \]

- Inspired by segregation of impurities in solid solutions (Burton, Prim, Slichter model)

\[
k_{eff} = k \frac{C(0)}{C_\infty} = \frac{k}{k+(1-k)\exp\left(-\frac{z_{bi}v_i}{D}\right)}
\]

\[
k_{eff} = \frac{0.26}{0.26 + 0.74 \exp(-7243v_i)}, \quad v_i > 3.6 \times 10^{-5} \text{ cm s}^{-1}
\]

\[
k_{eff} = 0.8925 + 0.0568 \ln v_i, \quad 3.6 \times 10^{-5} \geq v_i \geq 2.0 \times 10^{-6} \text{ cm s}^{-1}
\]

\[
k_{eff} = 0.12, \quad v_i < 2.0 \times 10^{-6} \text{ cm s}^{-1}
\]
Comparison with data

Combining solute segregation, gravity drainage, brine expulsion

Eicken (2003)
Inferred Influence of Oceanic Heat Flux

Salinity profiles from Cox and Weeks model

Influence of positive ocean heat flux:
→ slows down growth
→ lower salinity

Eicken (1992)
Microstructural Evolution

\[
\begin{align*}
  \text{a} \leq \text{b} < \text{c} \\
  \text{a} &\sim 0.1 \text{ to } 0.3 \text{ mm; } \text{b} &\sim 1 \text{ to } 5 \times \text{a; } \text{c} > 5 \times \text{a} \\
  \text{d} &\sim 0.25 \text{ to } 1.25 \text{ mm (avg } 0.7\text{)}
\end{align*}
\]

Frozen Interface
Seawater Interface

(Kovacs, 1996)
Critical behavior of fluid transport in sea ice

\[ S = \text{salinity} \]

\[- \frac{dS}{dt} \times 10^5 \]

impermeable \hspace{1cm} \text{permeable}

or permeability vs. diffusivity?

(Cox and Weeks, 1975)

brine volume fraction \( \phi \) (%)

\( \phi = \phi (T, S), T = \text{temperature} \)

critical brine volume fraction \( \phi_c \approx 5\% \)

\( T_c \approx -5^\circ\text{C}, S \approx 5 \text{ ppt} \)

RULE OF FIVES
Critical Porosity in the Context of Percolation Theory

Percolation example
- 2-dimensional domain (10 x 10)
- periodic horizontally
- add pockets at random locations
- pocket size 1 x 1
- test for vertical percolation

\[ N = 180 \]
\[ f_t = 0.66 \]
\[ f_e = 0.55 \]

Total porosity
Interconnected porosity
Porous medium

Cluster formation and growth

\( f_e \) vs. \( f_t \) graph

Model
2d
3d

Permeability structure of first-year sea ice

- Highly permeable winter bottom layers
- Interior ice permeability low throughout ice-growth season, increases by 1-2 orders of magnitude during melt season

\[
k = 4.708 \times 10^{-14} \exp(0.07690V_b) \quad [m^2] \quad V_b \leq 96\% \quad (r = 0.74)
\]
\[
k = 3.738 \times 10^{-11} \exp(0.007265V_b) \quad [m^2] \quad V_b > 96\% \quad (r = 0.32)
\]
Desalination in summer

Meltwater flushing (Untersteiner, 1968) as a key desalination process

→ formation and importance of large brine channels

Eicken et al., 1995
Summer desalination
(surface topography, lateral redistribution, drainage)

Eicken et al., 2002
Example of (massive) lateral fluid flow

early in the melt season

Barrow, 6 June 2008

(show movie)
Oil in Ice

entrapment, release of compounds, upward percolation
Oil in laboratory grown sea ice

oil entrapment during growth

→ behavior during the melt season…