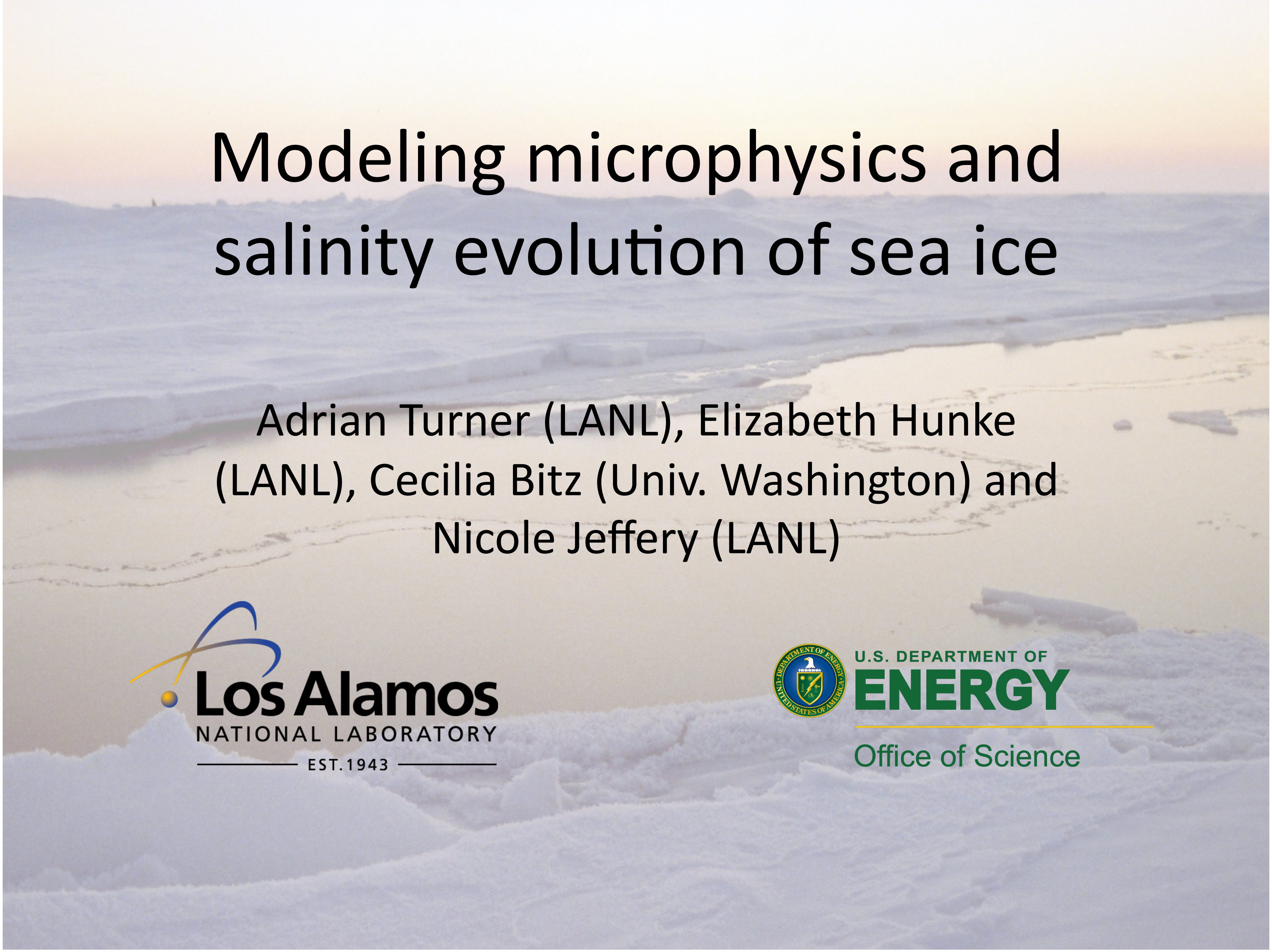


Modeling microphysics and salinity evolution of sea ice

Adrian Turner (LANL), Elizabeth Hunke (LANL), Cecilia Bitz (Univ. Washington) and Nicole Jeffery (LANL)

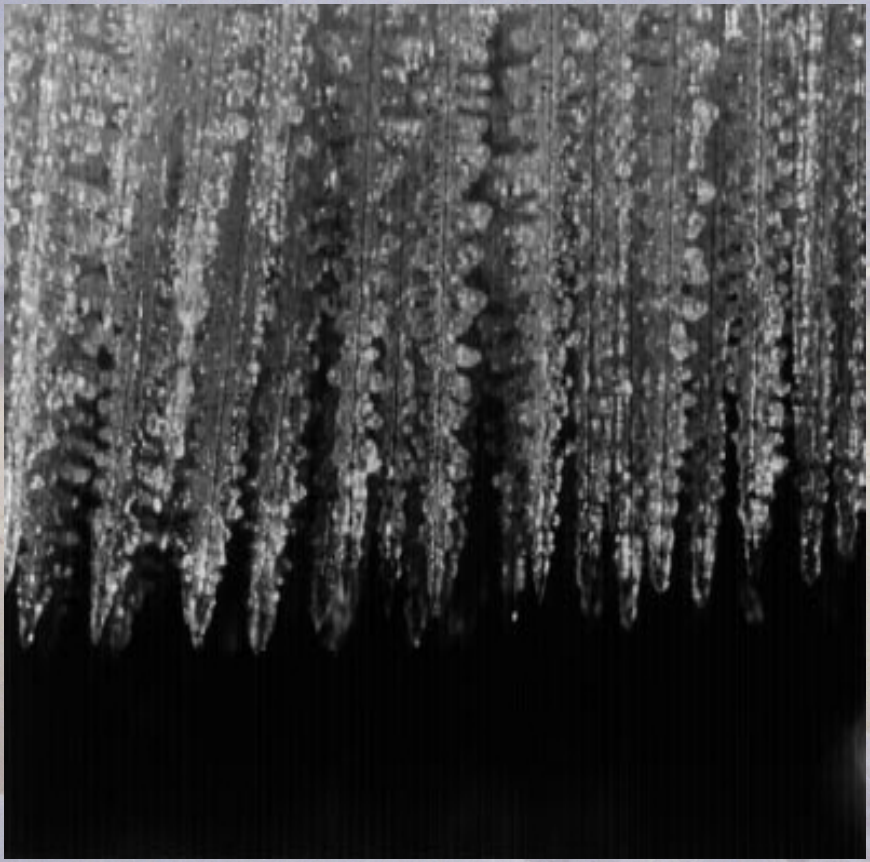
Los Alamos
NATIONAL LABORATORY
EST. 1943

U.S. DEPARTMENT OF
ENERGY
Office of Science

Project goal

- Currently Los Alamos sea ice model, CICE, has fixed salinity profile
- Aim to include salinity as a prognostic variable in the model
- Model processes that move brine around the ice and change salinity profile

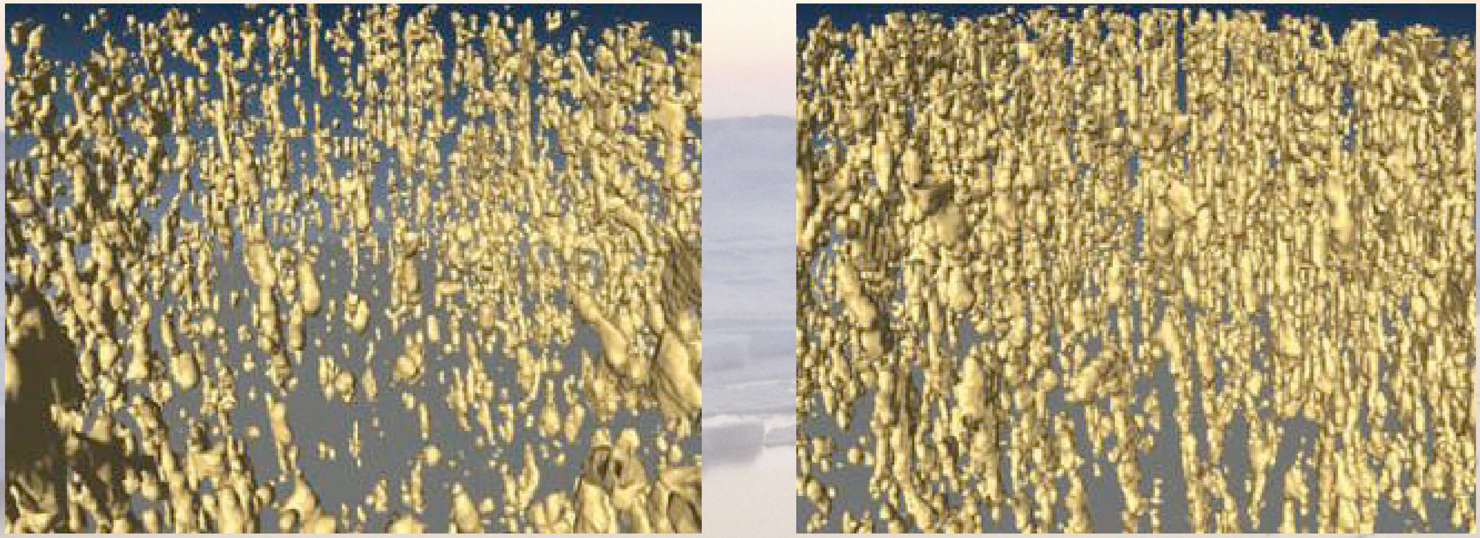
Sea ice formation



Worster (1999)

- Freezing interface becomes morphologically unstable during growth
- Brine is trapped between dendritic crystals
- Resulting structure is termed a “mushy layer”

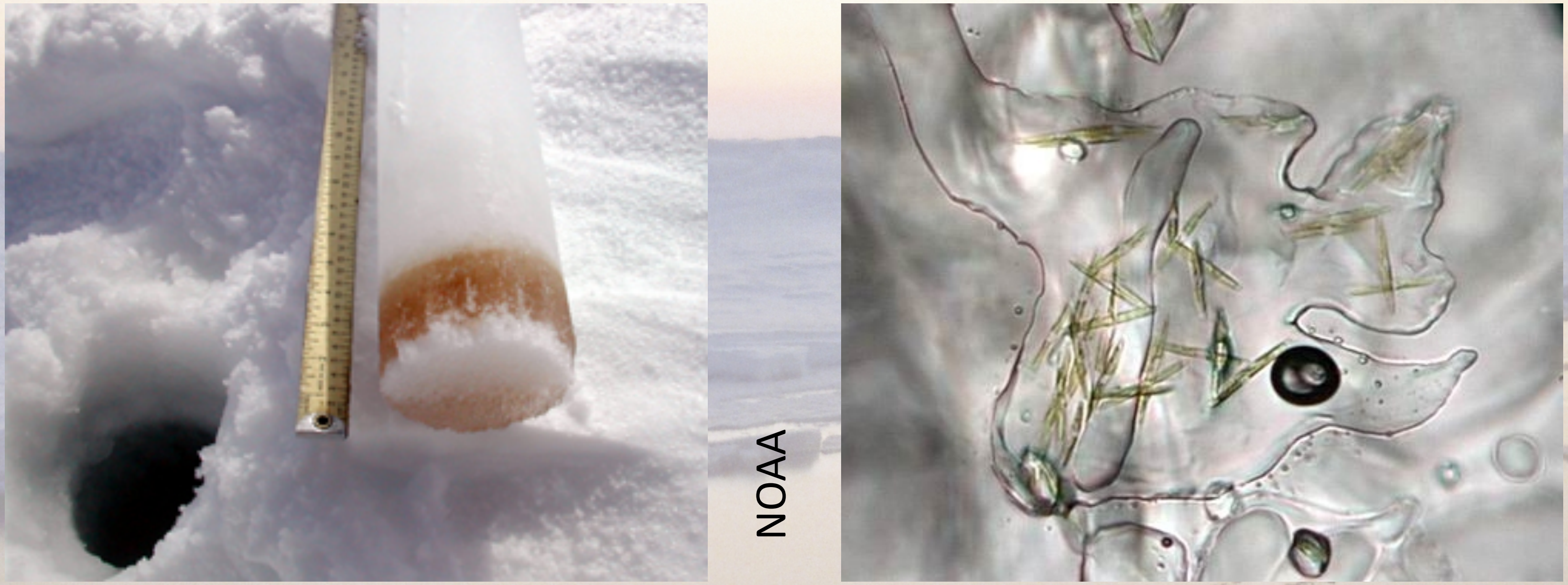
Sea ice pore structure



K. M. Golden et al. (2007)

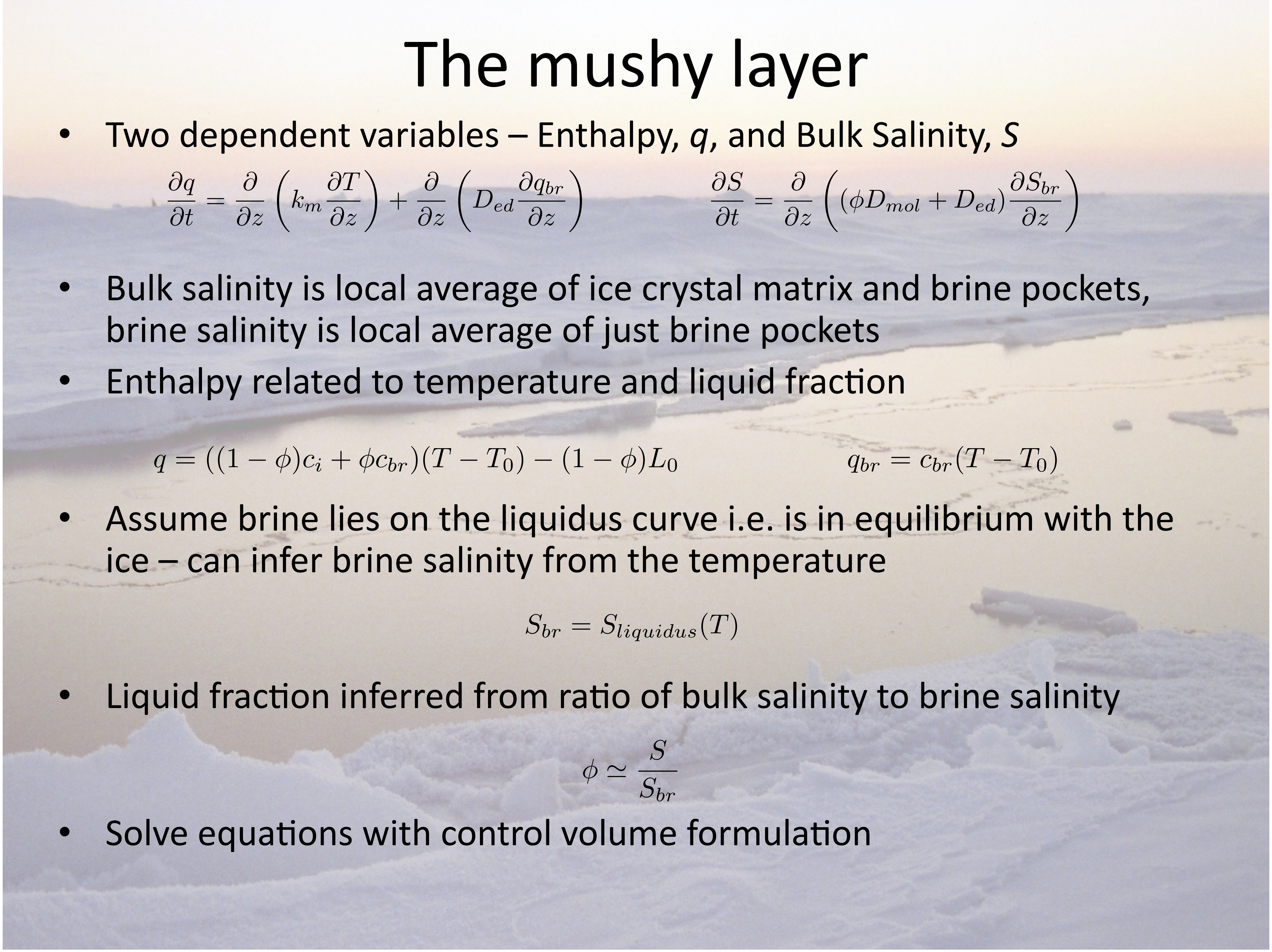
- Pore structure changes dynamically according to changes in temperature and brine pocket salinity
- Temperature increase melts surrounding ice and increases liquid fraction
- Salinity increase dissolves surrounding ice and increases liquid fraction
- Brine actively flows through connected brine pockets

Effect of salinity structure



NOAA

- Sea ice is home to a wide variety of organisms – bacteria, diatoms
- Need to be able to simulate flow of brine around sea ice to model flow of nutrients that supports this life
- Biology affects radiation absorption through albedo
- Salinity profile also effects physical properties – ice strength, melt rate



The mushy layer

- Two dependent variables – Enthalpy, *q*, and Bulk Salinity, *S*

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(k_m \frac{\partial T}{\partial z}\right) + \frac{\partial}{\partial z}\left(D_{ed}\frac{\partial q_{br}}{\partial z}\right) \qquad \frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left((\phi D_{mol} + D_{ed})\frac{\partial S_{br}}{\partial z}\right)$$

- Bulk salinity is local average of ice crystal matrix and brine pockets, brine salinity is local average of just brine pockets
- Enthalpy related to temperature and liquid fraction

$$q = ((1-\phi)c_i + \phi c_{br})(T - T_0) - (1-\phi)L_0 \qquad q_{br} = c_{br}(T - T_0)$$

- Assume brine lies on the liquidus curve i.e. is in equilibrium with the ice – can infer brine salinity from the temperature

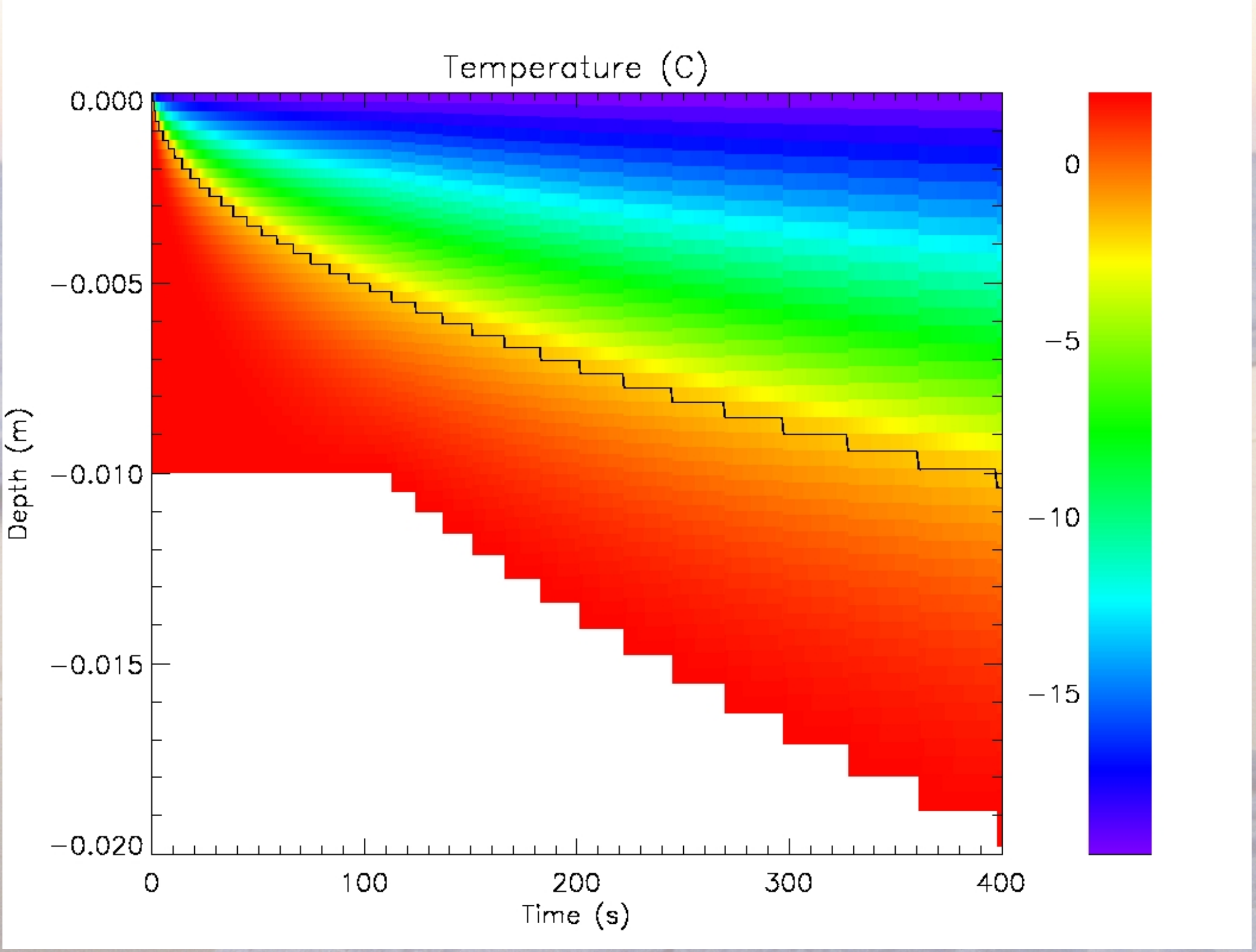
$$S_{br} = S_{liquidus}(T)$$

- Liquid fraction inferred from ratio of bulk salinity to brine salinity

$$\phi \simeq \frac{S}{S_{br}}$$

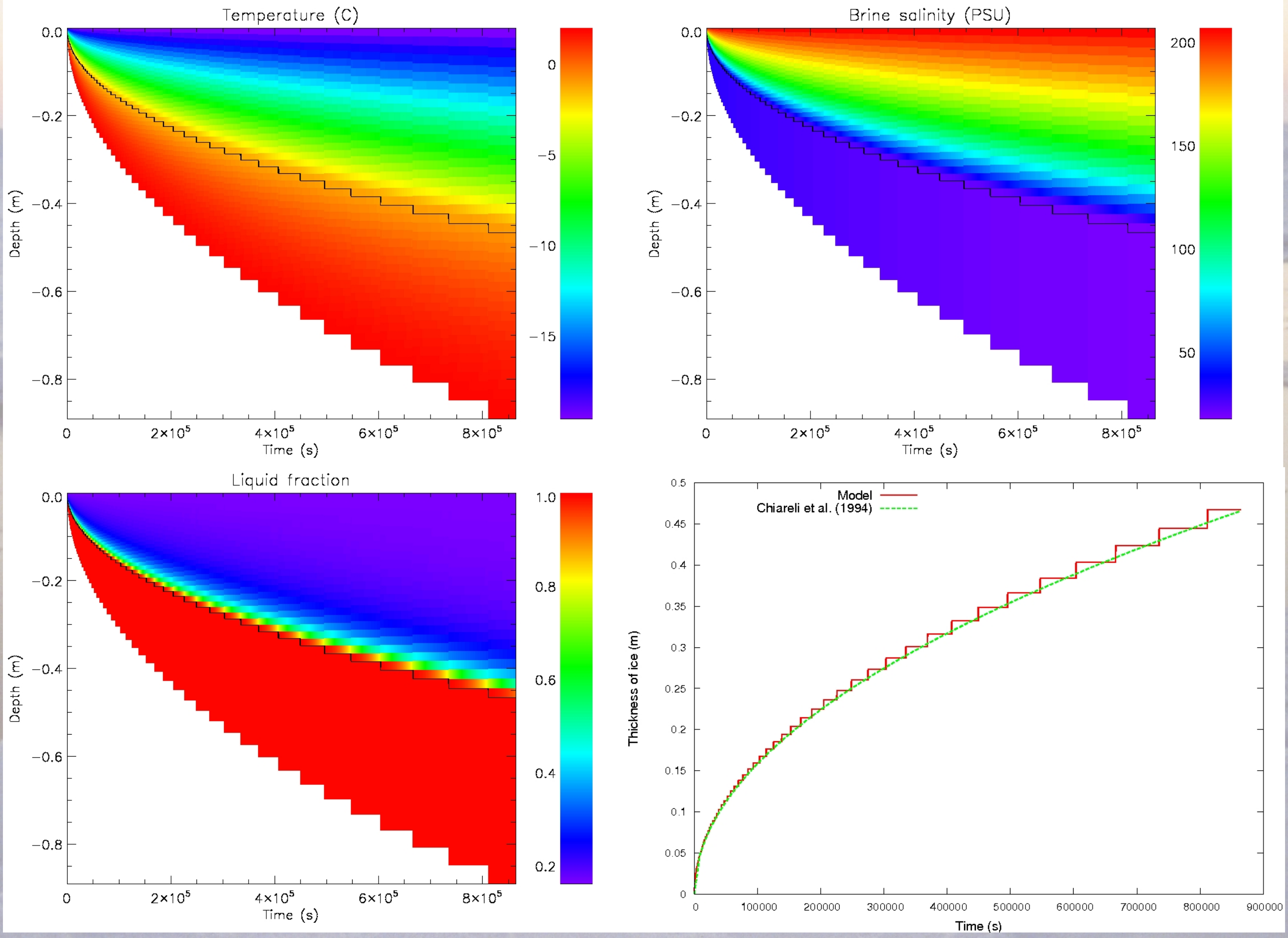
- Solve equations with control volume formulation

Growing a simple mushy layer

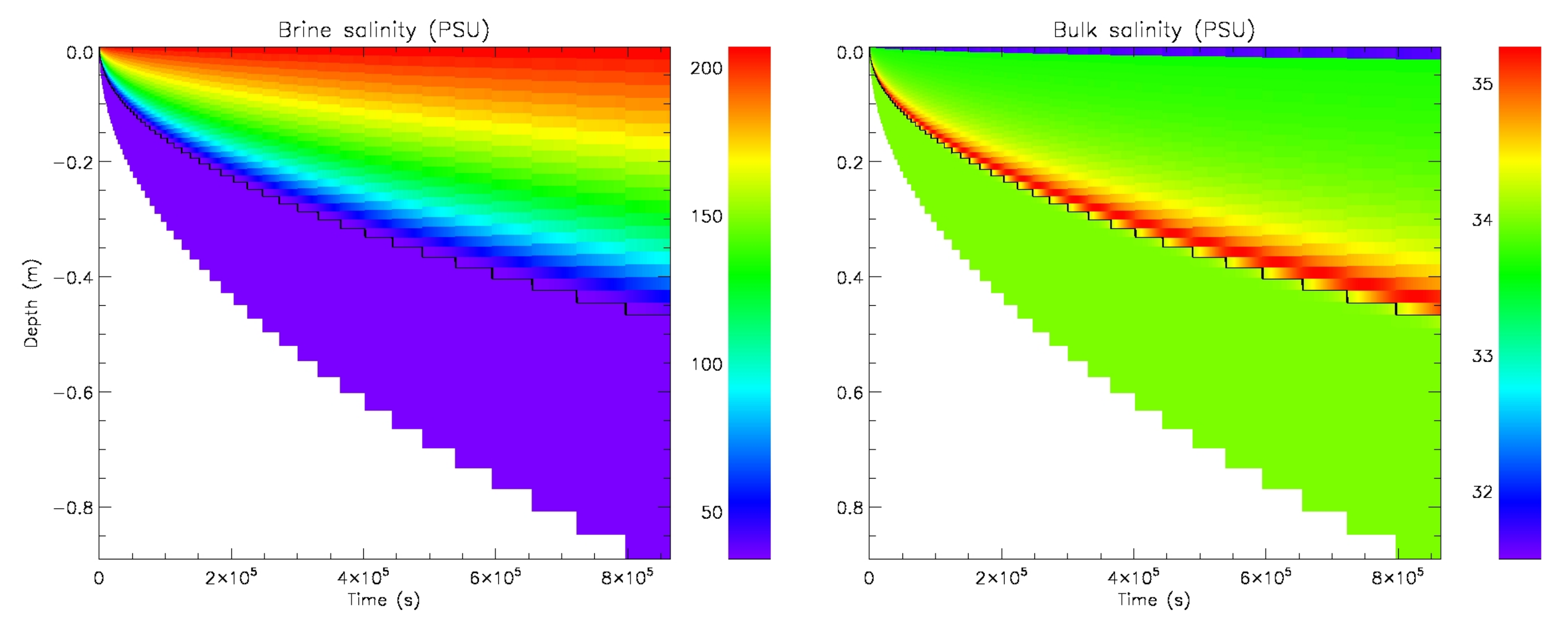


- 1cm of 2°C, 34 PSU salt water cooled from above at -20°C for 10 days
- Fixed domain including both pure liquid and mush which is periodically regrided to allow for growing ice interface
- No salt transport processes

Growing a simple mushy layer II



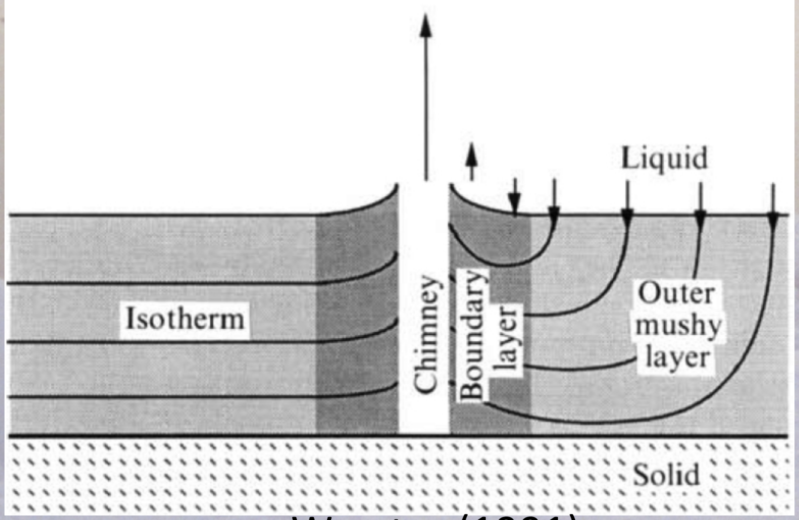
Molecular diffusion of salt



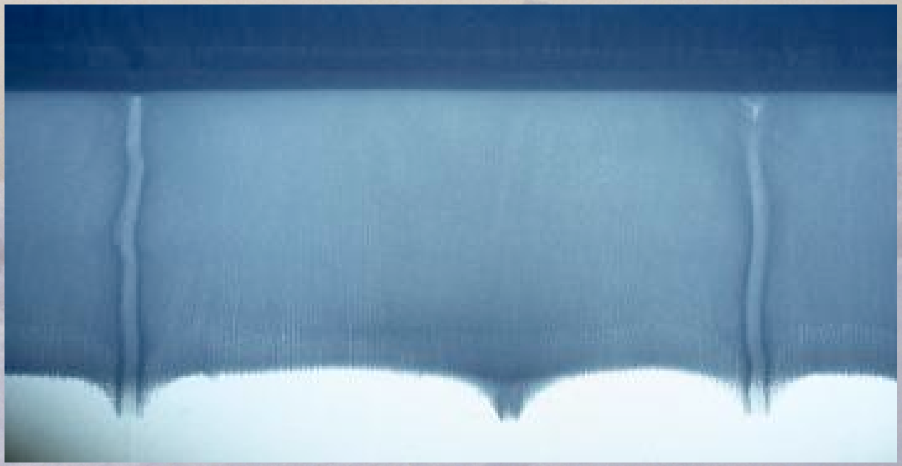
- Salt diffuses through pore structure down steep concentration gradient in brine
- Zero surface gradient in brine salinity for salt conservation
- Mild desalination of surface and increase in concentration at growing interface

Convection and Gravity Drainage

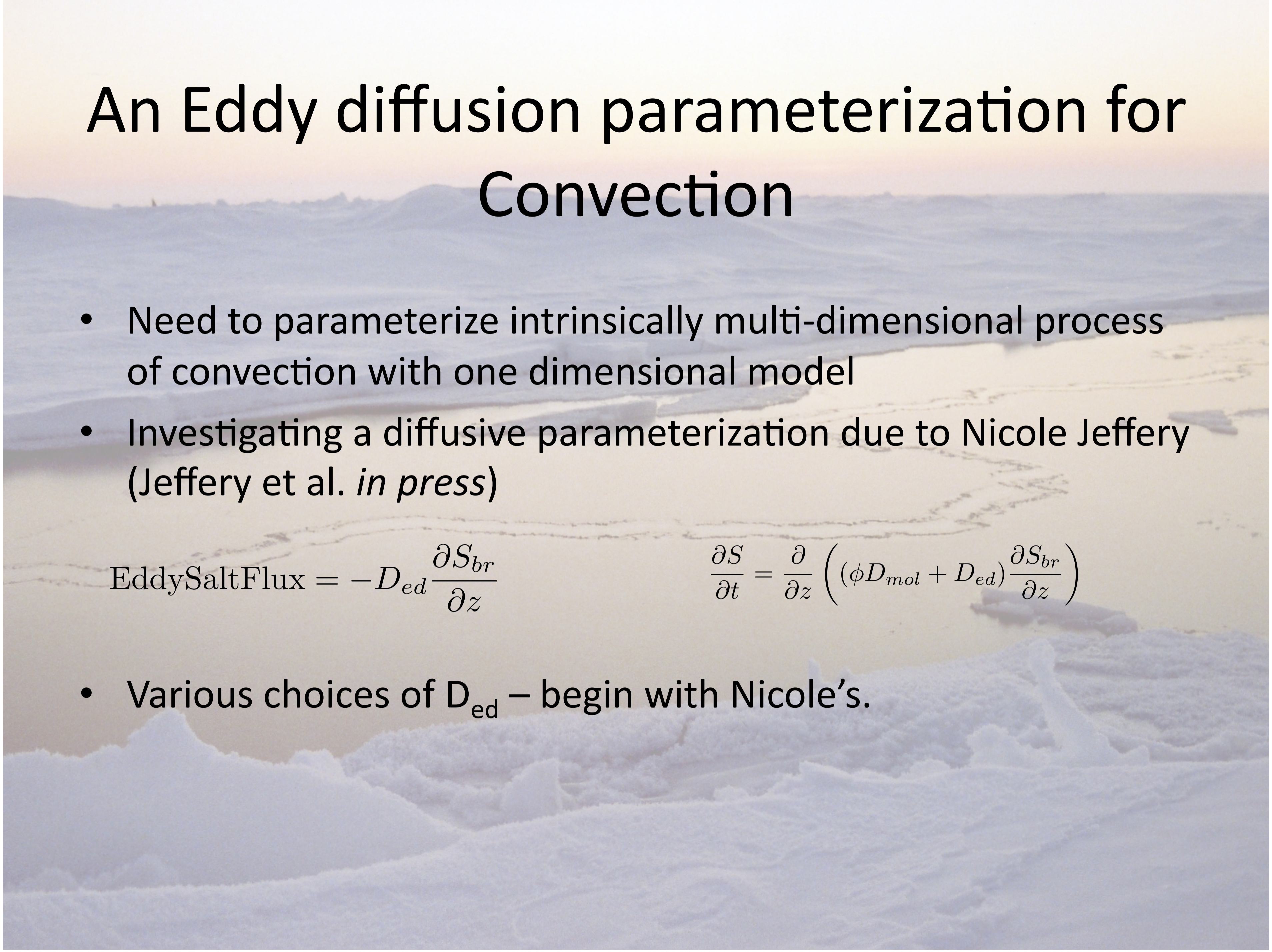
- Growing ice has high salinity brine overlaying low salinity brine – higher density brine over lower density brine
- Convection overturning of brine in ice matrix
- Brine motion results in change in ice matrix structure – development of chimneys
- Resulting brine loss from ice responsible for desalination of ice



Worster (1991)



Worster (2000)



An Eddy diffusion parameterization for Convection

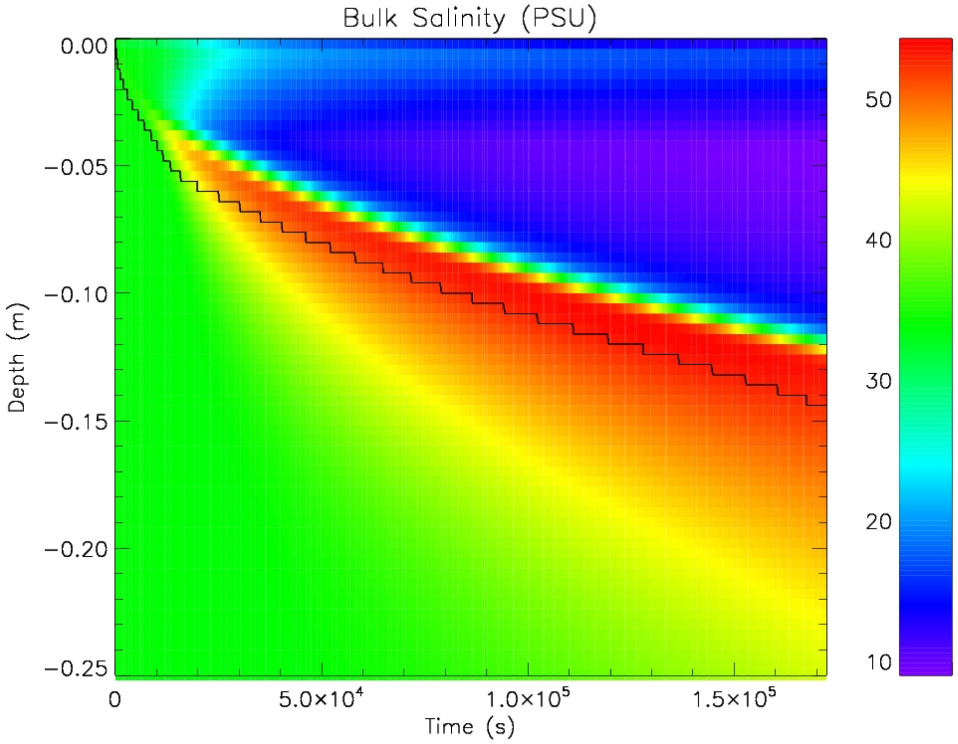
- Need to parameterize intrinsically multi-dimensional process of convection with one dimensional model
- Investigating a diffusive parameterization due to Nicole Jeffery (Jeffery et al. *in press*)

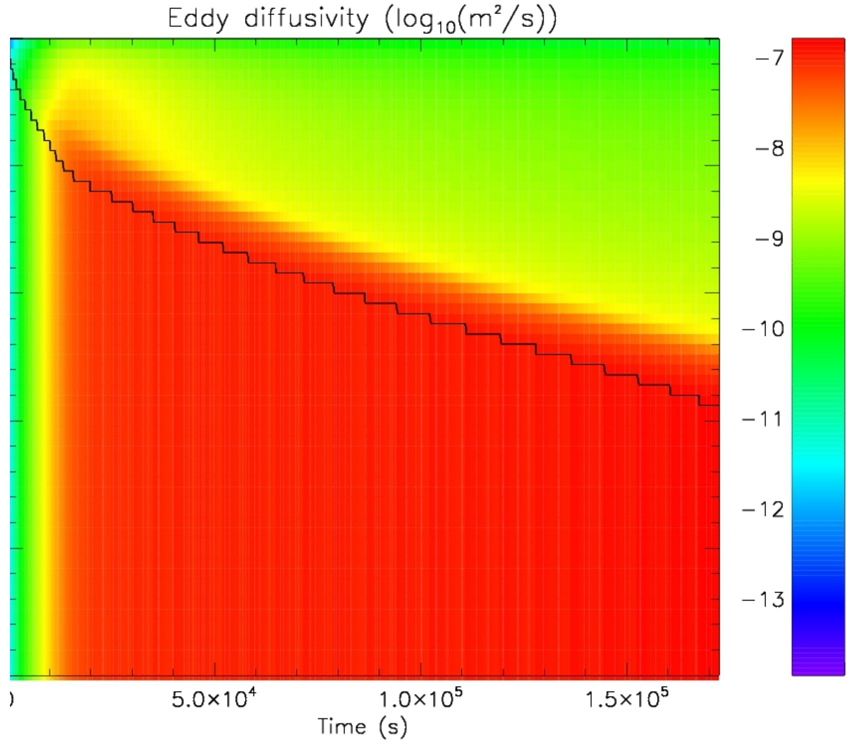
$$\mathrm{EddySaltFlux} = -D_{ed}\frac{\partial S_{br}}{\partial z}$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left((\phi D_{mol} + D_{ed})\frac{\partial S_{br}}{\partial z}\right)$$

- Various choices of D_{ed} – begin with Nicole’s.

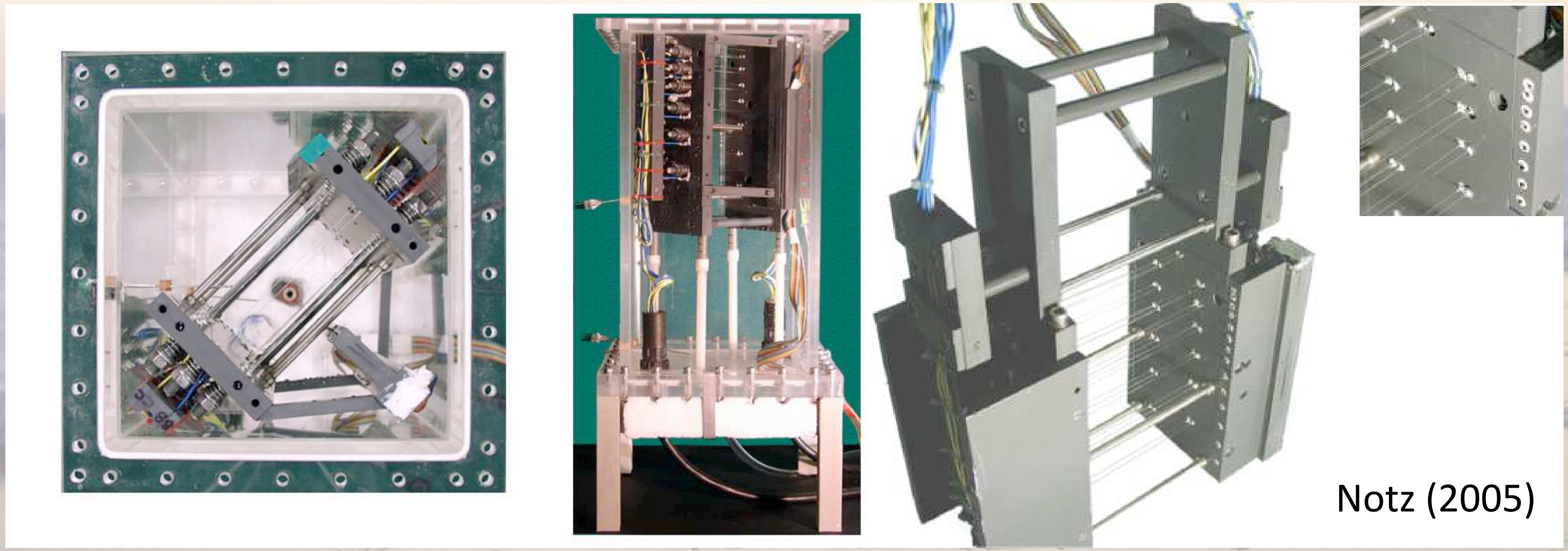
Preliminary results





- Fixed domain
- Switch on drainage when ice thickness reaches 5cm
- Get “C” shaped profile but salt buildup near interface

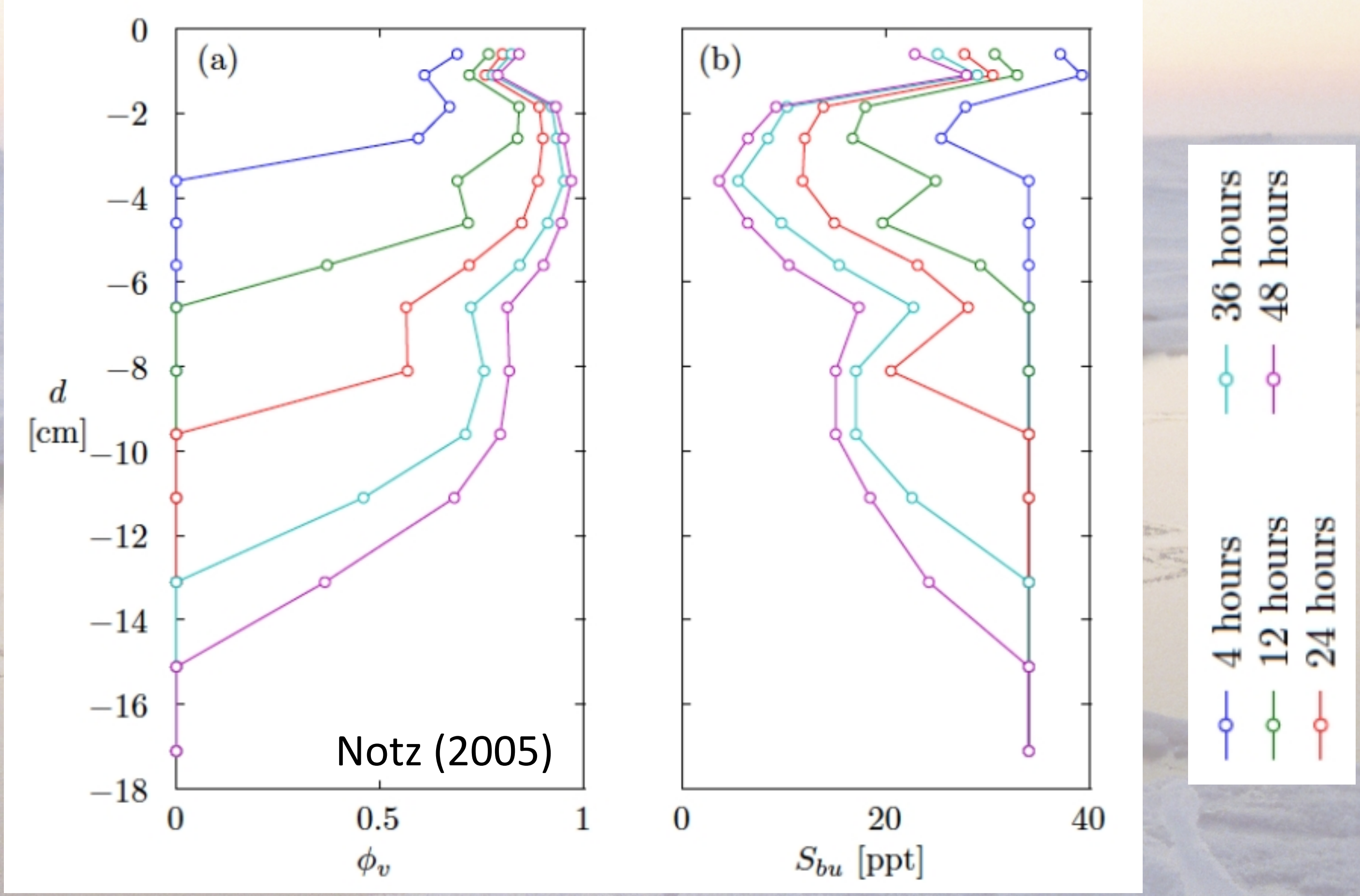
Experimental Results of Convection



Notz (2005)

- Desalination experiments of Dirk Notz (2005) measured bulk salinity, temperature and solid fraction during ice growth
- 40×20×20cm Perspex tank with custom instrumentation
- Impedance measured between Platinum wires, temperature by thermisters.
- Solid fraction determined from wires. Bulk salinity inferred from temperature and solid fraction using Liquidus curve.

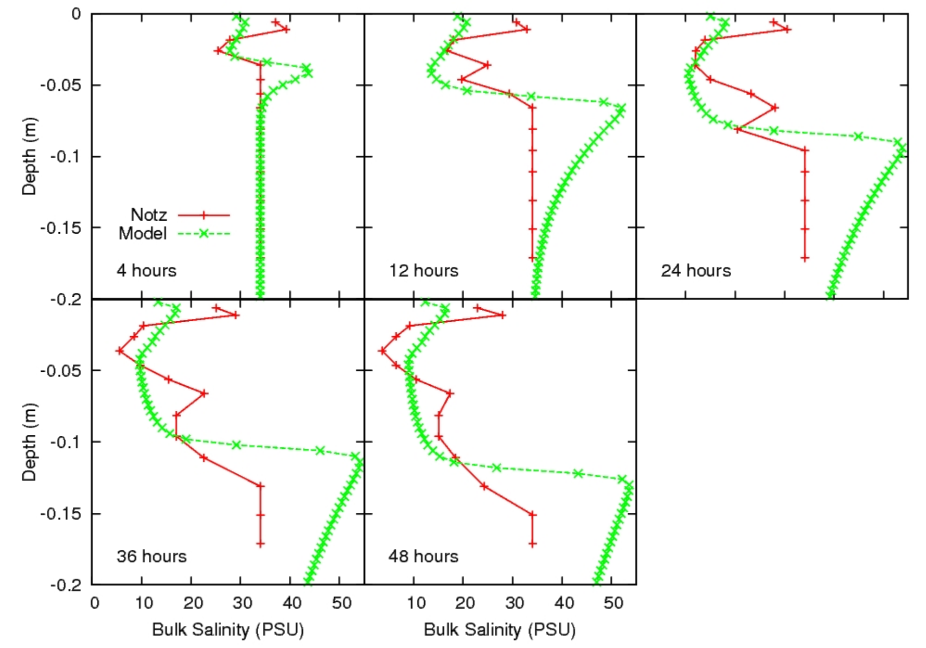
Experimental Results

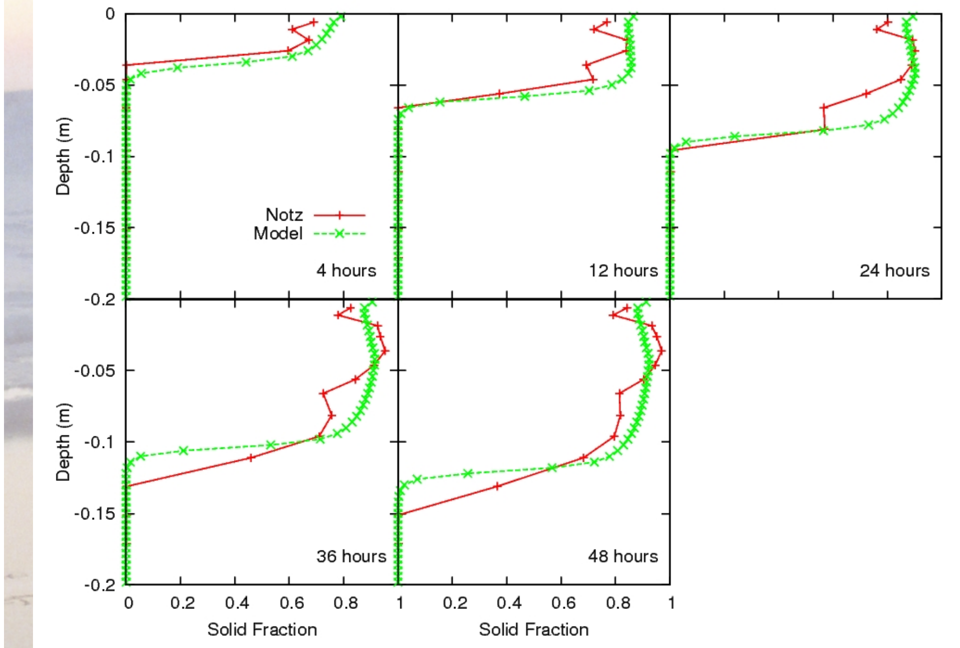


Notz (2005)

- Profiles of bulk salinity and solid fraction for two day period.
- See ice growth and desalination of resulting ice.

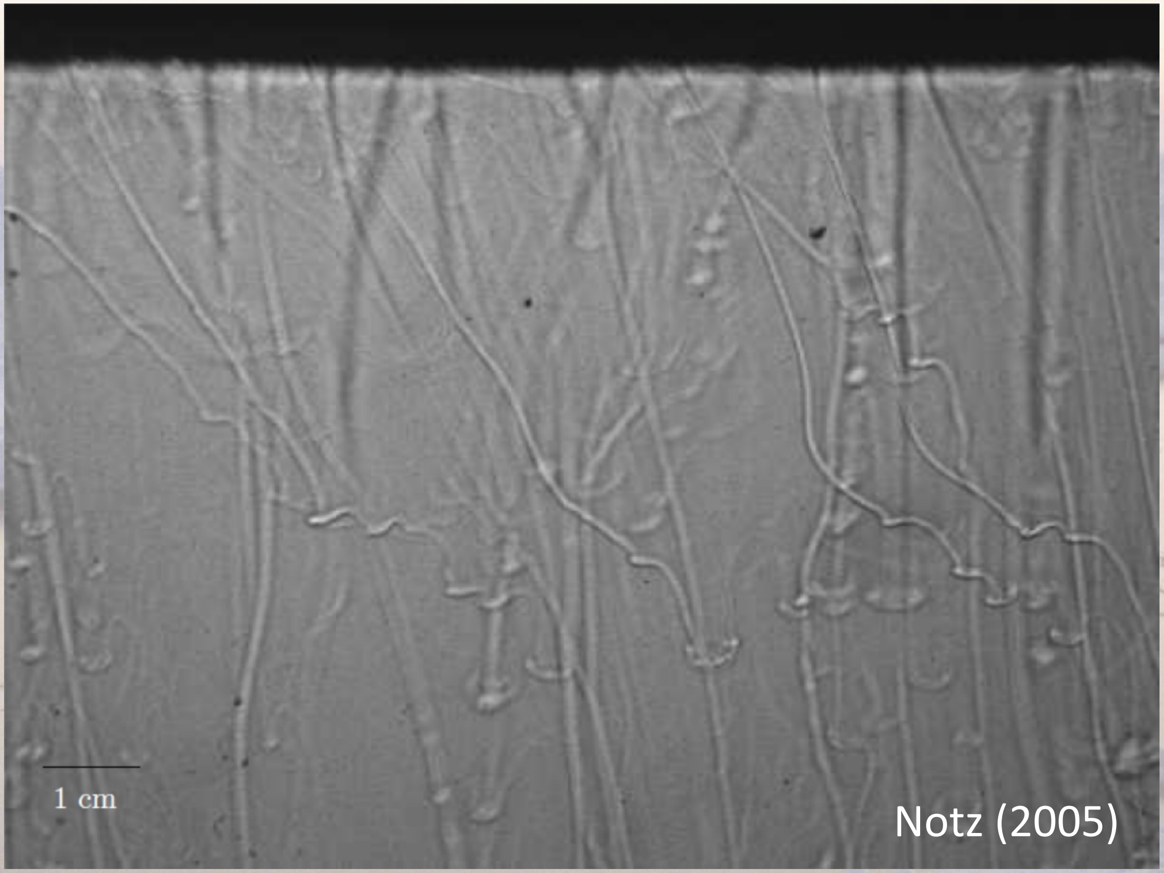
Eddy diffusion vs. Experiment





- Not terrible agreement
- Too much drainage in model at surface
- Salt is trapped near interface with liquid
- Insufficient drainage at later times near surface

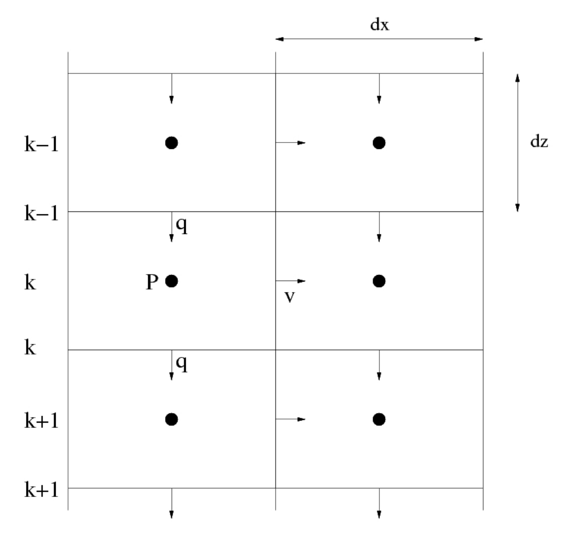
Flow in the liquid

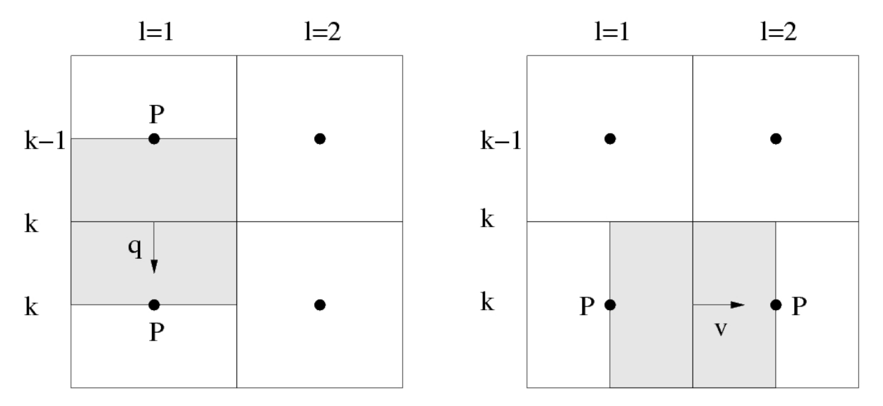


Notz (2005)

- In the experiment thin plumes of salty water were observed sinking from brine channels at the ice-water interface
- Rejected dense brine moves down much more quickly than by diffusive processes alone

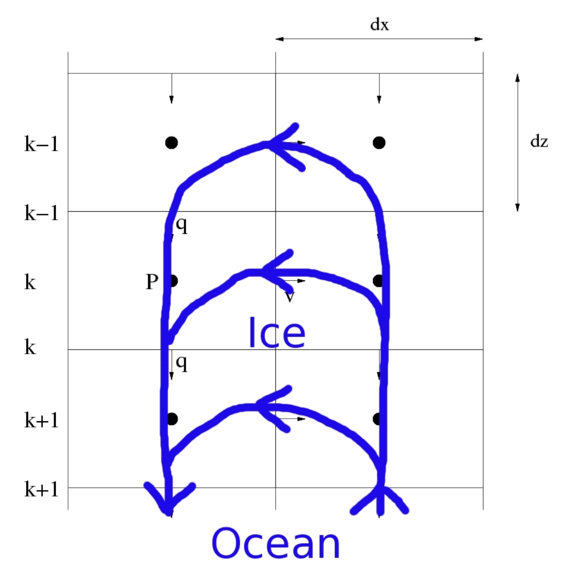
Two column flow model - I

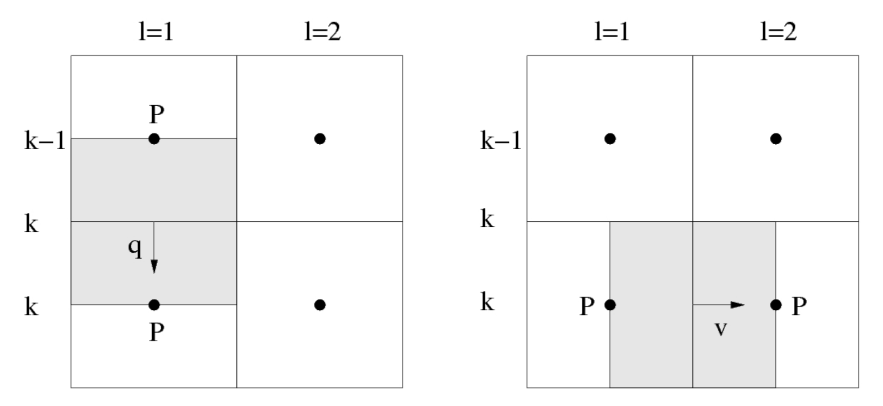




- Can also model explicit flow of brine around ice
- Simplest method is using a two column model with Darcy flow between grid cells
- Calculate pressures and fluid flows from Darcy equation and conservation of volume

Two column flow model - I





- Can also model explicit flow of brine around ice
- Simplest method is using a two column model with Darcy flow between grid cells
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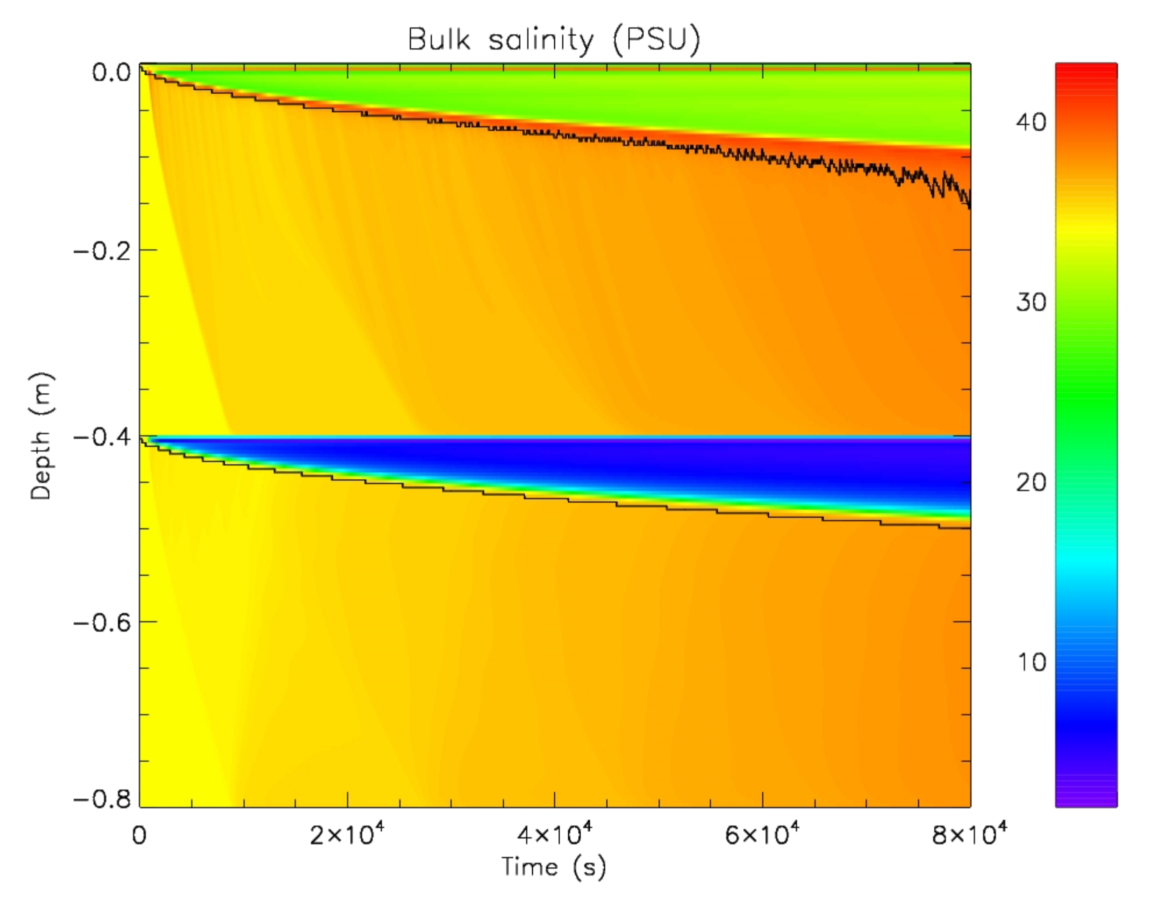
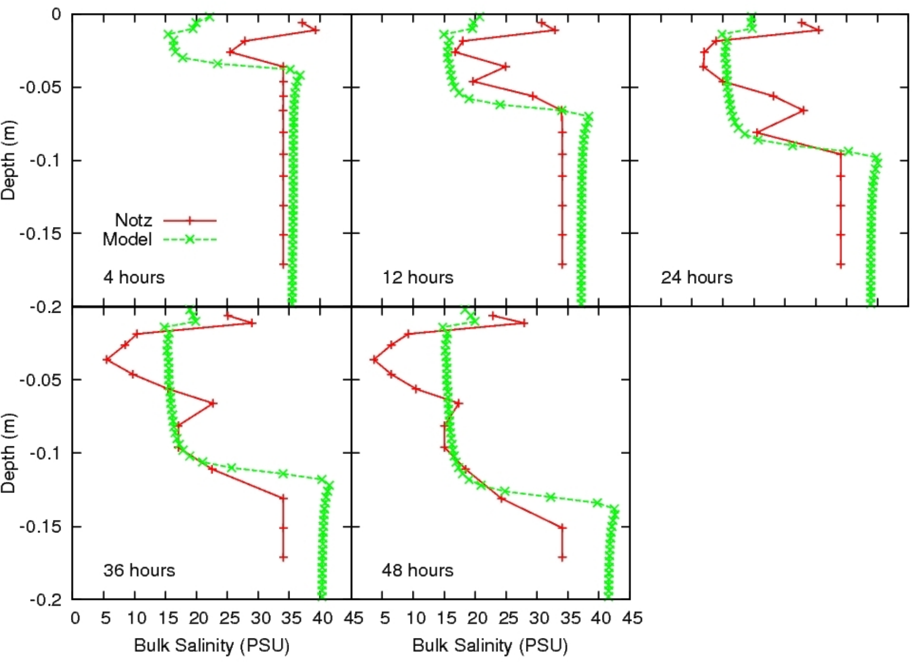
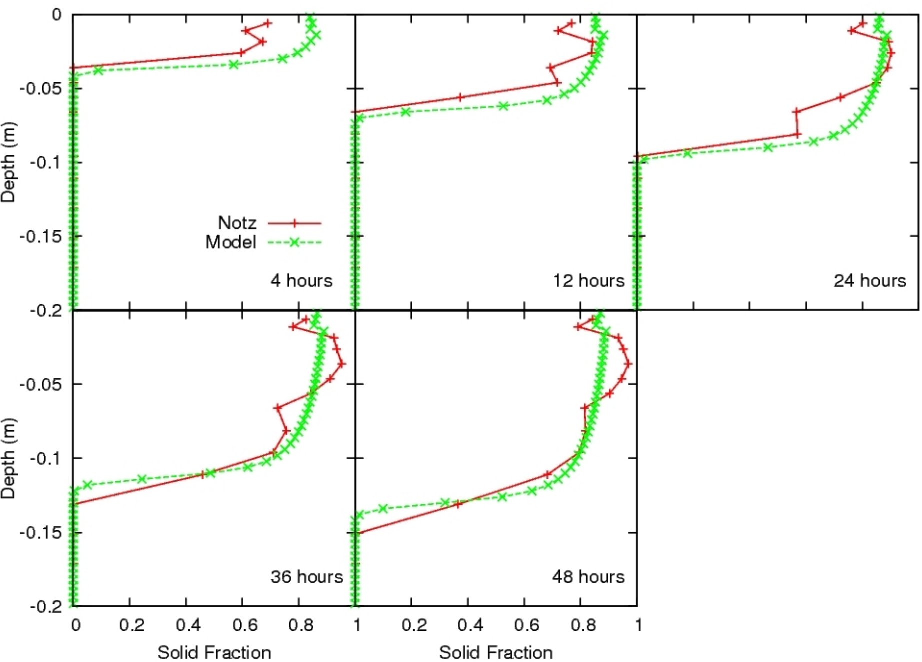
Two column flow model - II



- Flow develops after a while – upward flow in one column, downward in the other
- Salt rejected by the ice

Two column flow model - II

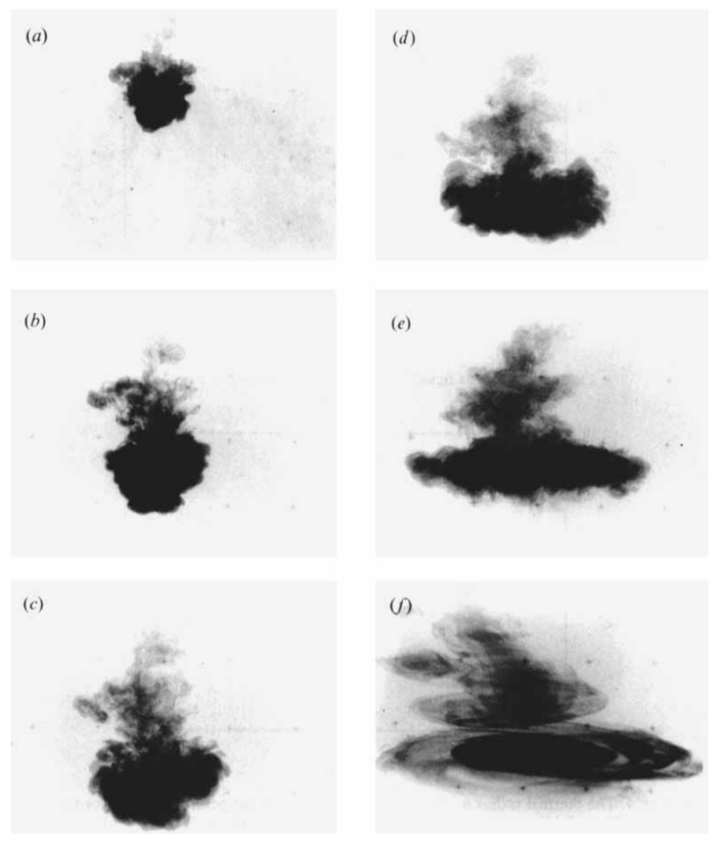




- No build up of salt near interface
- Too much drainage at surface
- Too much initial drainage and insufficient at later times near the surface
- Too sharp an interface near base of ice
- Interface instability on downward flow side

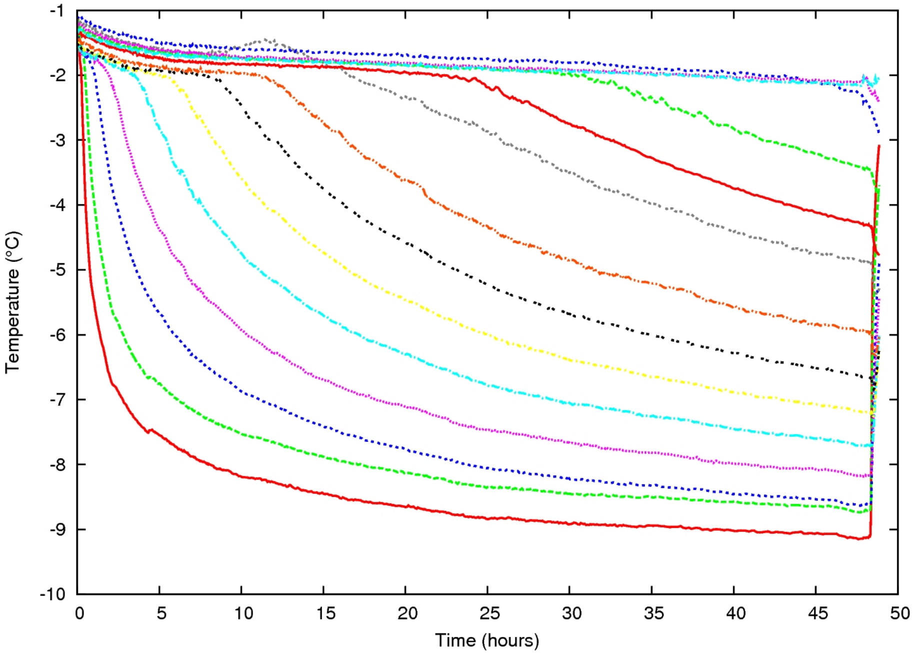
Salt transport in the ocean

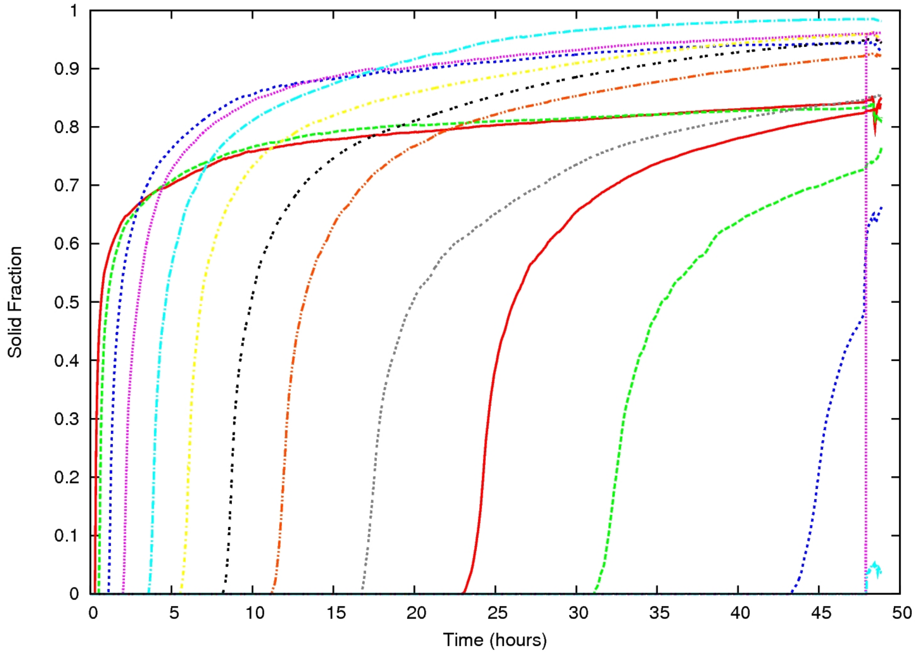
- For comparisons with tank experiment will need some mixing parameterization
- For field comparisons with real field observations of the ocean will have to decide parameterization – turbulent model (e.g. that of McPhee), salt plume model (e.g. Nguyen et al. 2009) or perfectly mixed layer
- Also issue of how to couple to ocean in GCM

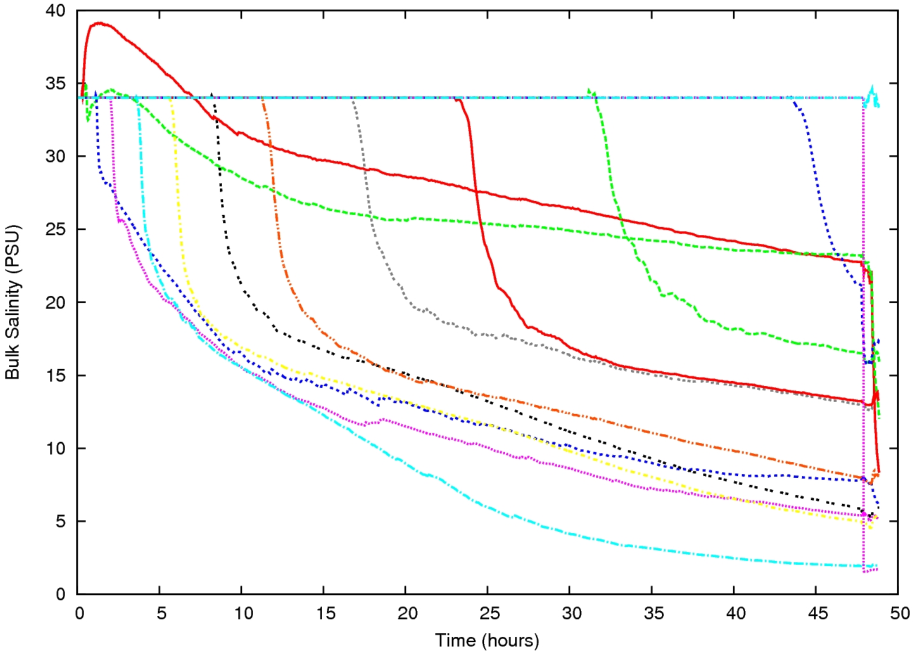


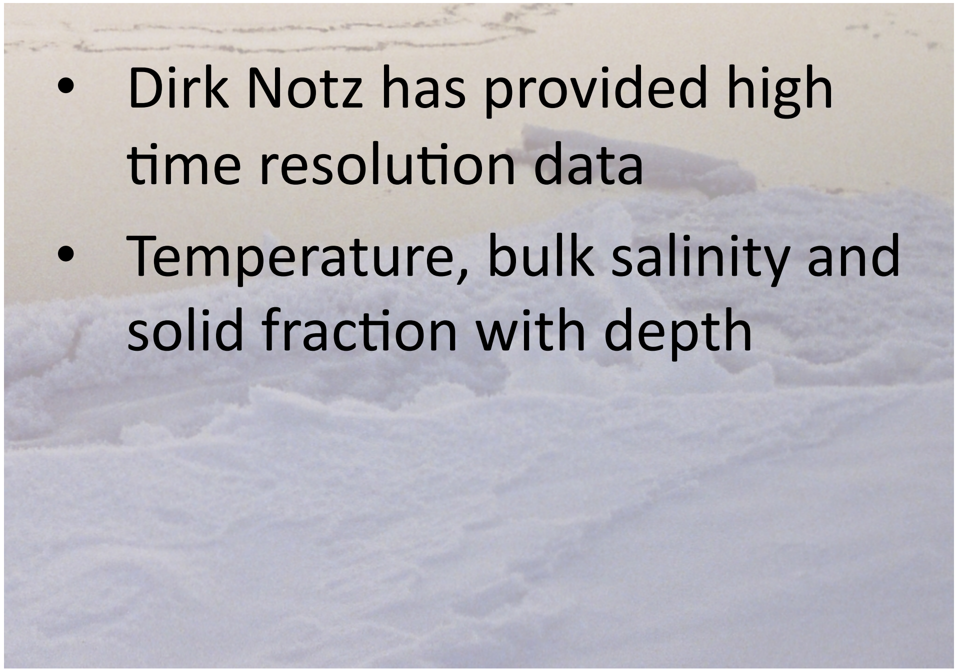
Helfrich (1994)

High time resolution data I



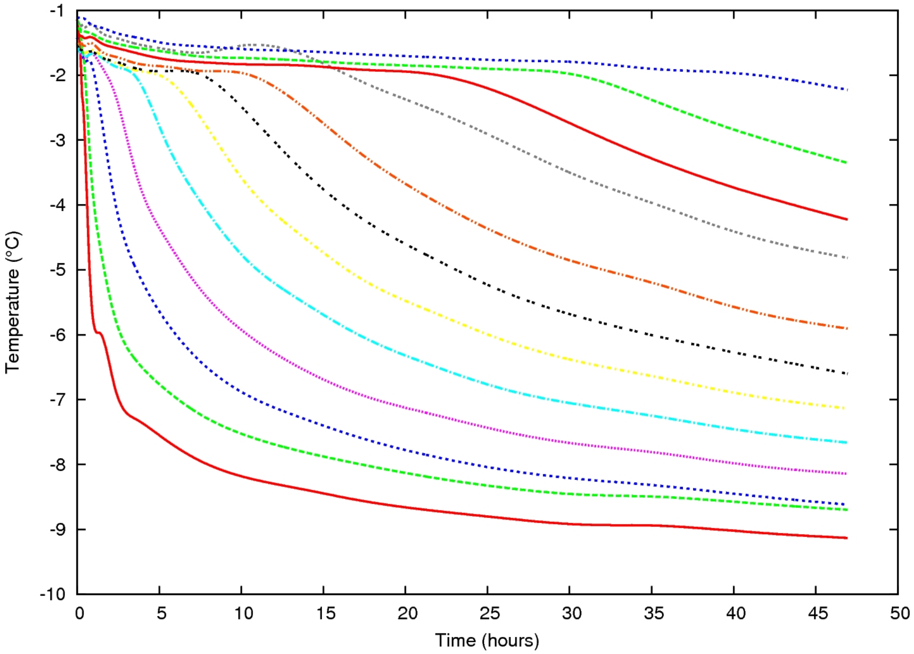


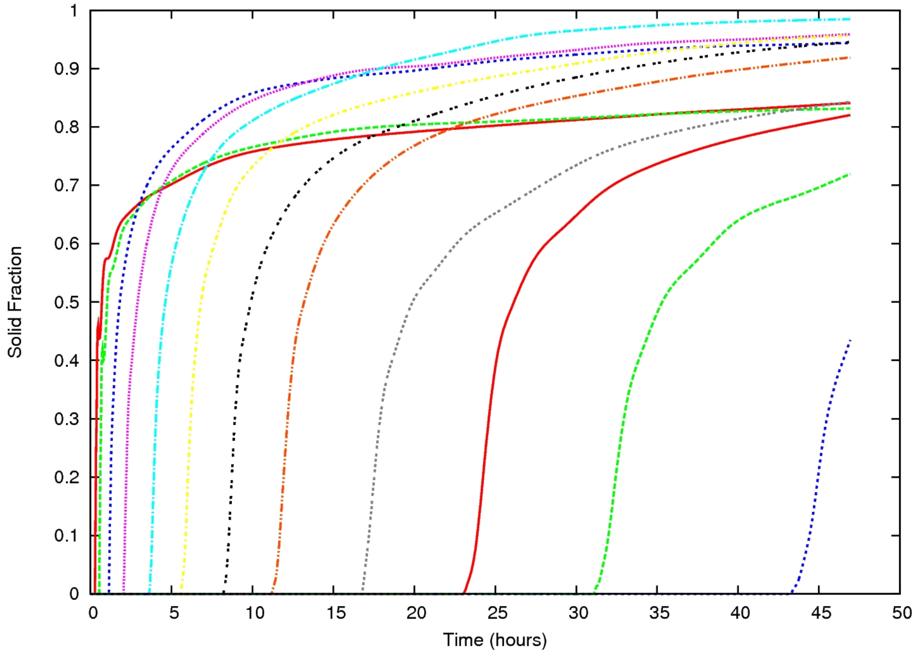


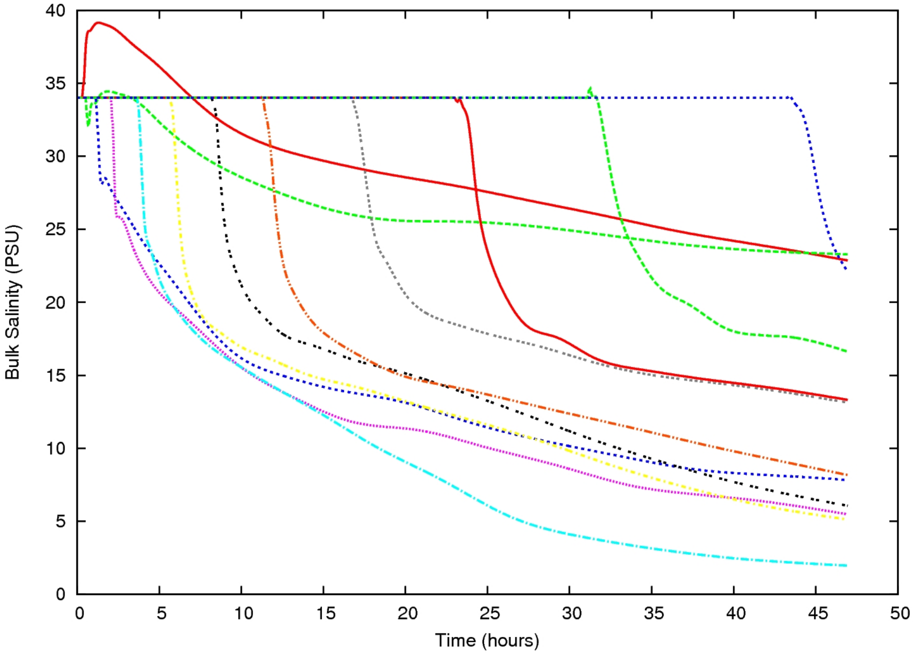


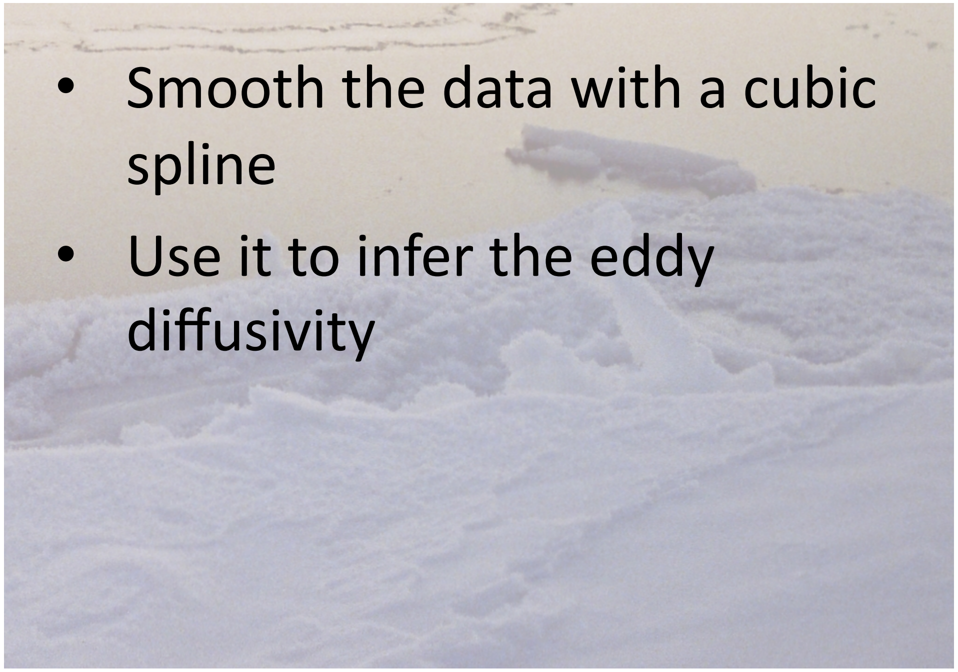
- Dirk Notz has provided high time resolution data
- Temperature, bulk salinity and solid fraction with depth

High time resolution data II

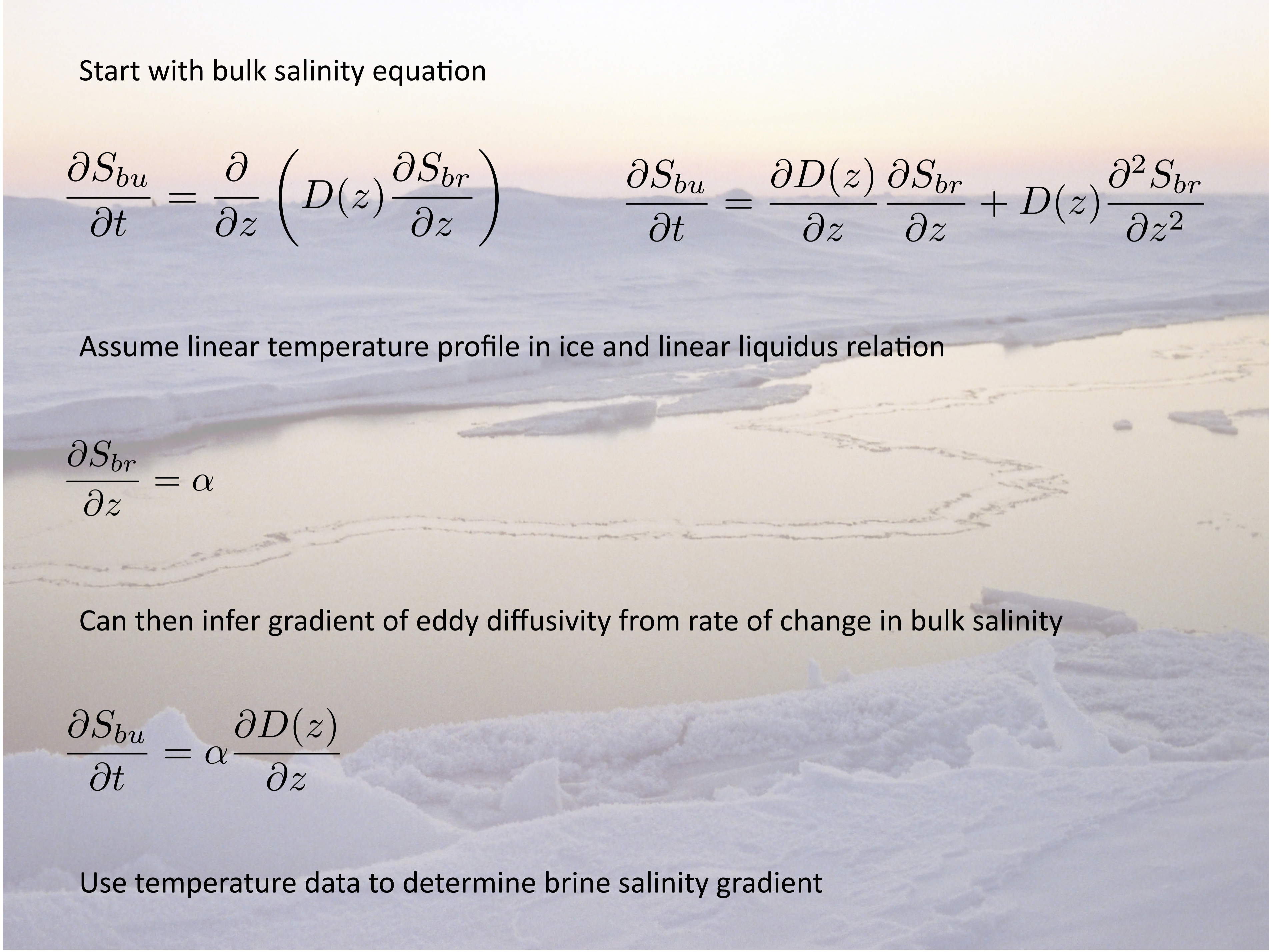








- Smooth the data with a cubic spline
- Use it to infer the eddy diffusivity



Start with bulk salinity equation

$$\frac{\partial S_{bu}}{\partial t} = \frac{\partial}{\partial z}\left(D(z)\frac{\partial S_{br}}{\partial z}\right)$$

$$\frac{\partial S_{bu}}{\partial t} = \frac{\partial D(z)}{\partial z}\frac{\partial S_{br}}{\partial z} + D(z)\frac{\partial^2 S_{br}}{\partial z^2}$$

Assume linear temperature profile in ice and linear liquidus relation

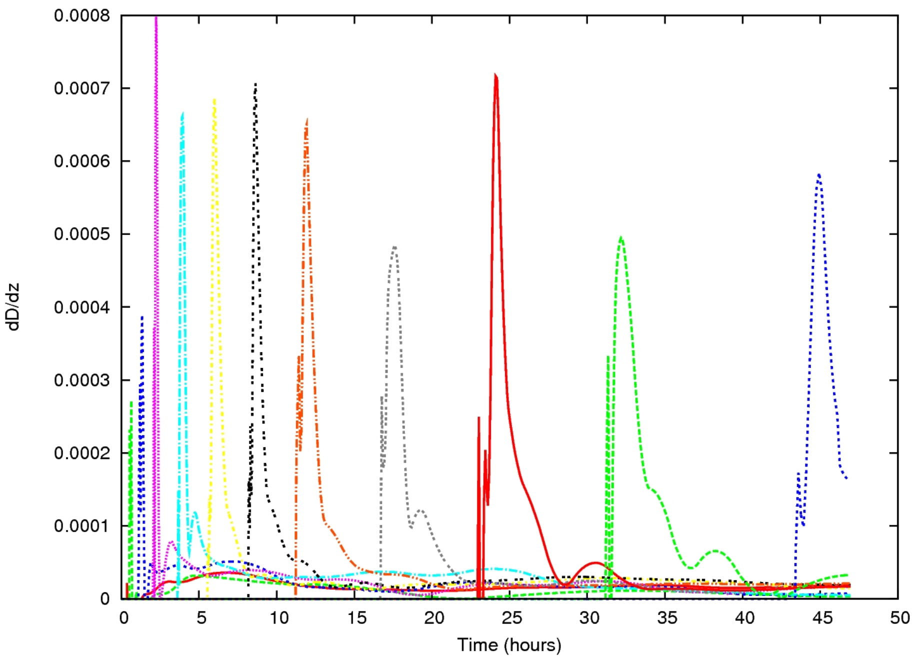
$$\frac{\partial S_{br}}{\partial z} = \alpha$$

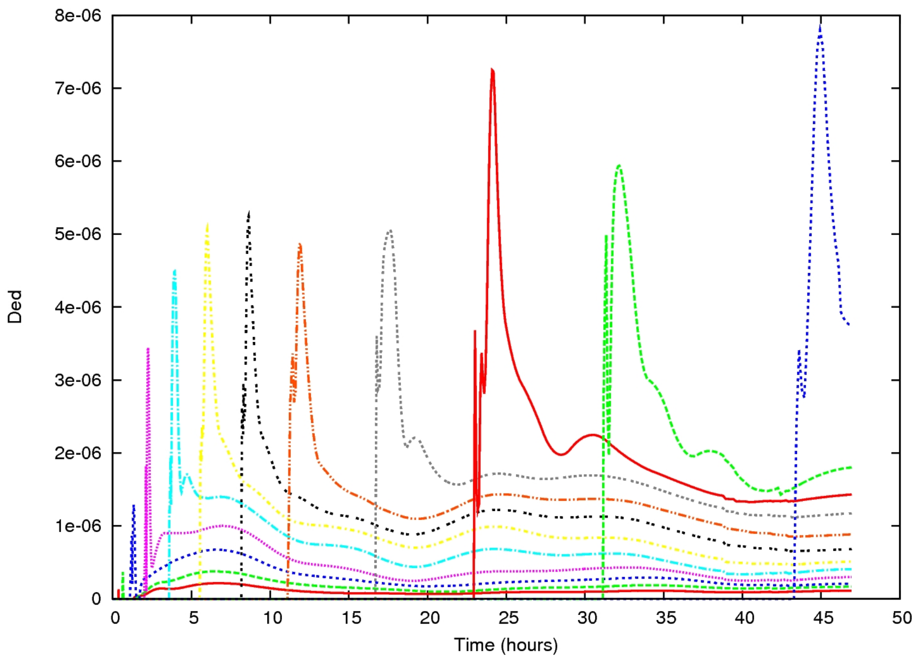
Can then infer gradient of eddy diffusivity from rate of change in bulk salinity

$$\frac{\partial S_{bu}}{\partial t} = \alpha\frac{\partial D(z)}{\partial z}$$

Use temperature data to determine brine salinity gradient

Eddy Diffusivity





- As ice passes a point have strong eddy diffusivity initially
- Then surprisingly constant lower level diffusivity -> due to continued desalination at later times of all layers
- Will now compare this diffusivity to possible ones to use in the model

Numerics

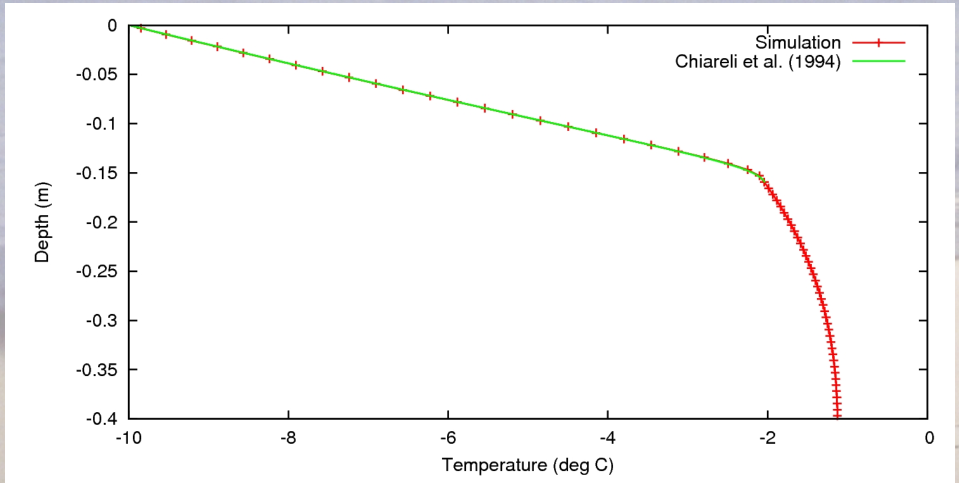
- Need to solve system of non-linear coupled equations
- Currently developing two solvers:
  - Rosenbrock Runge-Kutta – explicit method with Jacobian calculated numerically and adaptive stepsize (results shown here)
  - Jacobian-free Newton Krylov – implicit method widely used for non-symmetric non-linear systems (needs work on preconditioning – working with Dana Knoll (at LANL))

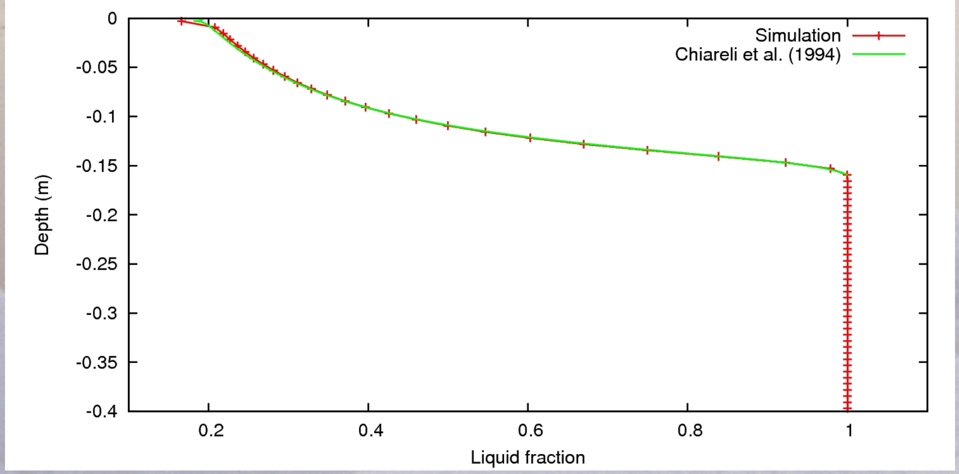
High resolution 2D simulations

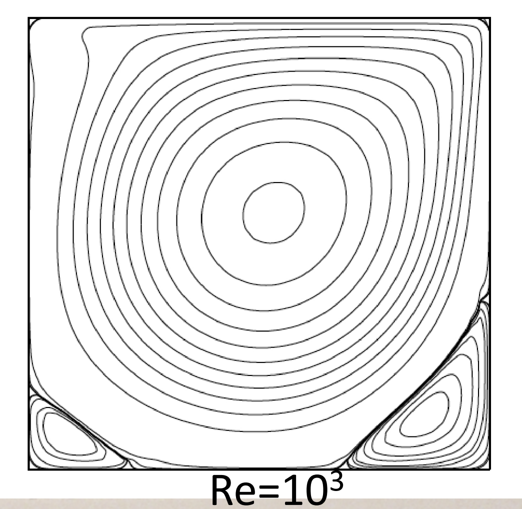
- Develop 2D CFD code to simulate convective overturning occurring during growing sea ice
- Use results to guide simple 1D parameterizations
- Heavily based on work of Chris Petrich (IARC)
- SIMPLE/SIMPLER (Patankar 1980) for flow solver
- Temperature/brine salinity/liquid fraction as thermodynamic variables
- Assumes thermal equilibrium (mush is on Liquidus curve)
- Uses a multigrid technique to solve discretised equations

High resolution 2D simulations - II

- Results so far – Non-flowing mush and forced cavity

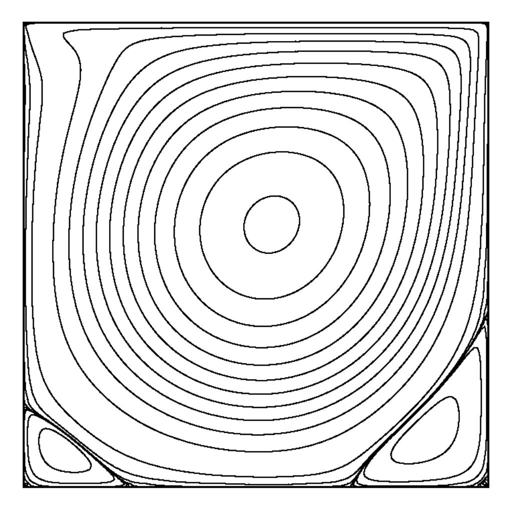






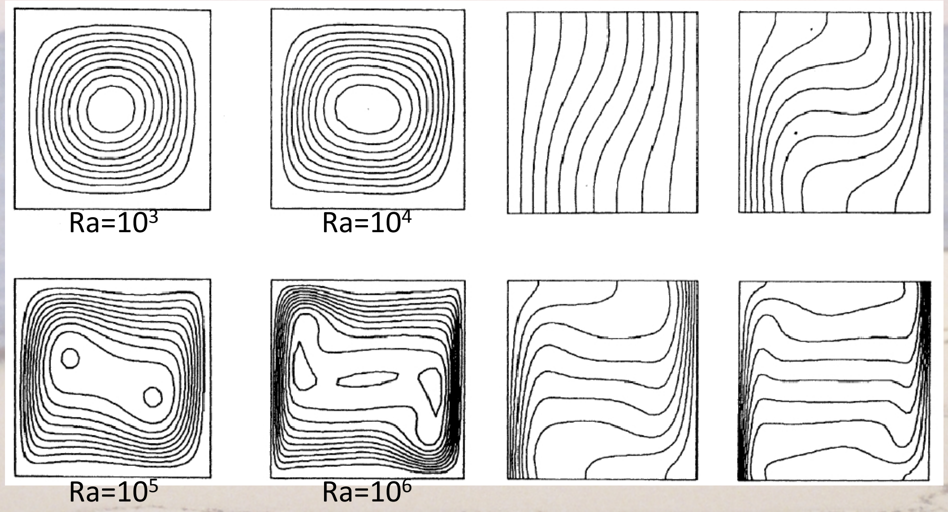
Re=10^3

Norris (2001)



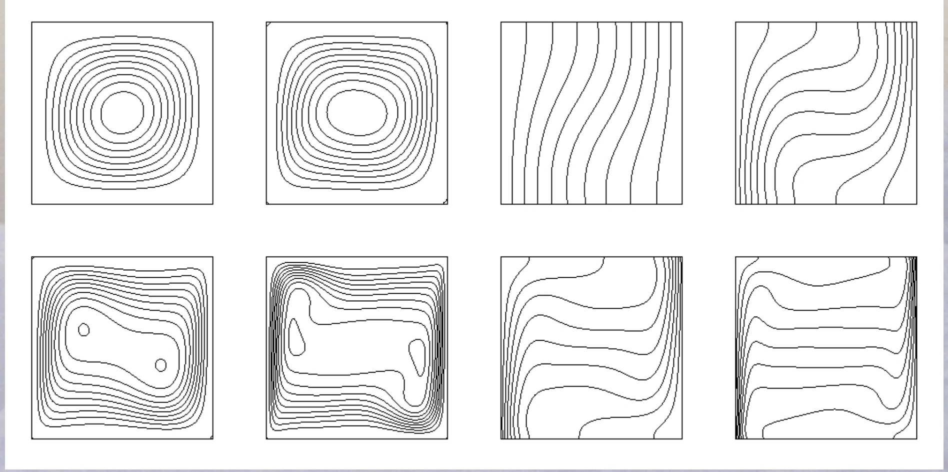
High resolution 2D simulations - III

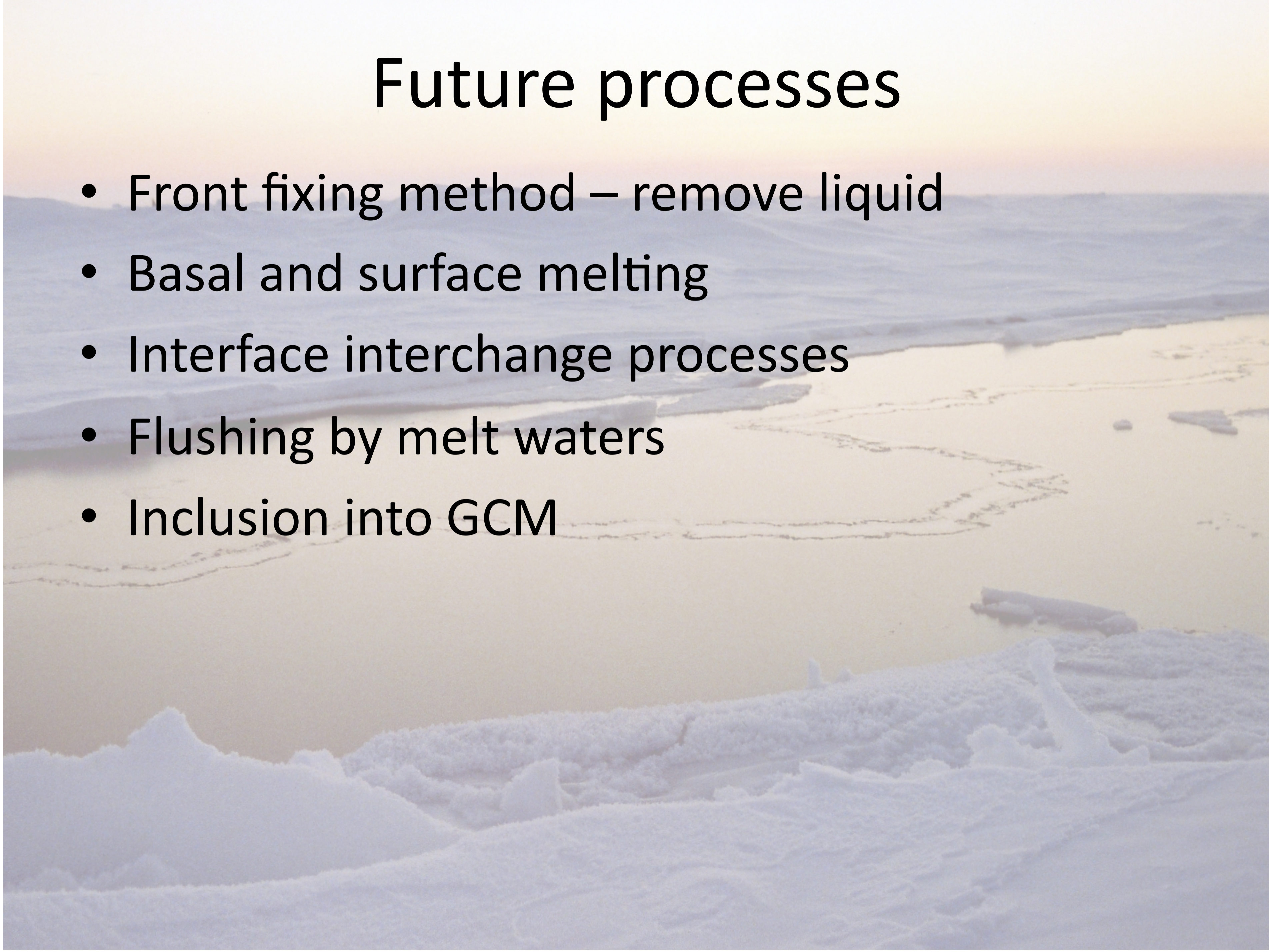
- Results so far – Natural convection in a cavity



De Vahl Davis (1983)

Stream function Temperature





Future processes

- Front fixing method – remove liquid
- Basal and surface melting
- Interface interchange processes
- Flushing by melt waters
- Inclusion into GCM