Modeling microphysics and salinity evolution of sea ice

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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
- Ultimate aim is to model sea ice biogeochemistry and the flow of nutrients necessary for life

The mushy layer

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

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

- 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

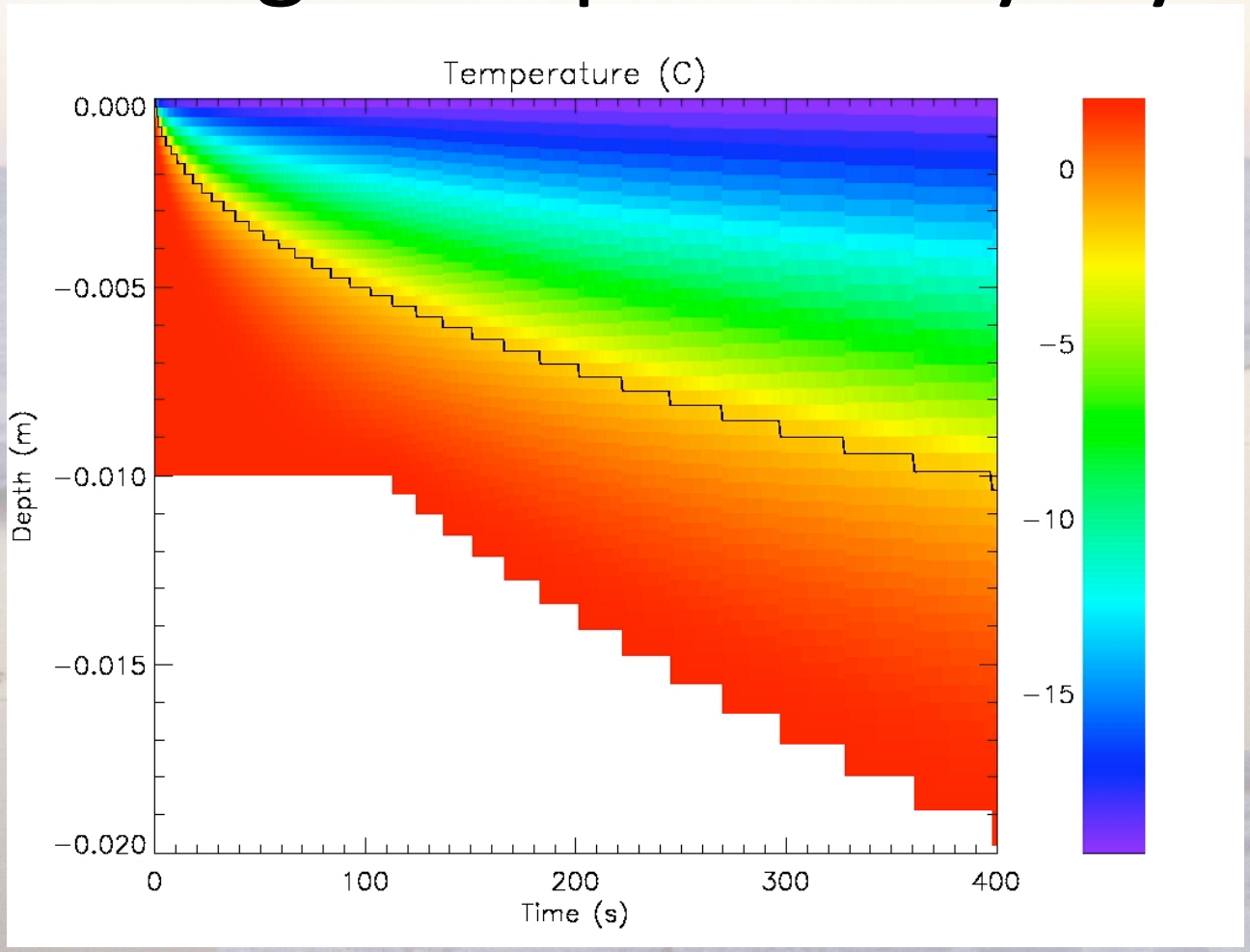
$$S_{br} = S_{liquidus}(T)$$

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

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

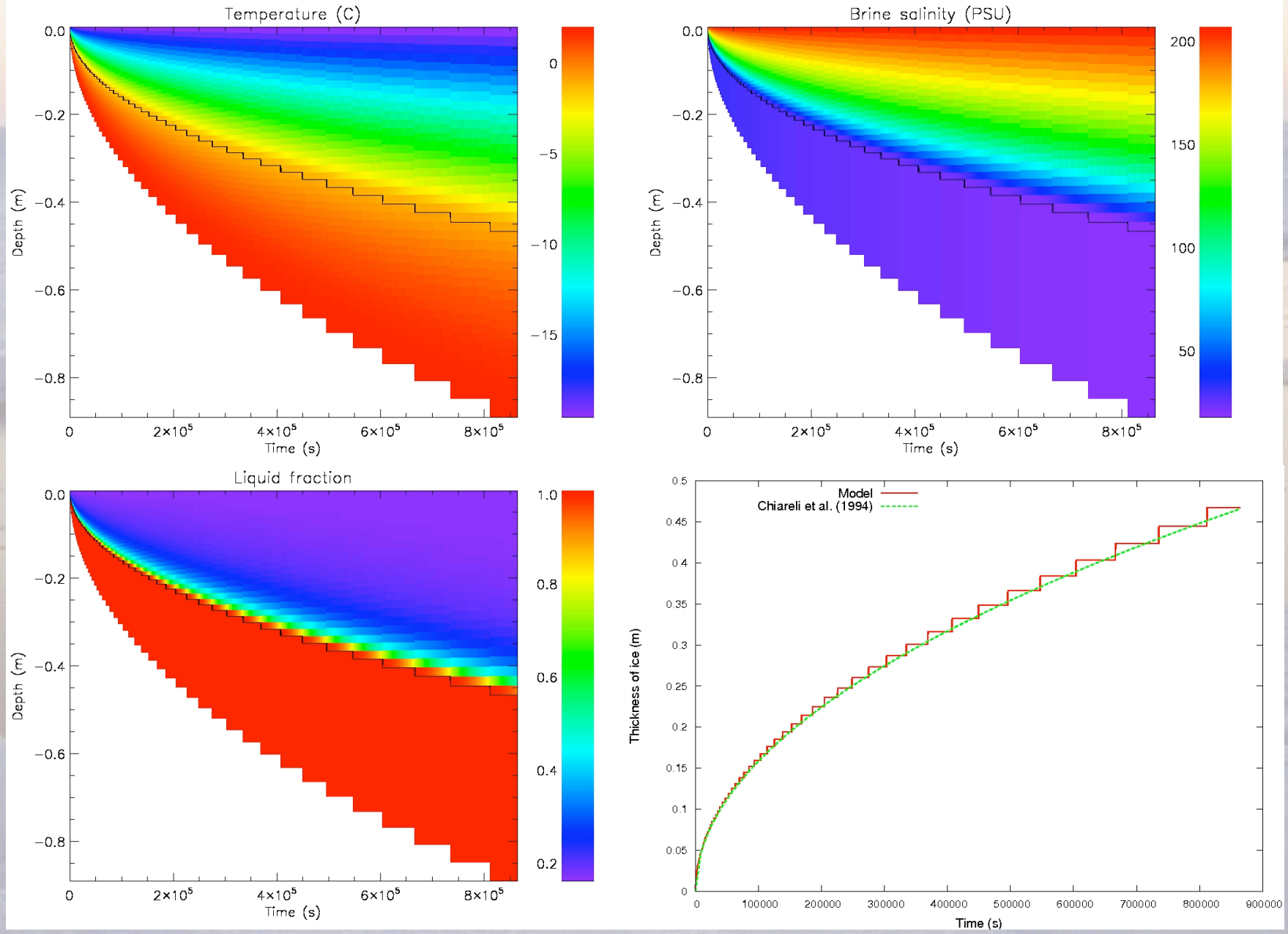
- Solve equations with control volume formulation

Growing a simple mushy layer

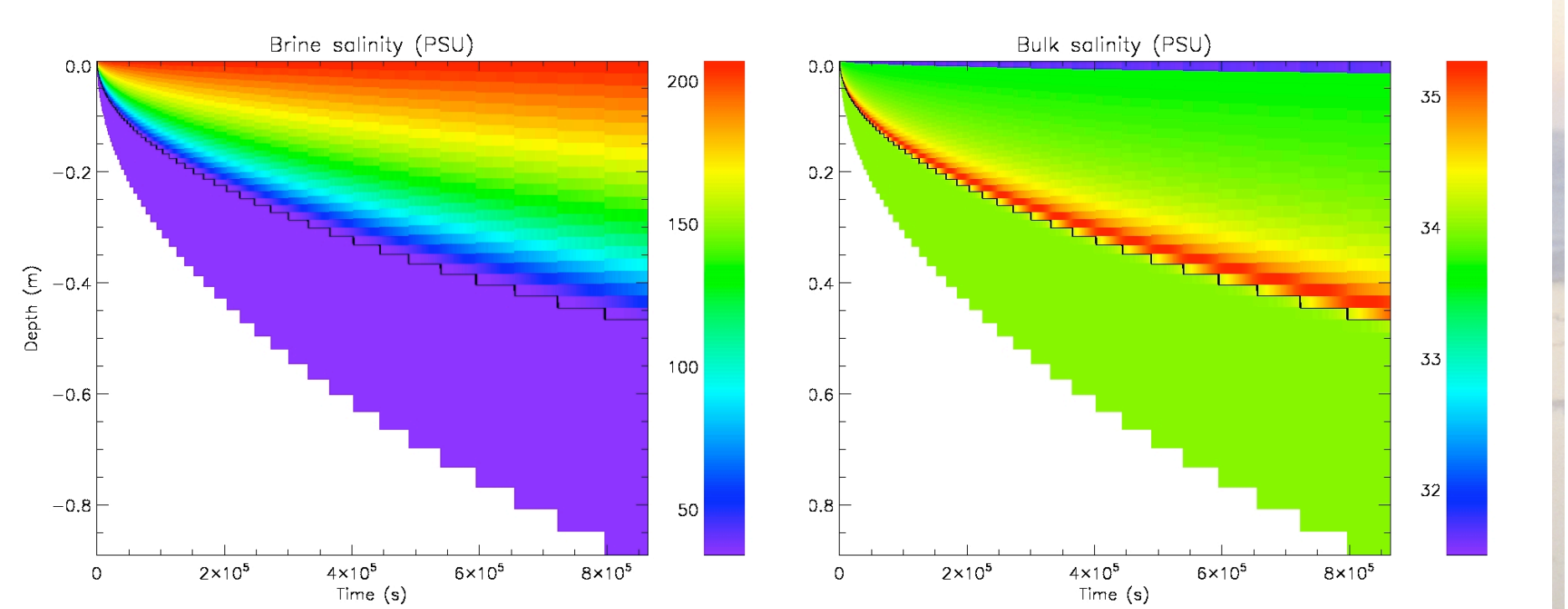


- 1cm of 2°C, 34 PSU salt water cooled from above at -20°C for 10 days
- Fixed domain including both pure liquid and mush which is periodically regrided to allow for growing ice interface
- No salt transport processes

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

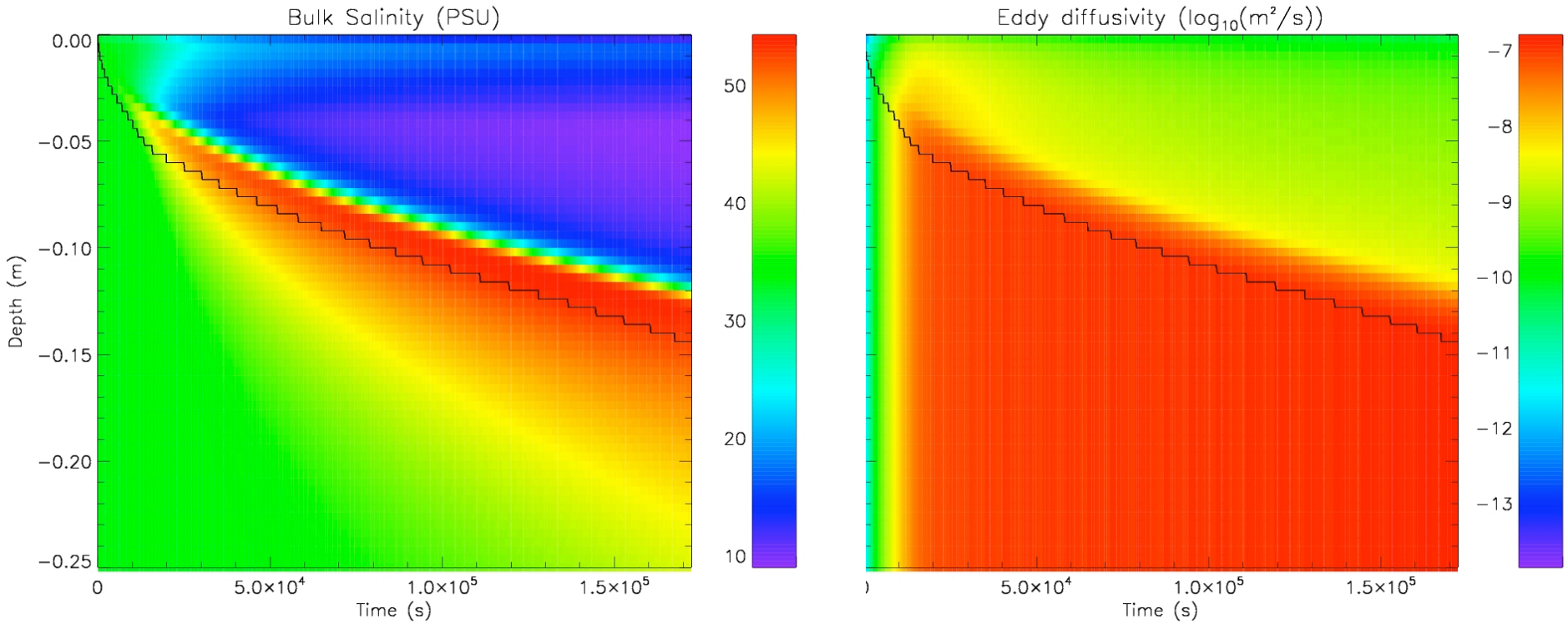
An Eddy diffusion parameterization for Convection

- 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 prep*)

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

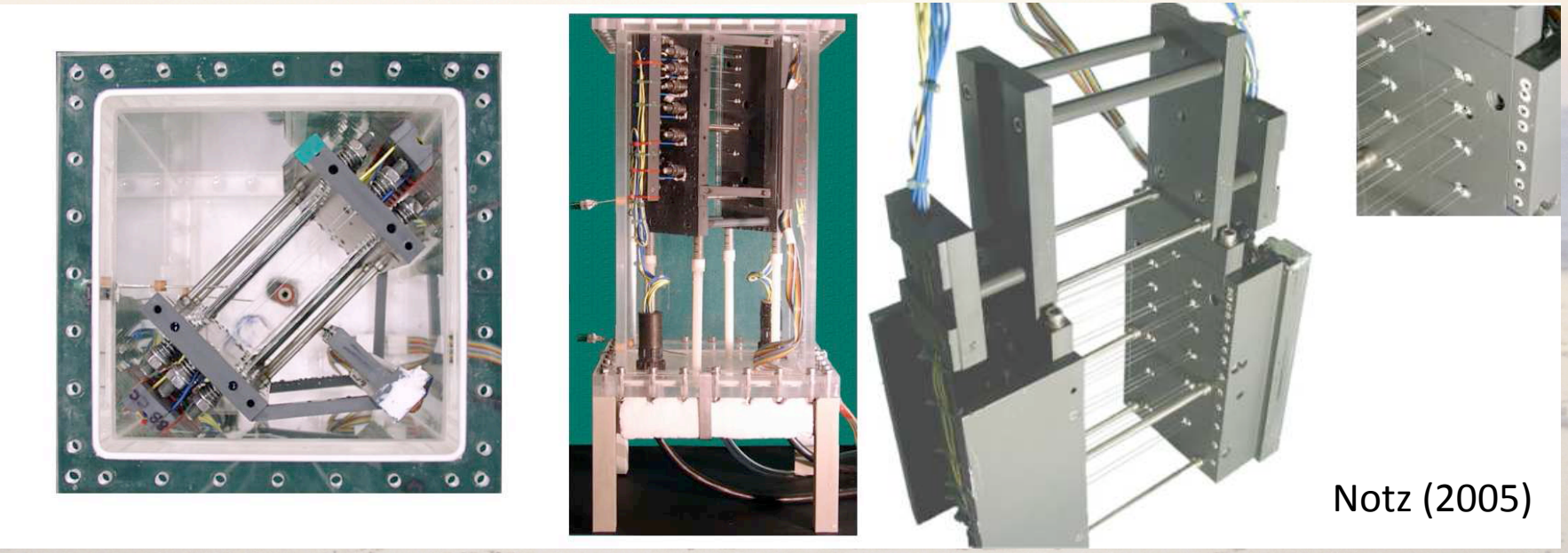
- Various choices of D_{ed} – begin with Nicole's.

Preliminary results



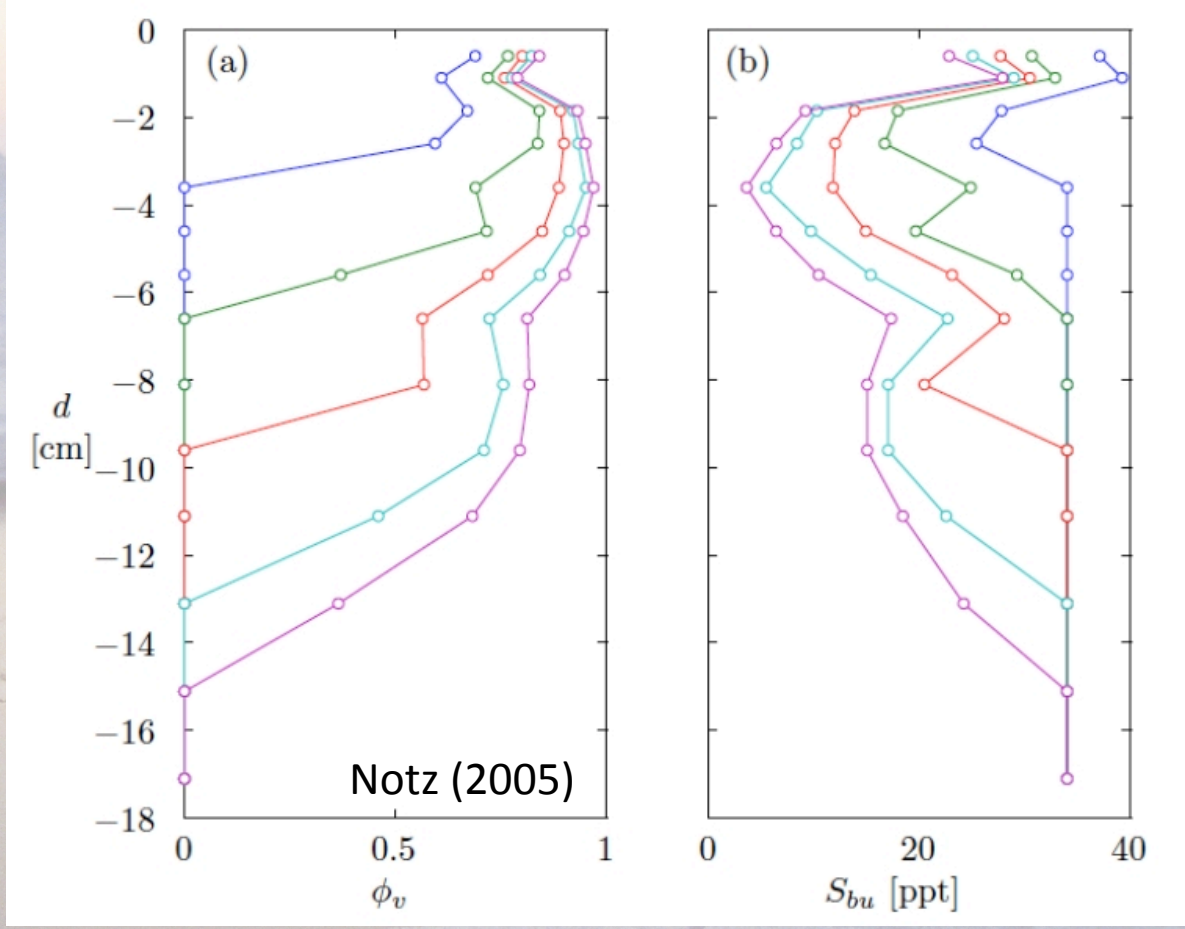
- Fixed domain
- Switch on drainage when ice thickness reaches 5cm
- Get “C” shaped profile but salt buildup near interface

Experimental Results of Convection



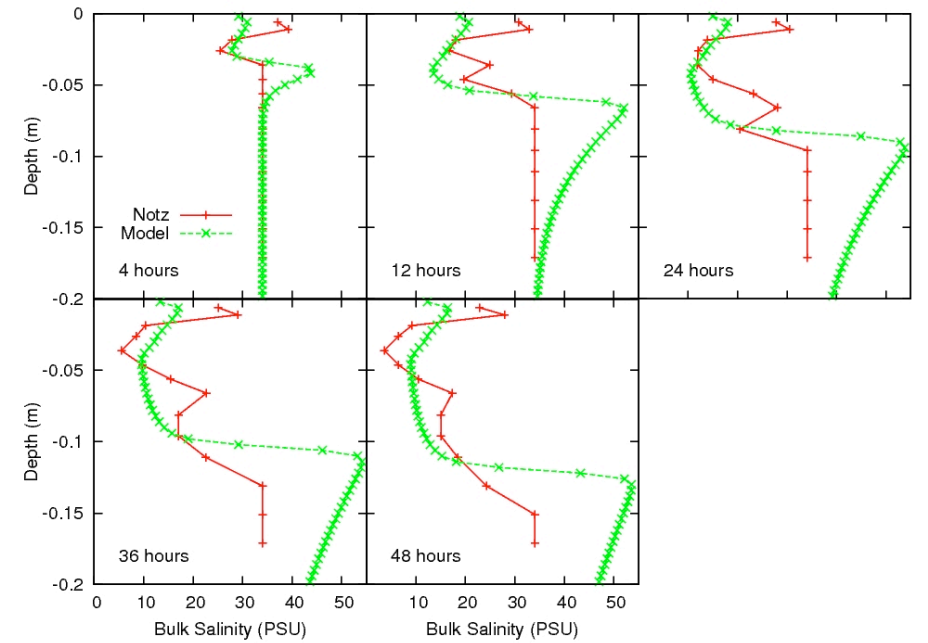
- Desalination experiments of Dirk Notz (2005) measured bulk salinity, temperature and solid fraction during ice growth
- 40×20×20cm Perspex tank with custom instrumentation
- Impedance measured between Platinum wires, temperature by thermisters.
- Solid fraction determined from wires. Bulk salinity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

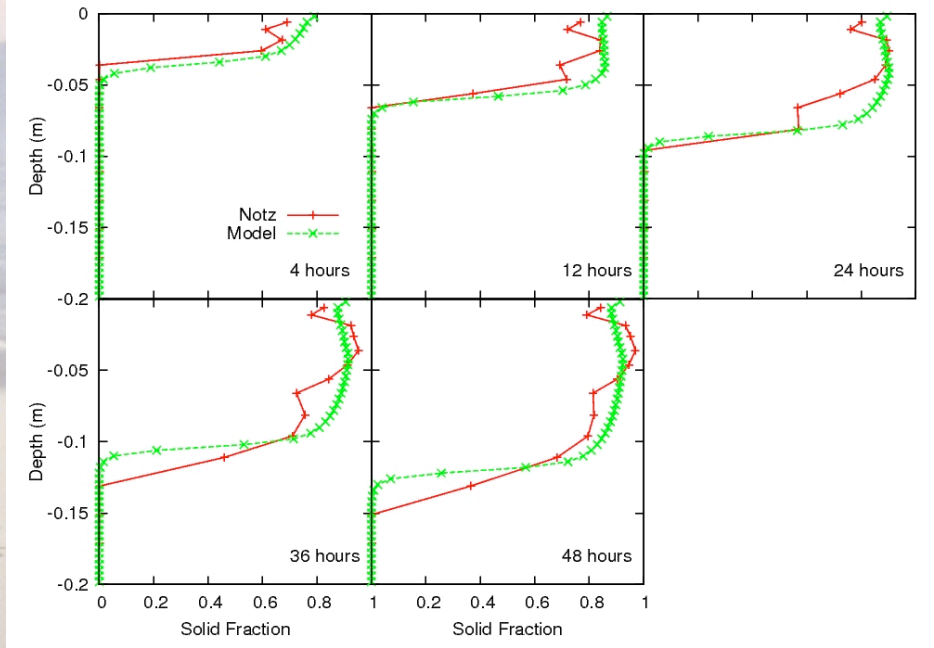
Experimental Results



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

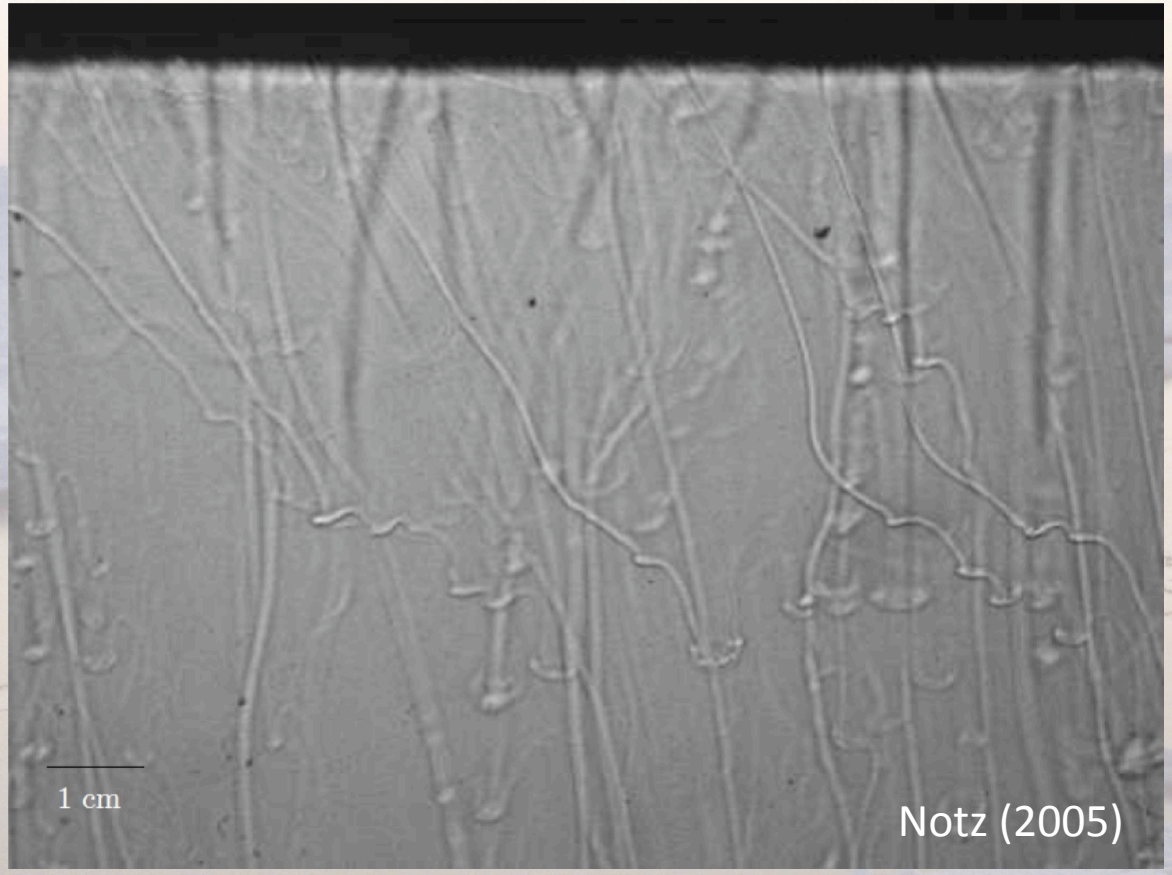
Eddy diffusion vs. Experiment





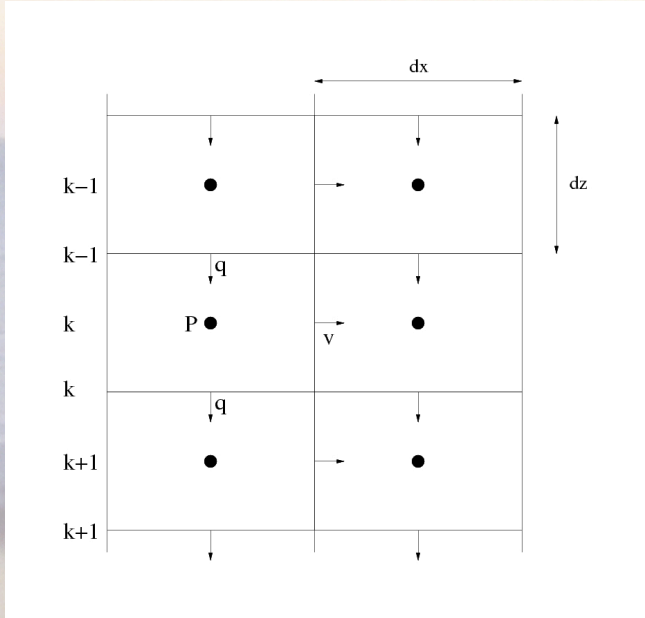
- Too much drainage in model at surface
- Salt is trapped near interface with liquid
- Insufficient drainage at later times near surface

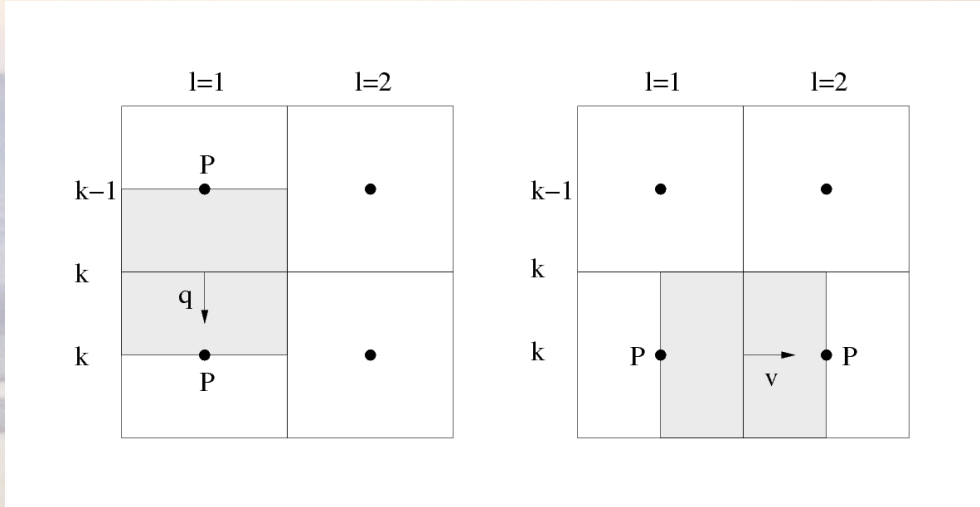
Flow in the liquid



- 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

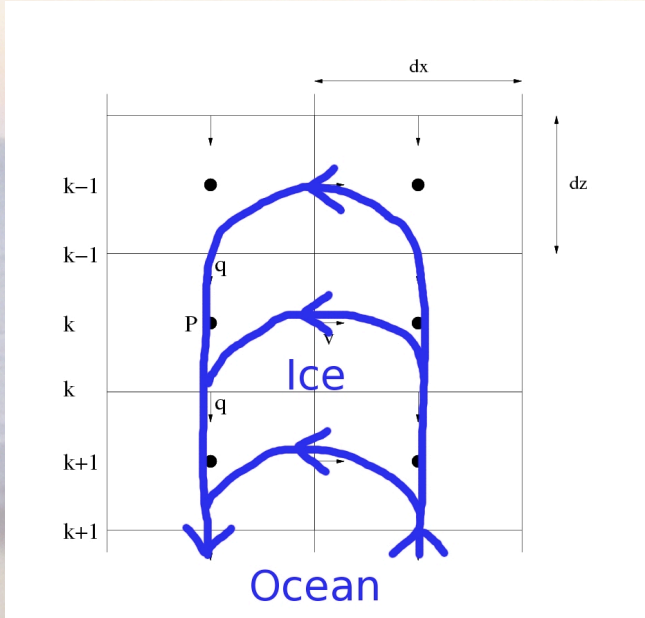
Two column flow model - I

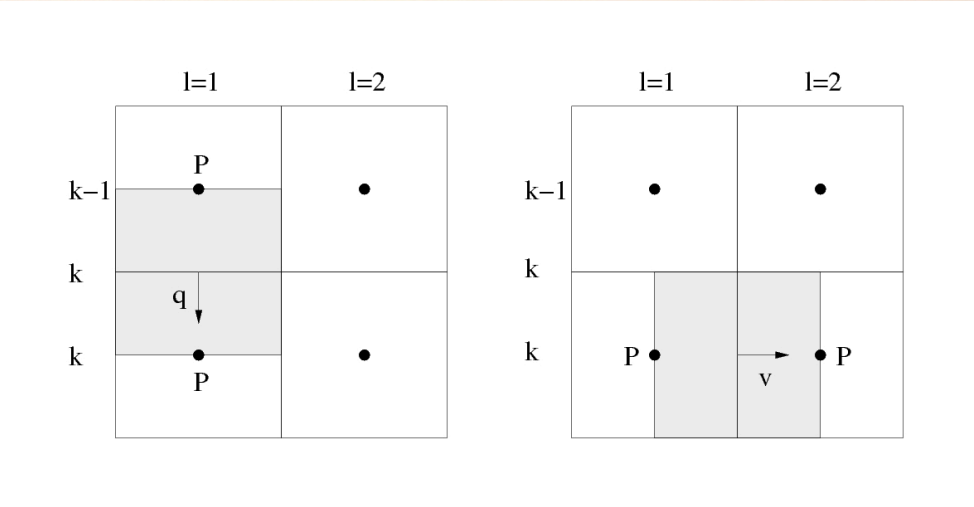




- Can also model explicit flow of brine around ice
- Simplest method is using a two column model with Darcy flow between grid cells
- Calculate pressures and fluid flows from Darcy equation and conservation of volume

Two column flow model - I





- Can also model explicit flow of brine around ice
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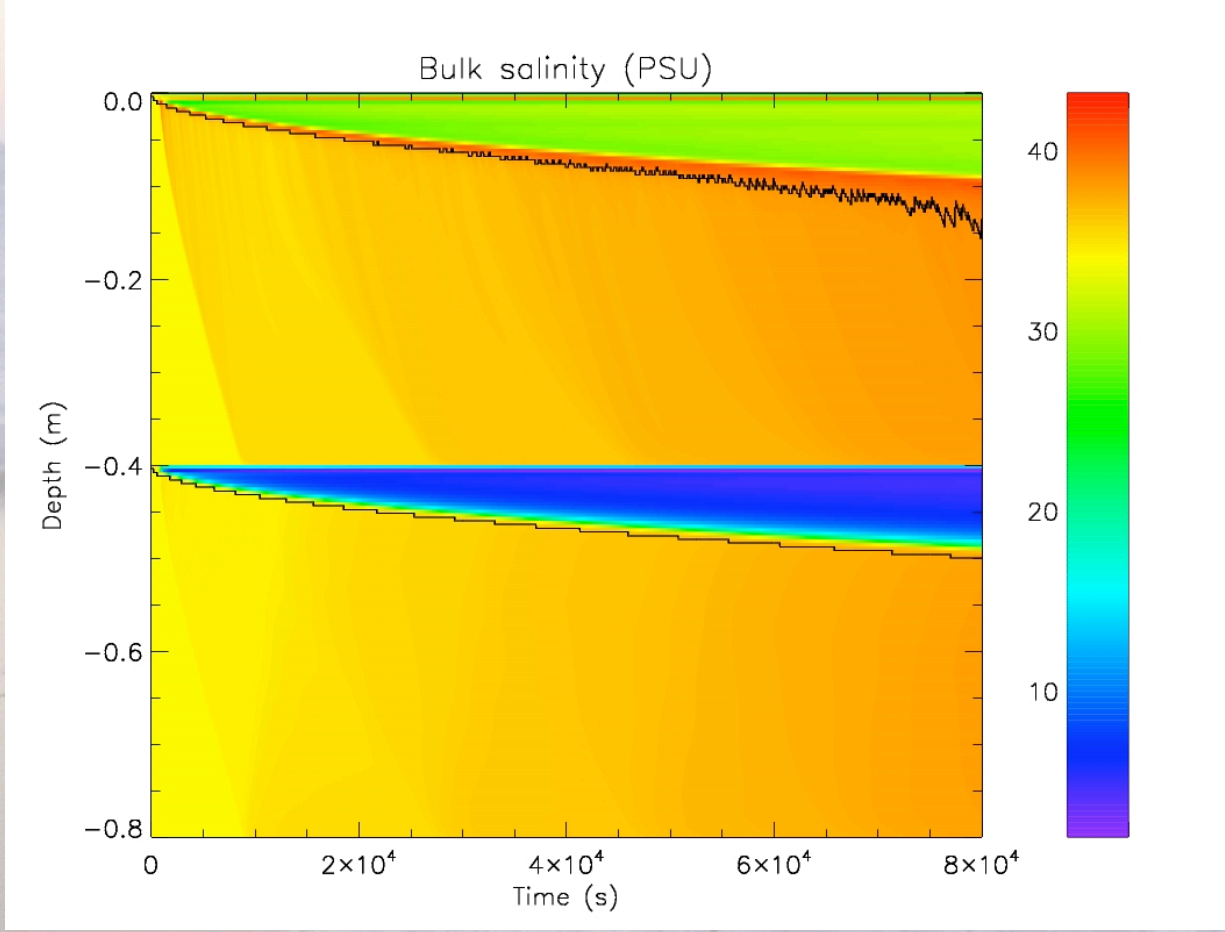
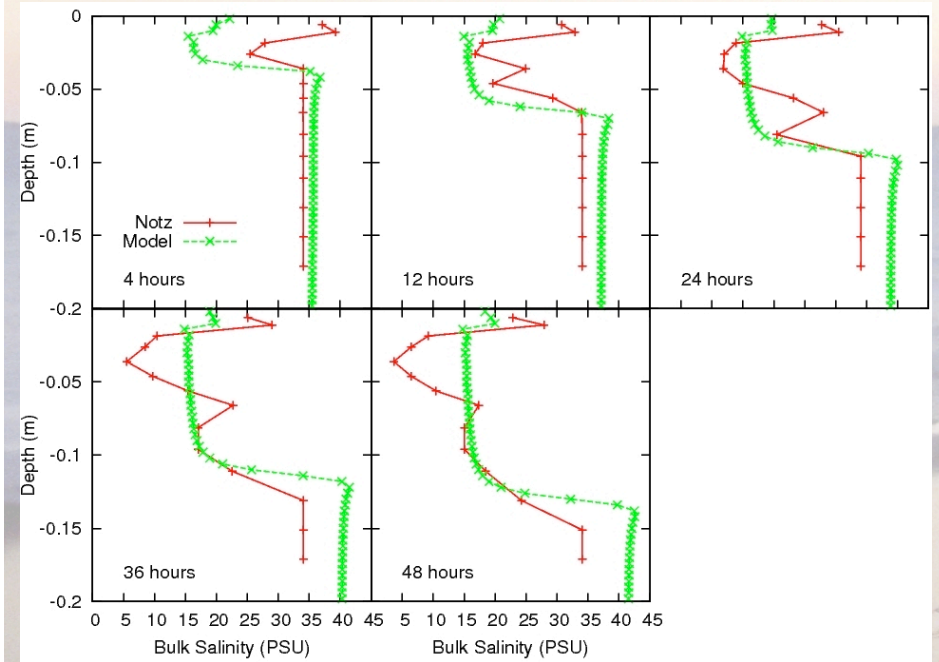
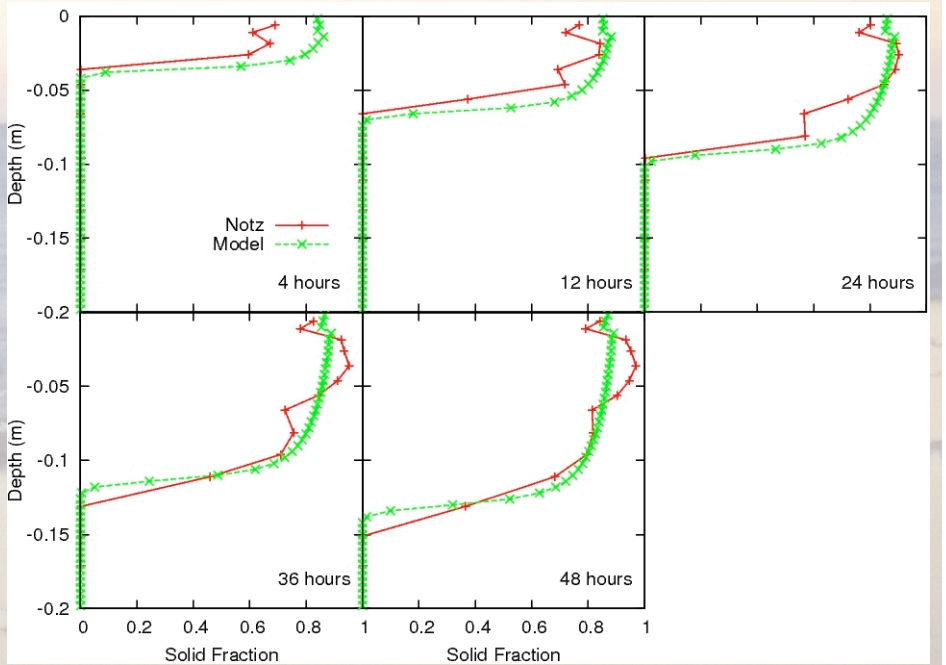
Two column flow model - II



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

Two column flow model - II



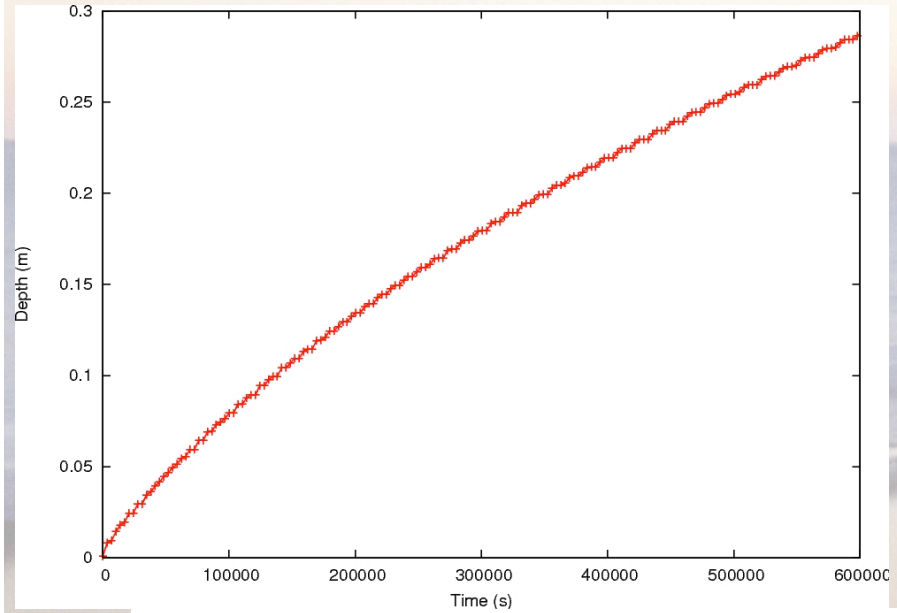


- No build up of salt near interface
- Too much drainage at surface
- Too much initial drainage and insufficient at later times near the surface
- Too sharp an interface near base of ice
- Interface instability on downward flow side

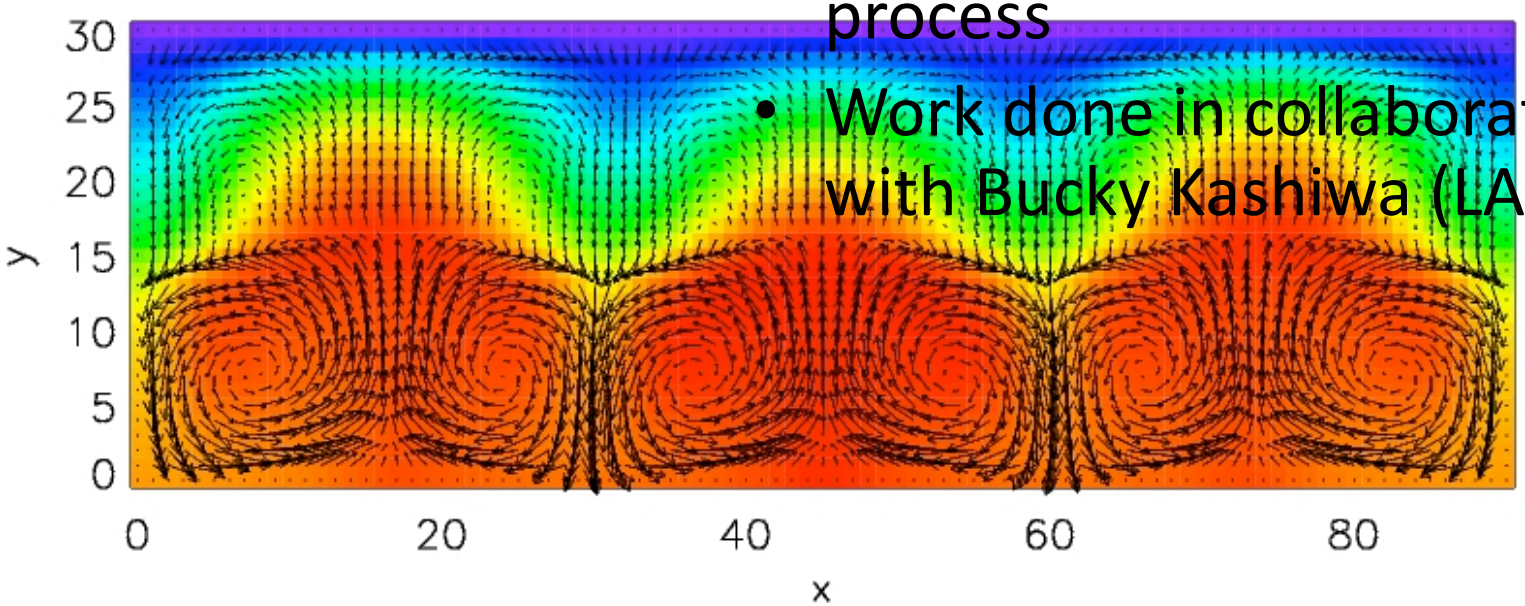
Numerics

- 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 (been developed up to salt diffusion – needs work on preconditioning – working with Dana Knoll)

High resolution 3D simulations



- Use LANL cfdlib to directly simulate convective overturning in growing sea ice.
- Use results to guide simple 1D parameterizations.
- Have added ice formation process
- Work done in collaboration with Bucky Kashiwa (LANL)



Future processes

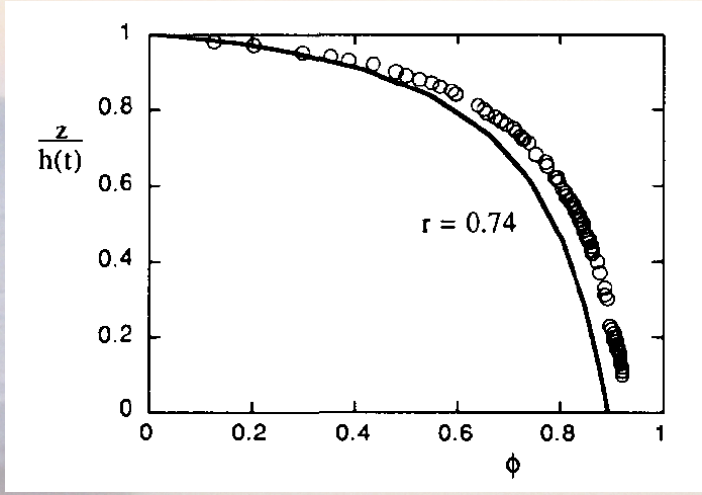
- Basal and surface melting
- Interface interchange processes
- Flushing by melt waters
- Inclusion into GCM

Questions I'd like answering

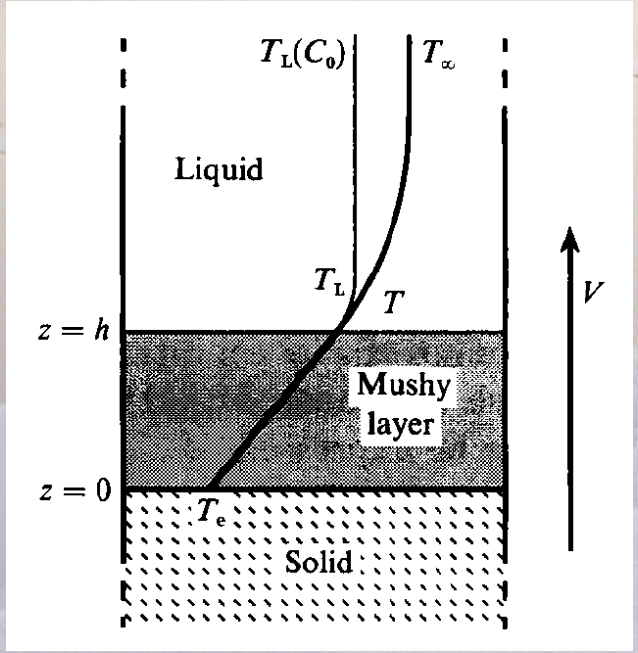
- How do you compute the growth rate of the ice at base when can't apply a Stefan condition?
- What is the appropriate boundary condition at the base of the ice with real life conditions? (i.e. an ocean not a tank)
- Can the permeability be expressed simply as a function of porosity and if so what function?
- When does convection move from symmetric flow to asymmetric (i.e. chimney) flow?
- During convection how inhomogeneous is the bulk salinity horizontally?
- What is the relationship of horizontal and vertical flow strength with position and time during convection?
- What is the best way to model 3D convection in a 1D model?

Basal Interface Condition

Chiareli et al. (1992)



Worster (1991)



- Solid fraction as interface is zero – *Danny's talk* – so can't strictly apply Stefan condition

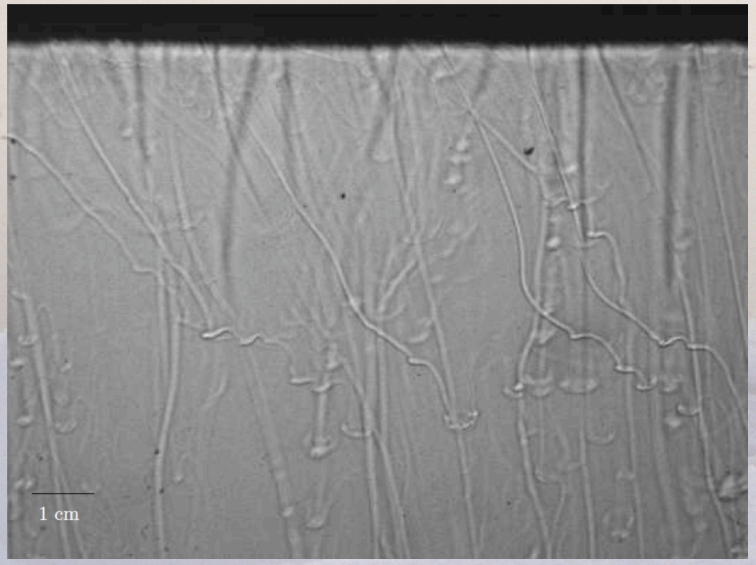
$$\rho L[\phi]\dot{h} = [k\frac{\partial T}{\partial z}] \qquad [\phi] = 0$$

- Interface condition is that of marginal equilibrium
- How do we use a front tracking method with accurate growth rates?

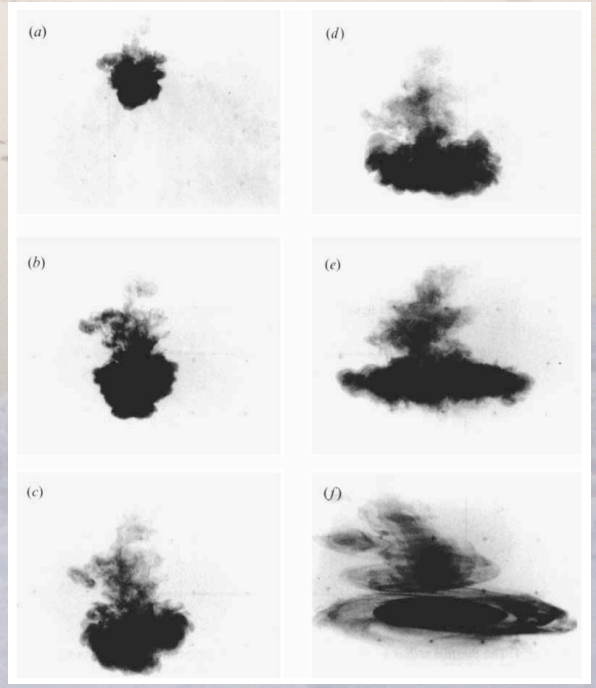
Interface condition with a real ocean

- Is the solid fraction always zero at the interface? Even in a highly mixed, turbulent ocean? Does marginal equilibrium always apply? – *Answered by Danny*?

- How do we parameterize mixing/plume/coupling/turbulent processes in the ocean?



Notz (2005)



Helfrich (1994)

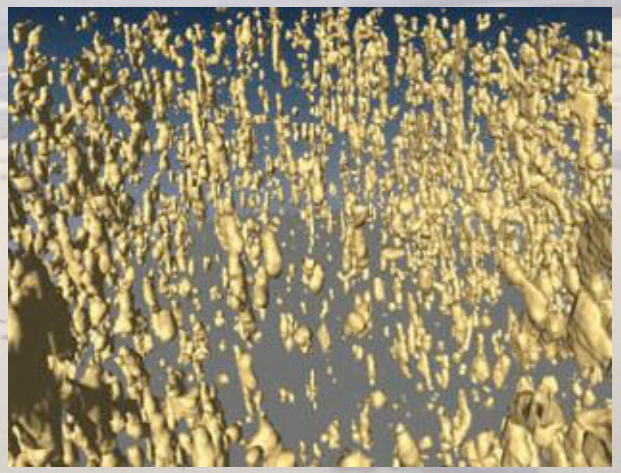
Porosity versus Permeability

- Can permeability be written just as a function of porosity? Different microstructure (e.g. columnar vs granular), growth history etc
- If so what function to use and what parameters?

$$\Pi(\phi) = A(\phi - \phi_C)^B$$

Hierarchical model: B=3, Φ_C=0

Percolation model: B=2, Φ_C=0.05



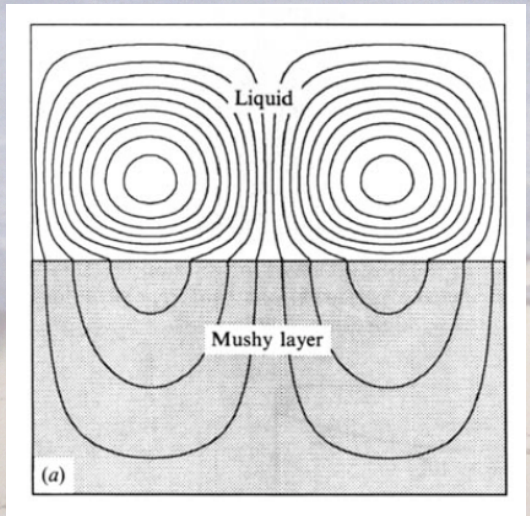
K. M. Golden et al. (2007)

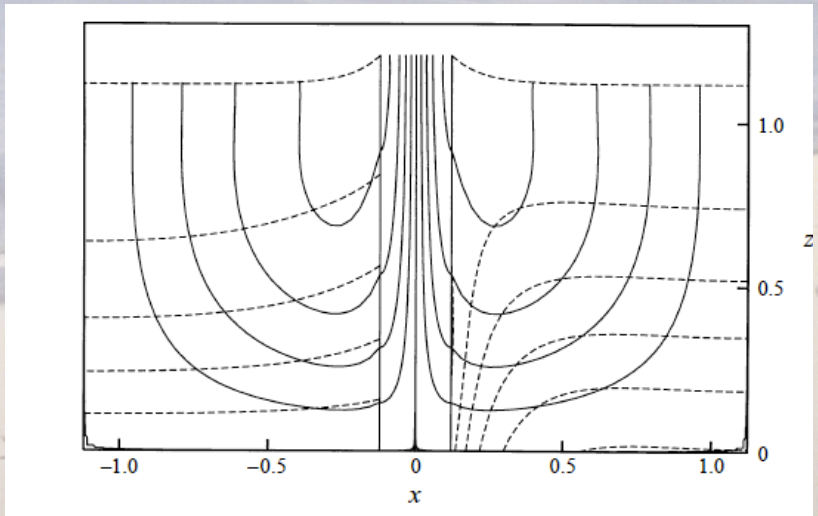
- What uncertainties on A, B and Φ_C? How much can I tune these?
- Is it anisotropic and, if so, by how much? What effect does it have on convection?
- *Ken and Chris discussed this*

Convection

- When does convection move from symmetric flow to asymmetric (i.e. chimney) flow?

Worster (1992)



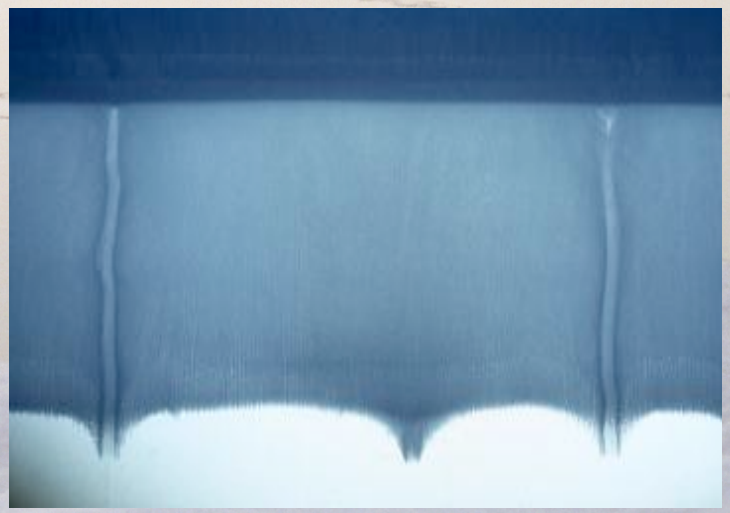


Schulze & Worster (1998)

- How much of the drainage is each responsible for?
- How asymmetric are the two flow directions in early convection? How much does T, Bulk S vary horizontally
- What are the flows/velocities during convection?
- *Chris' simulations showed this?*

(my) $64,000,000 question

- What's the best way to parameterize 3D convection in a 1D model?
  - Diffusion? Advection?



Worster (2000)