Predictability of sea ice salinity and microstructure from crystal growth theory

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Motivation: microstructure and salinity

Saline ice observations: NaCl

Linkage of salinity and microstructure

Morphological Stability

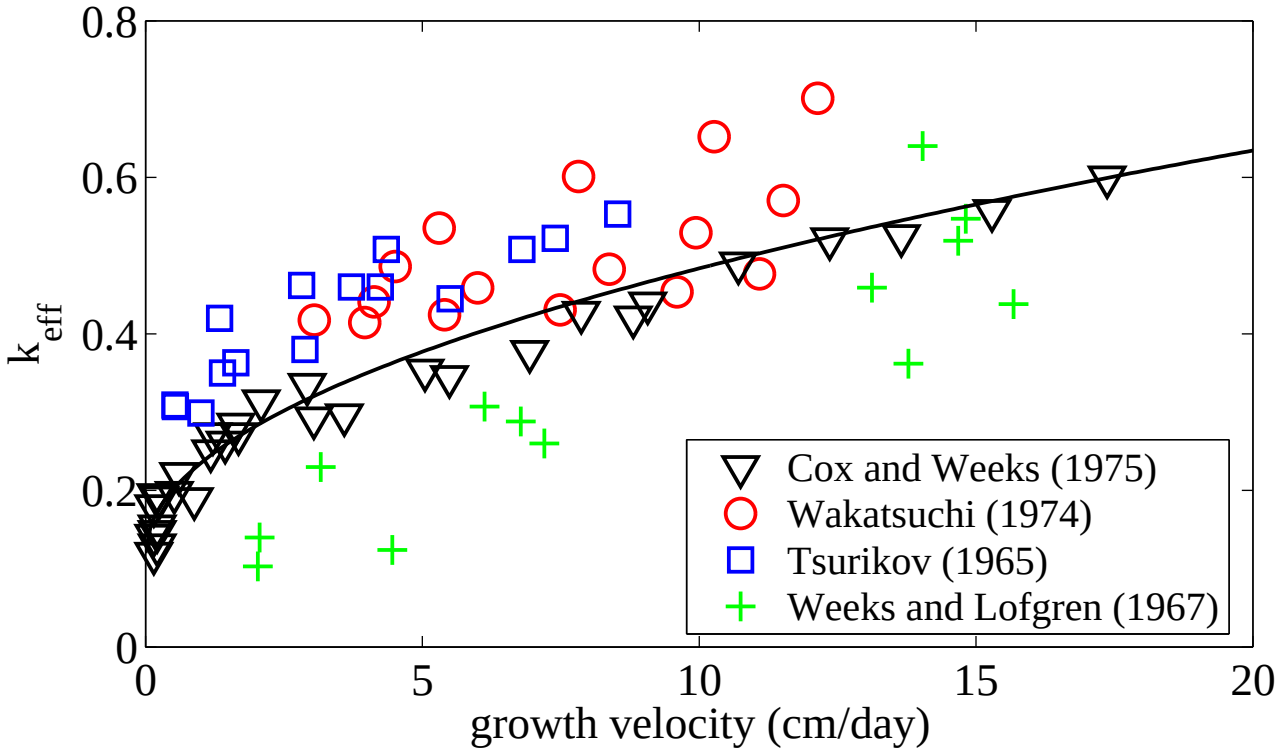
Planar-cellular transition

Cellular plate spacing

Convective scales and salt fluxes

Motivation: Relevance of microstructure

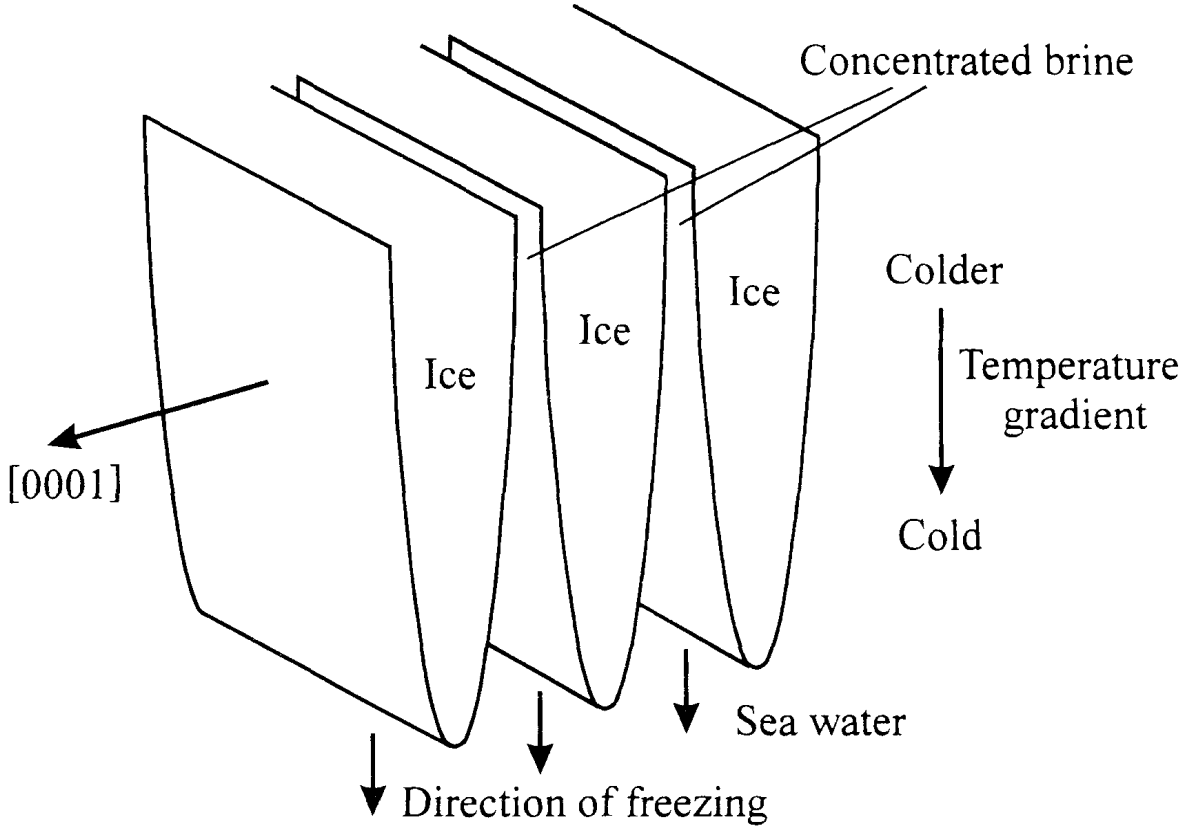
- Biology, chemistry, sea ice ecosystem
- Contamination, oil
- Mechanical properties
- Engineering, platforms, navigation
- Optical properties
- Remote Sensing: Scattering, brine volume
- Geophysics: climate system and sea ice models
  - geophysical ice strength P_* (friction, mechanical properties)
  - salt fluxes in polynyas and leads
  - spring flushing and summer melt, permeability



Initial salinity of thin ice

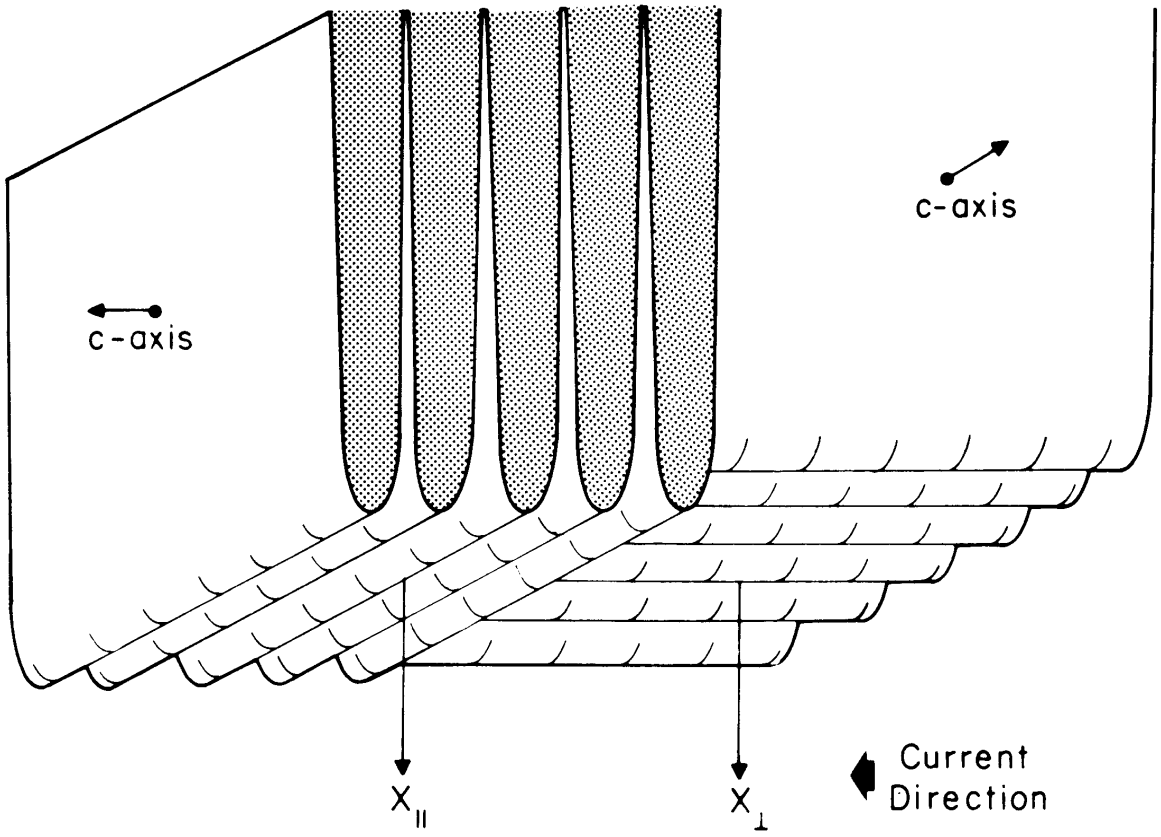
Ratio of seawater to ice salinities:

$$k_{eff} = \frac{S_i}{S_w}$$



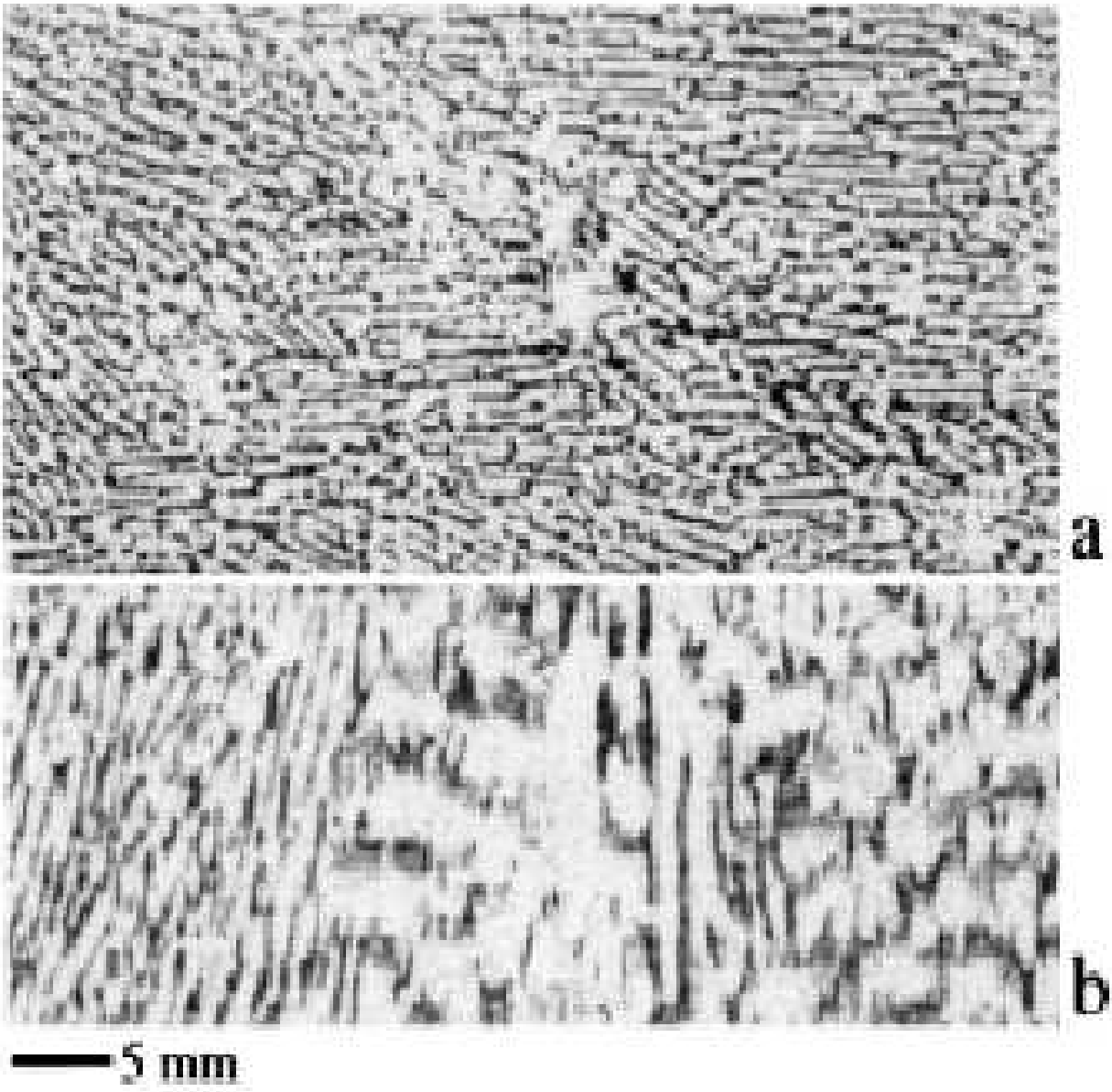
from Petrenko and Whitworth (1999)

How does the salt get into the ice?



from Weeks and Gow (1978)

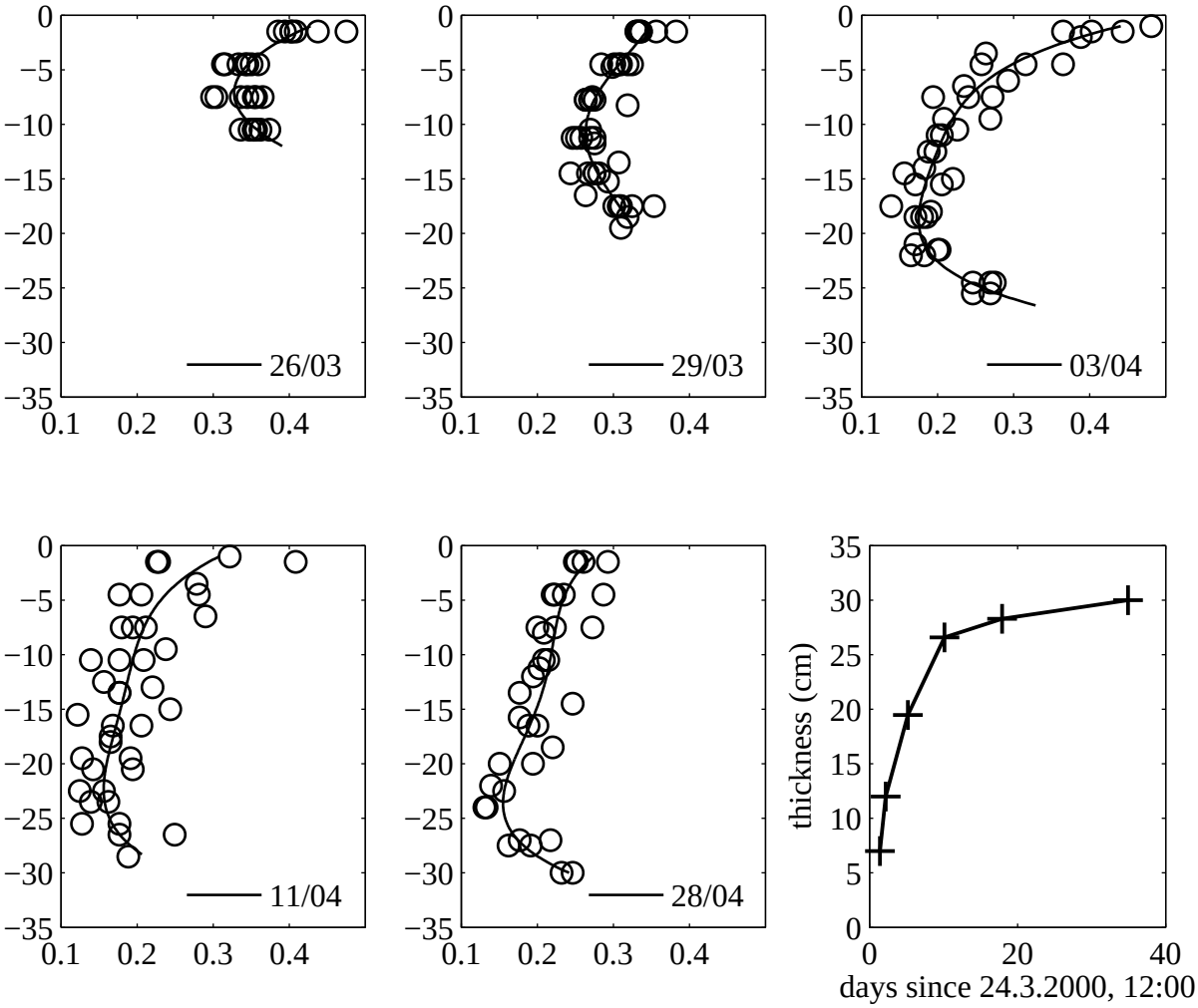
How does the salt get into the ice?



from Eicken et al. (2000)

Thin section micrographs:

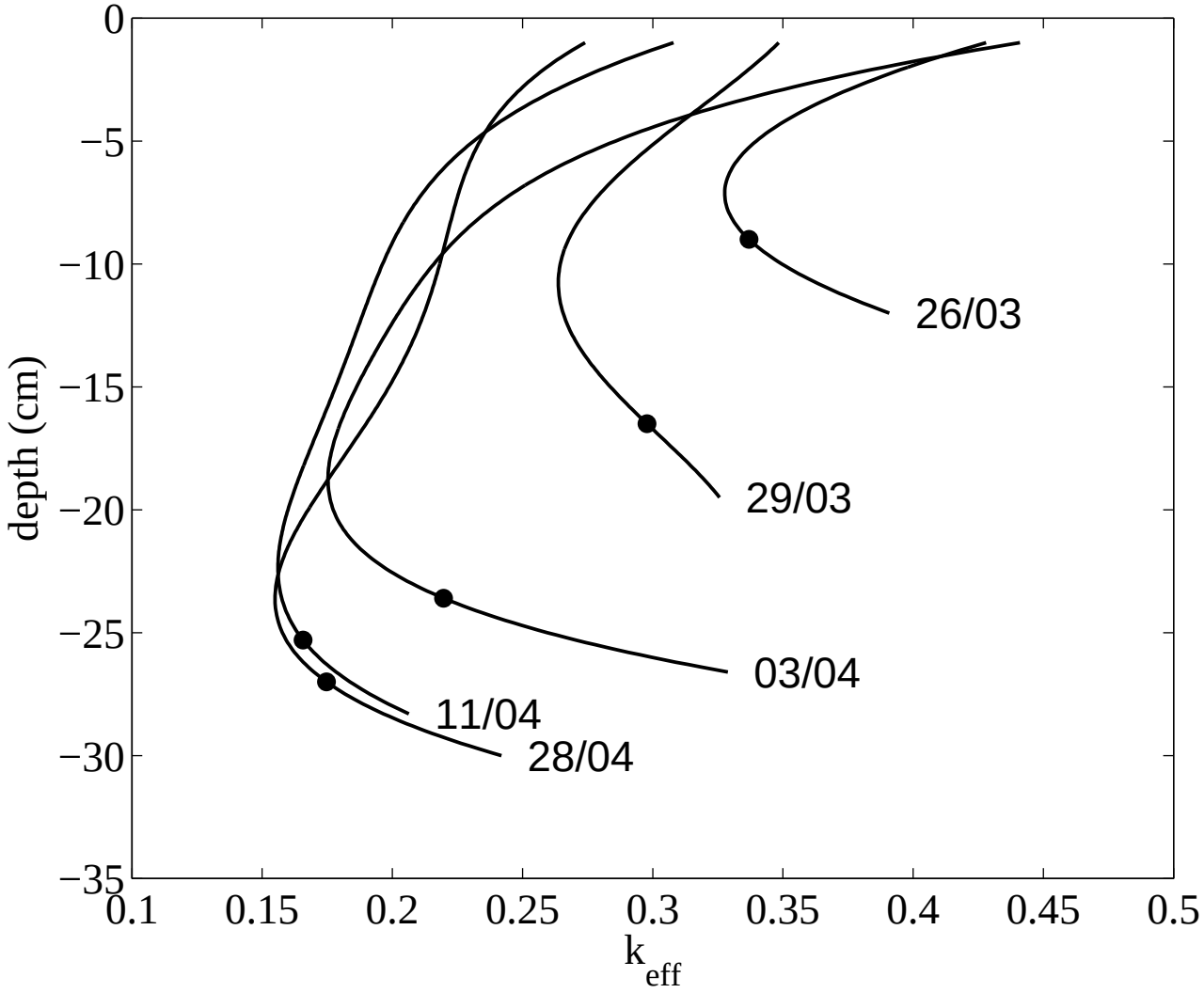
ice plates
and brine layers



Adventfjorden, Svalbard 2000 (Maus and Bennet, unpublished)

Field cores

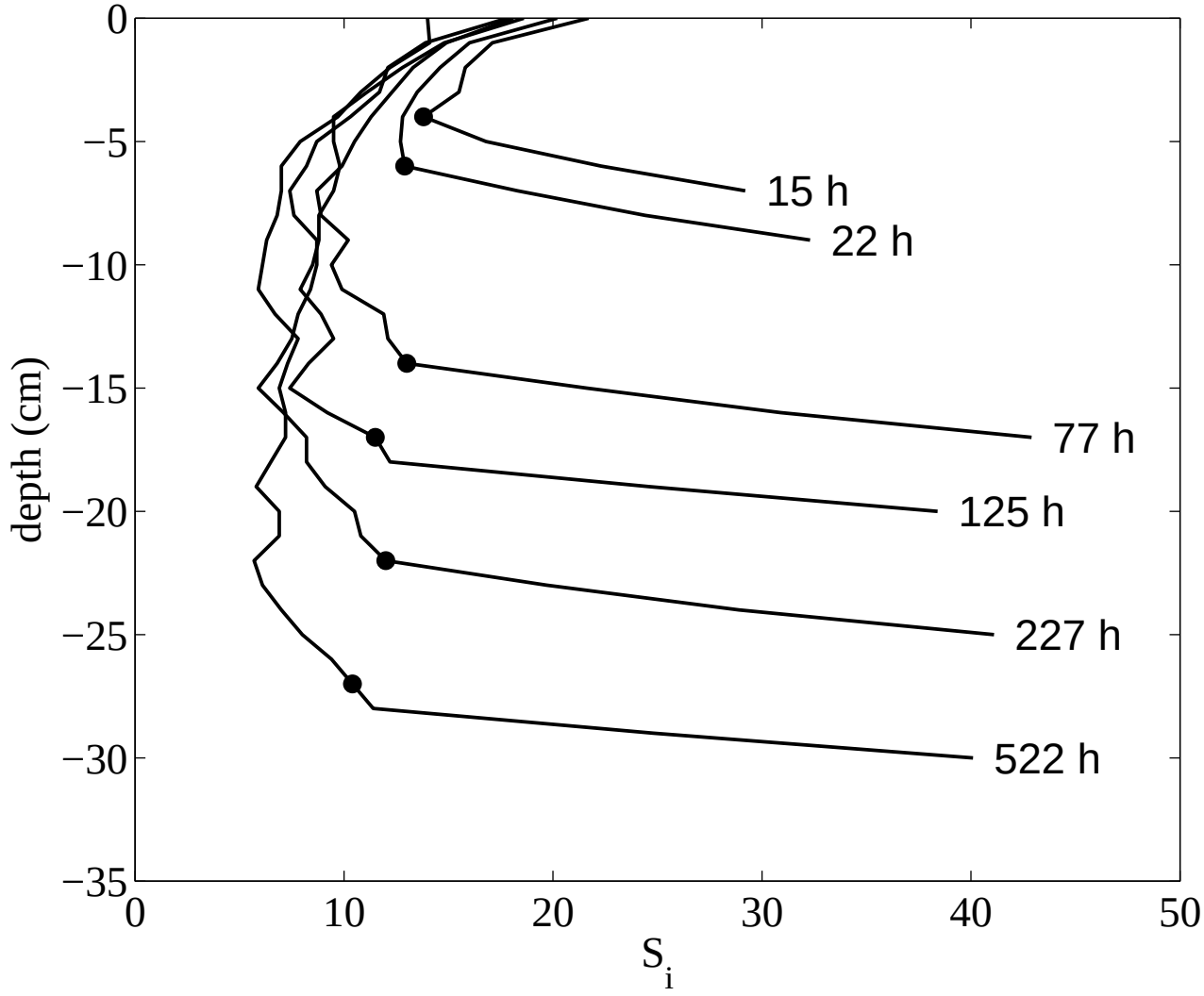
Ice salinity scatter and brine channels



Salinity profiles and evolution

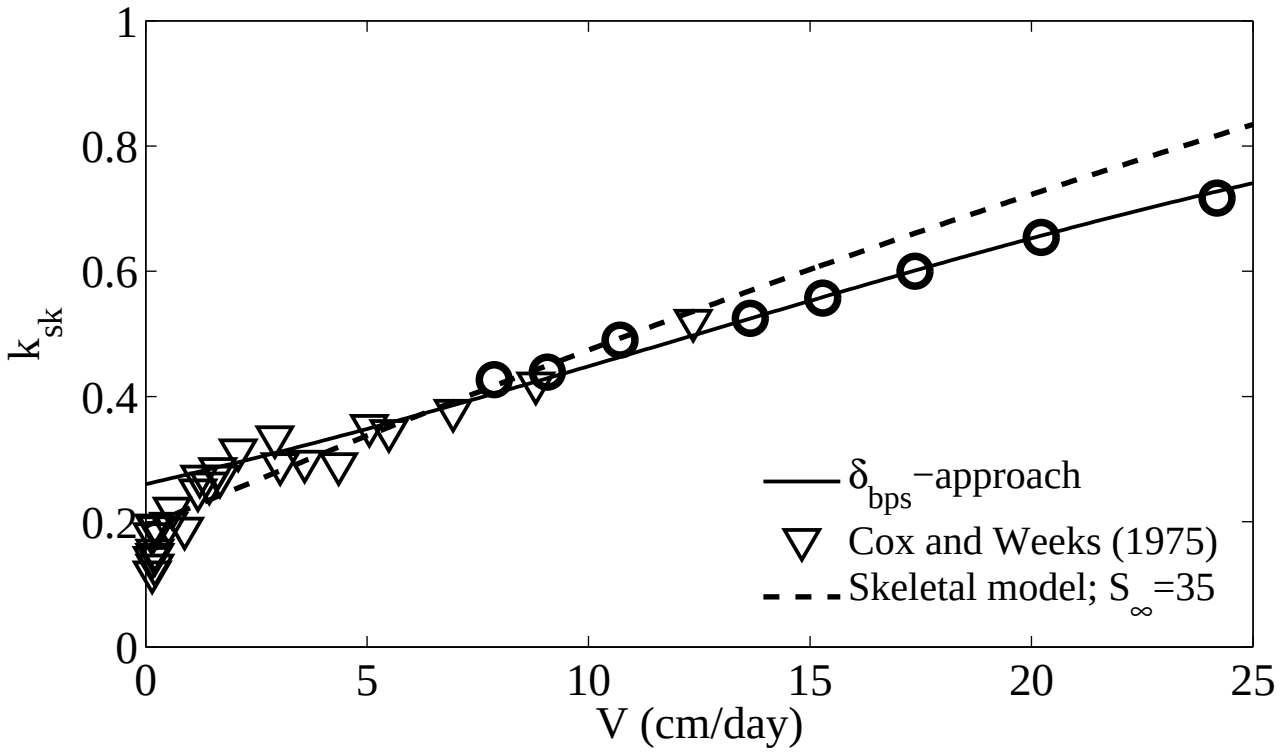
Three distinct regimes

- upper: growth velocity decay
- lower: skeletal layer (≈ 3 cm)
- transition: percolation transition ($\approx 6 - 10$ cm)



Salinity profiles from Cox and Weeks (1975)

Skeletal layer ≈ 3 cm



A simple model

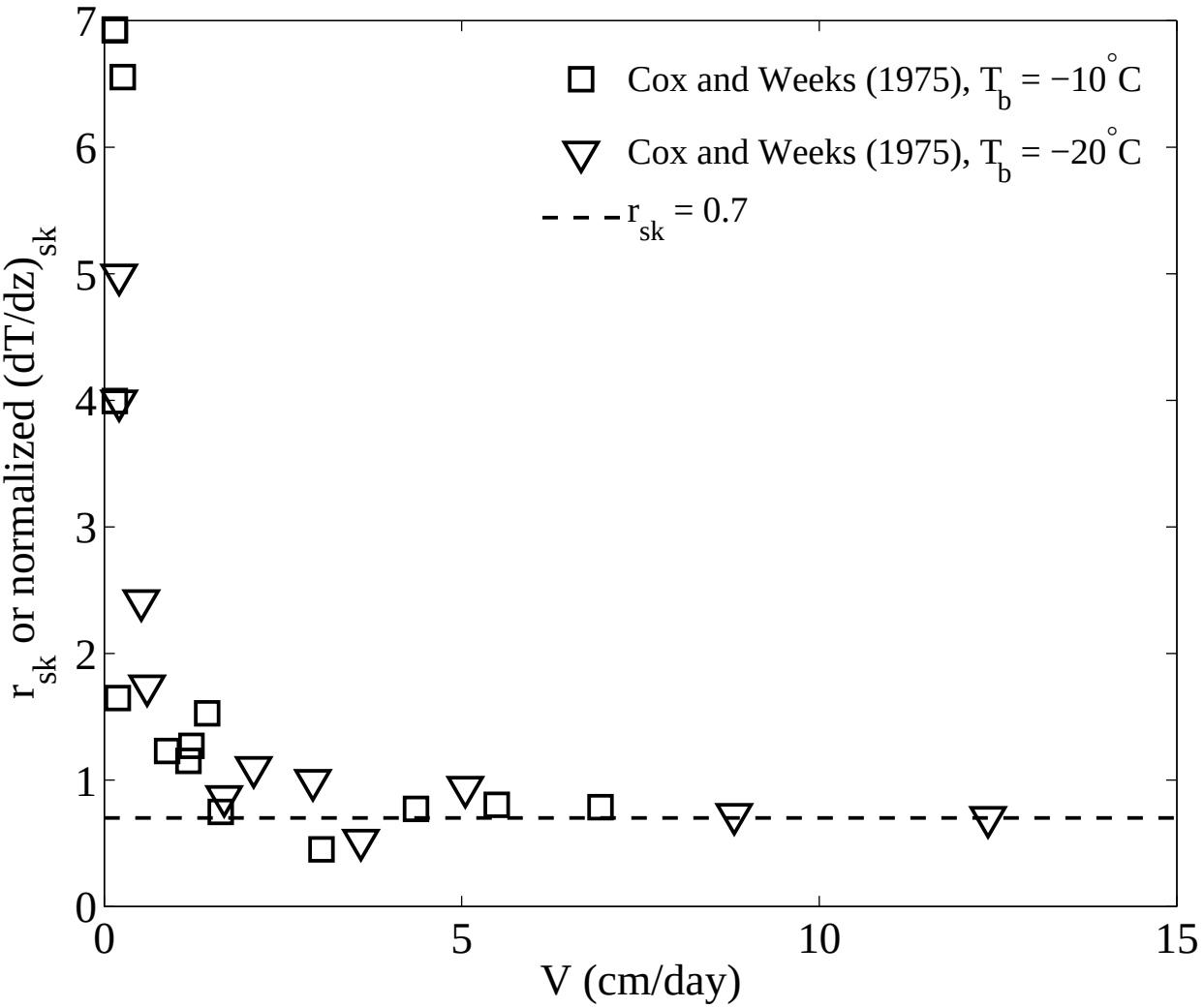
for the sea ice salinity

$$\frac{S_i}{S_w} = c_\rho \frac{d_0}{a_0}\left(1 + \frac{dS}{dz} H_{sk}\right)$$

brine layer width: d_0?

plate spacing: a_0?

skeletal transition: H_{sk}?



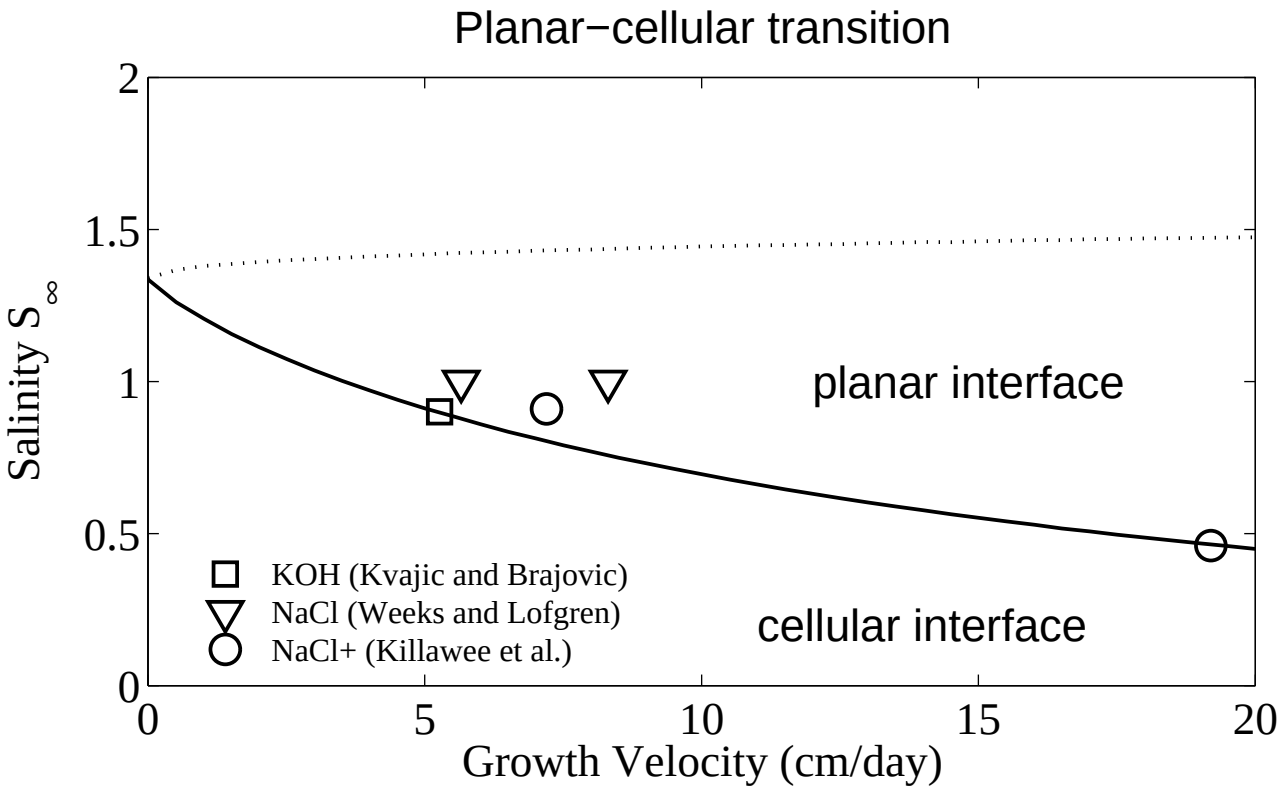
Laboratory data from Cox and Weeks (1975):

Problems with thermal convection

Plate spacing a0: Morphological Stability

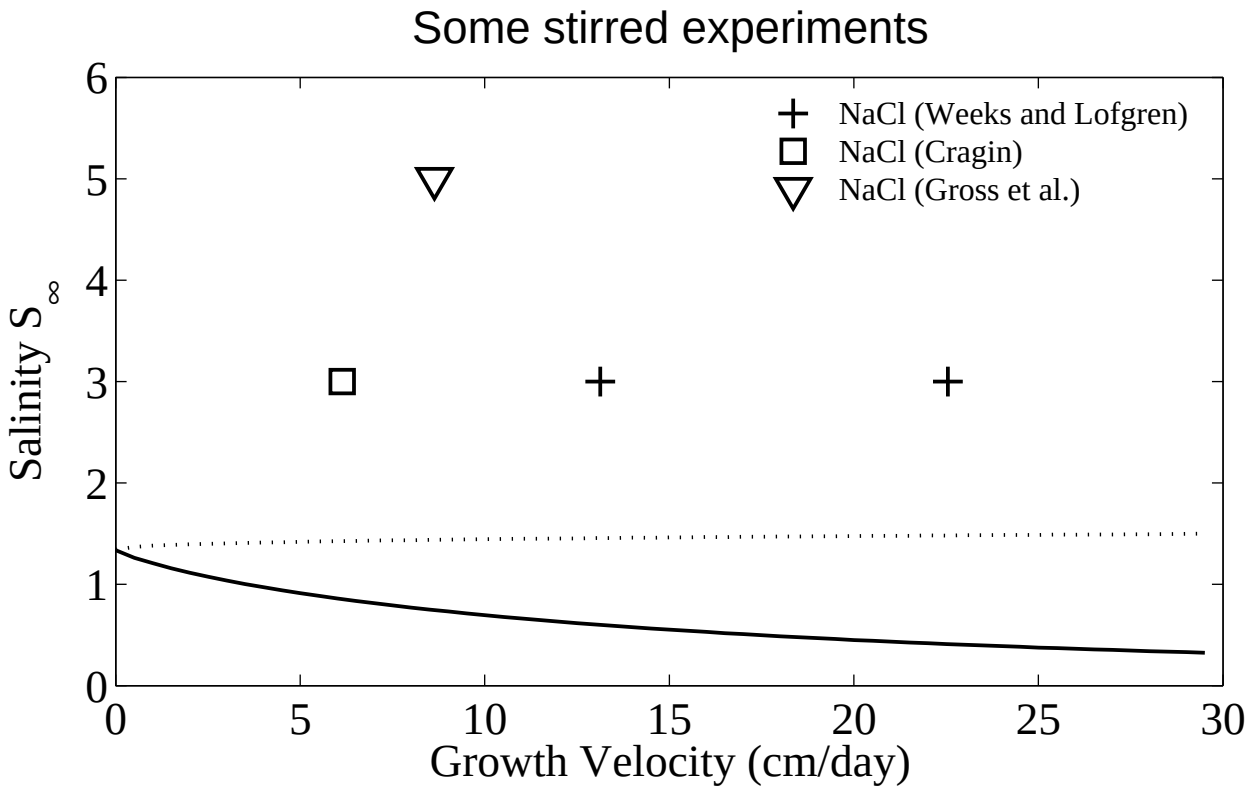
- Mullins and Sekerka (1964)
- Constitutional supercooling
- Double diffusion
- Perturbation growth: Ice water interface unstable
- Scales
  - diffusion: D/V
  - surface tension: $\Gamma/\Delta T$
- Turbulent Rayleigh convection

Morphological stability (Sekerka, J. Cryst. Growth, 1976)



Morphological stability:

Planar-cellular transition



Planar-cellular transition

The effect of stirring

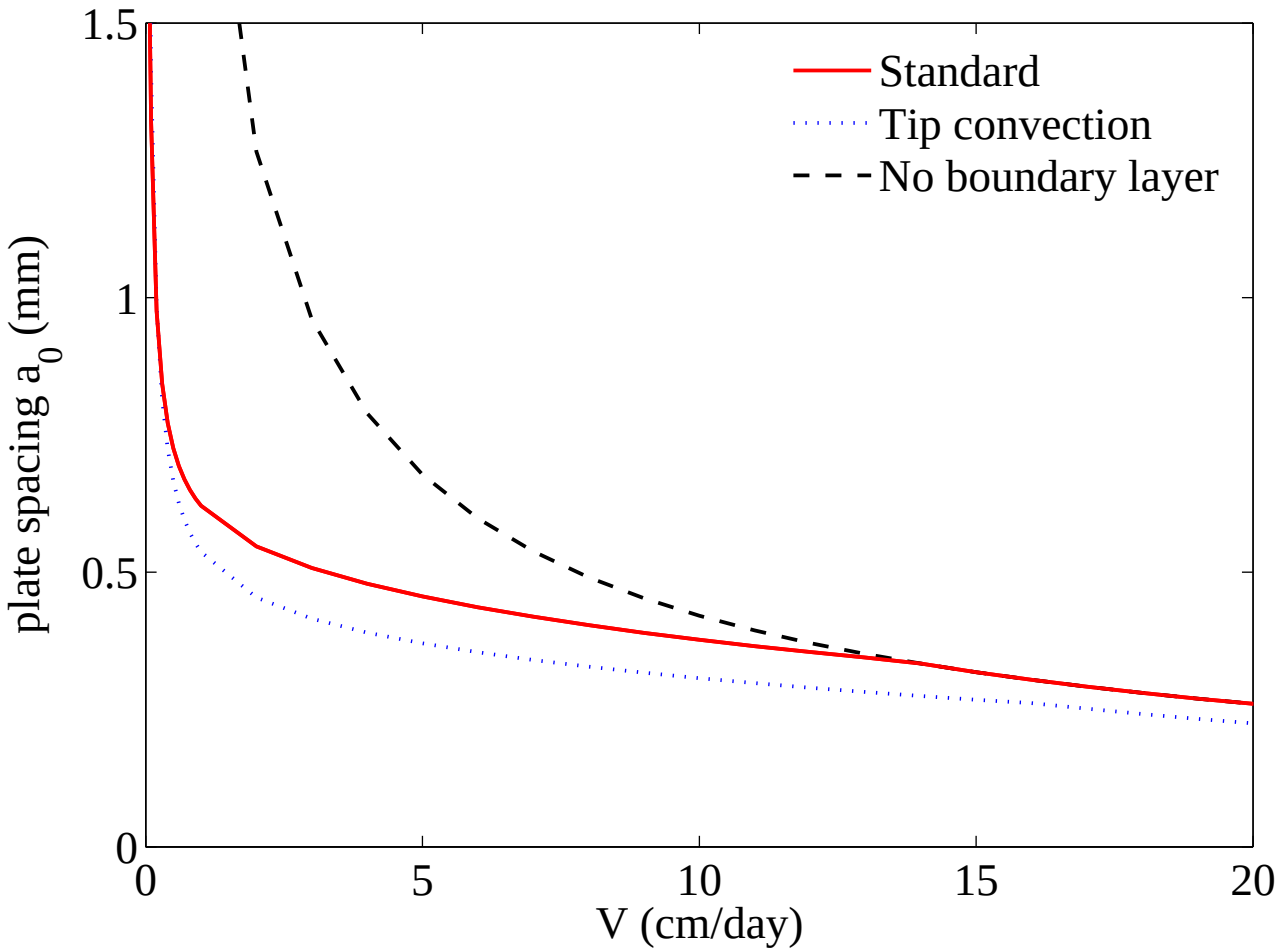


Plate spacing for $S_w = 35$

Natural growth velocity regime

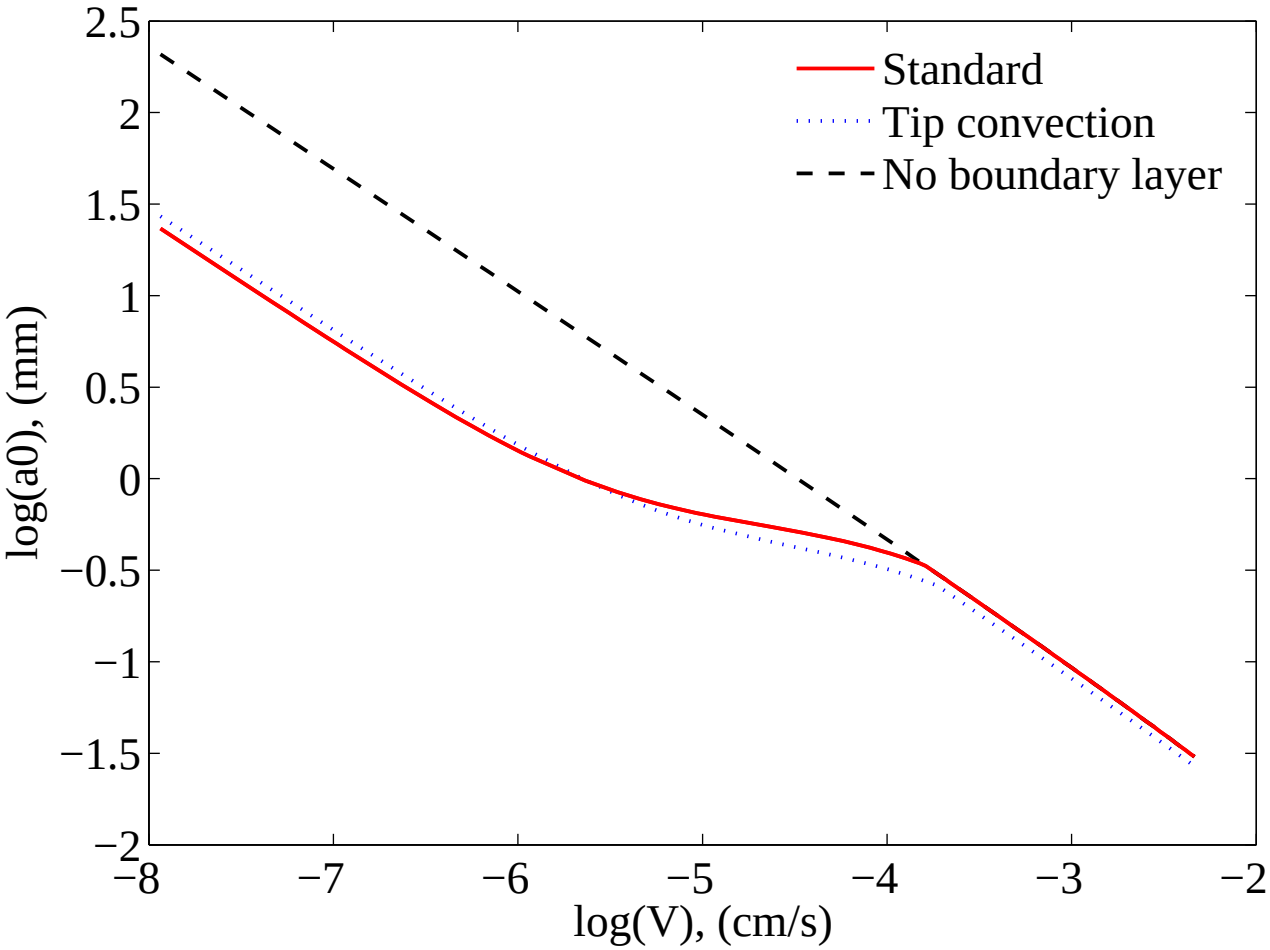


Plate spacing for $S_w = 35$

Growth regime 0.005 to 300 cm/day

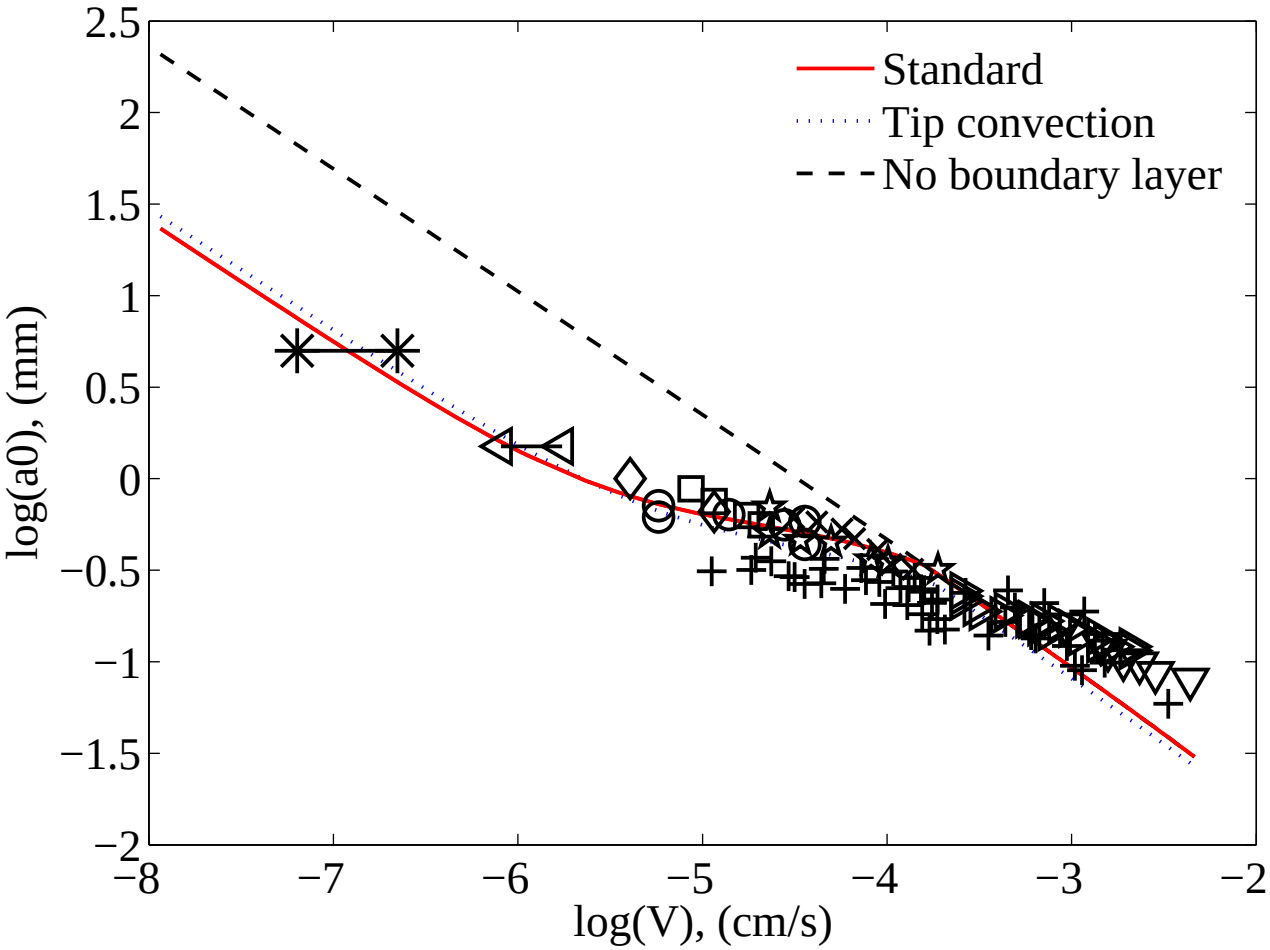


Plate spacing for $S_w = 35$

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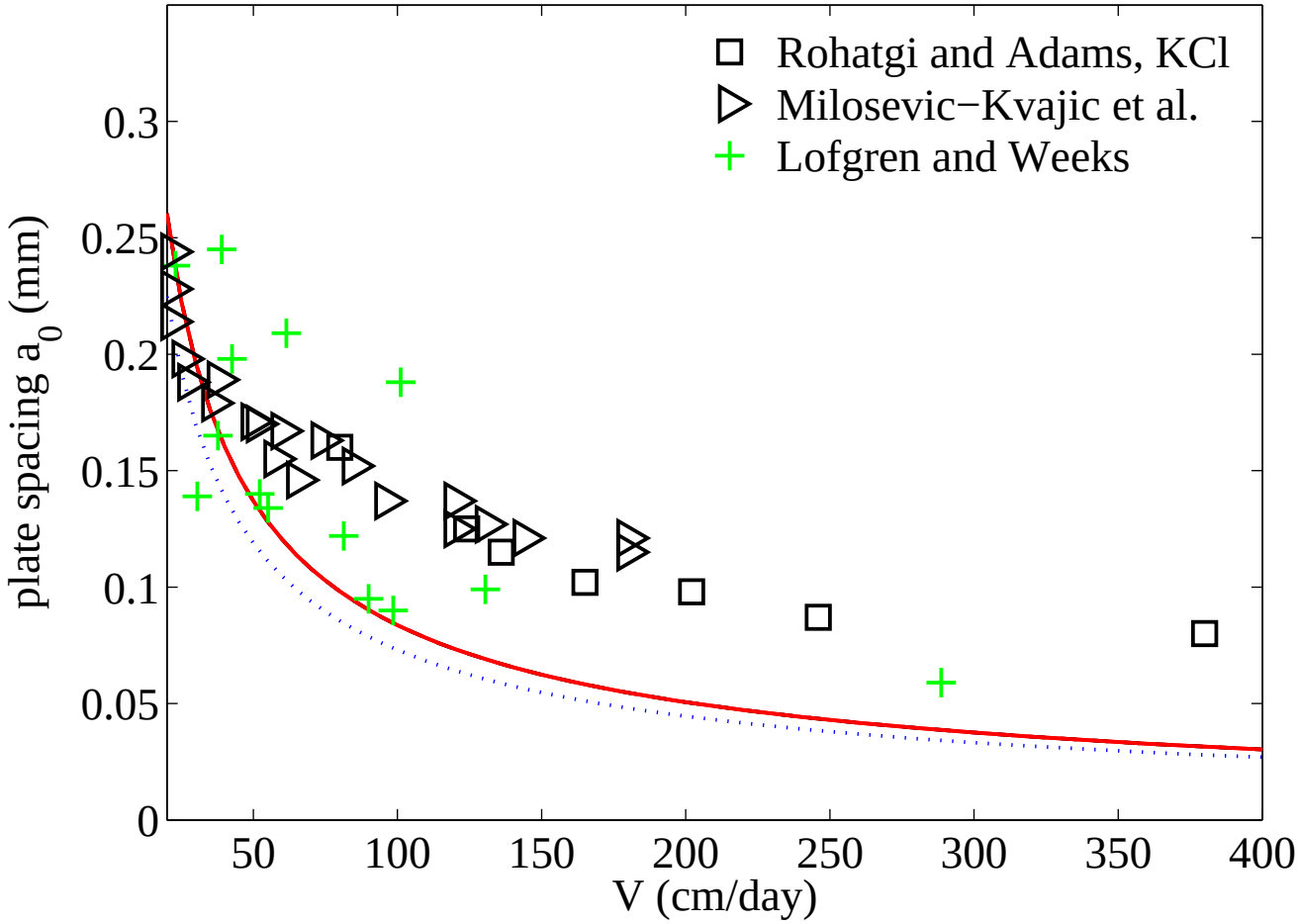


Plate spacing for $S_w = 35$

High laboratory growth velocities

Dendritic regime

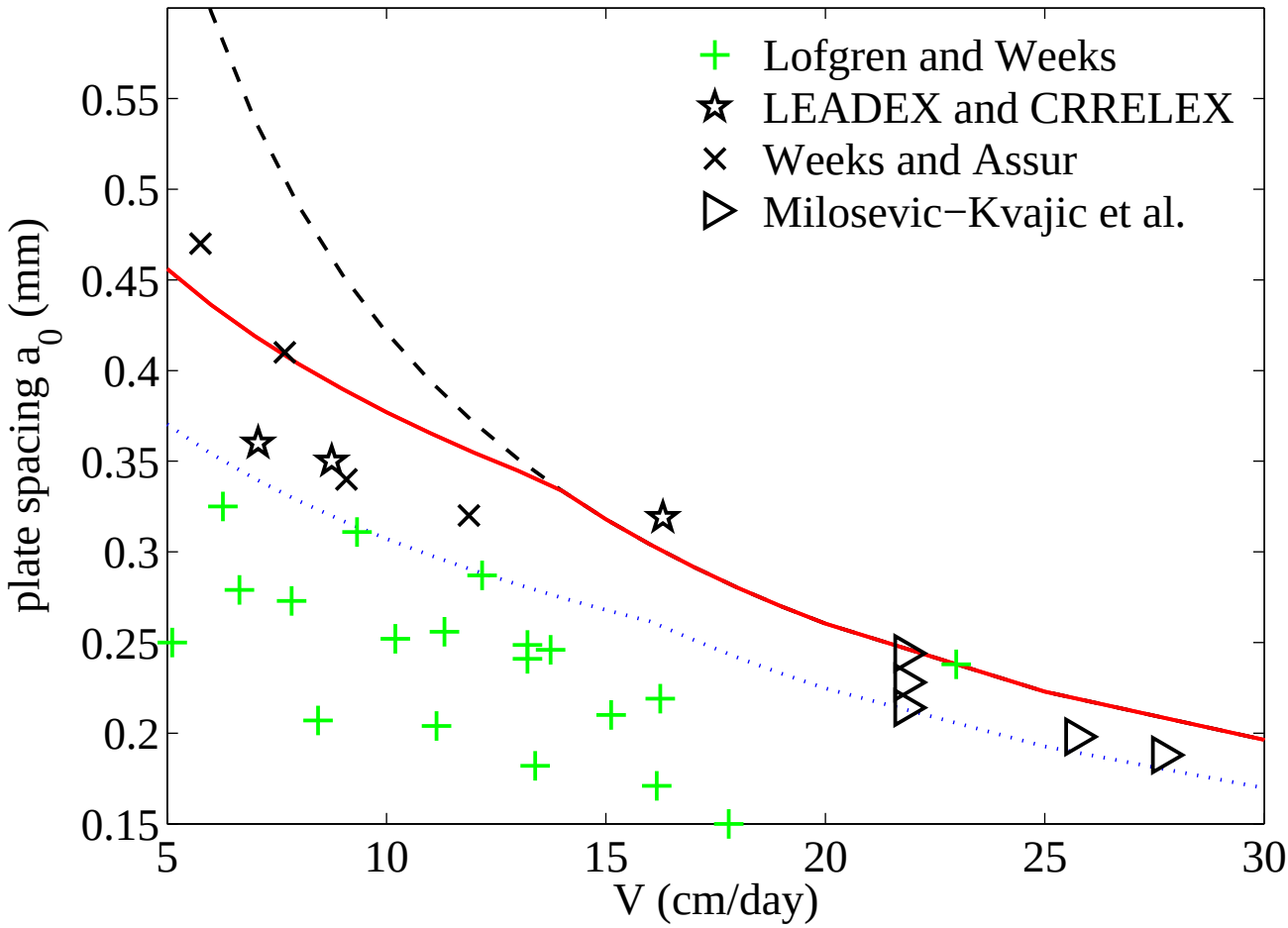


Plate spacing for $S_w = 35$

High natural growth velocities

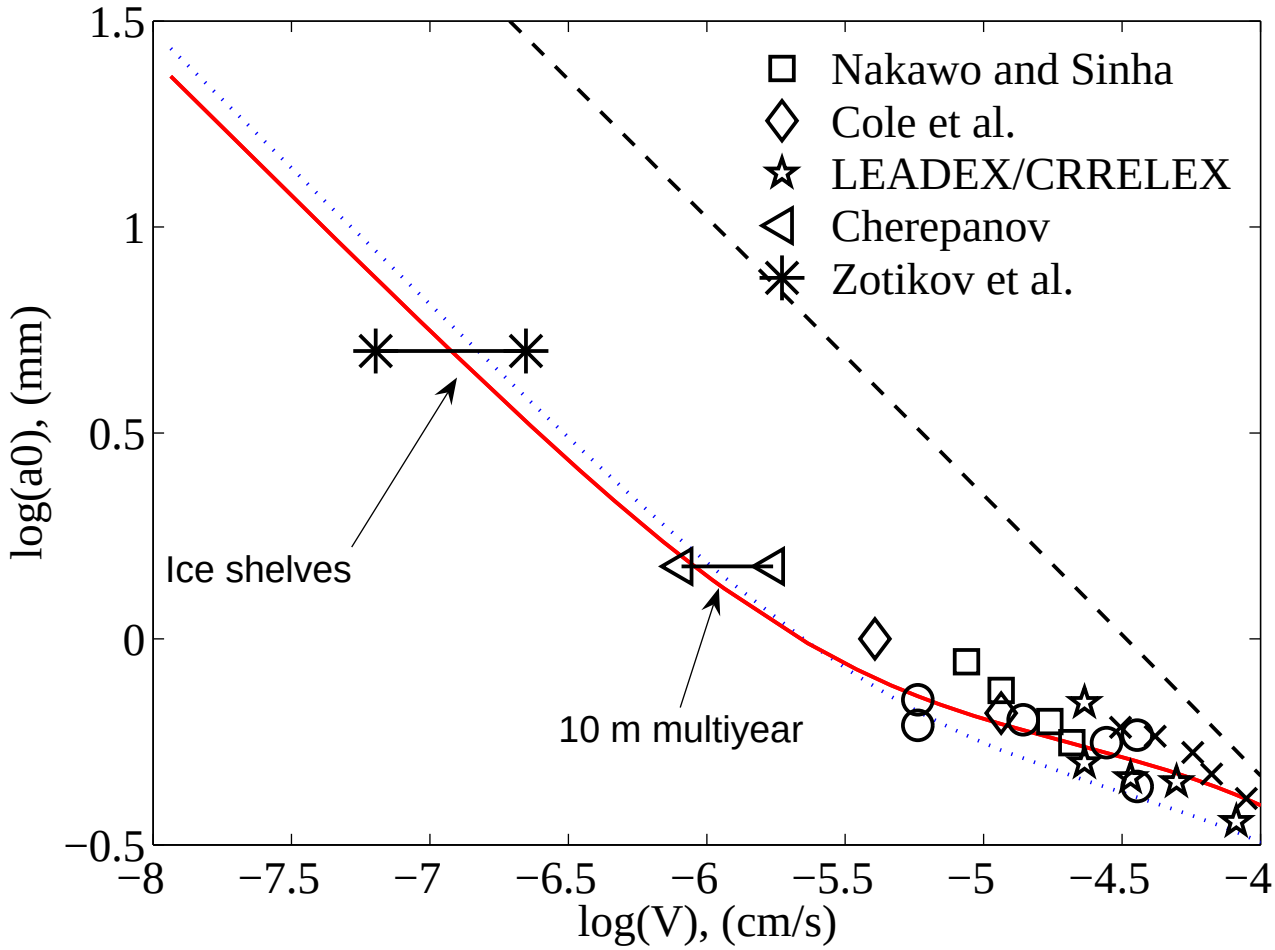
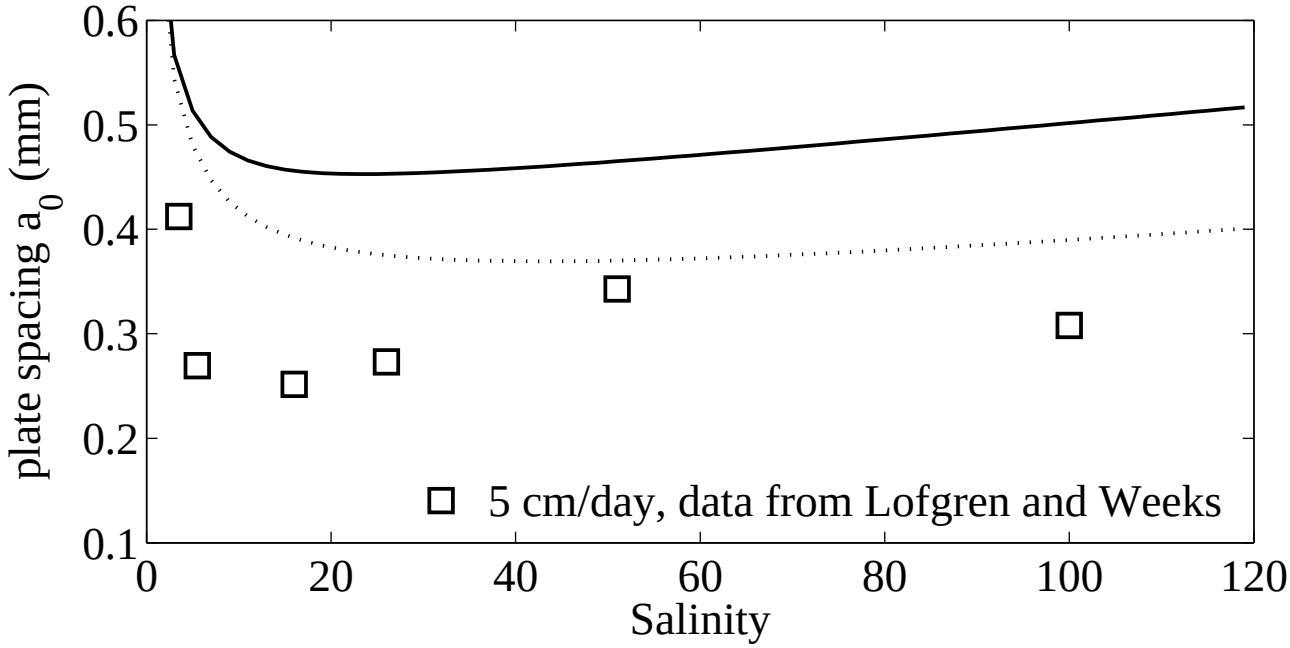
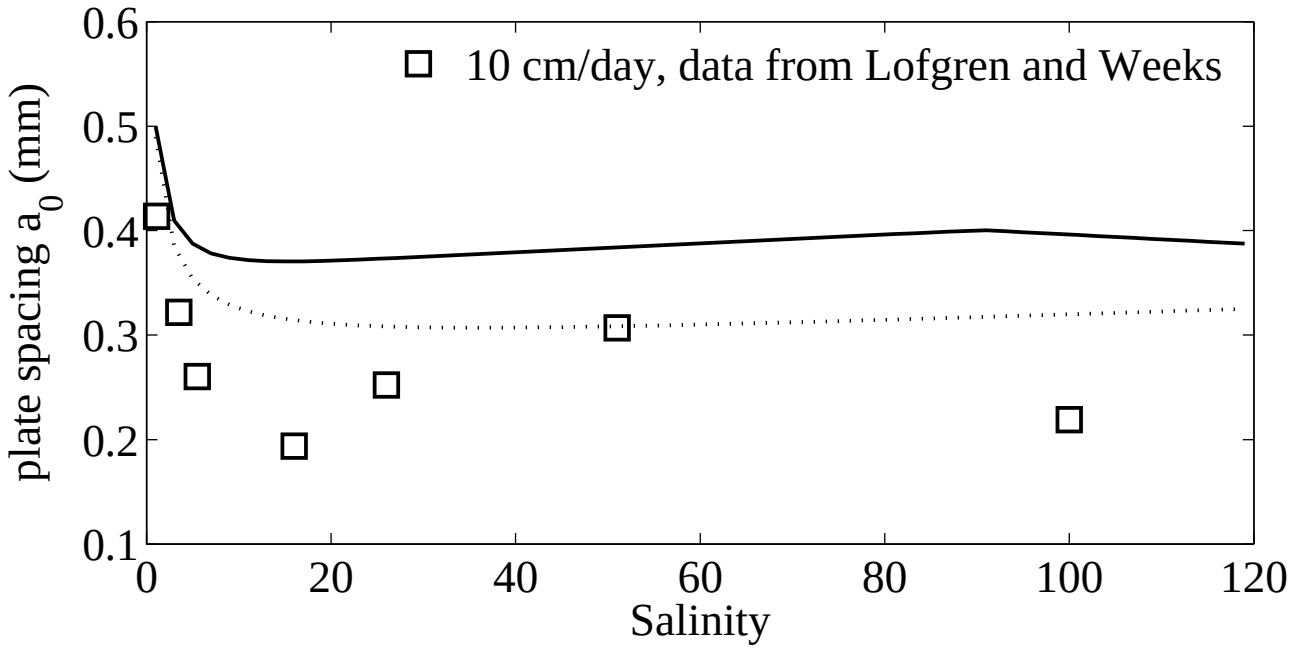


Plate spacing for $S_w = 35$

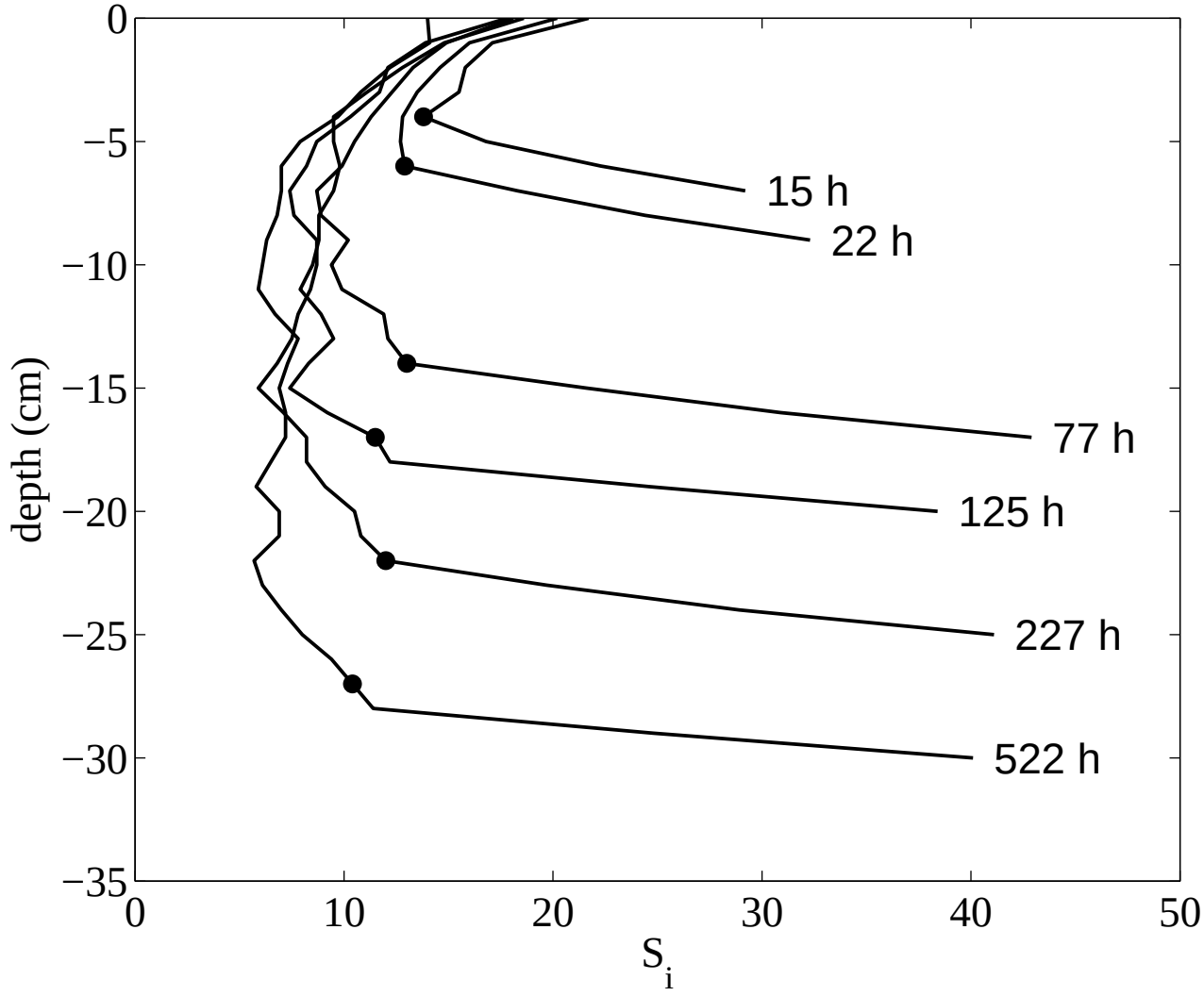
Low natural growth velocities



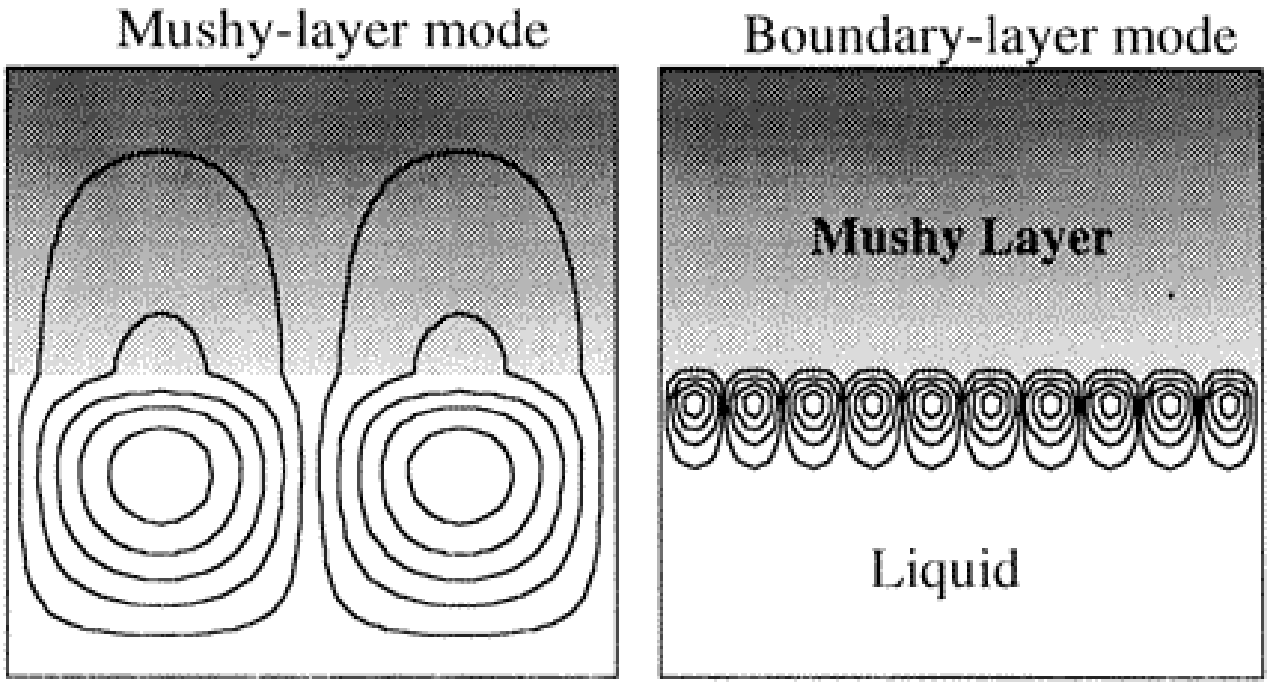


Salinity dependence of plate spacing

Little valid data available. Baltic Sea?



Convection in the skeletal layer?

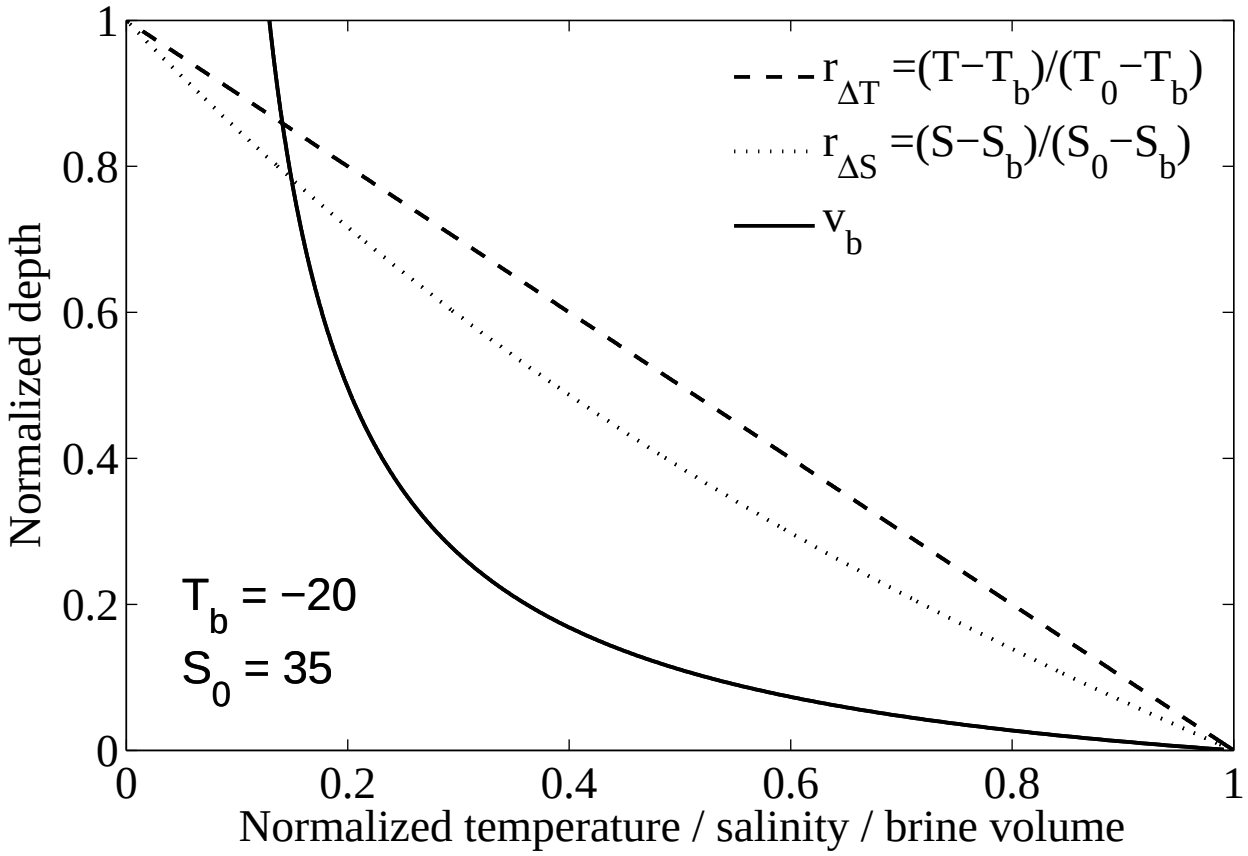


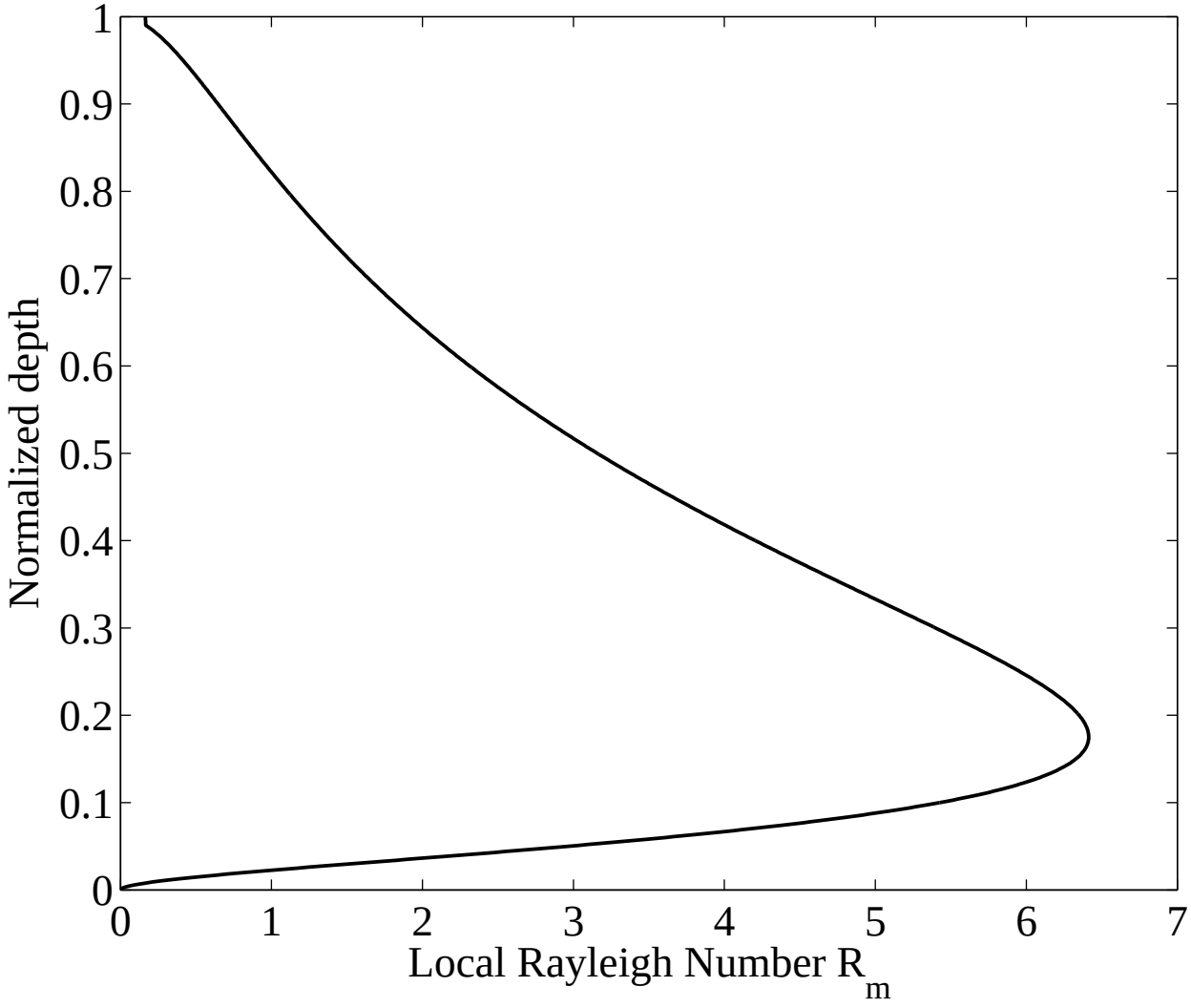
from Worster et al. (1997)

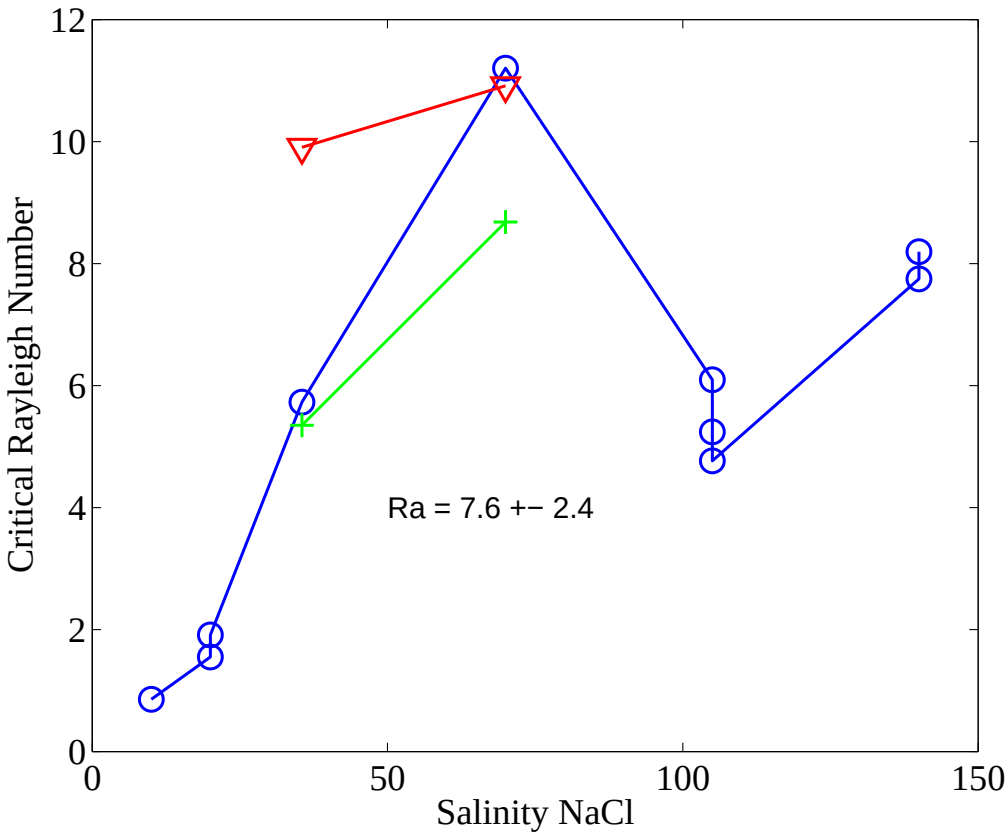
Convection in the skeletal layer

What are the length scales?

$$Ra_m = (\Pi \beta \Delta S_b H) \left(\frac{g}{\kappa_b \nu_b} \right)$$


Normalized depth
Normalized temperature / salinity / brine volume
$r_{\Delta T} = (T - T_b)/(T_0 - T_b)$
$r_{\Delta S} = (S - S_b)/(S_0 - S_b)$
v_b
$T_b = -20$
$S_0 = 35$
0
0.2
0.4
0.6
0.8
1


Normalized depth
Local Rayleigh Number R_m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7

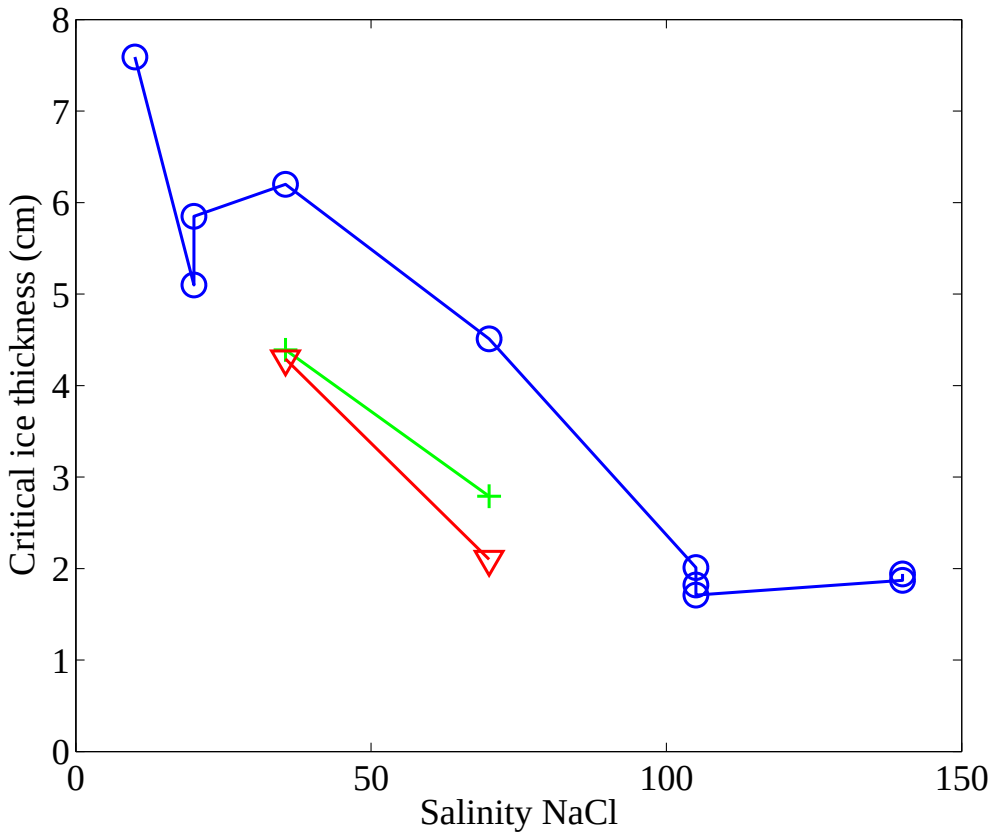


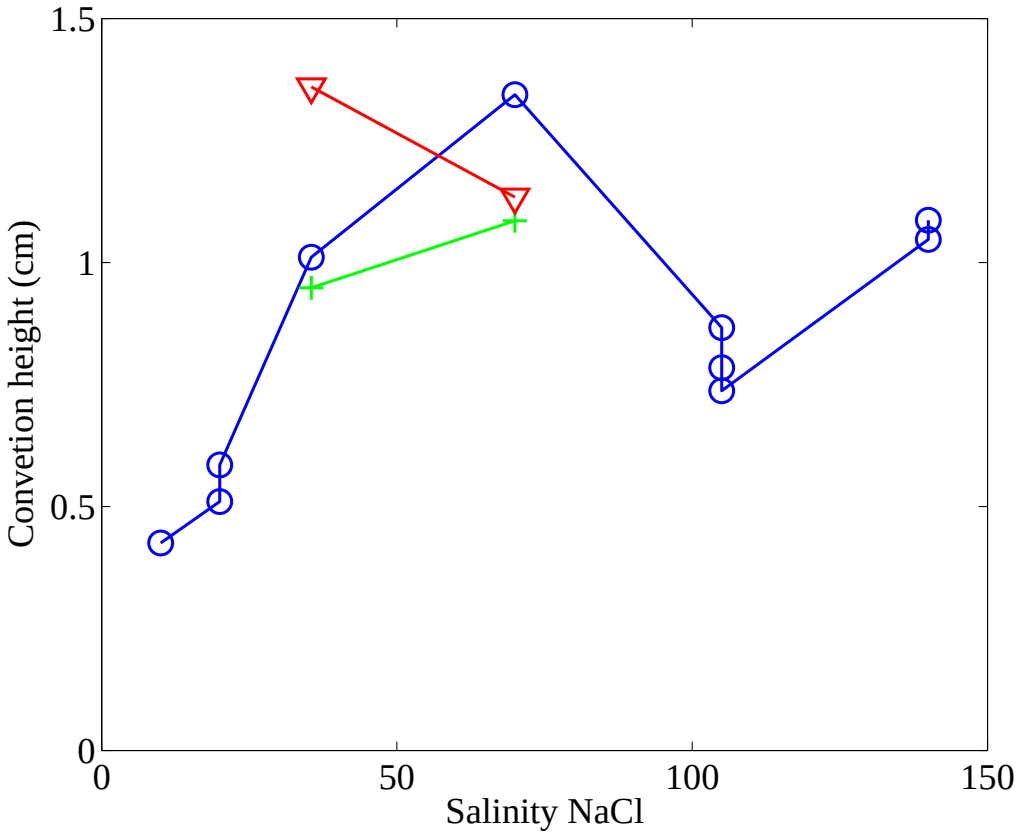
Laboratory freezing of NaCl solutions

Wettlaufer, Worster and Huppert (1997)

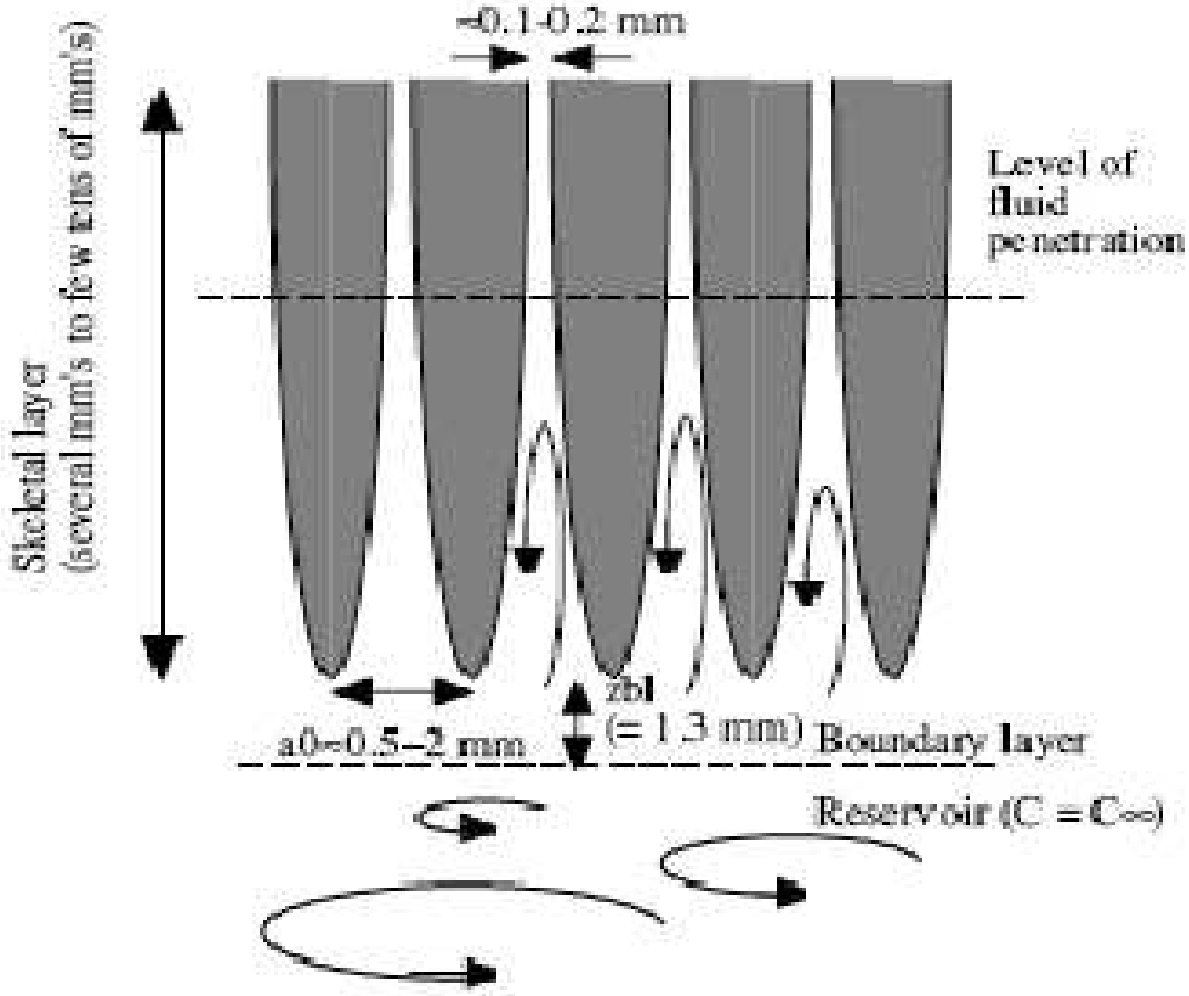
(J. Fluid Mech., 344, 291−316)

Critical Rayleigh Number $\approx 6 - 10$





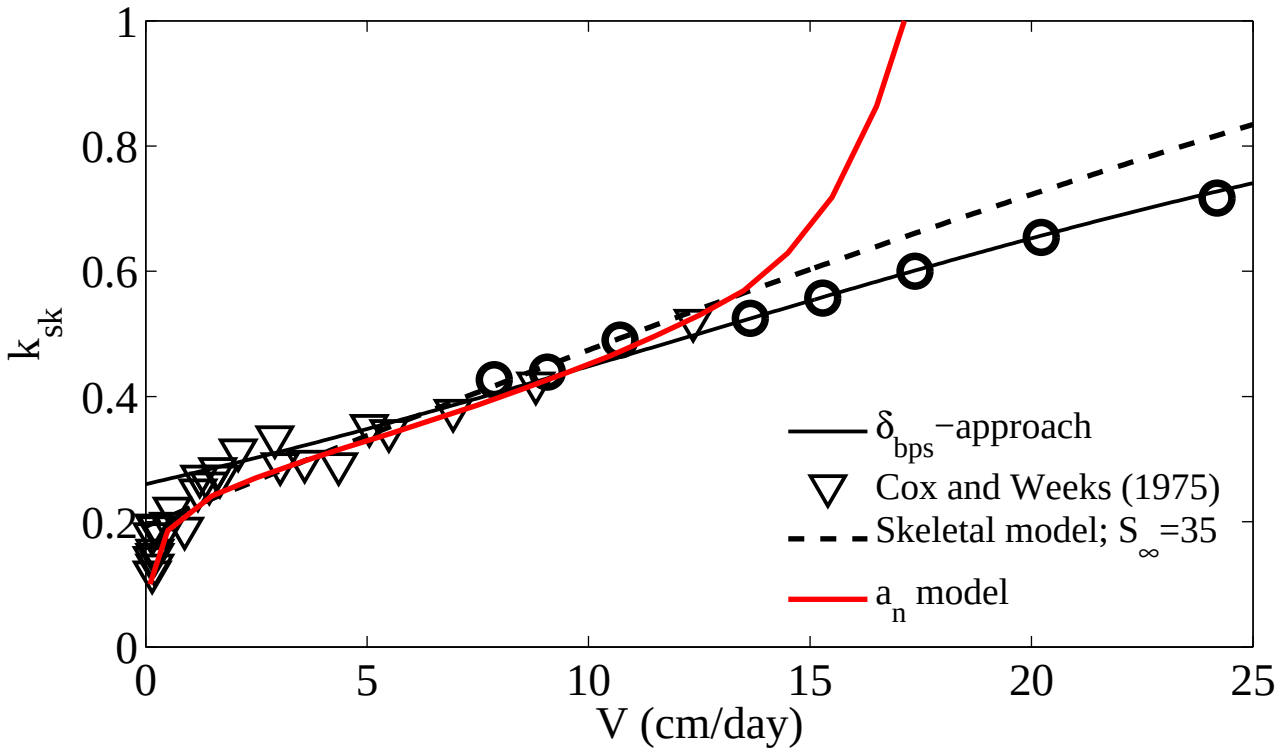
Convective layer ≈ 1 cm



from Eicken(1998)

How large is d_0?

More data required: $d_0 \approx 0.1$ mm



Ice salinity prediction

- a_0 from morphological stability theory
- $Ra_m = 8$, convective stability criterion
- $d_0 \approx 0.1$ mm, brine layer pinch-off

Salinity and microstructure

- The plate spacing a_0 is a fundamental lengthscale of sea ice microstructure
- a_0 is reasonably predicted theoretically
- Data on a_0 in brackish waters are lacking
- The brine inclusion pinch-off $d_0 \approx 0.1$ mm requires further studies
- Sea ice salinity becomes principally predictable
- Sea ice bottom regimes

  - strong convecion: 1-3 cm

  - weak convection: ≈ 10 cm
- Baltic Sea ice?