Haline Convection during Freezing of Seawater

Sönke Maus, Bergen 19.05.2006

- Rayleigh number
- Free convection
- Geophysical systems
- Sea ice

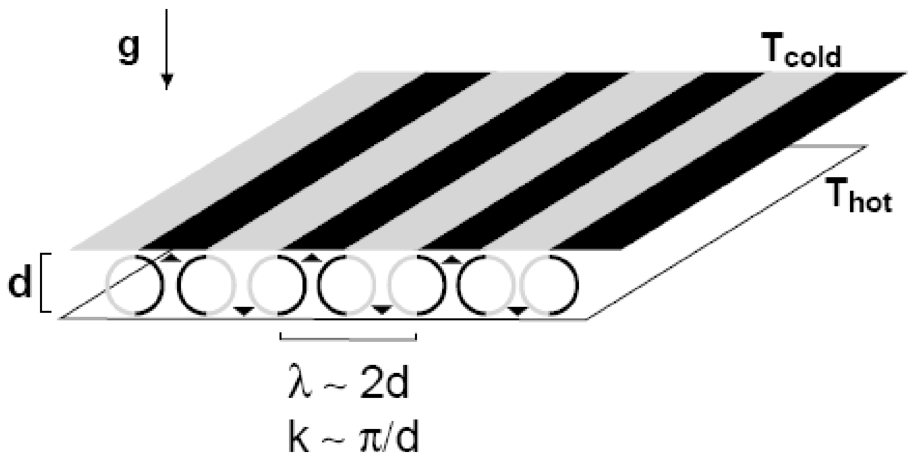
$$Ra = \frac{\beta \Delta S g H^3}{\nu D_s}$$

John William Strutt (1916)
Lord Rayleigh

$$Ra = \left(\frac{H}{H_*}\right)^3$$

$$H_* = \left(\frac{\nu D_s}{b}\right)^{1/3}$$

$$b = \beta \Delta S g$$



Silveston (1958)

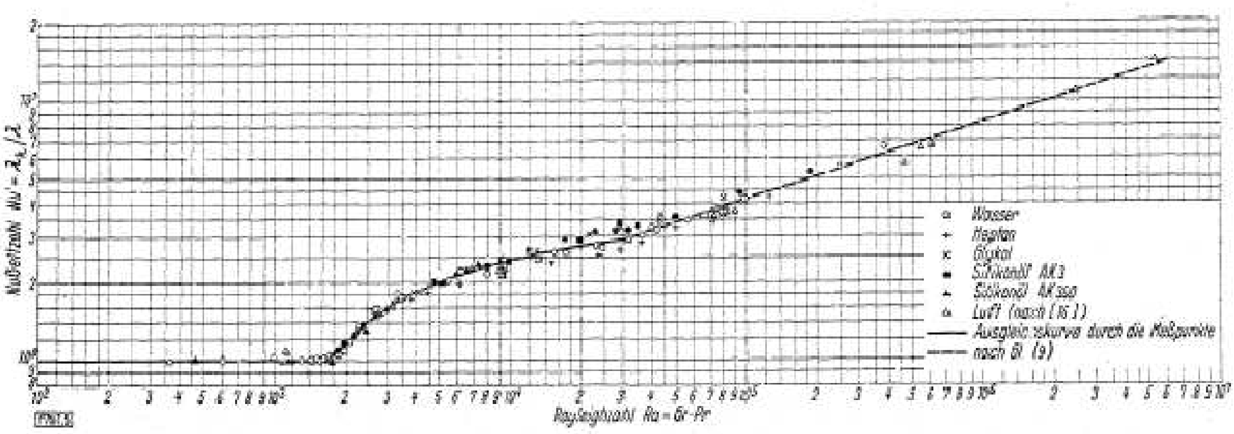


Bild 5. Abhängigkeit der Nußeltzahl Nu′ von der Rayleighzahl Ra.
λ und λ_k wahre bzw. scheinbare Wärmeleitzahl, Gr Grashof-, Pr Prandtlzahl

(rigid, rigid , T=const. , T=const.)

$$Ra_c \approx 1700$$

Chandrasekhar (1961)

"Hydrodynamic and Hydromagnetic Instability"

Rotation, Magnetic fields, Couette flow, Kelvin-Helmholtz

Superposed Fluids, Jets and Cylinders

Rayleigh, 1916 (free, free , T=const. , T=const.)

$$Ra_c = 657.511$$

Reid/ Harris, 1958 (rig, rig , T=const. , T=const.)

$$Ra_c = 1707.765$$

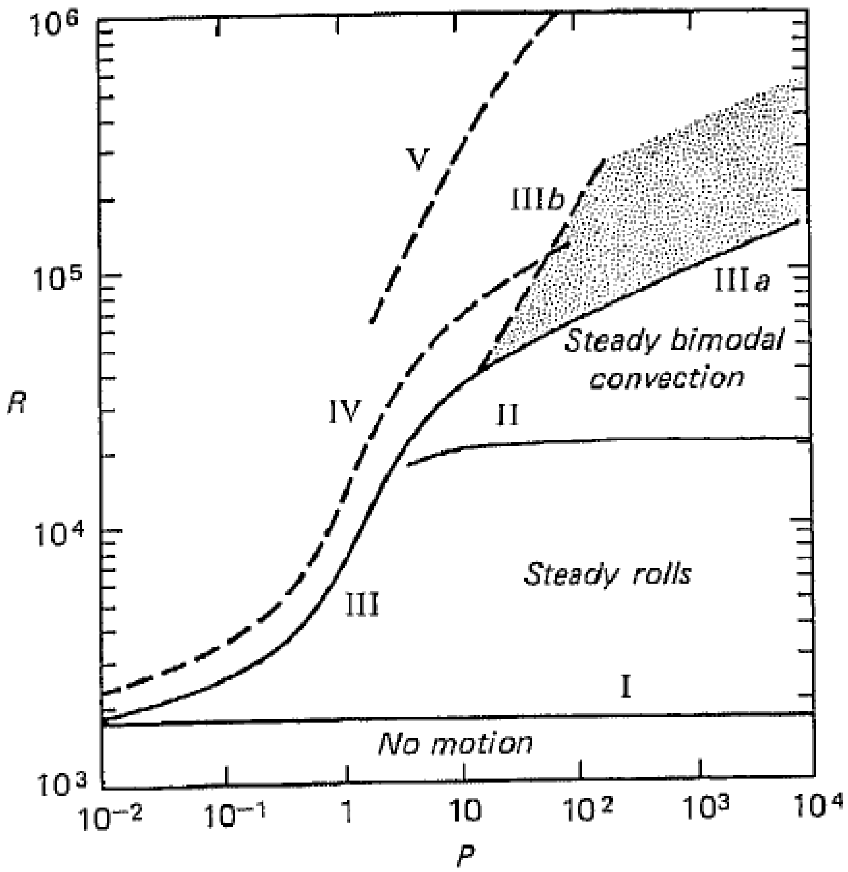
Nield, 1967 (free, free , Q=const. , Q=const.)

$$Ra_c = 120$$

$4 + 3 + 2 + 1 = 10$ combinations

Transition to turbulence

Schmidt and Saunders (1938), Malkus (1954), Krishnamurti (1973)



Krishnamurti (1973)

Transition to oscillating flow depends on Pr

Free convection: $Ra \to \infty$

$$Nu \sim Ra^{1/3}$$

$\|$: Saunders (1939), $=$: Weise (1940)

$$\underline{Ra \Rightarrow \infty \;\; \to \;\; Q \to const.}$$

Interfacial flux Q must become independent of depth H

$$Nu = c_* Ra^{1/3} = c_* \frac{H}{H_*}$$

$$Q = Nu \frac{D_s \Delta S}{H}$$

$$\Rightarrow Q = c_* \frac{D_s \Delta S}{H_*}$$

$$H_* = \left(\frac{\nu D_s}{g \beta \Delta S} \right)^{1/3}$$

$$\Rightarrow Q = c_* \Delta S^{4/3} \left(\frac{D_s^2 g \beta}{\nu} \right)^{1/3}$$

Nonlinear flux law

$$Q = c_* \Delta S^{4/3} \left(\frac{D_s^2 g \beta}{\nu} \right)^{1/3}$$

How large is c_* ?

Intermittent convection

Howard's (1966) simple concept

$$c_* \approx Ra_c^{-1/3}$$

Howard: $Ra_c \approx 1000 \Rightarrow \; c_* \approx 0.1$

Generally, ad-hoc:

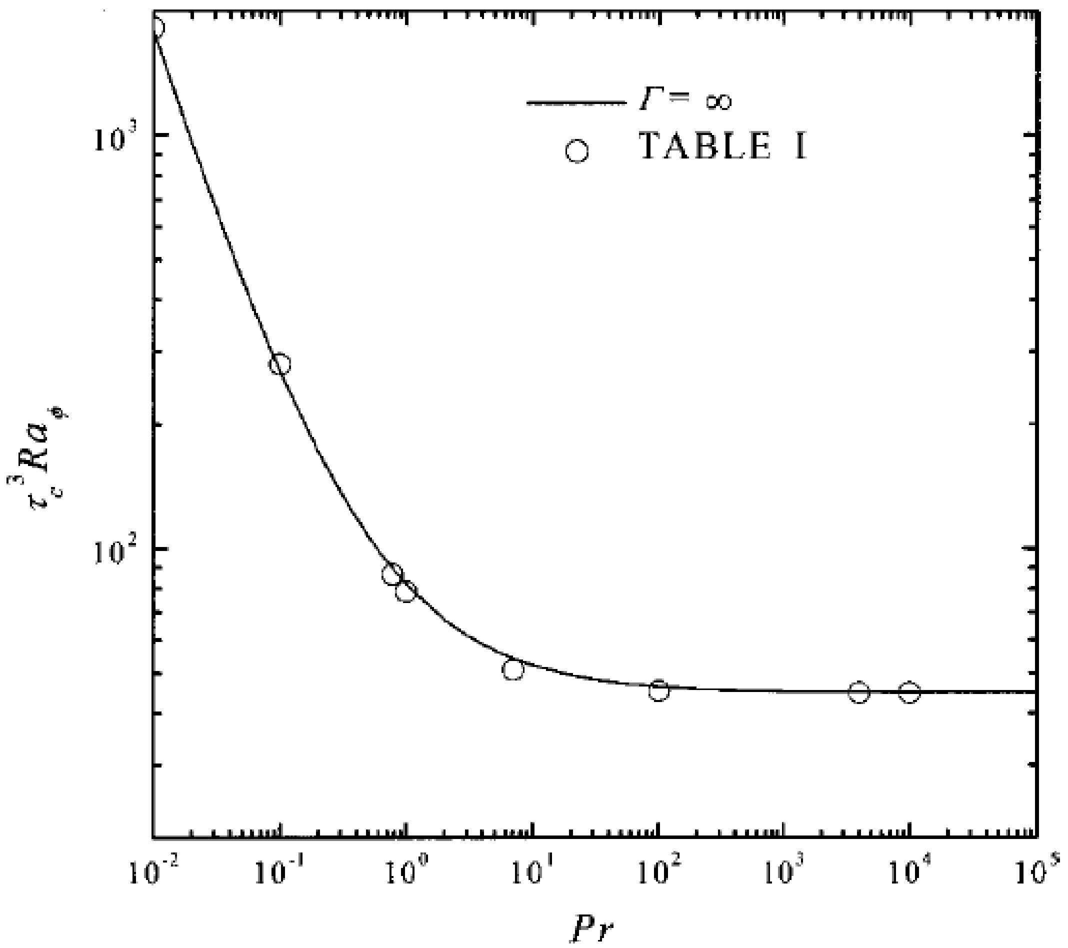
$$120 < Ra_c < 1708$$

$$\Rightarrow$$

$$0.08 < c_* < 0.28$$

Q and c_* depend on

- boundary conditions
- Prandtl Number



Yang and Choi (2002, Phys. Fluids)

See also: Foster (1968, Phys. Fluids),

Different Boundary Conditions

Free, rigid, mixed

Flux, double-diffusive

Geophysical Applications

Unstable Atmosphere

(Herring, Priestley, Deardorff)

Convection in Stars

(Spiegel)

Oceanic double diffusion

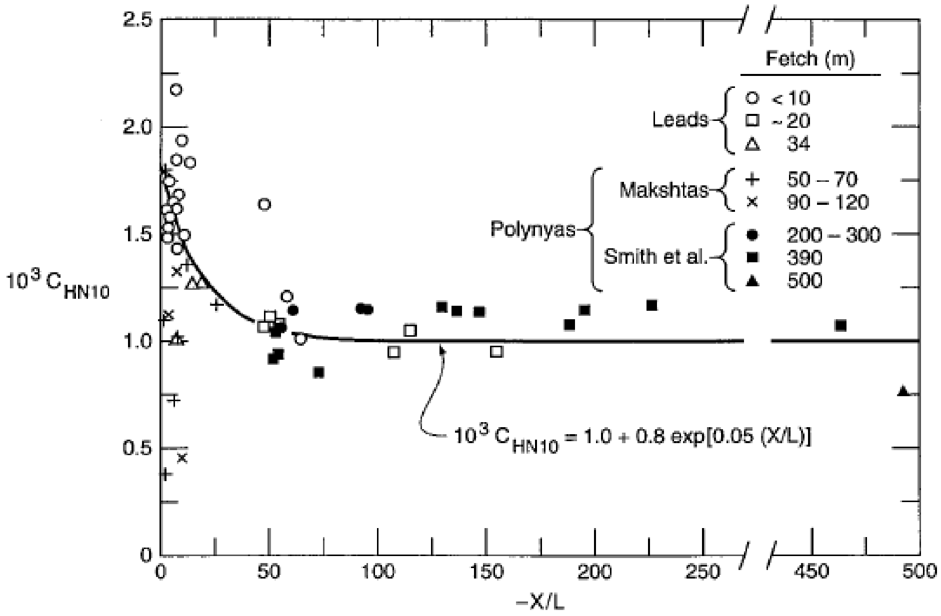
(Stommel, Stern)

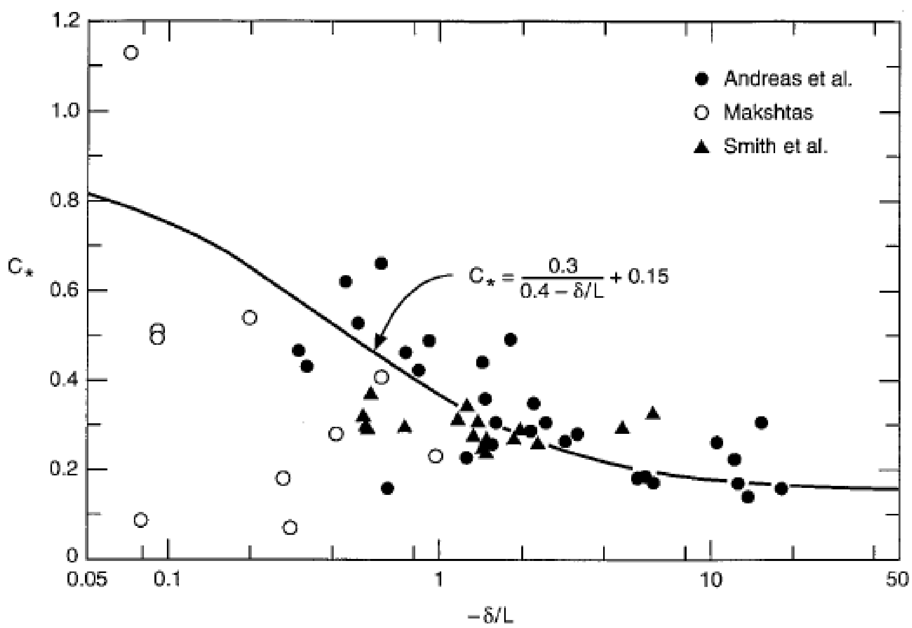
Sea ice freezing

(Foster)

Arctic Leads

Austausch Coefficients

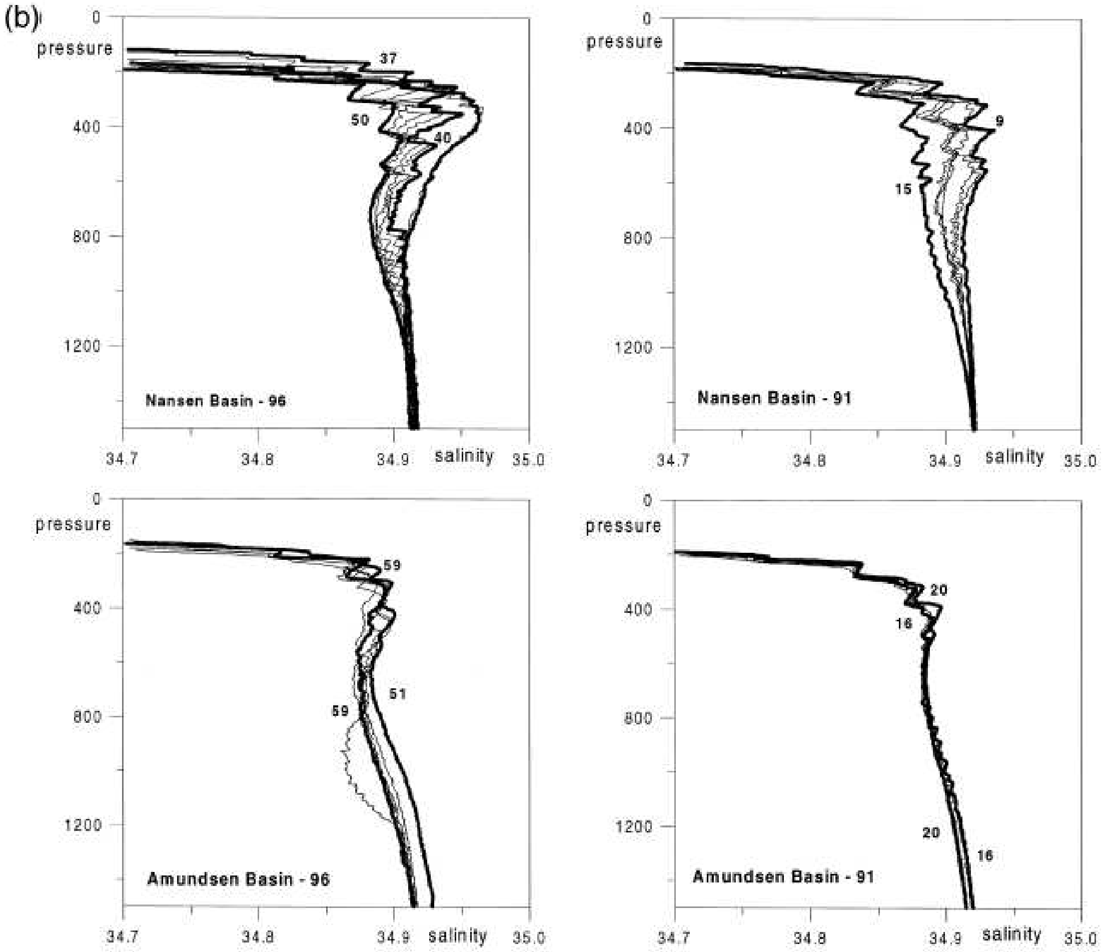




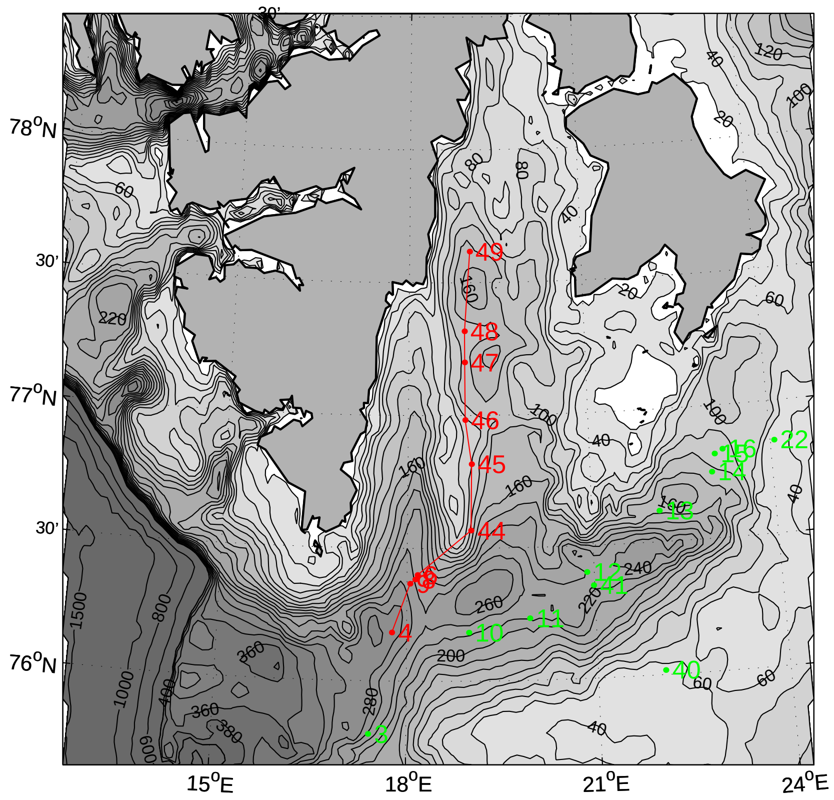
Andreas and Cash (1999, JGR)

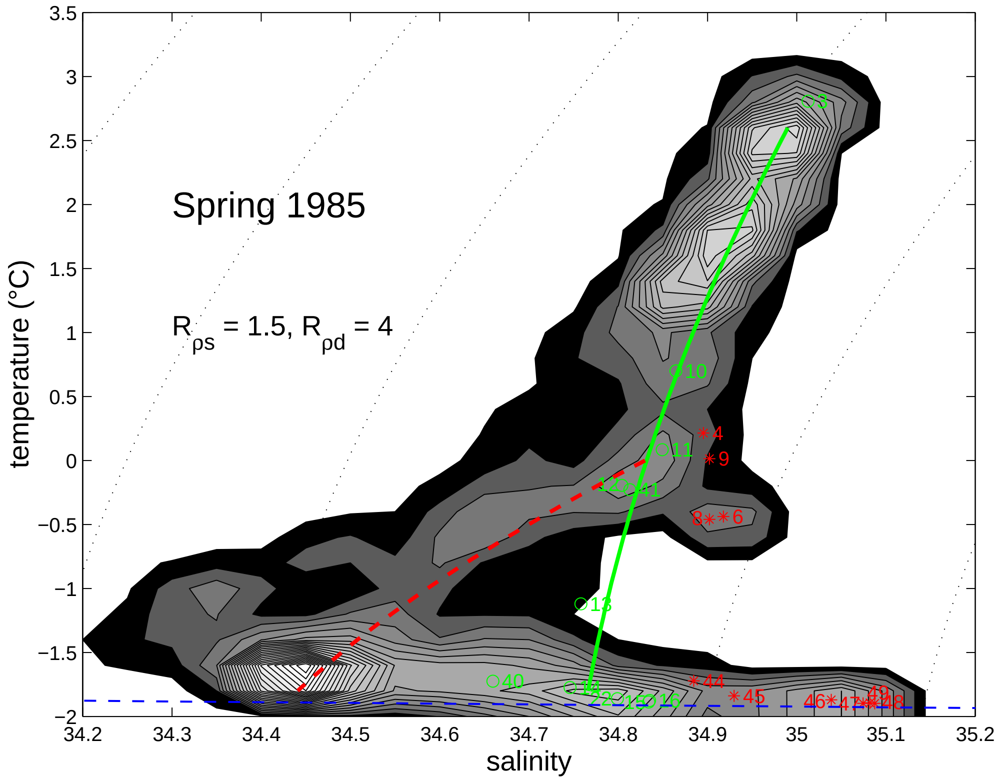
Oceanic Double diffusion

Salt fingering
Thermohaline staircases



Rudels et al. (1999, J Mar. Syst.)





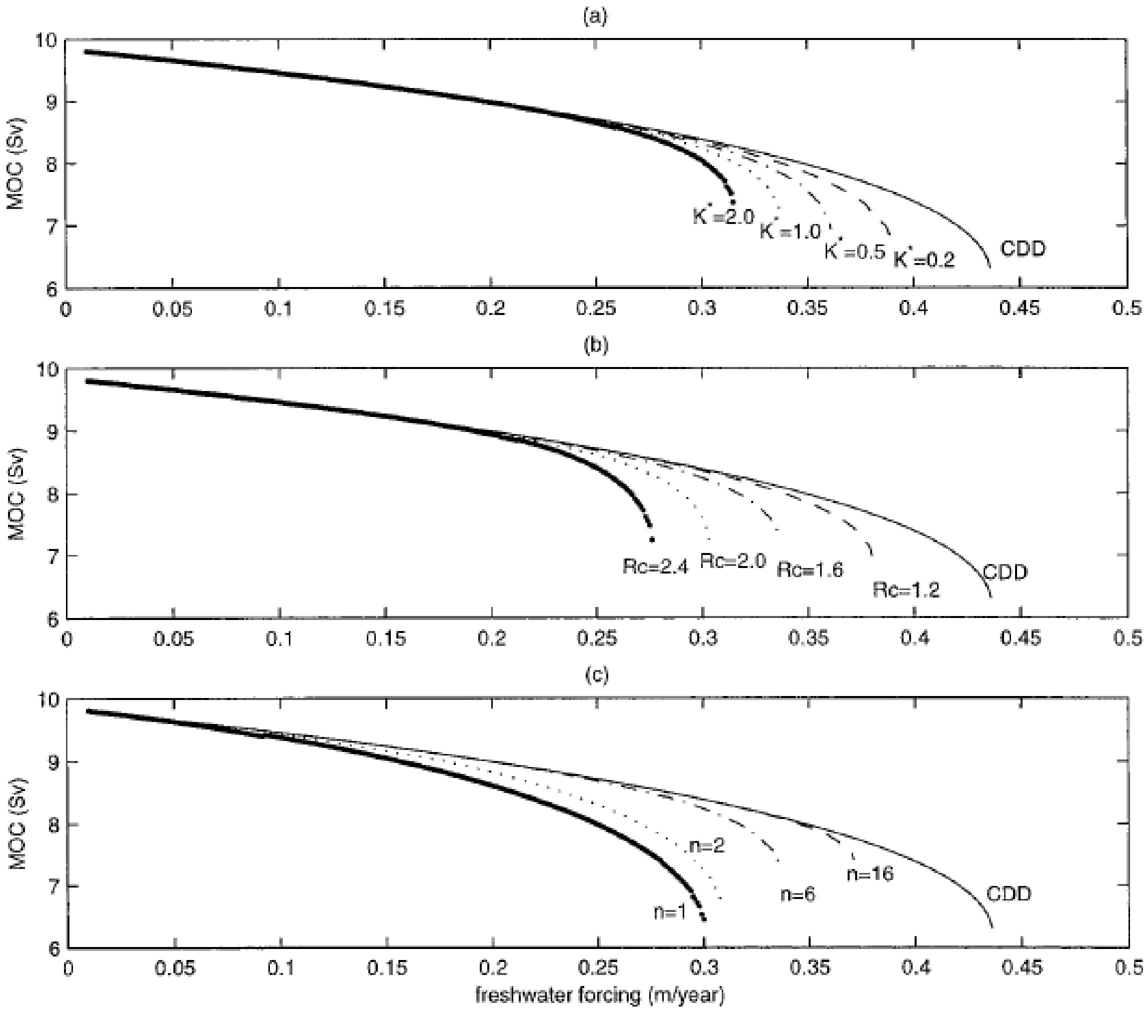
Ice melt

Salt fingering

Dense plume convection

Climate Models

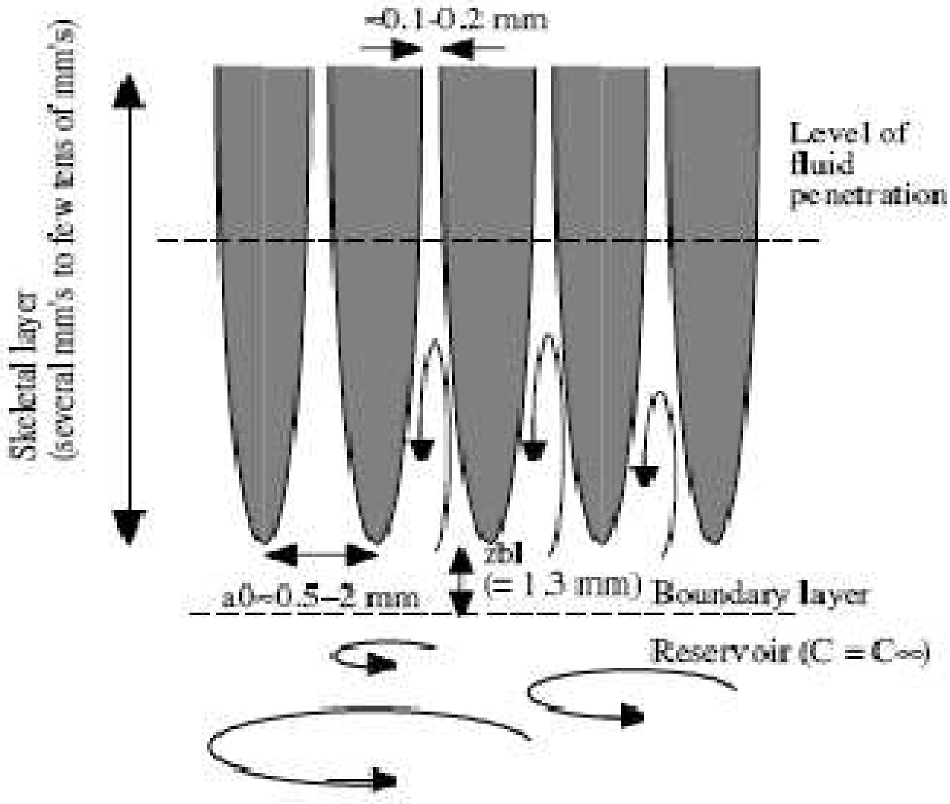
Diapycnical mixing

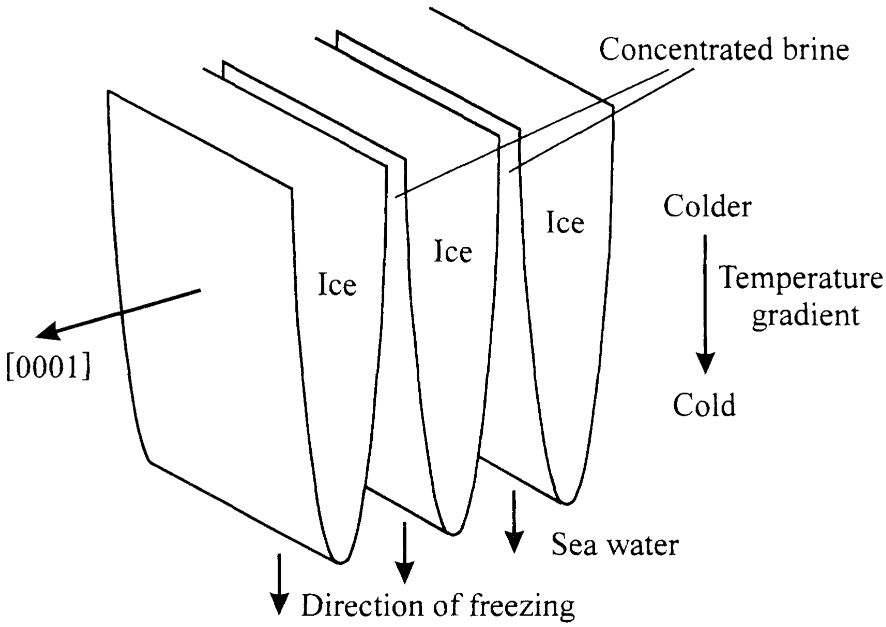


Zhang and Schmitt (1999, JPO)

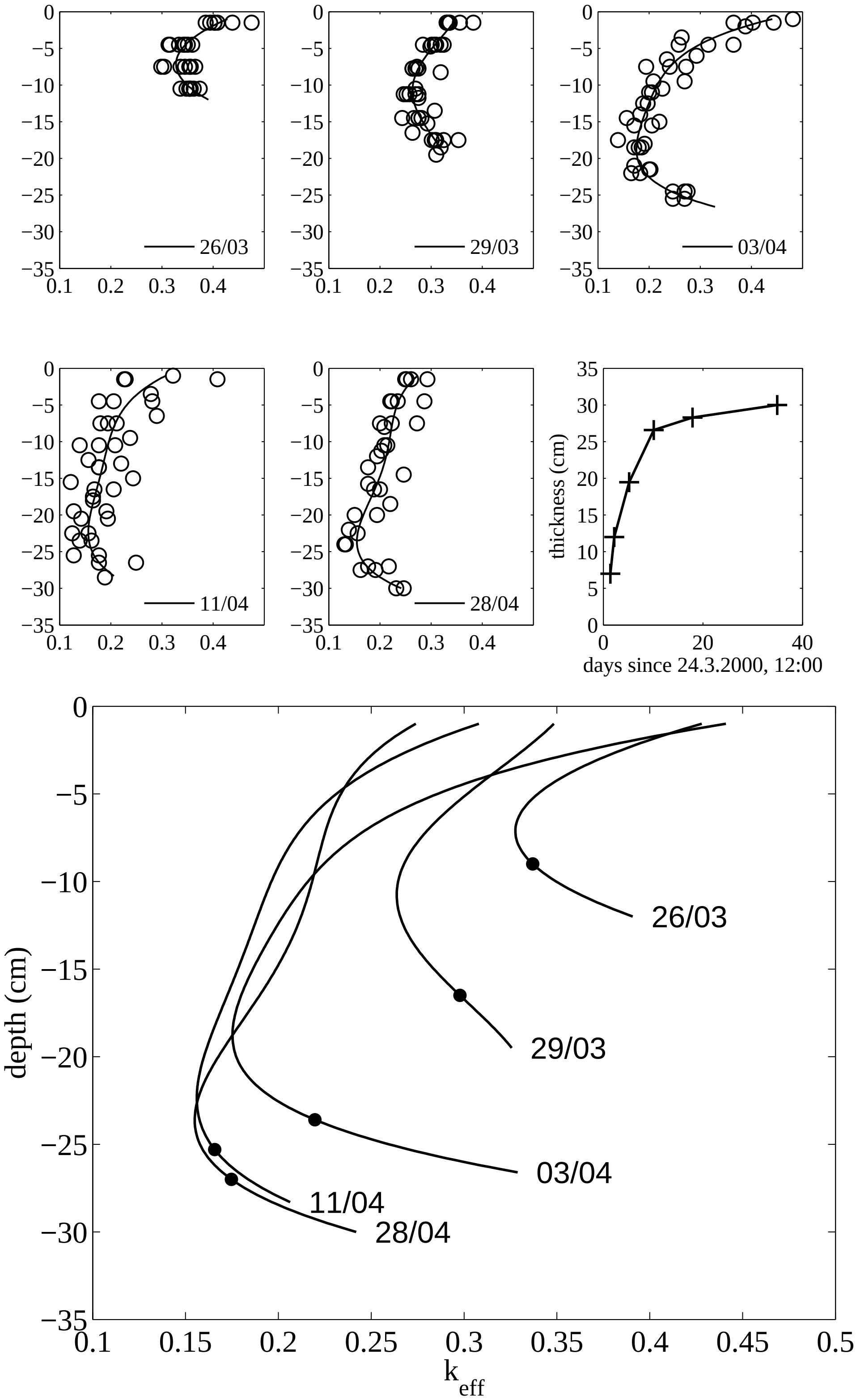
Sea ice freezing

Salt entrapment
Salt fluxes



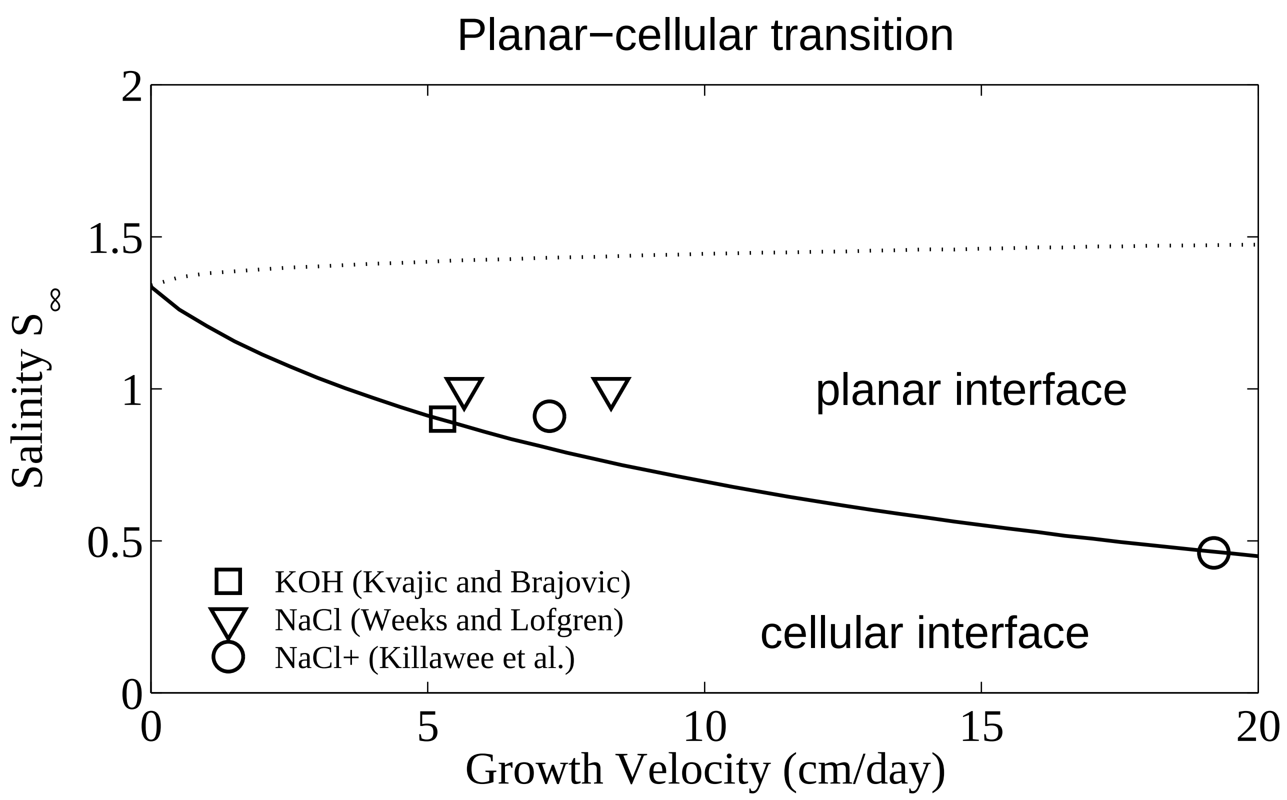


Salinity entrapment
Salt fluxes



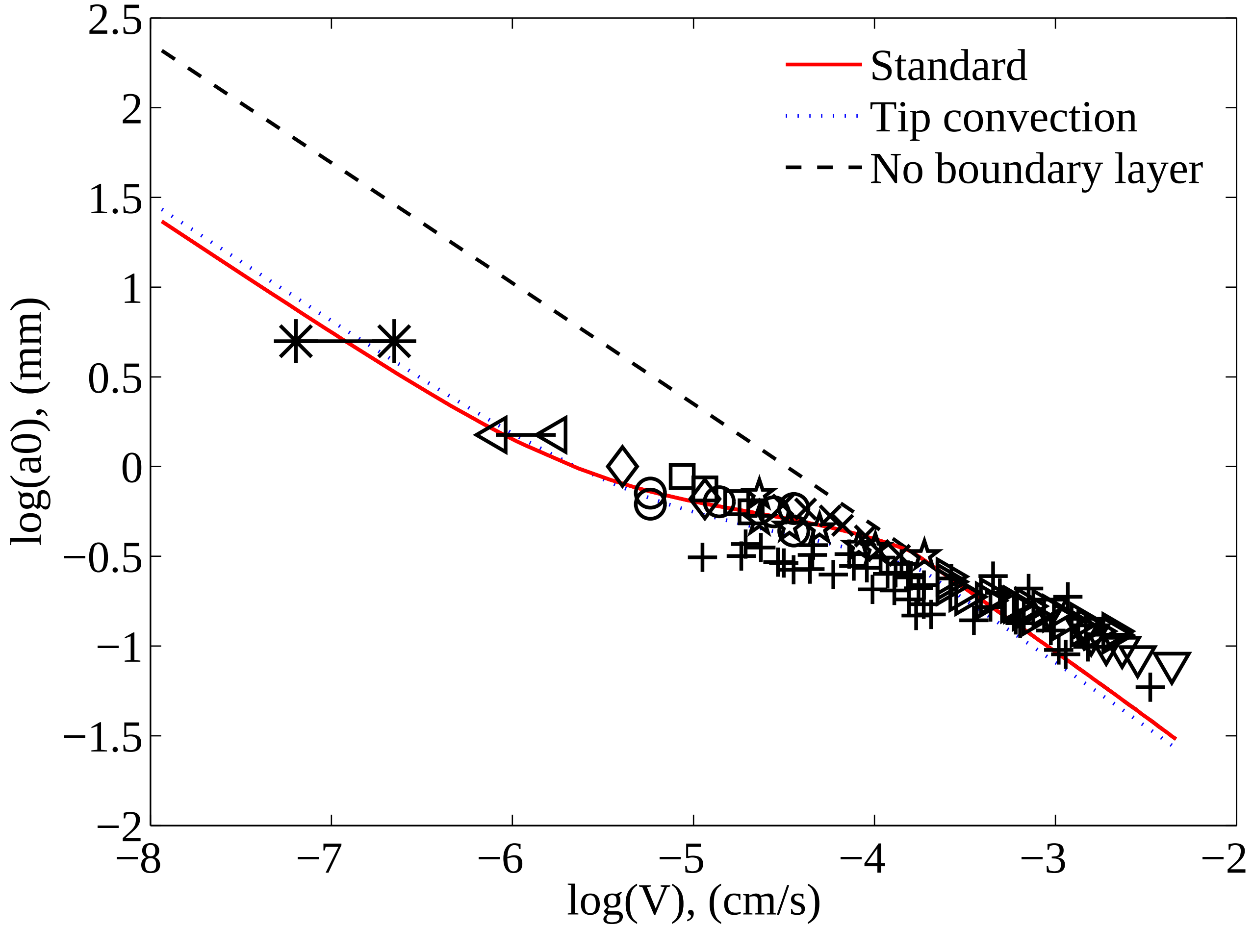
Adventfjorden observations 2000

Planar-cellular transition
Fresh versus salt ice



Sea ice microstructure

Crystal growth



Sea ice microstructure

Sea ice salinity

Salt fluxes to the ocean

Ice shelves