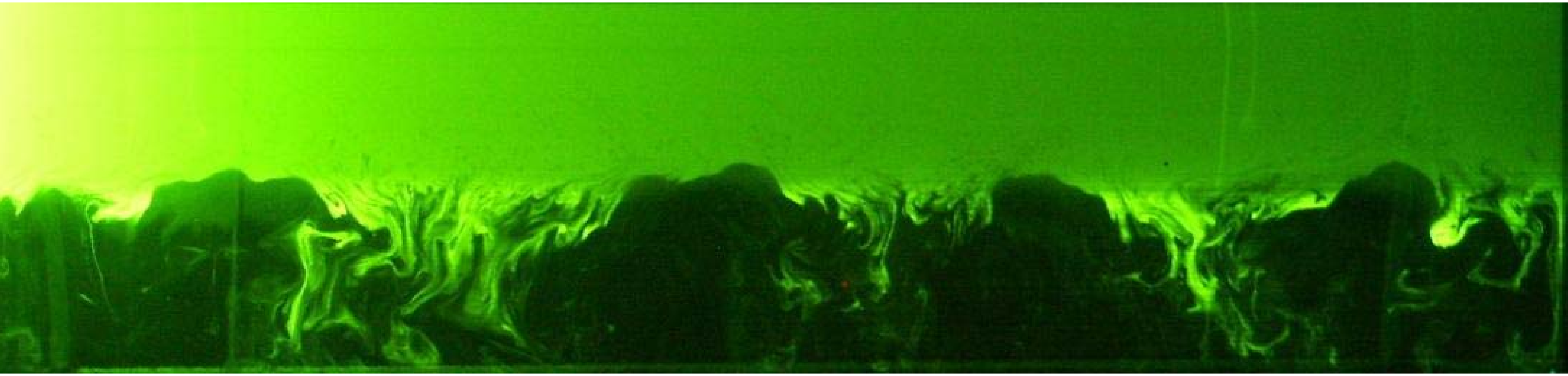
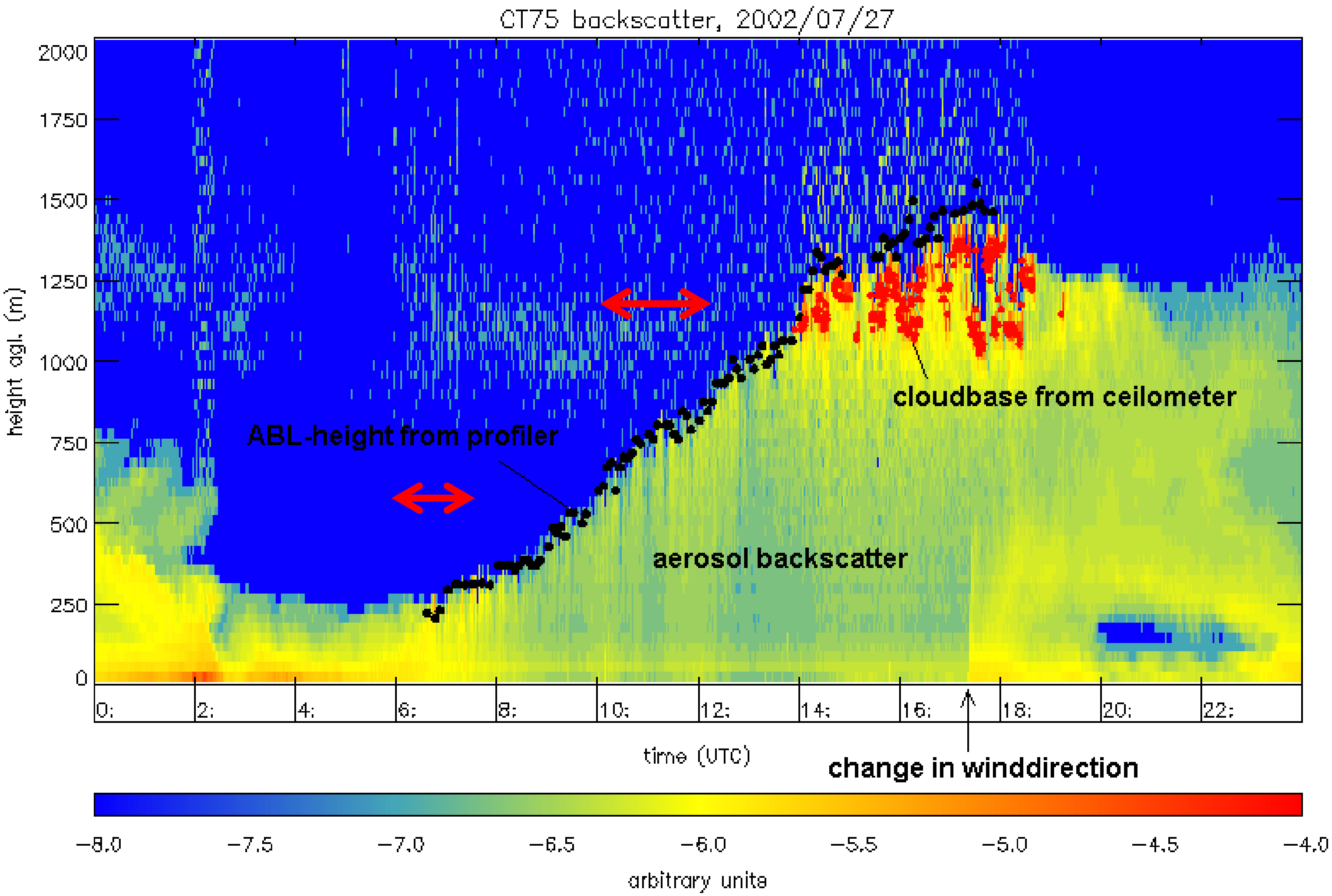
Laboratory experiments of the convective boundary layer



Harm Jonker

Multi-Scale Physics   Faculty of Applied Sciences

Evolution of the boundary layer

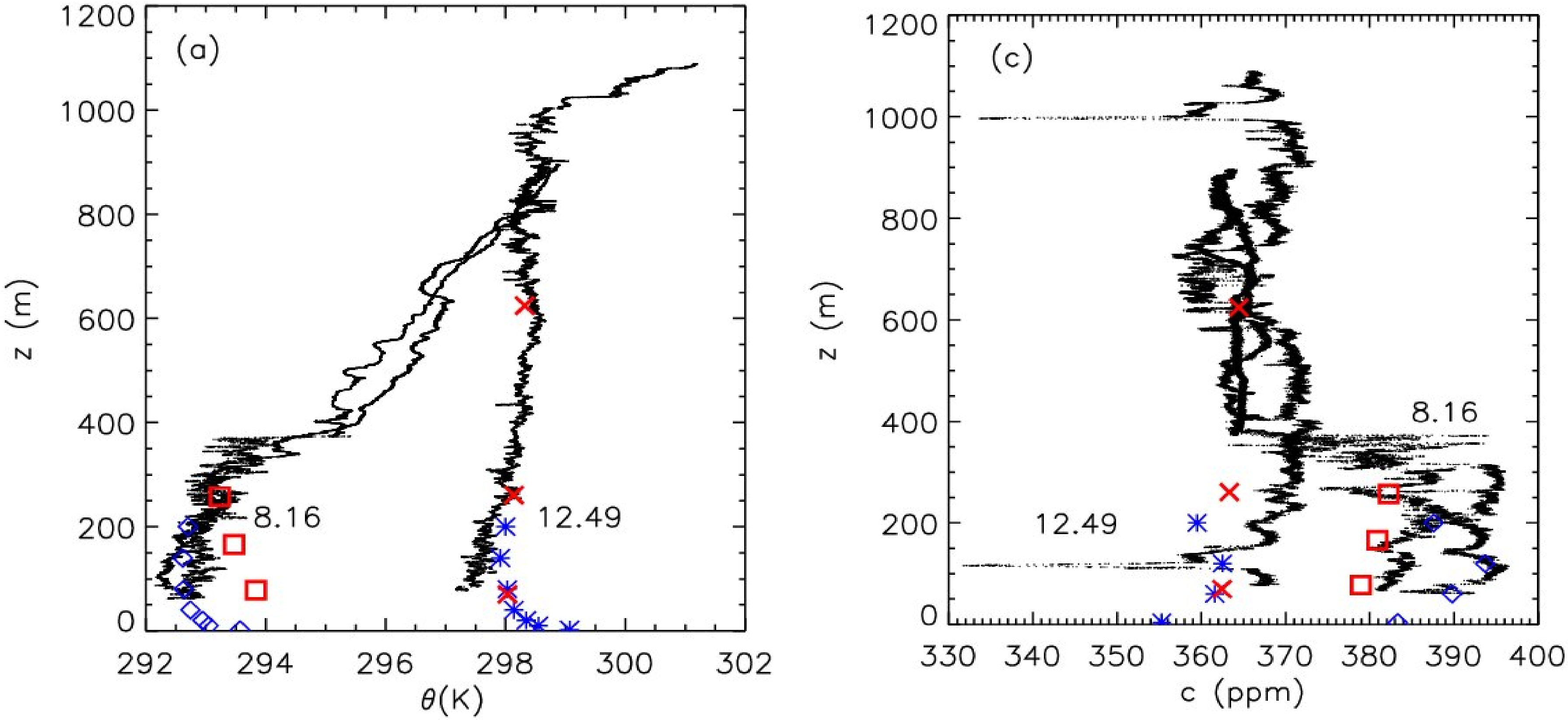


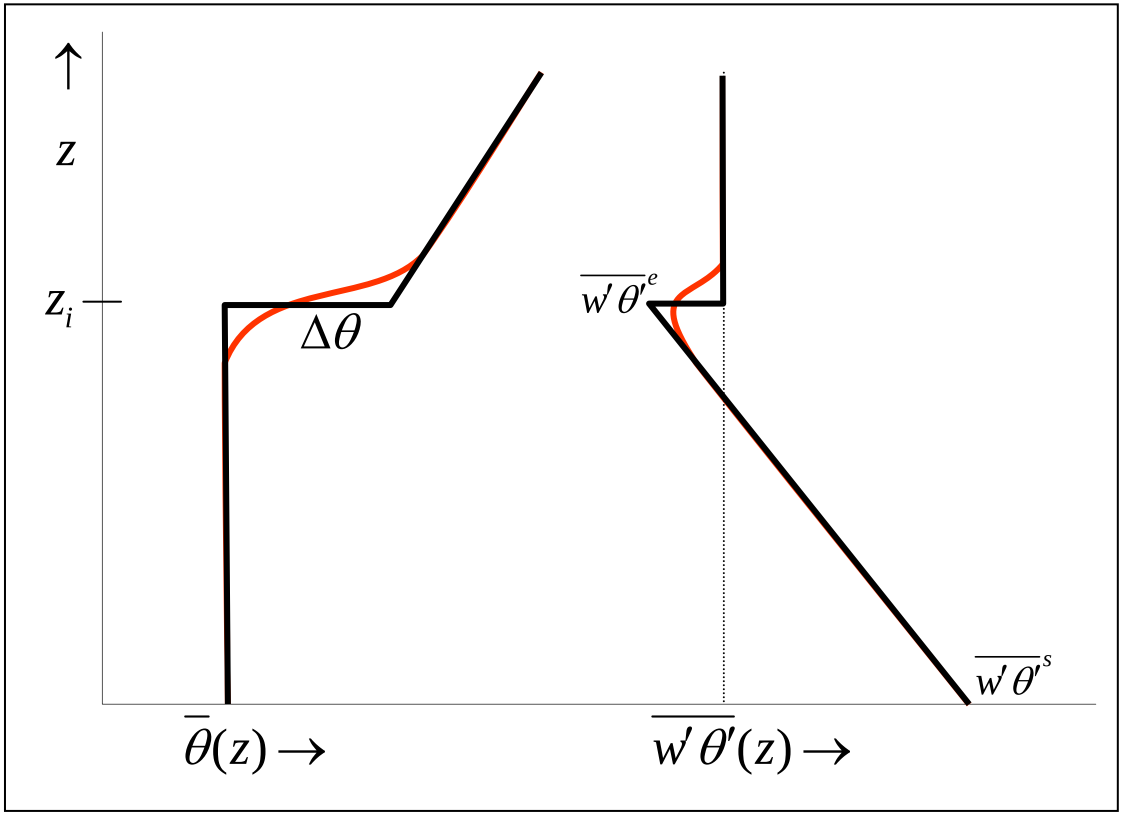
↔ Aircraft observational period

Vertical profiles

Potential temperature

Carbon dioxide





LES

e.g. Sullivan et al. 1998
van Zanten et al. 1998
Fedorovich et al. 2004

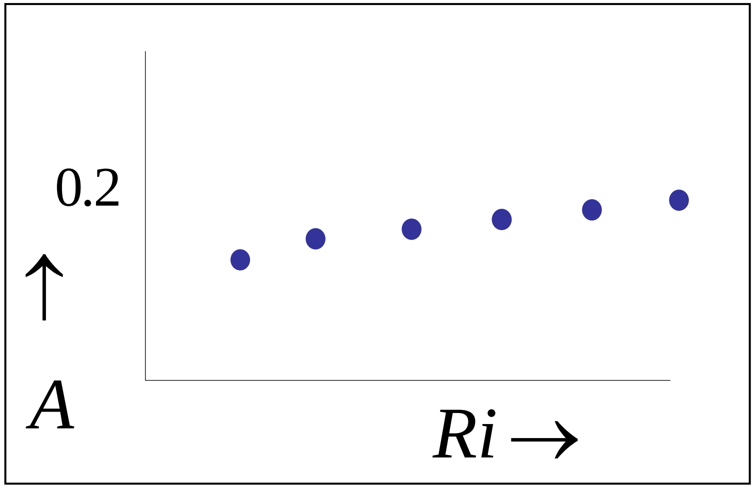
Entrainment ratio

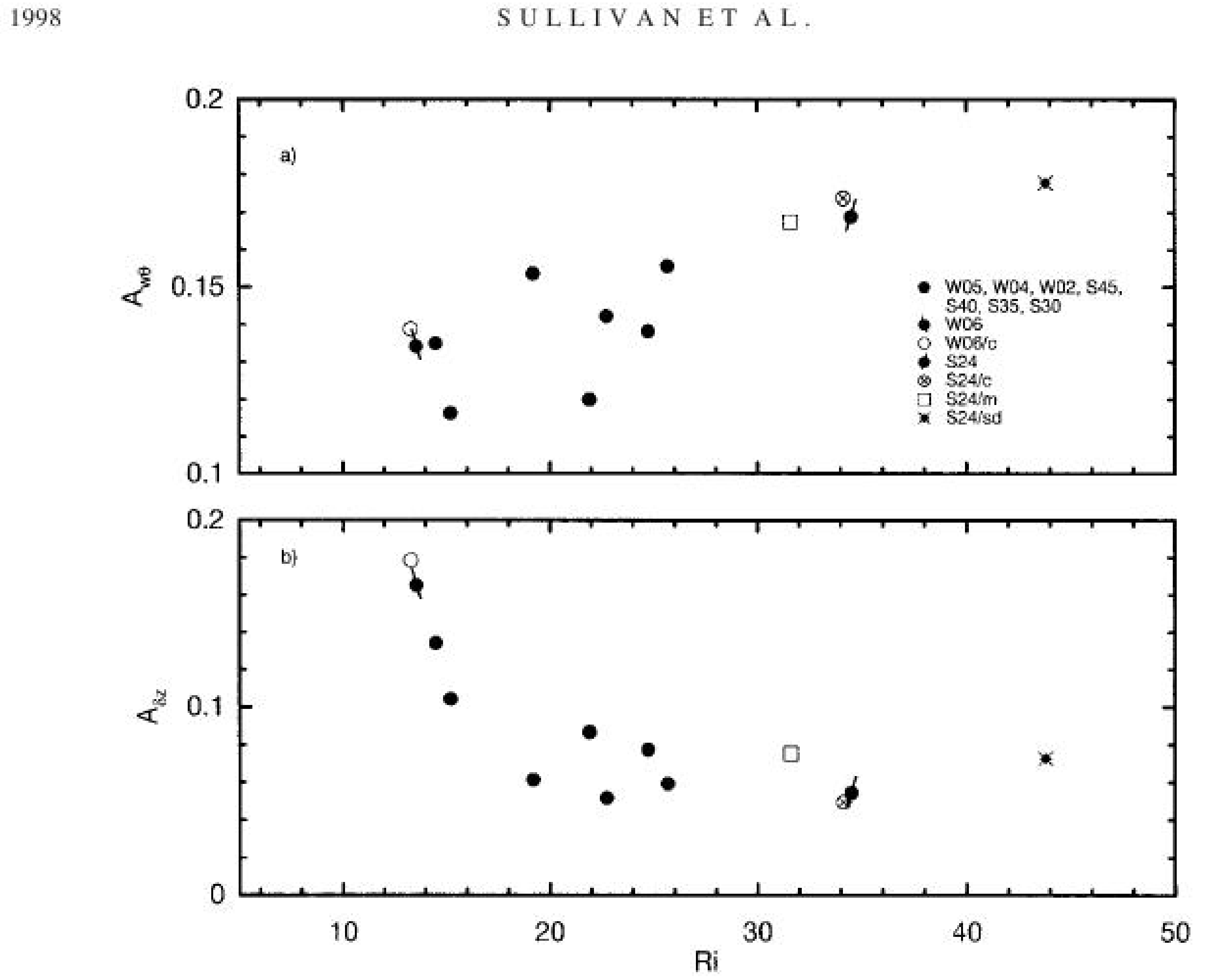
$$A = \frac{-\overline{w'\theta'}^e}{\overline{w'\theta'}^s}$$

Richardson number

$$Ri = \frac{\Delta\theta}{\theta_*} = \frac{\Delta\theta}{\overline{w'\theta'}^s / w_*}$$

$$= \frac{g}{\theta_0}\Delta\theta\, z_i / w_*^2$$





1998 SULLIVAN ET AL.

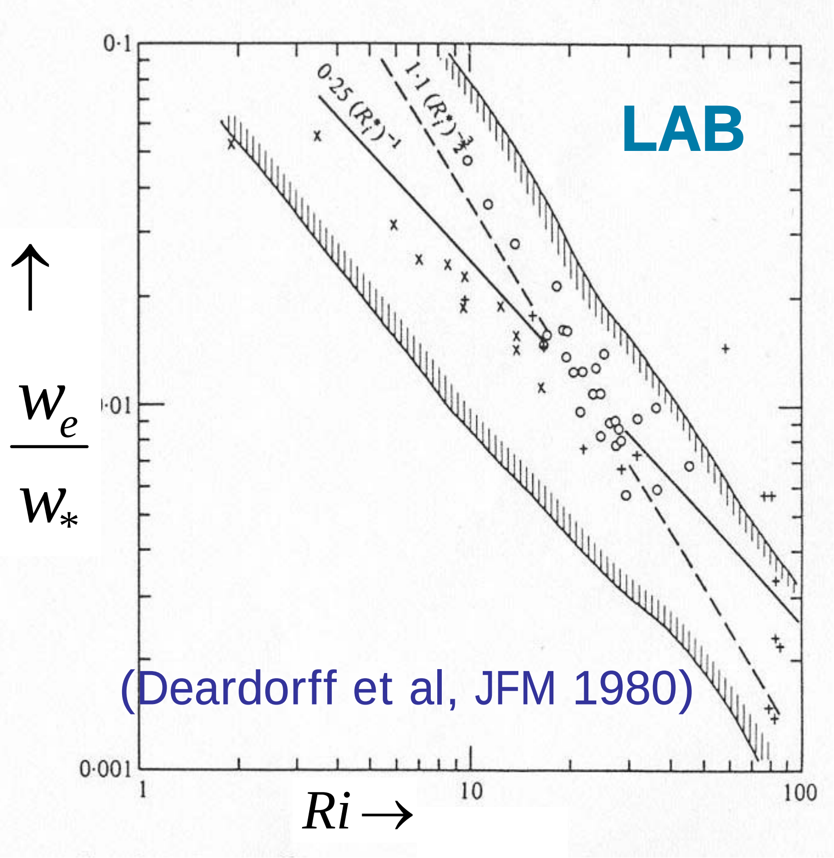
Entrainment rate

$$w_e = \frac{dz_i}{dt}$$

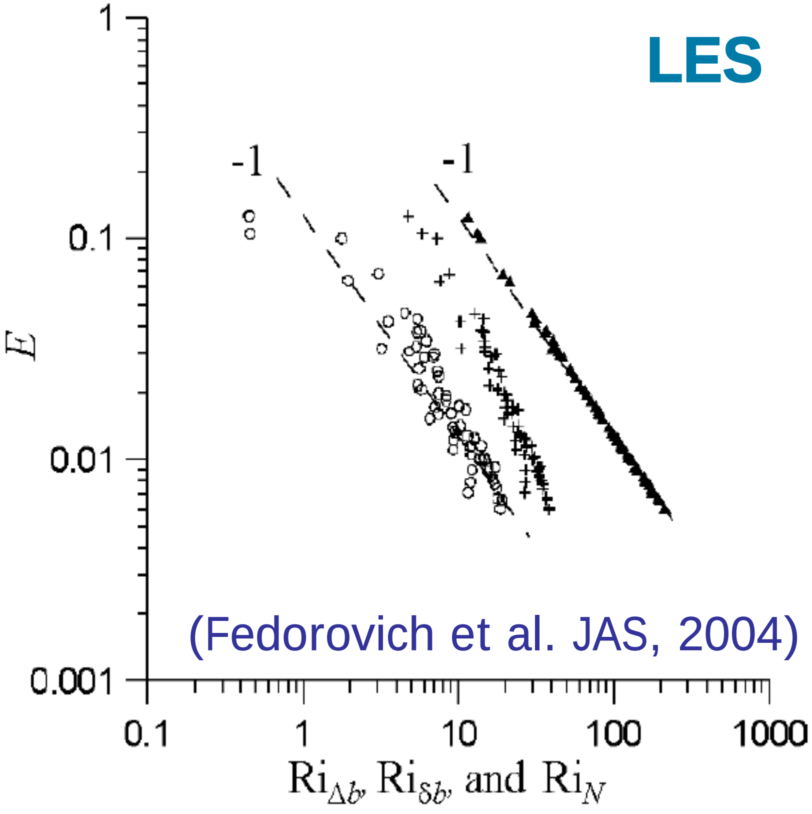
$$A = \frac{-\overline{w'\theta'}^{e}}{\overline{w'\theta'}^{s}}$$

$$\frac{w_e}{w_*} = \frac{A}{Ri}$$

$$\overline{w'\theta'}^{e} = -w_e \Delta\theta$$



(Deardorff et al, JFM 1980)



(Fedorovich et al. JAS, 2004)

Atmospheric Observations/Field experiments

- the real thing!

- incomplete information (3D,t)
- as is (no control)
- reproducibility
- parameter studies impossible

Numerical Simulation: LES (RANS, ...)

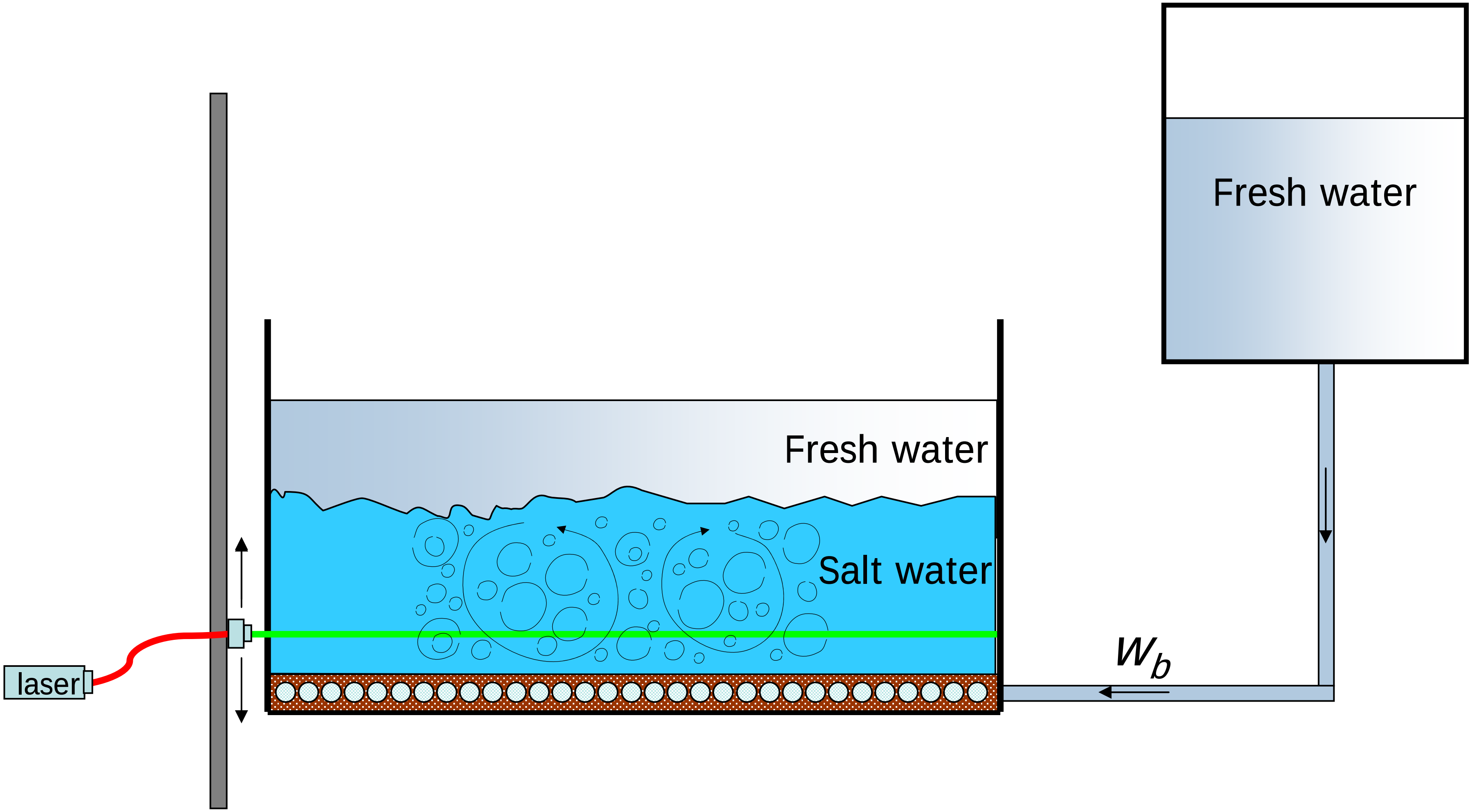
- complete information
- excellent control (forcings, b-conditions)
- reproducibility
- parameter studies!

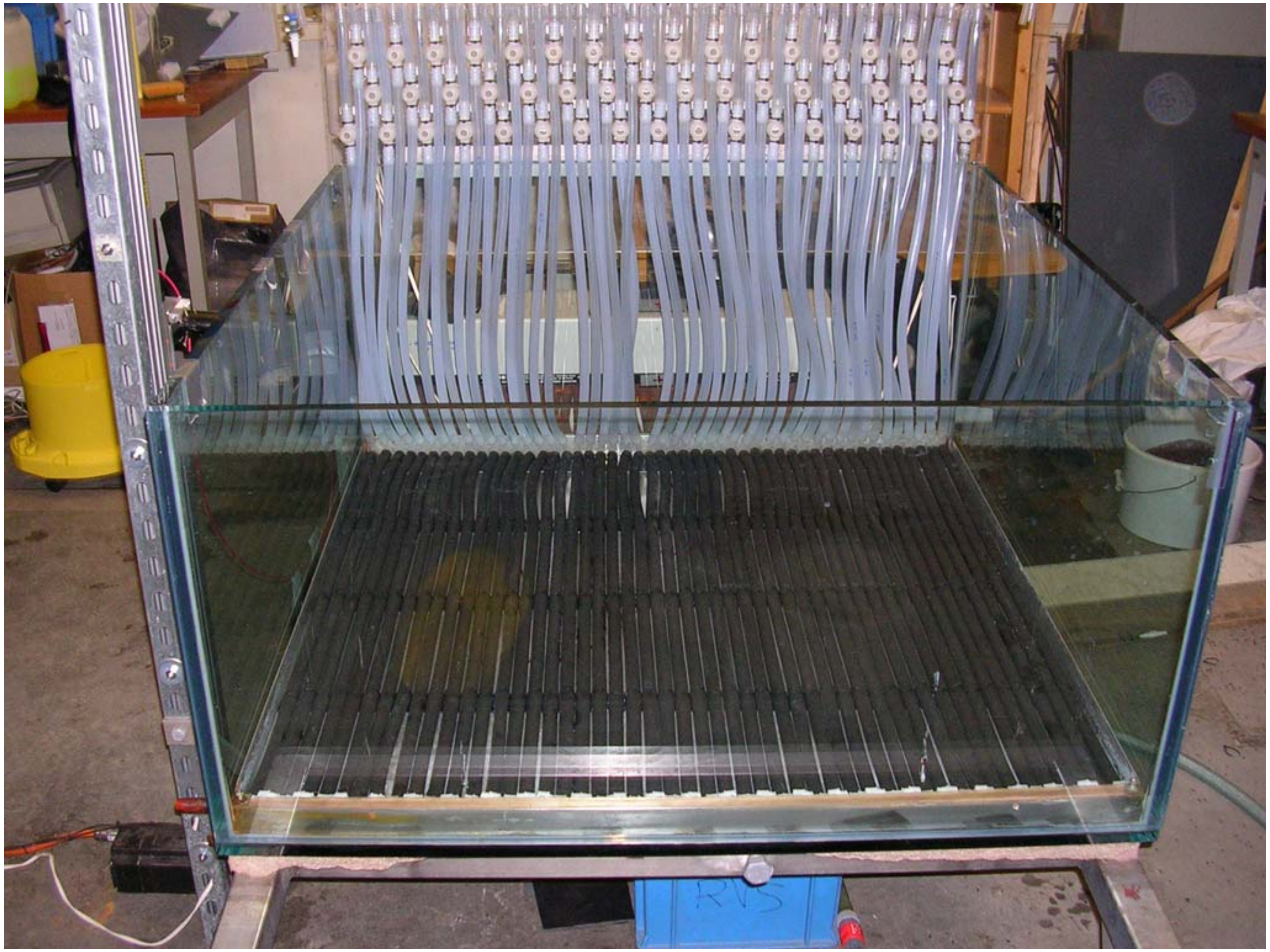
- not real
- lack of critical tests

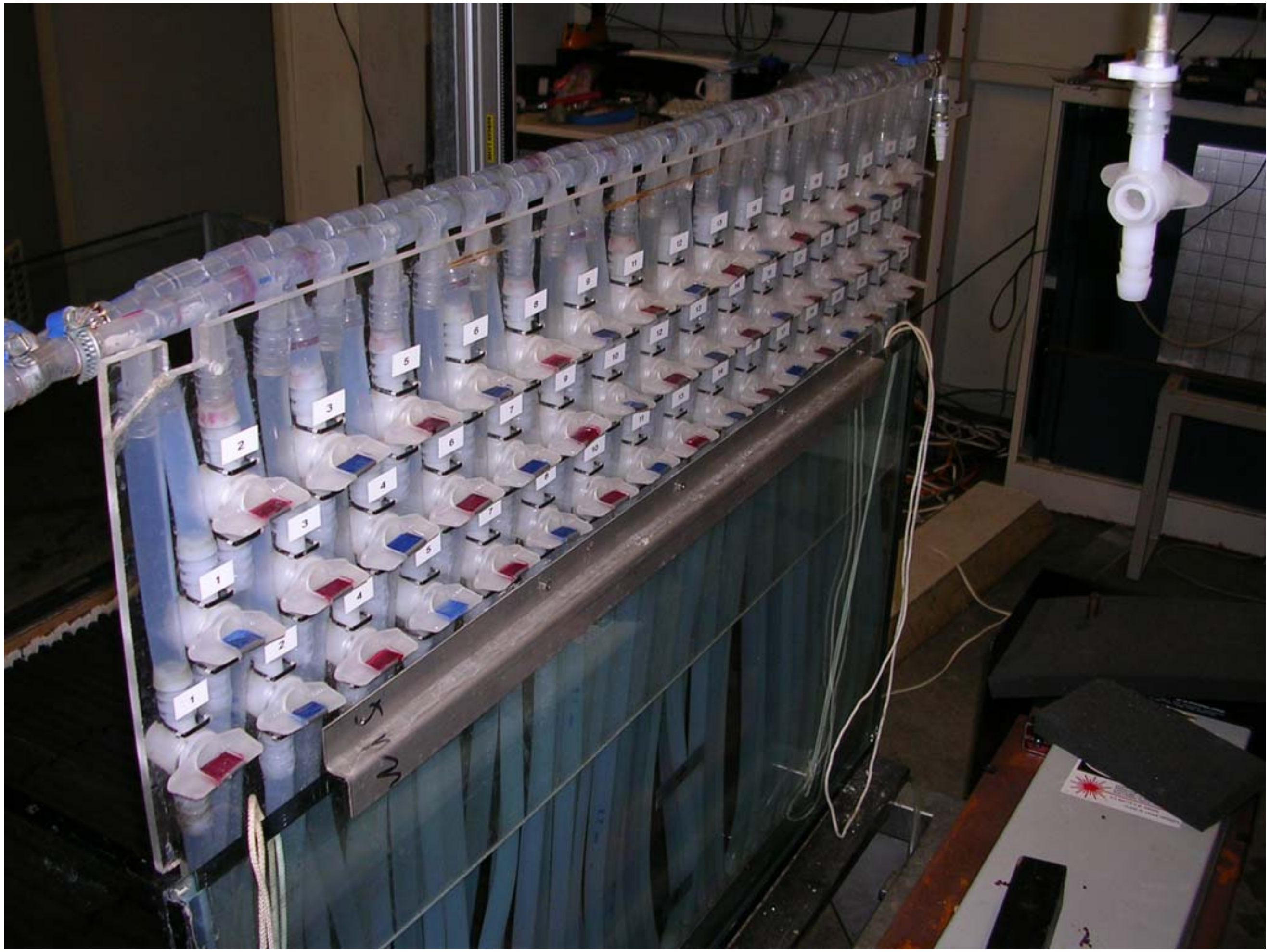
Laboratory Experiments (convection tank)

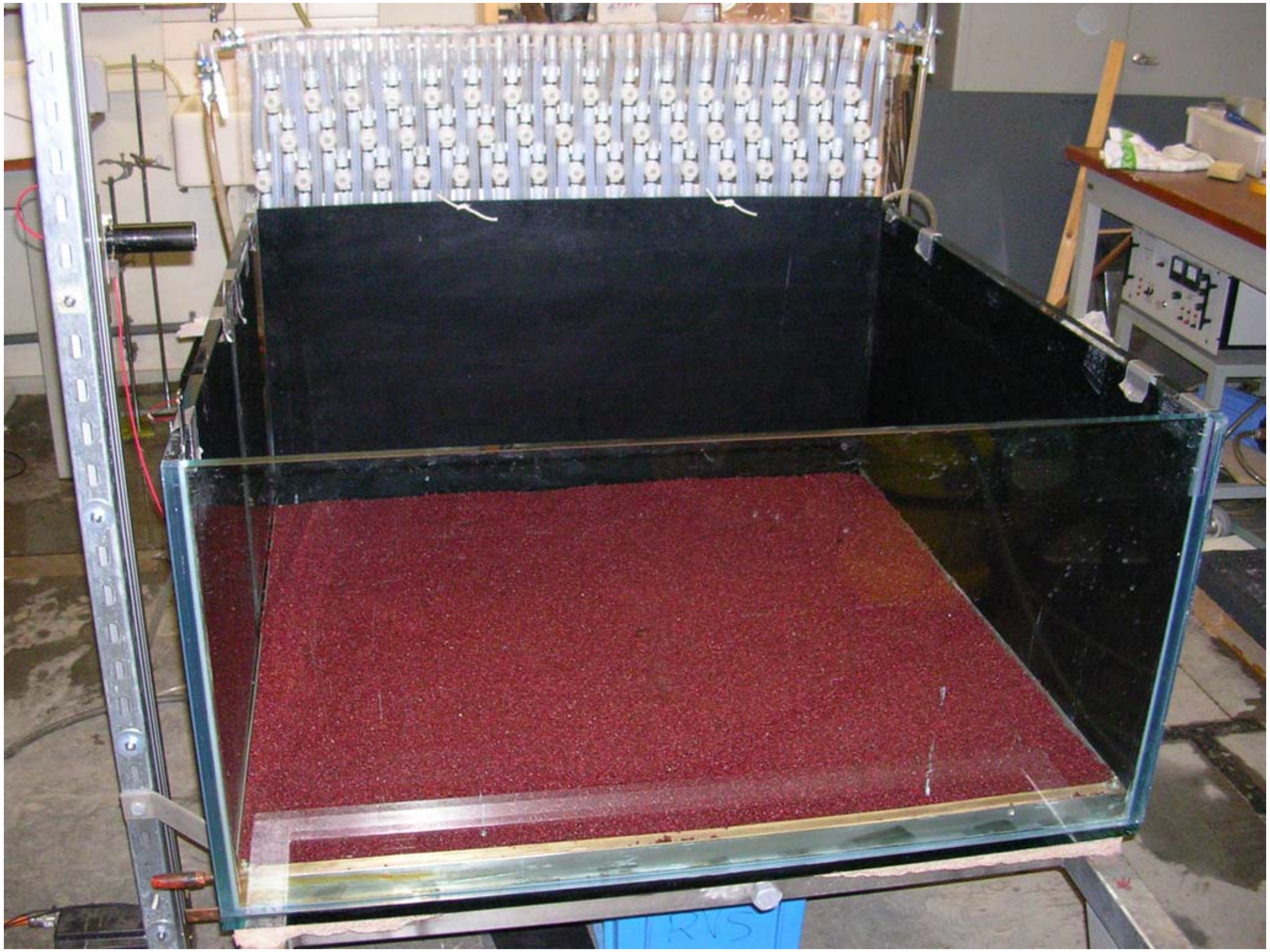
- reasonable amount of information
- reasonable control (forcings, b-conditions)
- reasonable reproducibility
- parameter studies possible
- it is real
- yields critical test for LES

Experimental setup

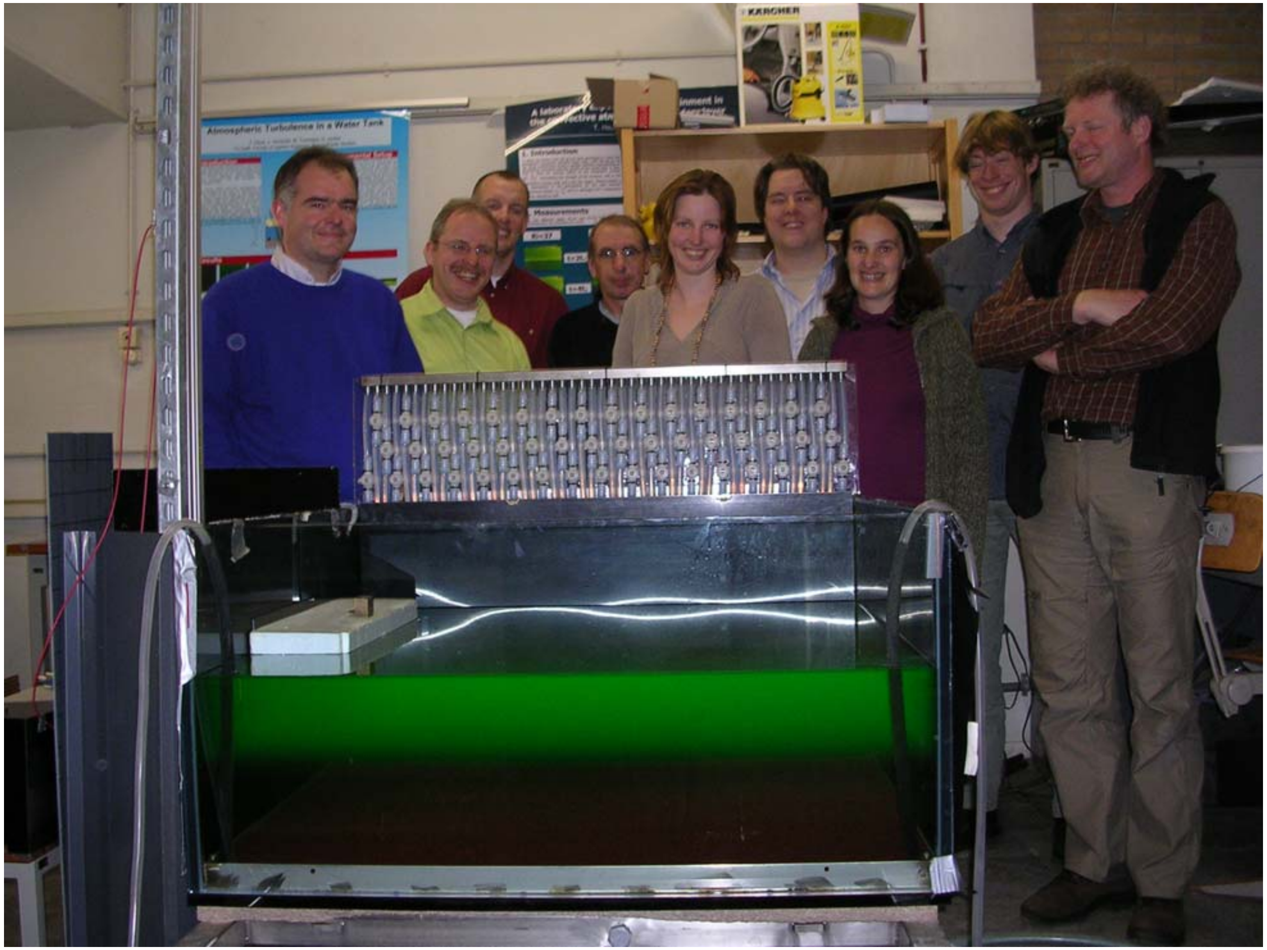



RVS



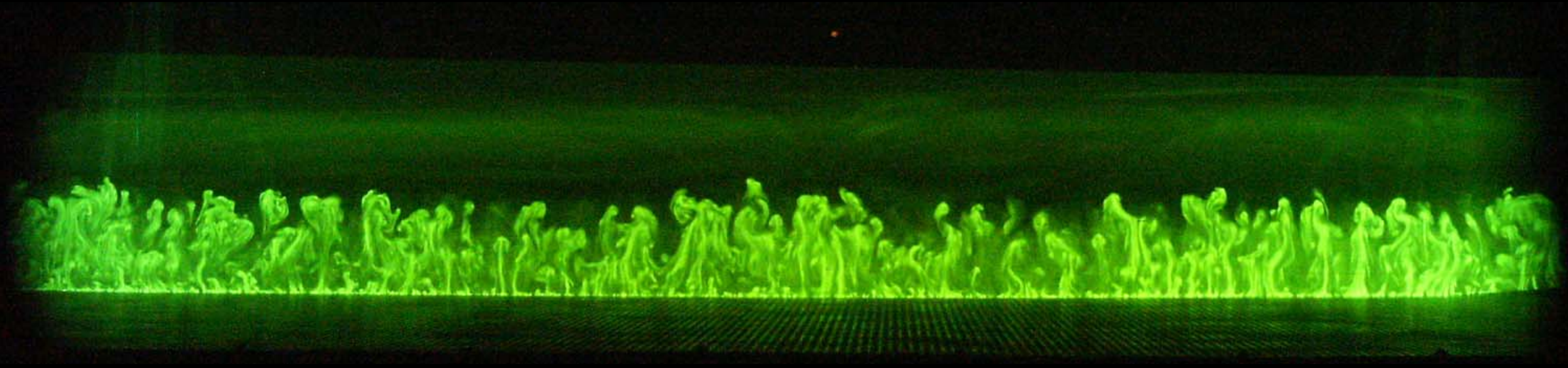


Towards quantitative results ...

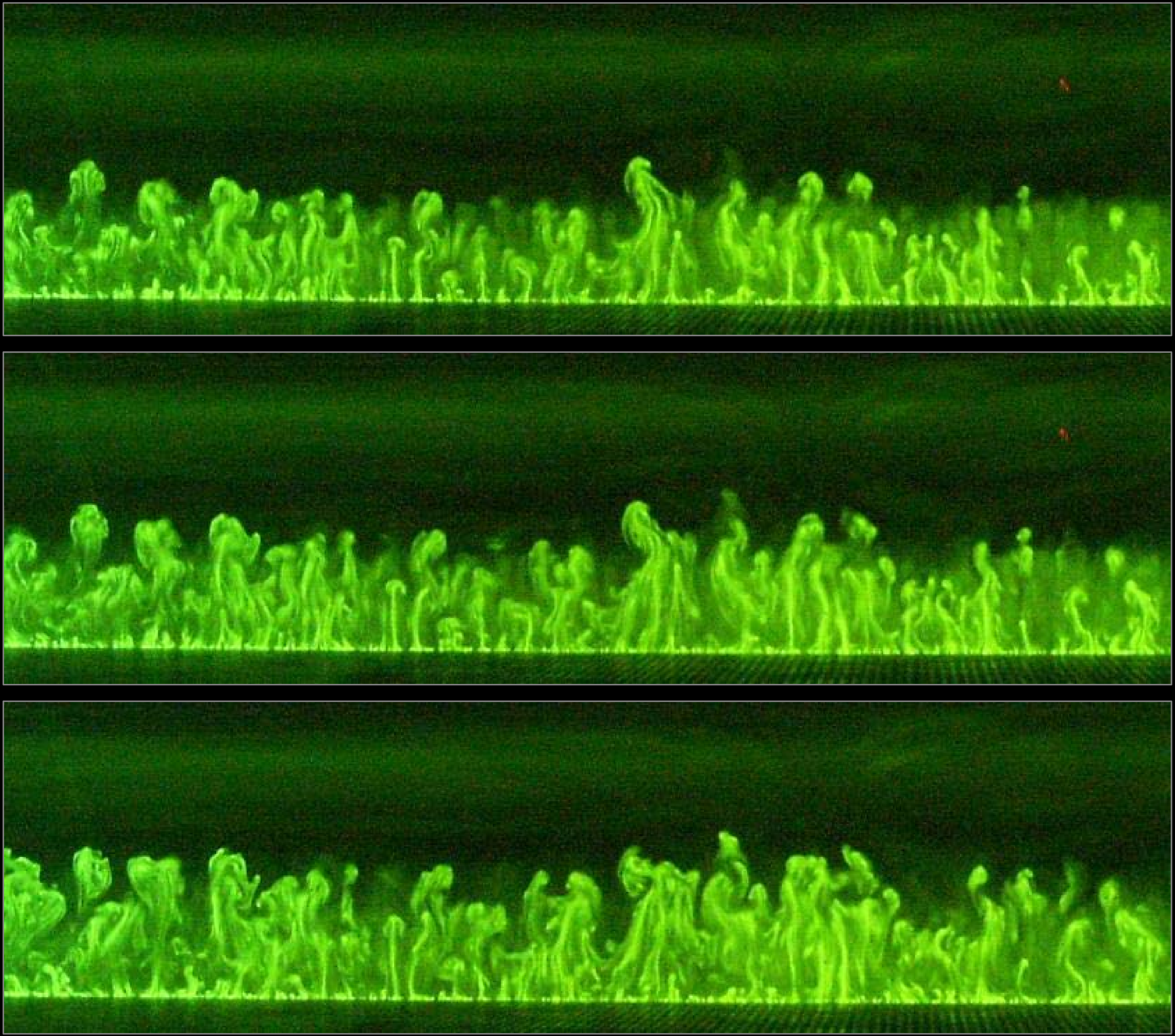


thanks to:

Erwin de Beus, Jos Verdoold, Pier Verhagen,
Esther Hagen, Jeroen Lebouille, Dr. Maria Antonia Jimenez,
Thijs Heus, Rob Rodink, Philia Lijdsman, Daniel Abrahams



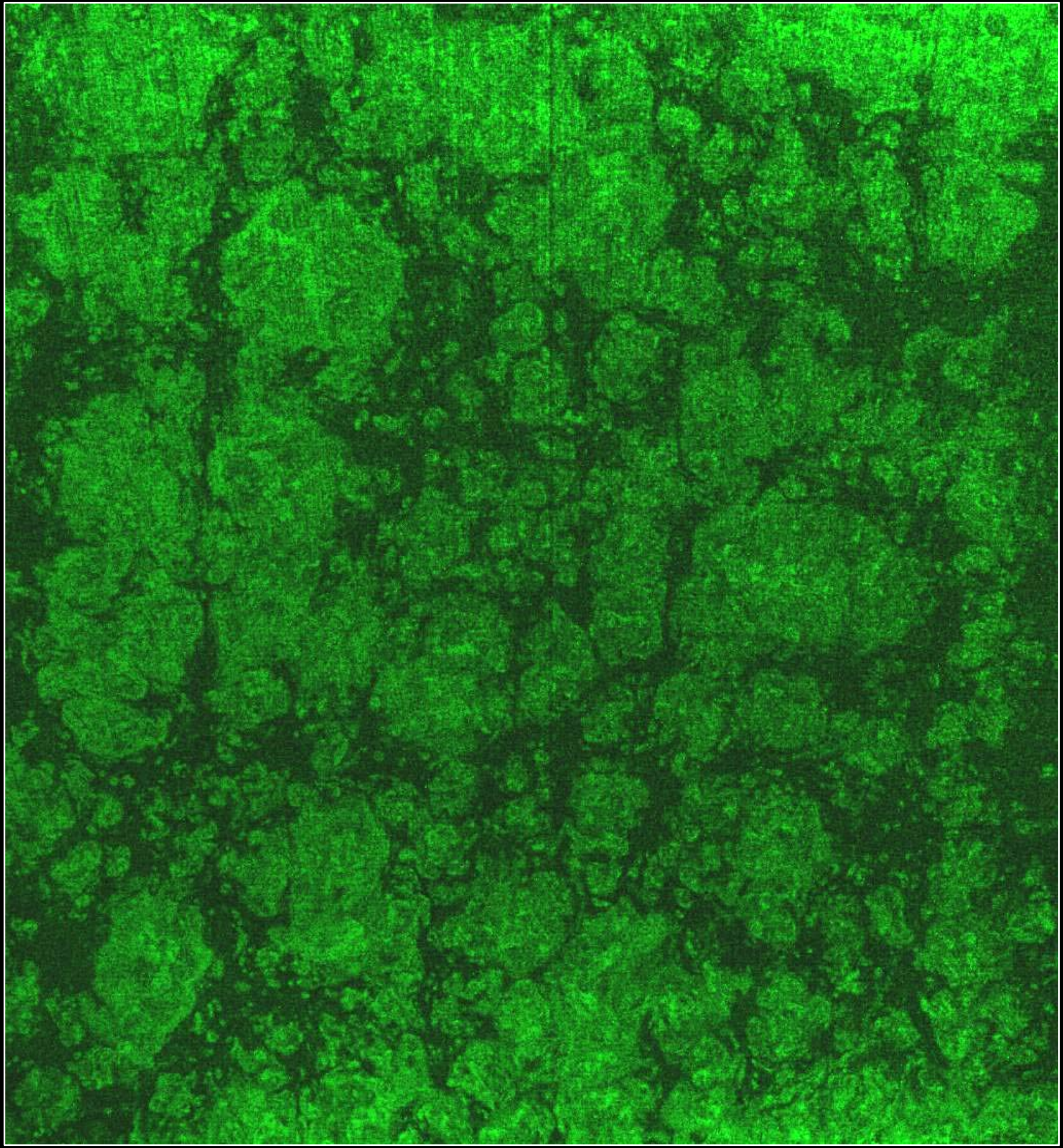
LIF
Vertical
sheet
Δt: 4s

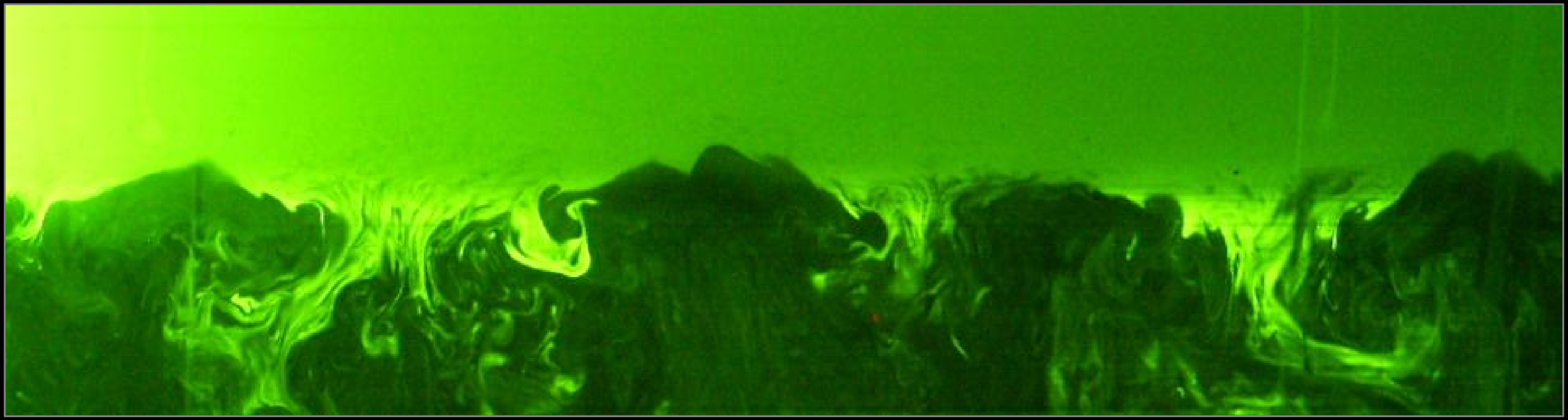


Lab. Exp.

Horizontal cross section

"bottom-up" tracer





Tank parameters:

Density difference $\Delta\rho = \rho_{ml} - \rho_0$

Draining velocity w_b

Mixed layer depth h

Viscosity ν **Diffusivity** D

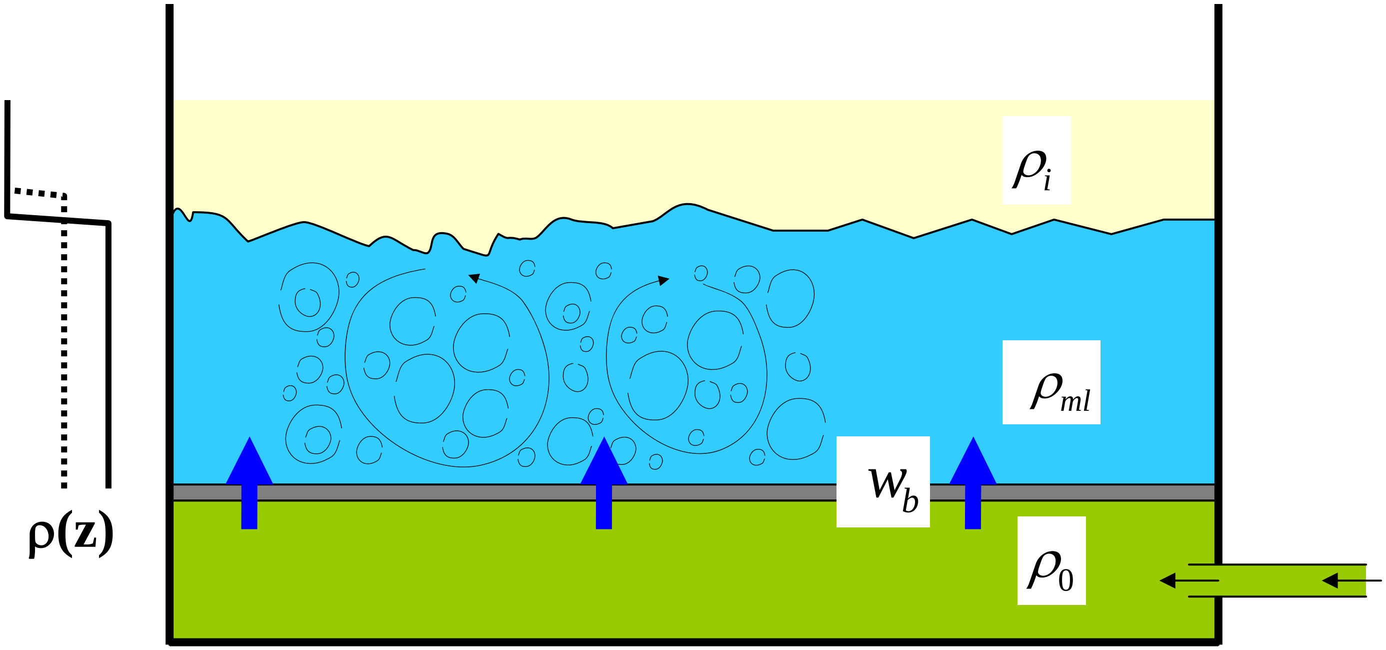
Buoyancy flux:

$$B_s = \frac{g}{\rho_0} w_b (\rho_{ml} - \rho_0)$$

$$= g w_b \frac{\Delta\rho}{\rho_0}$$

$$w_* = (B_s h)^{1/3}$$

Convective velocity scale



Tank parameters:

Buoyancy flux:

Density difference $\Delta\rho/\rho_0 = 10^{-2} (= 1\%)$

Fill velocity $w_b = 10^{-5} m/s$

Mixed layer depth $h = 0.1m$

$$B_s = g w_b \frac{\Delta\rho}{\rho_0}$$

$$= 10^{-6} m^2/s^3$$

Viscosity $\nu = 10^{-6} m^2/s$ **Diffusivity** $D = 10^{-9} m^2/s$

➡ $w_* = (B_s h)^{1/3} \cong 1 cm/s$

$$\mathrm{Re} = \frac{w_* h}{\nu} = 1000 \qquad \mathrm{Pe} = 10^6$$

$$t_* = h/w_* \cong 10s$$

$$\eta = h\,\mathrm{Re}^{-3/4} \cong 1mm$$

$$Ra_{flux} = \frac{B_s h^4}{\nu D^2} = 10^{15} = 10^9 Sc^2$$

Atmosphere

- h_i = 1 km
- w_* = 1 m/s
- t_* = 15 min
- Re = 10^8
- Pe = 10^8

$$\eta = 1\text{mm}$$

$$\varepsilon = 10^{-3}\,\text{m}^2\text{s}^{-3}$$

Water tank

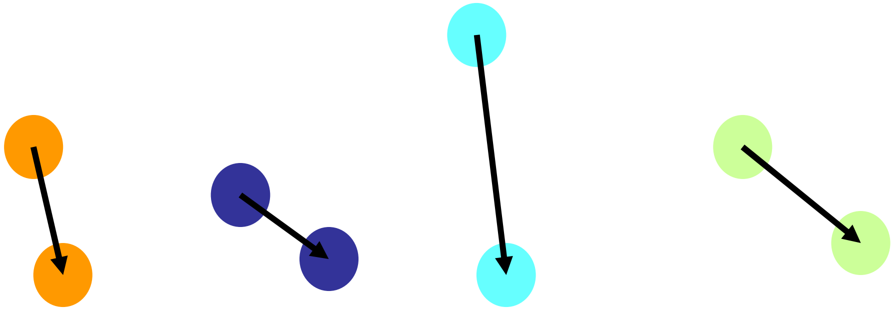
- h_i = 10 cm
- w_* = 1 cm/s
- t_* = 10 sec
- Re =10^3
- Pe = 10^6

$$\eta = 1\text{mm}$$

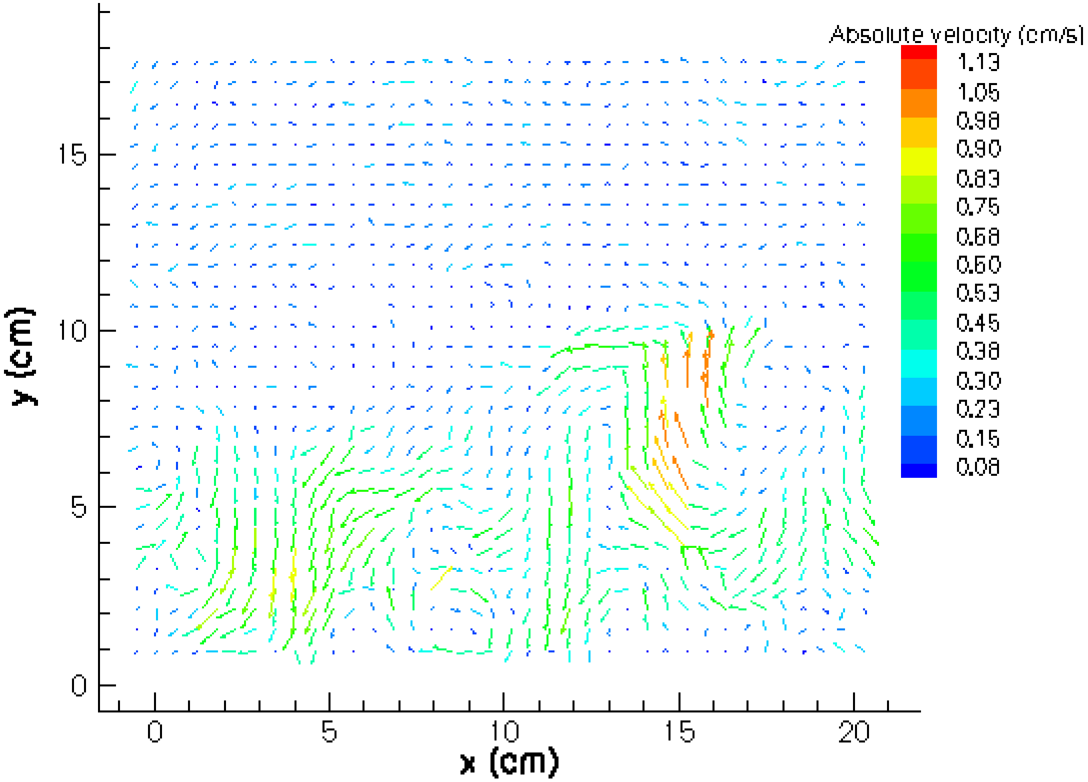
$$\varepsilon = 10^{-5}\,\text{m}^2\text{s}^{-3}$$

Measurement Methods
PIV
LIF

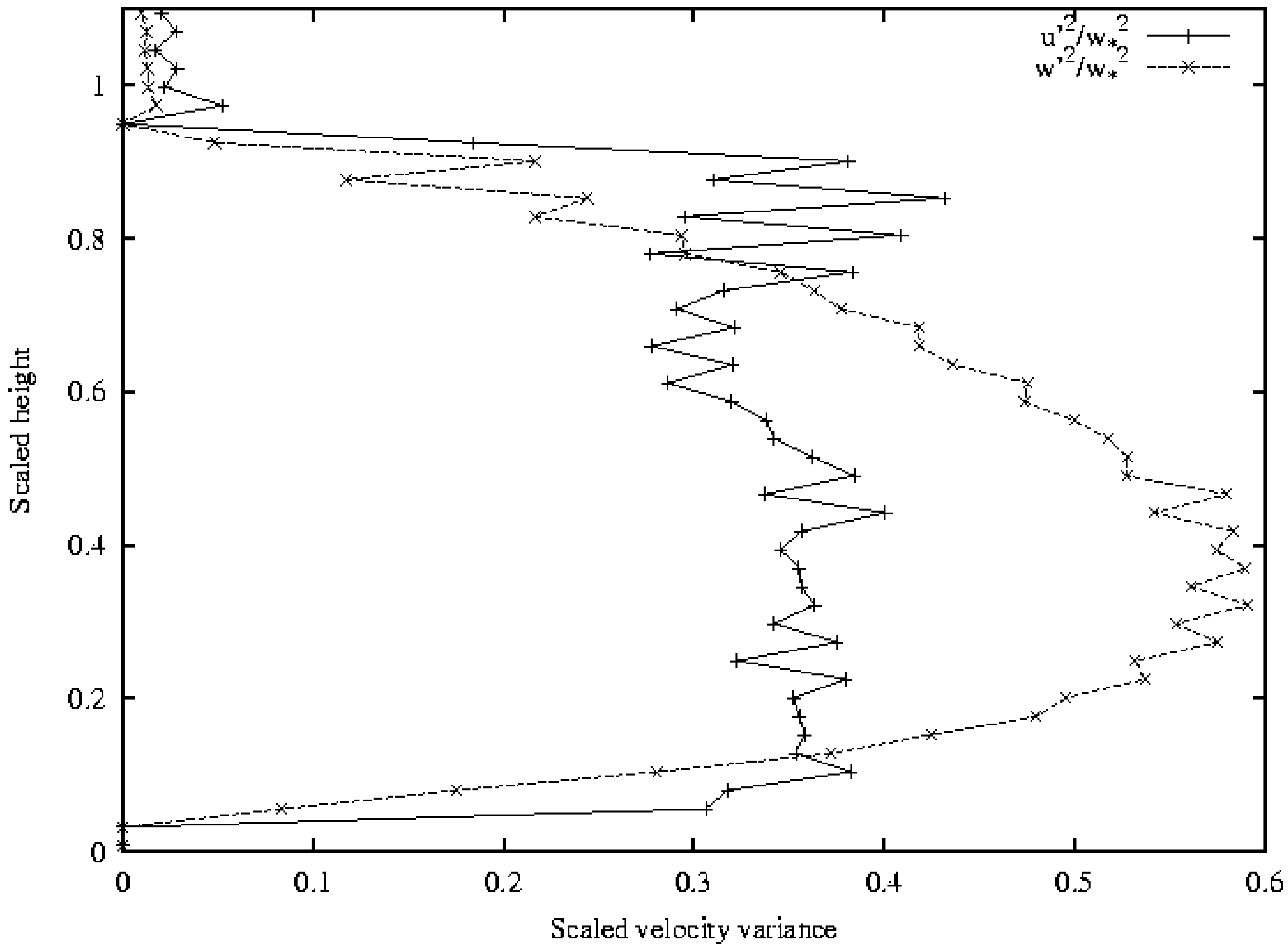
Particle Imaging Velocimetry (PIV)



PIV


Absolute velocity (cm/s)
1.13
1.05
0.98
0.90
0.83
0.75
0.68
0.60
0.53
0.45
0.38
0.30
0.23
0.15
0.08
y (cm)
15
10
5
0
x (cm)
0
5
10
15
20

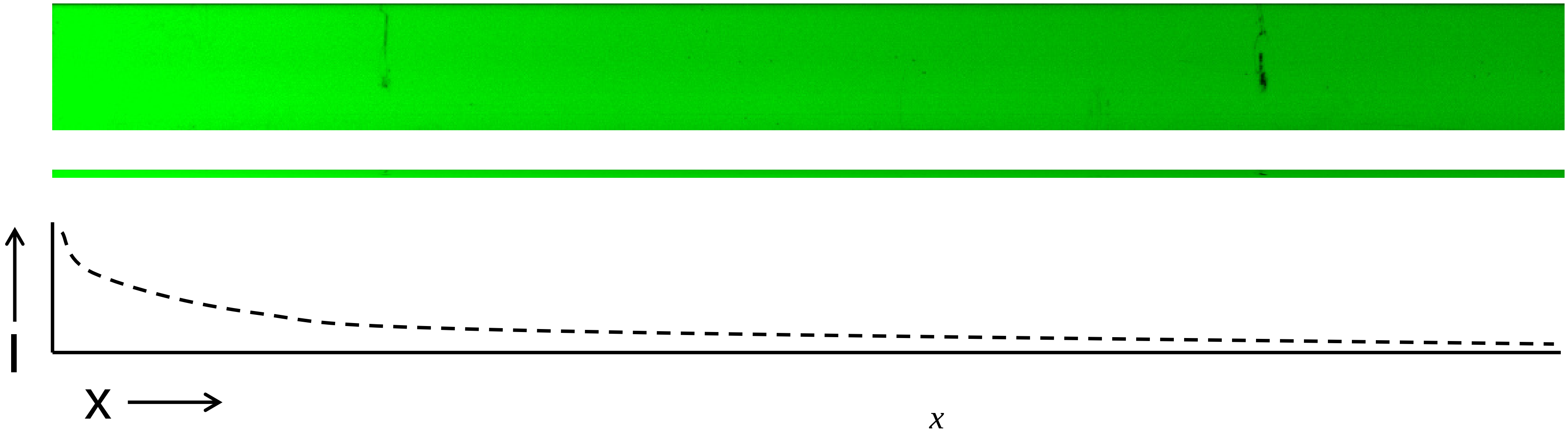
PIV-results



u'^2/w_*^2
w'^2/w_*^2
Scaled height
Scaled velocity variance
0
0.2
0.4
0.6
0.8
1
0
0.1
0.2
0.3
0.4
0.5
0.6

Accurate measurement concentration

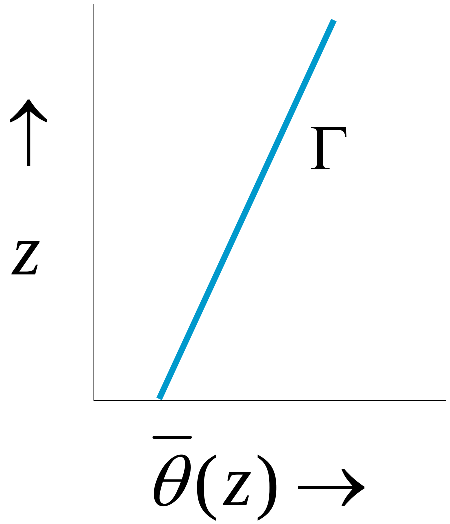
Extinction

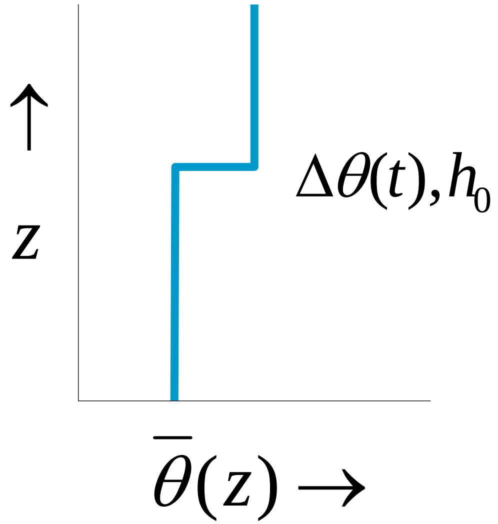


$$I(C,x) = \beta I_0 C(x) e^{-\int_0^x \varepsilon C(x)\,dx - \eta x}$$

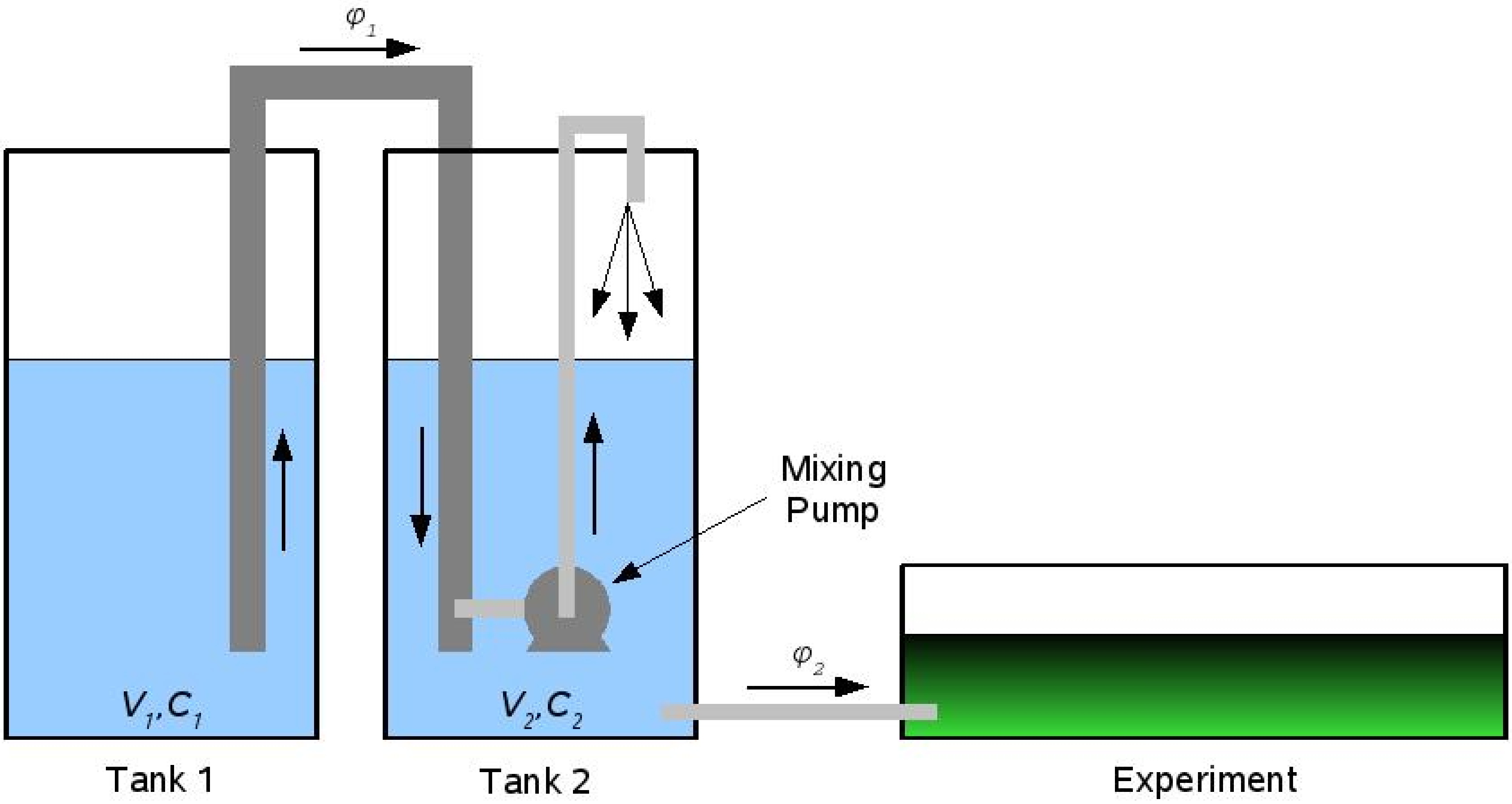
$$I(C,x) = \beta I_0 C e^{-(\varepsilon C + \eta) x}$$

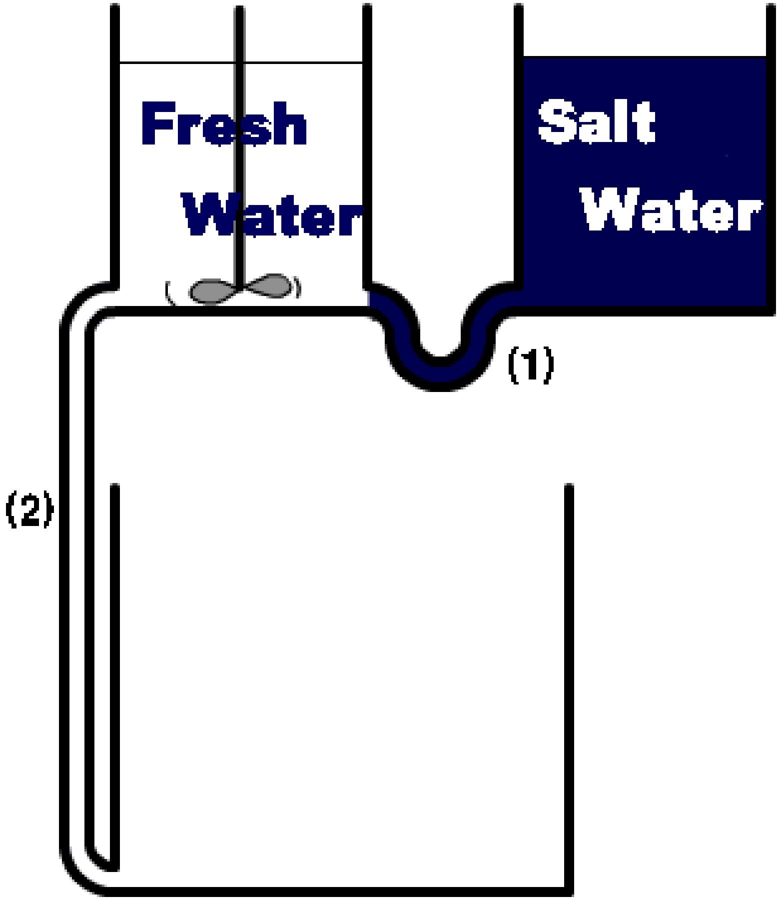
Part I: linear stratification



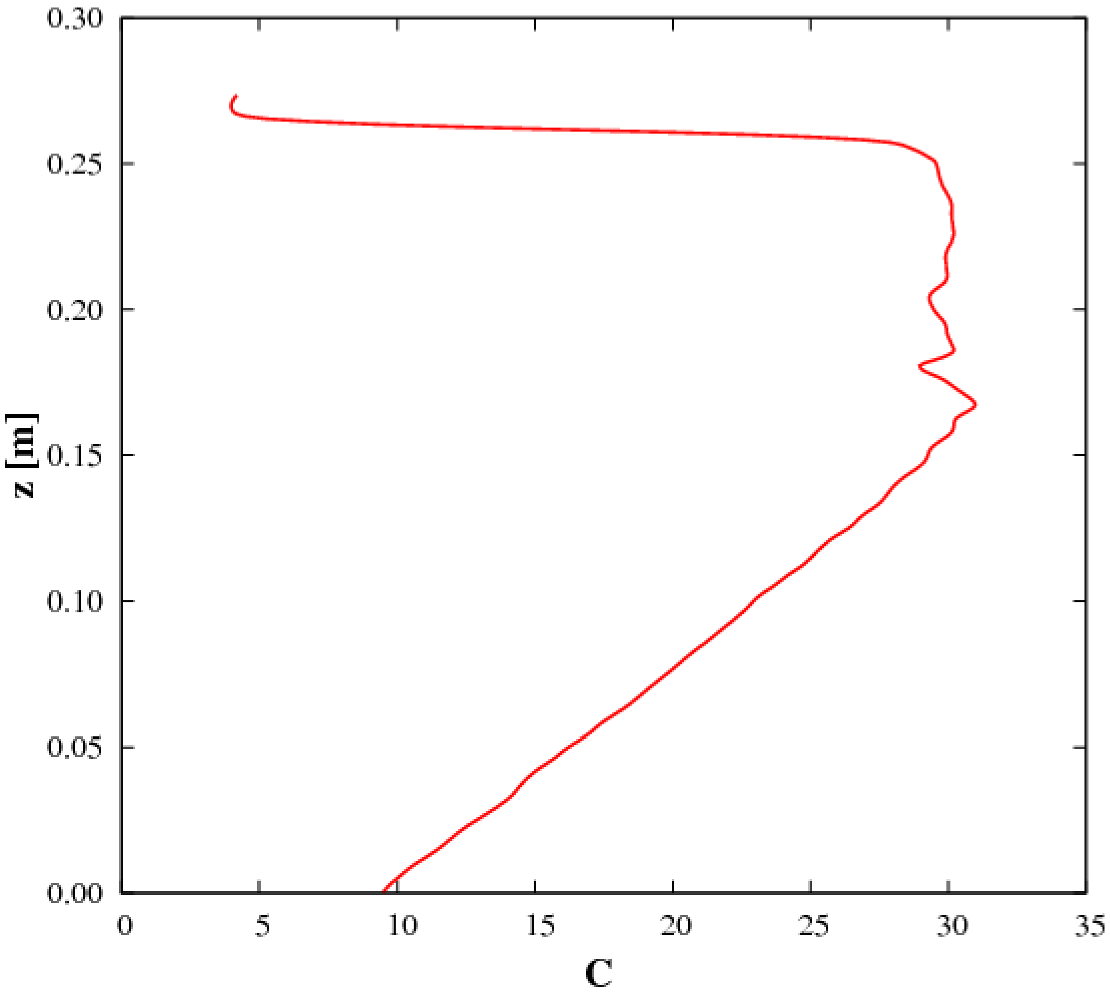


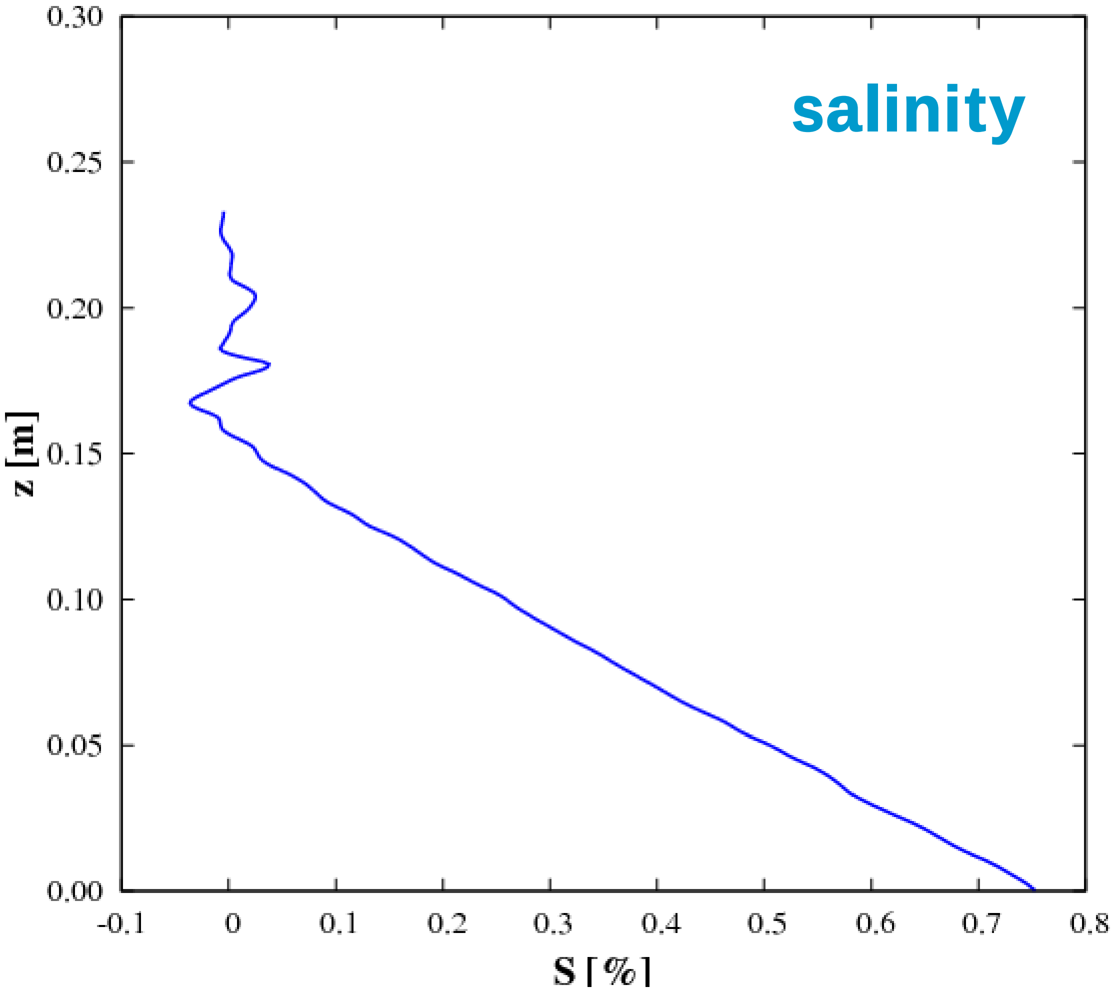
Part II: two-layer system

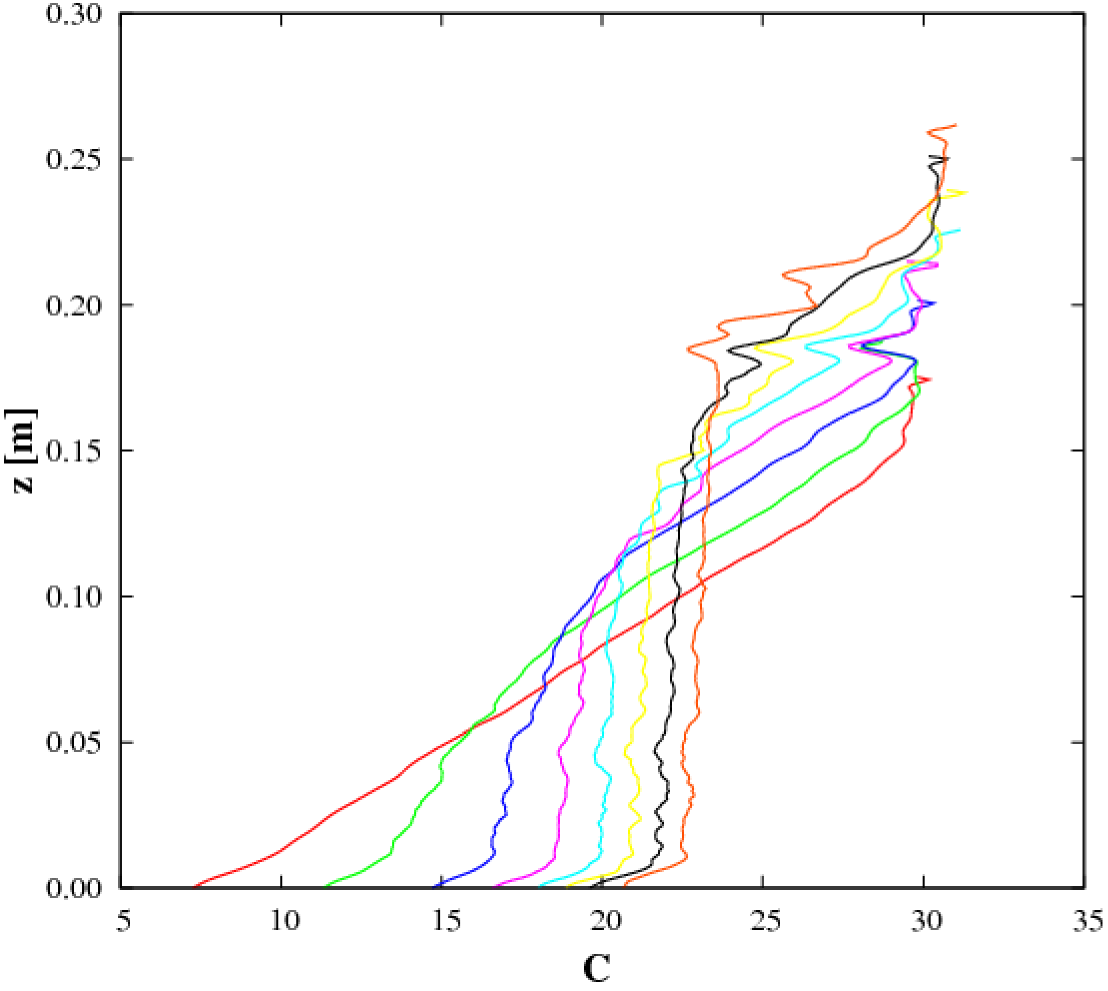

φ_1
Mixing Pump
V_1,C_1
V_2,C_2
φ_2
Tank 1
Tank 2
Experiment


Fresh
Water
Salt
Water
(1)
(2)

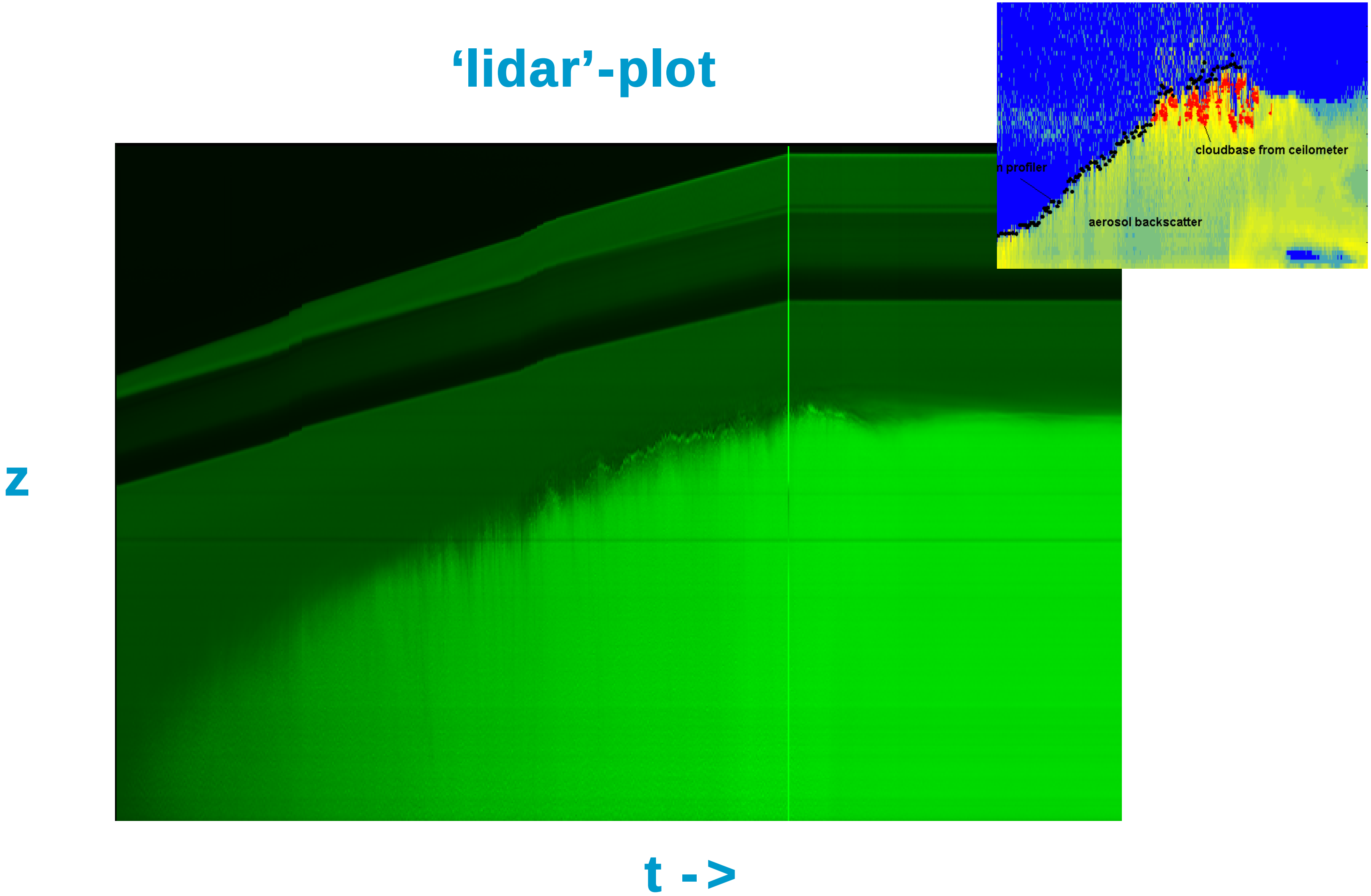
tracer concentration profile at t=0

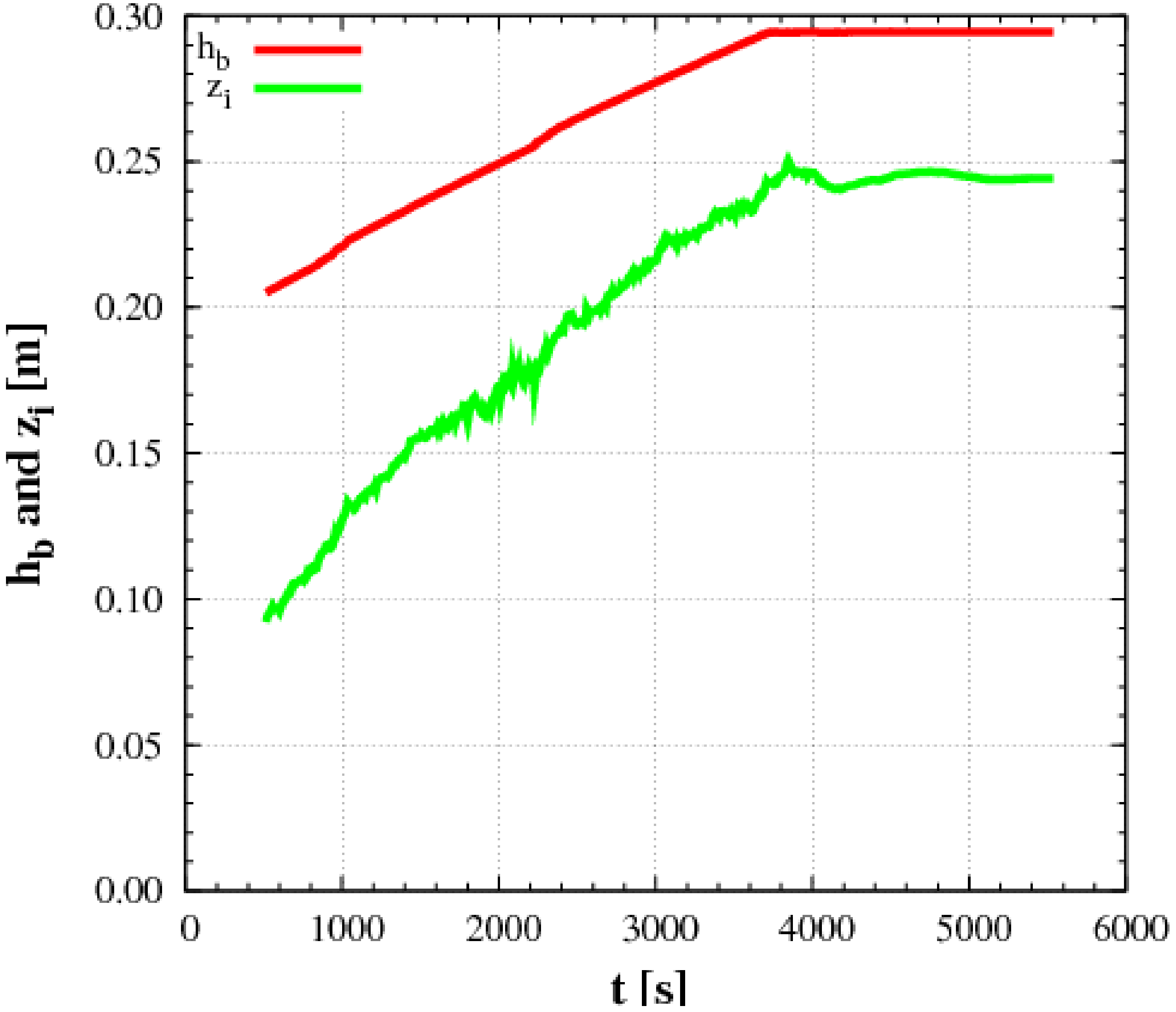


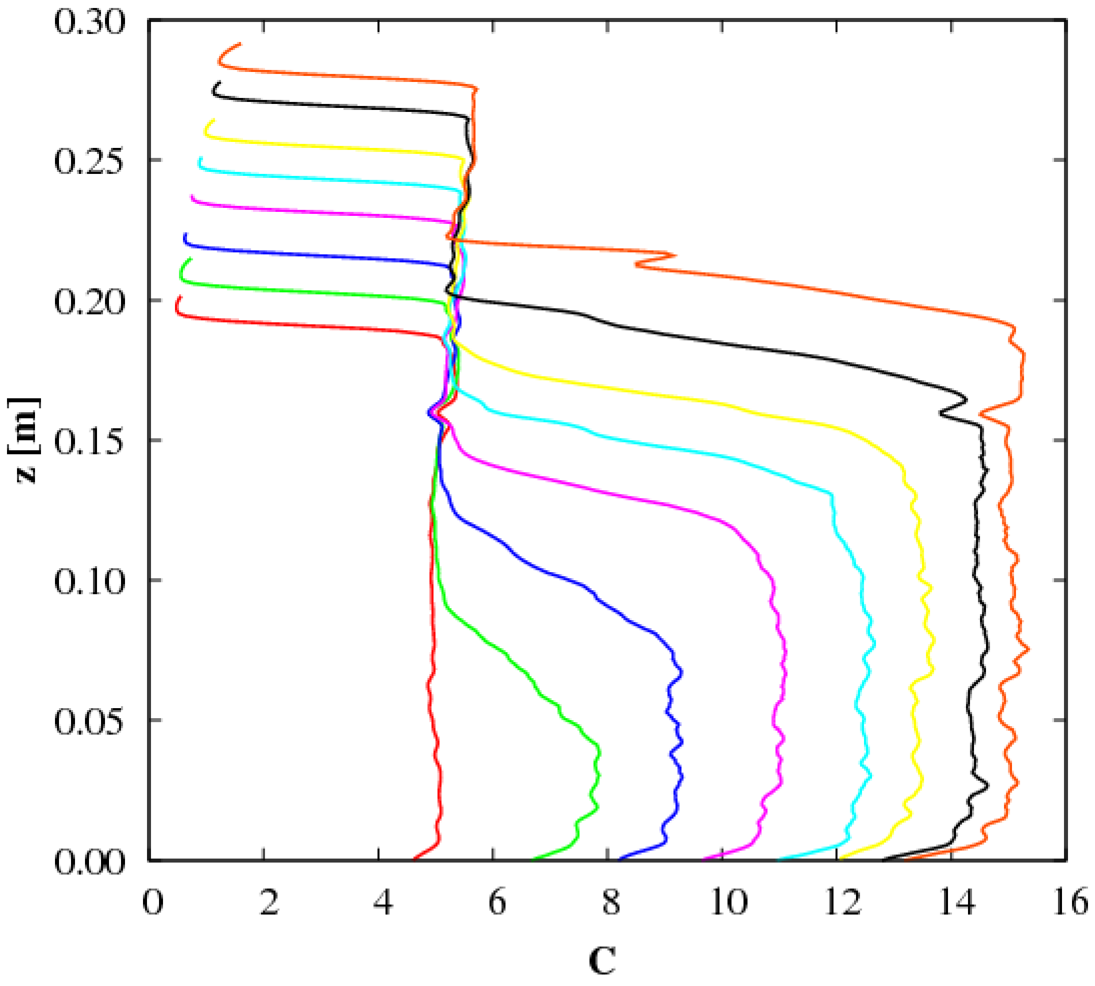

salinity
z [m]
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
S [%]


0.30
0.25
0.20
0.15
0.10
0.05
0.00
z [m]
5
10
15
20
25
30
35
C

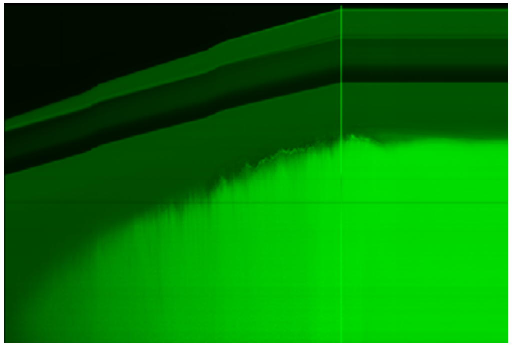
‘lidar’-plot

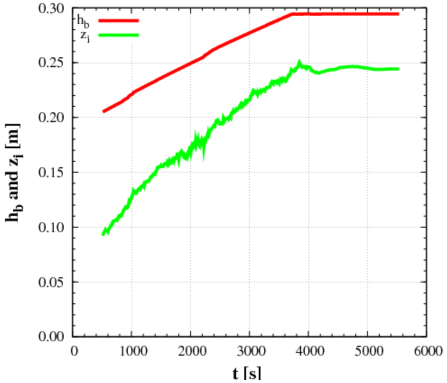

n profiler
cloudbase from ceilometer
aerosol backscatter
z
t ->

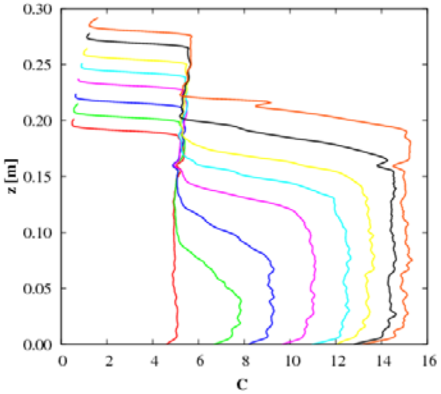

h_b
z_i
h_b and z_i [m]
t [s]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
1000
2000
3000
4000
5000
6000

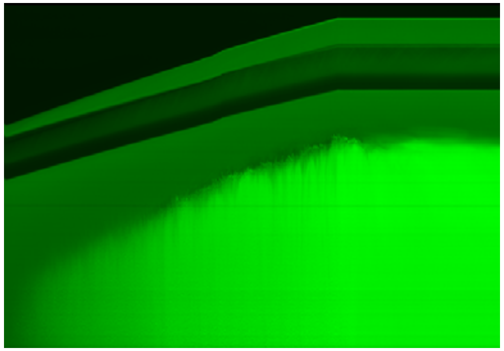

0.30
0.25
0.20
0.15
0.10
0.05
0.00
z [m]
0
2
4
6
8
10
12
14
16
C

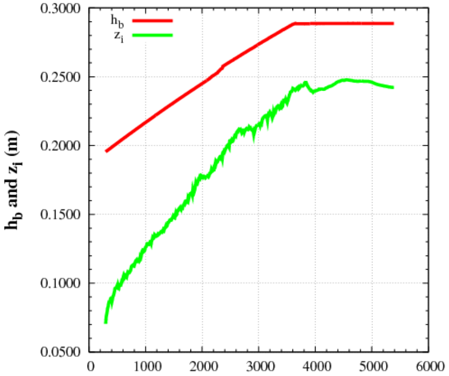
reproducibility

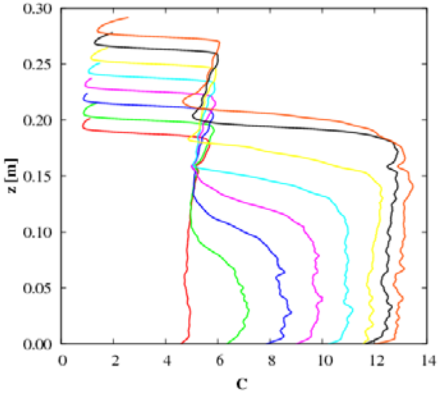




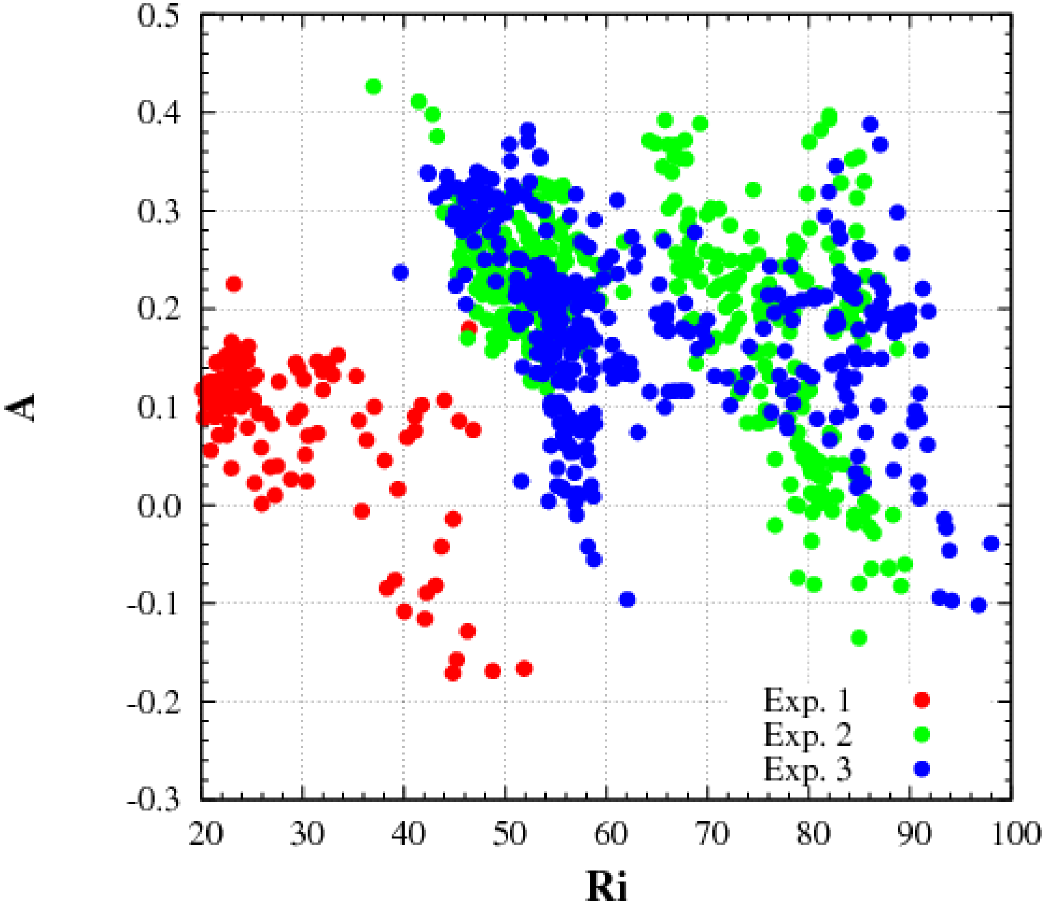




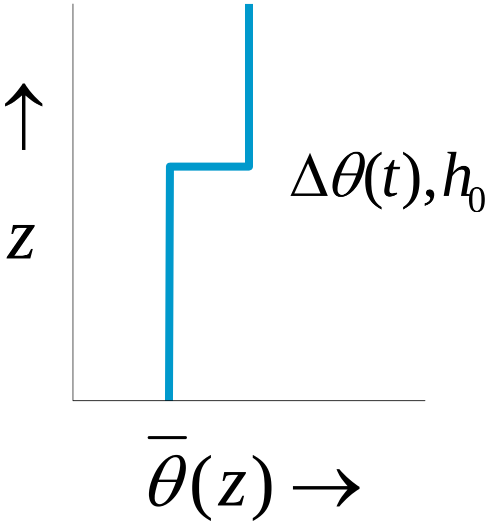


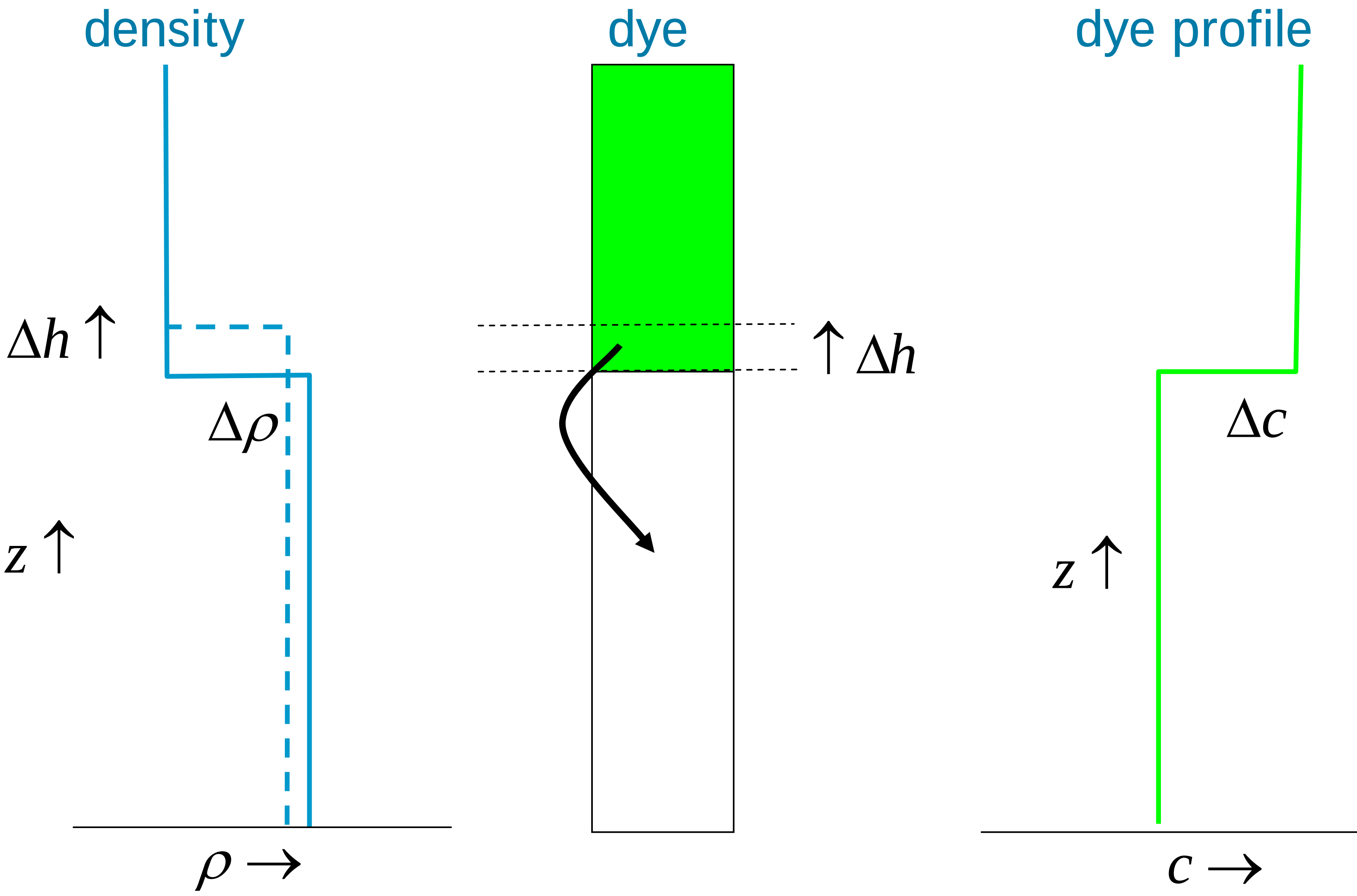


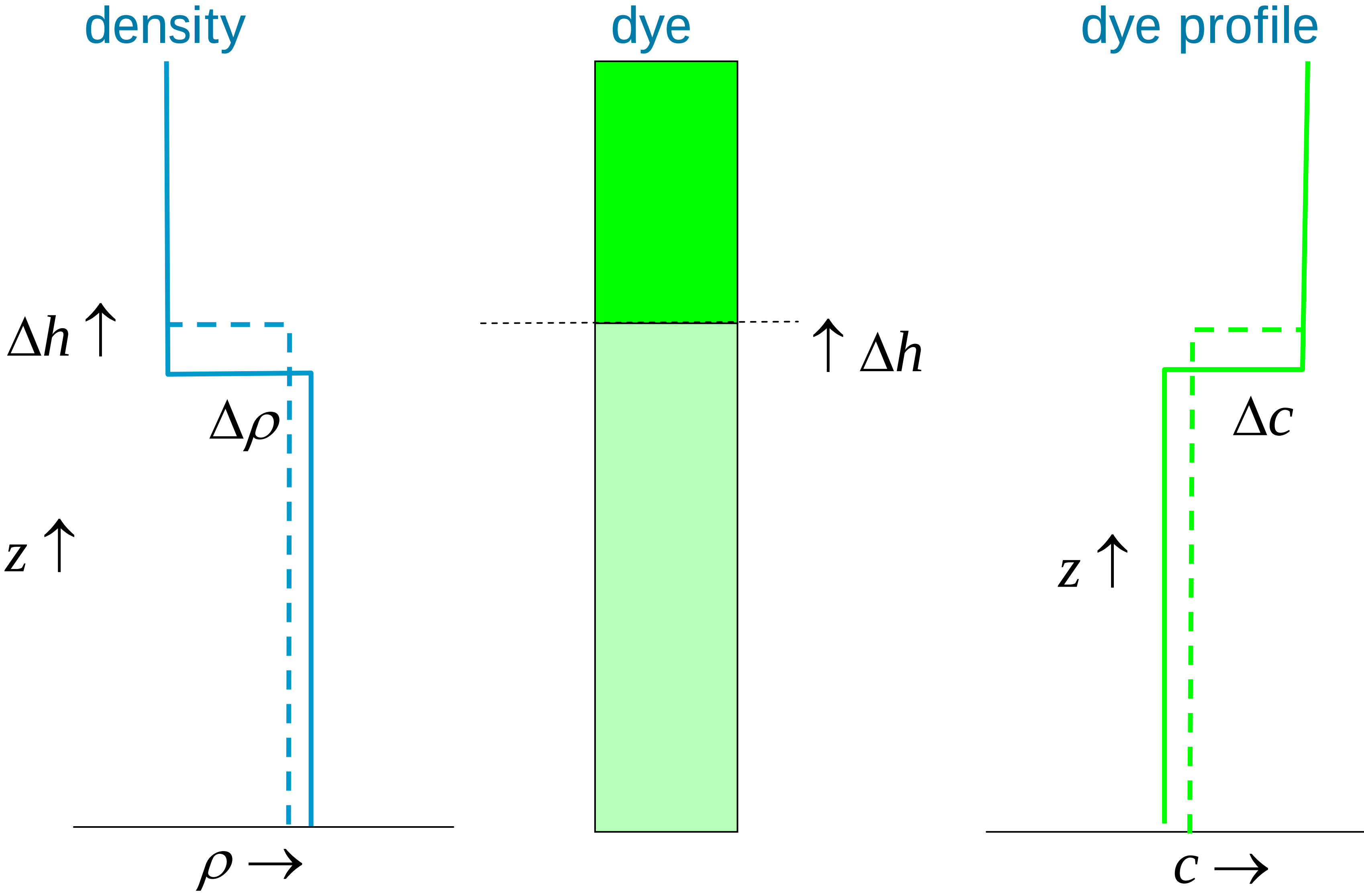
$$A = \frac{w_e}{w_*} Ri$$


A
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
20
30
40
50
60
70
80
90
100
Ri
Exp. 1
Exp. 2
Exp. 3

Part II: two-layer systems



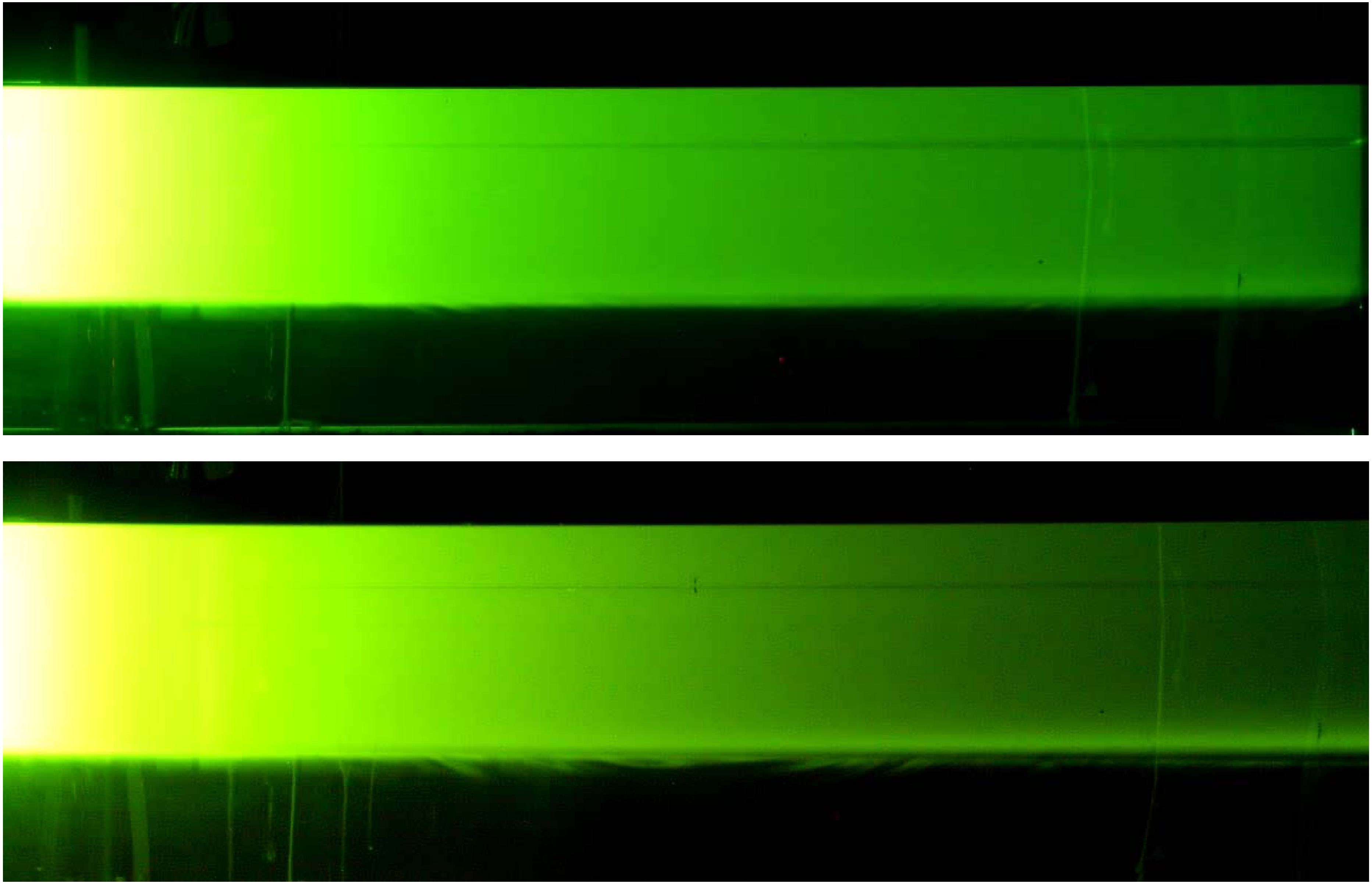

density
$\Delta h \uparrow$
$\Delta\rho$
$z \uparrow$
$\rho \rightarrow$
dye
$\uparrow \Delta h$
dye profile
Δc
$z \uparrow$
$c \rightarrow$

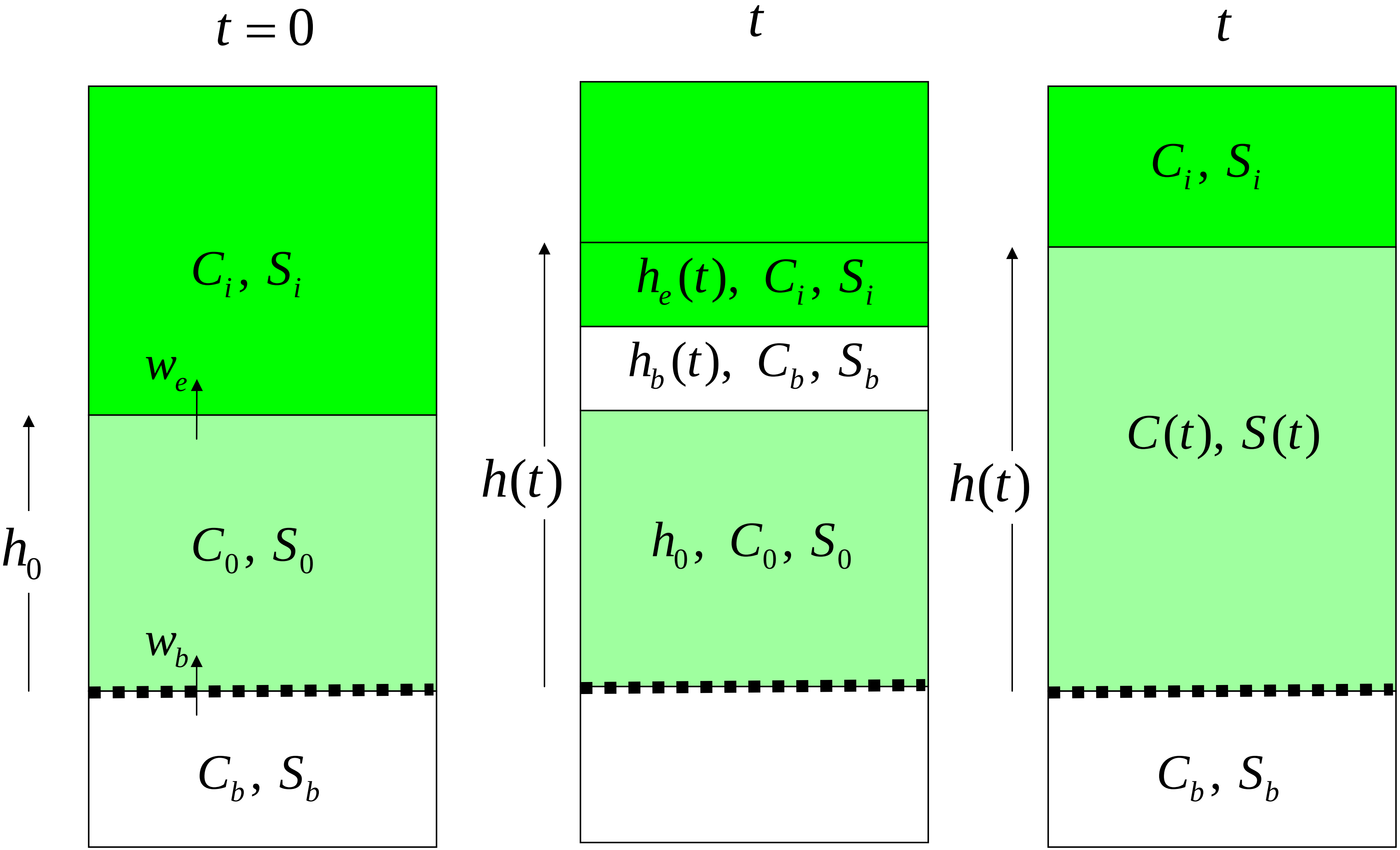


Entrainment rate $w_e = \Delta h / \Delta t$

LES $w_e \propto Ri^{-1}$

Ri = 30 and Ri = 120




$t=0$
t
t
C_i, S_i
w_e
h_0
C_0, S_0
w_b
C_b, S_b
$h(t)$
$h_e(t),\ C_i, S_i$
$h_b(t),\ C_b, S_b$
$h_0,\ C_0, S_0$
$h(t)$
C_i, S_i
$C(t), S(t)$
C_b, S_b

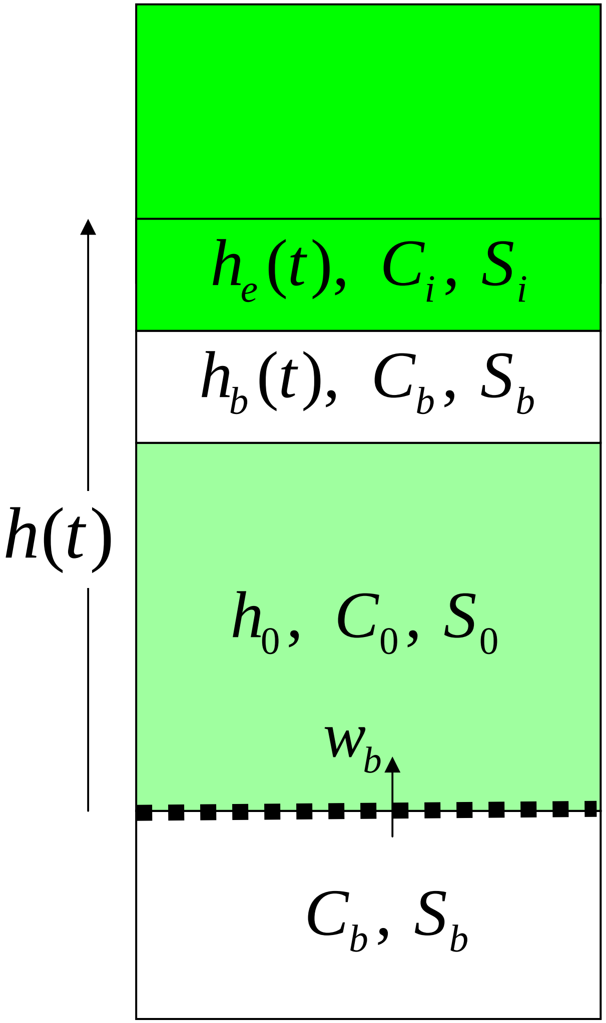
Post processing

$$h(t) = h_0 + h_b(t) + h_e(t)$$

$$C(t) = \frac{C_0 h_0 + C_b h_b + C_i h_e}{h_0 + h_b + h_e}$$

$$h_e(t) = \frac{h_b[C(t) - C_b] + h_0[C(t) - C_0]}{C_i - C(t)}$$

$$w_e = \frac{dh_e}{dt}$$



Post processing

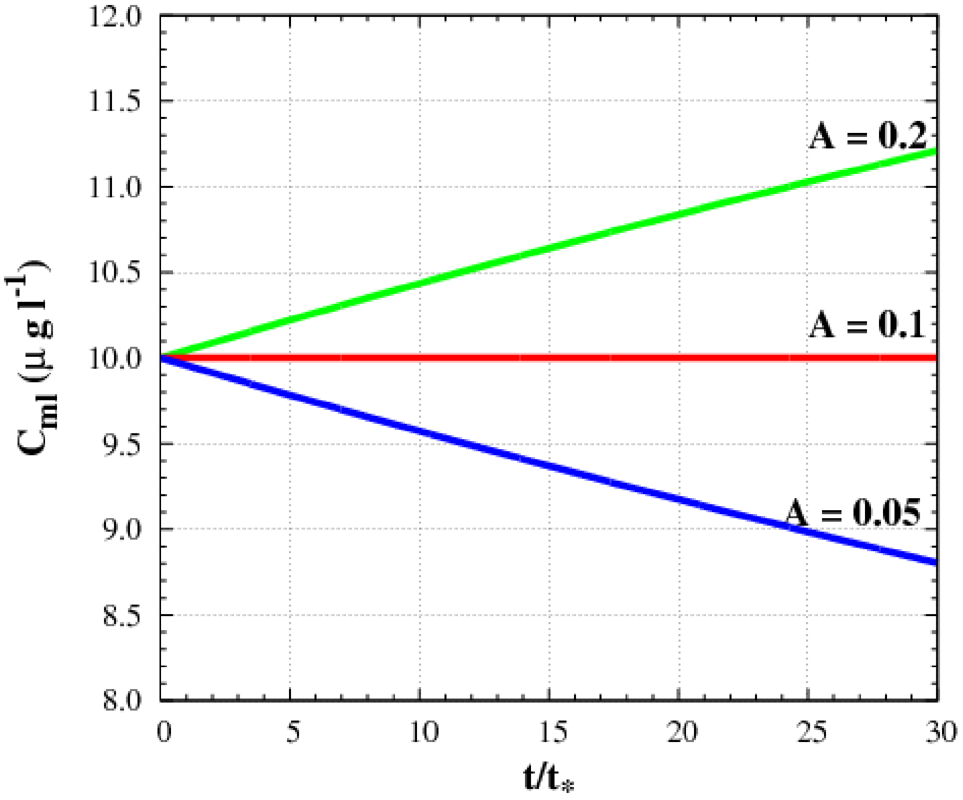
$$S(t) = \frac{S_0 h_0 + S_b h_b + S_i h_e}{h_0 + h_b + h_e}$$

$$w_* = (g w_b h (S - S_b))^{\frac{1}{3}}$$

$$Ri(t) = \frac{S(t) - S_i}{S(t) - S_b} \cdot \frac{w_*}{w_b}$$

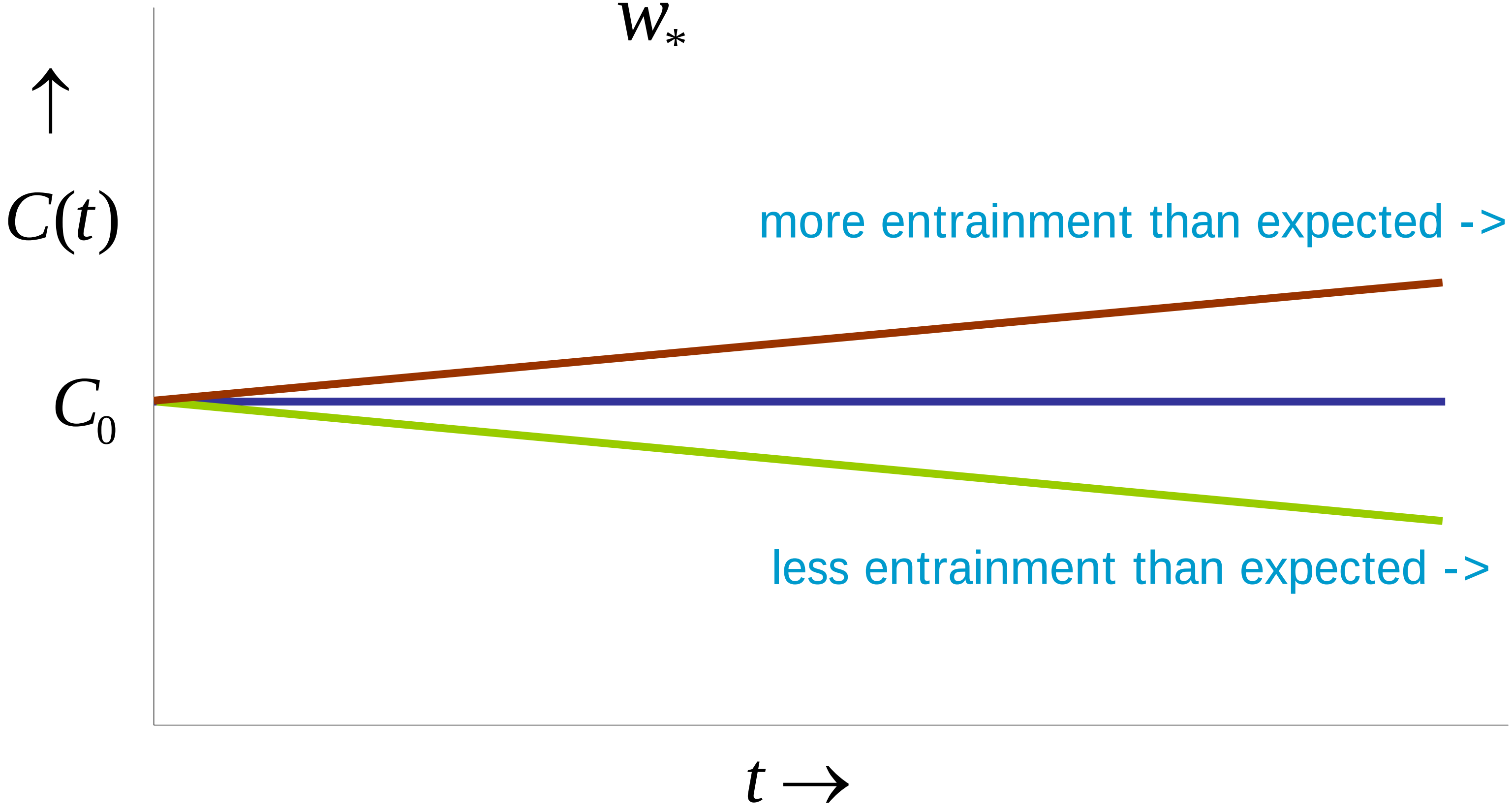
Methodology

$$C_{eq} = \frac{C_b\left(w_b / w_*\right)A^{-1}Ri + C_i}{1 + A^{-1}Ri\left(w_b / w_*\right)}$$



new strategy for measuring entrainment

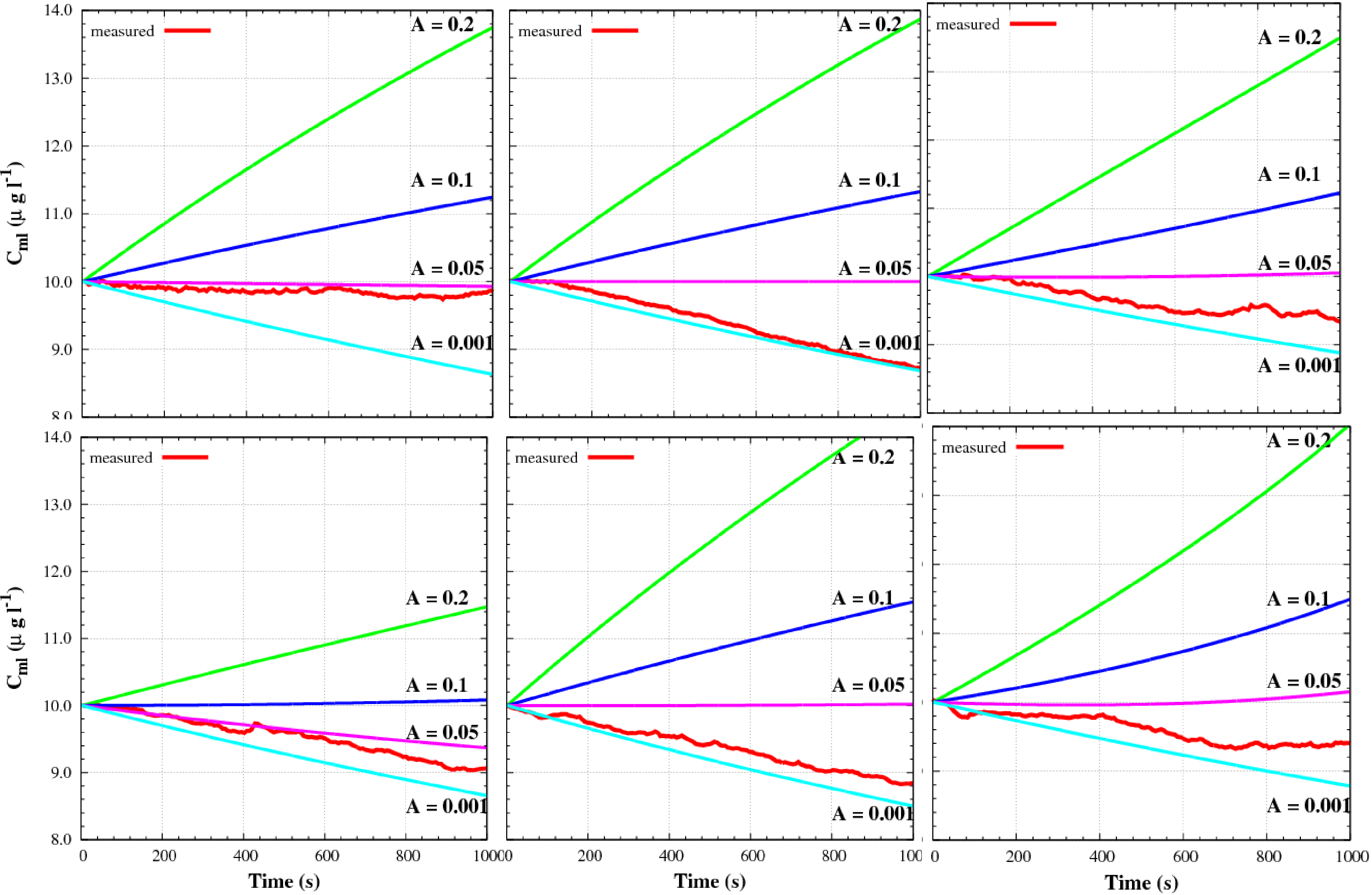
assume entrainment law: $$\frac{w_e}{w_*} = A\,Ri^{-1}$$ start value $A = 0.2$



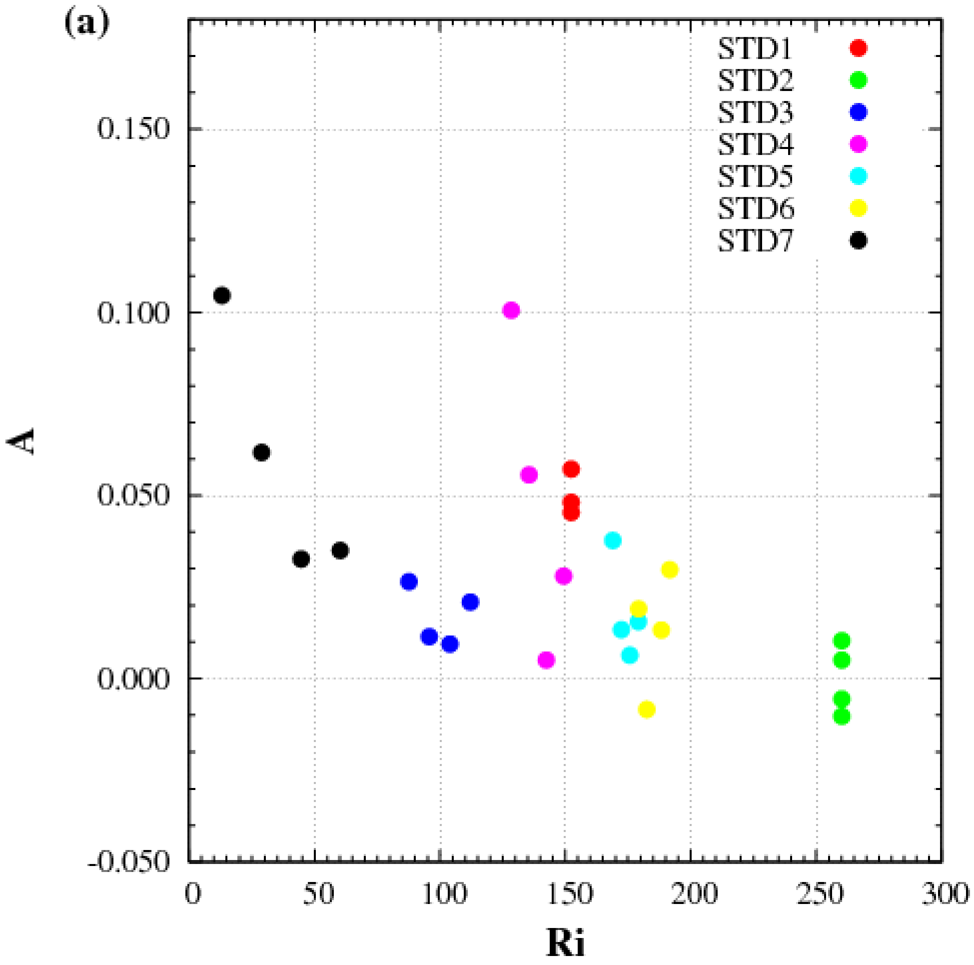
more entrainment than expected -> increase A

less entrainment than expected -> lower A

Experiments vs Mixed Layer Model

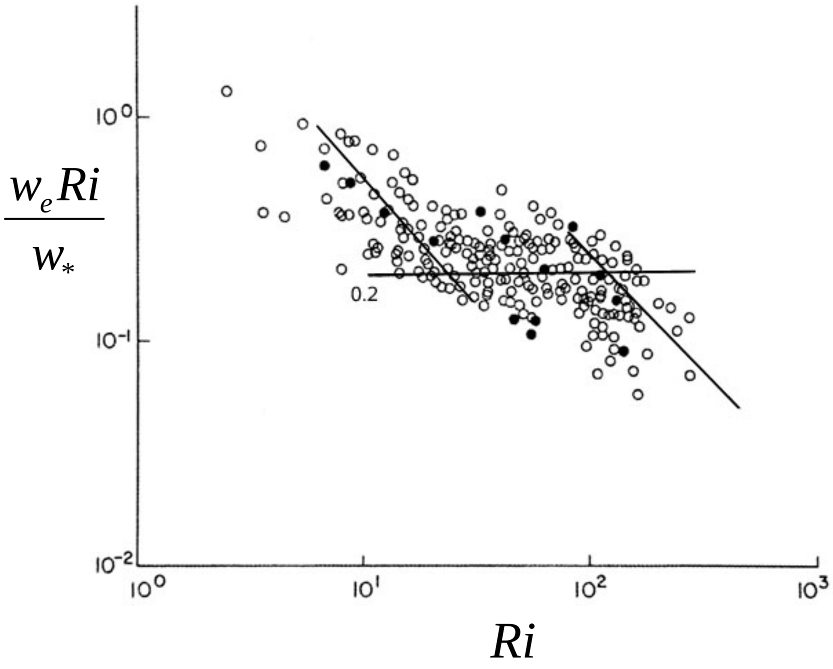


$$A = \frac{w_e}{w_*} Ri$$

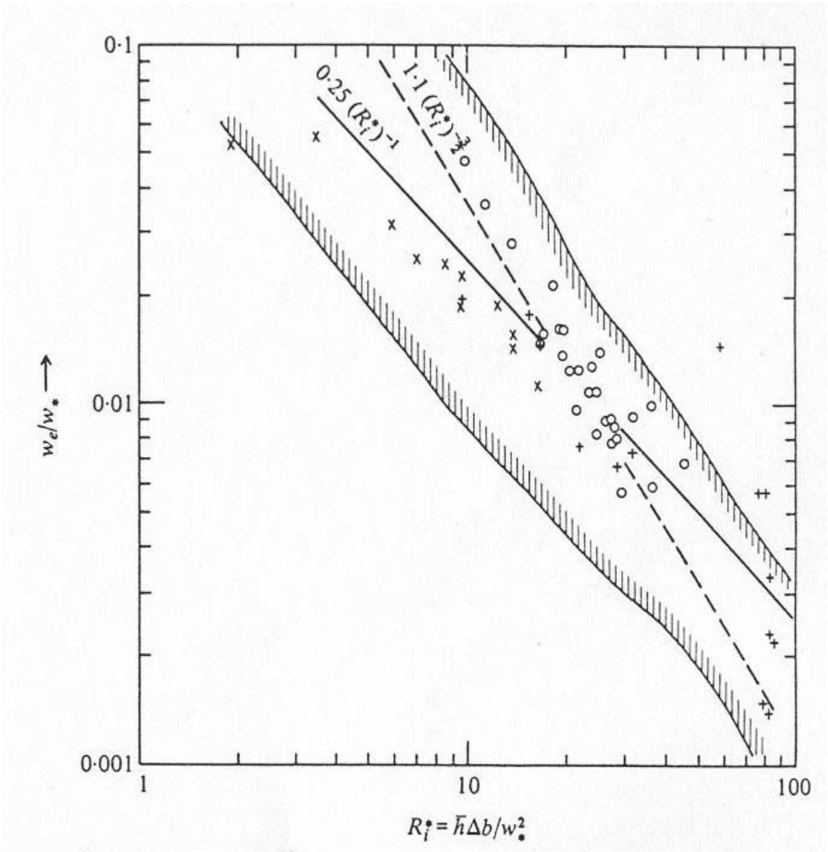

(a)
A
Ri
0.150
0.100
0.050
0.000
-0.050
0
50
100
150
200
250
300
STD1
STD2
STD3
STD4
STD5
STD6
STD7

The two-layer system behaves really different !

Richardson –1 law



Results of Kantha (1980)



Deardorff, Willis and Stockton, JFM 1980

van Dop et al
BLM 2005,
CSIRO saline tank

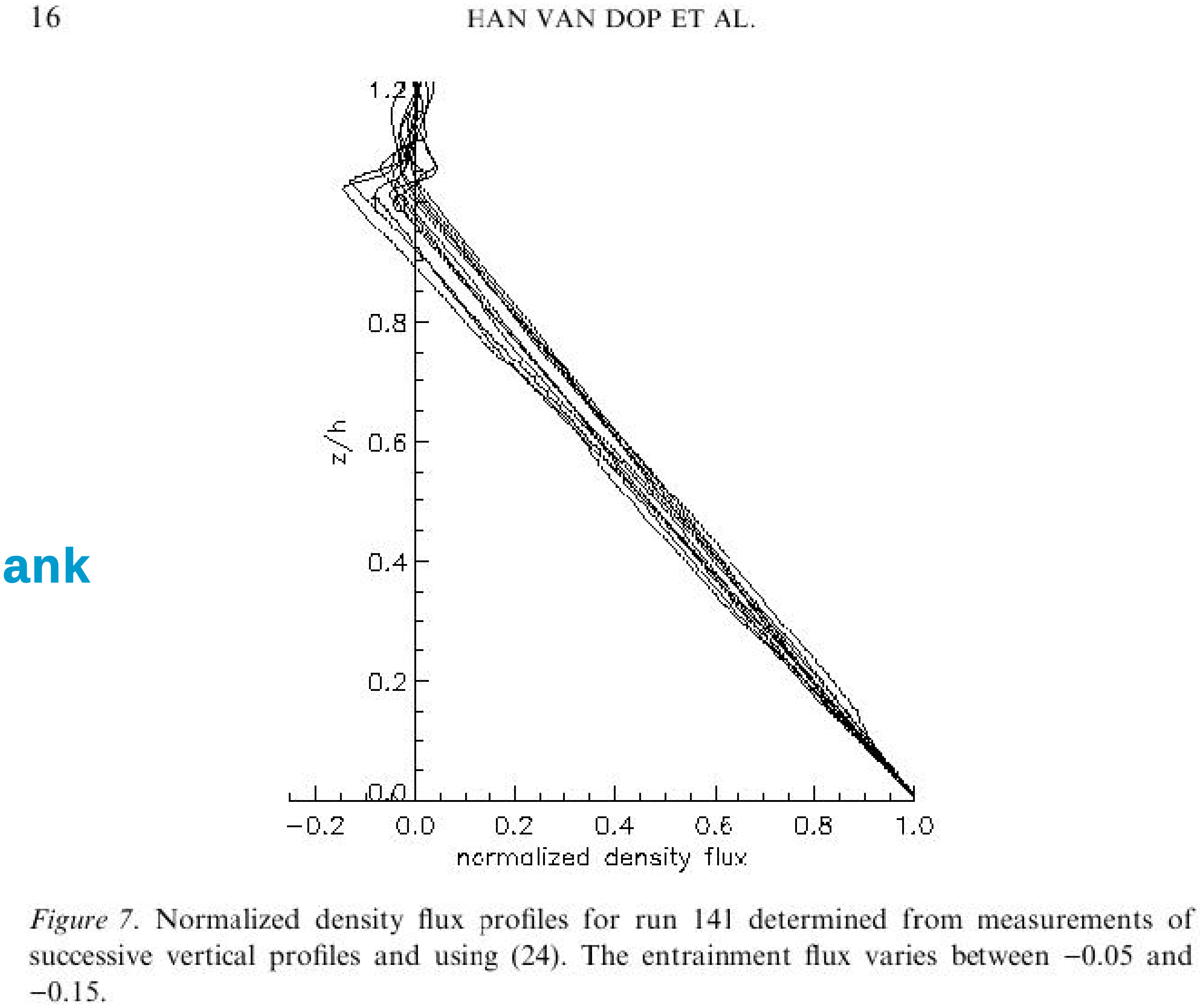


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Figure 7. Normalized density flux profiles for run 141 determined from measurements of successive vertical profiles and using (24). The entrainment flux varies between −0.05 and −0.15.

Discussion

-two-layer: very low values for A, 0.02 rather than 0.2

- Compare with atmosphere:
  - No wind shear in experiment
  - No lapse rate -> no waves
  - Surface flux very homogeneous
  - Reynolds number much lower (Re ~ 1000)

-tank with lapse rate: A = 0.1-0.2

Discussion

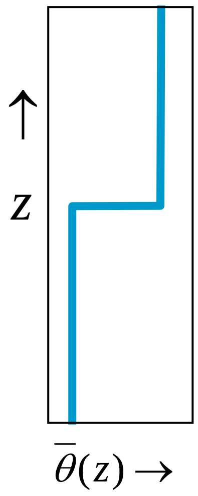
- Two layer system behaves different than a linear stratification system:
- Very low values for A, 0.02 rather than 0.2

- Saline convection tanks differ from

  -LES

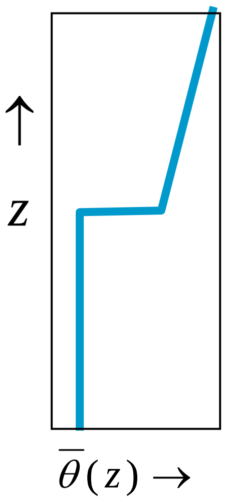
  -Heat driven tanks

  (e.g. Deardorf et al 1980)



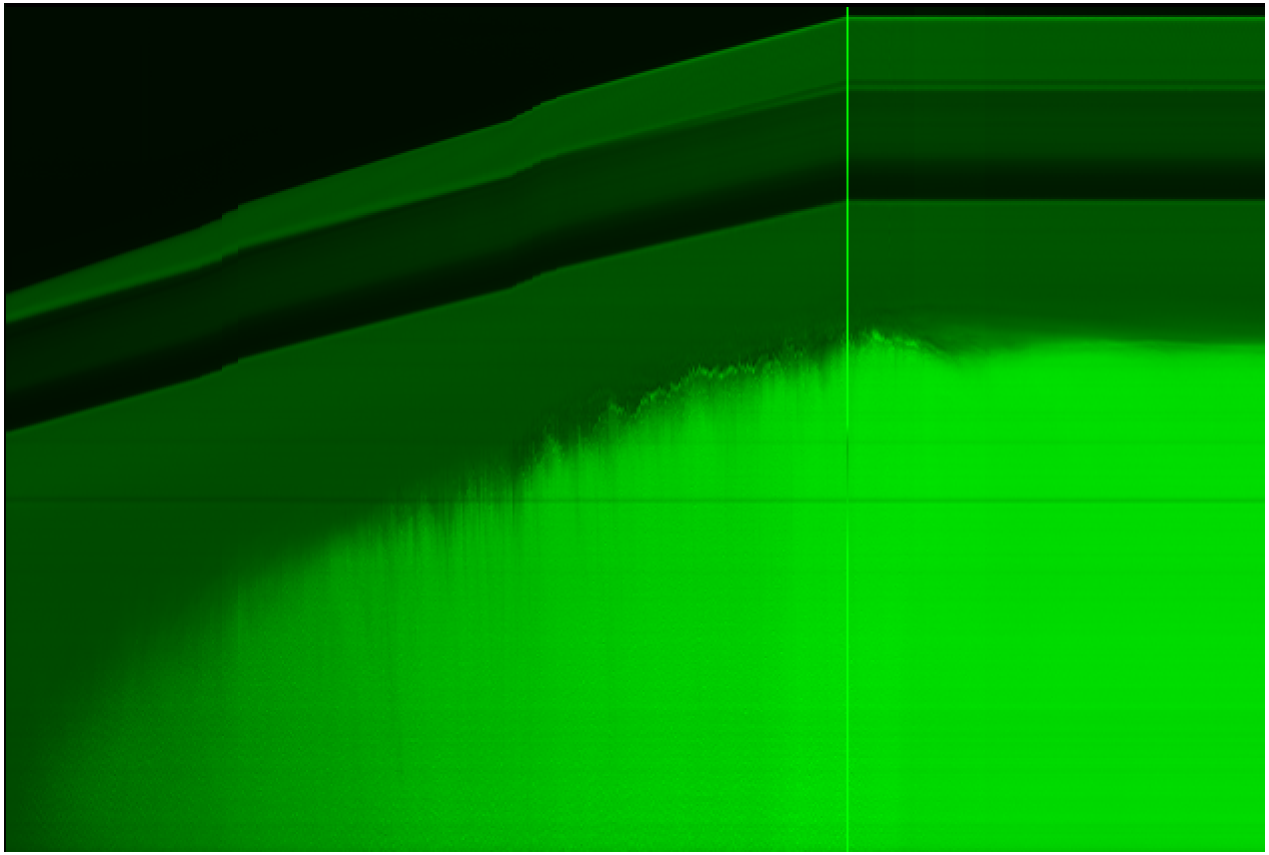
Discussion

$$w_e = w_* \frac{A}{Ri}$$



- Ri and w* do not uniquely define the problem
- ‘preconditioning’ of the interface
- structure of the entrainment zone

interesting future experiment ...



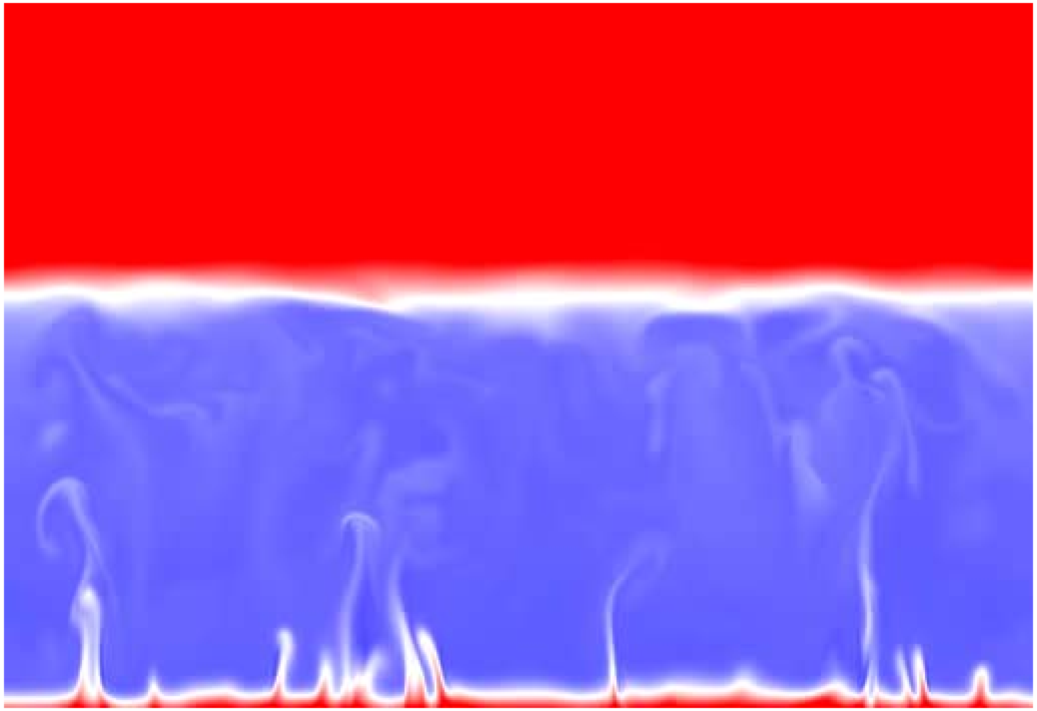
start bottom flux again ...

entrainment

Fernando, 1991, Annu. Rev. Fluid Mech.

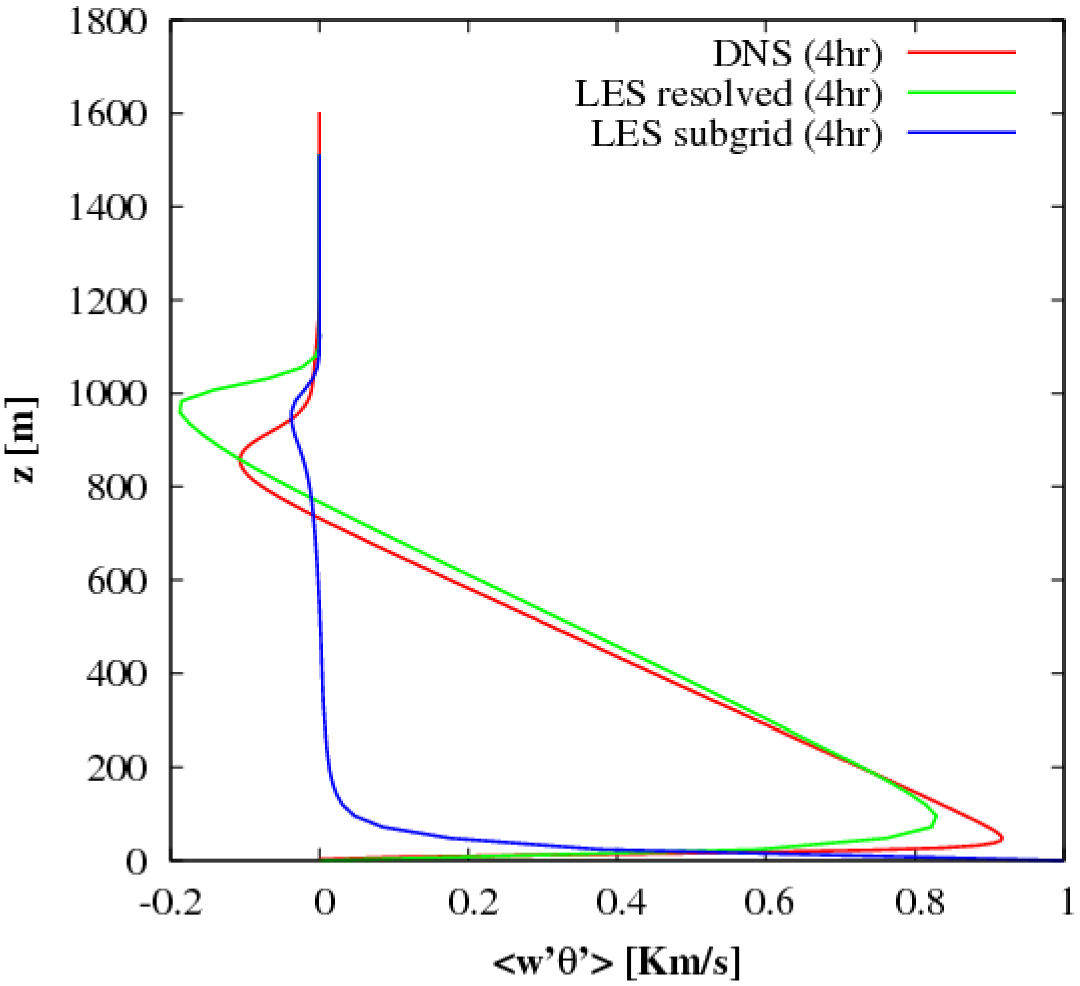
In this area of research, perhaps no other specific topic has been more controversial than the entrainment law.
[...],
and it is surprising that the experiments performed by different investigators, [..], have reported entrainment rates sometimes differing by a factor of five.

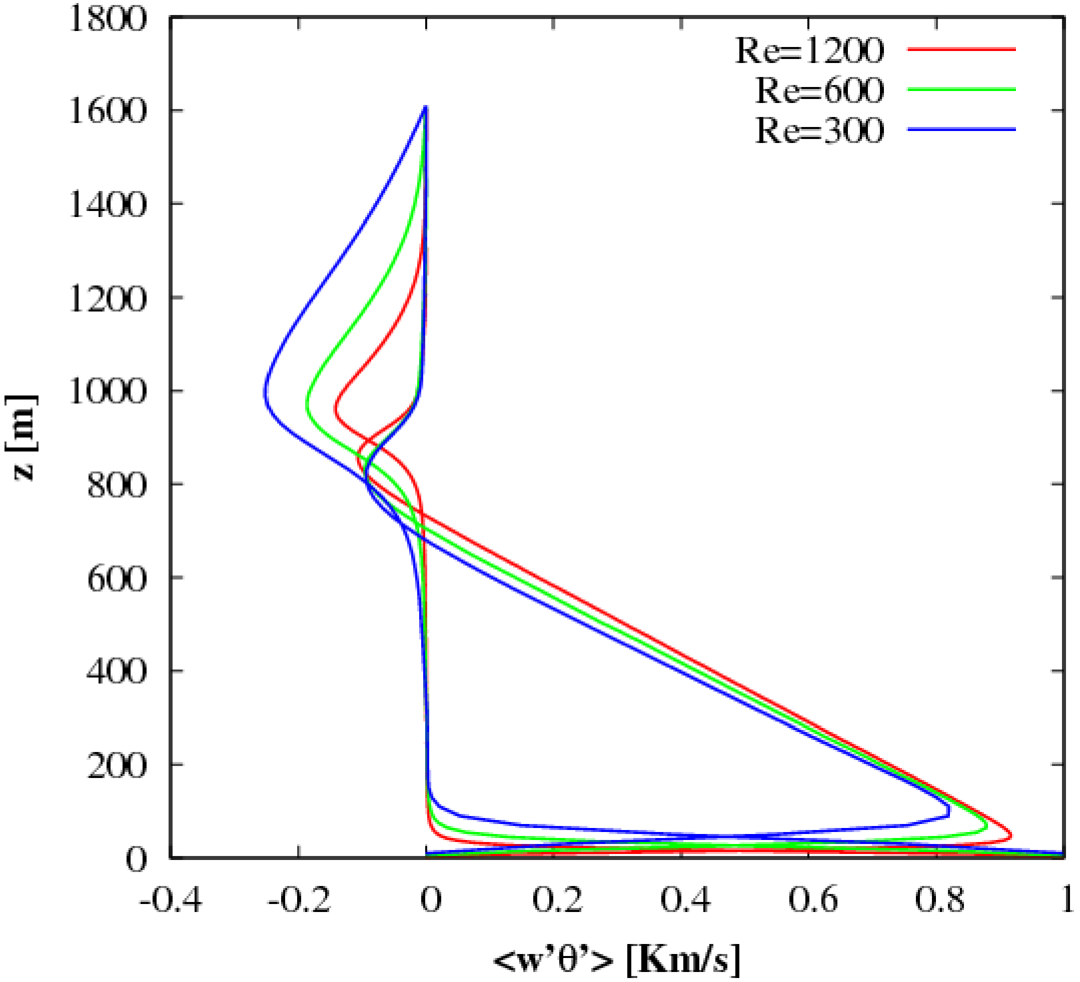
Direct Numerical Simulations



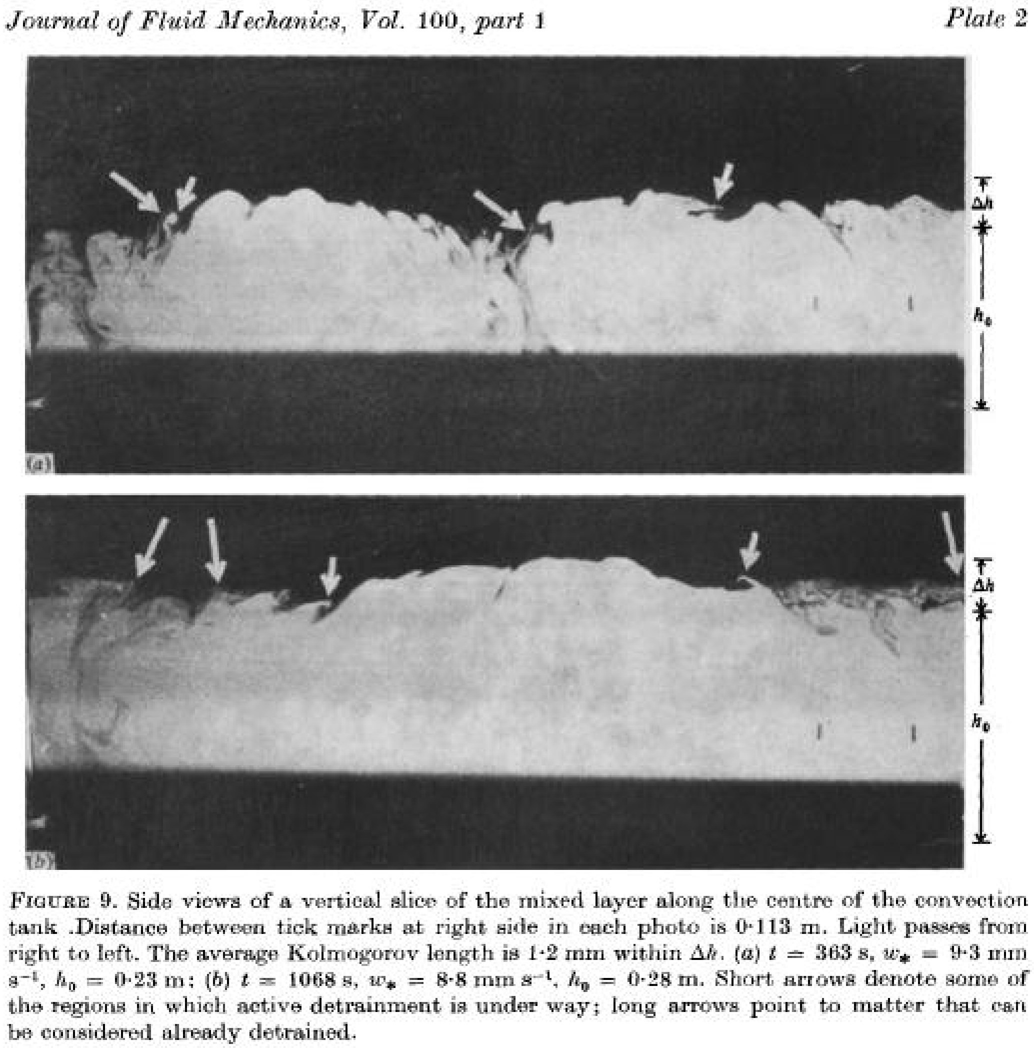
DEISA (Distributed European Infrastructure for Supercomputing Applications), grant, 2008

Jonker, Sullivan, Patton, van Reeuwijk


DNS (4hr)
LES resolved (4hr)
LES subgrid (4hr)
z [m]
0
200
400
600
800
1000
1200
1400
1600
1800
-0.2
0
0.2
0.4
0.6
0.8
1
<w'θ'> [Km/s]


Re=1200
Re=600
Re=300
z [m]
0
200
400
600
800
1000
1200
1400
1600
1800
<w'θ'> [Km/s]
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Detrainment?



Journal of Fluid Mechanics, Vol. 100, *part* 1

Plate 2

FIGURE 9. Side views of a vertical slice of the mixed layer along the centre of the convection tank .Distance between tick marks at right side in each photo is 0·113 m. Light passes from right to left. The average Kolmogorov length is 1·2 mm within Δh. (*a*) t = 363 s, w_* = 9·3 mm s^{-1}, h_0 = 0·23 m; (*b*) t = 1068 s, w_* = 8·8 mm s^{-1}, h_0 = 0·28 m. Short arrows denote some of the regions in which active detrainment is under way; long arrows point to matter that can be considered already detrained.

Detrainment?