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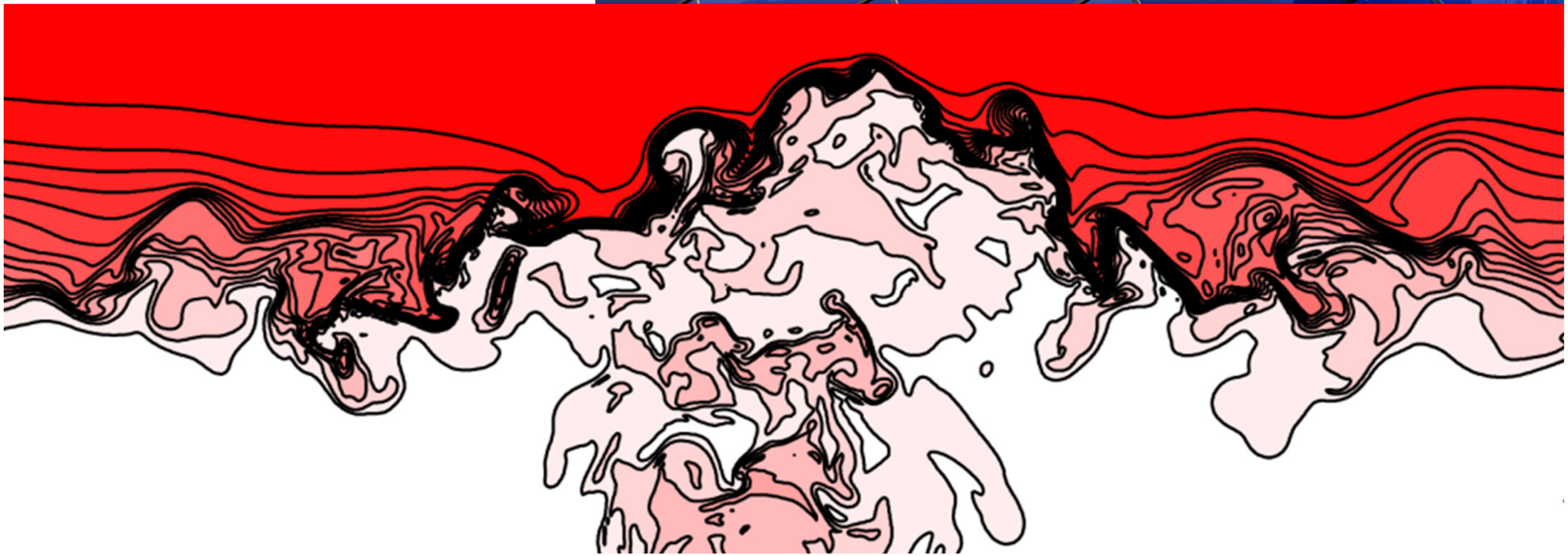
PRACE

Partnership for Advanced Computing in Europe



Direct simulation of turbulent entrainment across density interfaces

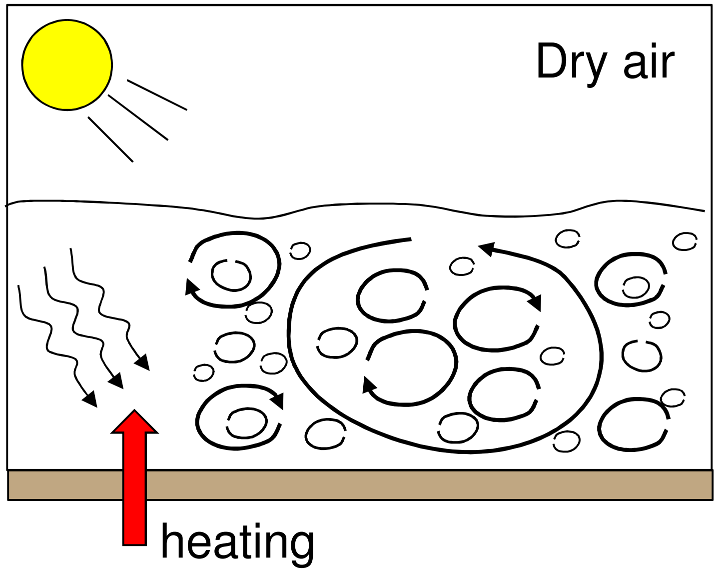
<u>Maarten van Reeuwijk</u>[1],

Harm Jonker[2], Gary Hunt[1], Peter Sullivan[3], Ned Patton[3]

[1]Imperial College London, UK [2]Delft University of Technology, NL [3]NCAR USA

PRACE Scientific Conference, Hamburg, 17 July 2012

Entrainment in geophysical flows

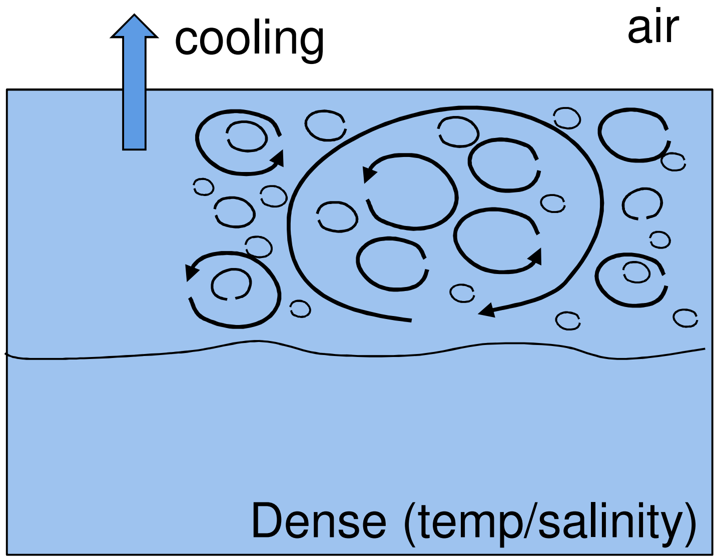


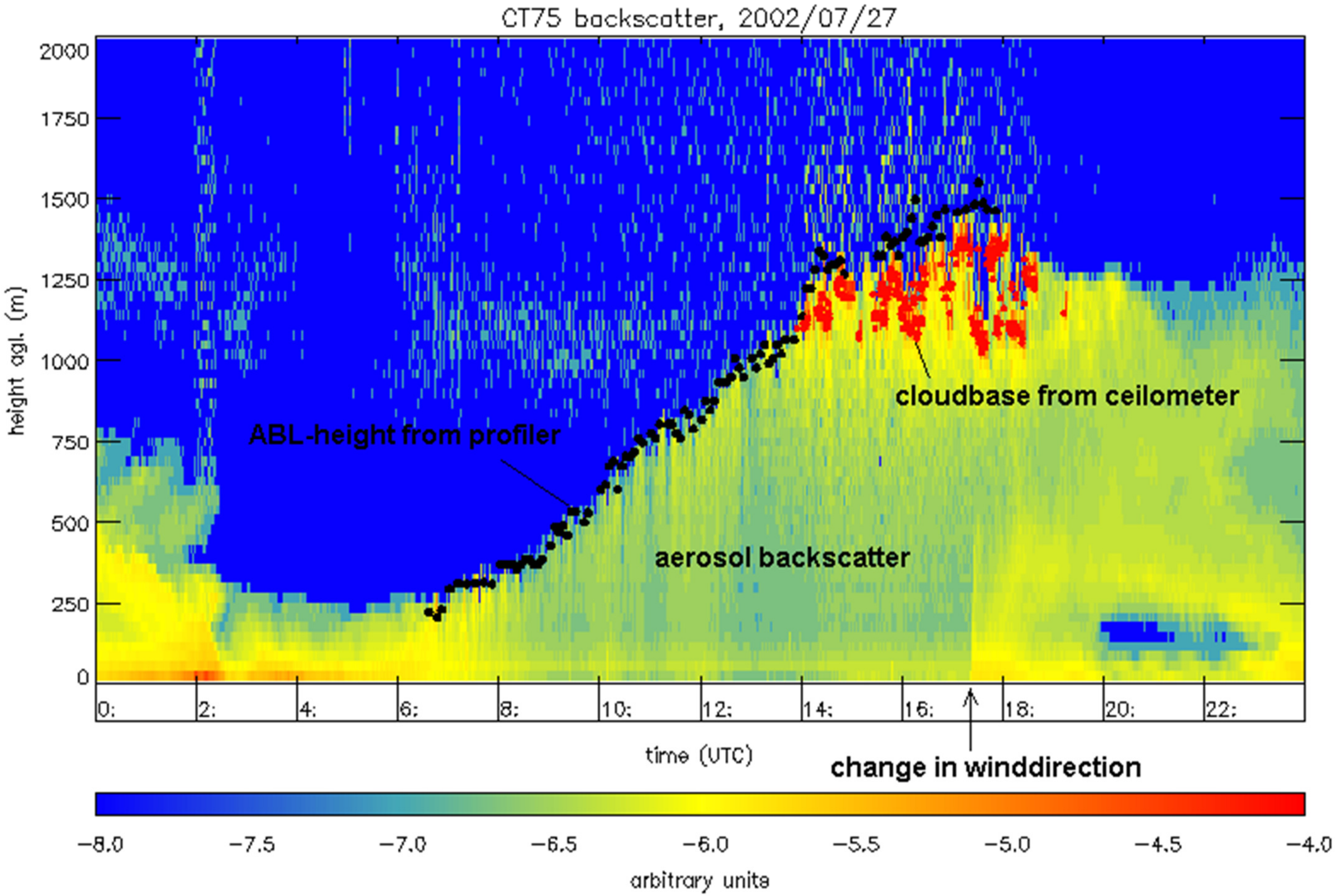
Atmospheric boundary layer

Daytime convection

Marine boundary layer

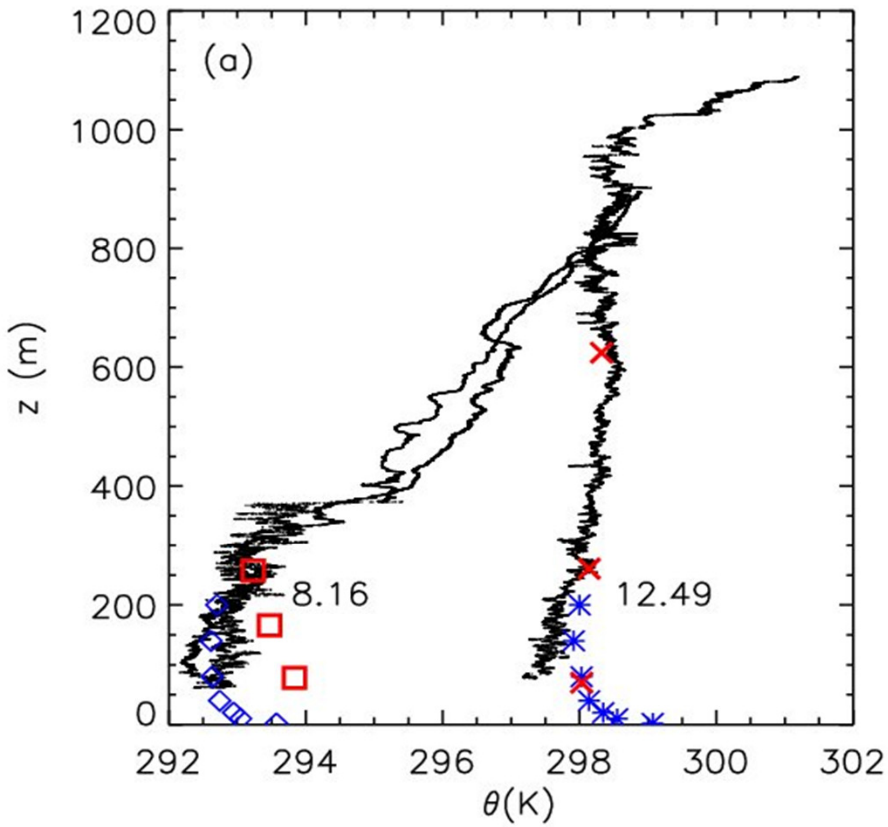
Night-time convection



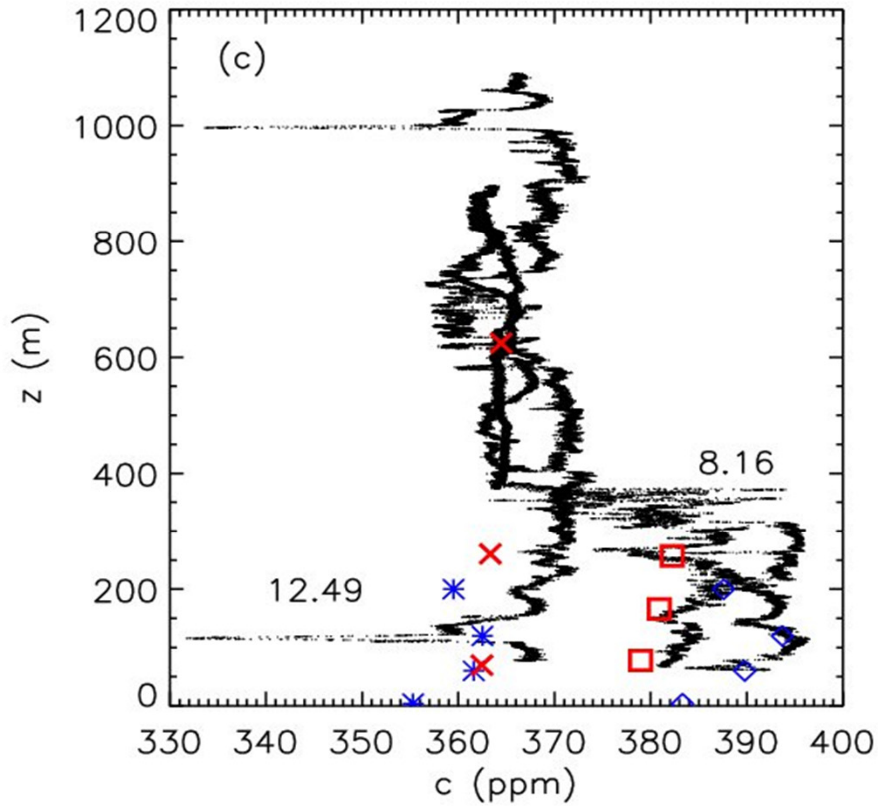

CT75 backscatter, 2002/07/27
2000
1750
1500
1250
1000
750
500
250
0
height agl. (m)
0:
2:
4:
6:
8:
10:
12:
14:
16:
18:
20:
22:
time (UTC)
ABL-height from profiler
cloudbase from ceilometer
aerosol backscatter
change in winddirection
−8.0
−7.5
−7.0
−6.5
−6.0
−5.5
−5.0
−4.5
−4.0
arbitrary units

Measurements in the ABL

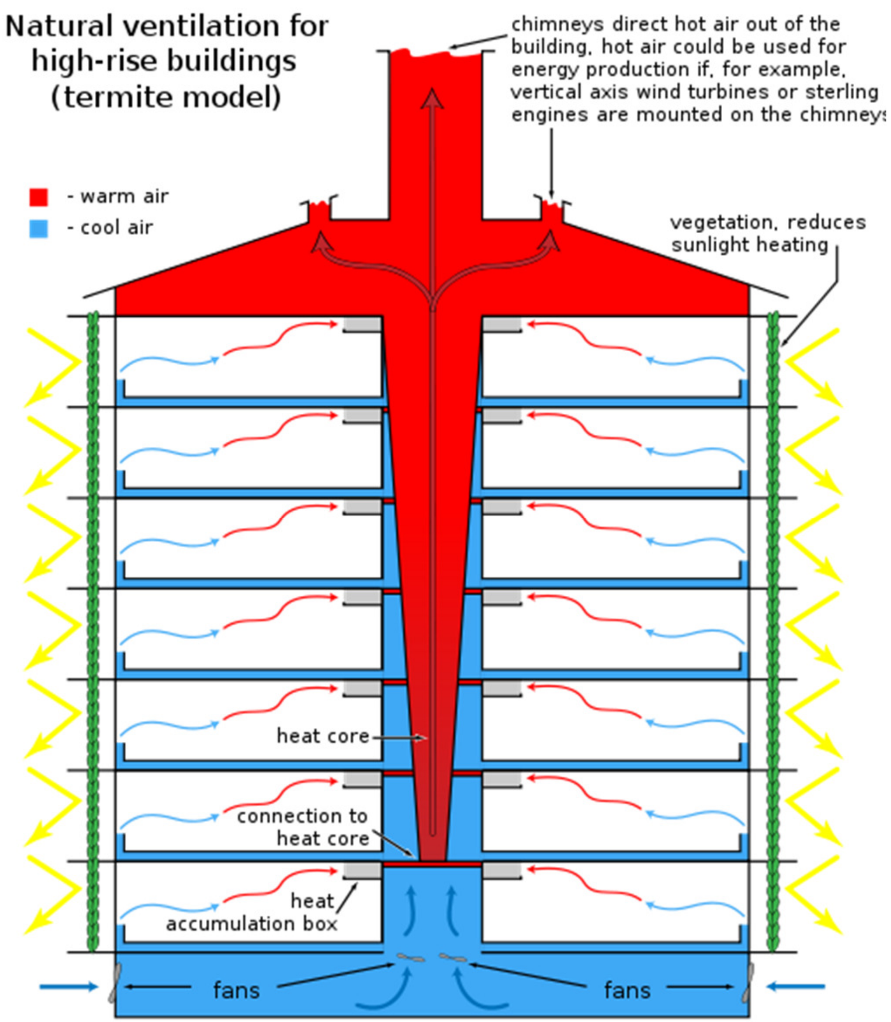
Potential temperature

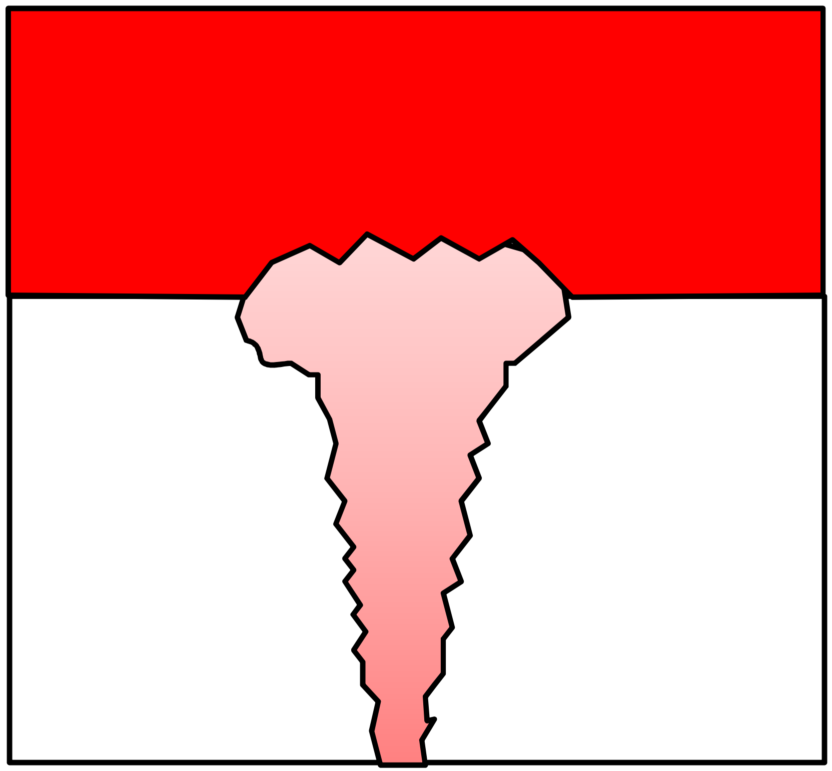


Carbon dioxide



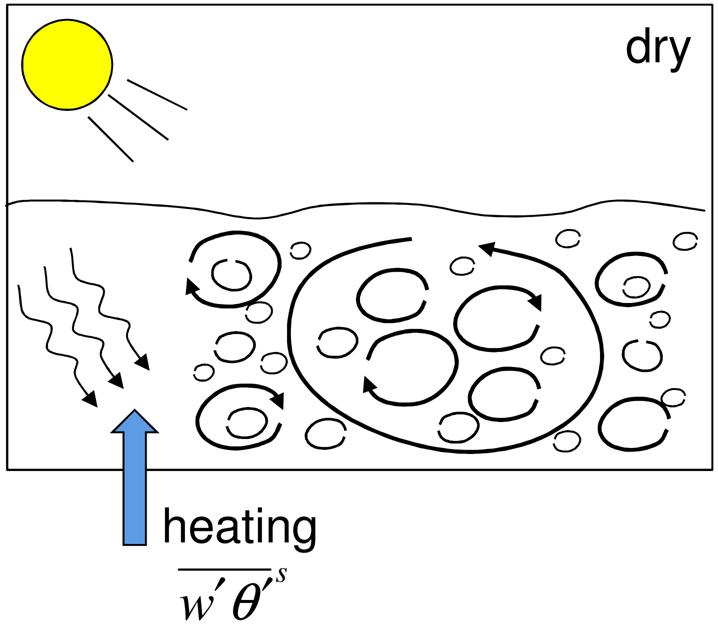
Entrainment in engineering flows

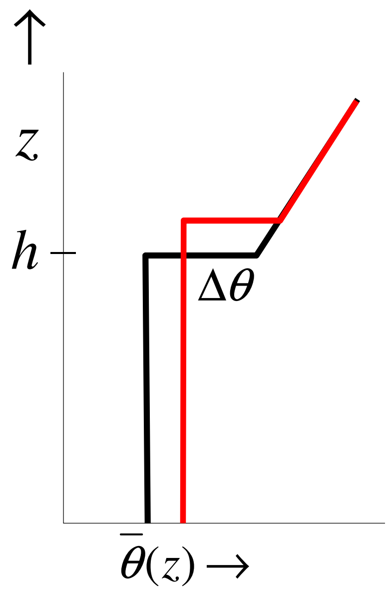




Occupant, Equipment, …

Governing parameters – homogeneous case





Velocity scale

$$w_* = \left(\frac{g}{\theta_0} \overline{w'\theta'}^s h \right)^{1/3}$$

Reynolds number: $\mathrm{Re} = \dfrac{w_* h}{\nu}$

Richardson number: $\mathrm{Ri} = \dfrac{g}{\theta_0} \dfrac{\Delta\theta\, h}{w_*^2}$

Péclet number: $\mathrm{Pe} = \dfrac{w_* h}{\kappa}$

Prandtl number: $\mathrm{Pr} = \dfrac{\nu}{\kappa}$

Entrainment laws

- The entrainment velocity w_e is defined as the time rate of change of the mixed layer depth:

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

- We expect there to be a unique entrainment law E:

$$\frac{w_e}{w_*} = E(\mathrm{Ri}, \mathrm{Re}, \mathrm{Pe})$$

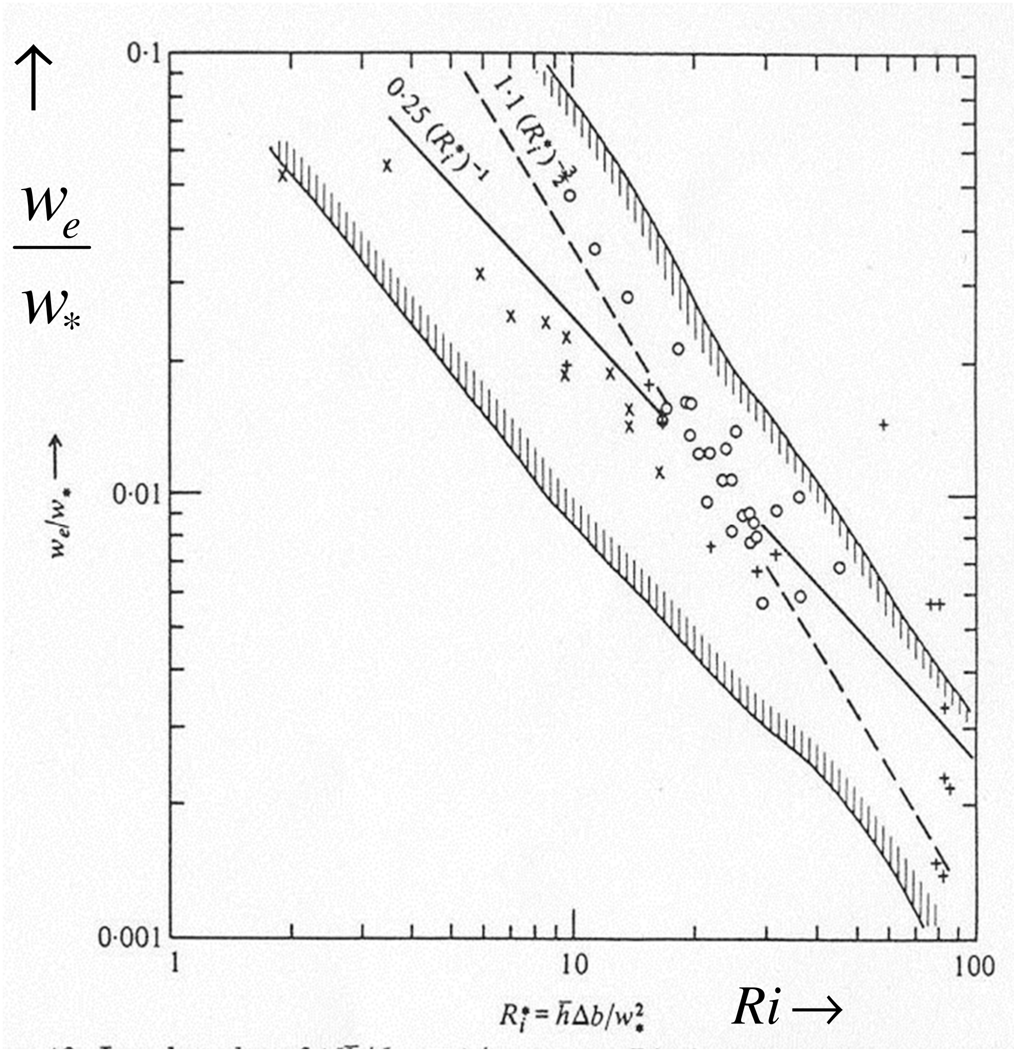
- which in the case of Re, Pe -> ∞ (asymptotic state) becomes

$$\frac{w_e}{w_*} = E(\mathrm{Ri})$$

How to obtain the entrainment law?

- Atmospheric Observations/field experiments
  - The real thing!
  - But … incomplete information, as is (no control), reproducibility, parameter studies impossible
- Numerical Simulation: LES (RANS, ...)
  - Complete information, excellent control (BCs, forcing), reproducible, parameter studies
  - But … not real, relies on turbulence closures.
- Laboratory Experiments (convection tank)
  - Reasonable amount of information, reasonable control, reasonable reproducibility, parameter studies possible, it is real
  - Viscous effects play a role

Laboratory experiments with a heated water tank



Re=10^3

Pr = 7

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

$$\frac{w_e}{w_*} = ARi^{-1}$$

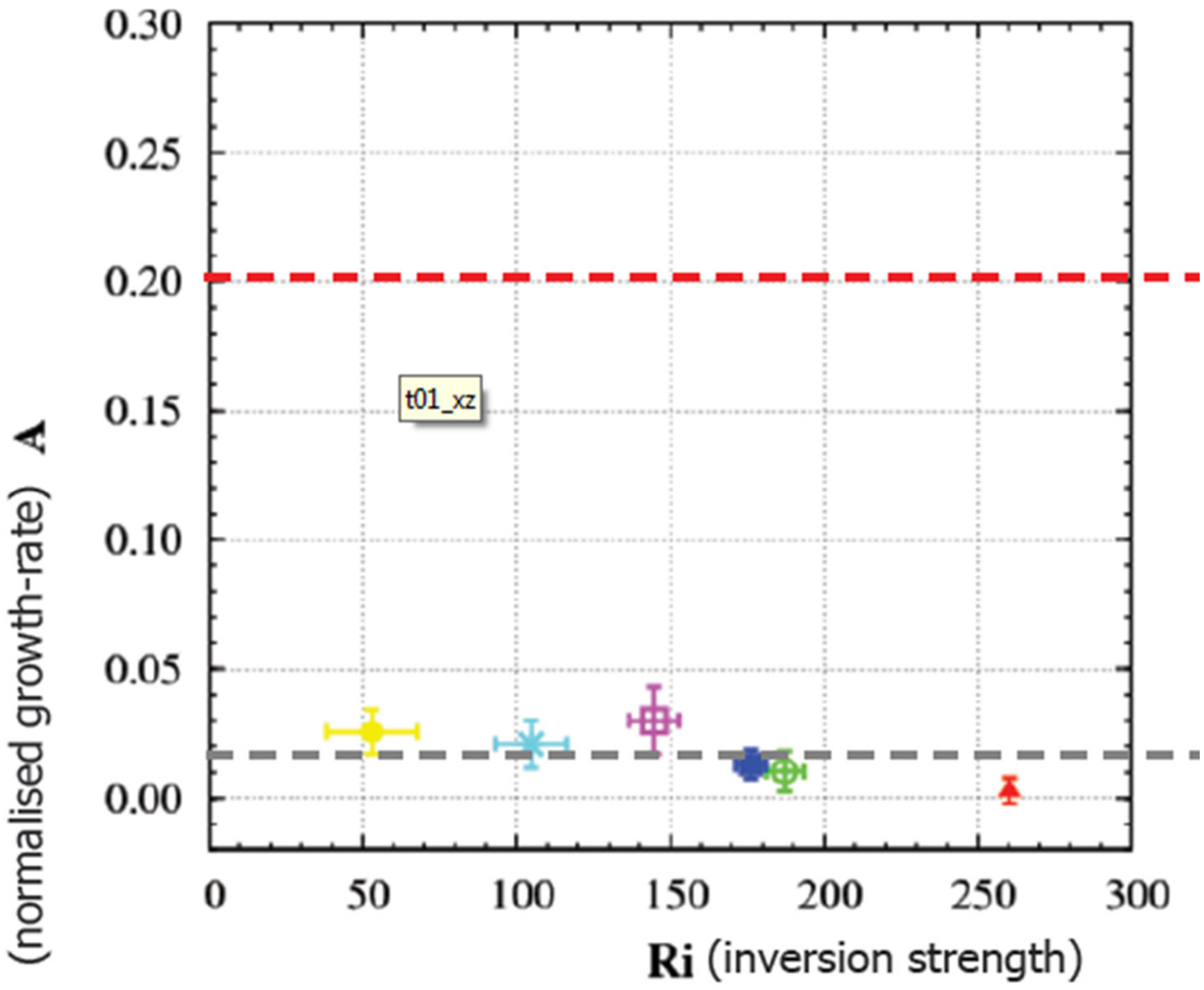
$$A = 0.25$$

(Deardorff, Willis and Stockton, JFM 1980)

Results of Delft saline tank

Re = 10^3

Pe = 10^6



$A \approx 0.25$

factor 10!

$A \approx 0.02$

(Jonker *et al.*, in preparation)

The case for direct numerical simulation

- **Ab initio simulation of fluid behaviour**

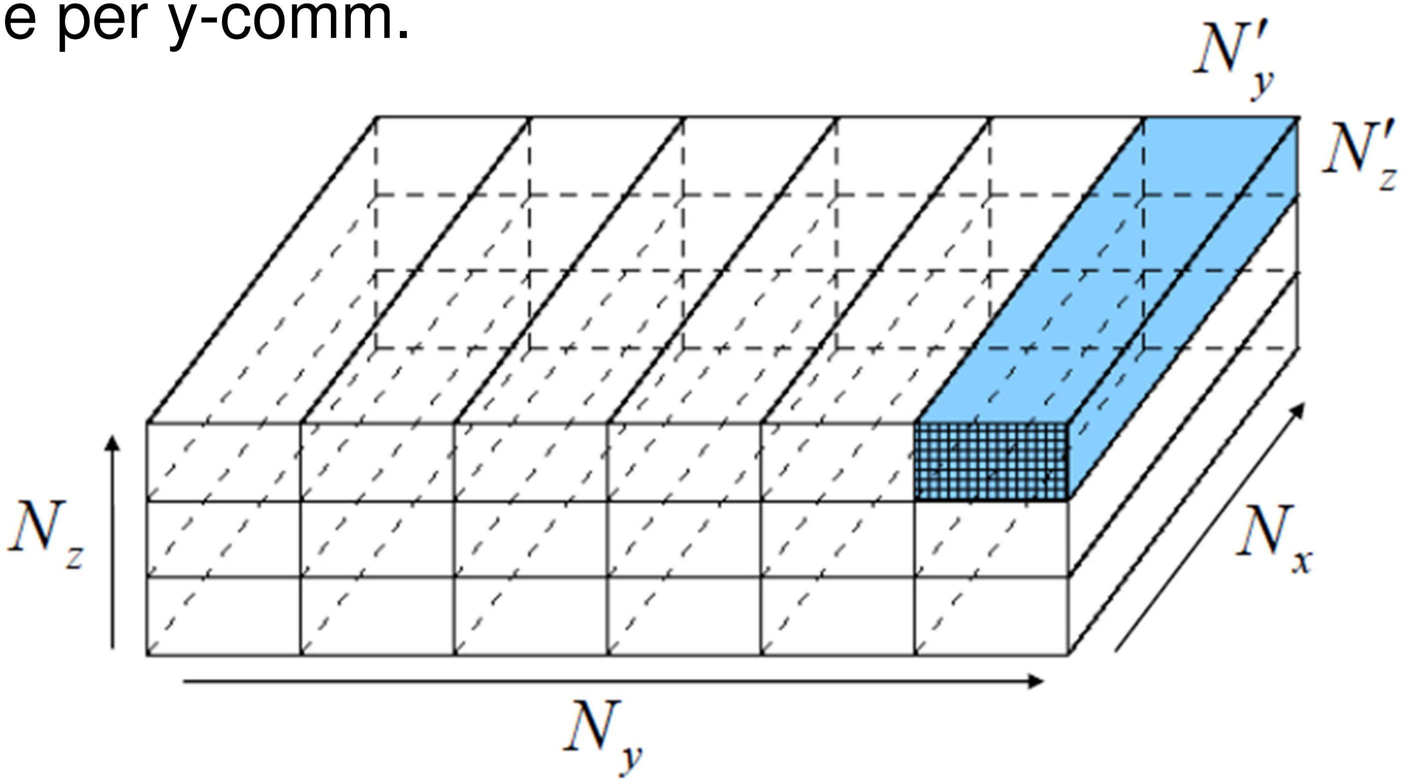
$$\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \theta \delta_{i3}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial u_j \theta}{\partial x_j} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}} \frac{\partial^2 \theta}{\partial x_j^2}$$

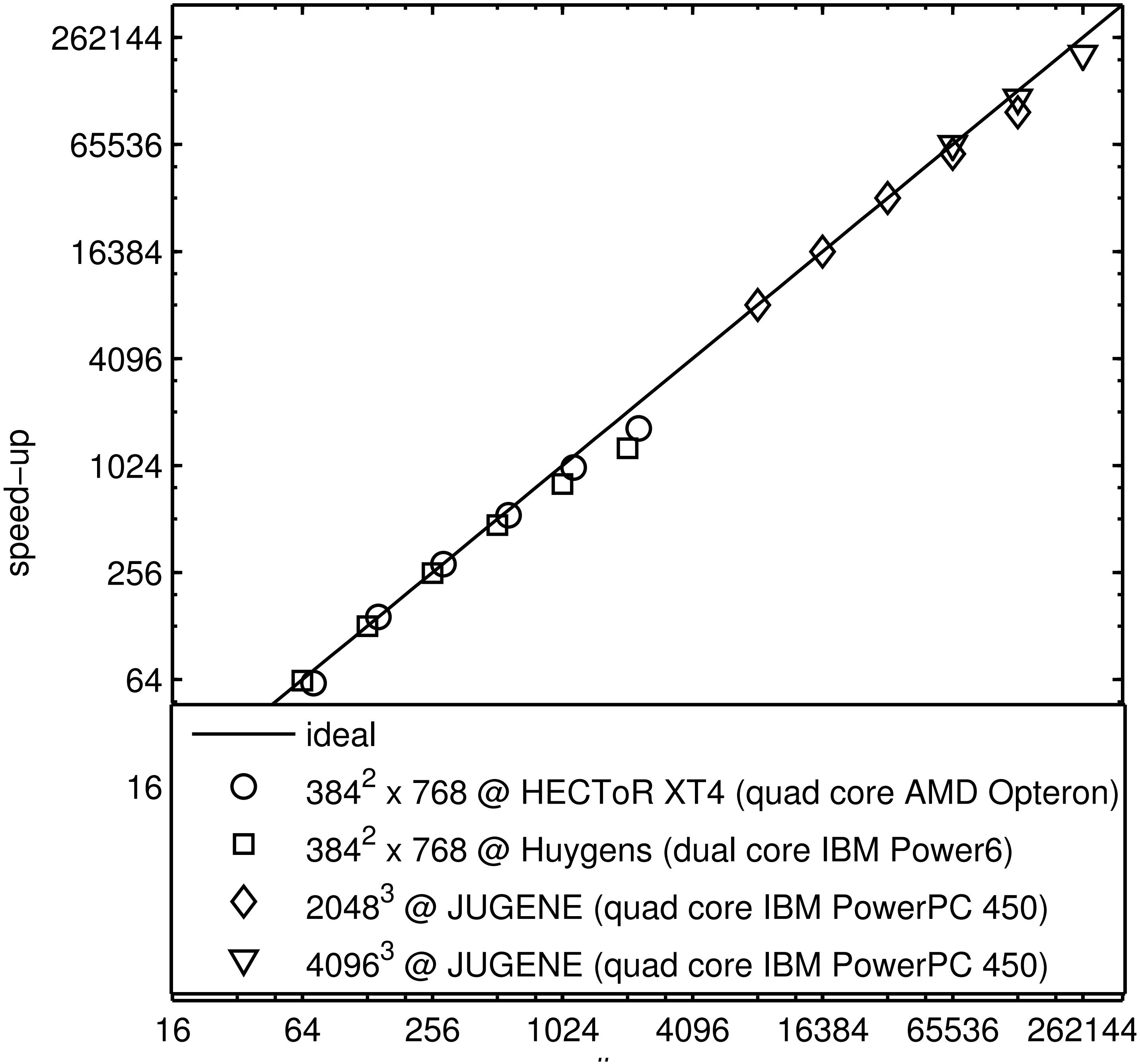
- (Navier-Stokes in Boussinesq approximation)
- Does not rely on empirical models
- Has become capable of reaching realistic Reynolds numbers on Tier-0 resources

DNS code sparkle

- Navier-Stokes equations in Boussinesq approximation;
- Fortran 90 with MPI and FFTW libraries;
- 2D domain decomposition using pencils;
- IO: one file per y-comm.



Speed-up


262144
65536
16384
4096
1024
256
64
16
speed–up
16
64
256
1024
4096
16384
65536
262144
ideal
384^2 x 768 @ HECToR XT4 (quad core AMD Opteron)
384^2 x 768 @ Huygens (dual core IBM Power6)
2048^3 @ JUGENE (quad core IBM PowerPC 450)
4096^3 @ JUGENE (quad core IBM PowerPC 450)

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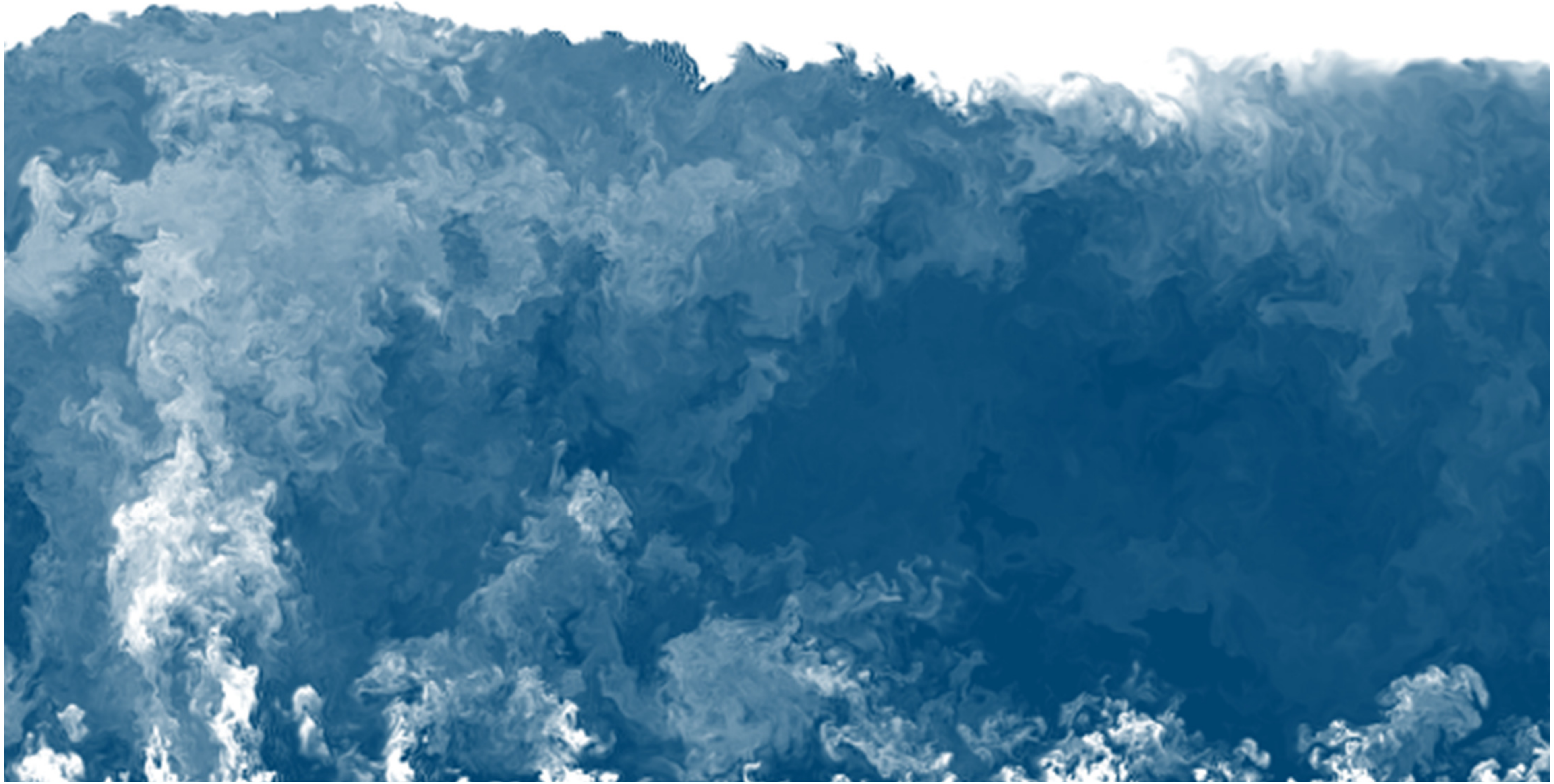
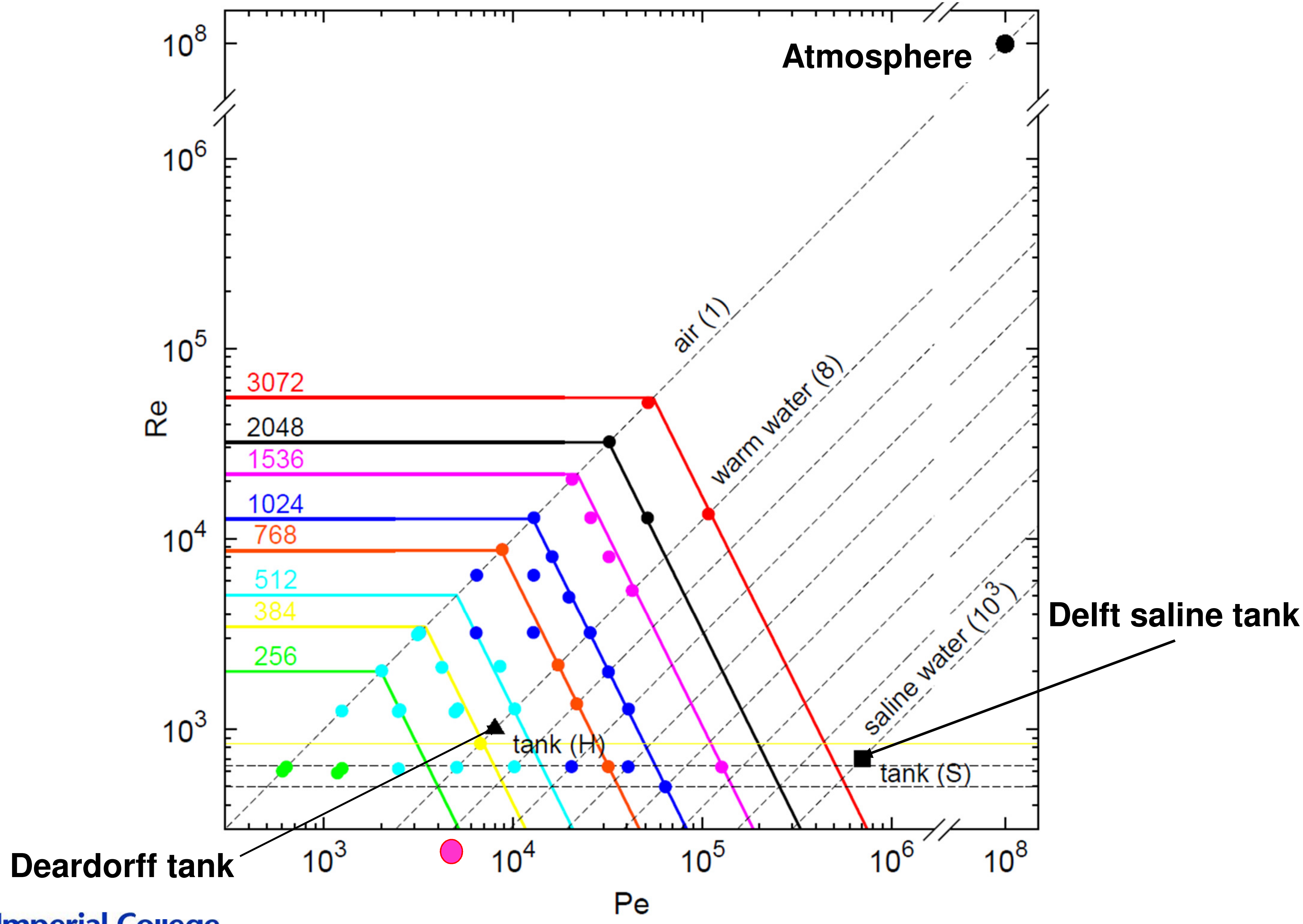
Homogeneous entrainment





Atmosphere
Delft saline tank
Deardorff tank
Re
Pe
3072
2048
1536
1024
768
512
384
256
air (1)
warm water (8)
saline water (10^3)
tank (H)
tank (S)
10^3
10^4
10^5
10^6
10^8

Simulations performed

Site	Architecture	Max nr of cores	Grid
SARA	IBM Power 6	1024	1024 x 1024 x 768
CINECA	IBM BCX/5120	2048	2048 x 2048 x 1024
LRZ	SGI Altix 4700	3072	1536 x 1536 x 768
Juelich	Bluegene	32,768	3072 x 3072 x 1536

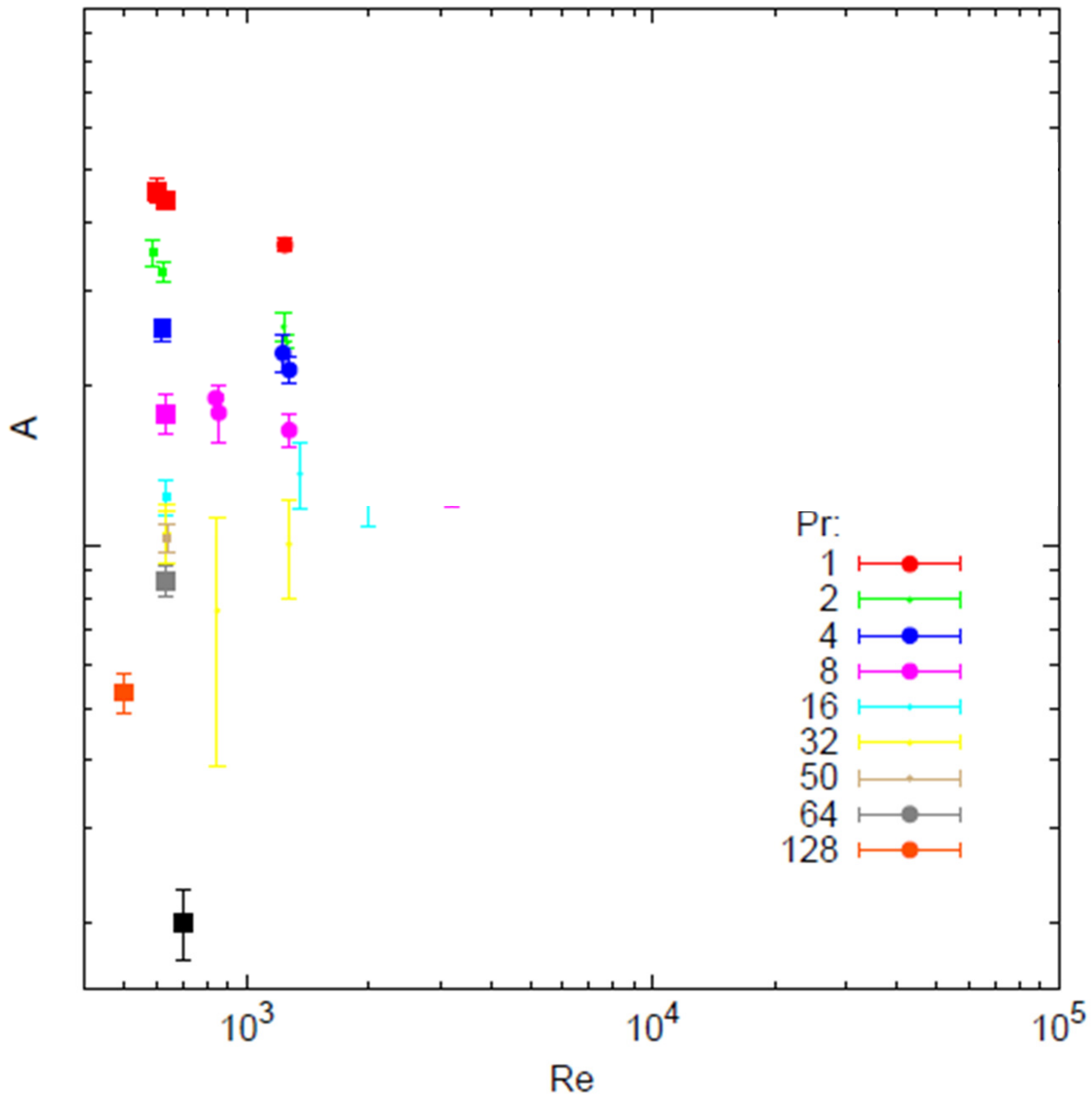
DEISA
DISTRIBUTED EUROPEAN INFRASTRUCTURE FOR SUPERCOMPUTING APPLICATIONS

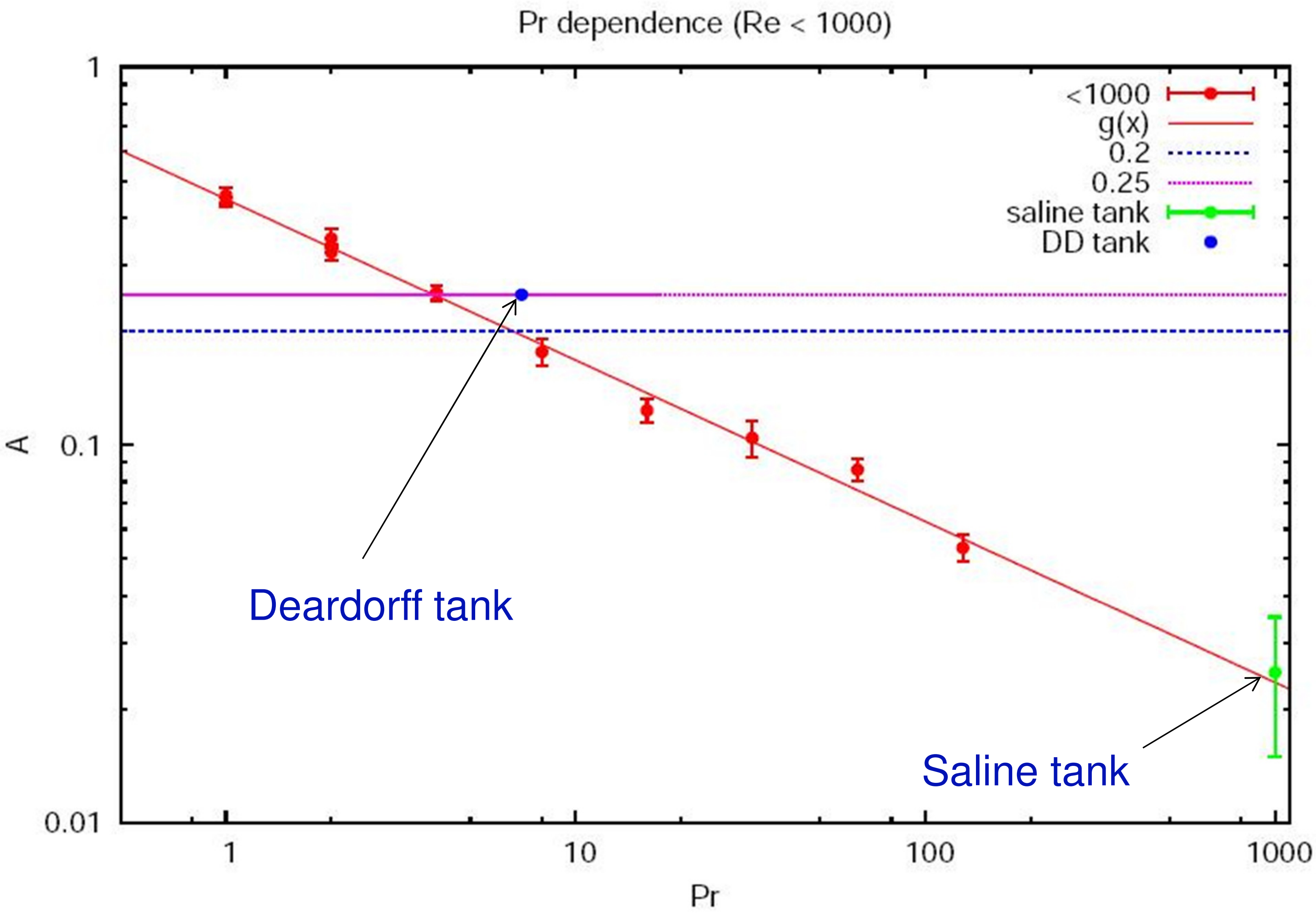
3Mhr

PRACE
Partnership for Advanced Computing in Europe

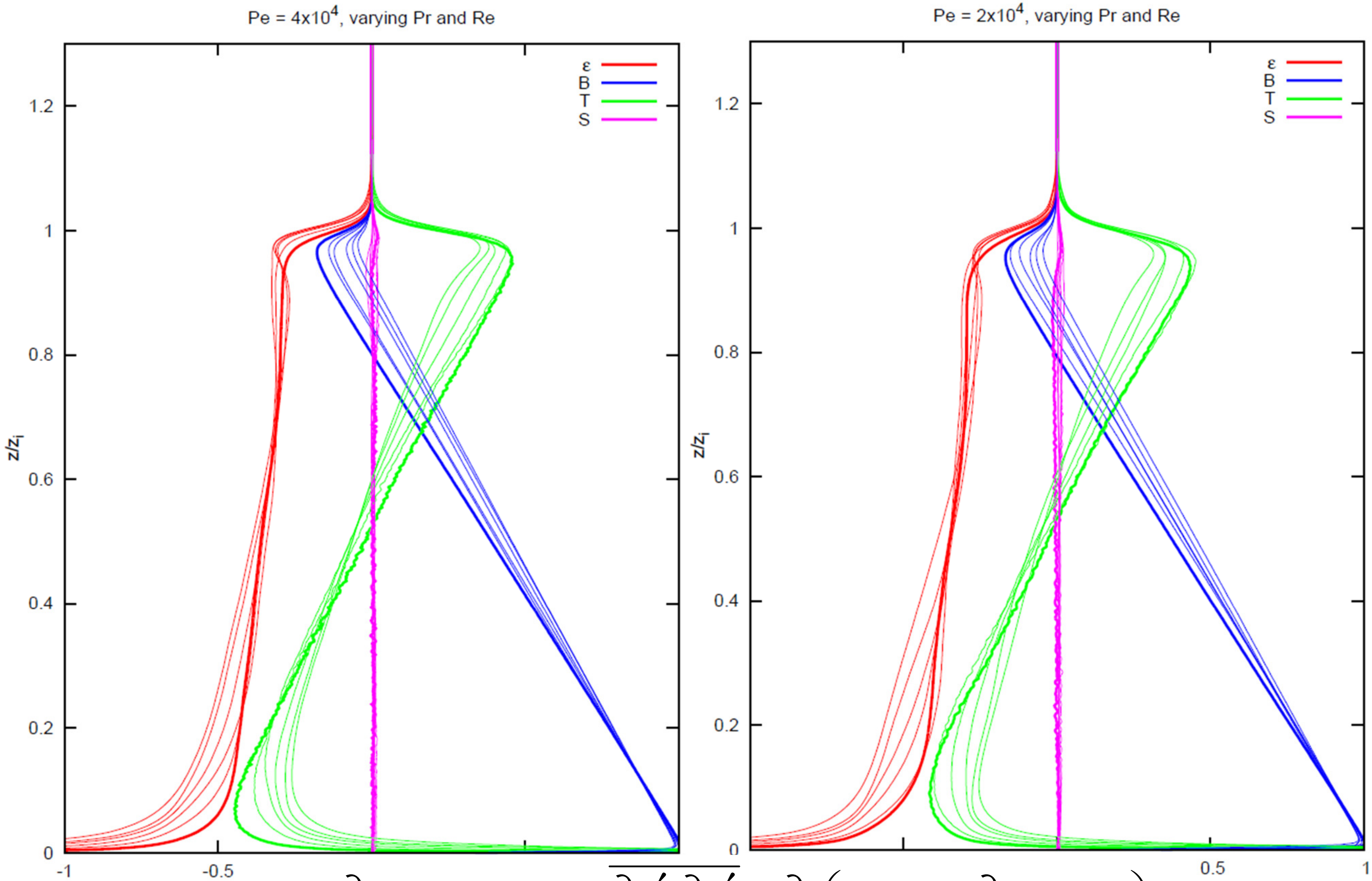
35Mhr

The need for extreme computing





Asymptotic regime NOT reached in laboratory experiments



$$\underbrace{\frac{\partial e}{\partial t}}_{S} = \underbrace{\beta g \overline{w'\theta'}}_{B} \underbrace{- \nu \overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}}}_{\varepsilon} \underbrace{- \frac{\partial}{\partial z}\left(\overline{w'e'} - \nu \frac{\partial e}{\partial z} + \overline{w'p'} \right)}_{T}$$

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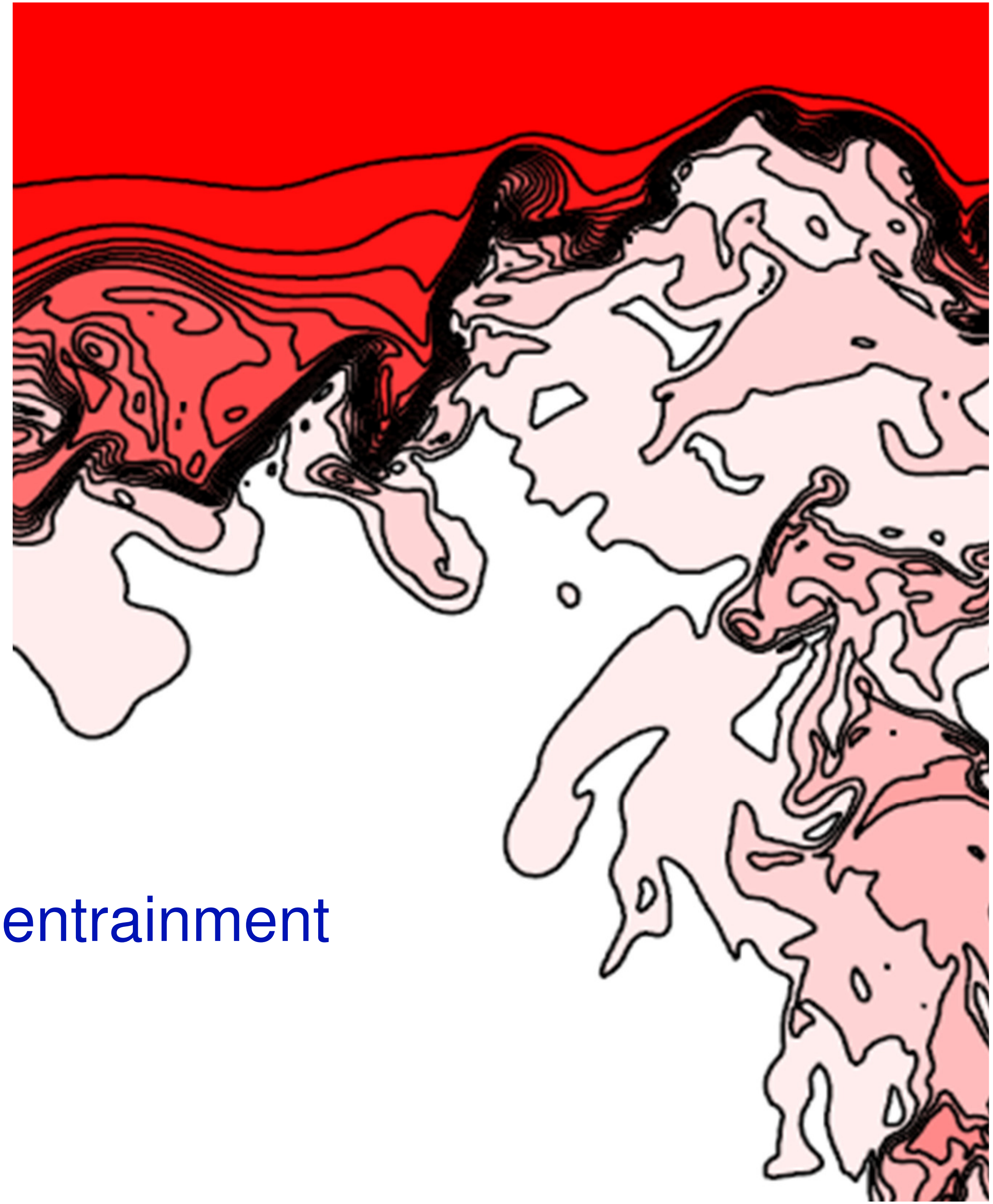


Localised entrainment

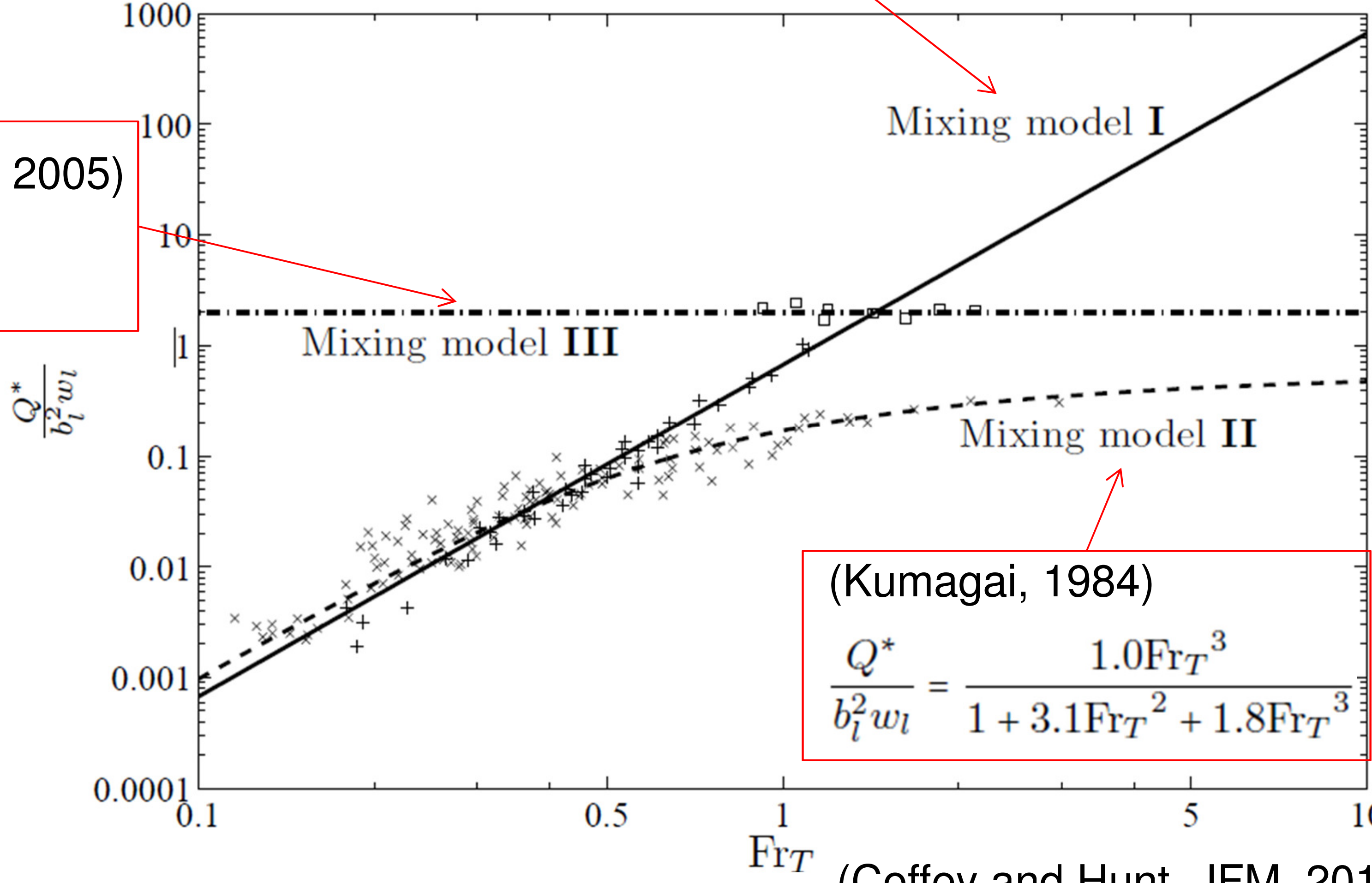
Interfacial mixing

(Baines, 1975)

$$\frac{Q^*}{b_l^2 w_l} = 0.67{\mathrm{Fr}_T}^3, \quad \mathrm{Fr}_T = \frac{w_l}{\sqrt{b_l \Delta g'}},$$

(Lin & Linden, 2005)

$$\frac{Q^*}{b_l^2 w_l} \approx 2.0.$$

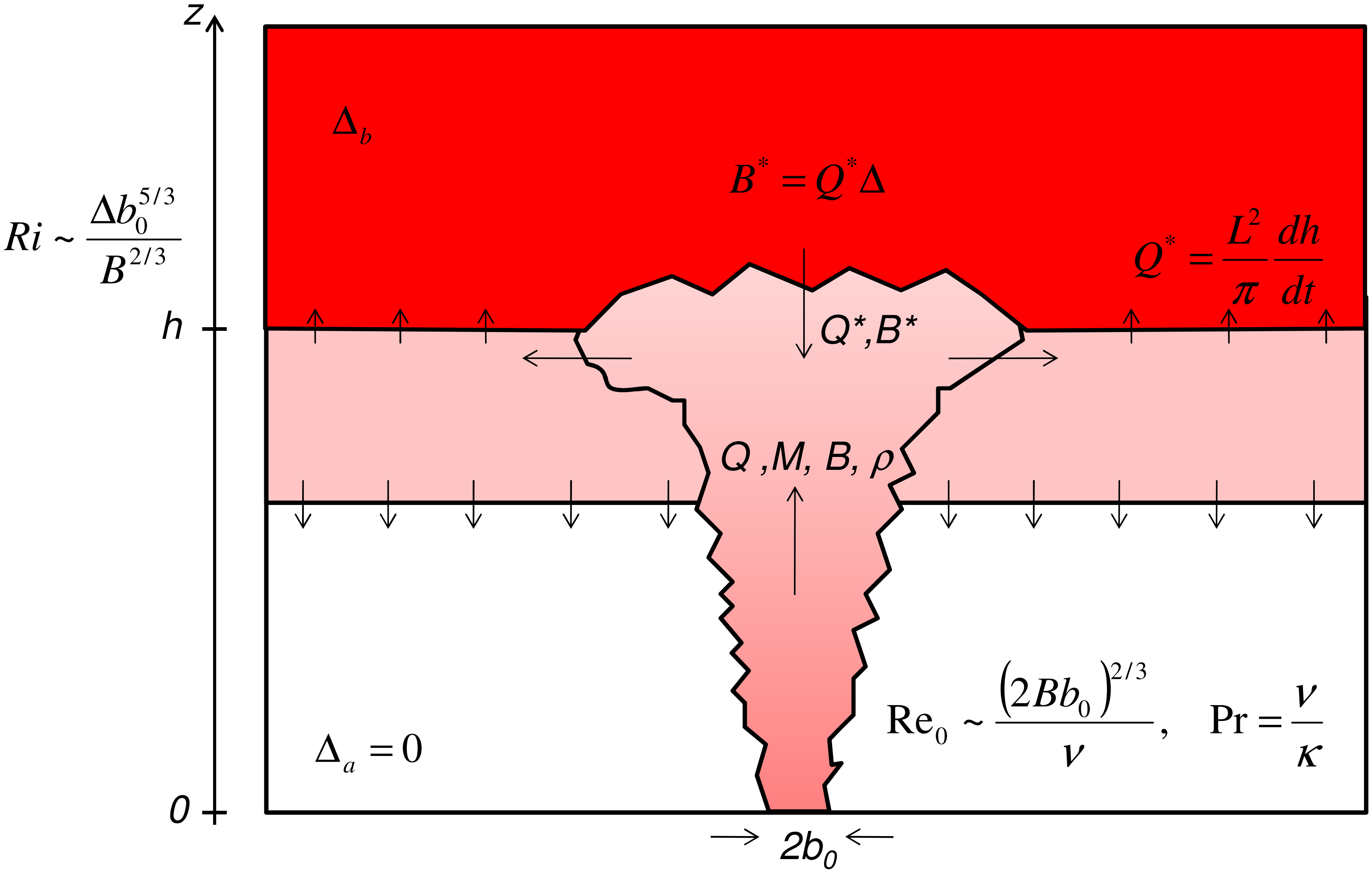


(Kumagai, 1984)

$$\frac{Q^*}{b_l^2 w_l} = \frac{1.0{\mathrm{Fr}_T}^3}{1 + 3.1{\mathrm{Fr}_T}^2 + 1.8{\mathrm{Fr}_T}^3}$$

(Coffey and Hunt, JFM, 2010)

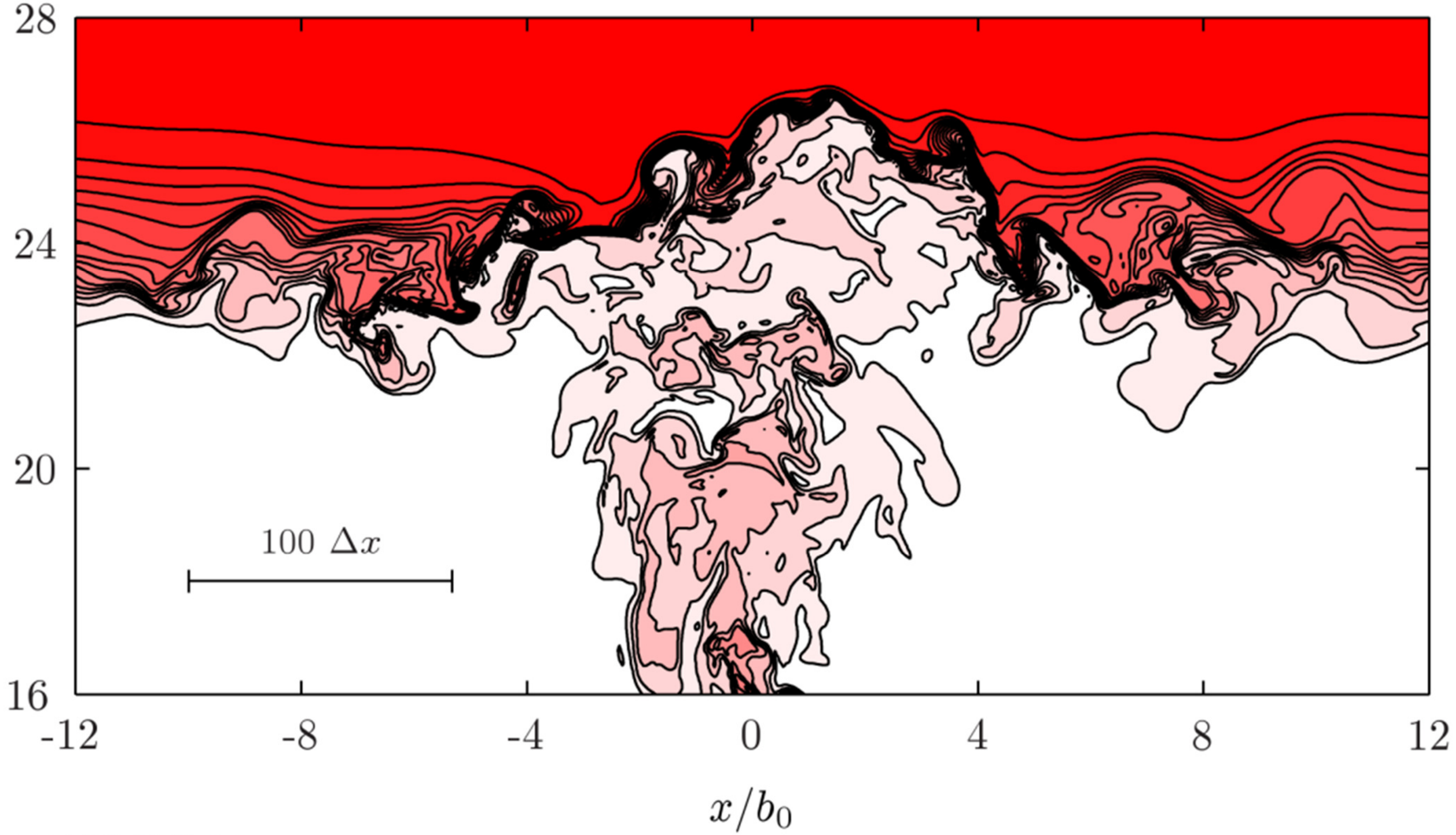
Entrainment across density interface



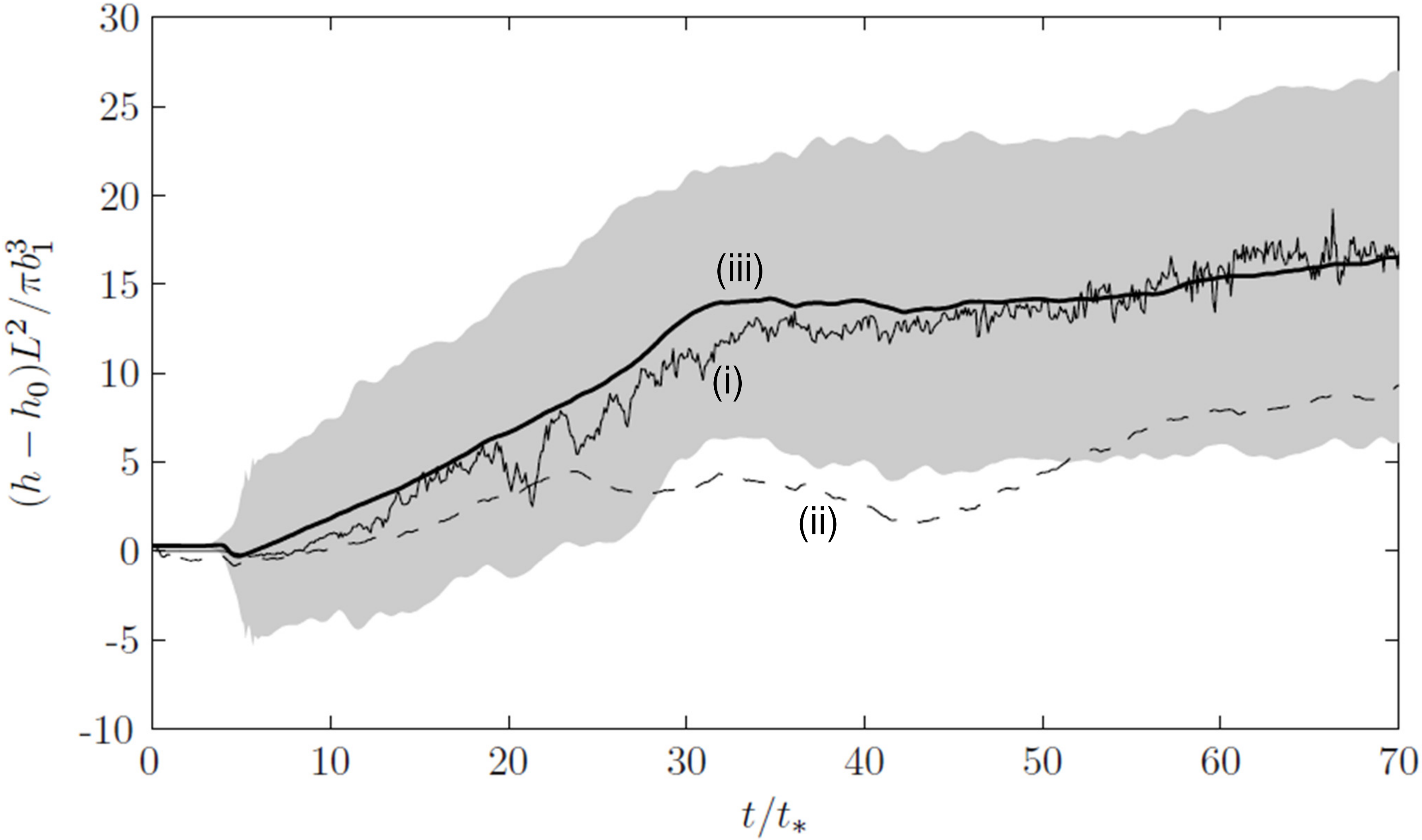
Simulation details

Re_0	Pr	Ri_0	Resolution	#procs	Required resources [CPU-hr]
600	0.71	various	1024x1024x768	8,192	200,000
1000	0.71	various	1536x1536x1024	32,768	600,000
1500	0.71	various	2048x2048x2048	65,536	3,000,000

30 Mhrs

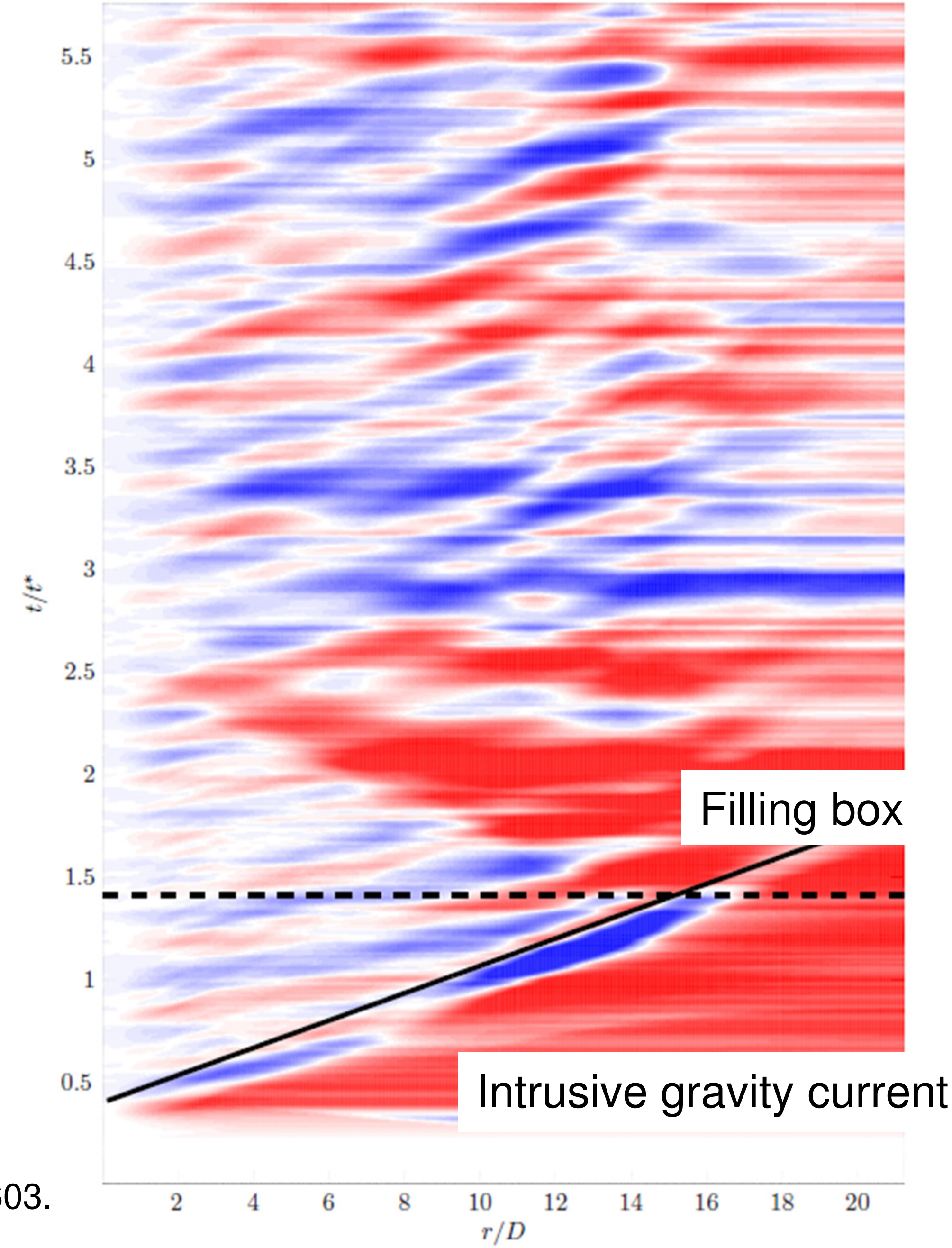

28
24
20
16
100 Δx
-12
-8
-4
0
4
8
12
x/b_0

Evolution of interface position over time



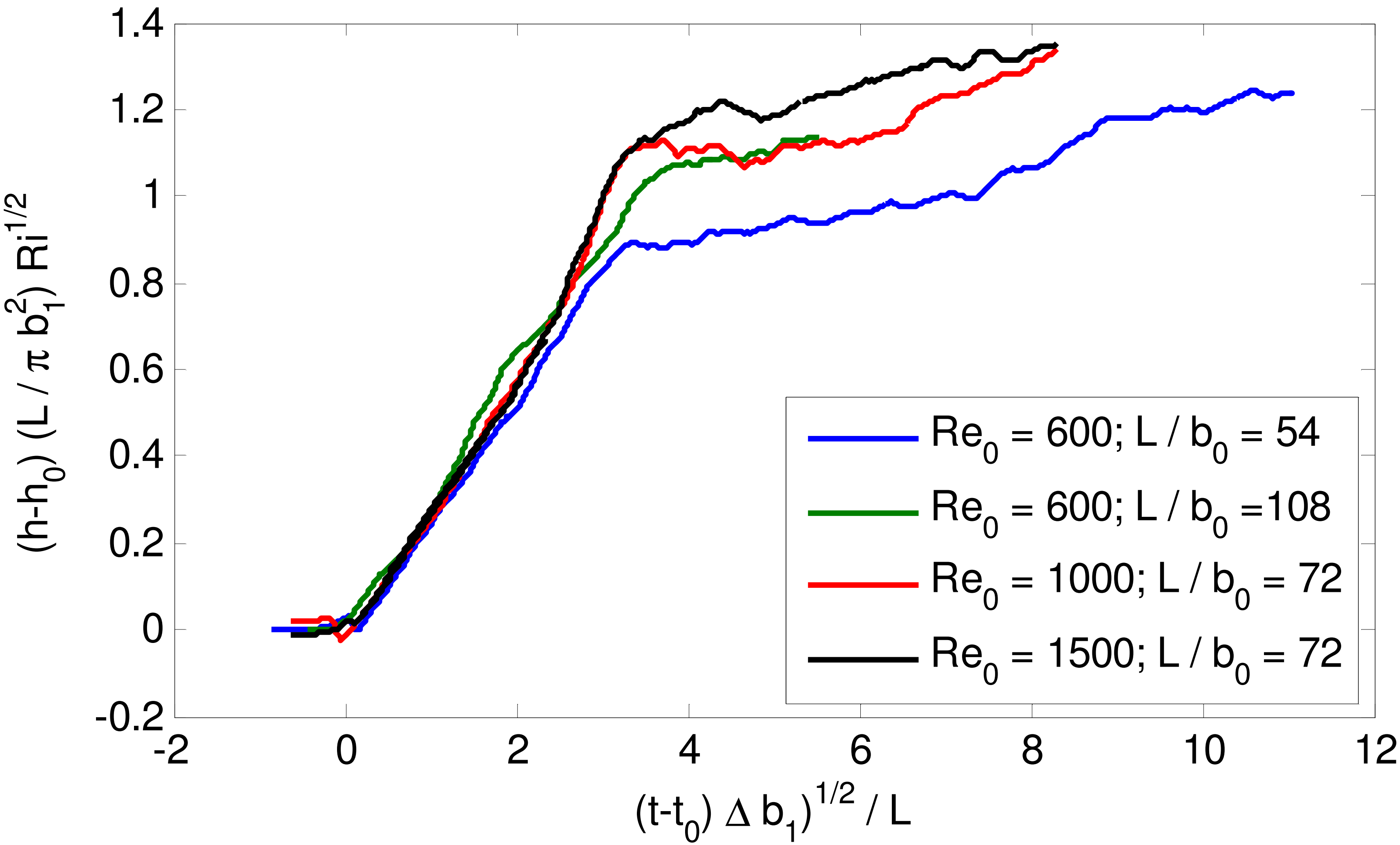
Why the kink?

- Associated with transition from intrusive gravity current to filling box behaviour
- Front velocity consistent with predictions for intrusive gravity current (e.g. Holdsworth, 2012).

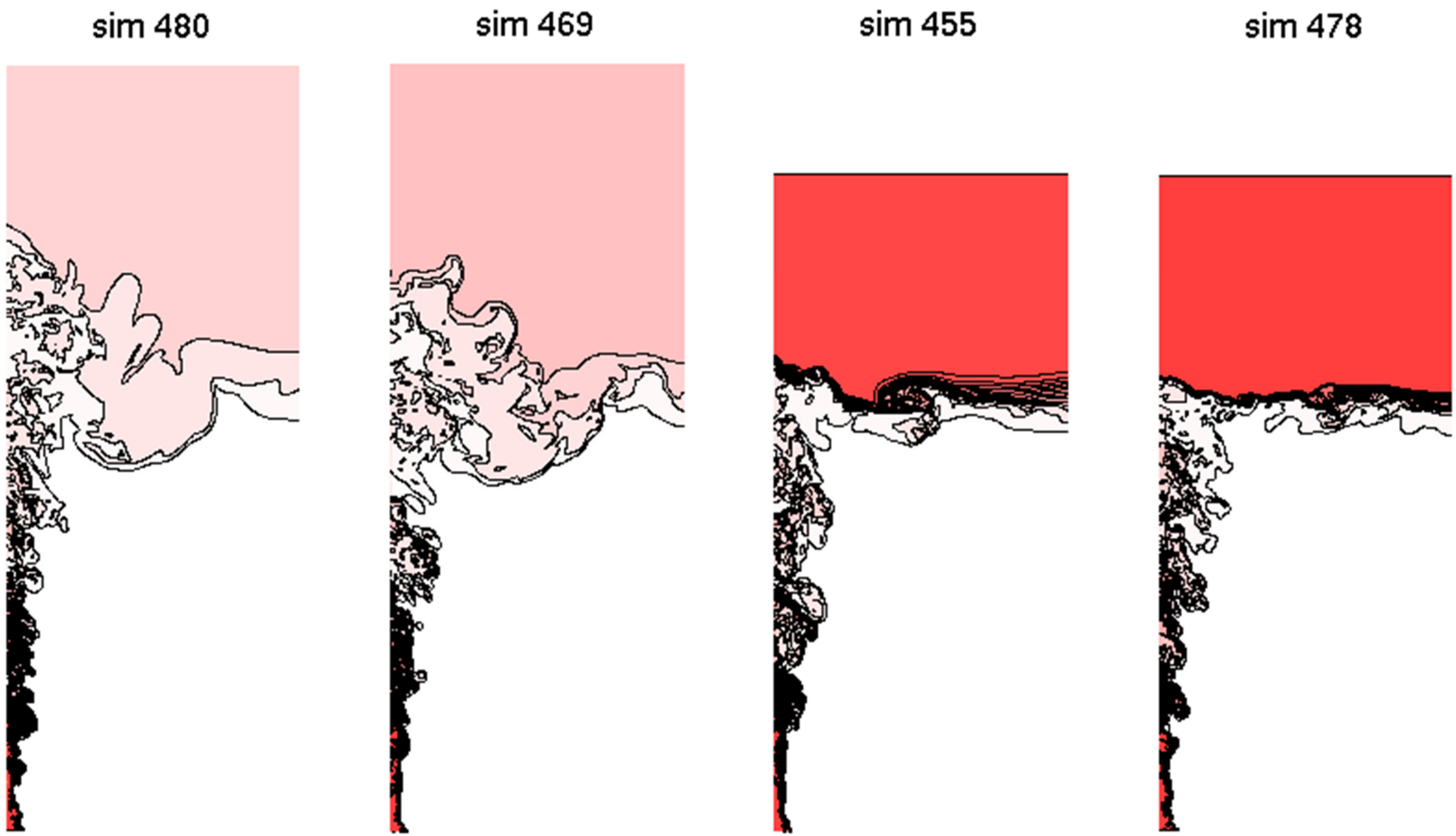


HOLDSWORTH *et al.* (2012) *Phys. Fluids* **24**, 036603.

Interface positions for various *L* and Re



Dependence on Richardson number (ongoing)



Conclusions

Homogeneous entrainment:

- In the asymptotic regime (Pe, Re -> infinity) the appropriate law is indeed

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

- Prefactor still uncertain; best estimate remains $A = 0.25$
- Laboratory experiments on entrainment have been influenced too much by molecular processes (Re, Pr)
- Improved parameterisations can be obtained by studying TKE budgets (ongoing)

Localised entrainment

- A plume in a filling box has a different entrainment behaviour than a plume in an unbounded domain;
- Work in development; much of the data still needs to be processed.

A bright future with DNS ideal experiments