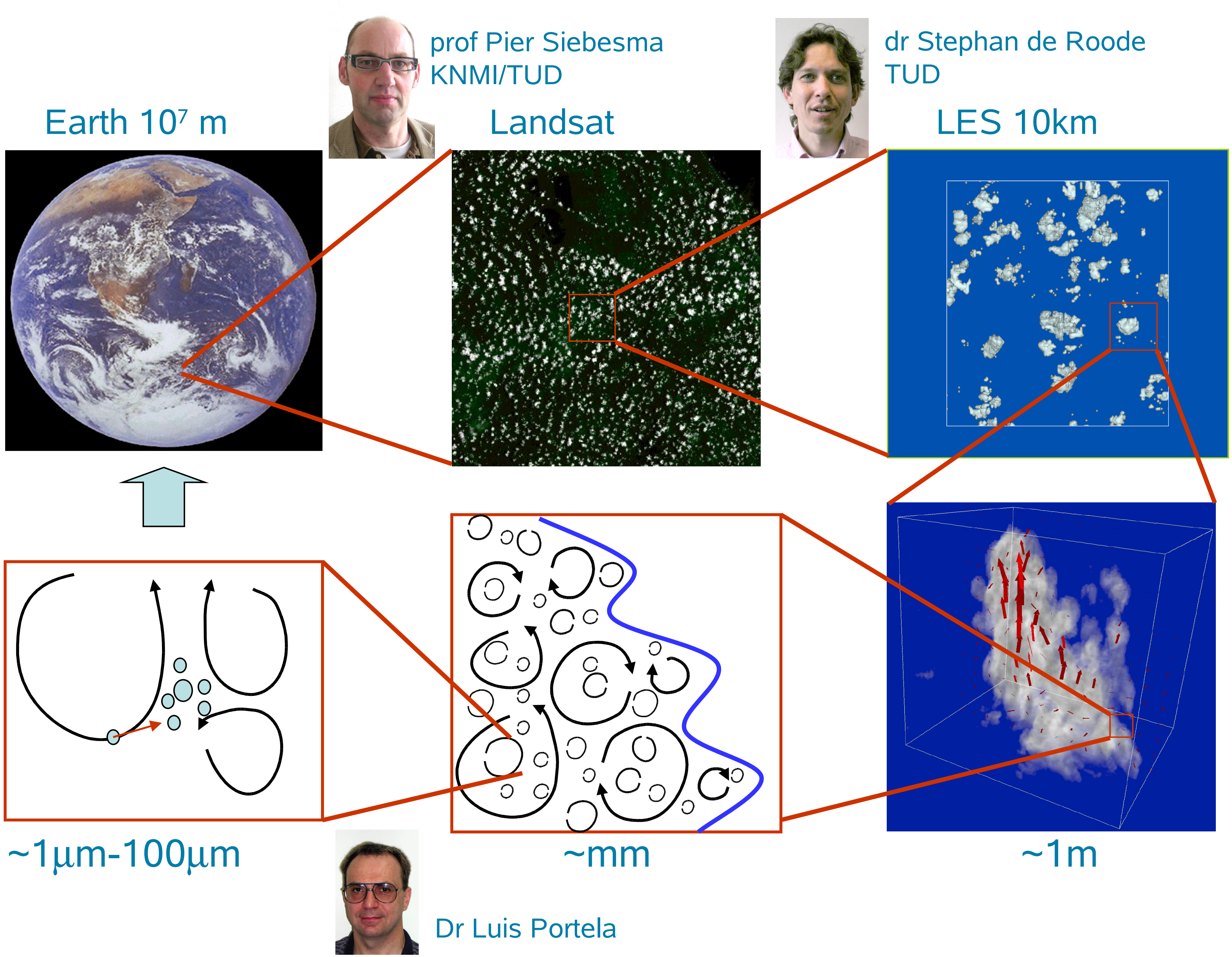
A complexity of entrainment and detrainment processes in "directly-simulated" plumes

Harm Jonker

contributions by: TUD: Maarten Sanders, Thijs Heus, Pier Siebesma
NCAR: Peter Sullivan, Don Lenschow

Clouds Climate and Air Quality

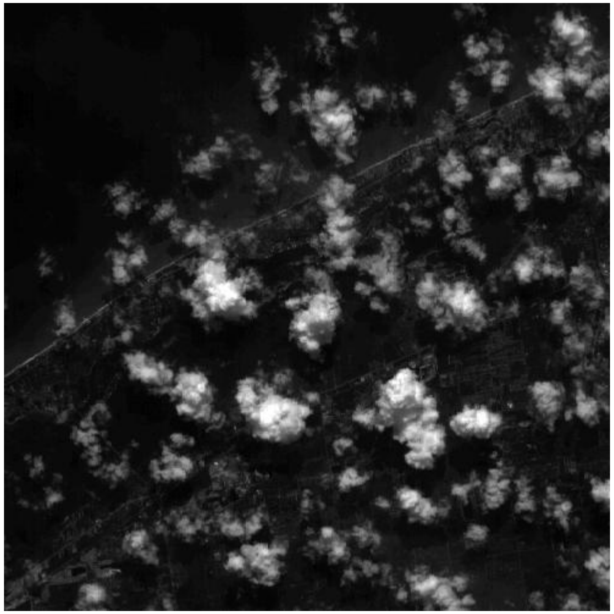


Small Cumulus Microphysics Study

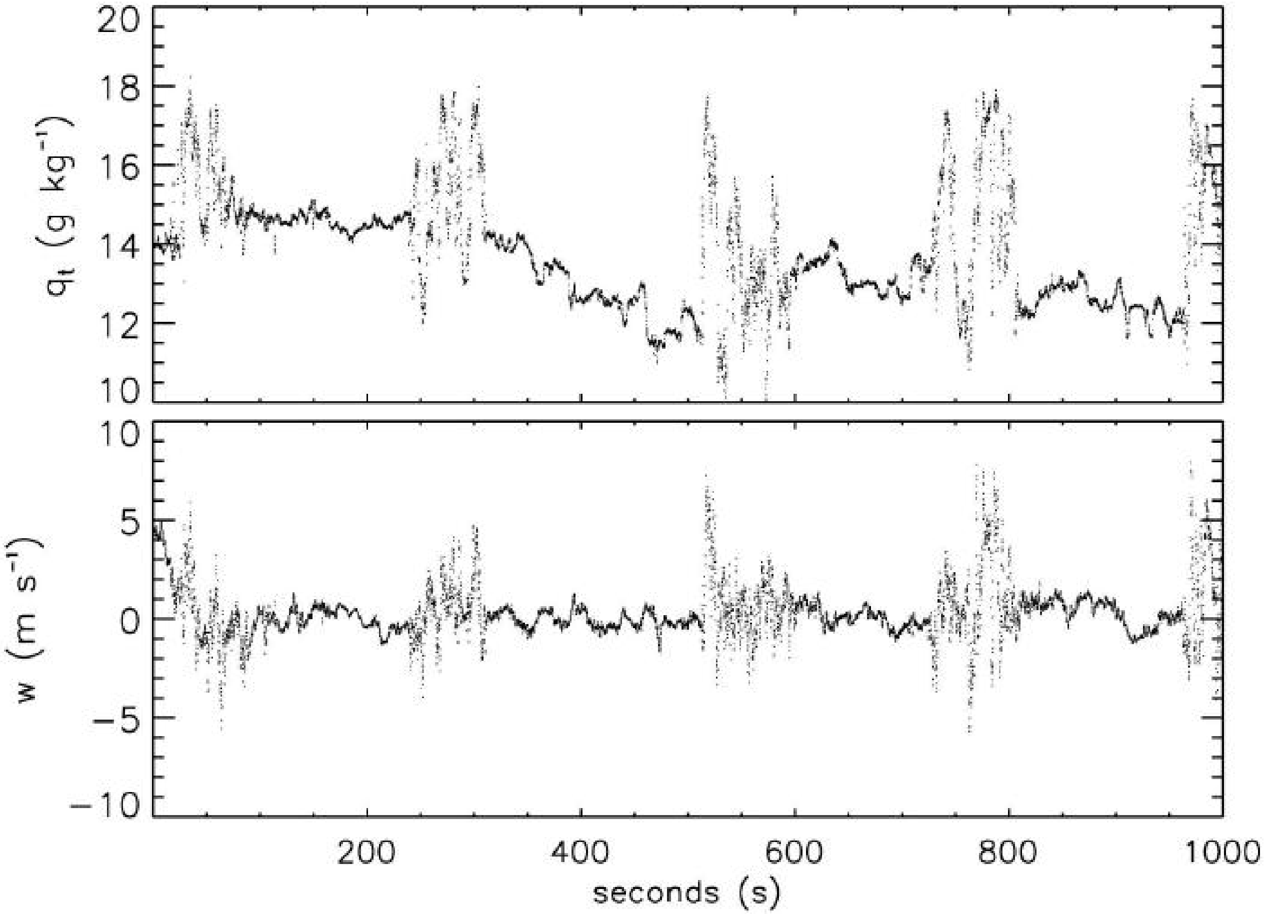
Florida, 1995

NCAR: C-130

Stefaan Rodts (IMAU/TUD)

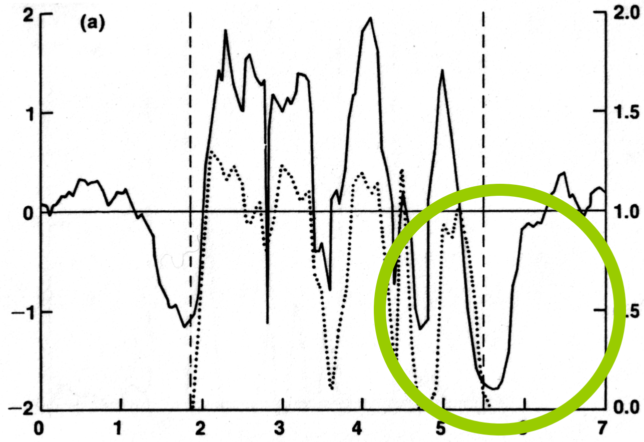


Landsat

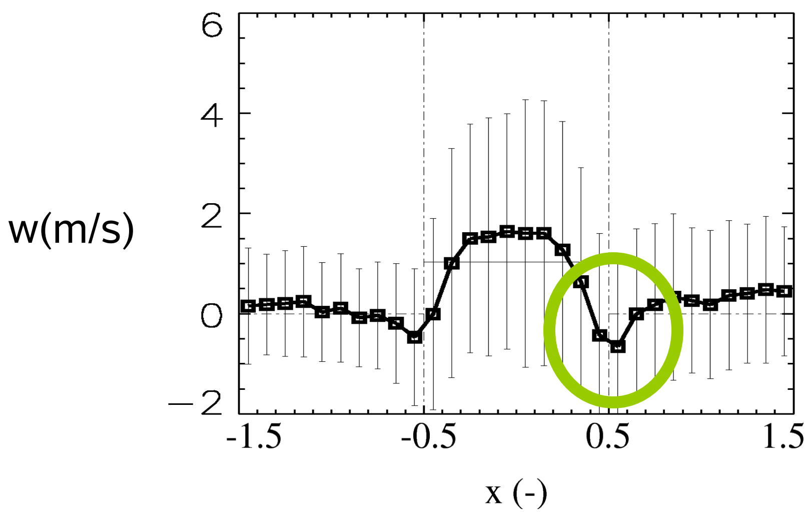


Descending Shells in Observations

Jonas
(Atmos. Res., 1990)

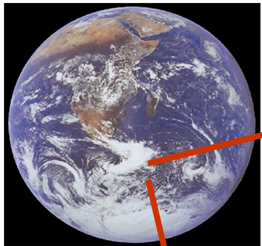


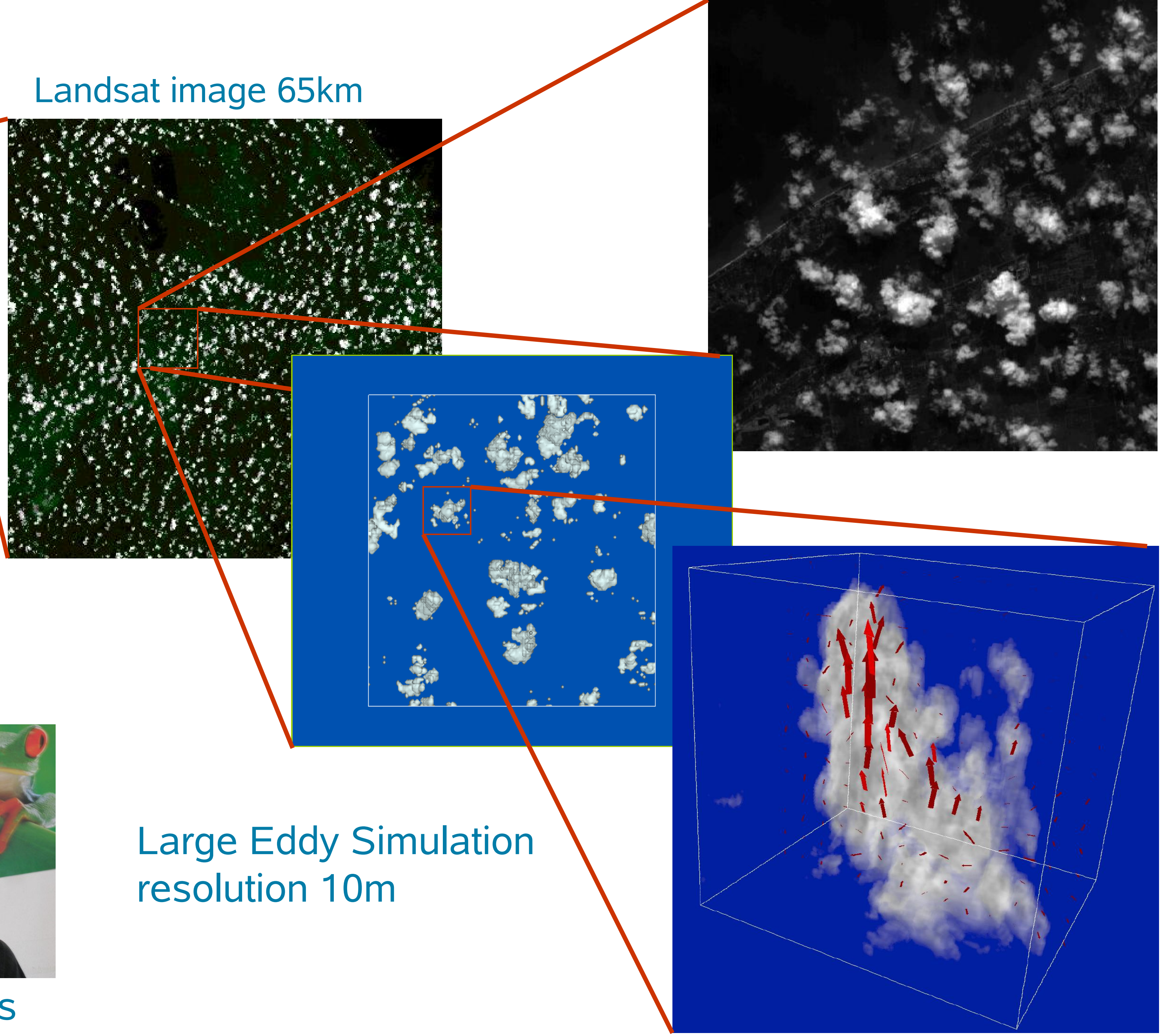
Rodts, Duynkerke, Jonker
(JAS, 2003)

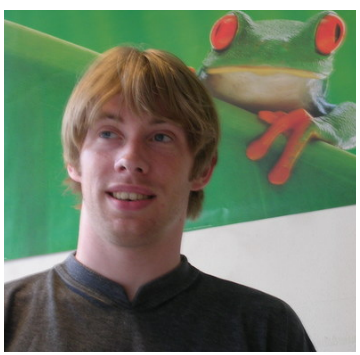


recently: observations by Siebert et al. 2007 (helipod)

debate about the origin of the shell

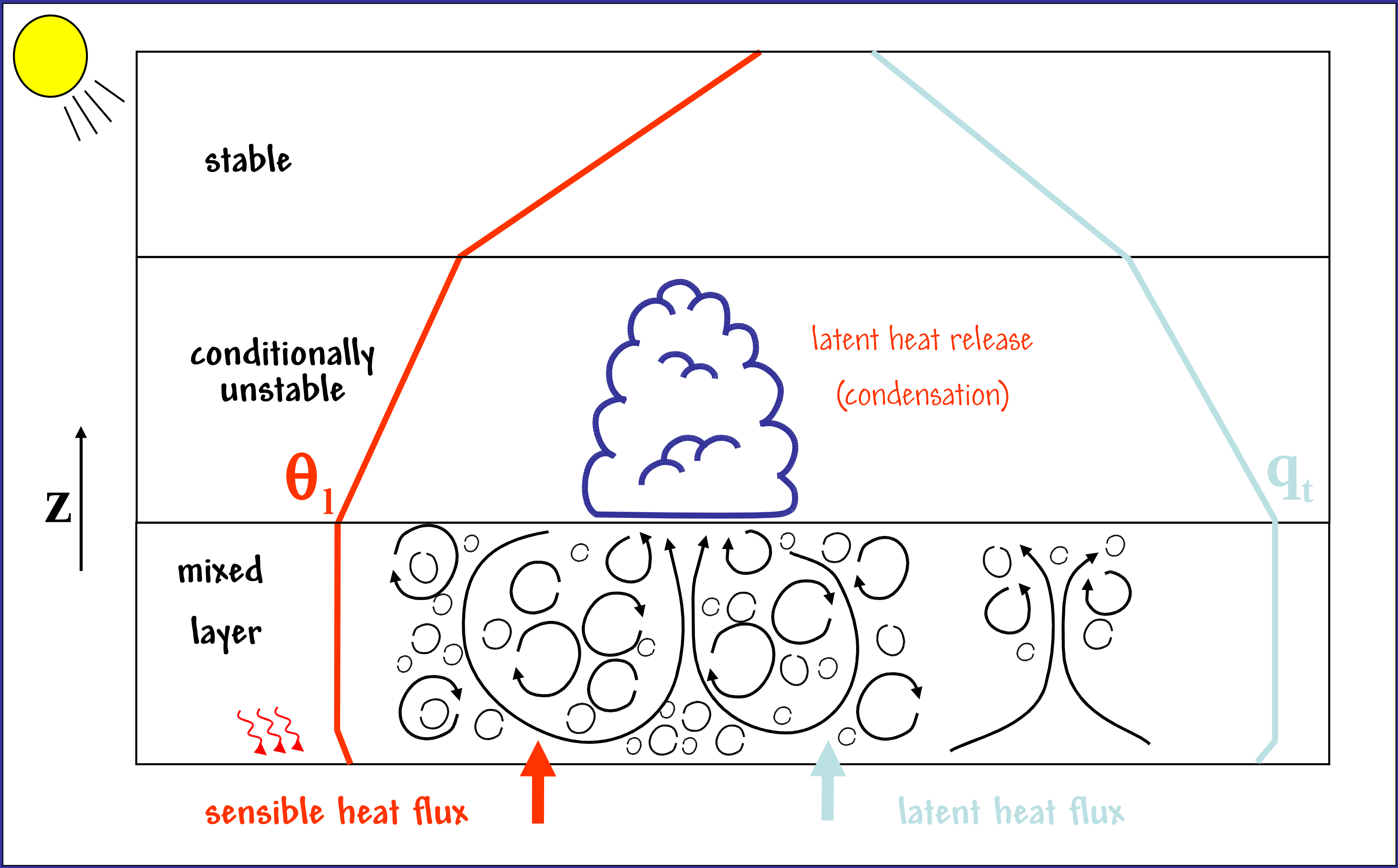


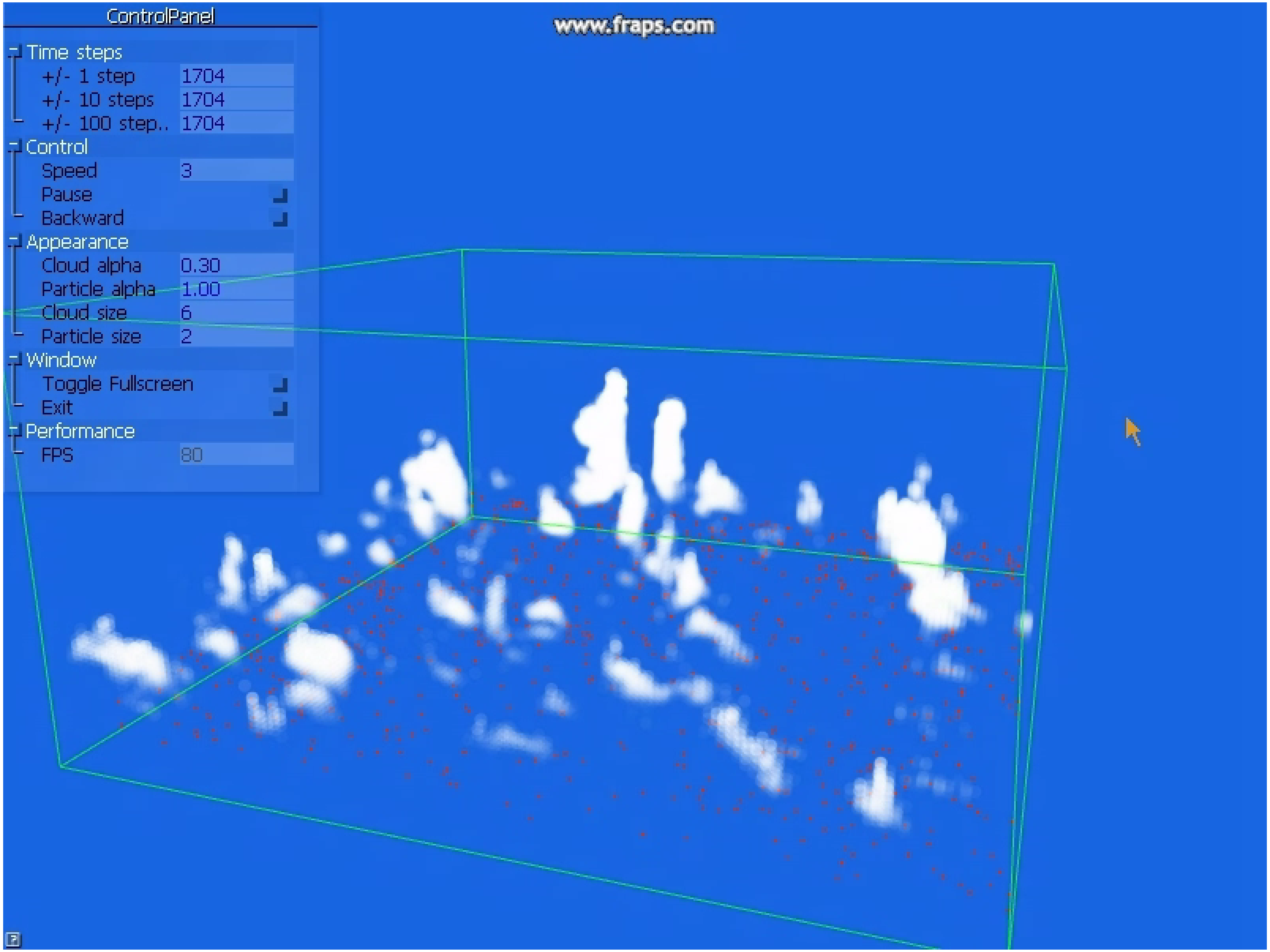




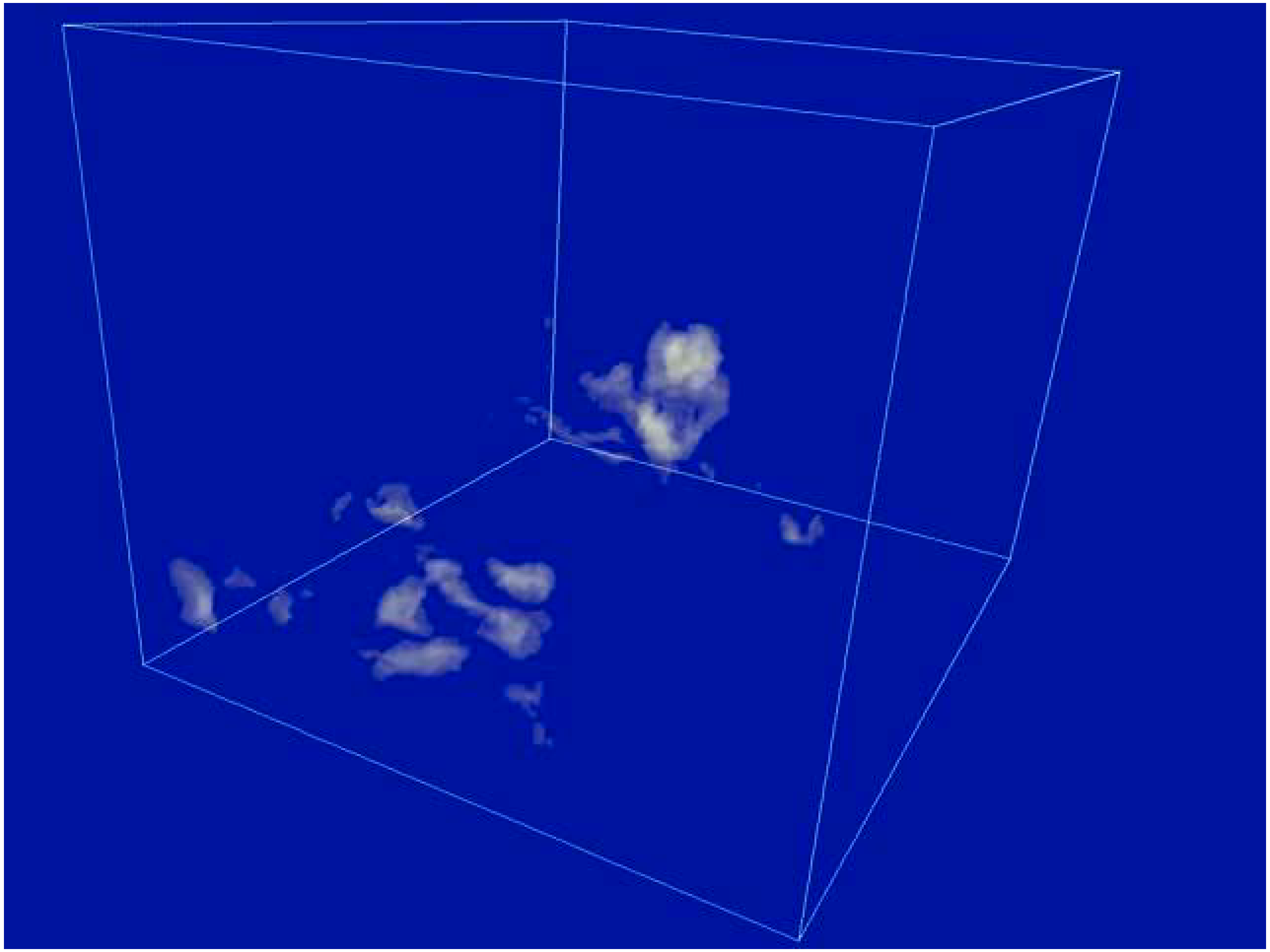
Thijs Heus

Cloud Topped Boundary Layer: Cumulus



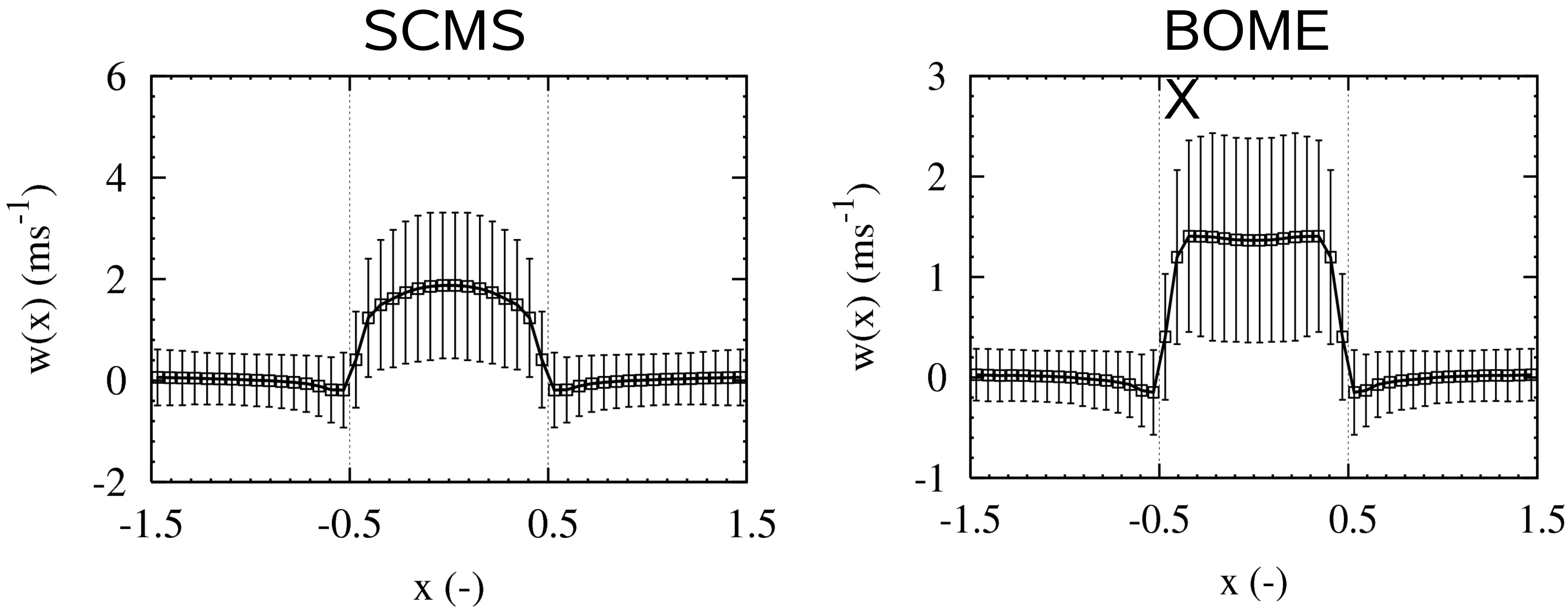


Courtesy Dylan Dussel, TUD



Courtesy Thijs Heus

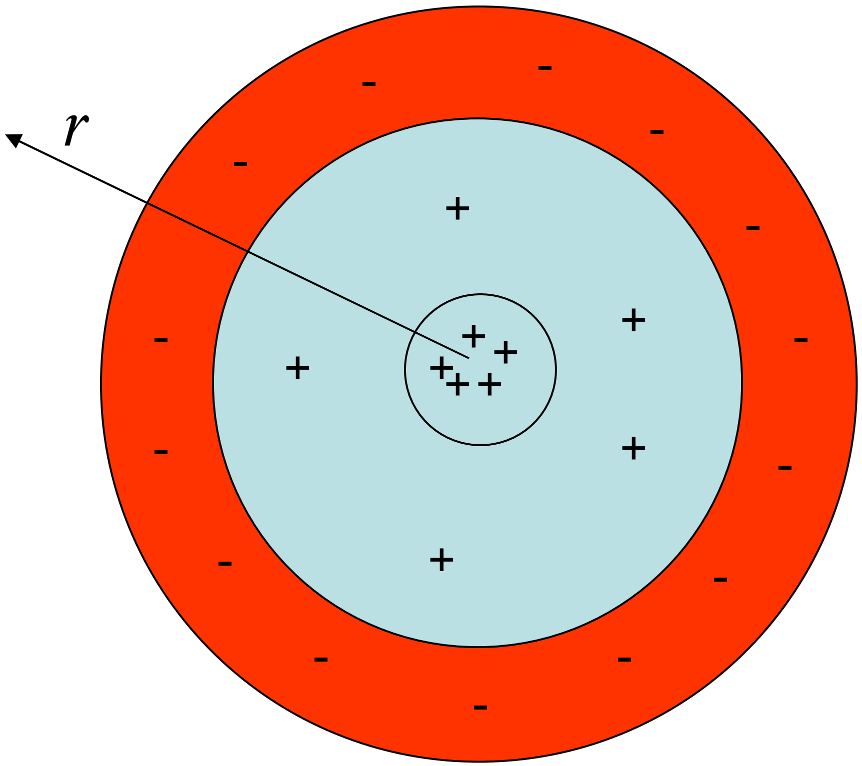
LES results for SCMS and BOMEX



Heus and Jonker, JAS 2007

Heus and Jonker, JAS 2007

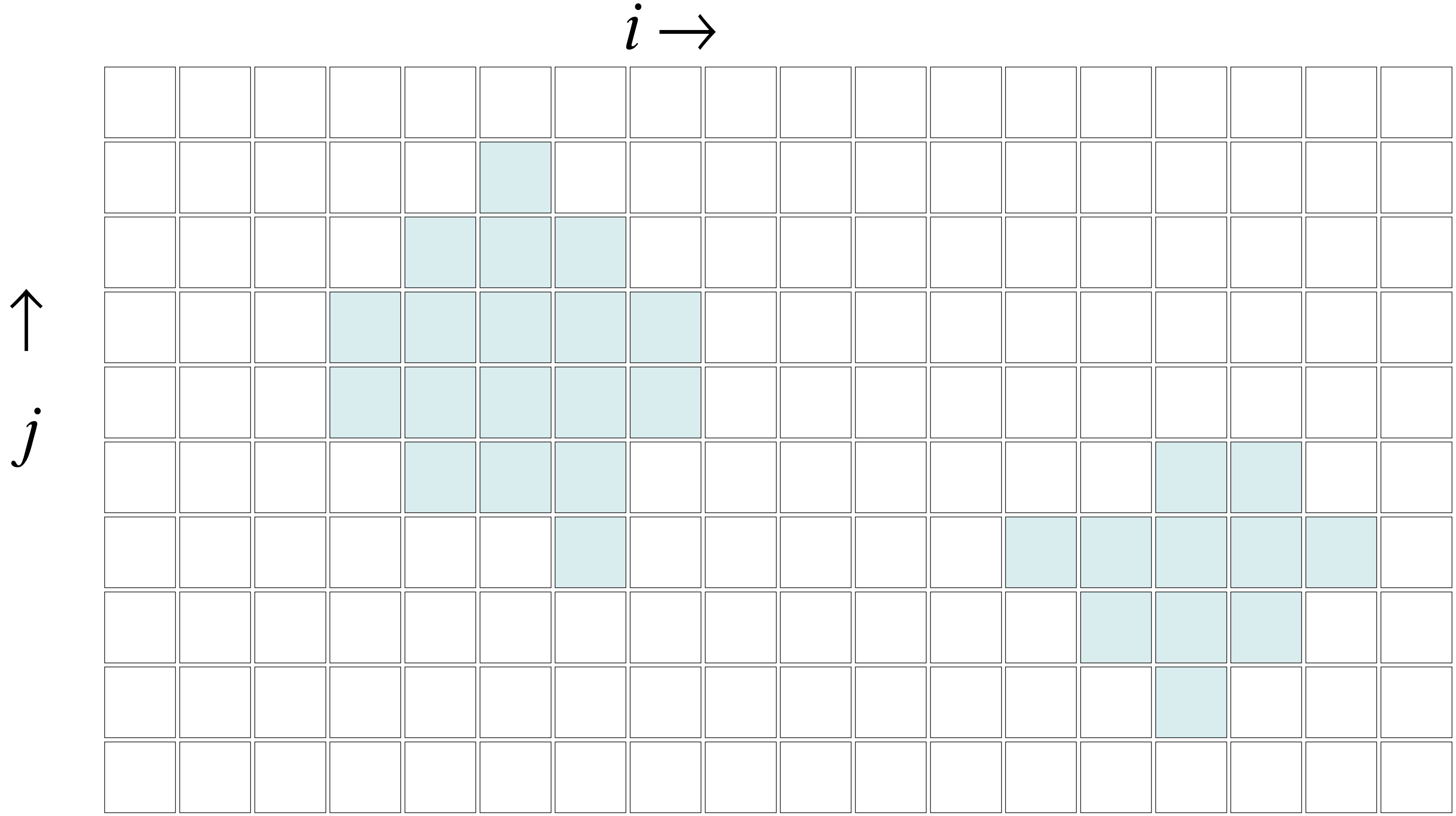
negative mass-flux in the shell could be significant!



mass-flux = velocity x area

area $2\pi\, r\, \Delta r$

$$m(r)\Delta r = 2\pi\, r \Delta r \;\; w(r)$$



cloud mass-flux: $M_c = \sum_C \mathrm{w(i, j)}$ $C = \{i, j \mid q_l(i, j) > 0\}$

env mass-flux: $M_E = \sum_E \mathrm{w(i, j)}$ $E = \{i, j \mid q_l(i, j) = 0\}$

$$M_C + M_E = \sum_{E@C} \mathrm{w(i, j)} = \sum \mathrm{w(i, j)} = 0$$

e.g. Siebesma and Cuijpers, JAS 1995

$i \rightarrow$

$\uparrow$ j

6	5	4	3	2	1	2	3	4	5	6	7	6	6	5	5	6	7
5	4	3	2	1	-1	1	2	3	4	5	6	5	5	4	4	5	6
4	3	2	1	-1	-2	-1	1	2	3	4	5	4	4	3	3	4	5
3	2	1	-1	-2	-3	-2	-1	1	2	3	4	3	3	2	2	3	4
3	2	1	-1	-2	-2	-2	-1	1	2	3	3	2	2	1	1	2	3
4	3	2	1	-1	-1	-1	1	2	3	3	2	1	1	-1	-1	1	2
5	4	3	2	1	1	-1	1	2	3	2	1	-1	-2	-2	-2	-1	1
6	5	4	3	2	2	1	2	3	4	3	2	1	-1	-2	-1	1	2
7	6	5	4	3	3	2	3	4	5	4	3	2	1	-1	1	2	3
8	7	6	5	4	4	3	4	5	6	5	4	3	2	1	2	3	4

mass-flux density: $m(r) = \sum_{I_r} \mathrm{w(i, j)}$ $\quad I_r = \{i, j \mid d(i, j) = r\}$

$$M_c = \int_{-\infty}^{0} m(\mathrm{r})\mathrm{dr} \qquad M_E = \int_{0}^{\infty} m(\mathrm{r})\mathrm{dr} \qquad \int_{-\infty}^{\infty} m(\mathrm{r})\mathrm{dr} = 0$$

mass-flux density: $$m(r) = \sum_{I_r} \mathrm{w(i,\,j)} \qquad I_r = \{i, j \mid d(i, j) = r\}$$

$$M_c = \int_{-\infty}^{0} m(\mathrm{r})\mathrm{dr} \qquad M_E = \int_{0}^{\infty} m(\mathrm{r})\mathrm{dr} \qquad \int_{-\infty}^{\infty} m(\mathrm{r})\mathrm{dr} = 0$$

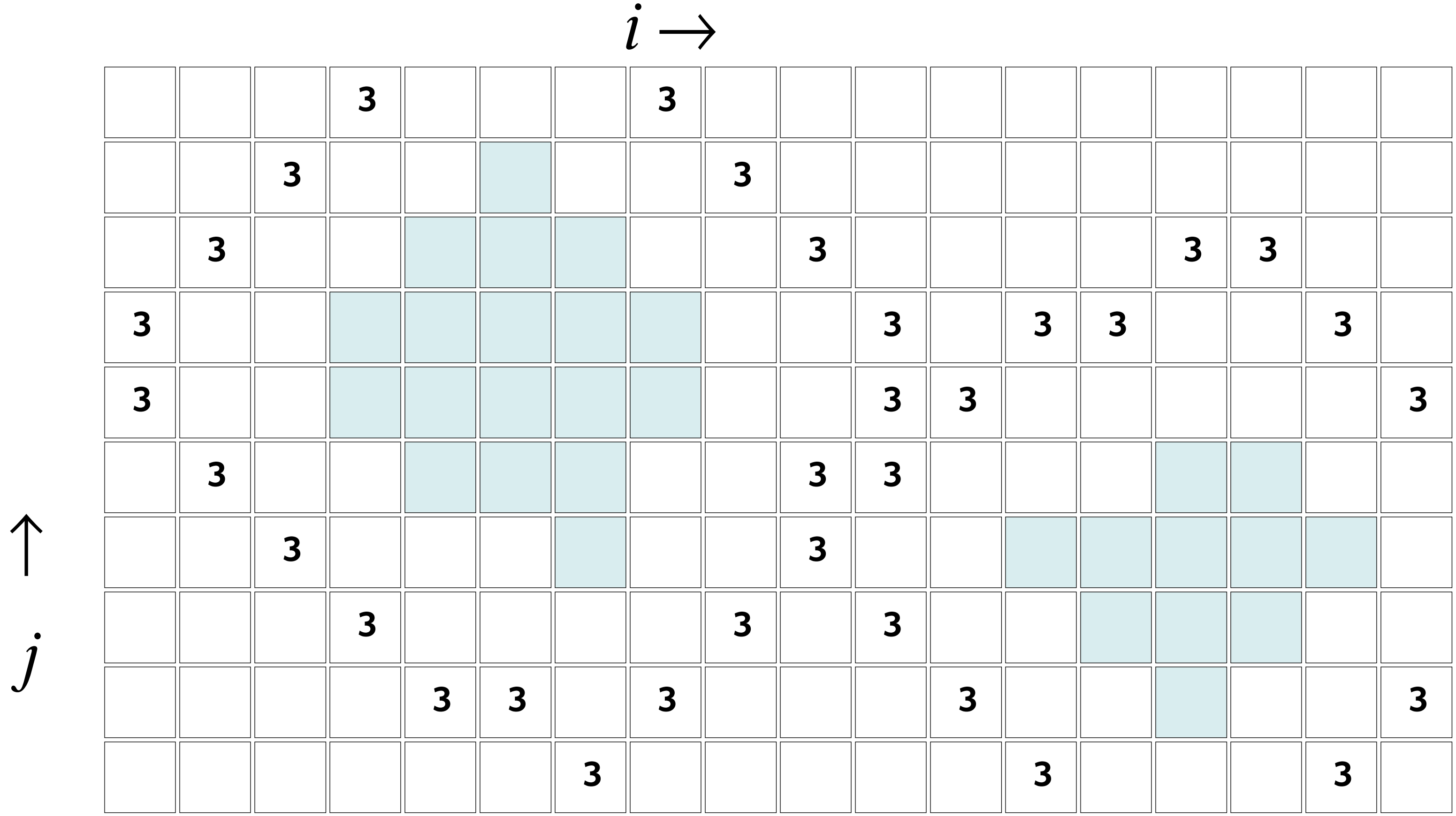
Conditional Averages

$$N(r) = | I_r |$$

nr of grid points with d(i,j)=r

$$w(r) = \frac{1}{N(r)} \sum_{I_r} \mathrm{w(i,\,j)}$$

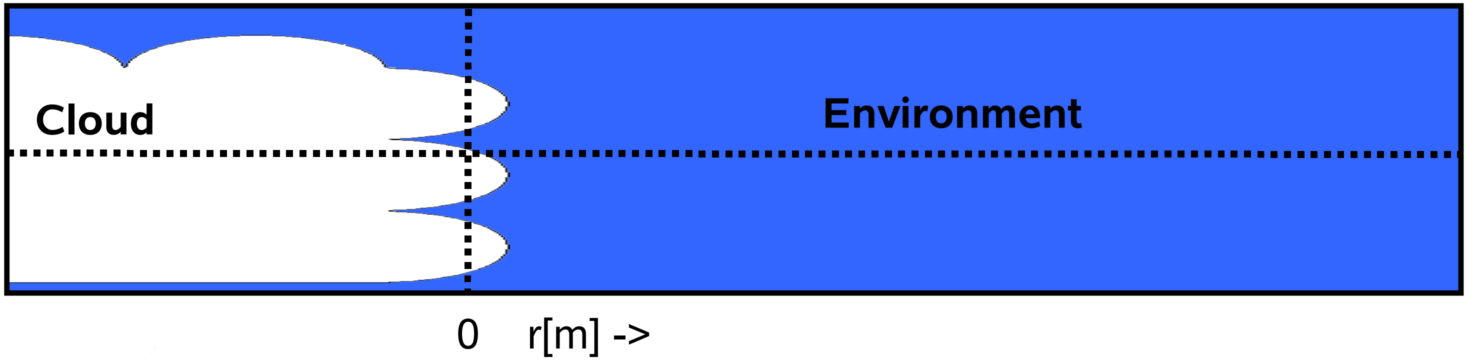
average velocity of points with d(i,j)=r

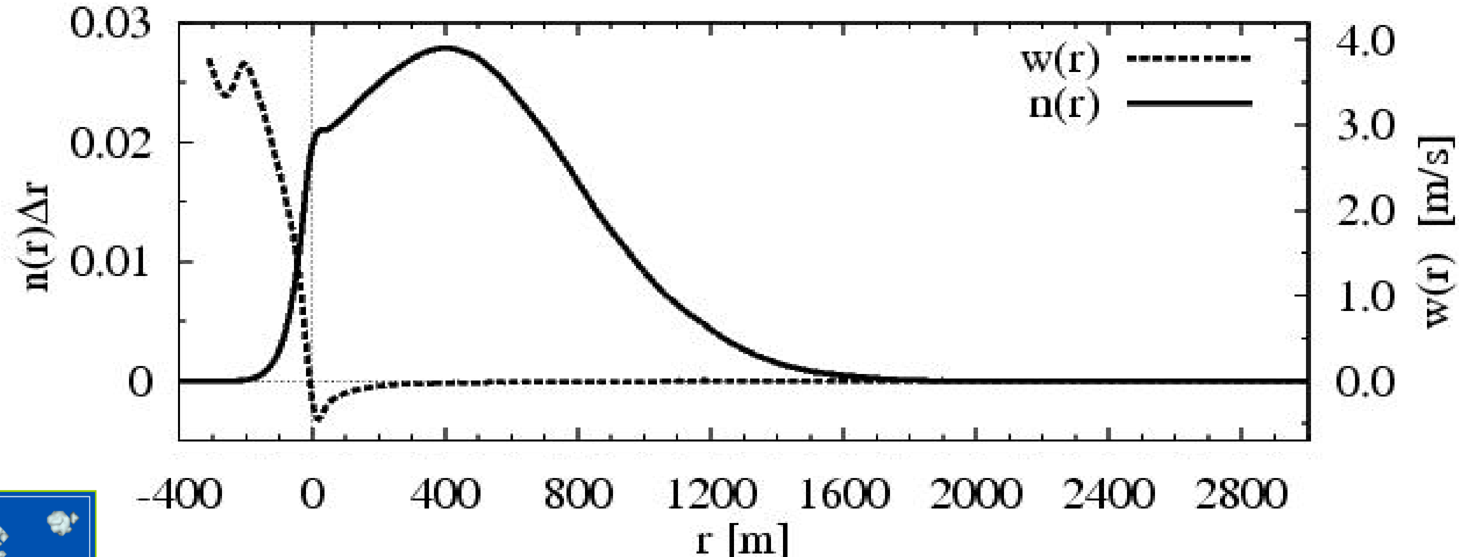


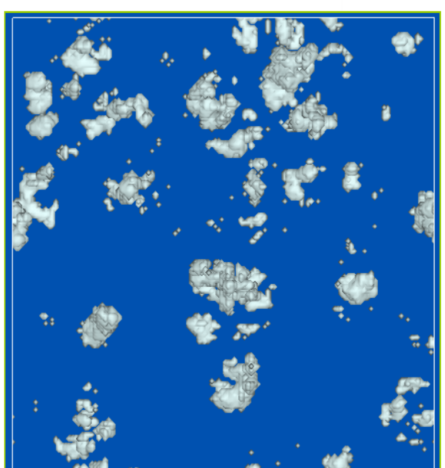
example
average velocity
of points with d(i,j)=3

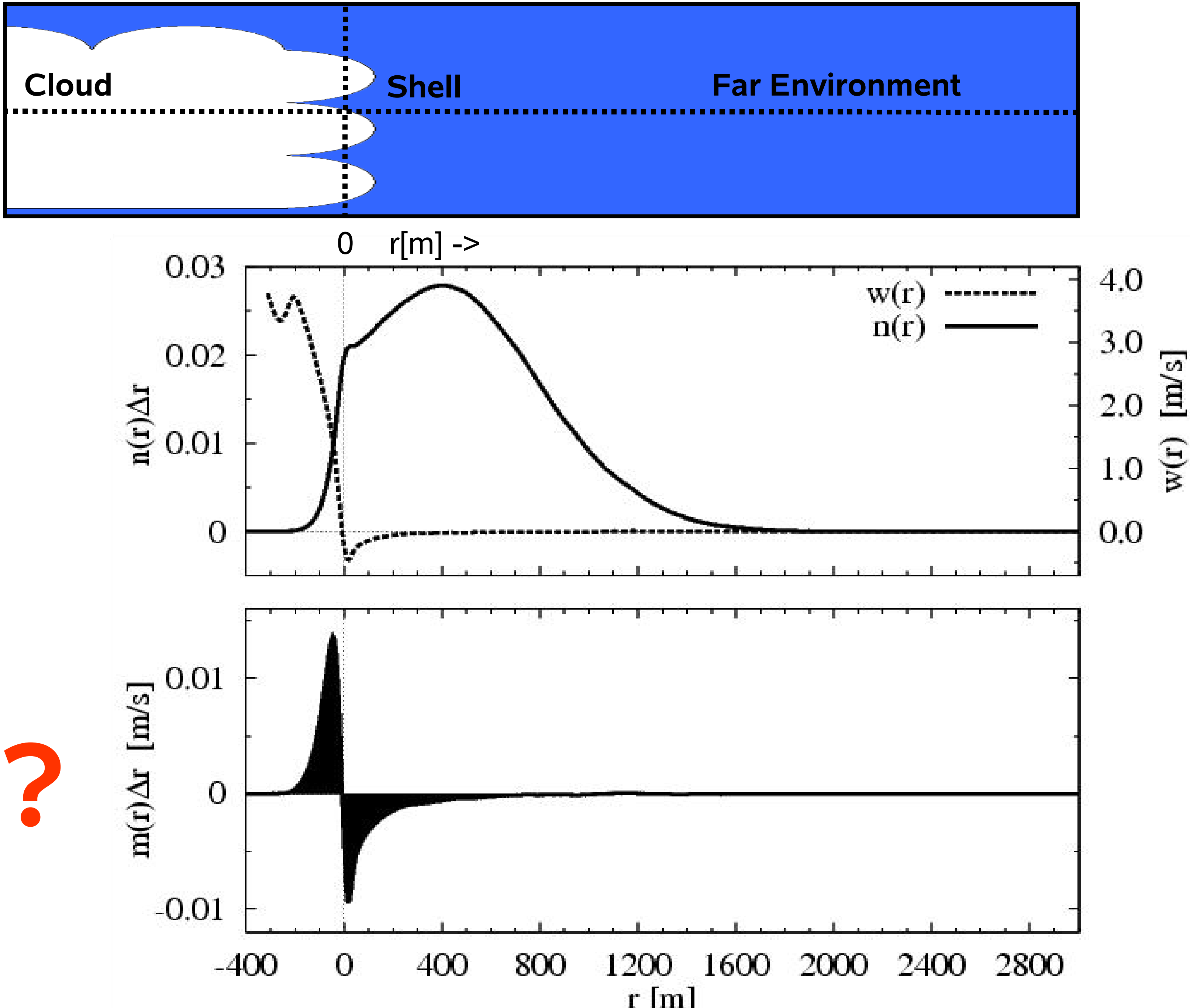
$$w(3\Delta) = \frac{1}{N(3\Delta)} \sum_{I_{r=3}} \mathrm{w(i, j)}$$

$$I_3 = \{i, j \mid d(i, j) = 3\}$$


Cloud
Environment
0 r[m] ->


0.03
0.02
0.01
0
n(r)Δr
4.0
3.0
2.0
1.0
0.0
w(r) [m/s]
w(r)
n(r)
-400
0
400
800
1200
1600
2000
2400
2800
r [m]



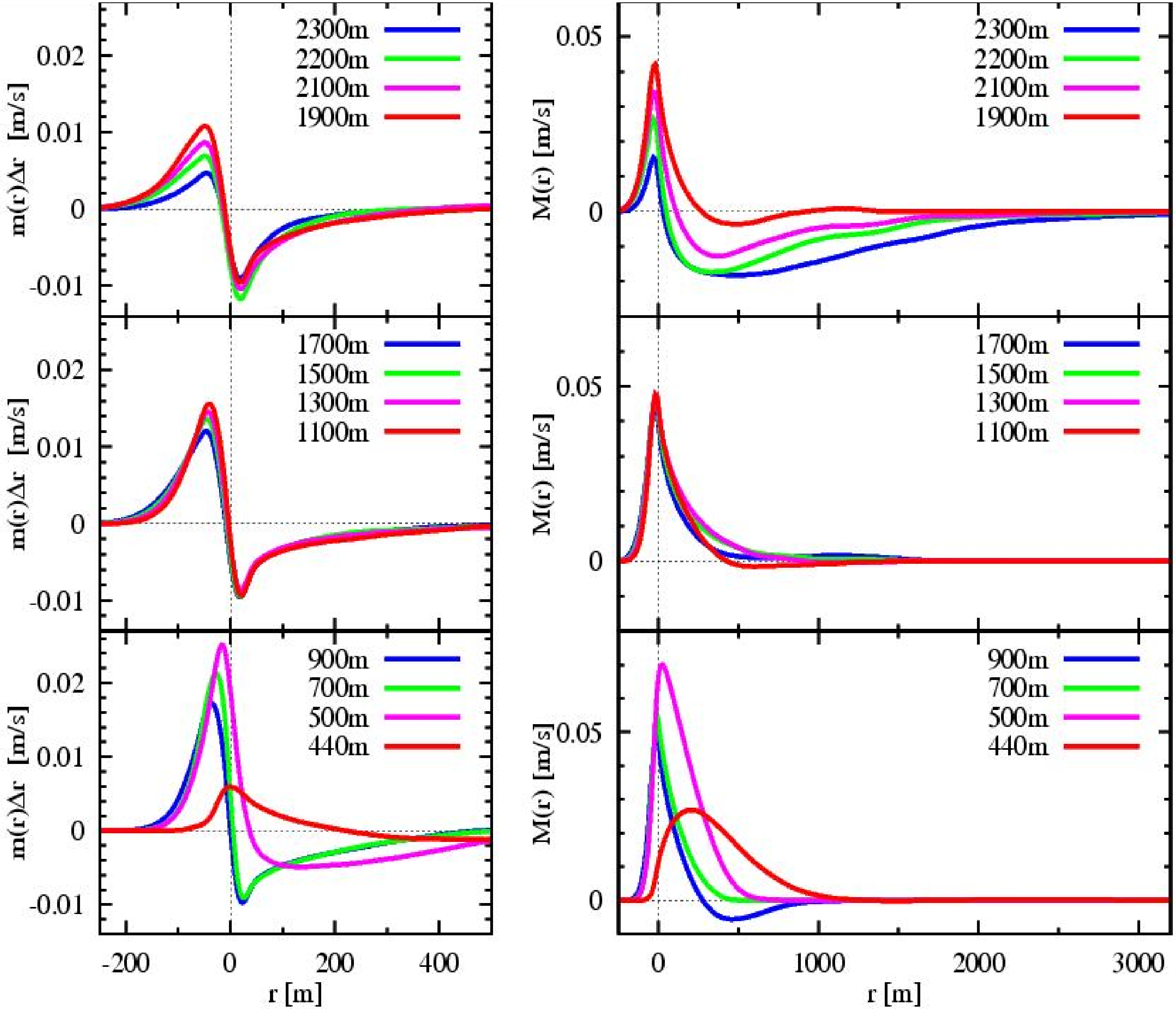


!!?

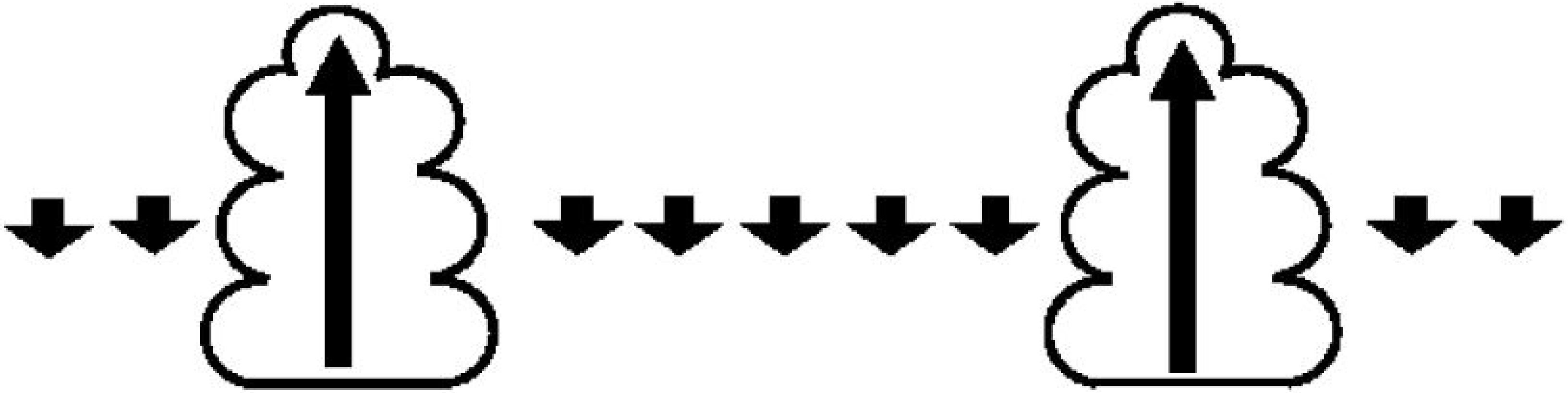
Jonker, Heus, Sullivan, GRL 2008

mass-flux density for various heights

cumulative mass-flux $M(r) = \int_{-\infty}^{r} m(r')dr'$



Traditional view



Refined view

Jonker, Heus, Sullivan, GRL 2008

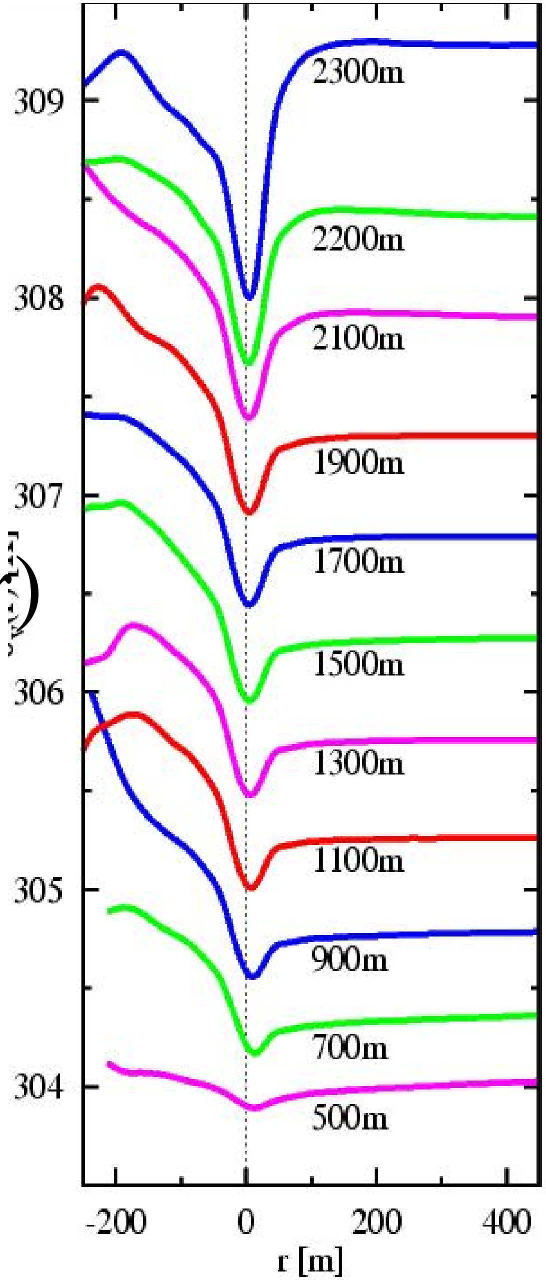
- is it conceivable? (mechanism)

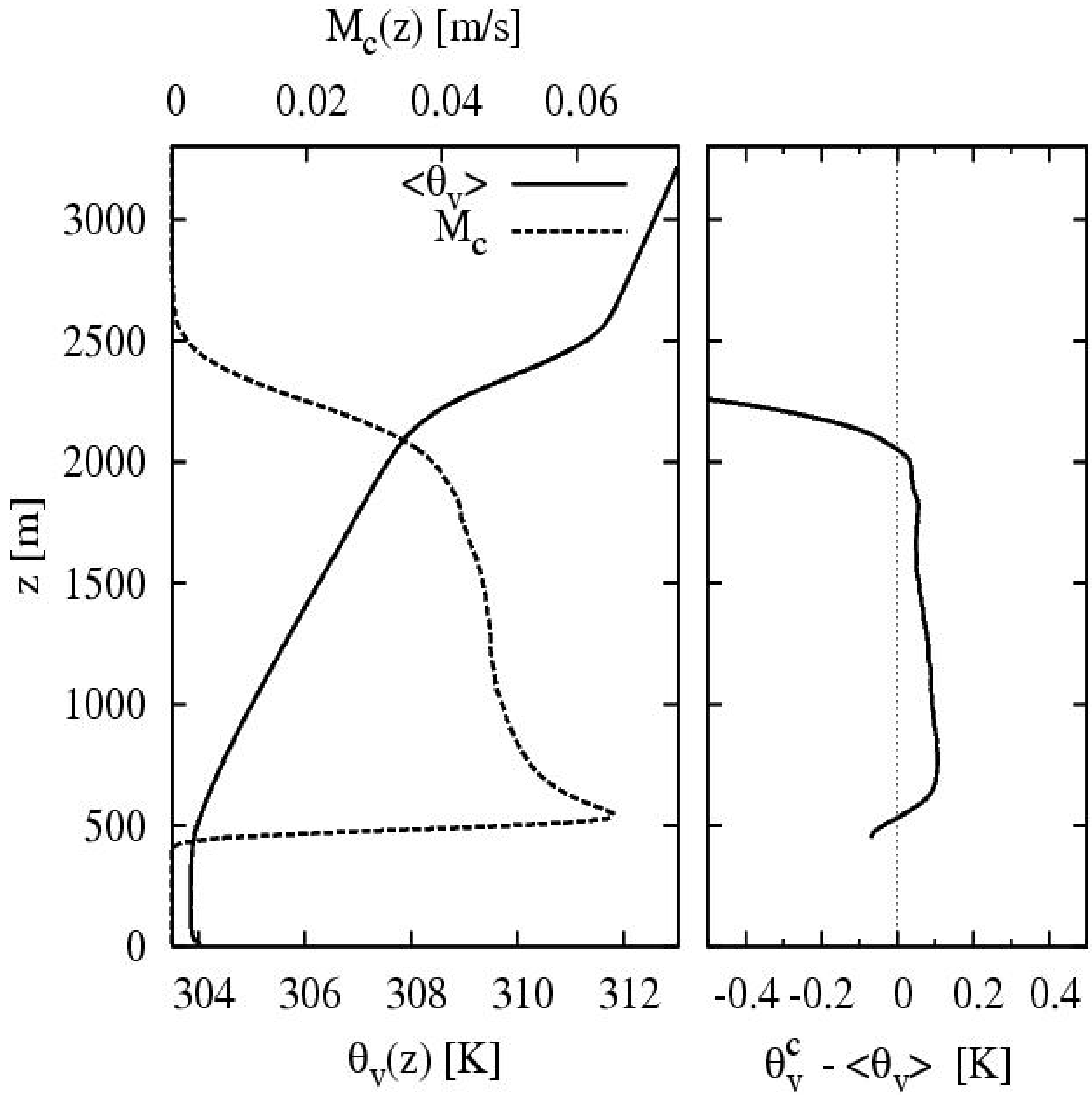
- is it true? (observational validation)

- is it relevant? (applications)

mechanism

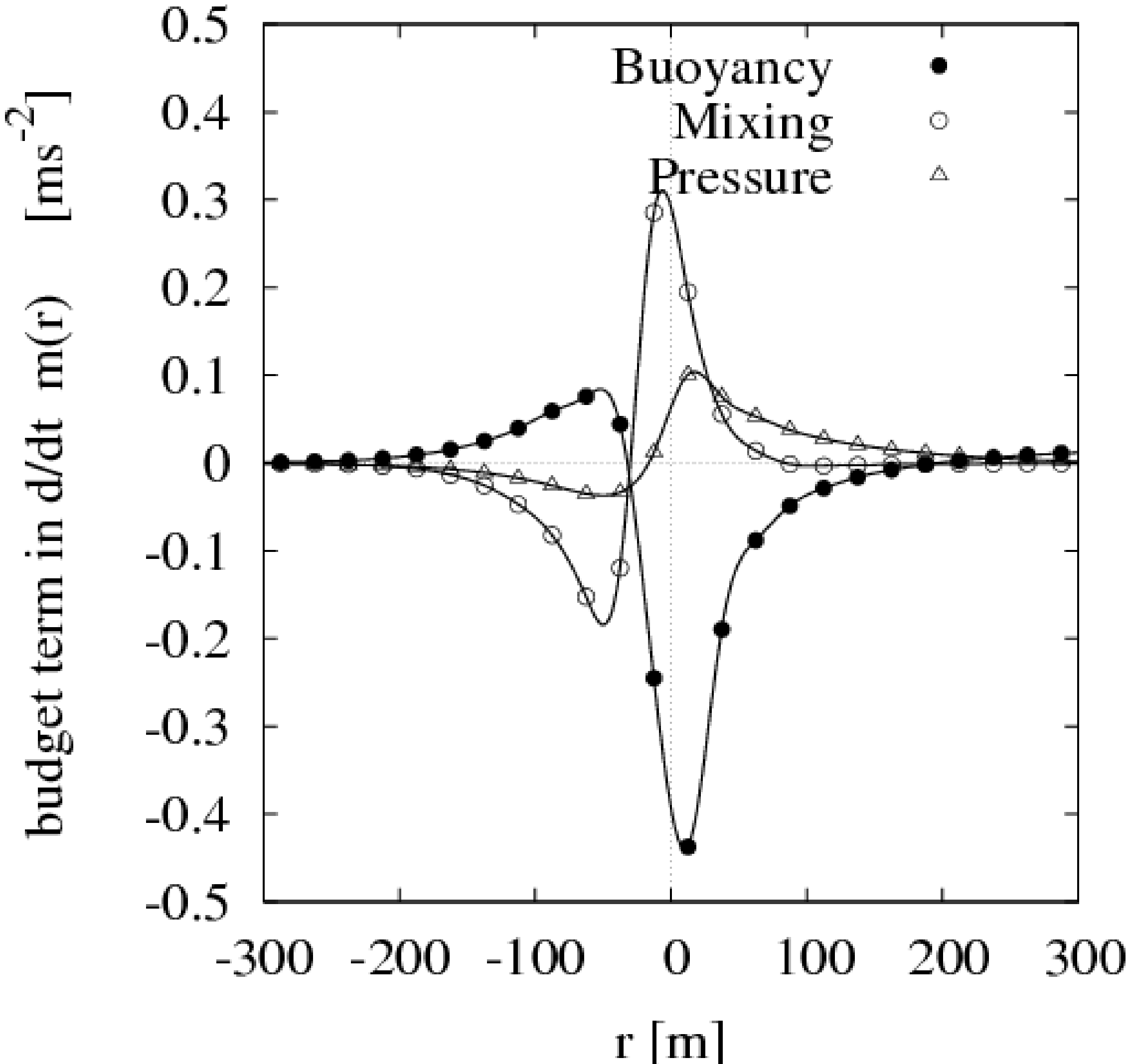
$\theta_v(r)$





w-budget vs distance to nearest cloud-edge

$$\frac{\partial w}{\partial t} = \frac{g}{\theta_0}\left(\theta_v - \overline{\theta}_v\right) - \frac{\partial u_j w}{\partial x_j} - \frac{\partial p'}{\partial z}$$



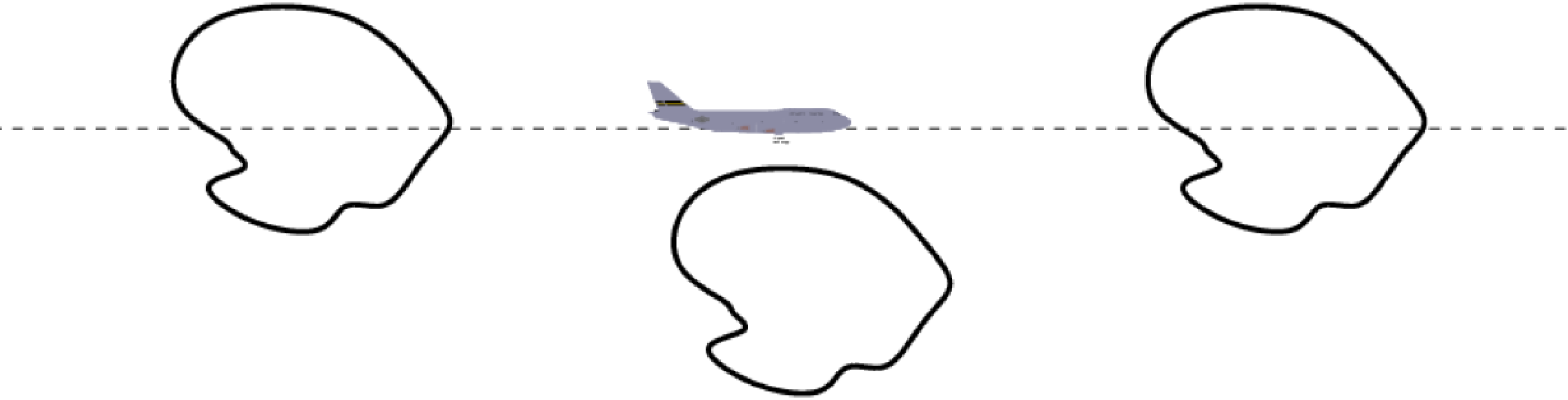
- is it conceivable? (mechanism)

-> is it true? (observational validation)

- is it relevant? (applications)

courtesy Bjorn Stevens

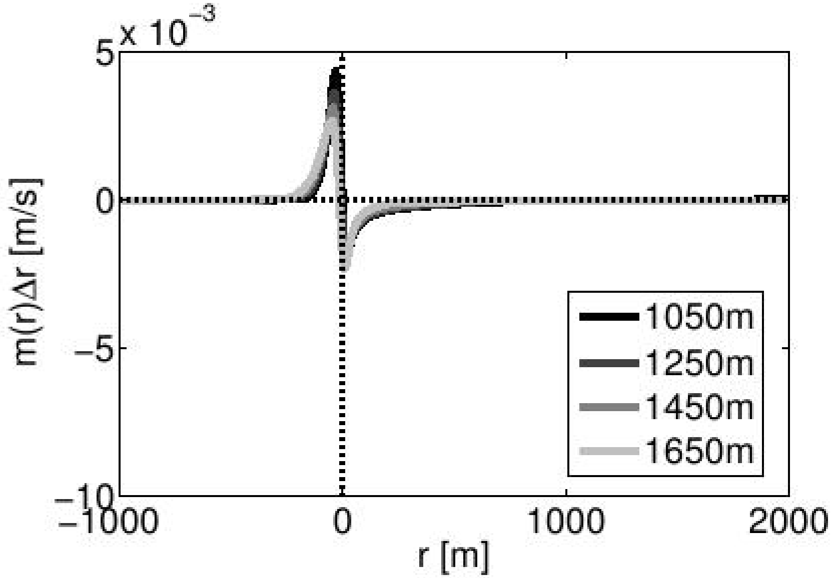
Rain in Cumulus over the Ocean: Observations and LES



How far is the nearest cloud?

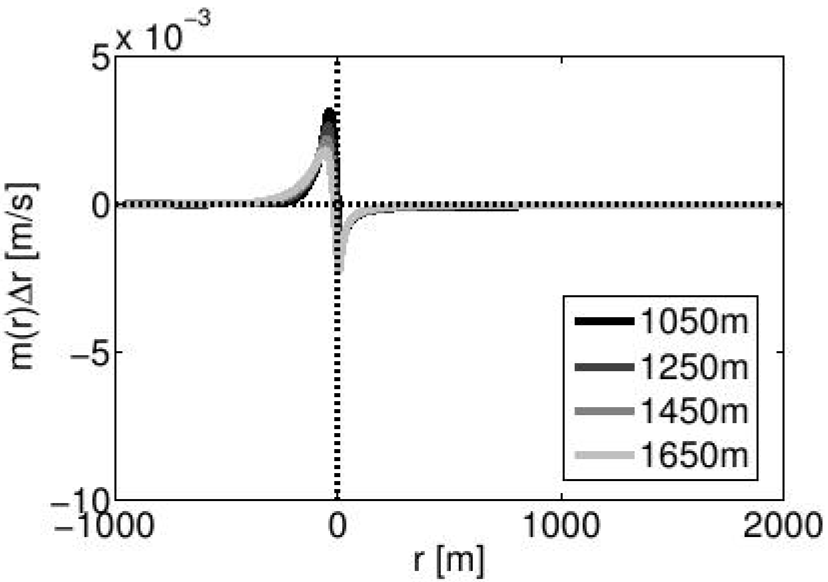
(Heus, Pols, Jonker, vd Akker, Lenschow, QJRMS 2009, in press)

LES 2D-distances

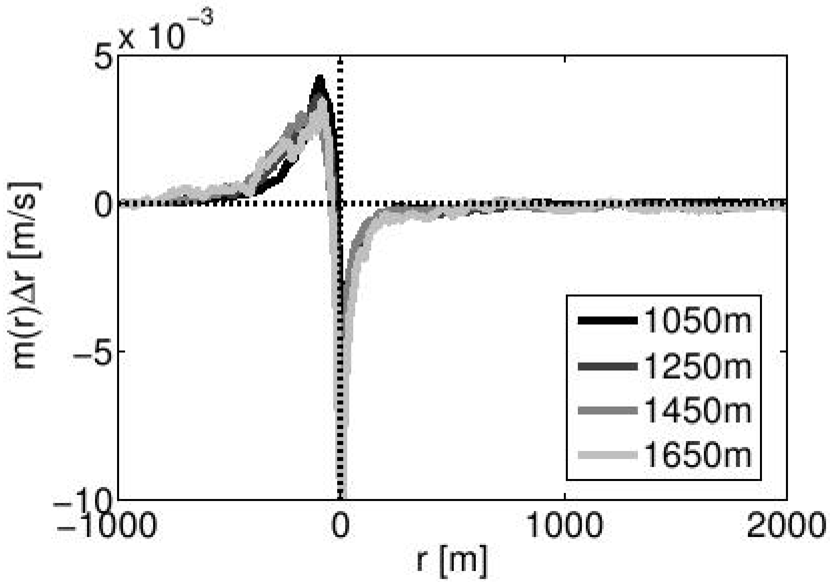


mass-flux densities m(r)

LES 1D-distances



Observations (1D-distances)



relevance

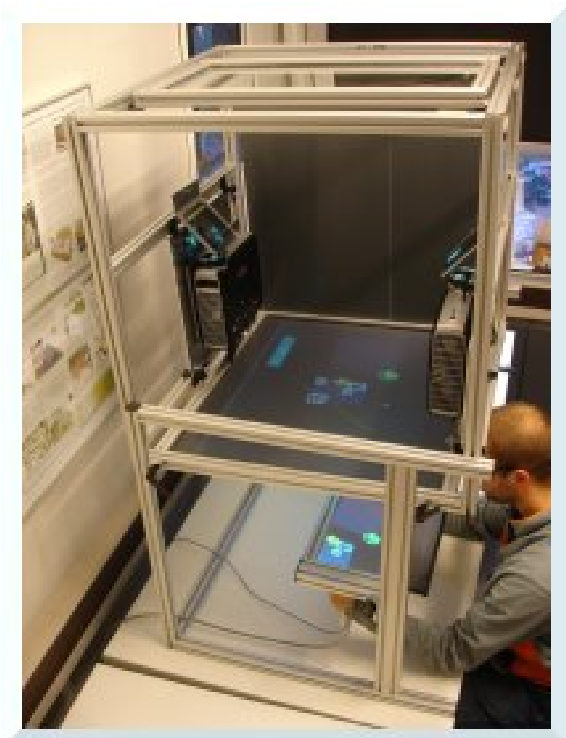
" two examples:

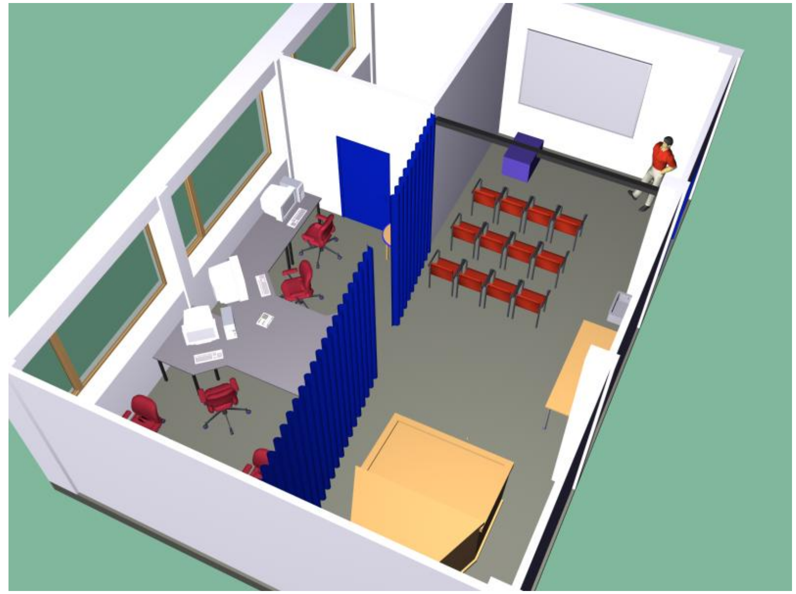
- dispersion
- parameterization (mass-flux model)

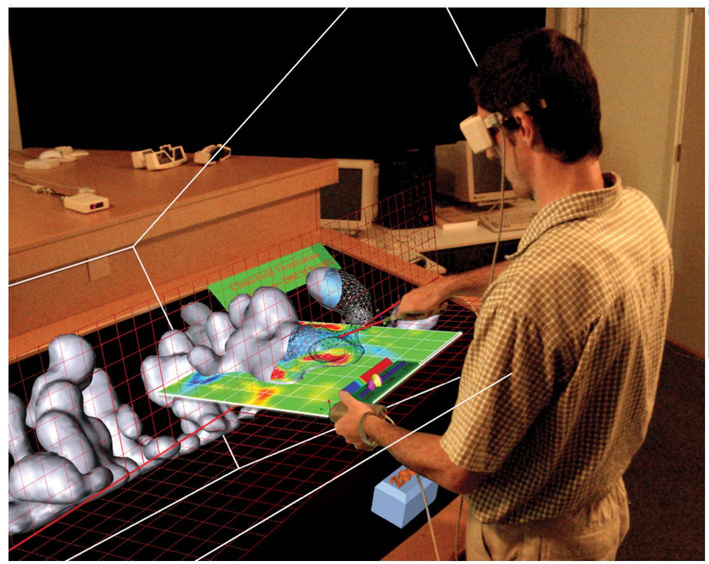
plume 'trapping'

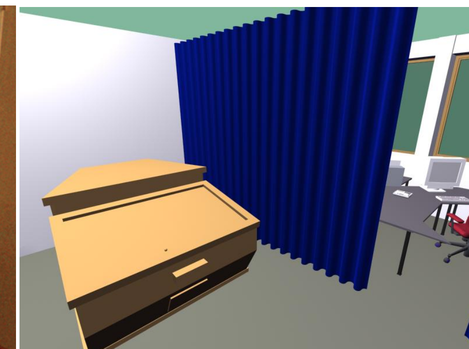
courtesy S. Galmarini

Virtual Reality Lab



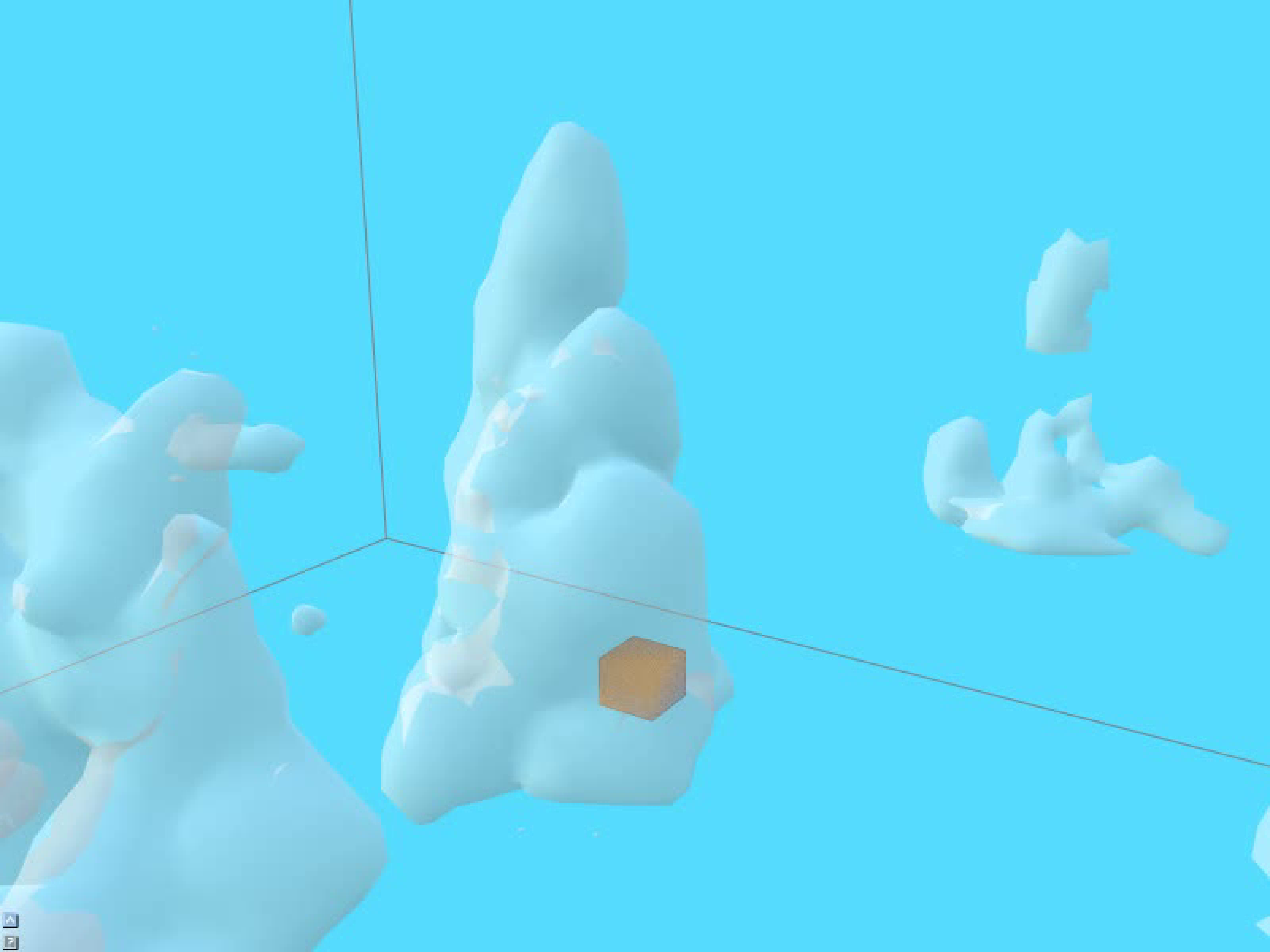


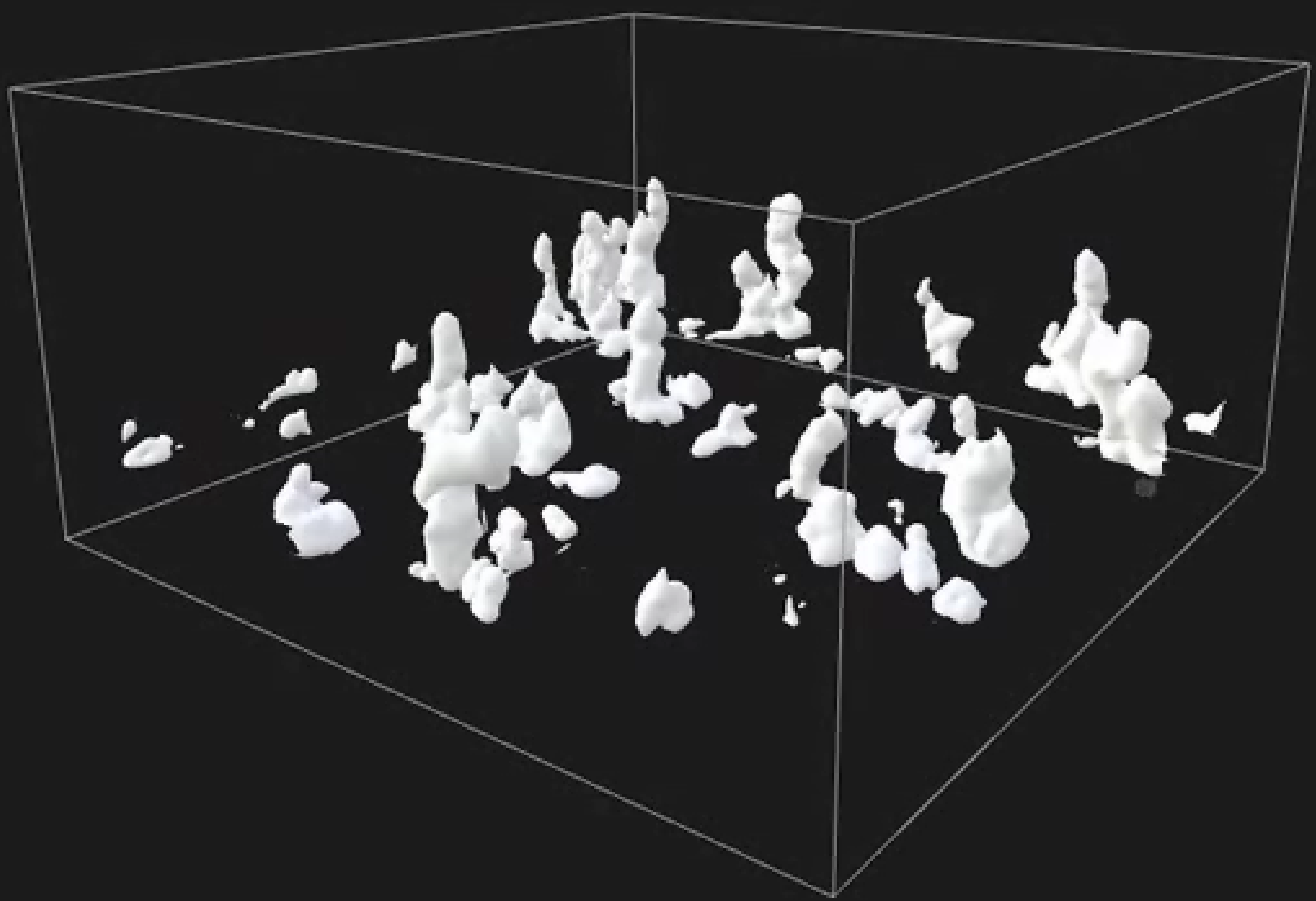




NWO/NCF

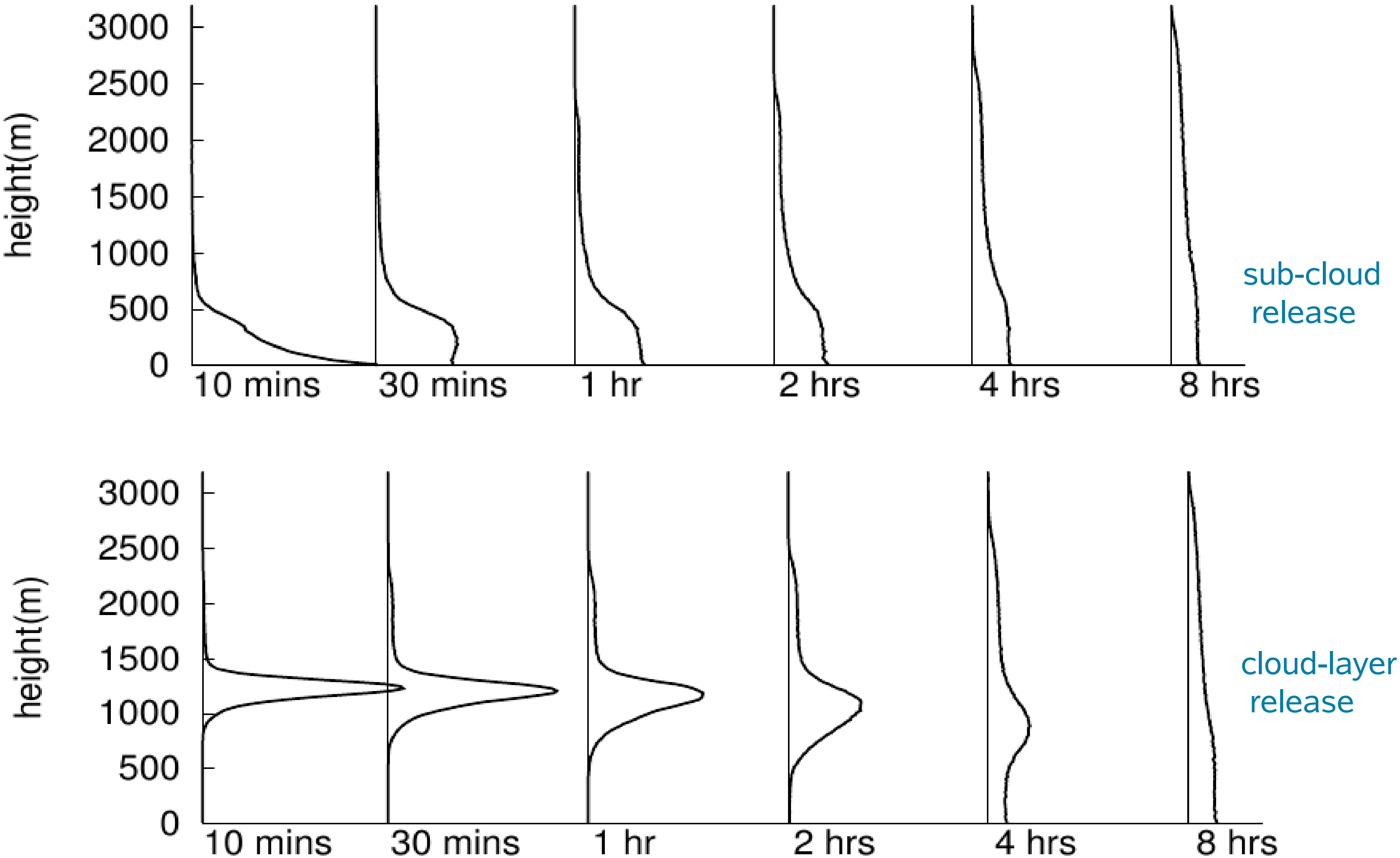
EWI:F. Post, M. Koutek, E. Griffith, D. Dussel



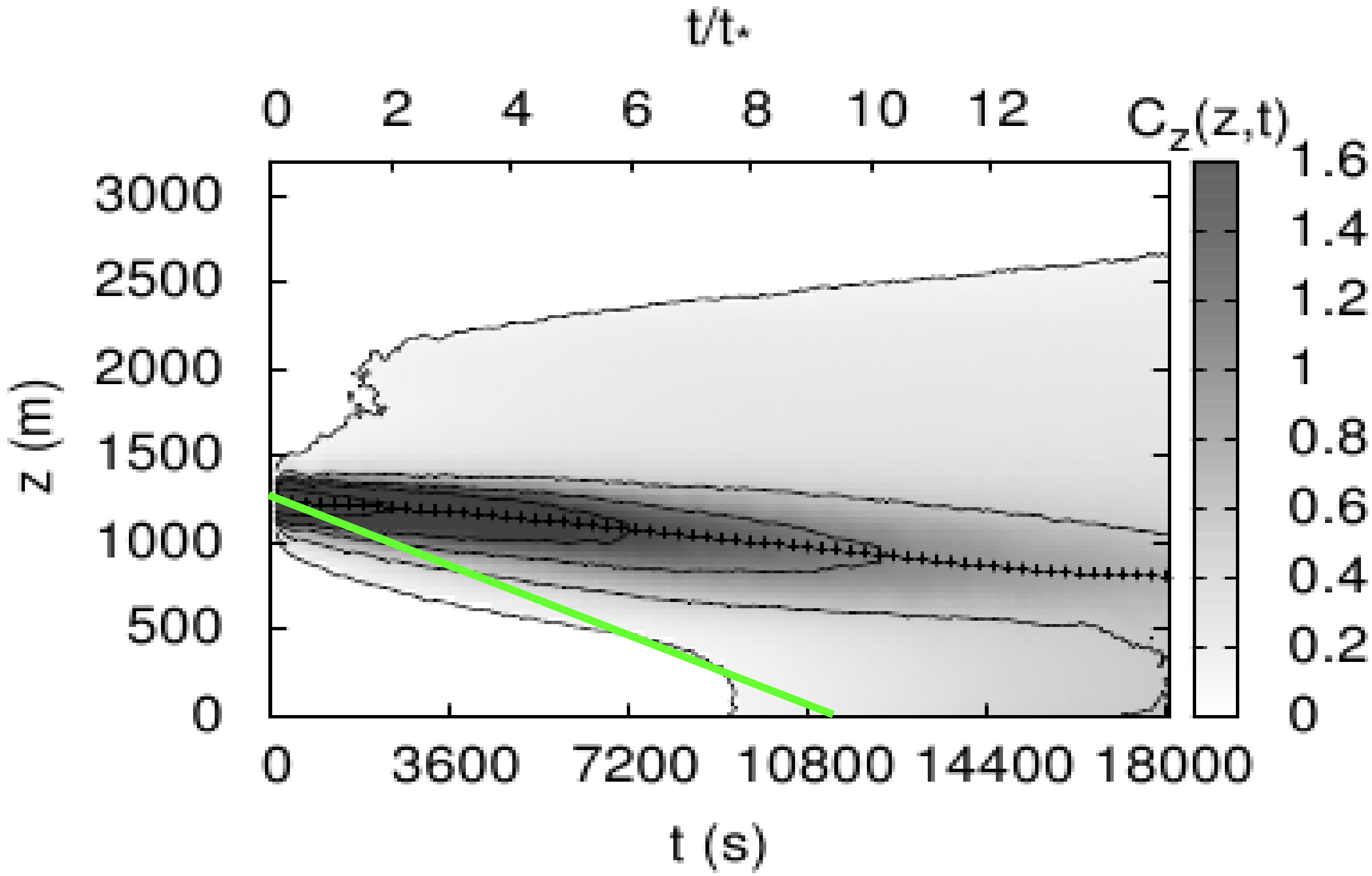



© 2001 by Axel Thielmann

dispersion of a plane source of mass-less particles



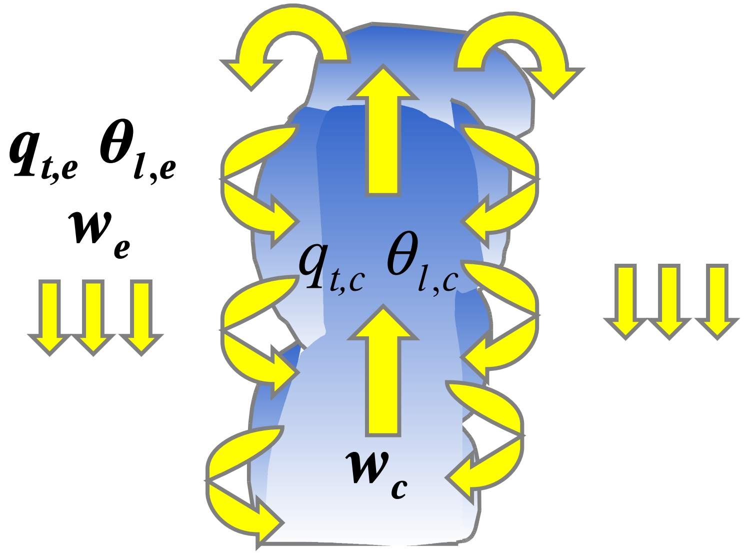
Verzijlbergh et al 2009, ACP

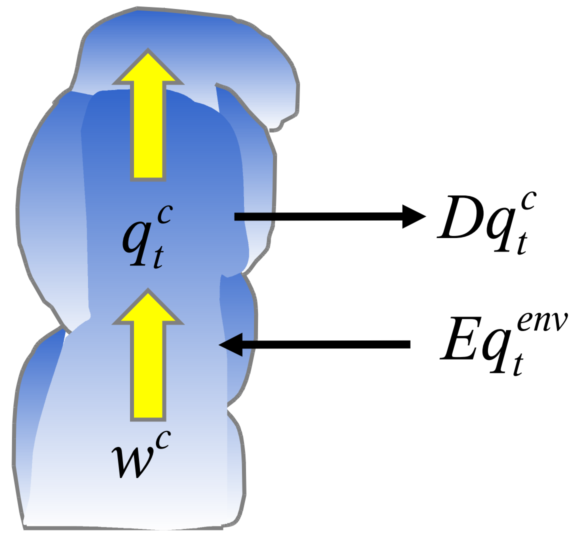


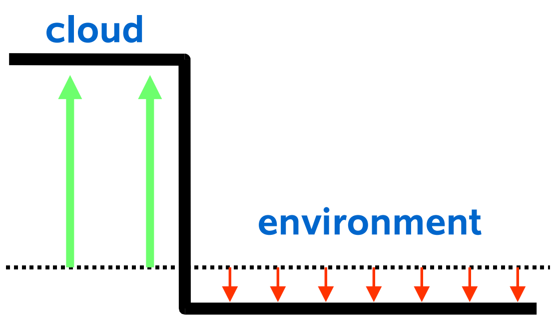
Verzijlbergh et al 2009, ACP

Part II

Mass-flux models of shallow cumulus

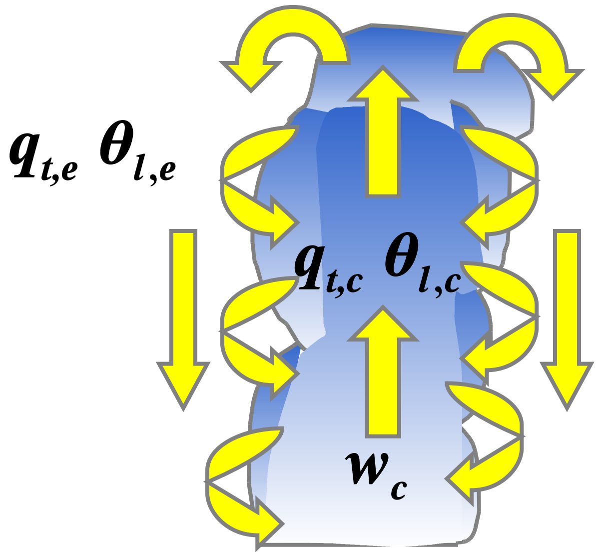


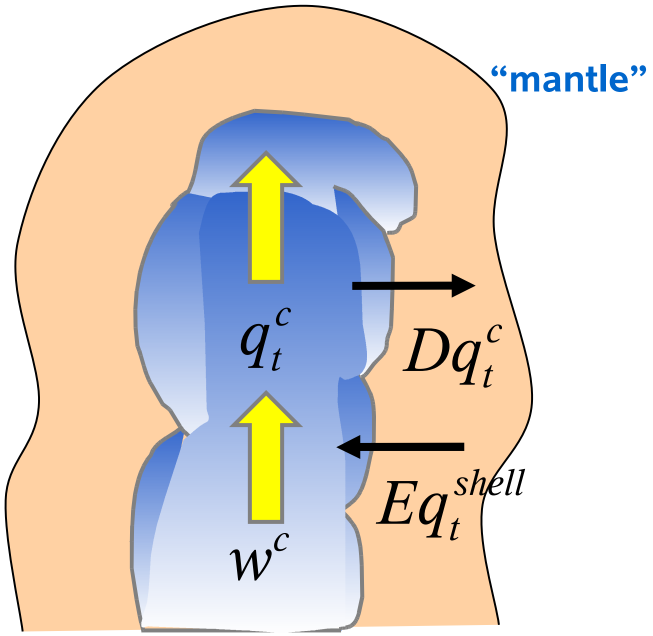


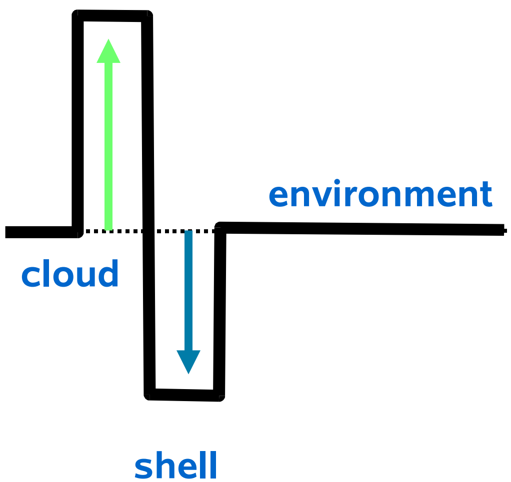


top-hat distribution

A refined view on Mass-flux models of shallow cumulus
1) cloud, 2) near cloud env. 3) far field







entrained air is "preconditioned"

Asai and Kasahara, JAS, 1967

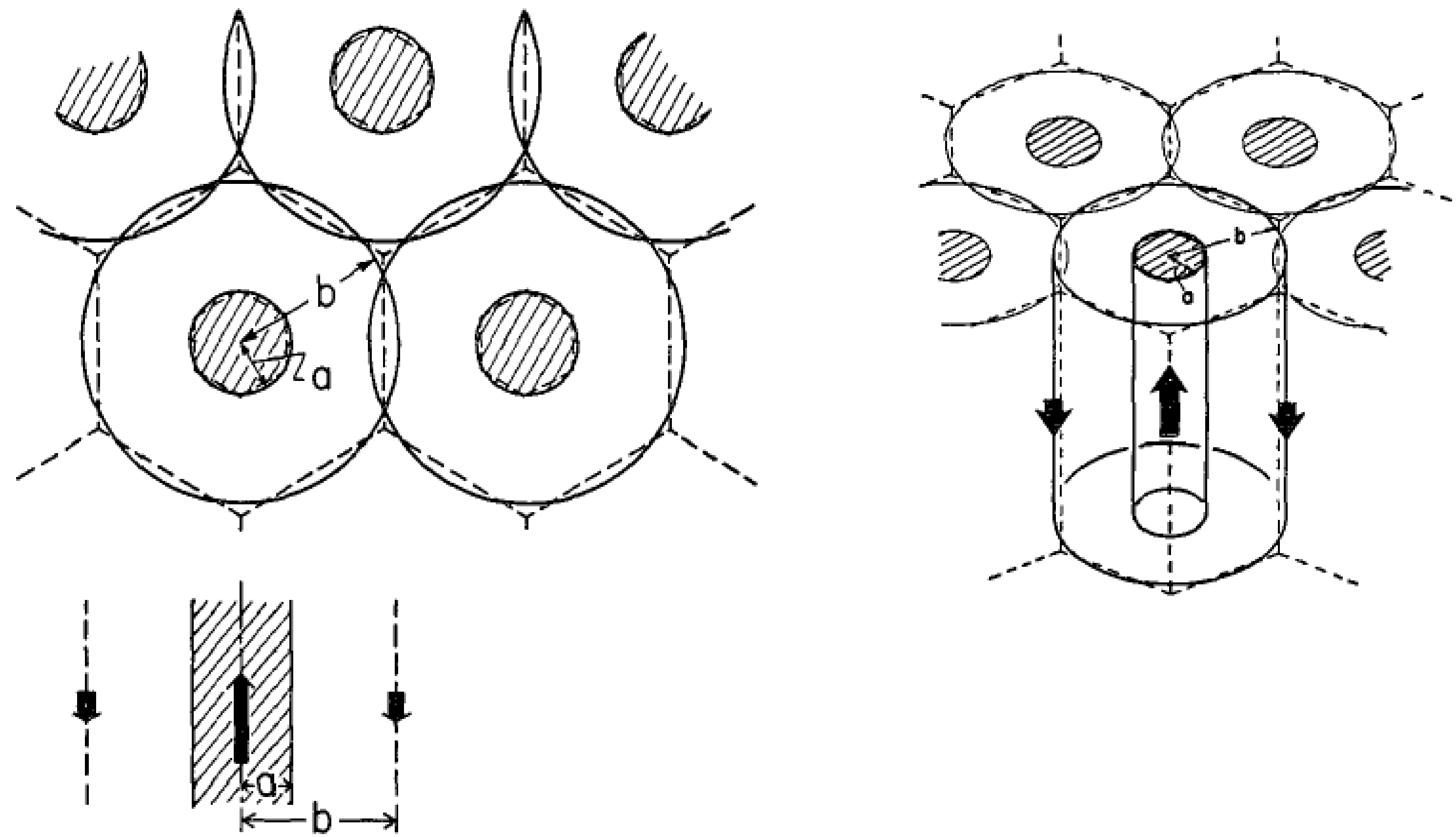


FIG. 1. The geometrical configuration of the model.

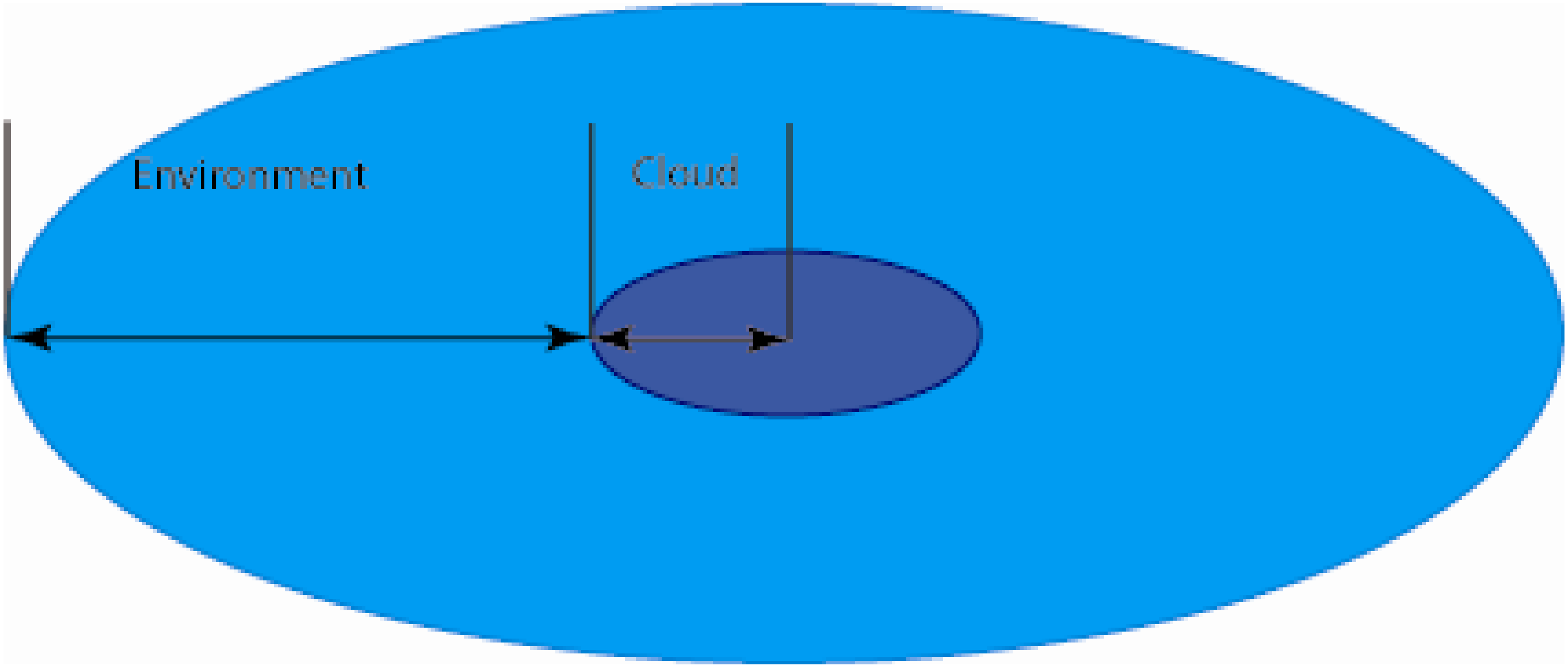
Ogura and Takahashi, *Mon Wea Rev* 1971

Cotton, *JAS*, 1975

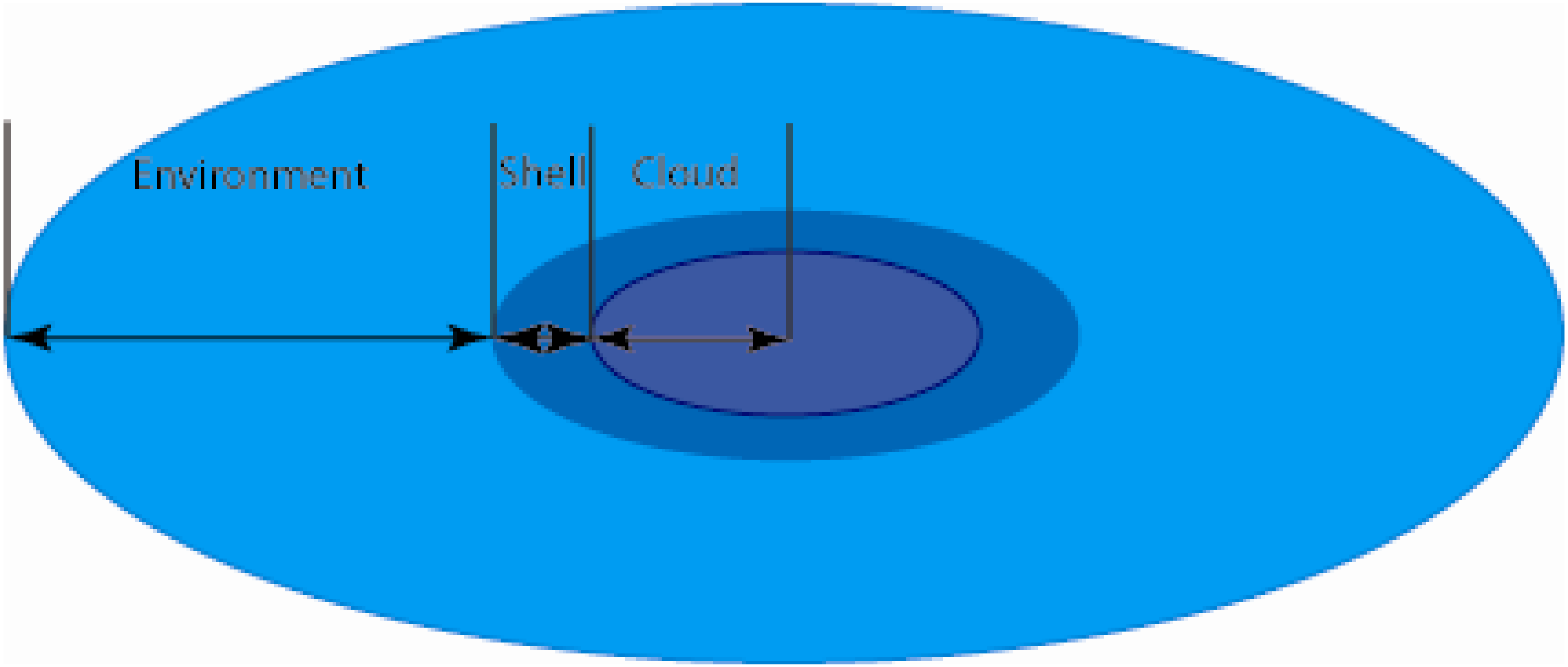
…

Ferrier and Houze, *JAS*, 1988

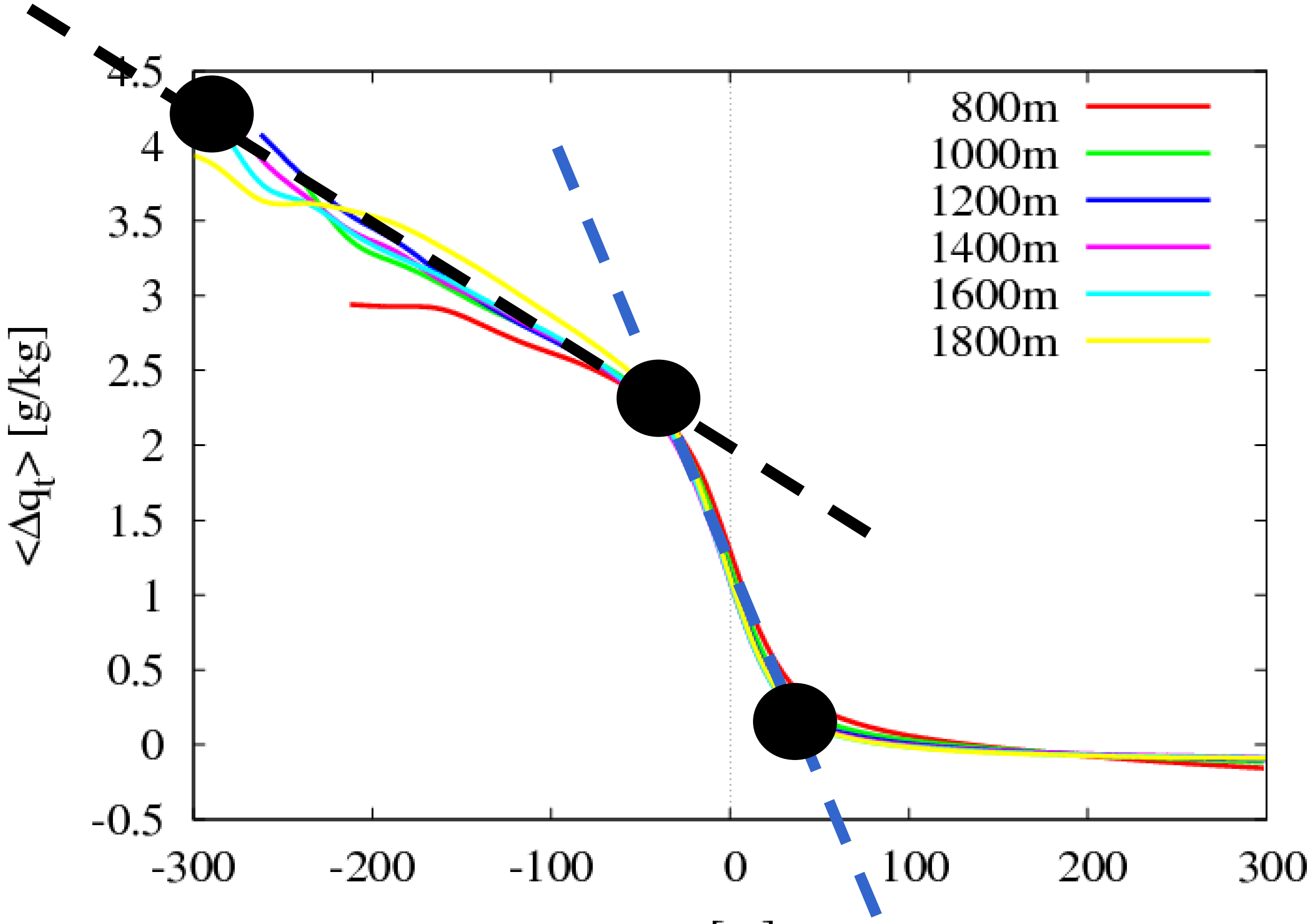
Asai and Kasahara, JAS, 1967

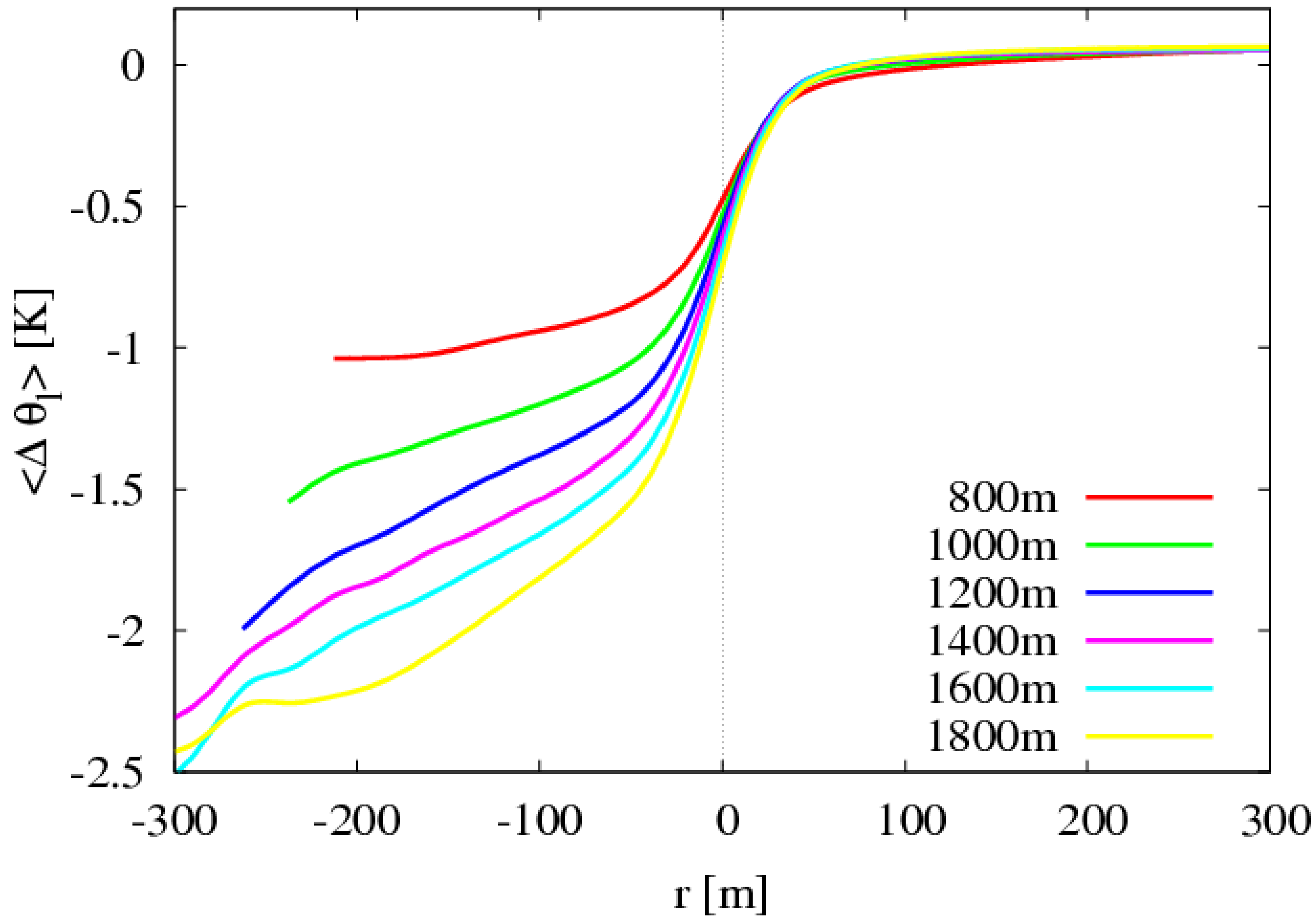


Asai and Kasahara's model+ extra ring

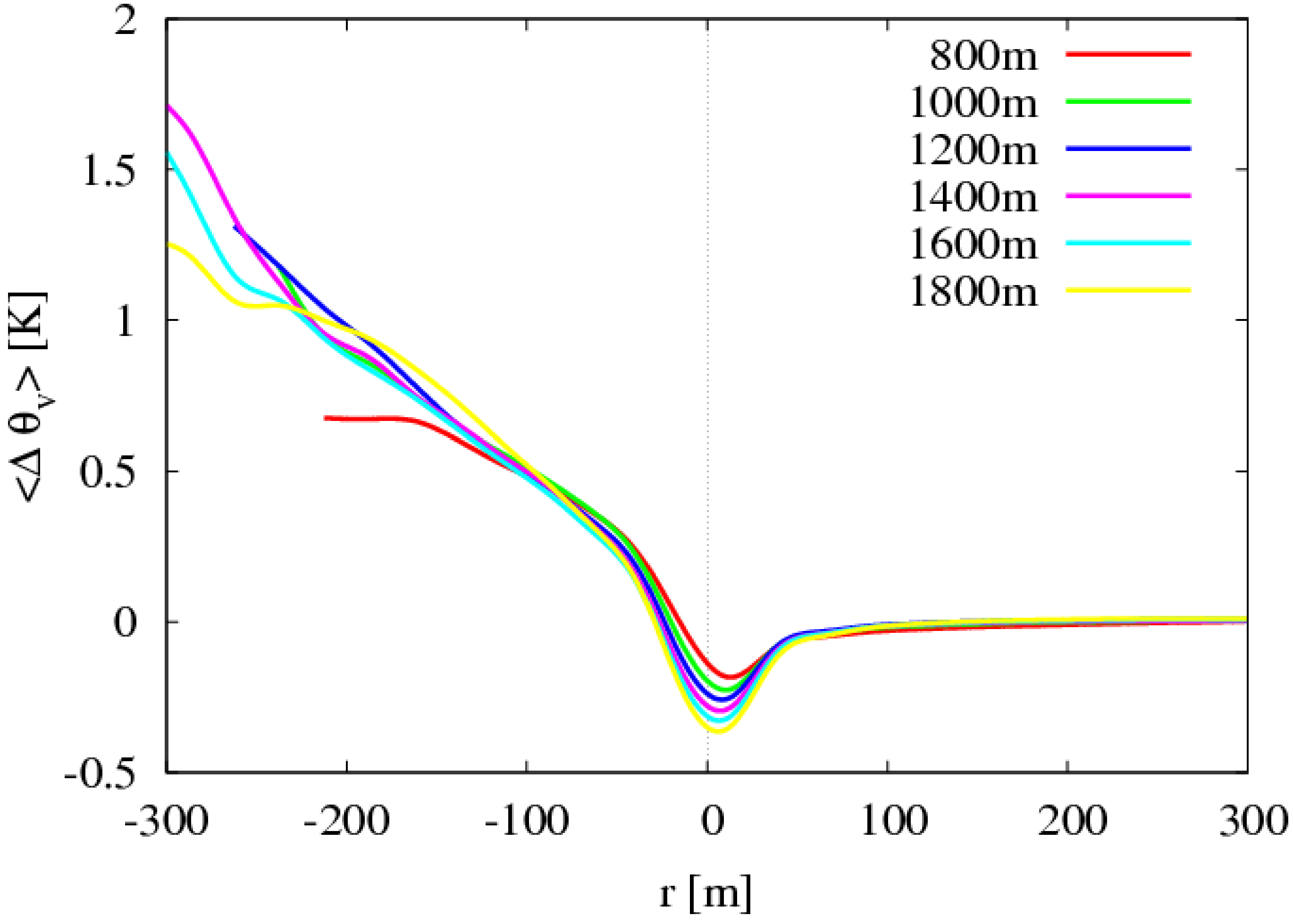


back to LES for a second ...



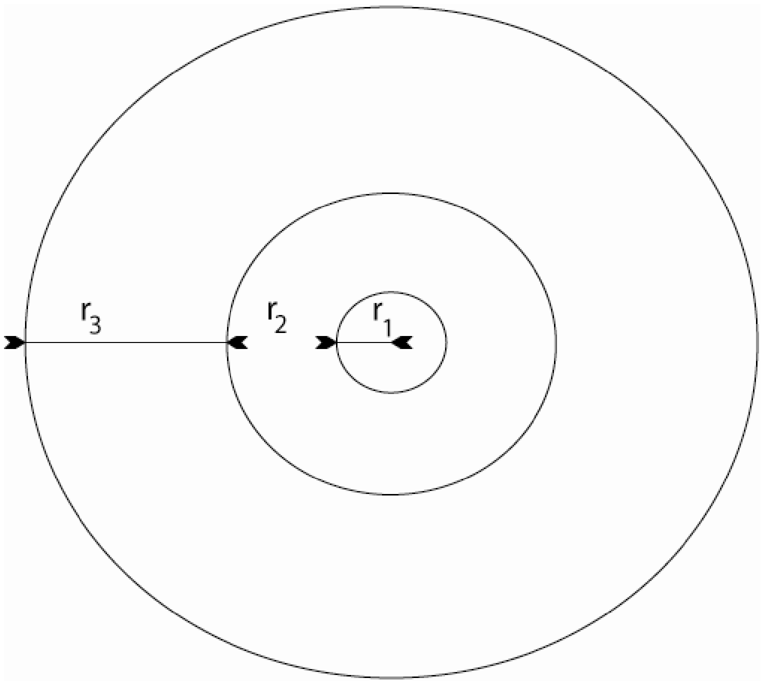


0
-0.5
-1
-1.5
-2
-2.5
<Δ θl> [K]
-300
-200
-100
0
100
200
300
r [m]
800m
1000m
1200m
1400m
1600m
1800m


800m
1000m
1200m
1400m
1600m
1800m
2
1.5
1
0.5
0
-0.5
-300
-200
-100
0
100
200
300
$<\Delta\theta_v>$ [K]
r [m]

Model geometric parameters

3 parameters determine the geometry of the model, during the sensitivity analysis they were fixed at the following values:



Parameter	Value
Cloud radius r_1	100m
Cloud cover σ_1	5%
Rel. shell size ζ	0.5

$$r_2 = r_1(\zeta + 1)$$

$$r_3 = \frac{r_1}{\sqrt{\sigma_1}}$$

$$\sigma_2 = \sigma_1 \left[(\zeta + 1)^2 - 1 \right]$$

$$\sigma_3 = 1 - \sigma_1 - \sigma_2$$

Model Description

- Model Equations derived from the Navier-Stokes equations in the Boussinesq-approximation:

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(u_j u_i\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \delta_{i3}\frac{g}{{}_0}\left(\theta_v - \overline{\theta_v}\right)$$

- And the continuity equation:

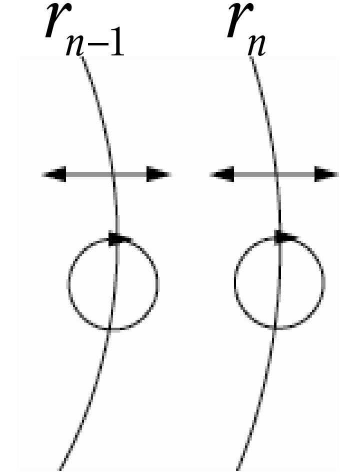
$$\frac{\partial u_j}{\partial x_j} = 0$$

- scalar transport

$$\frac{\partial}{\partial t}\varphi + \frac{\partial}{\partial x_j}(u_j\varphi) = F_\varphi$$

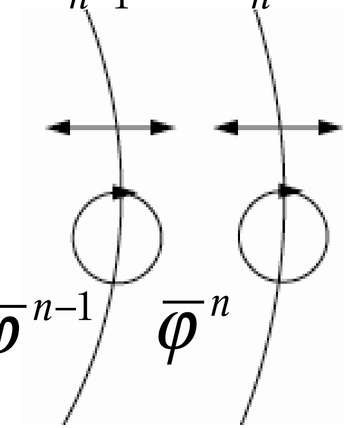
$$\varphi = \{\theta_l, q_t\}$$

$$2\pi \int_{r_{n-1}}^{r_n} \varphi \, r dr = \overline{\varphi}^{\,n} A_n \qquad A_n = \pi (r_n^2 - r_{n-1}^2)$$



$$\frac{\partial}{\partial t}\varphi + \frac{1}{r}\frac{\partial}{\partial r}(ru\varphi) + \frac{\partial}{\partial z}(w\varphi) = F_\varphi$$

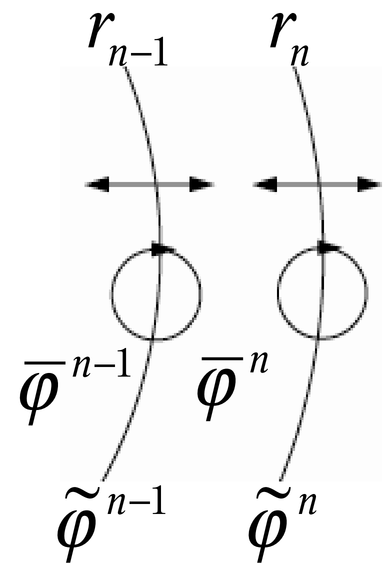
$$2\pi \int_{r_{n-1}}^{r_n} \varphi \, r dr = \overline{\varphi}^{\,n} A_n \qquad A_n = \pi (r_n^2 - r_{n-1}^2)$$



$$\frac{\partial}{\partial t}\varphi + \frac{1}{r}\frac{\partial}{\partial r}(ru\varphi) + \frac{\partial}{\partial z}(w\varphi) = F_\varphi$$

$$\frac{\partial}{\partial t}\overline{\varphi}^{\,n} + \frac{2\pi\, r_n}{A_n}\overleftrightarrow{u\varphi}^{\,n} - \frac{2\pi\, r_{n-1}}{A_n}\overleftrightarrow{u\varphi}^{\,n-1} + \frac{\partial}{\partial z}\overline{w\varphi}^{\,n} = \overline{F}_\varphi^{\,n}$$

$$2\pi \int_{r_{n-1}}^{r_n} \varphi \, r dr = \overline{\varphi}^{\,n} A_n \qquad A_n = \pi (r_n^2 - r_{n-1}^2)$$



$$\frac{\partial}{\partial t}\varphi + \frac{1}{r}\frac{\partial}{\partial r}(ru\varphi) + \frac{\partial}{\partial z}(w\varphi) = F_\varphi$$

$$\frac{\partial}{\partial t}\overline{\varphi}^{\,n} + \frac{2\pi\, r_n}{A_n}\overleftrightarrow{u\varphi}^{\,n} - \frac{2\pi\, r_{n-1}}{A_n}\overleftrightarrow{u\varphi}^{\,n-1} + \frac{\partial}{\partial z}\overline{w\varphi}^{\,n} = \overline{F}_\varphi^{\,n}$$

$$\overleftrightarrow{u\varphi}^{\,n} = \widetilde{u}^{\,n}\widetilde{\varphi}^{\,n} + \overleftrightarrow{u''\varphi''}^{\,n} \qquad \overline{w\varphi}^{\,n} = \overline{w}^{\,n}\,\overline{\varphi}^{\,n} + \overline{w'\varphi'}^{\,n}$$

$$\frac{2\pi\, r_n}{A_n}\widetilde{u}^{\,n} - \frac{2\pi\, r_{n-1}}{A_n}\widetilde{u}^{\,n-1} + \frac{\partial}{\partial z}\overline{w}^{\,n} = 0$$

$$\frac{\partial}{\partial t}\overline{\varphi}^{\,n} =$$

$$-\frac{2\pi\, r_n}{A_n}\left[\overleftrightarrow{u''\varphi''}^{\,n} + \widetilde{u}^{\,n}\widetilde{\varphi}^{\,n}\right]$$

$$+\frac{2\pi\, r_{n-1}}{A_n}\left[\overleftrightarrow{u''\varphi''}^{\,n-1} + \widetilde{u}^{\,n-1}\widetilde{\varphi}^{\,n-1}\right]$$

$$-\frac{\partial}{\partial z}\overline{w}^{\,n}\overline{\varphi}^{\,n}$$

$$-\frac{\partial}{\partial z}\overline{w'\varphi'}^{\,n}$$

$$+\overline{F}_{\varphi}^{\,n}$$

boundary terms

AK'67

$$\frac{\partial}{\partial t}\overline{\varphi}^{\,n} =$$

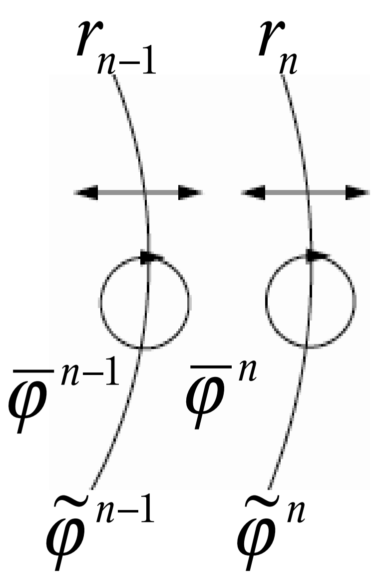
$$-\frac{2\pi\, r_n}{A_n}\left[\overleftrightarrow{u''\varphi''}^{\,n} + \widetilde{u}^{\,n}\widetilde{\varphi}^{\,n}\right]$$

$$+\frac{2\pi\, r_{n-1}}{A_n}\left[\overleftrightarrow{u''\varphi''}^{\,n-1} + \widetilde{u}^{\,n-1}\widetilde{\varphi}^{\,n-1}\right]$$

$$-\frac{\partial}{\partial z}\overline{w}^{\,n}\overline{\varphi}^{\,n}$$

$$-\frac{\partial}{\partial z}\overline{w'\varphi'}^{\,n}$$

$$+\overline{F}_{\varphi}^{\,n}$$



turbulent mixing

$$\overleftrightarrow{u''\varphi''} = -K\frac{d\varphi}{dr}$$

$$K = \kappa\, l^2\left|\frac{dw}{dr}\right|$$

dynamic entrainment/ detrainment

$$\overline{u}^{\,n} > 0 : \widetilde{\varphi}^{\,n} = \overline{\varphi}^{\,n}$$

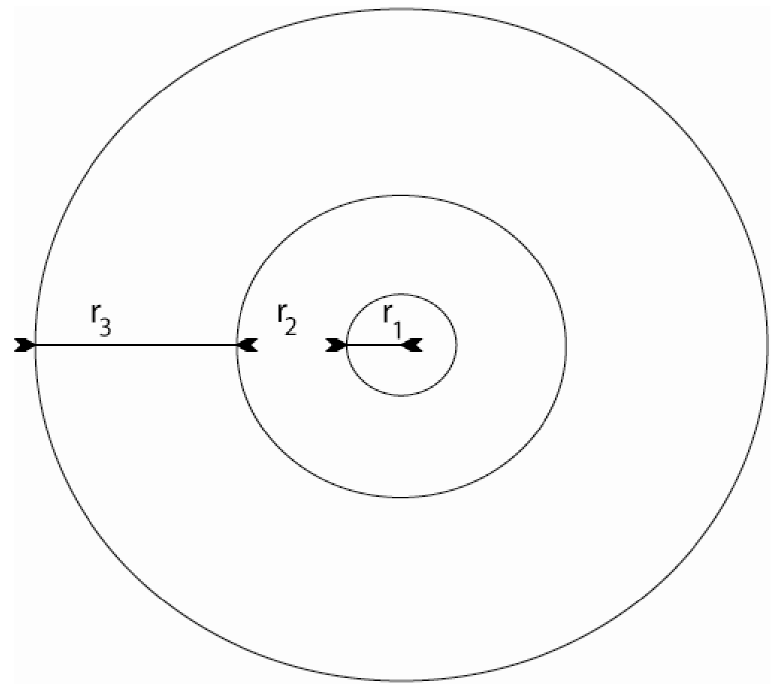
$$\overline{u}^{\,n} < 0 : \widetilde{\varphi}^{\,n} = \overline{\varphi}^{\,n+1}$$

$$\frac{\partial}{\partial t}\overline{w}^{n} = \ldots + \frac{g}{\Theta_0}\left(\overline{\theta}_v^{\,n} - \langle \theta_v \rangle\right)$$

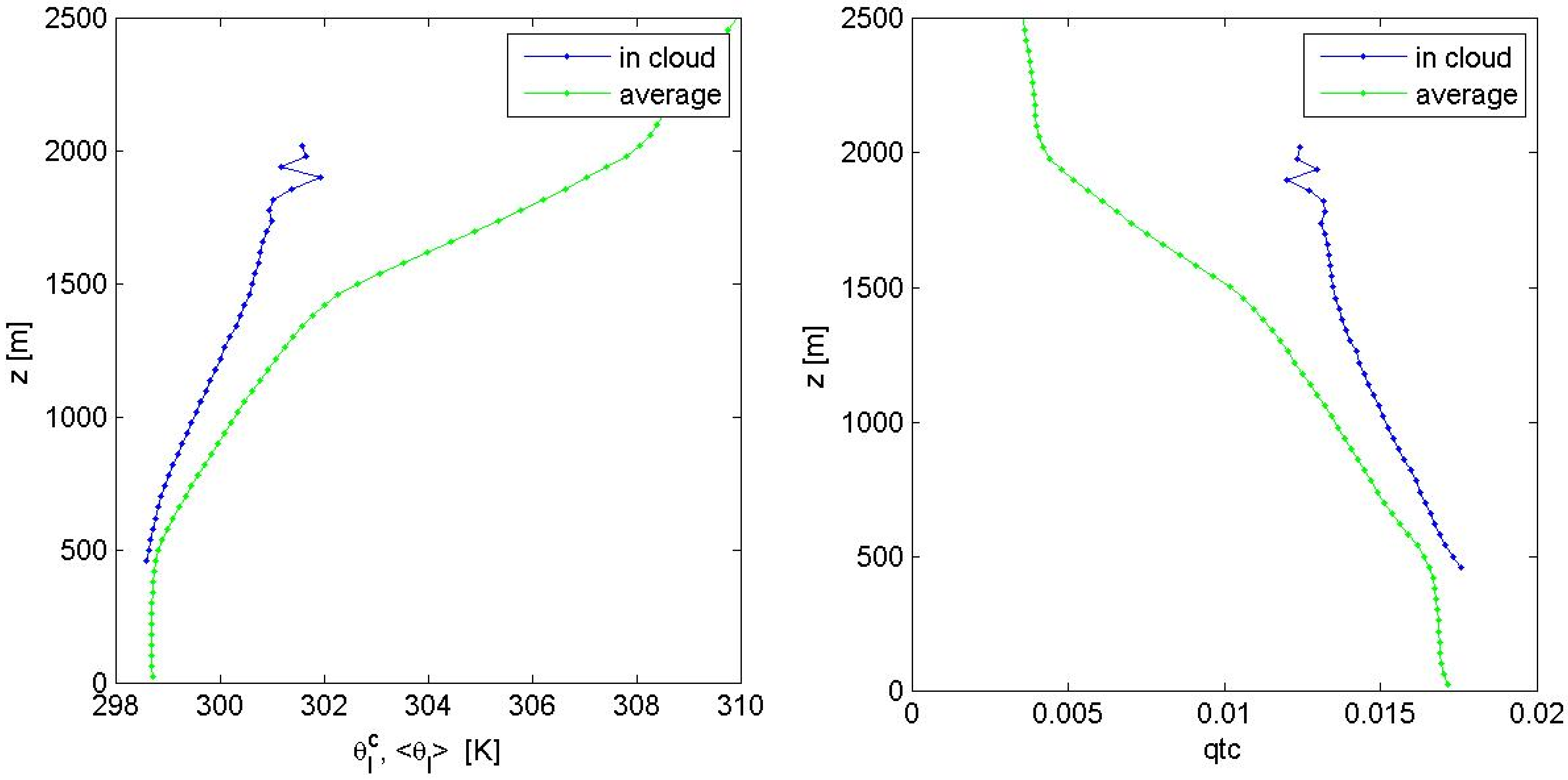
$$\frac{\partial}{\partial t}\overline{q}_t^{\,n} = \ldots$$

$$\frac{\partial}{\partial t}\overline{\theta}_l^{\,n} = \ldots$$

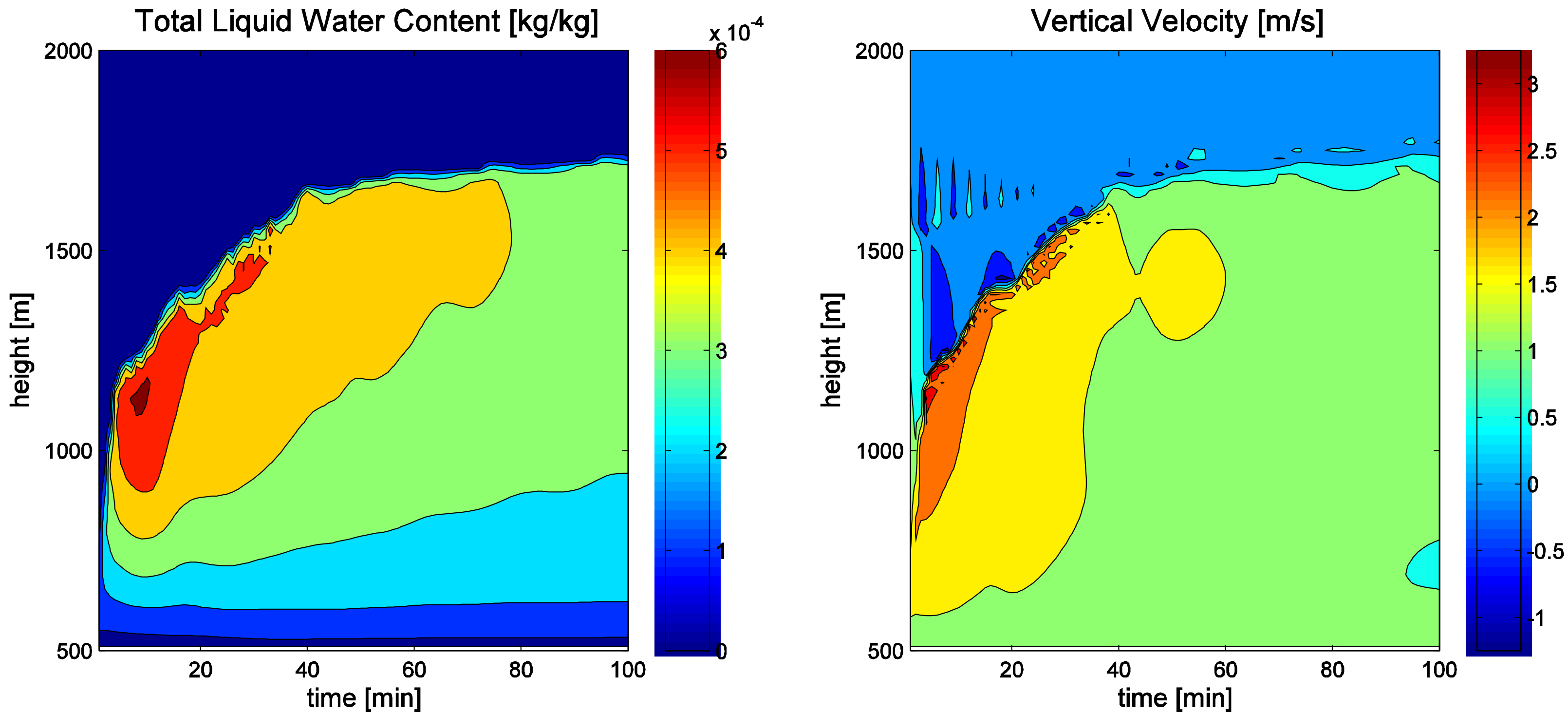
$$n = 1,2,3$$



Initial conditions: Bomex-LES

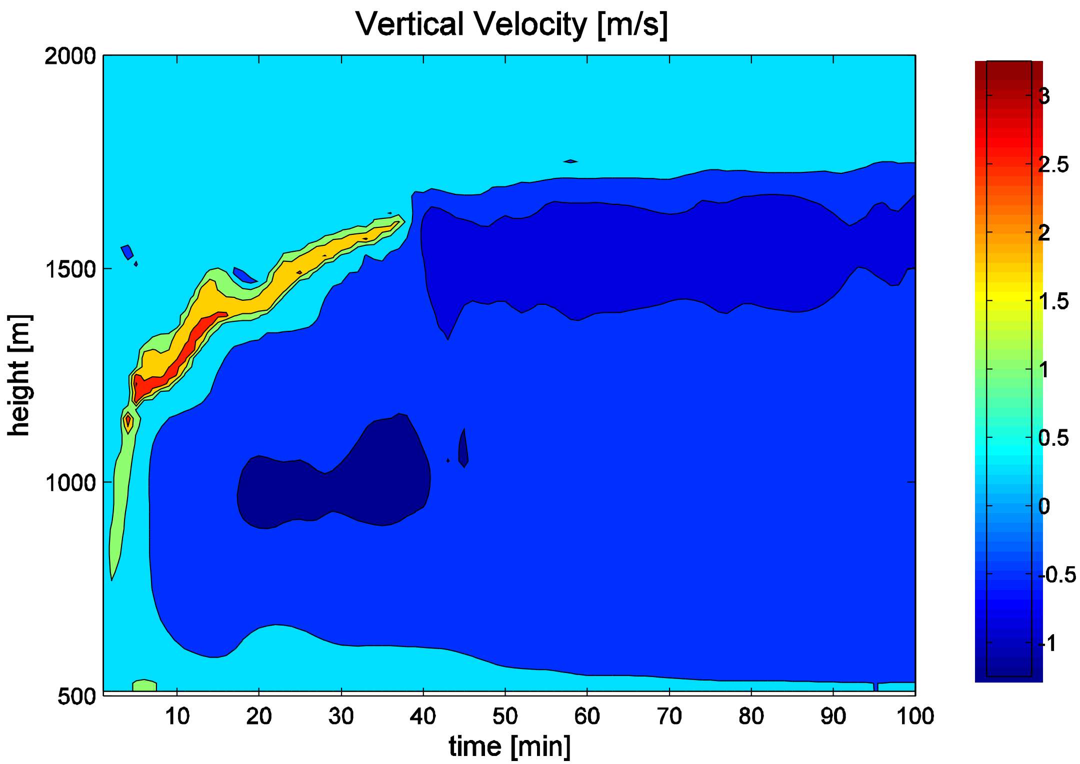


Bomex

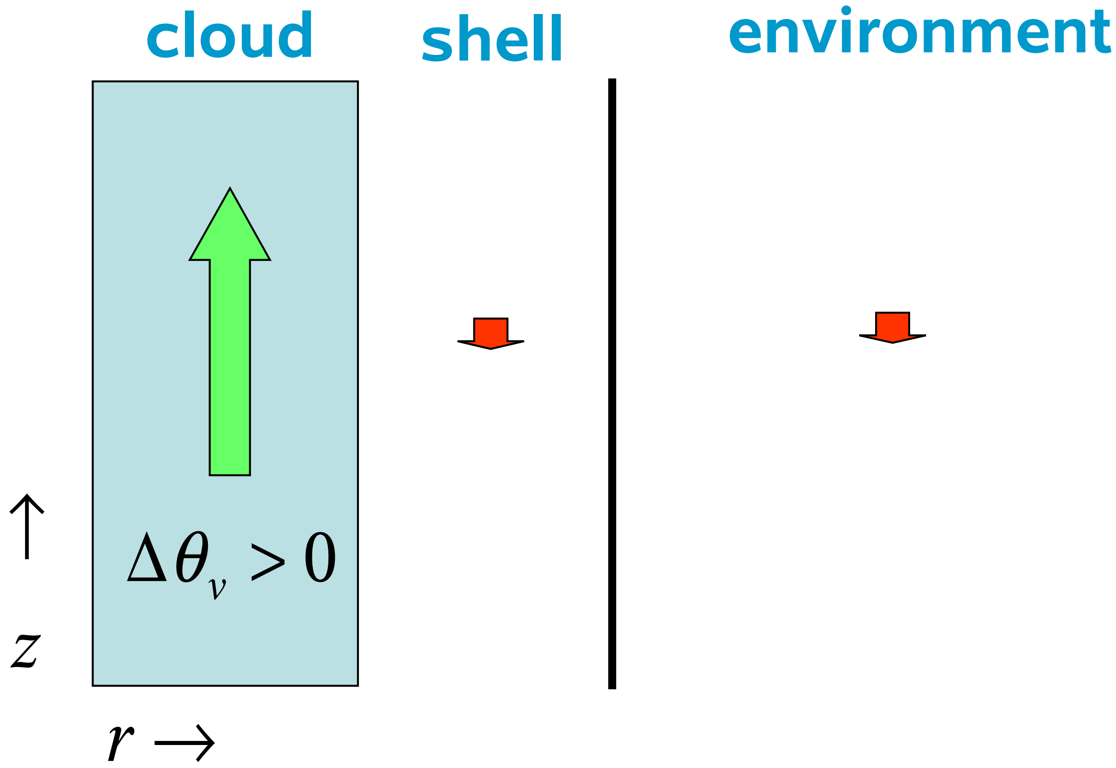


Total Liquid Water Content [kg/kg]
x 10^-4
height [m]
time [min]
Vertical Velocity [m/s]
height [m]
time [min]

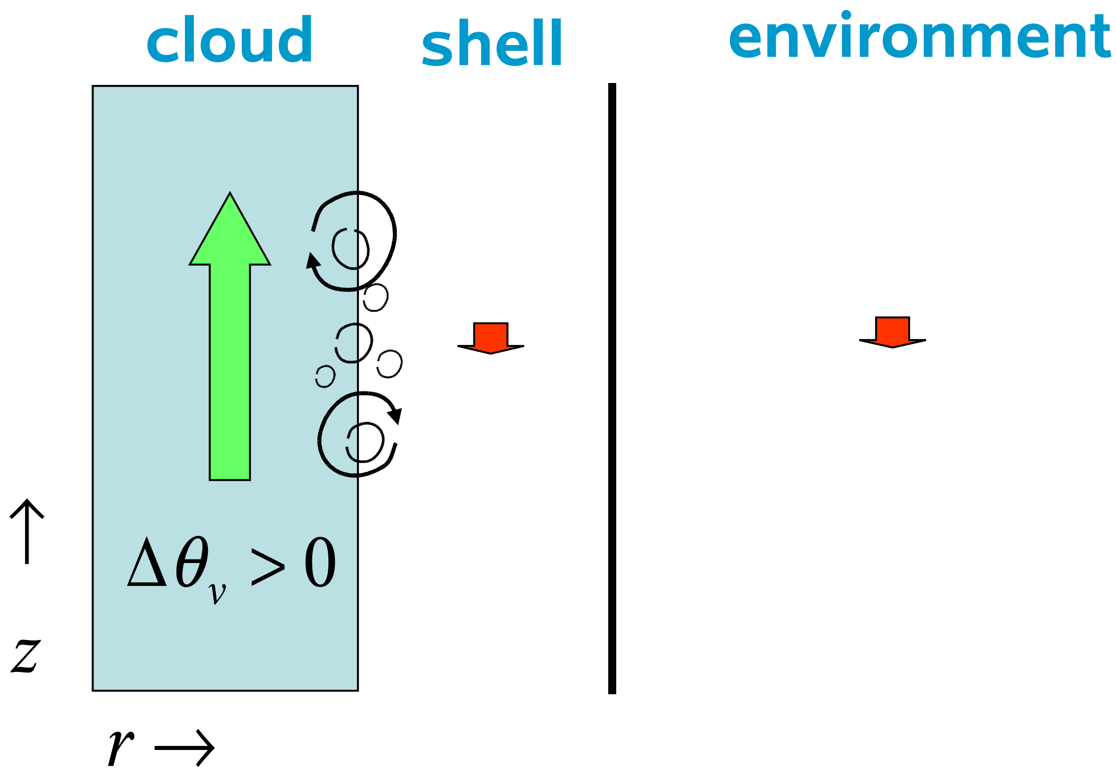
Shell vertical velocity



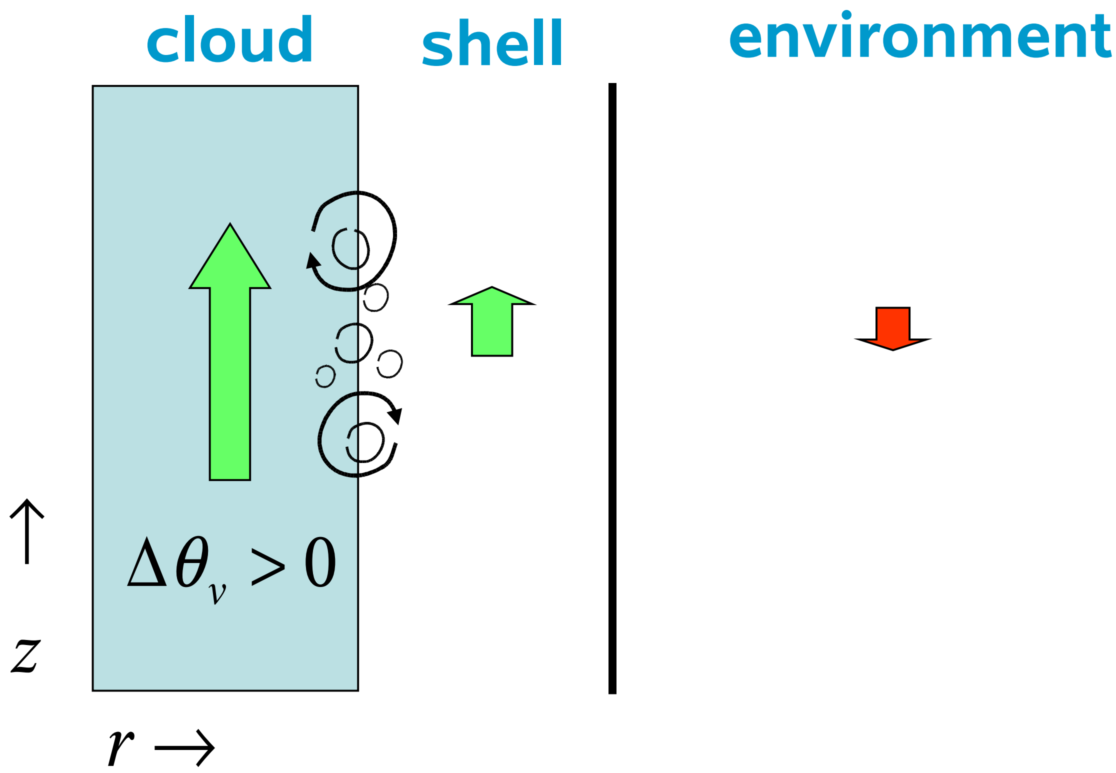
why a descending shell?



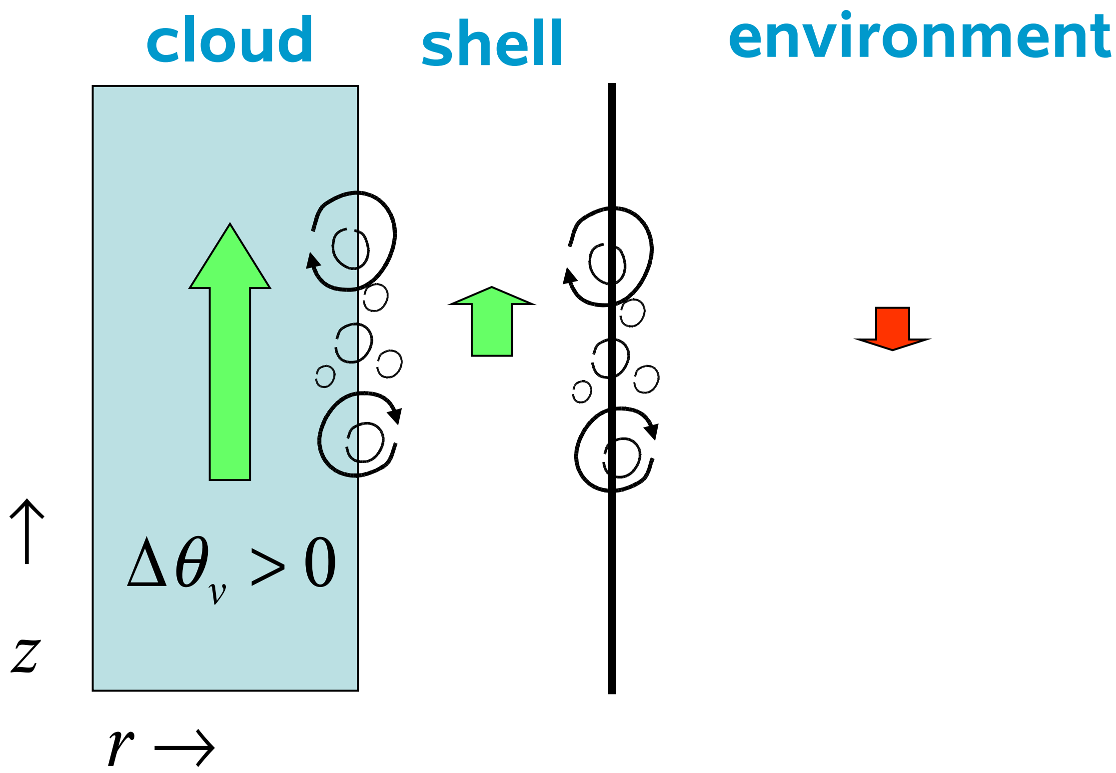
why a descending shell?



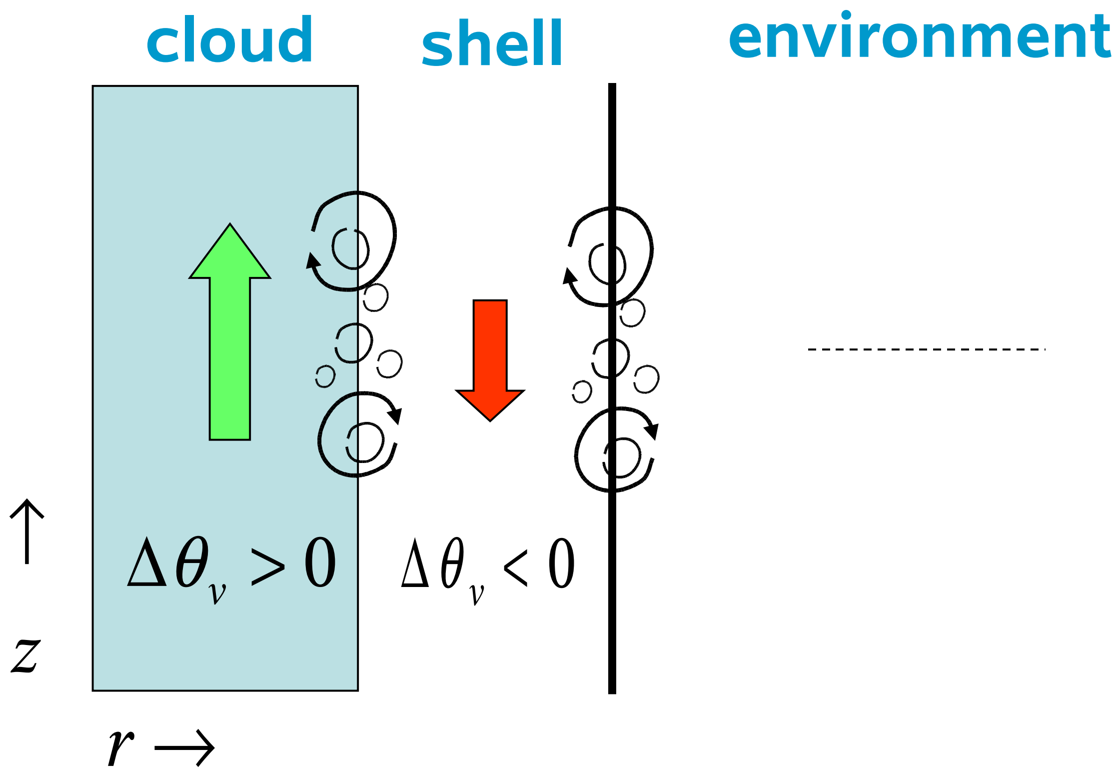
why a descending shell?



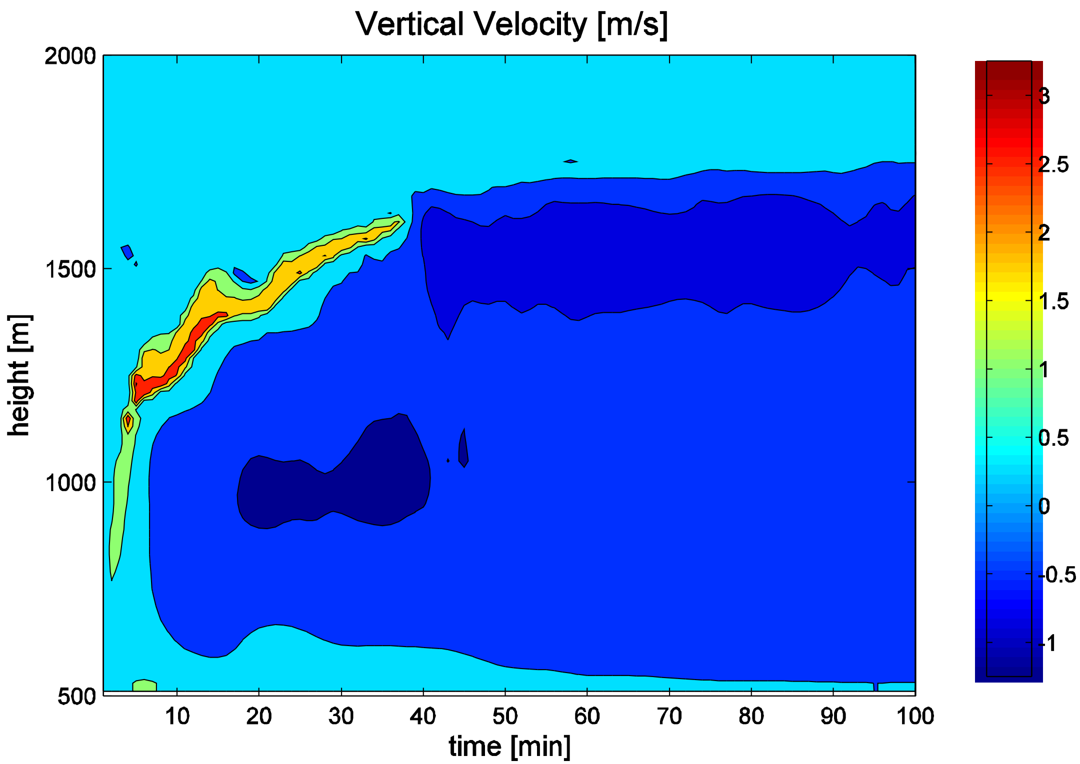
why a descending shell?



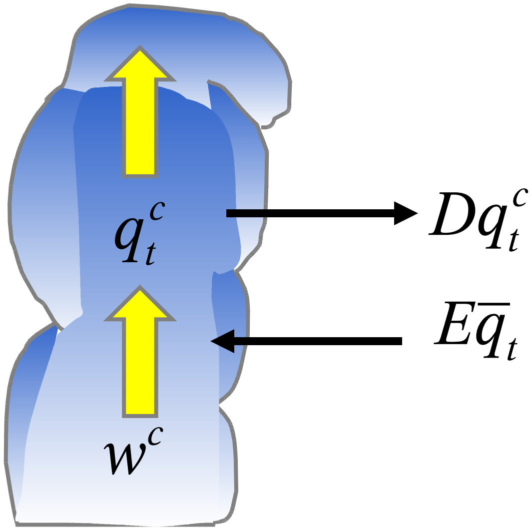
why a descending shell?



Shell vertical velocity



Entrainment/Detrainment



simple cloud mixing models

$$\frac{d}{dz} q_t^c = -\varepsilon (q_t^c - \overline{q}_t)$$

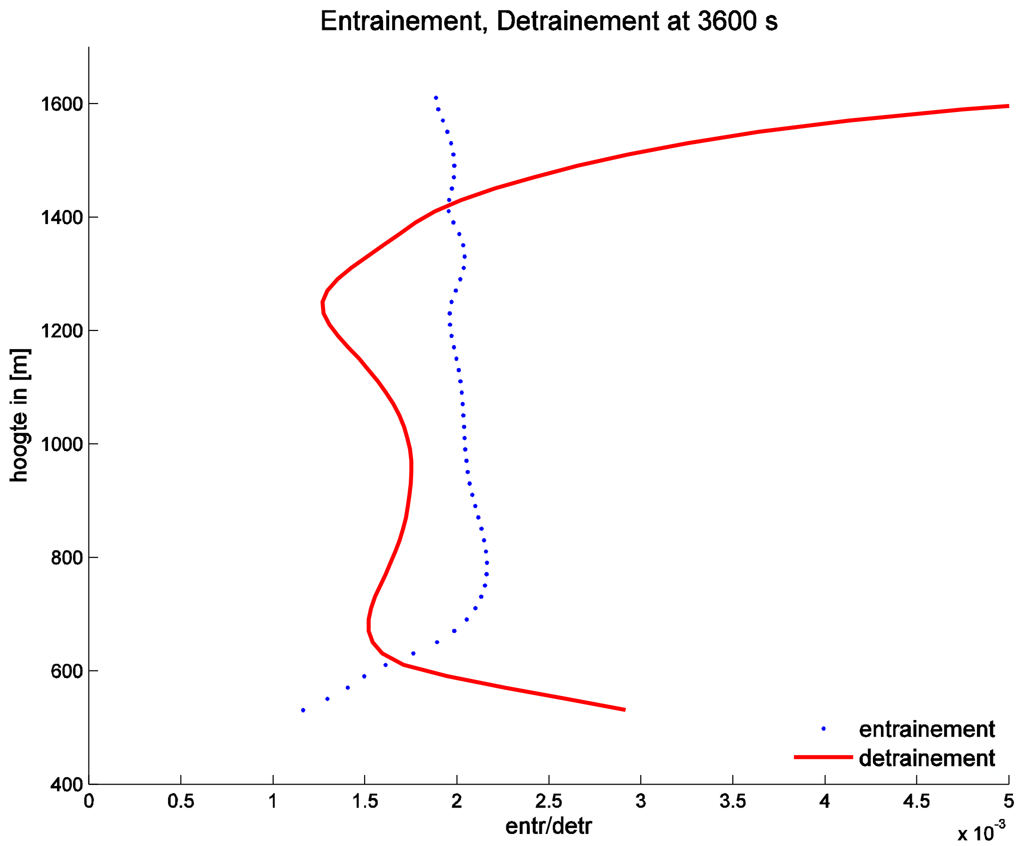
$$\varepsilon = \frac{\frac{d}{dz} q_t^c}{(\overline{q}_t - q_t^c)}$$

$$\delta = \varepsilon - \frac{1}{M} \frac{d}{dz} M$$

diagnose from LES or observations

(Siebesma and Cuijpers, 1995) $\varepsilon \sim 10^{-3} m^{-1}$

Entrainment/Detrainment



Siebesma et al JAS 2003
LES conditional sampling

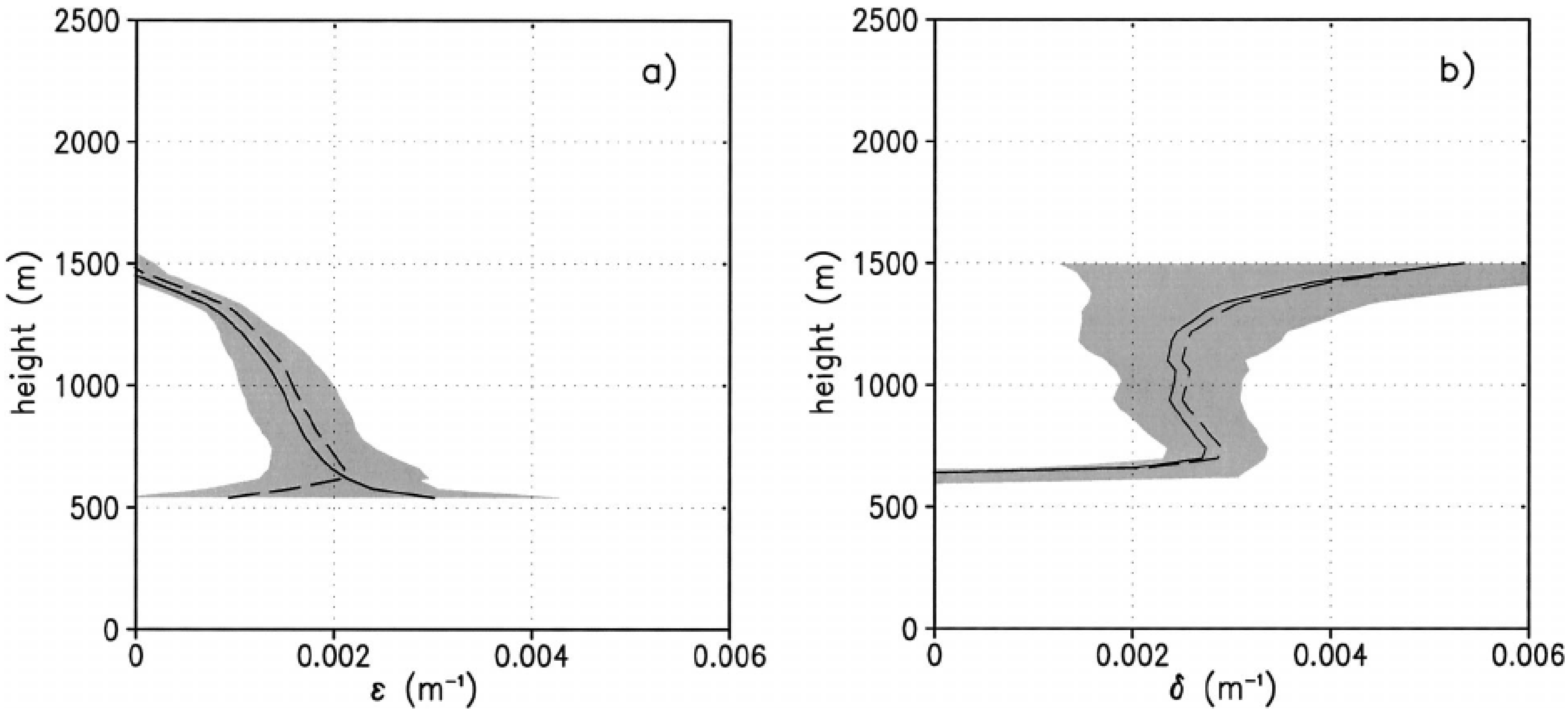
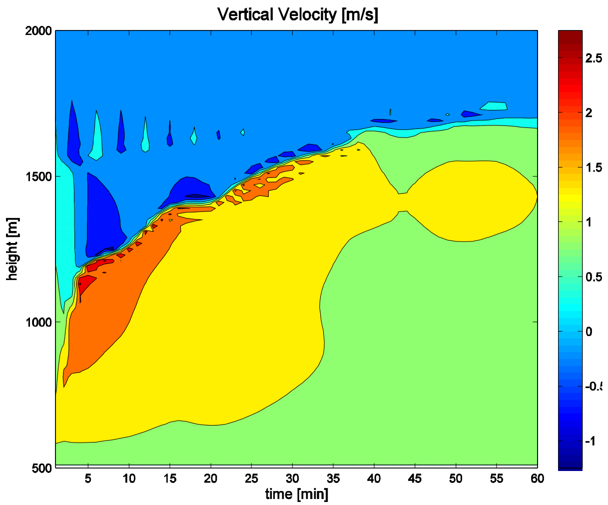


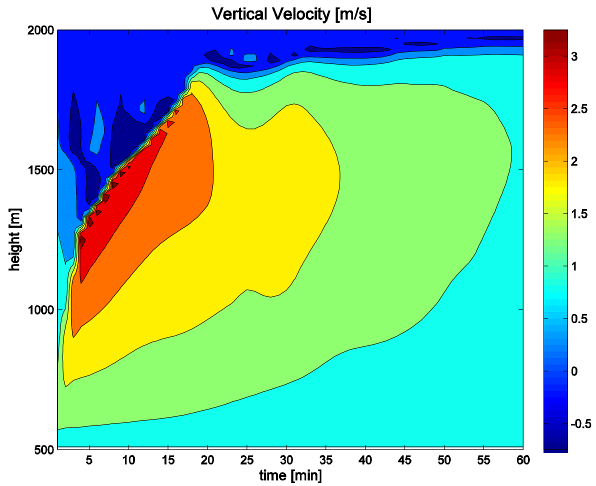
FIG. 9. Fractional entrainment rate ε and detrainment rate δ diagnosed using (10)–(11) for $\phi = q_t$ (solid line) and $\phi = \theta_l$ (dashed line).

Cloud Size (r_1)

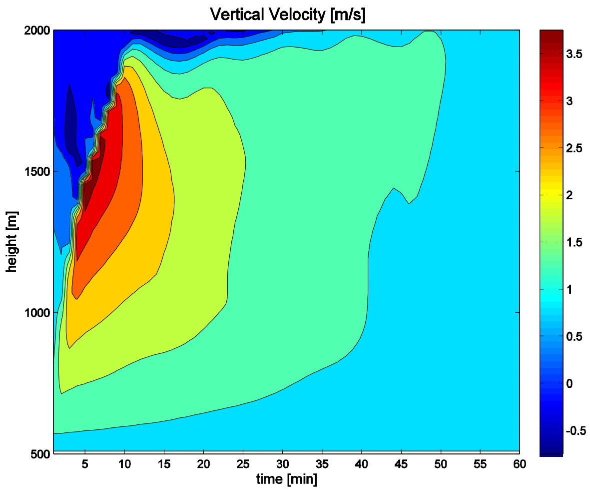
- The size of the cloud affects the maximum height of cloud
- Maximum height is also limited by the inversion height



100m



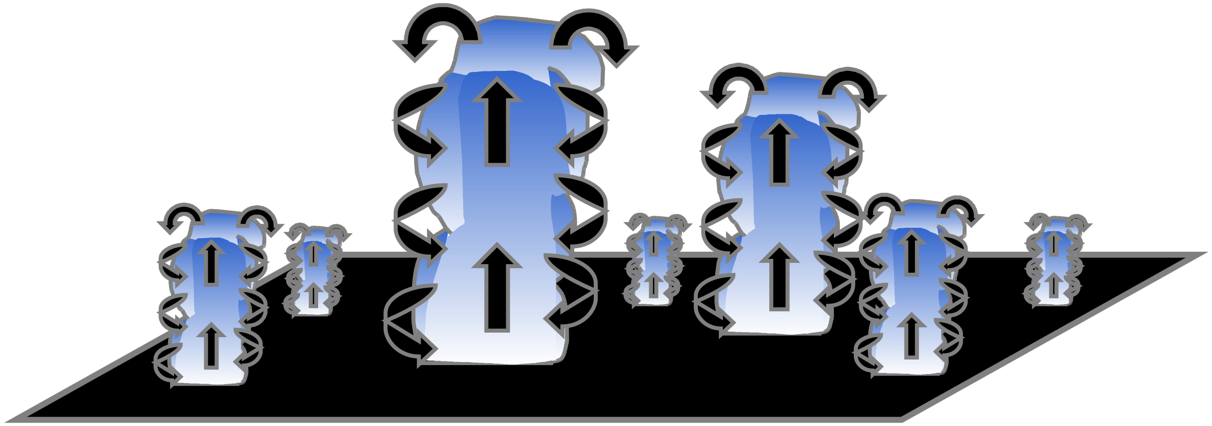
200m



400m

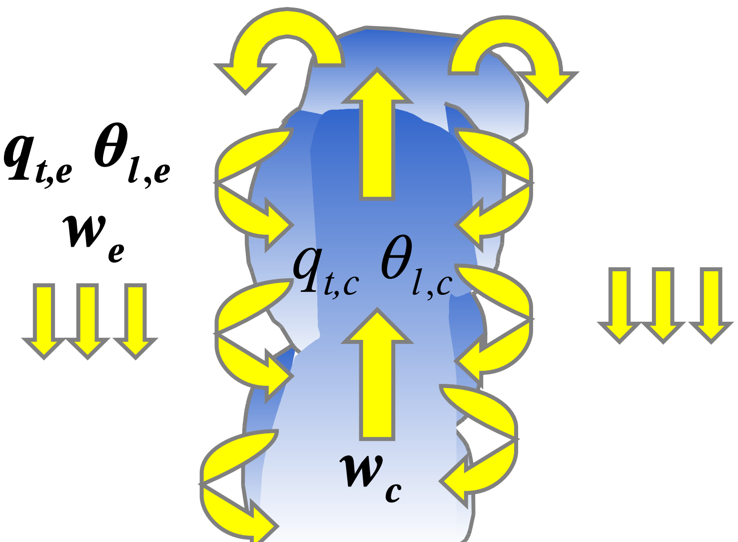
Bulk model:

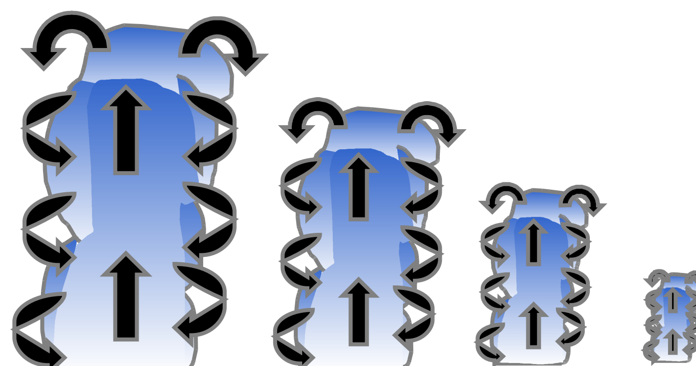
Cloud ensemble:



approximated by

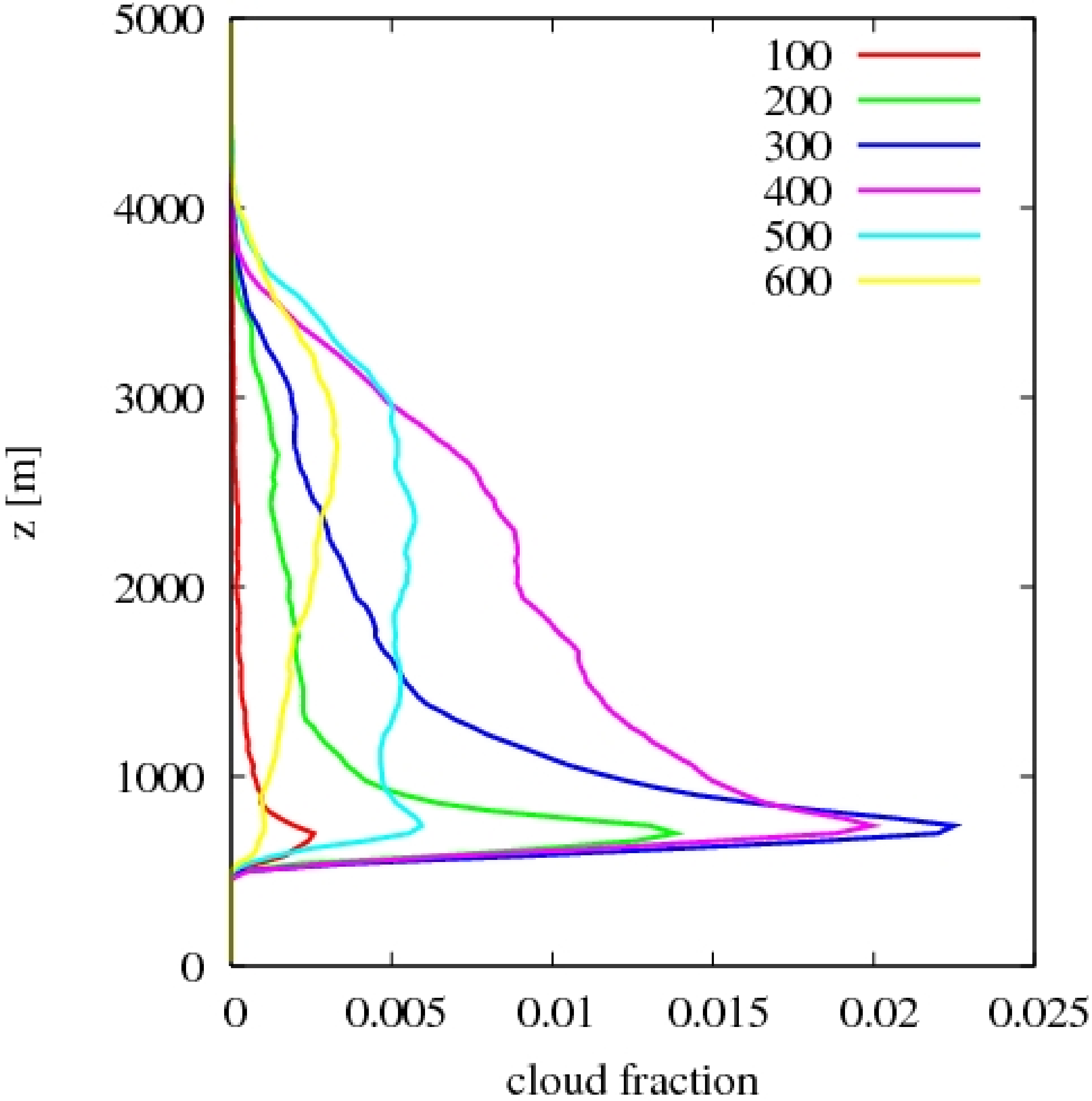
1 effective cloud:



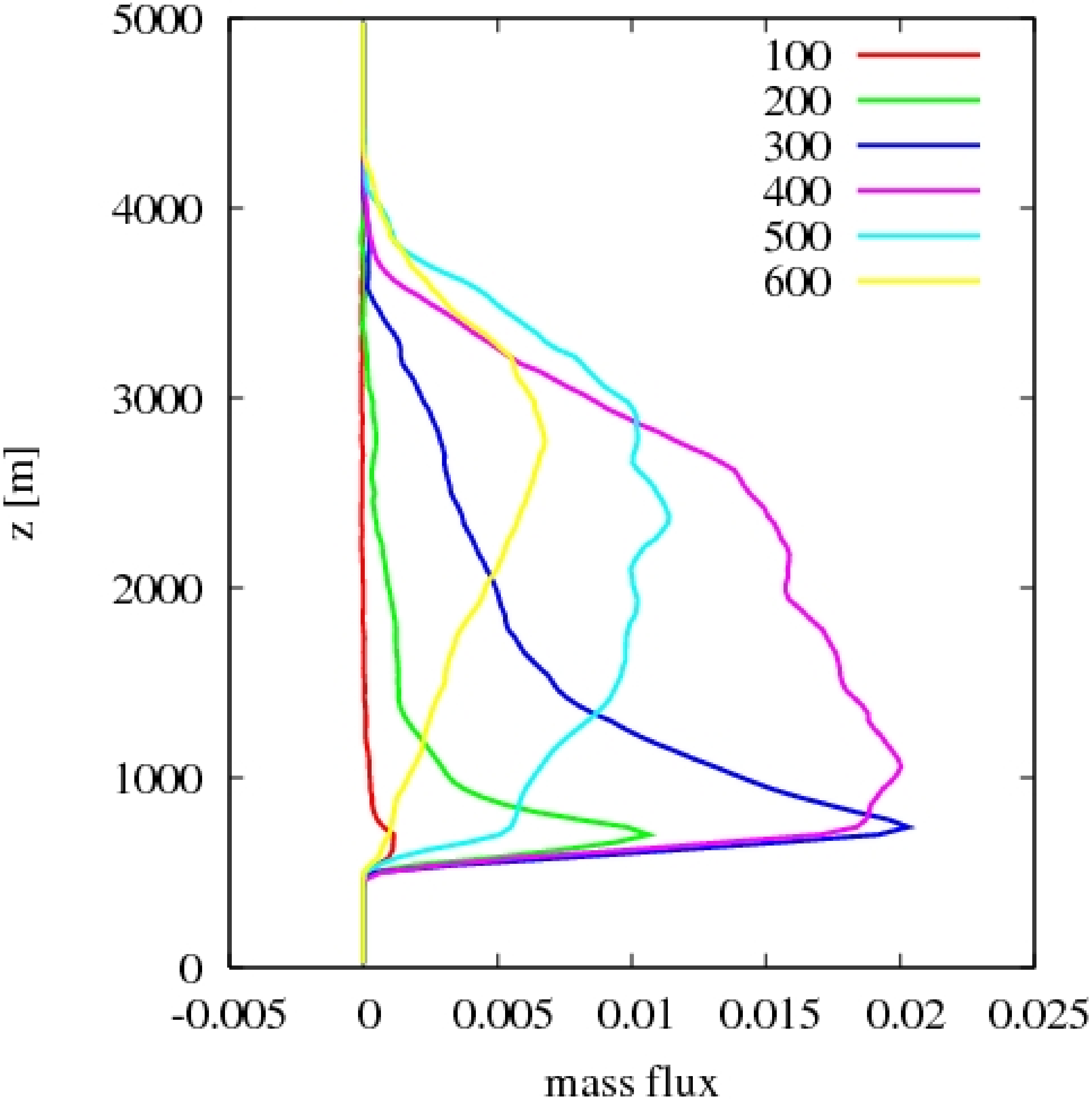


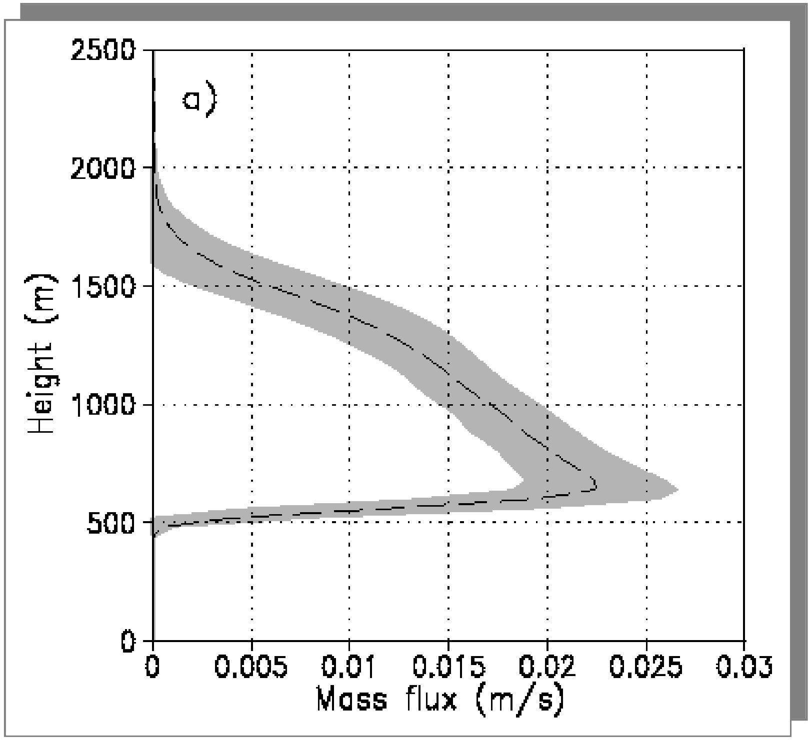
$N(l) \sim l^{-\beta}$

e.g. Neggers et al, JAS 2003

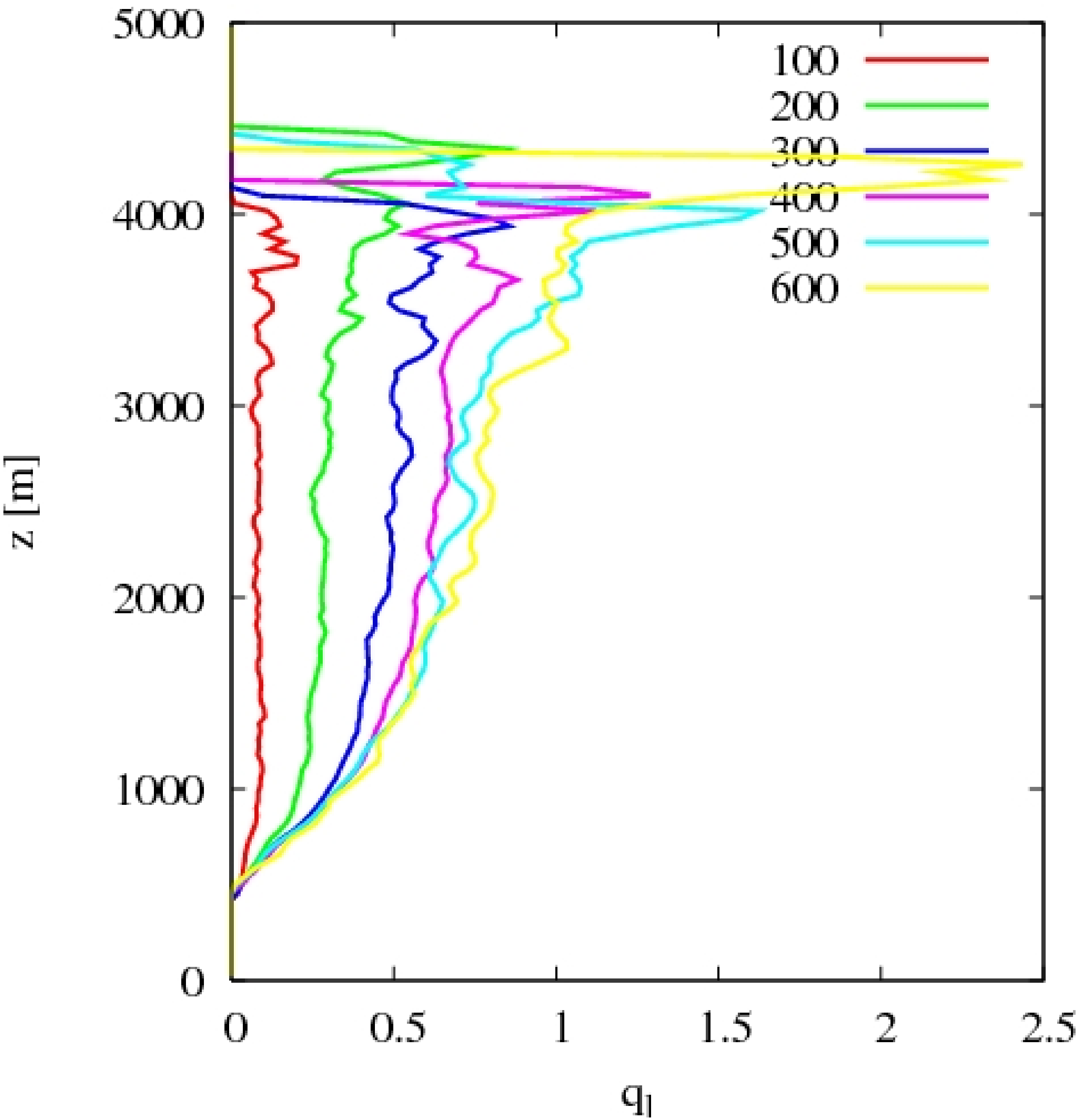


5000
4000
3000
2000
1000
0
z [m]
0
0.005
0.01
0.015
0.02
0.025
cloud fraction
100
200
300
400
500
600

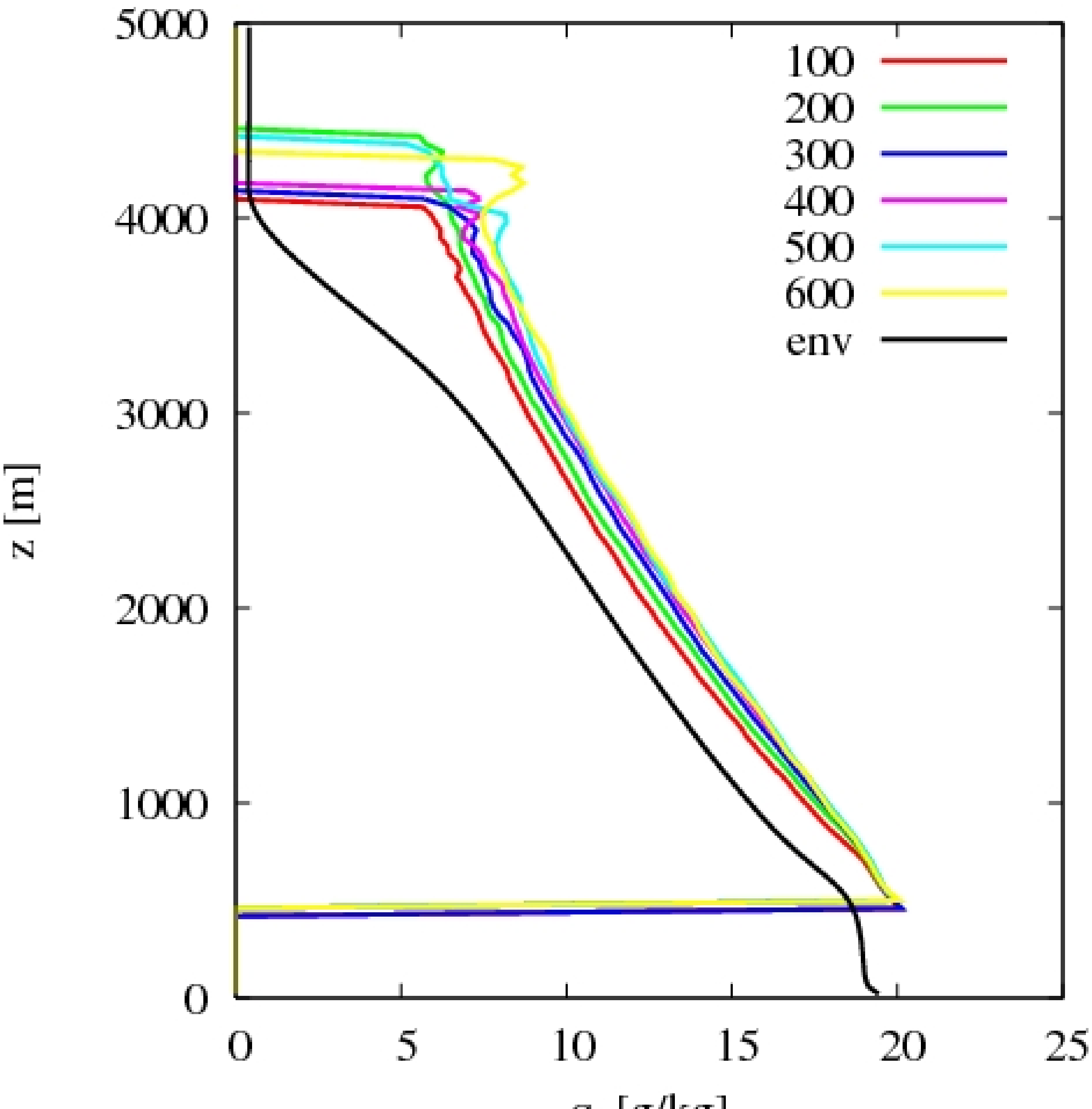

5000
4000
3000
2000
1000
0
z [m]
-0.005
0
0.005
0.01
0.015
0.02
0.025
mass flux
100
200
300
400
500
600



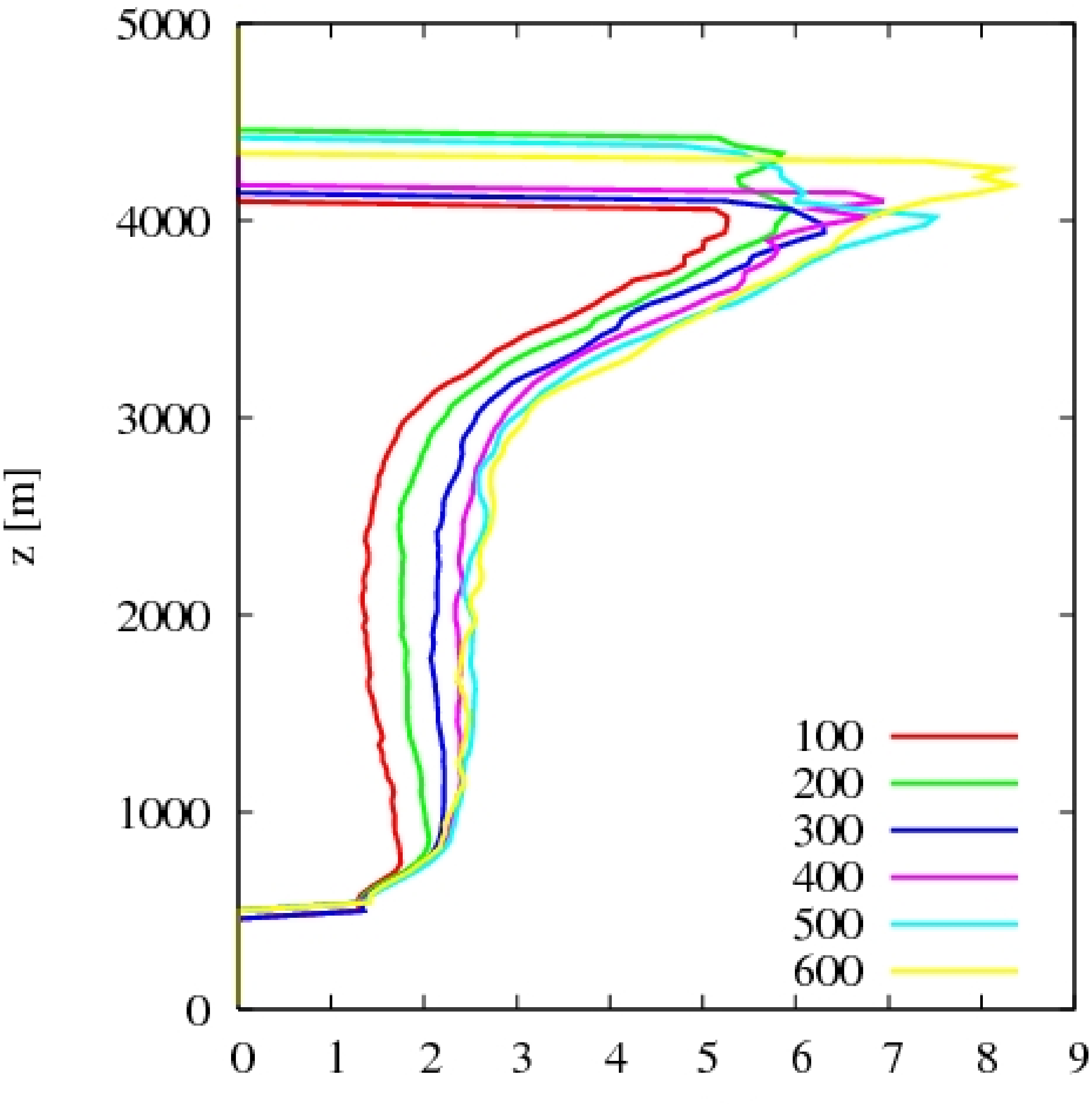
Bomex, intercomparison
Siebesma et al, 2003



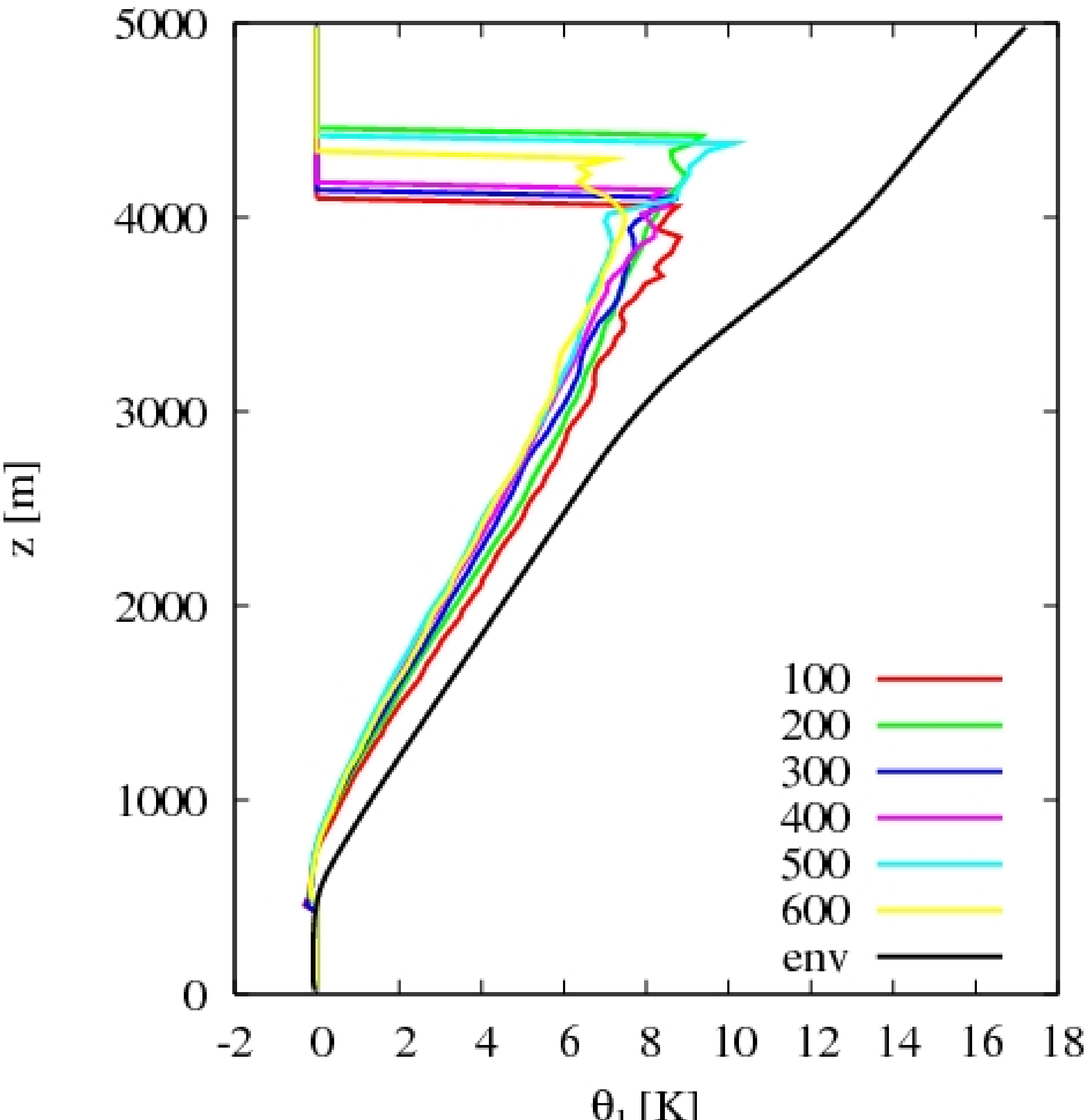
100
200
300
400
500
600
5000
4000
3000
2000
1000
0
z [m]
0
0.5
1
1.5
2
2.5
q_l



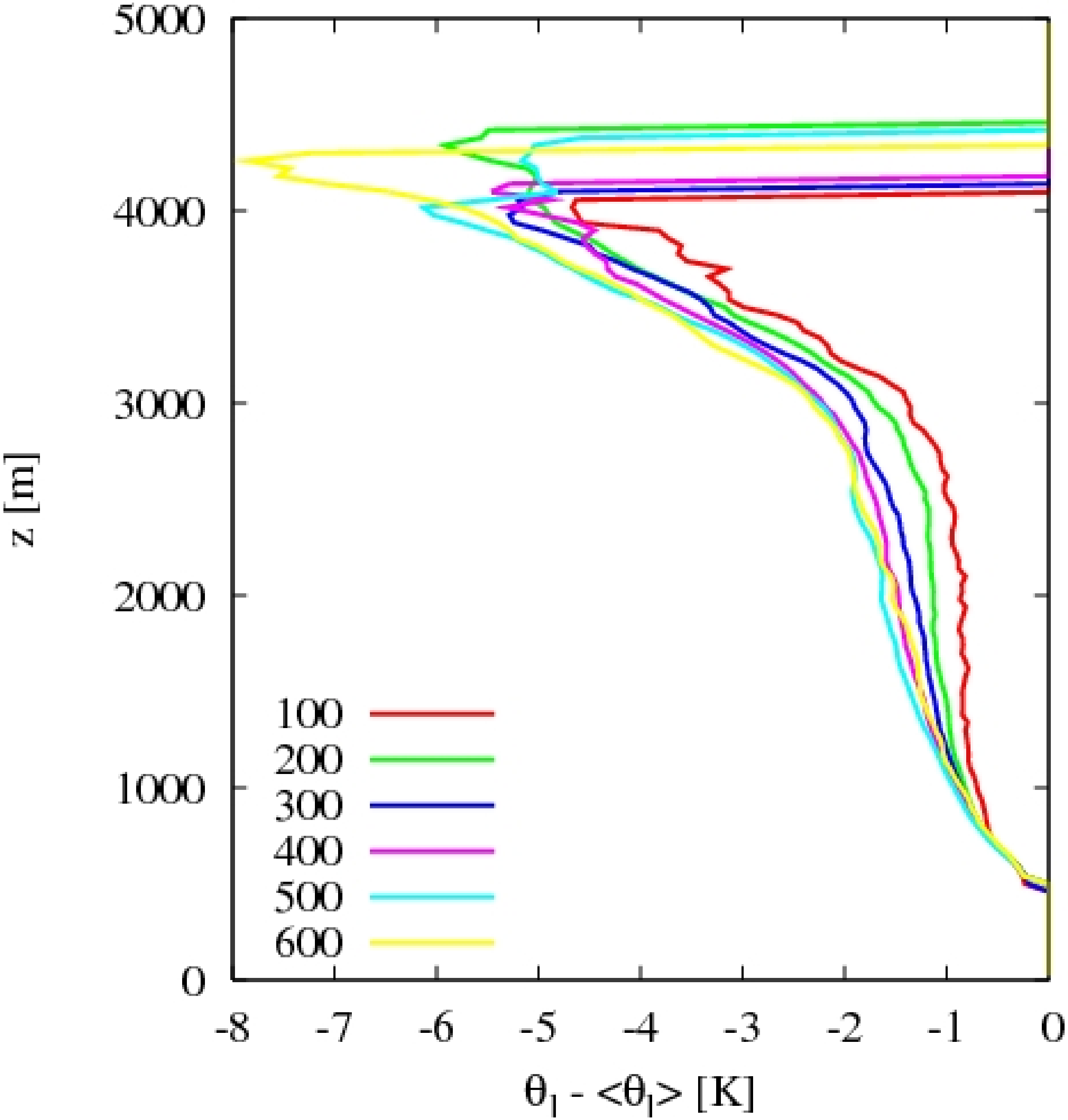
5000
4000
3000
2000
1000
0
z [m]
0
5
10
15
20
25
q_t [g/kg]
100
200
300
400
500
600
env



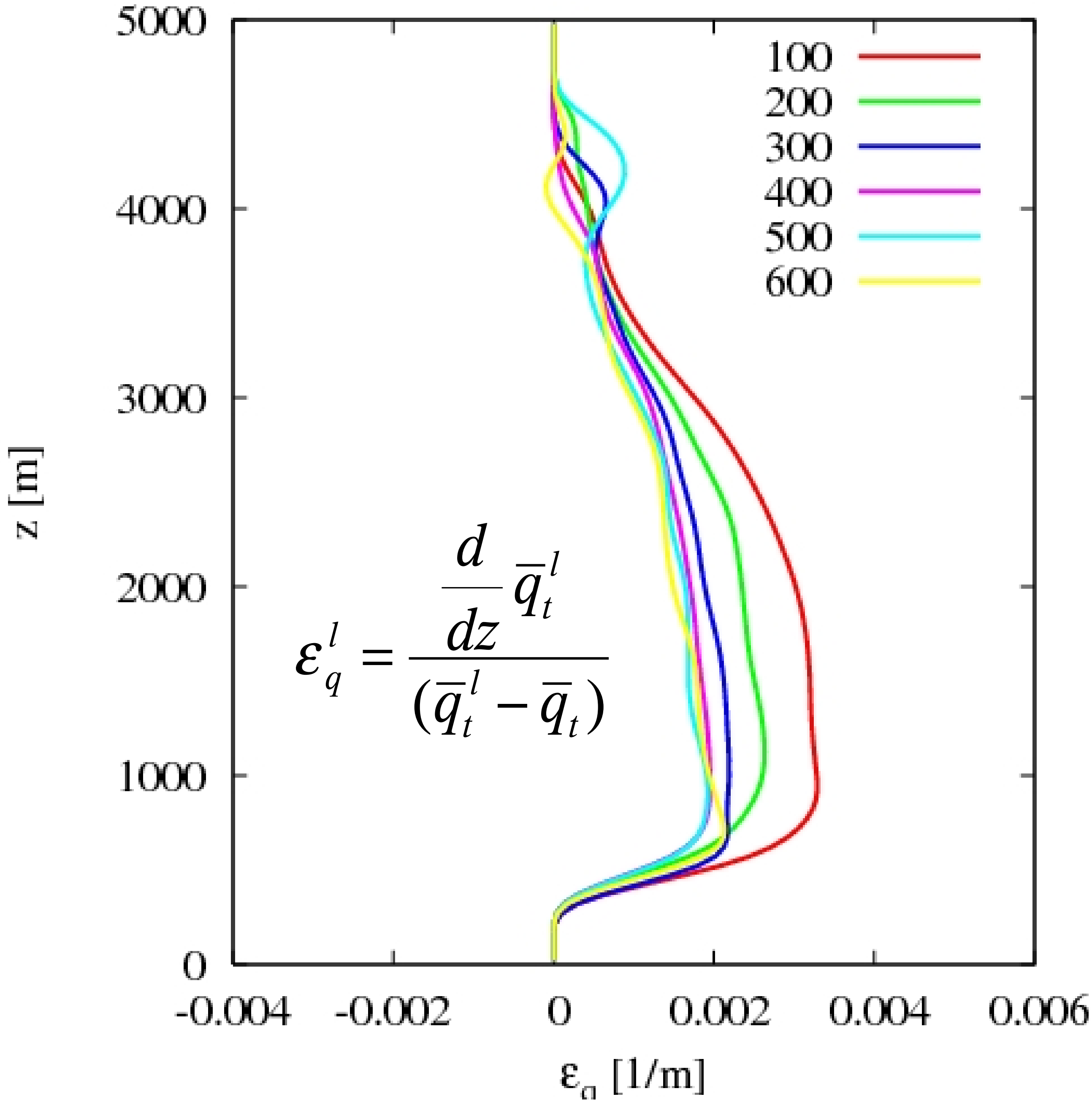
5000
4000
3000
2000
1000
0
z [m]
0
1
2
3
4
5
6
7
8
9
q_t - <q_t> [g/kg]
100
200
300
400
500
600



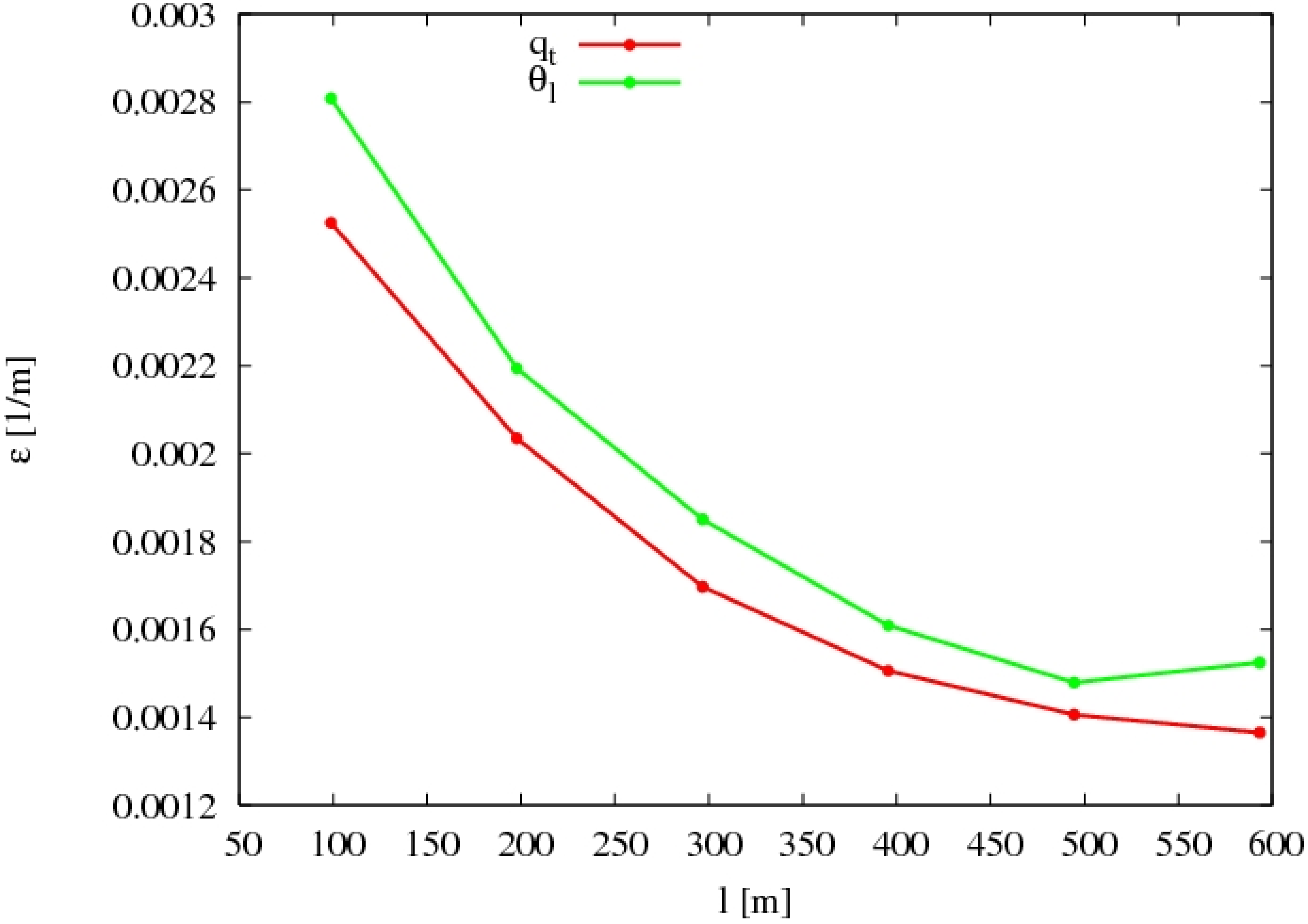
5000
4000
3000
2000
1000
0
-2
0
2
4
6
8
10
12
14
16
18
z [m]
θ1 [K]
100
200
300
400
500
600
env



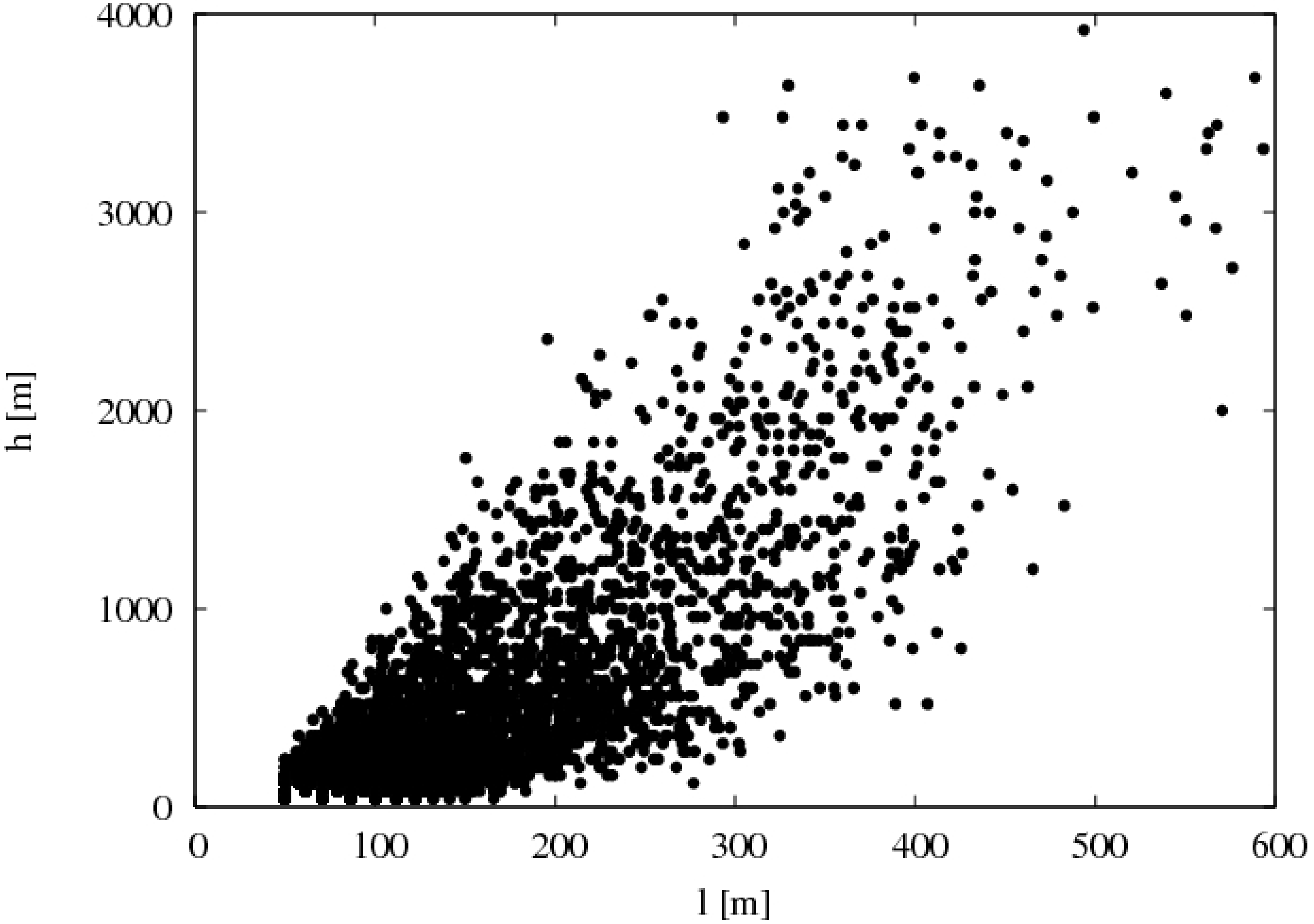
5000
4000
3000
2000
1000
0
z [m]
-8
-7
-6
-5
-4
-3
-2
-1
0
θ_l - <θ_l> [K]
100
200
300
400
500
600


5000
4000
3000
2000
1000
0
-0.004
-0.002
0
0.002
0.004
0.006
z [m]
ε_q [1/m]
100
200
300
400
500
600
$$\varepsilon_q^l = \frac{\frac{d}{dz}\overline{q}_t^l}{(\overline{q}_t^l - \overline{q}_t)}$$

entrainment versus lateral cloud size



cloud height versus lateral cloud size



Conclusions

" A refinement of the conceptual view may be useful
" Importance of cloud-edge processes on vertical transport
" Cloud mass-flux is compensated in the immediate proximity of shallow cumulus clouds.
" ‘Far field’ is very quiet (no downward vertical transport)

" Important for understanding the dispersion characteristics in shallow Cu
" Improve mass-flux parameterizations?

generalized AK'67 model

- descending shell is formed
- balance between shear, mixing of momentum, negative buoyancy
- entrainment/detrainment need not be prescribed
- small clouds are less tall

- improvements:
- cloud-shape (e.g. Ferrier and Houze 1988)
- pressure-fluctuations
- ...