LES simulations of entrainment and mixing at the top of stratocumulus

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Outline

- Motivation
- Model setup and its performance
- Top of Stratocumulus
- Passive scalar analysis of entrainment and mixing
- Summary

Motivation

• Global annual cloud cover > 50% (ICSSP)

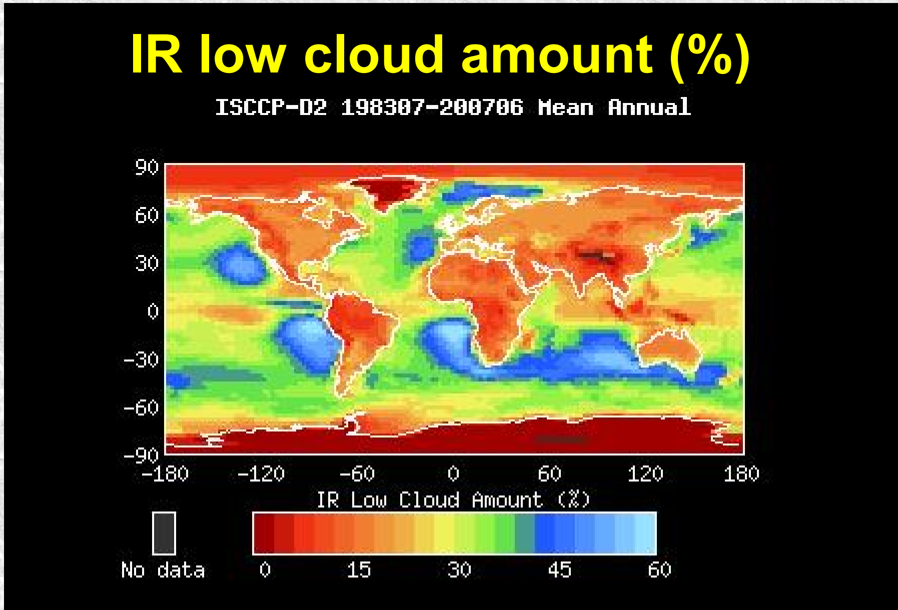
• 1/3 of them is Stratocumulus

• as low-level cloud causes a cooling effect

• 4% increase of Sc cover would balance warming effect induced by doubling of CO2 (Randall, 1984)

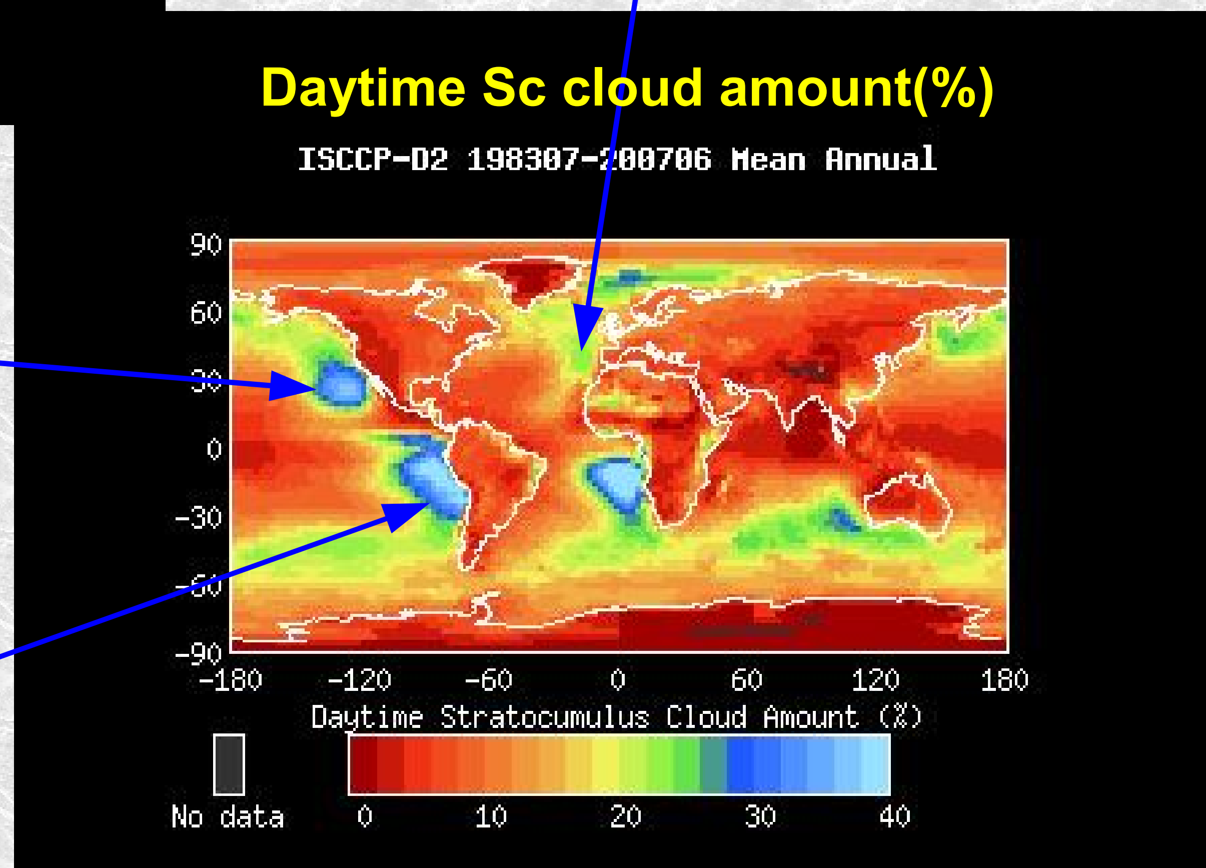
• Sc are the Earth's refrigerators – ideas of influencing its microphysics to modify the radiative budget and so the climate (Latham, 2000)

• to support measurements with more comprehensive picture of the processes (virtual laboratory)

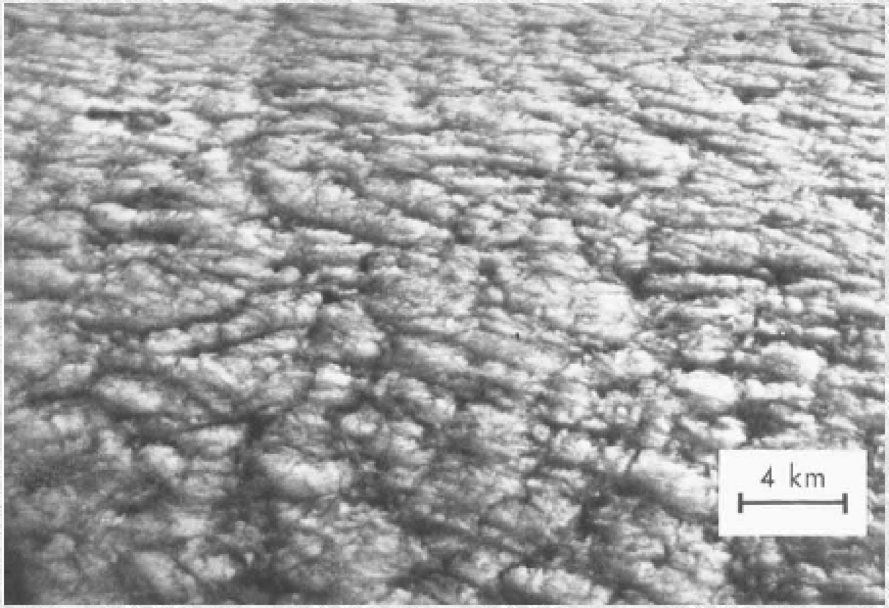


ASTEX (1992),
ACE-2 (1997)

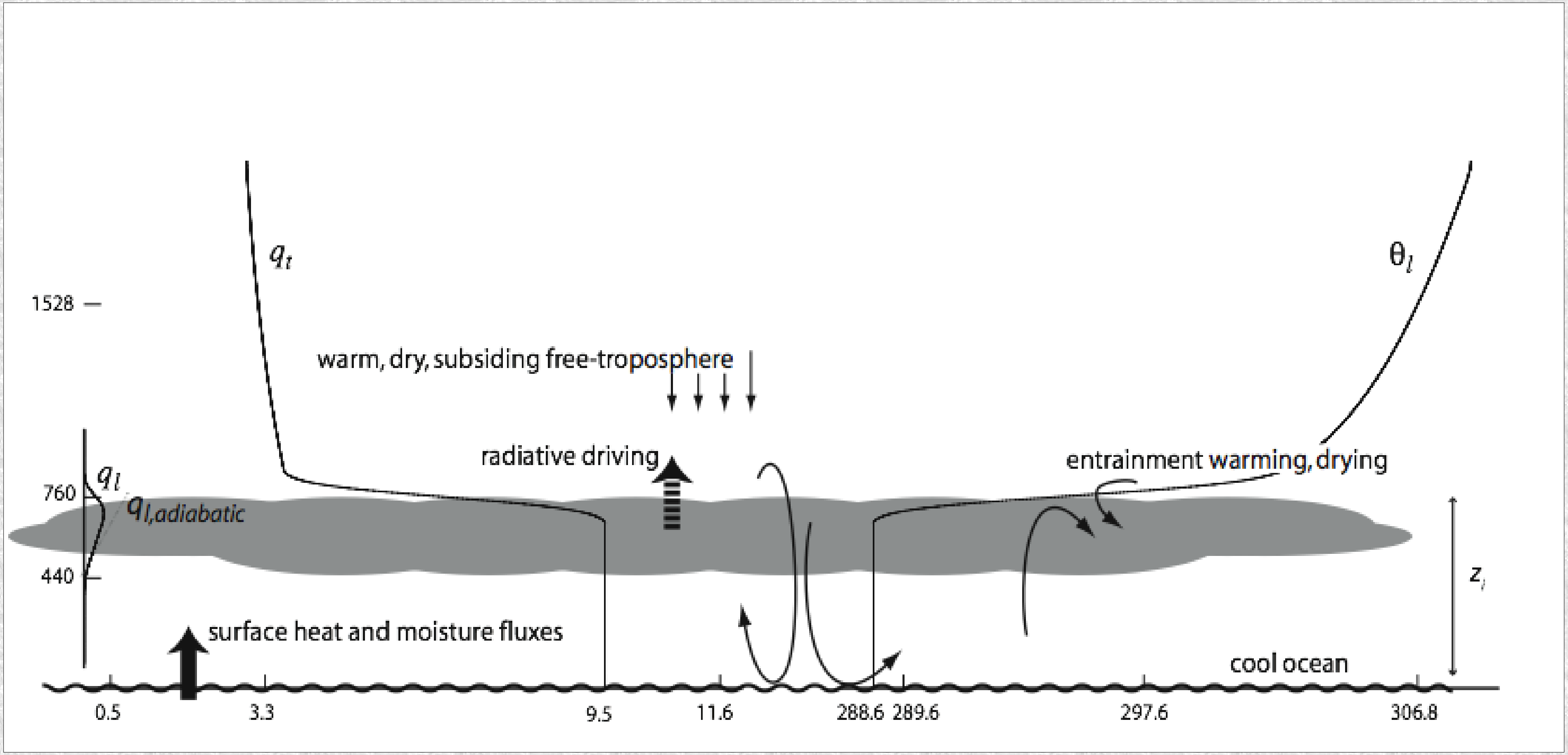
FIRE (1987),
DYCOMS (1988),
DYCOMS-II (2001),
POST(2008)



EPIC (2001),
VOCALS (2008)


4 km

Stratocumulus-topped boundary layer (STBL)



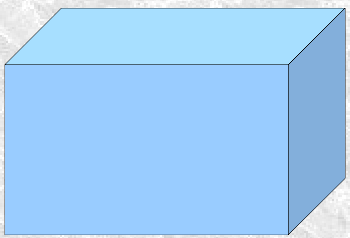
Entrainment influences microphysics, dynamics and radiative properties of Sc.

Stevens B., 2005, Annu. Rev.

Model setup

(based on Dycoms-II, RF01,
Stevens et al. 2005 Mon. Wea. Rev.)

GEOMETRY



Domain size: 96 x 96 x 301

Grid box size: dx = dy = 35m, dz = 5m

(3.36 x 3.36 x 1.5) km

Periodic boundary conditions

No orography (flat ocean)

Model setup

(based on Dycoms-II)

PHYSICS

geostrophic wind (7, -5.5) m/s

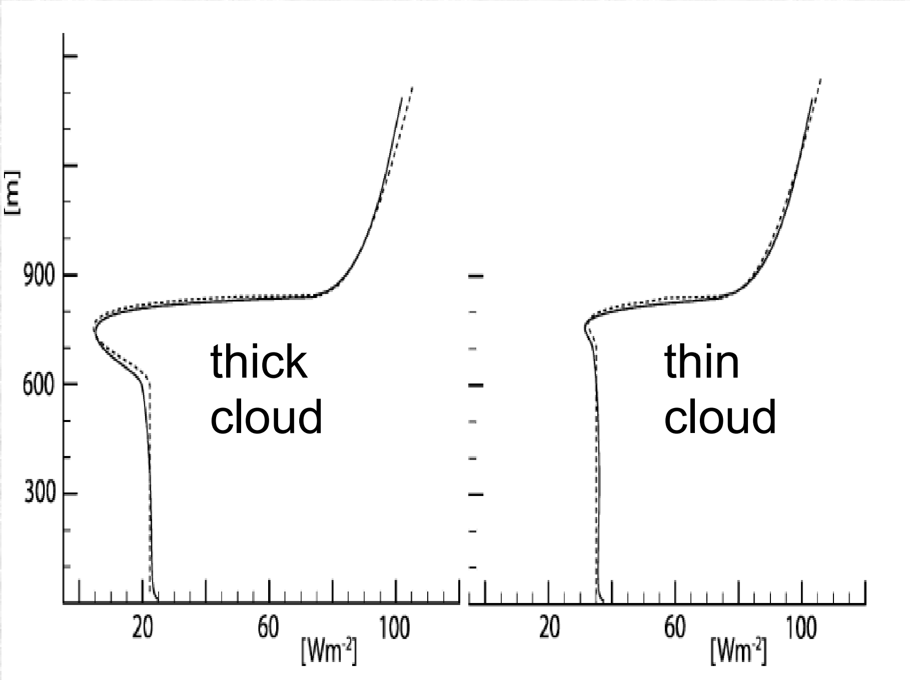
surface flux of heat: ~15 W/m2
surface flux of moisture: ~ 115 W/m2

large-scale subsidence: $w(z)=\int D_h dz$ ~mm/s

long-wave radiation:

$$F_{\mathrm{rad}}(x, y, z, t) = F_0 e^{-Q(z,\infty)} + F_1 e^{-Q(0,z)} + \rho_i c_p D \alpha_z \left[\frac{(z-z_i)^{4/3}}{4} + z_i (z - z_i)^{1/3} \right]$$

$$Q(a, b) = \kappa \int_a^b \rho r_l \, dz$$

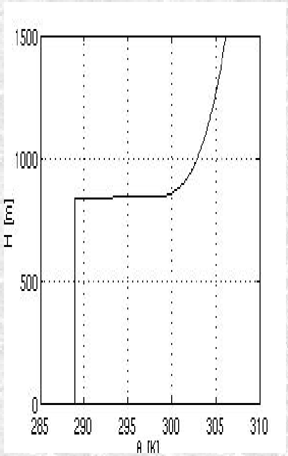


Model setup
(based on Dycoms-II
RF01)

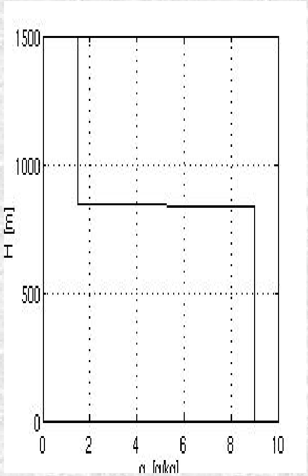
INITIAL PROFILES

Temperature
(liquid water potential temperature)
Θ_l=289K $z<z_i$, z_i=840m
Θ_l=297.5+($z-z_i$) K $z>z_i$

$$\Theta_l = \Theta - \frac{L}{c_p}\frac{\bar{\Theta}}{\bar{T}} q_l$$



Atmospheric water
(total water mixing ratio q_v+q_l)
q_t=9 g/kg $z<z_i$
q_t=1.5 g/kg $z>z_i$



{q_t, Θ_l} are constraints of moist adiabatic processes

EULAG: **dynamics –** ***Smolarkiewicz and Margolin (1997)***
bulk thermodynamics – ***Grabowski and Smolarkiewicz (1996)***
subgrid-scale turbulence mixing – ***Margolin et al. (1999)***

How well do the models reconstruct STBL?

ensemble (10 models, Stevens et al. 2005,Mon.Wea.Rev):

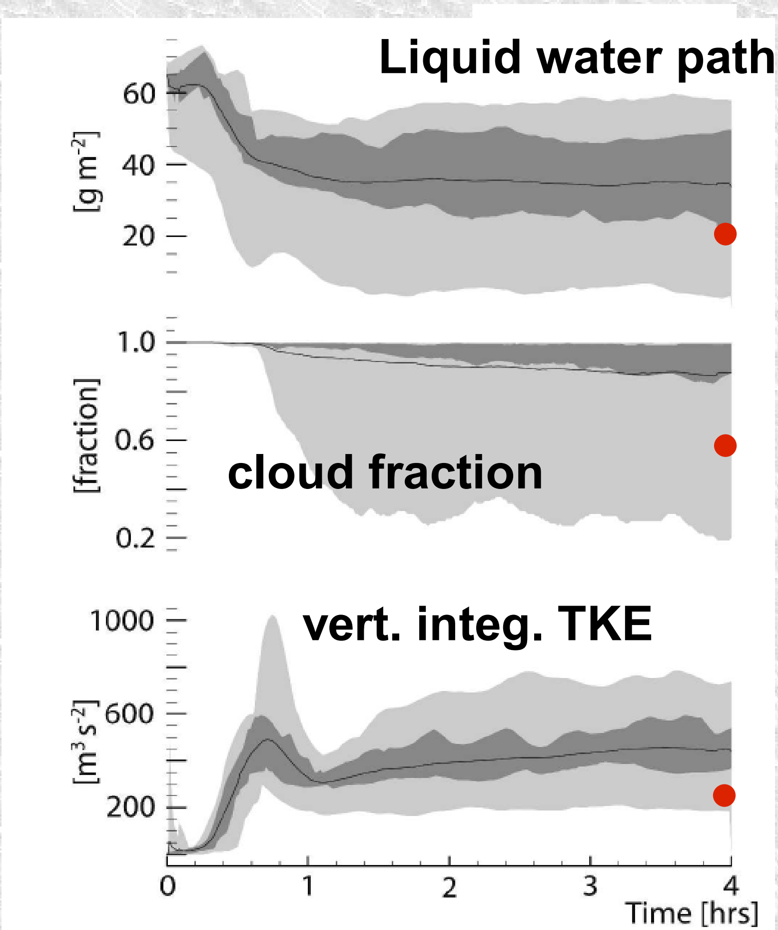
DHARMA (**A**, A.Ackerman, M. Kirkpatrick, D. Stevens)
IMAU (**B,** Institute for Marine and Atmospheric Research, S. de Roode)
MPI (**B,** A. Chlond, F. Muller)
NCAR (**B,** C.-H. Moeng)
COAMPS (**C**, J.-C. Golaz)
RAMS (**C**, Colorado; H.-L. Jiang)
UCLA (**A,** B. Stevens, J. Edwards)
SAM (**A,** Colorado State Univ., M. Khairoutdinov, C. Bretherton, P. Zhu, Randall)
METO (**B,** Met Office, E. Whelan, A. Lock)
WVU (**B,** D. Levellen)

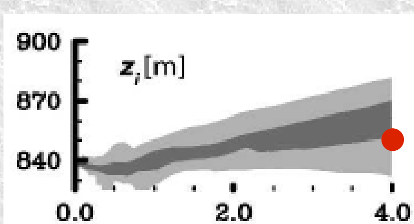
B - Boussinesq
A - Anelastic
C - Compressible

+ **EULAG** (Smolarkiewicz, Grabowski, Margolin...)

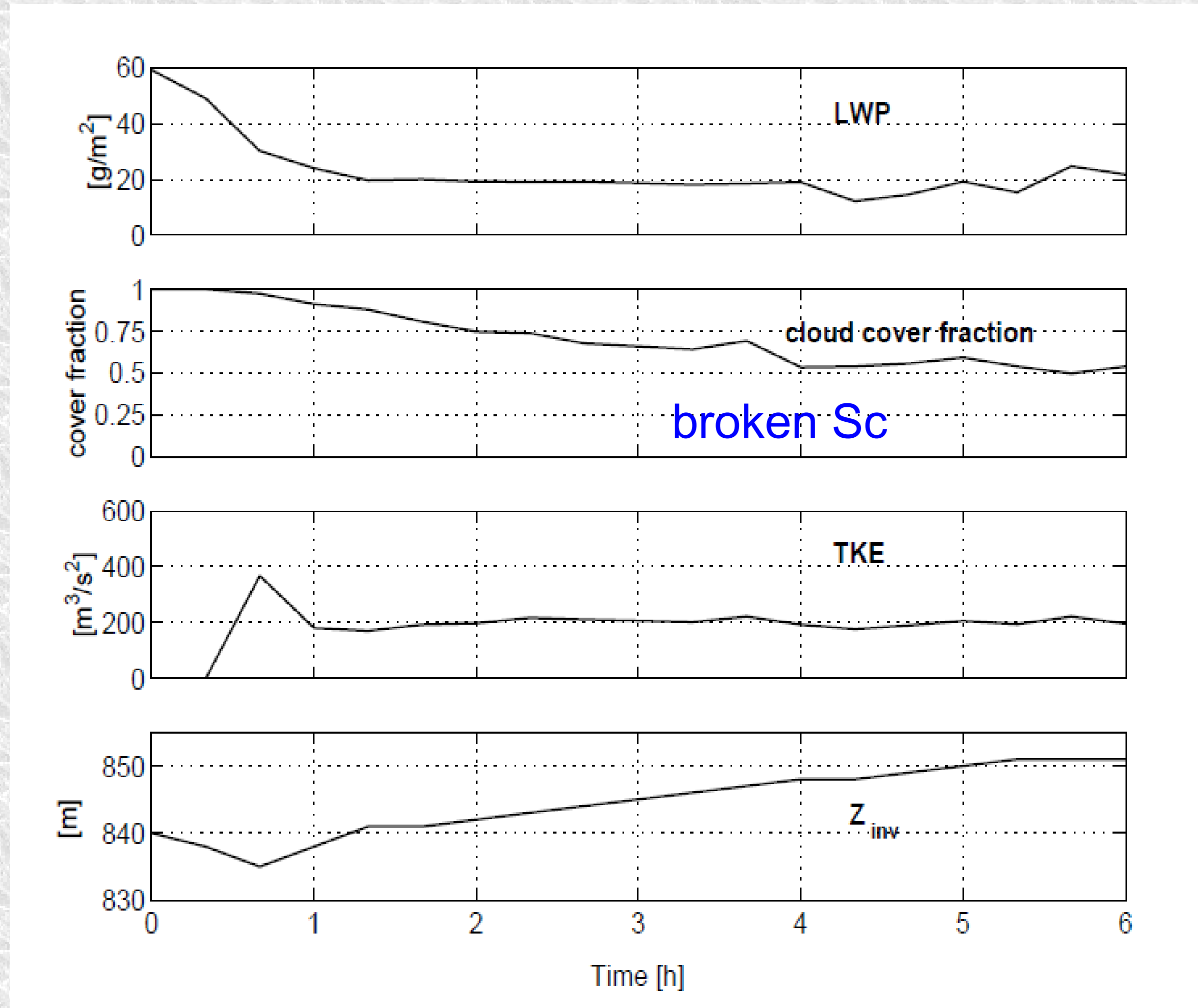
How well do the models reconstruct STBL?

ensemble:

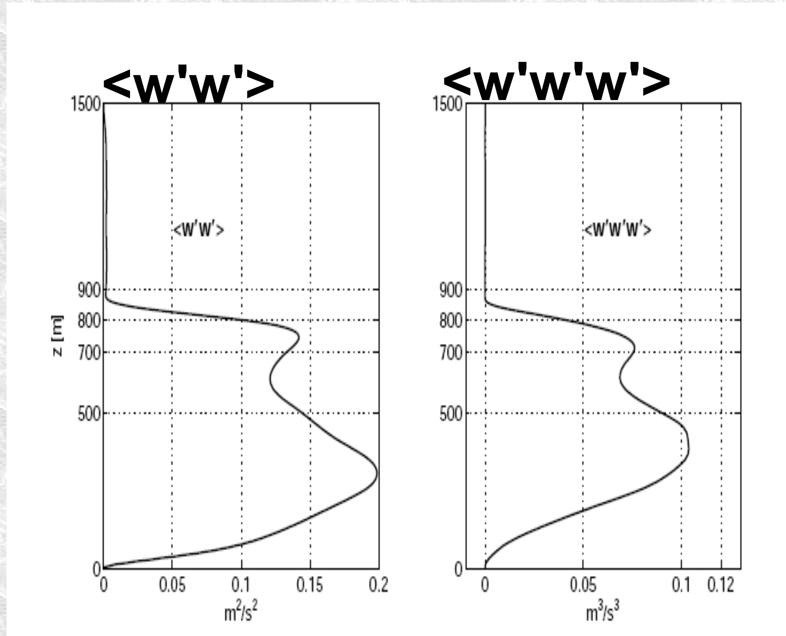




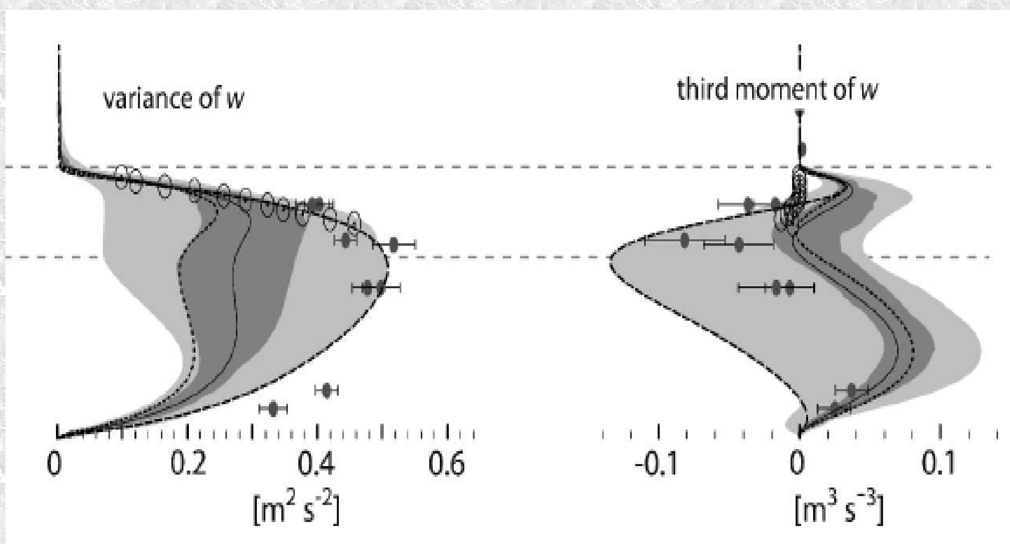
EULAG



Decoupling within STBL



EULAG



ENSEMBLE

Cloud Top Entrainment Instability

$$\kappa = \frac{c_p \Delta \Theta_e}{L \Delta q_t} > \kappa_c, \kappa_c = 0.23$$

Deardorff, 1980
Randall, 1980

Evaporative cooling vs warming by entrainment

In DYCOMS-II *κ=0.4-0.6* (instability),
but the cloud did not decay

Where is the interface of STBL?

various definitions (local and mean)

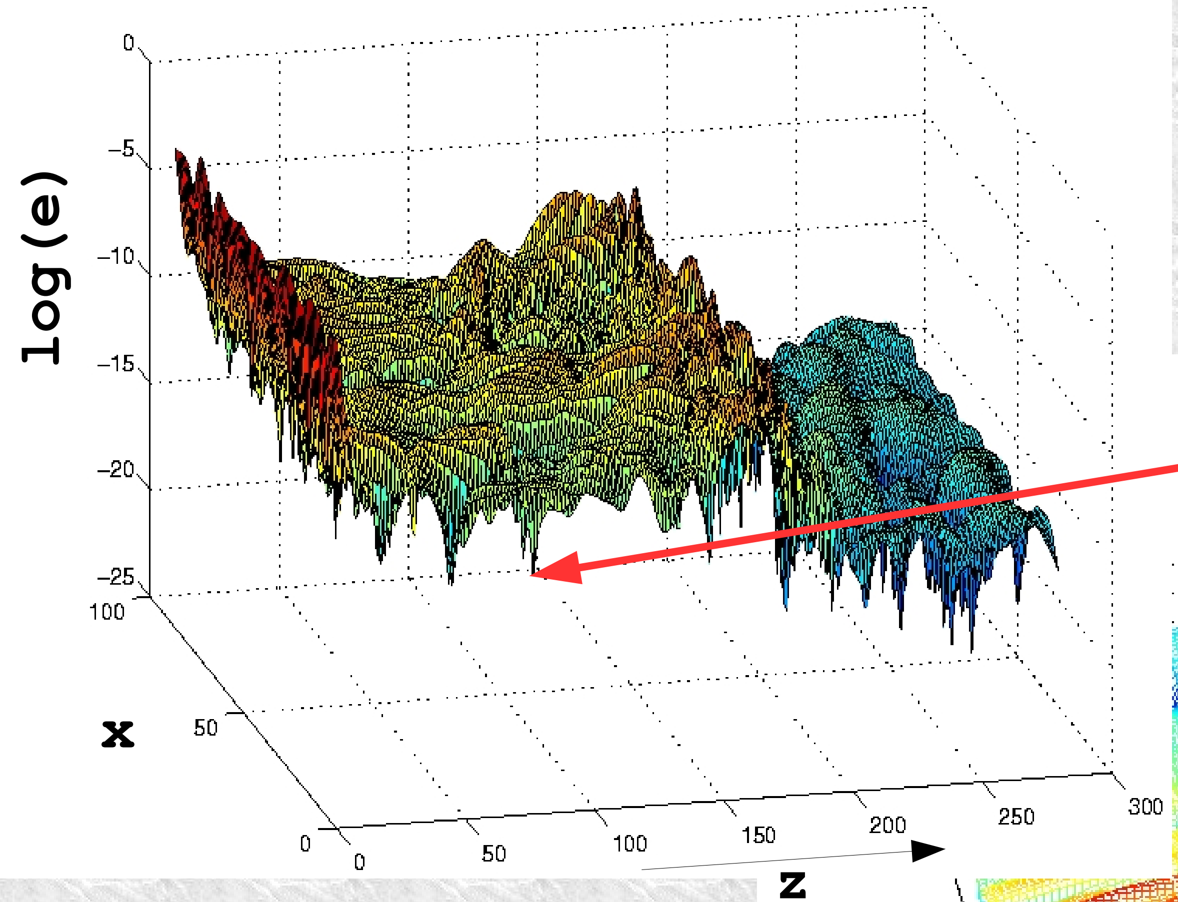
material - (visible top of cloud – Moeng, 2005)
or threshold of some conservative scalar –
total water mixing ratio, q_t

thermodynamic – level of maximum static stability
(maximal gradient of virtual potential temperature θ_v)

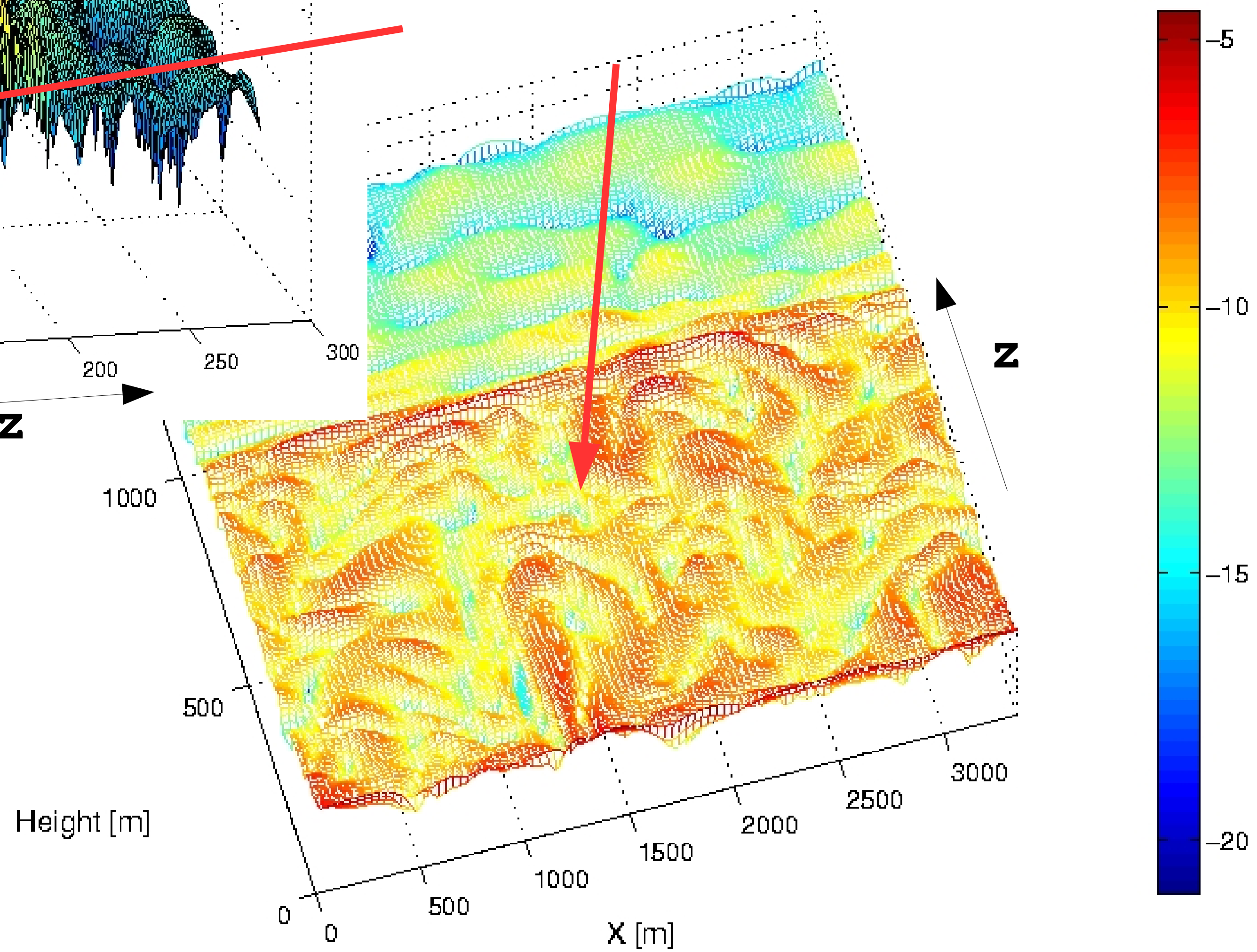
dynamic – threshold of enstrophy (ω^2)

$$\frac{D\omega_i}{Dt} = \omega_j \frac{\partial V_i}{\partial x_j} - \omega_i \frac{\partial V_j}{\partial x_j} + e_{ijk} \frac{1}{\rho^2} \frac{\partial \rho}{\partial x_j} \frac{\partial p}{\partial x_k} + e_{ijk} \frac{\partial}{\partial x_j} \left(\frac{1}{\rho} \frac{\partial \tau_{km}}{\partial x_m} \right) + e_{ijk} \frac{\partial B_k}{\partial x_j}$$

Finite thickness of Entrainment Interface Layer (EIL),
(i.e. Randall 1980, Caugey et al. 1982)



Small local values also within boundary layer



$$e=(rot\ \bar{U})^2$$

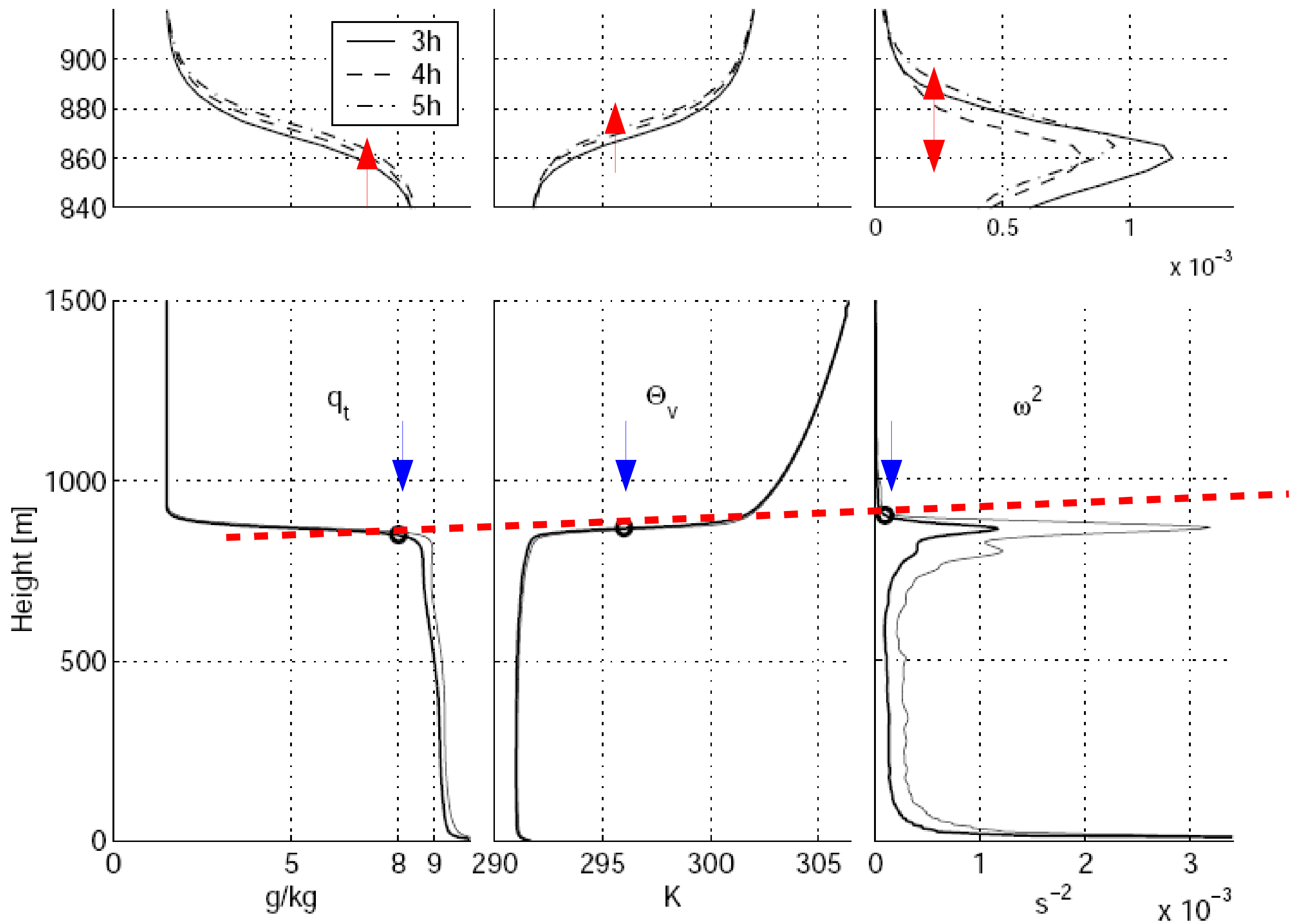
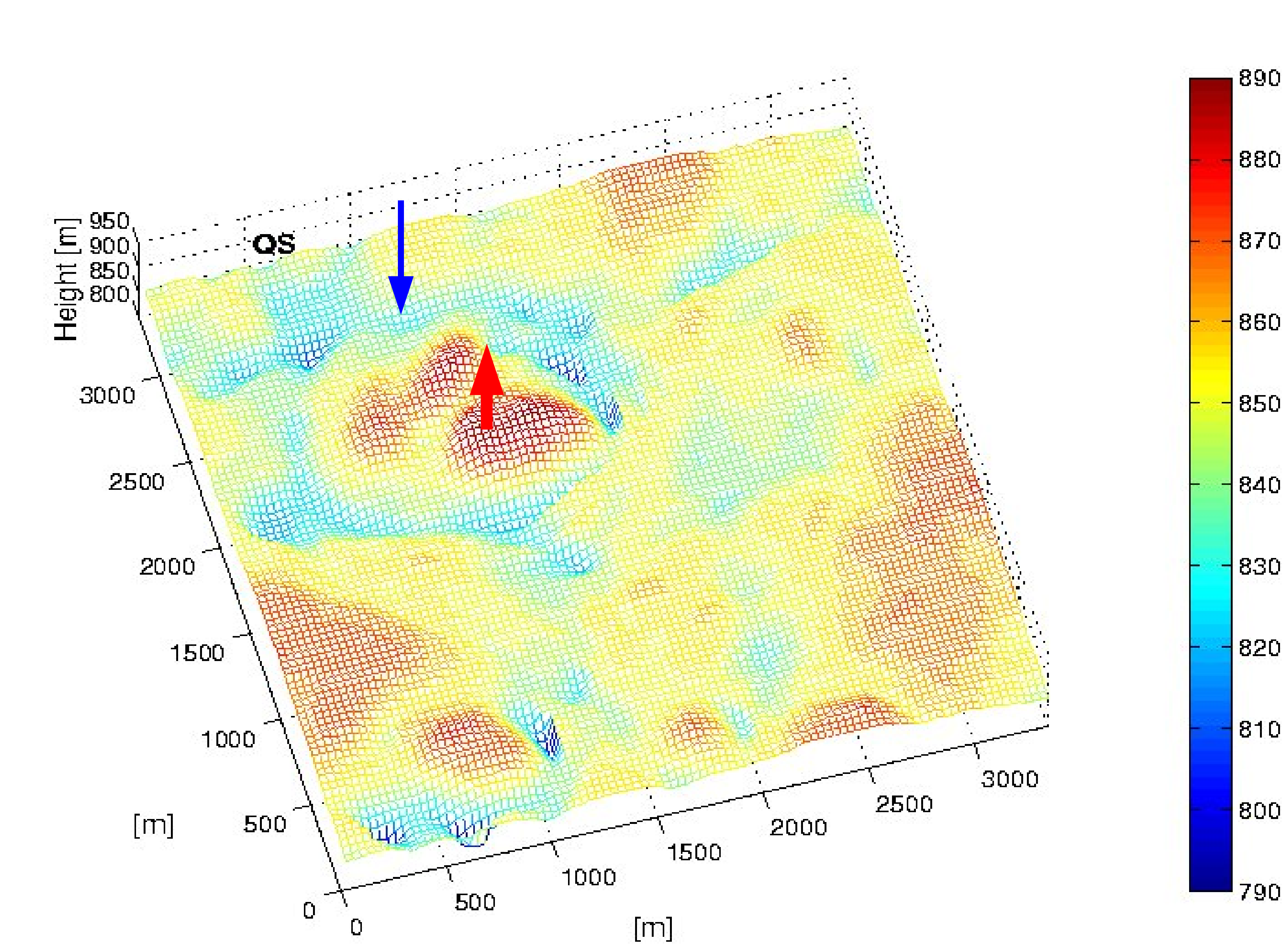
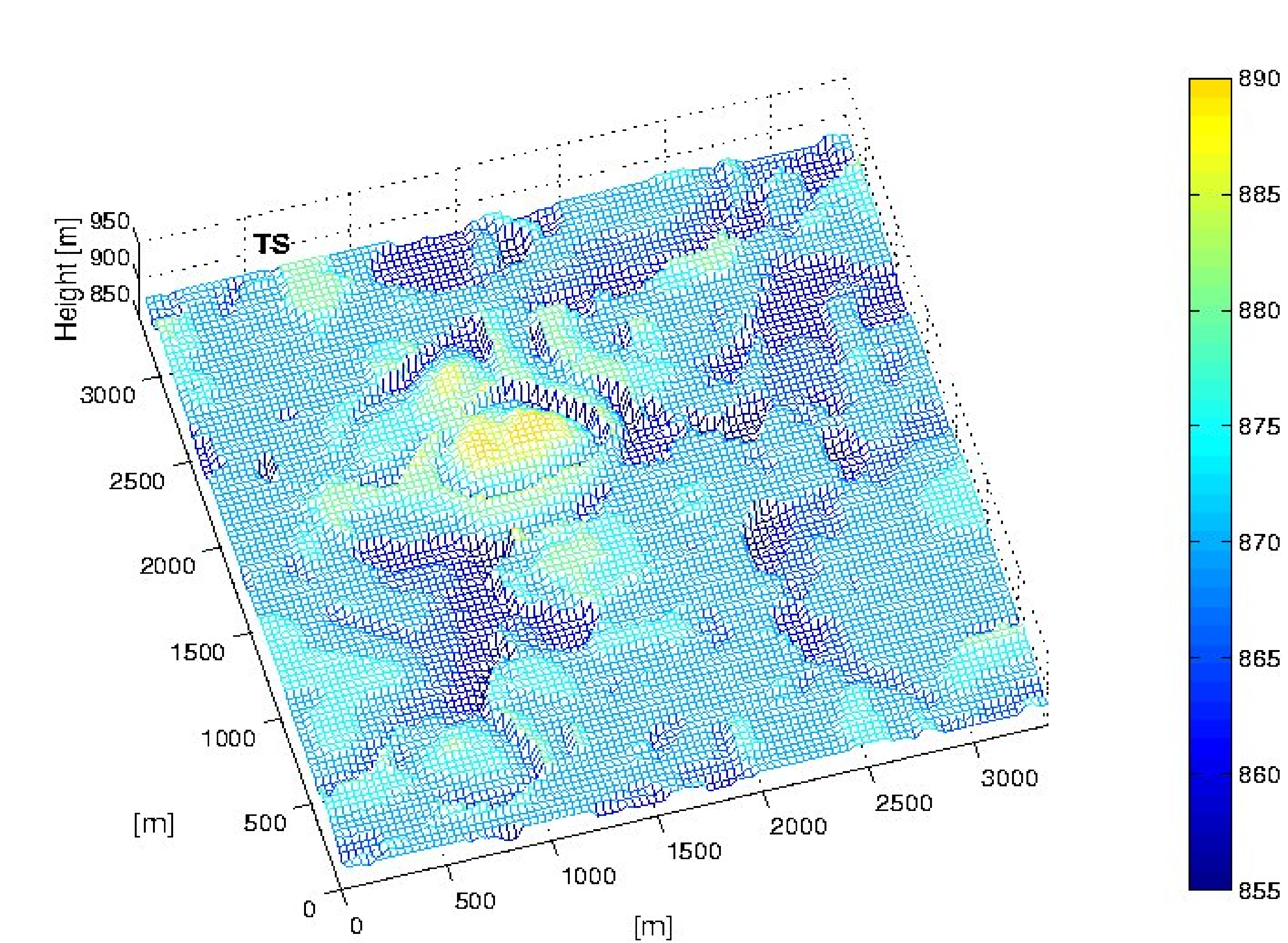


Figure 3: Mean profiles of the total water mixing ratio, virtual potential temperature, and enstrophy at $t = 3$ hr (lower panels, thick lines). Thin lines are sums of profiles and their standard deviations. Circles mark the mean height of QS, TS, and ES. Upper panels show enlarged details of the profiles around the STBL top at $t = 3$, 4 and 5 hours.

QS – 'material' surface



TS – thermodynamic surface



LES

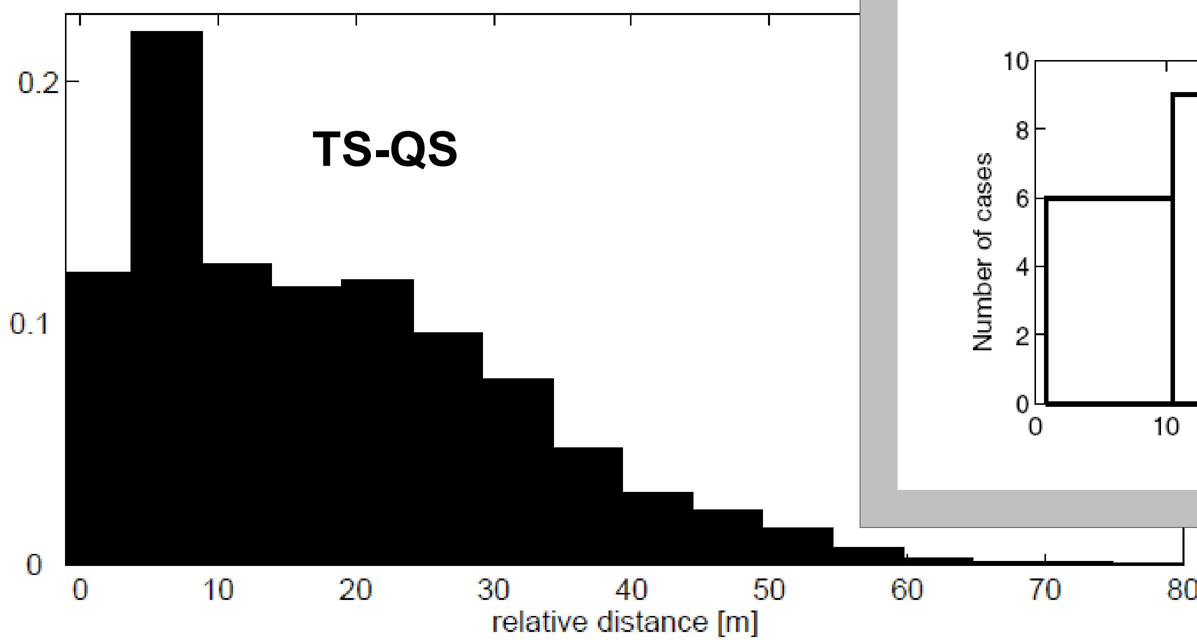
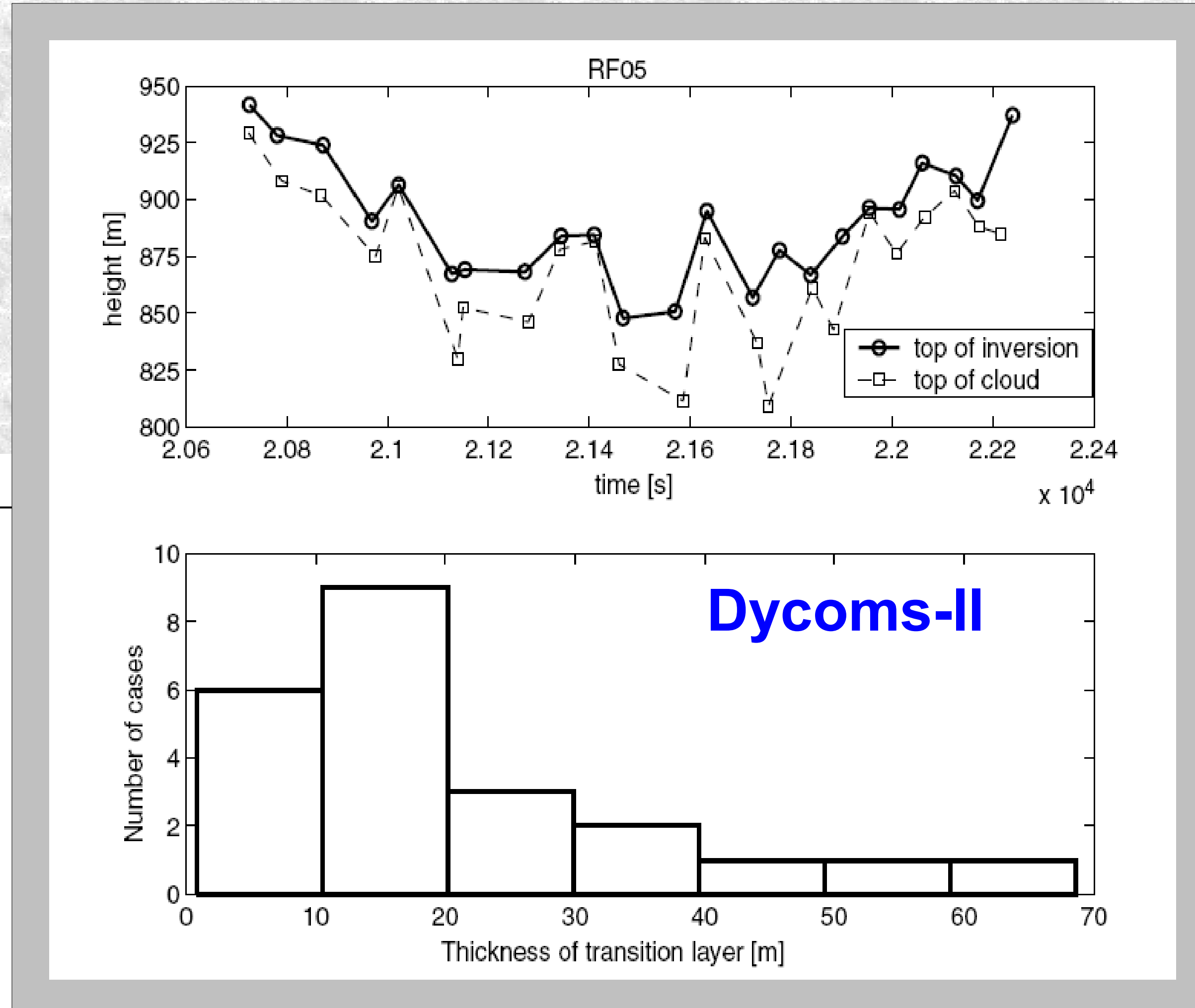


Figure 6: Histogram of the distance between TS and QS at $t = 3$ hr.



Haman et al.
2007, QJRMS

$$C_r = \frac{\sum_{i,j} (h_1(i,j) - \bar{h}_1)(h_2(i,j) - \bar{h}_2)}{\sqrt{\sum_{i,j} (h_1(i,j) - \bar{h}_1)^2 \sum_{i,j} (h_2(i,j) - \bar{h}_2)^2}}$$

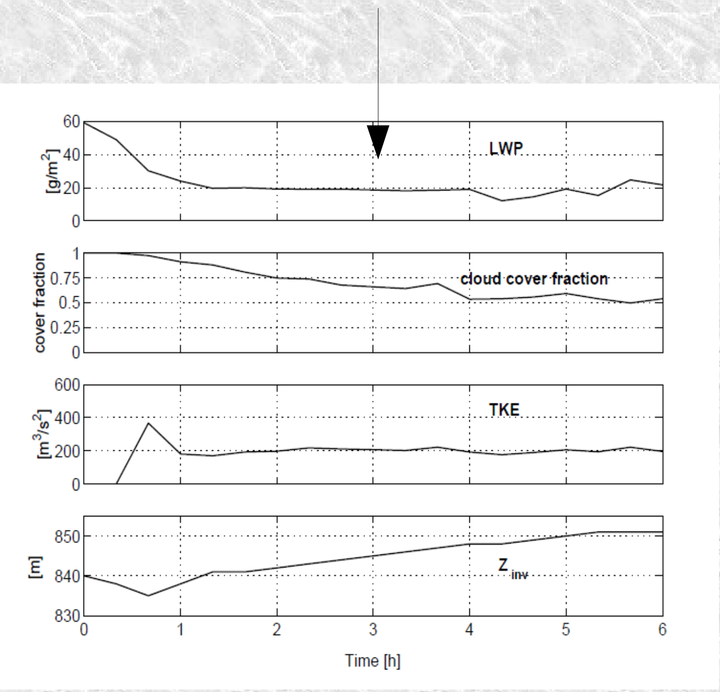
C_r(TS,QS)=0.04

time [hr]	mean [m]	standard deviation [m]	skewness [1]	min [m]	max [m]	increase of surface area [%]
			QS			
3	847.8	12.7	-1.3	750	880	1.1
4	852.7	12.1	-0.7	785	885	1.0
5	854.9	13.4	-0.7	775	890	1.1
6	856.0	13.9	-1.1	760	890	1.5
			TS			
3	866.1	5.3	-0.2	850	880	1.0
4	873.5	5.8	-0.3	855	895	1.2
5	875.6	5.6	-0.5	845	895	1.2
6	879.1	5.8	-0.4	755	900	1.4
			ES			
3	899.4	-	-	-	-	-
4	901.5	-	-	-	-	-
5	904.9	-	-	-	-	-
6	919.3	-	-	-	-	-

Passive scalar analysis of entrainment

Idea: mark the air originating from a free-atmosphere (*dry and warm*) with a tracer and observe its distribution within BL after some time

=> injection of passive scalar into free troposphere (above TS=1, below=0) after 3h of spin-up of model



passive scalar is advected, diffused and affected by large-scale subsidence

NO SINKS AND SOURCES

Mean profiles of passive scalar

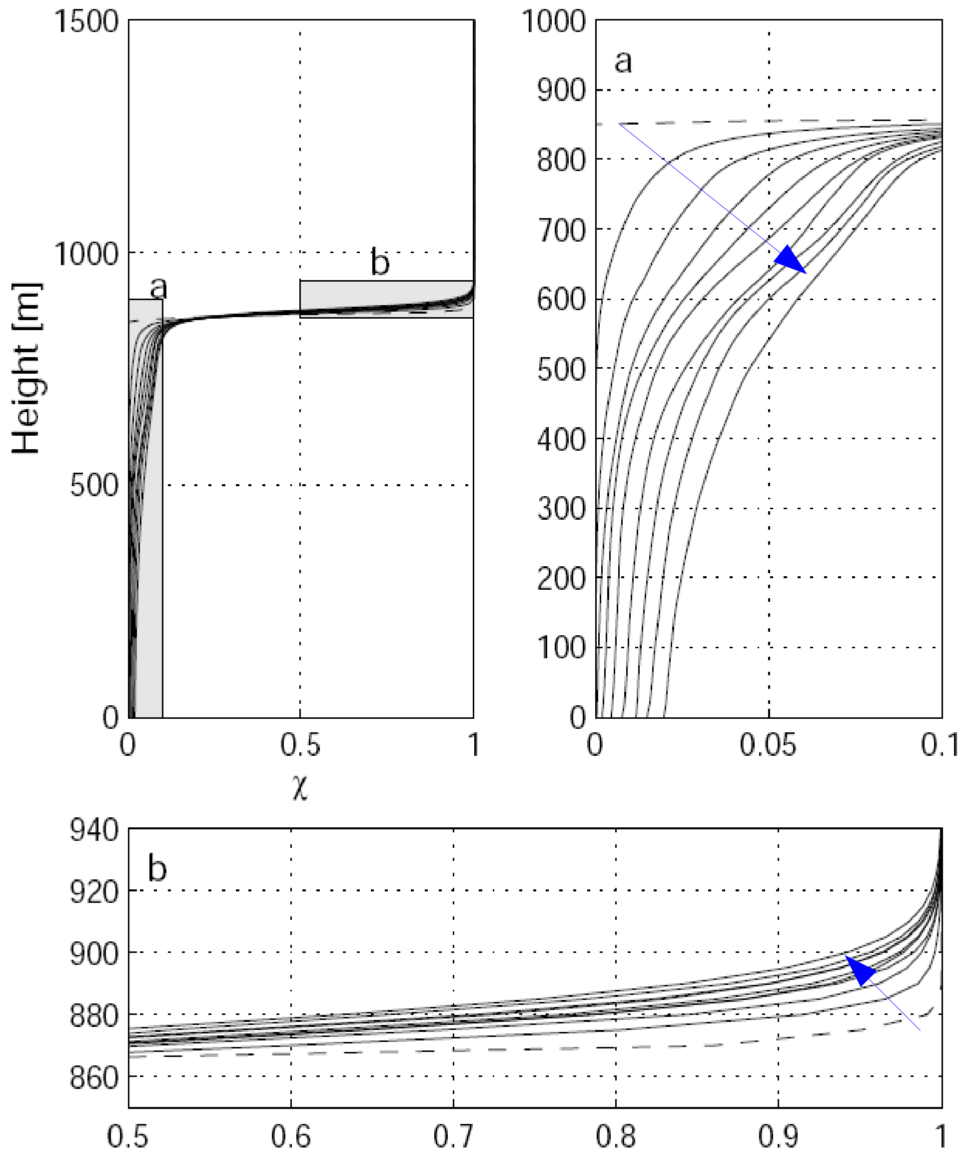
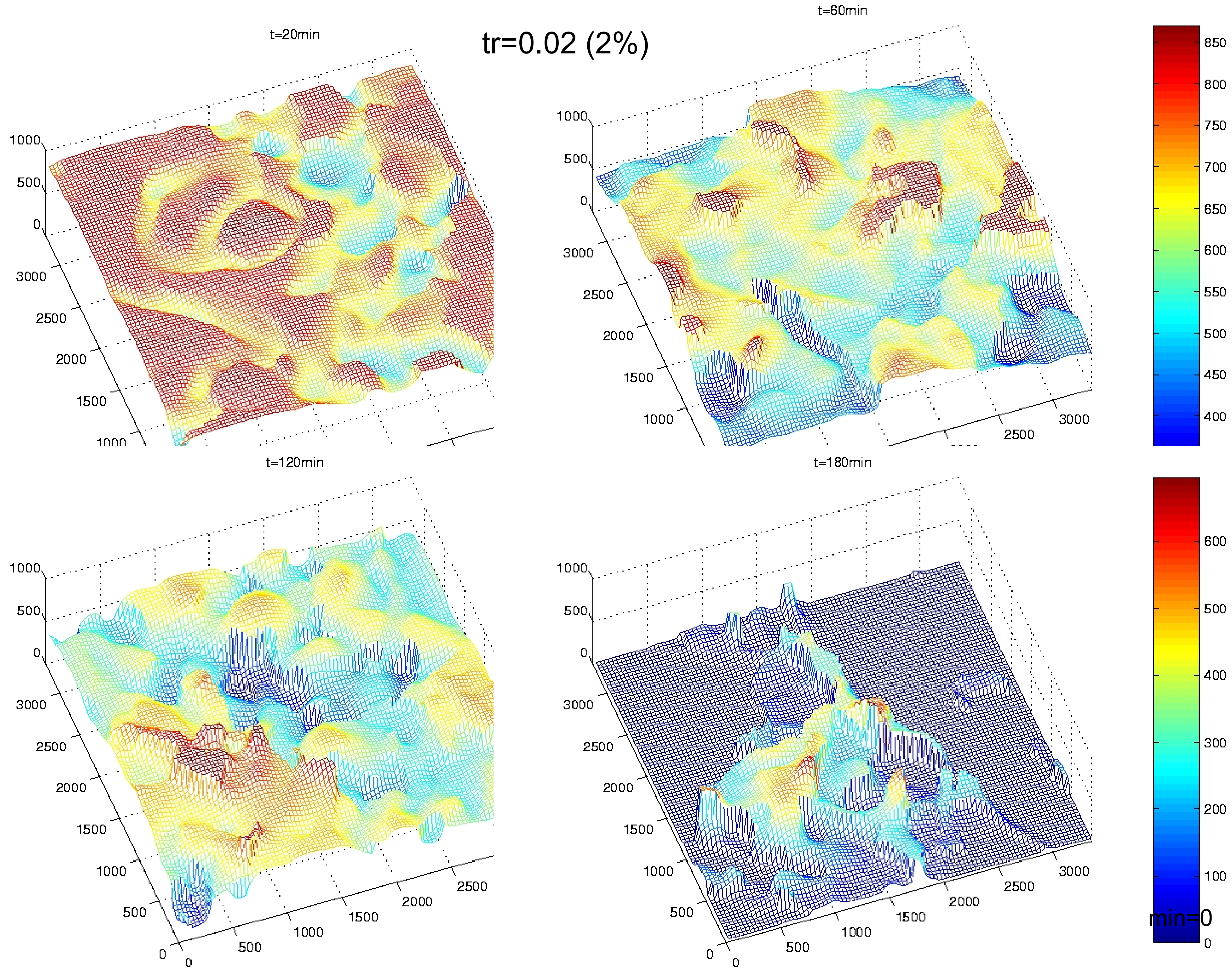
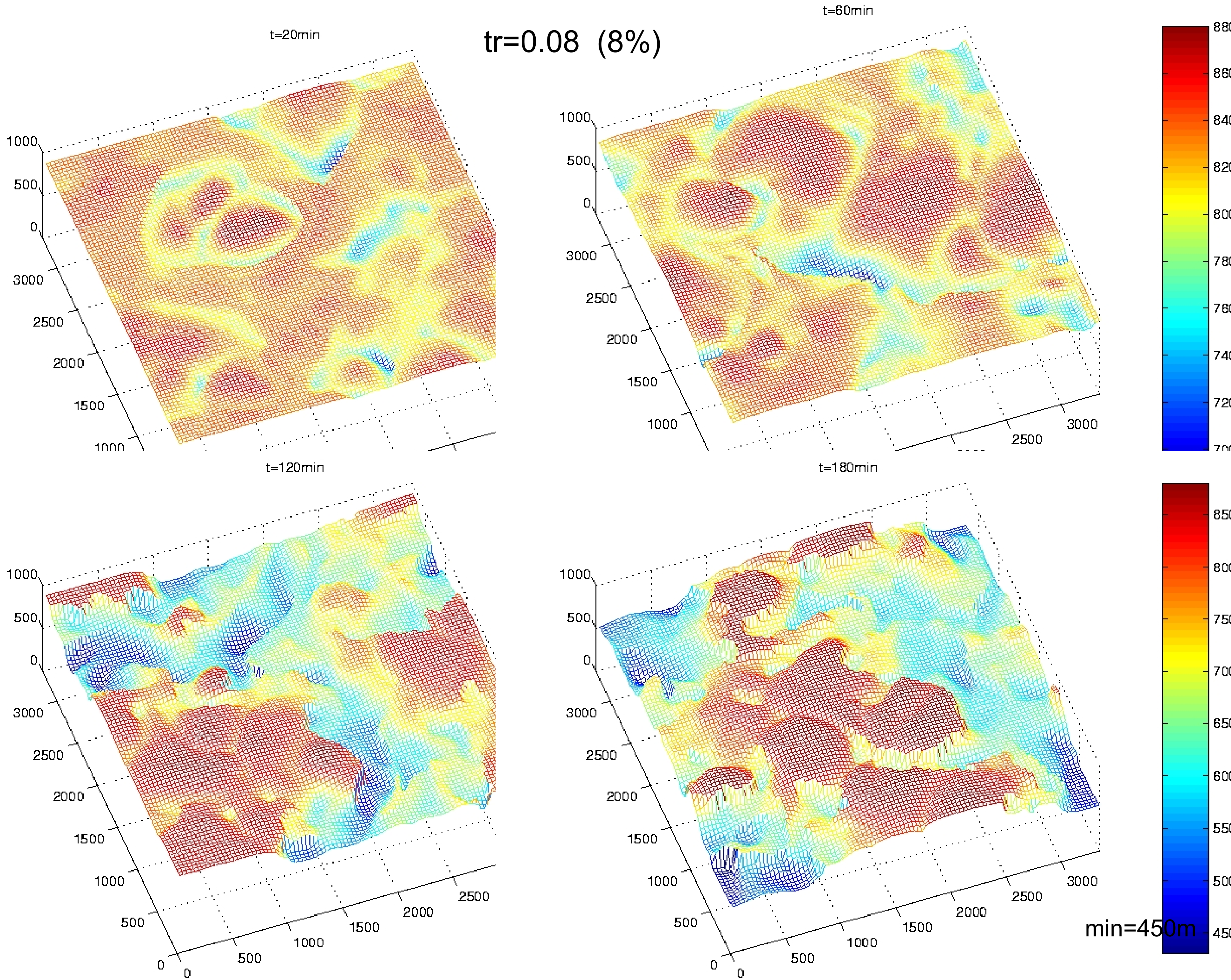
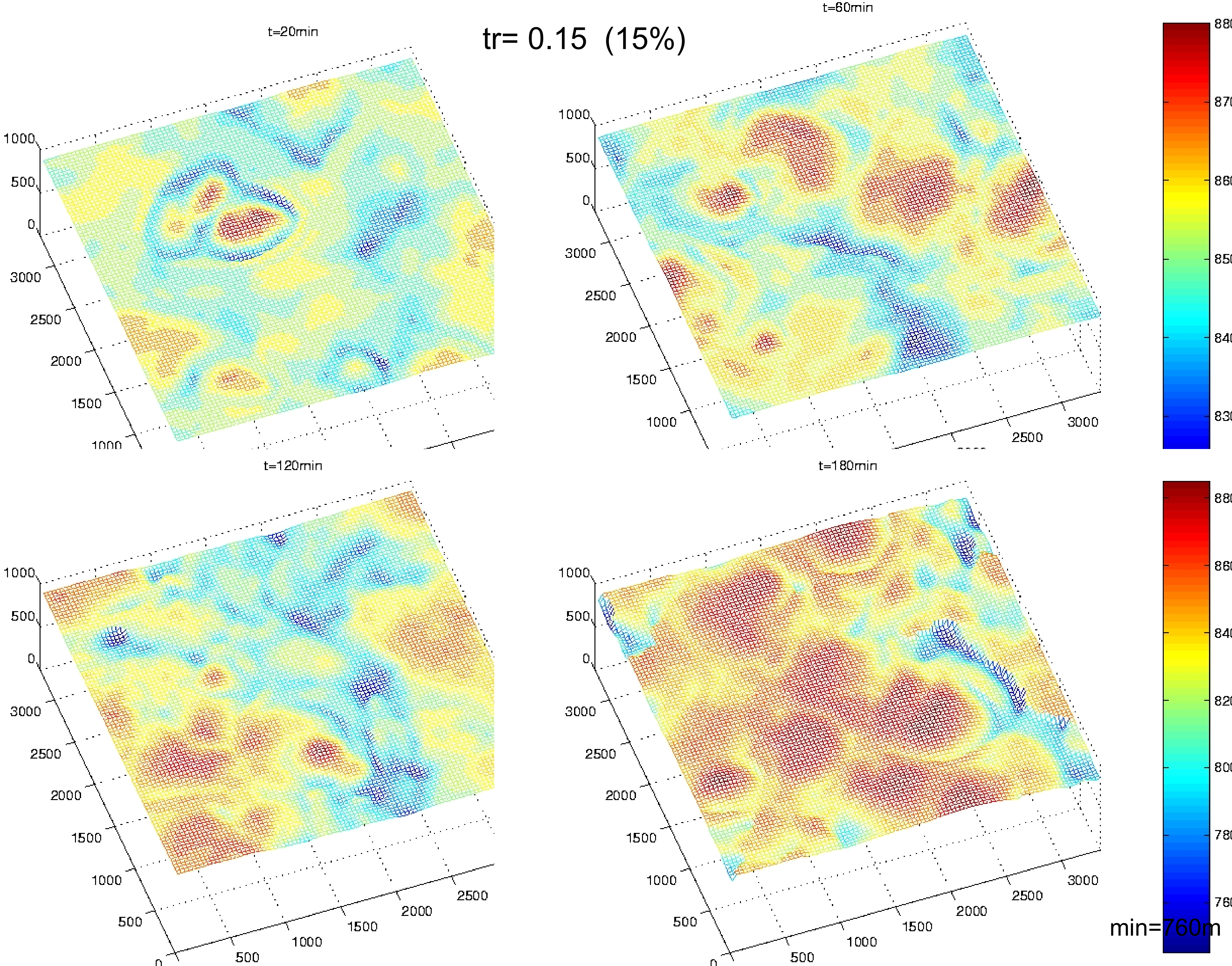


Figure 8: Evolution of the mean χ profiles. The profiles are plotted every 20 minutes. Panels (a) and (b) show details of the profiles.


tr=0.02 (2%)
t=20min
t=60min
t=120min
t=180min
min=0


tr=0.08 (8%)
t=20min
t=60min
t=120min
t=180min
min=450m



tr= 0.15 (15%)
t=20min
t=60min
t=120min
t=180min
1000
500
0
3000
2500
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
880
870
860
850
840
830
880
860
840
820
800
780
760
min=760m

Table 2: Statistics of concentration isosurfaces for different concentration thresholds of the tracer (0.01, 0.05, 0.1, 0.5, and 0.9) at various times of the simulation with 20-min intervals. The first column shows time and the subsequent columns provide the mean height, its standard deviation and skewness, the extreme values, the increase of the surface area due to vertical undulations, and the descent rate of the mean height.

time [min]	mean [m]	standard deviation [m]	skewness [1]	min [m]	max [m]	increase of surface area [%]	descent rate [m/min]
			χ=0.01				
20	743.8	81.5	-0.6	425	870	23.3	7
60	503.3	126.4	-0.1	120	865	40.2	12
100	364.3	180.1	-0.1	0	865	73.3	7
140	25.4	89.6	4.3	0	670	20.1	17
			χ=0.05				
20	833.5	25.6	-1.9	670	875	5.2	1.6
100	688.9	81.4	0.4	380	880	24.2	1.8
180	539.1	155.4	0.3	165	880	50.9	1.8
			χ=0.1				
20	852.4	9.6	-1.0	800	880	1.0	0.37
100	826.7	31.1	-1.2	670	885	5.6	0.31
180	784.7	68.0	-0.6	565	885	13.1	0.53
			χ=0.5				
20	870.3	3.7	1.0	860	890	0.2	-0.07
100	873.4	3.3	0.7	865	895	0.2	-0.03
180	877.4	3.1	0.8	870	895	0.2	-0.05
			χ=0.9				
20	880.9	5.1	1.2	870	905	0.3	-0.24
100	890.3	5.4	0.3	875	910	0.3	-0.12
180	896.9	5.2	0.0	880	915	0.3	-0.09

$$Ri = \frac{g/T_{density}\, \Delta_z \Theta_v\, dz}{(\Delta_z u)^2 + (\Delta_z v)^2 + (\Delta_z w)^2}$$

Ri – (in)stability of the flow

ω^2 – enhanced mixing

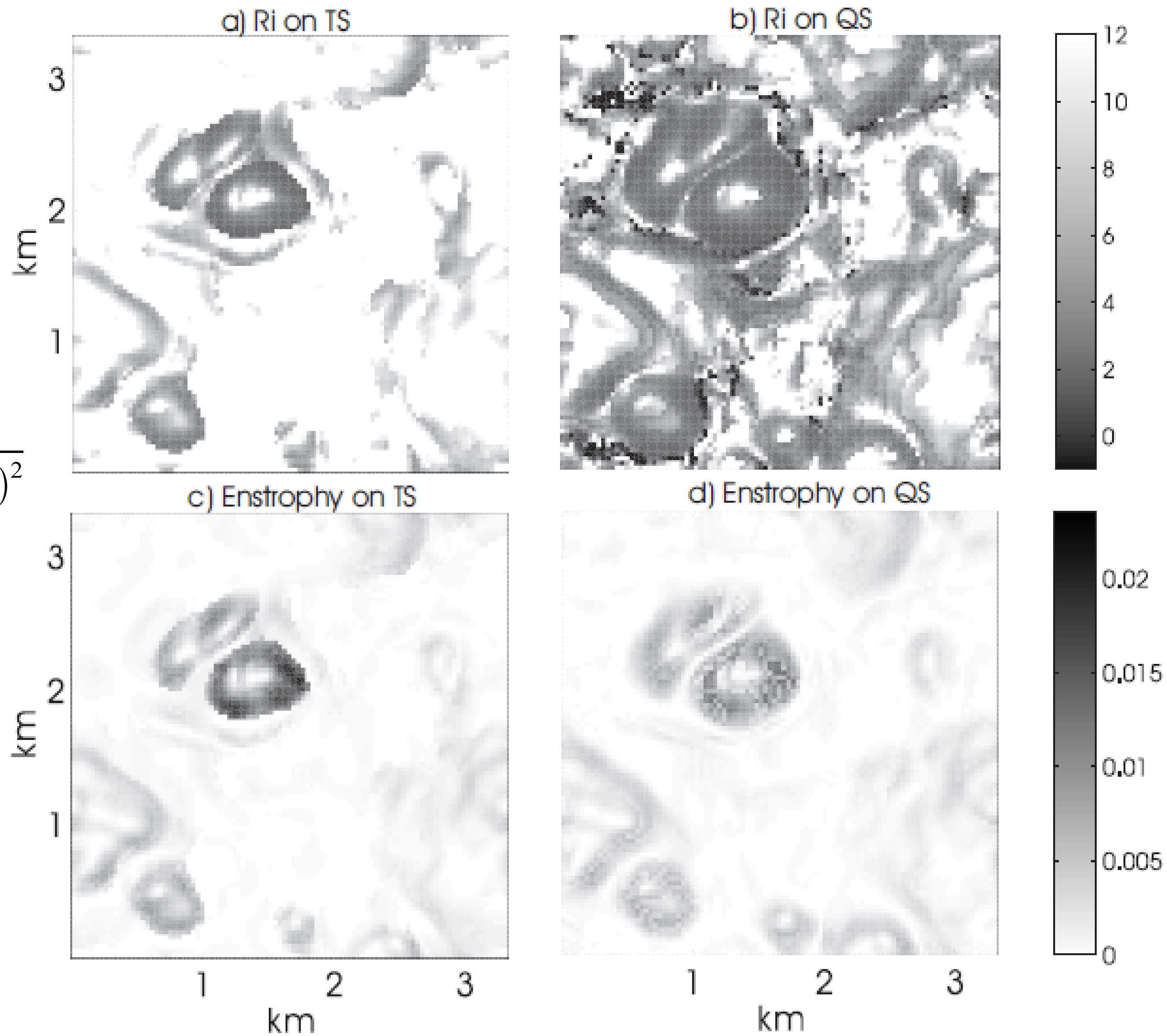
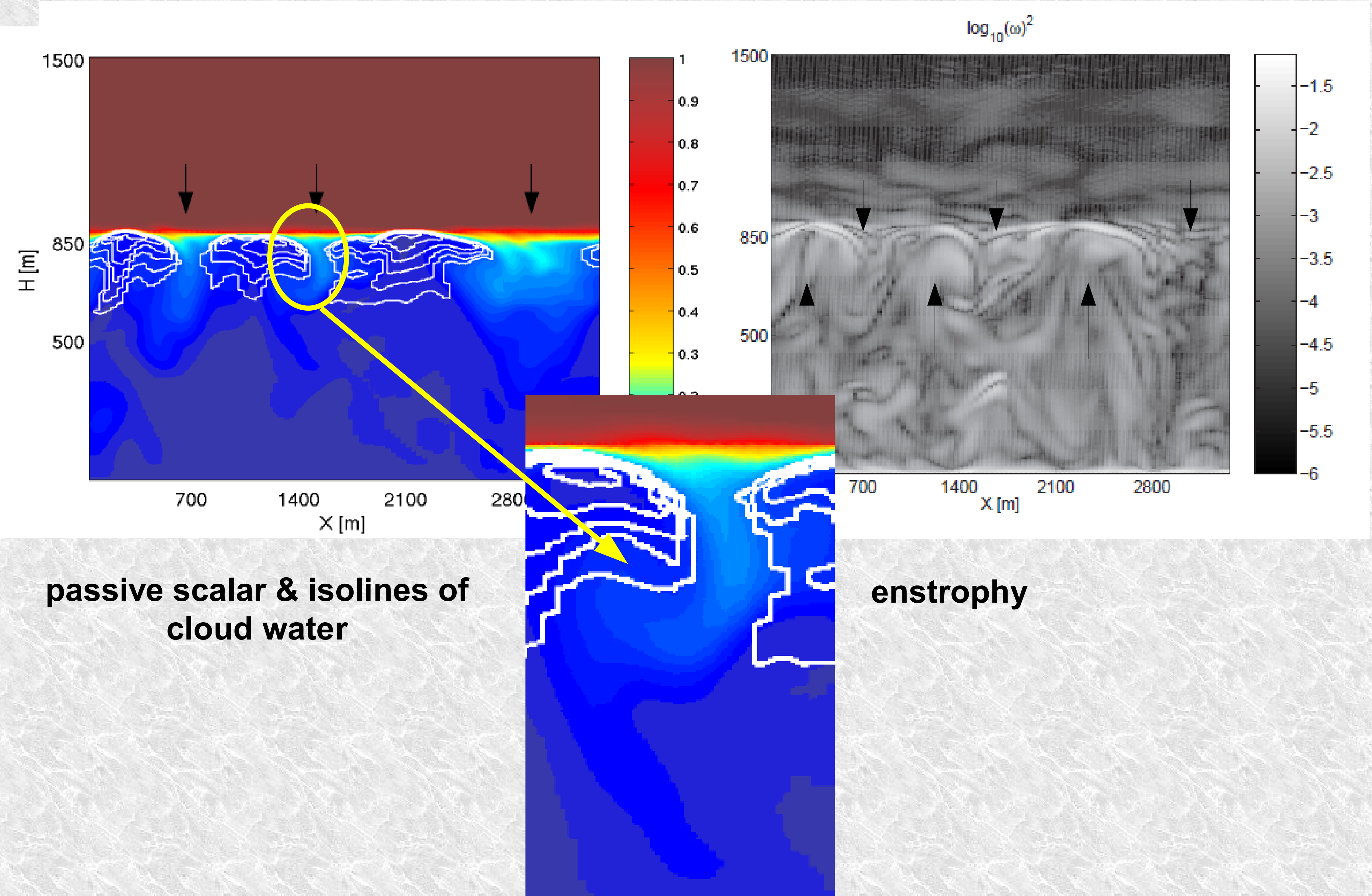


Figure 7: The gradient Richardson number Ri on the TS (a) and QS (b), as well as the enstrophy on TS (c) and QS (d) at $t = 3$ hr. Note that the darkest shading in (a) and (b) corresponds to values of Ri suggesting instability.

2D crosssection of domain, 3h after injection of passive scalar into the free troposphere



passive scalar & isolines of cloud water

enstrophy

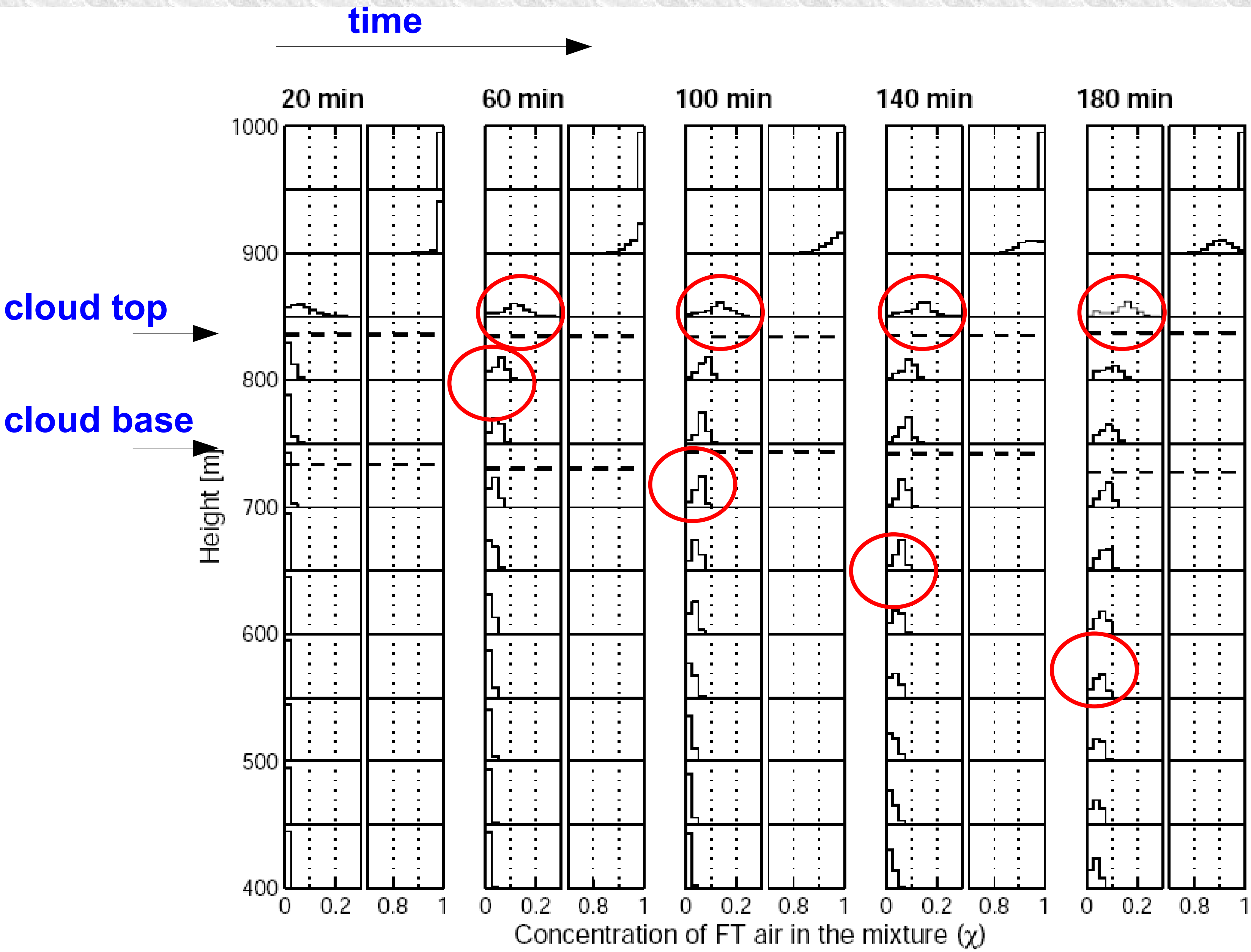
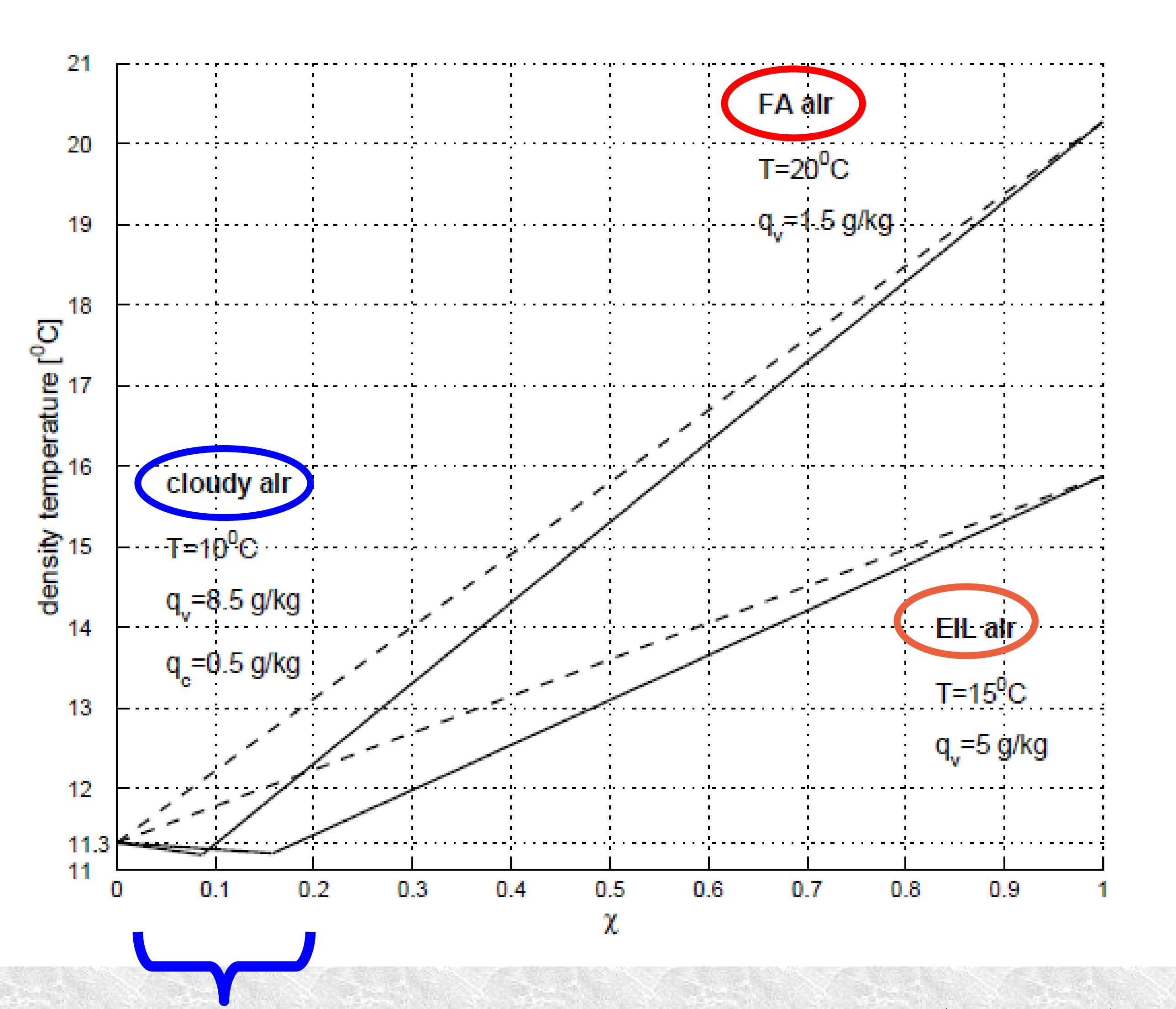


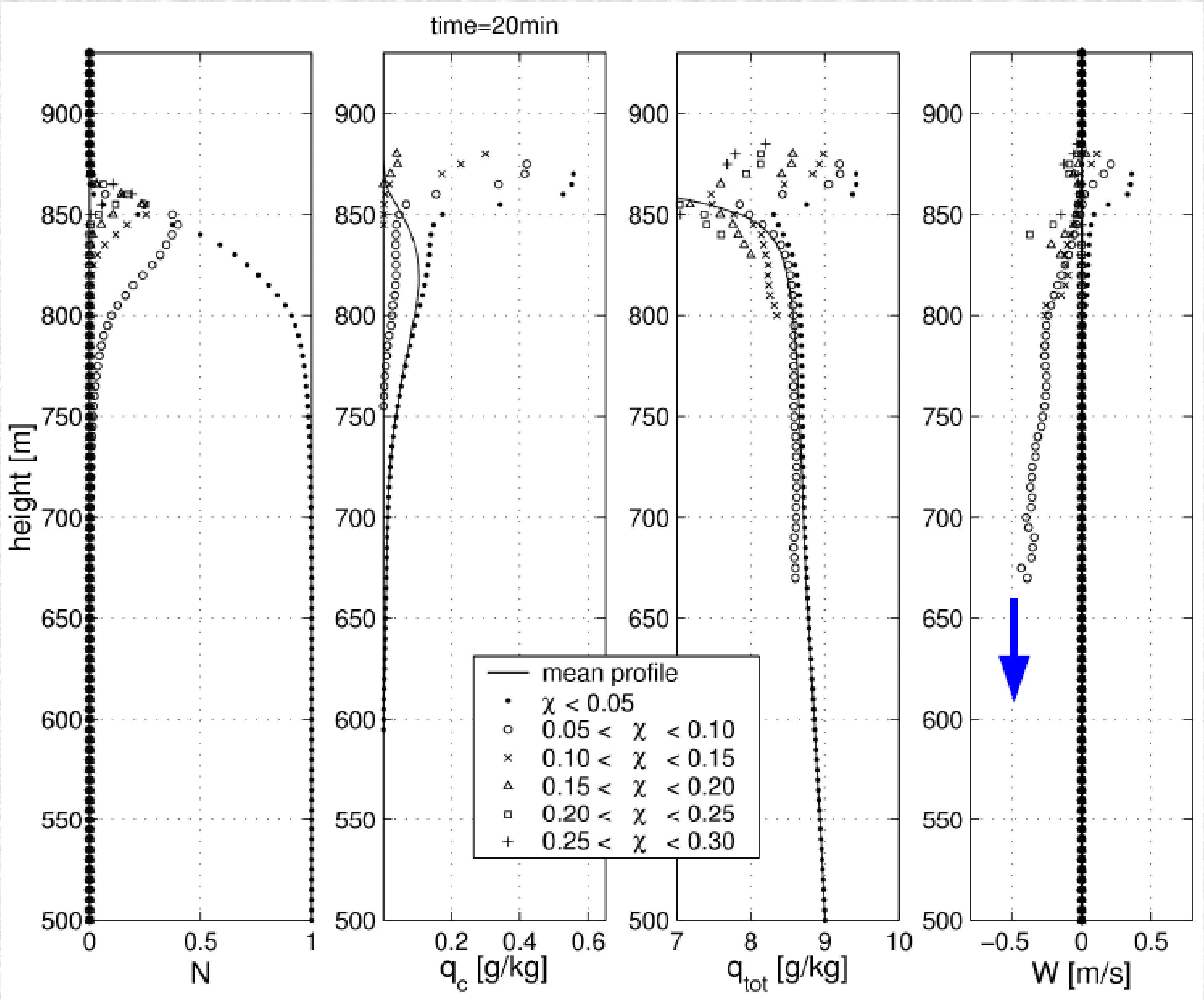
Figure 10: Histograms of χ at altitudes between 400 and 1000 m plotted every 50 m. Middle part of each histogram (between 0.3 and 0.7) is not shown. The two horizontal dashed lines mark the mean cloud base and the mean cloud top.

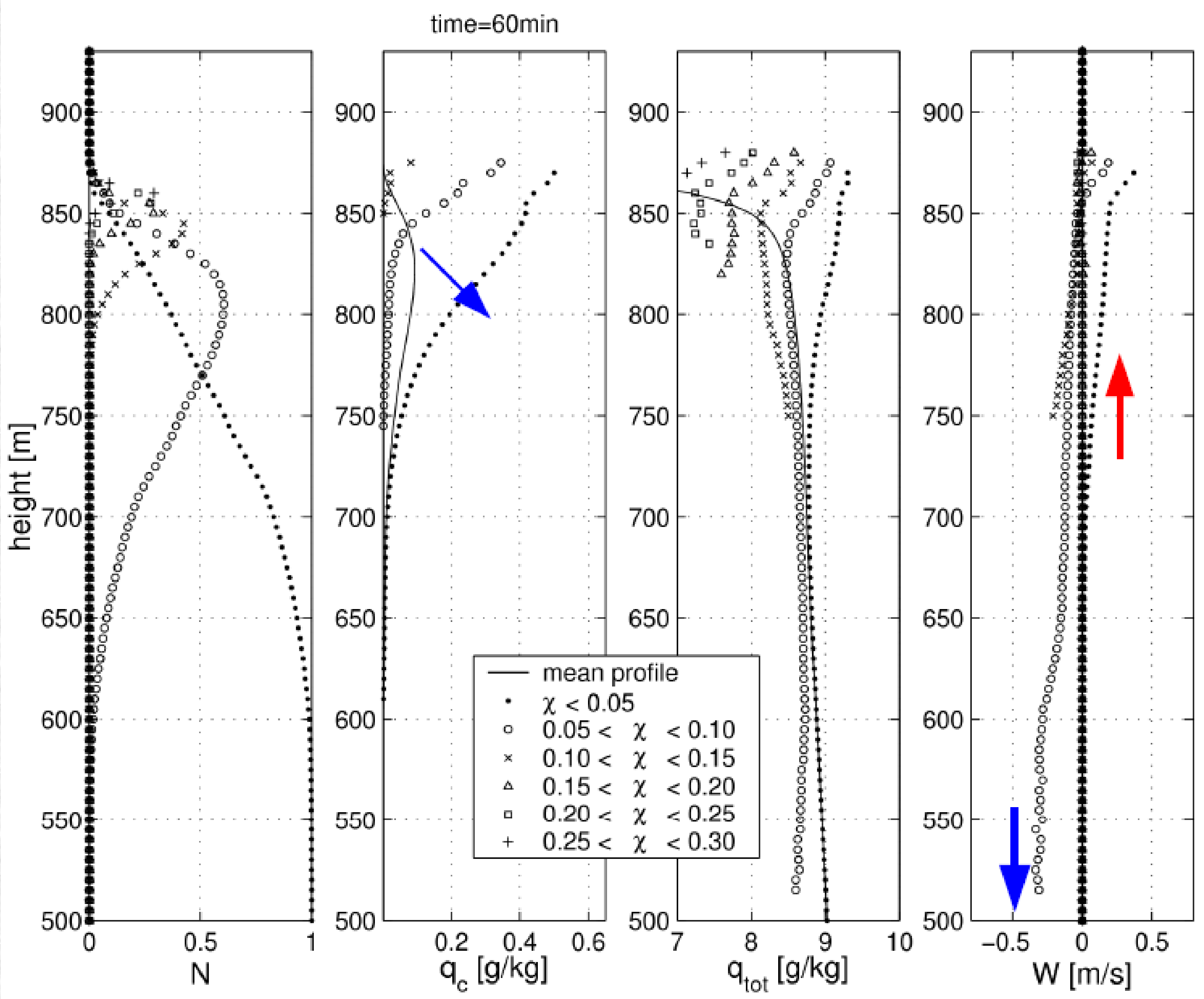


weak negative buoyancy production
for 0< χ < 0.18

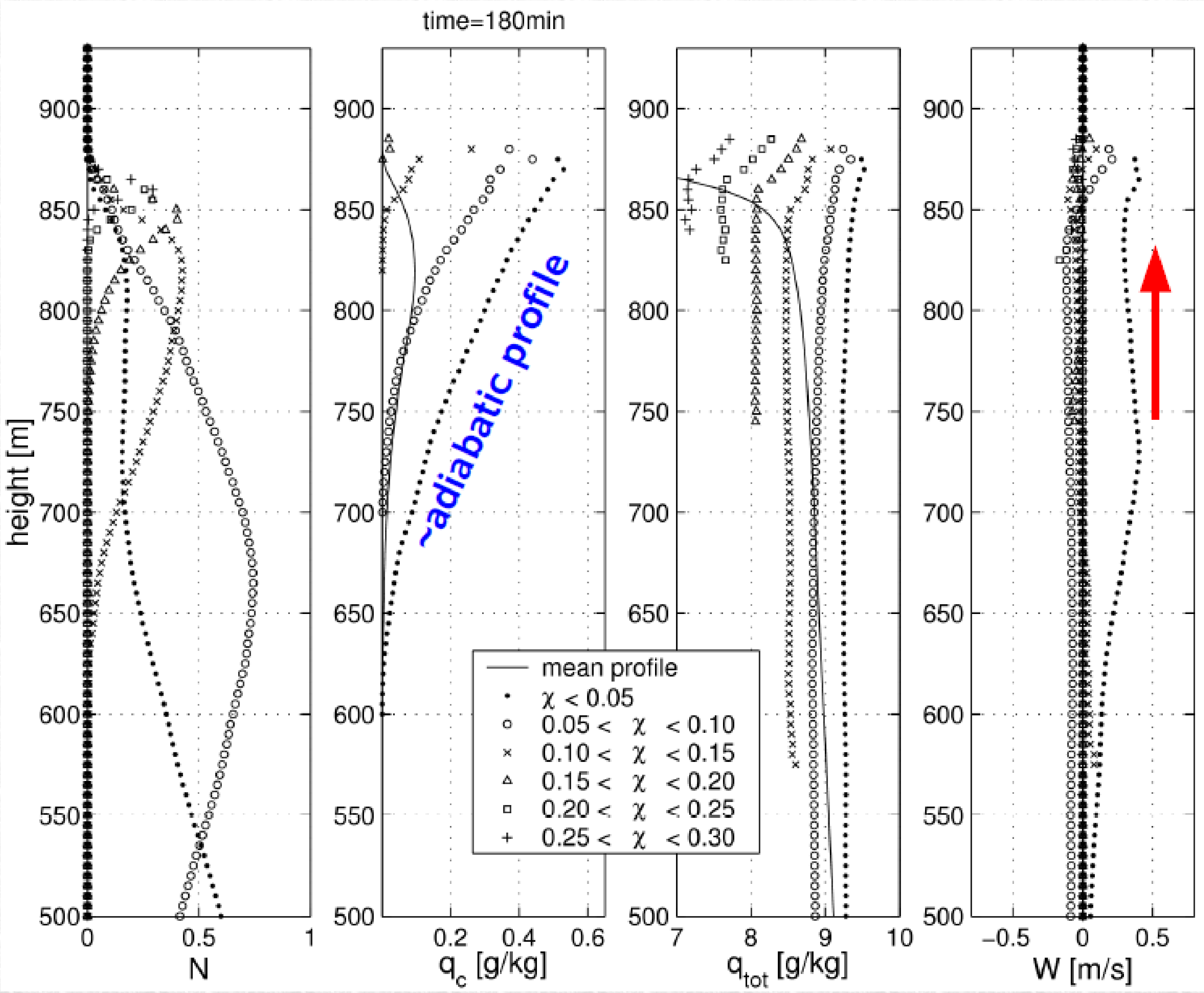
$$T_{density} = T \frac{(1 + r_v/\epsilon)}{(1 + r_l + r_v + r_r)}$$

Conditional profiles





time=60min
height [m]
N
q_c [g/kg]
q_tot [g/kg]
W [m/s]
mean profile
χ < 0.05
0.05 < χ < 0.10
0.10 < χ < 0.15
0.15 < χ < 0.20
0.20 < χ < 0.25
0.25 < χ < 0.30



time=180min
height [m]
N
q_c [g/kg]
q_{tot} [g/kg]
W [m/s]
~adiabatic profile
mean profile
χ < 0.05
0.05 < χ < 0.10
0.10 < χ < 0.15
0.15 < χ < 0.20
0.20 < χ < 0.25
0.25 < χ < 0.30

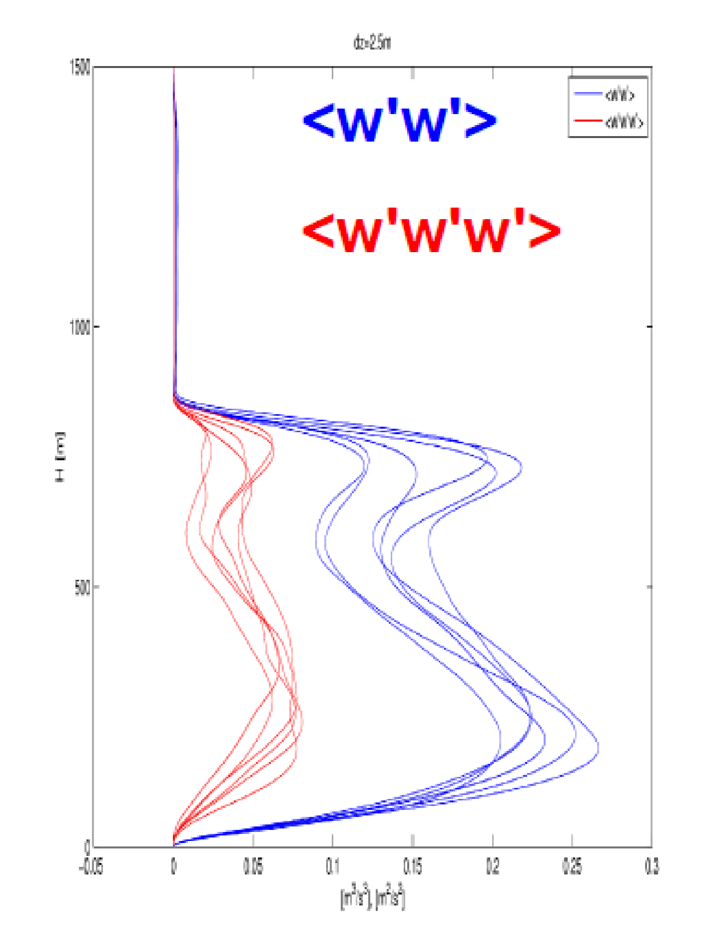
Sensitivity study

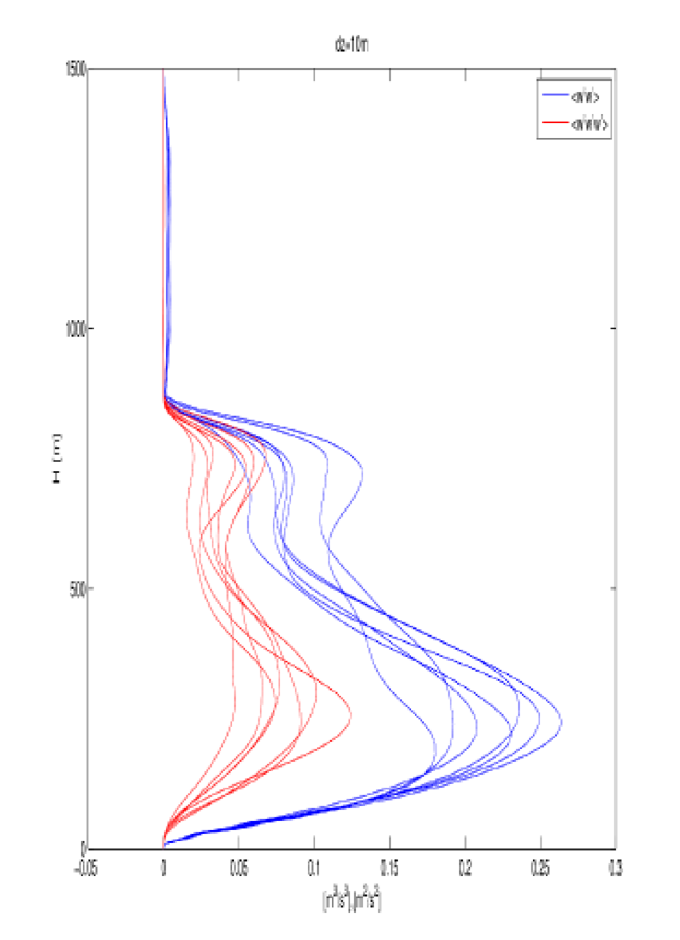
dz	LWP $[g/m^2]$				cloud cover [1]				TKE $[m^3/s2]$			
time	2h	3h	4h	5h	2h	3h	4h	5h	2h	3h	4h	5h
2.5m	24	23	21	23	0.83	0.73	0.65	0.58	195	190	193	207
5m	21	20	19	18	0.82	0.63	0.59	0.55	190	208	205	198
10m	20	19	17	21	0.58	0.42	0.38	0.34	180	171	161	171
ivs 5m	40	36	32	30	1.0	0.99	0.99	0.97	150	214	222	200

dz=2.5m

dz=10m

dz=5m,
ivs0





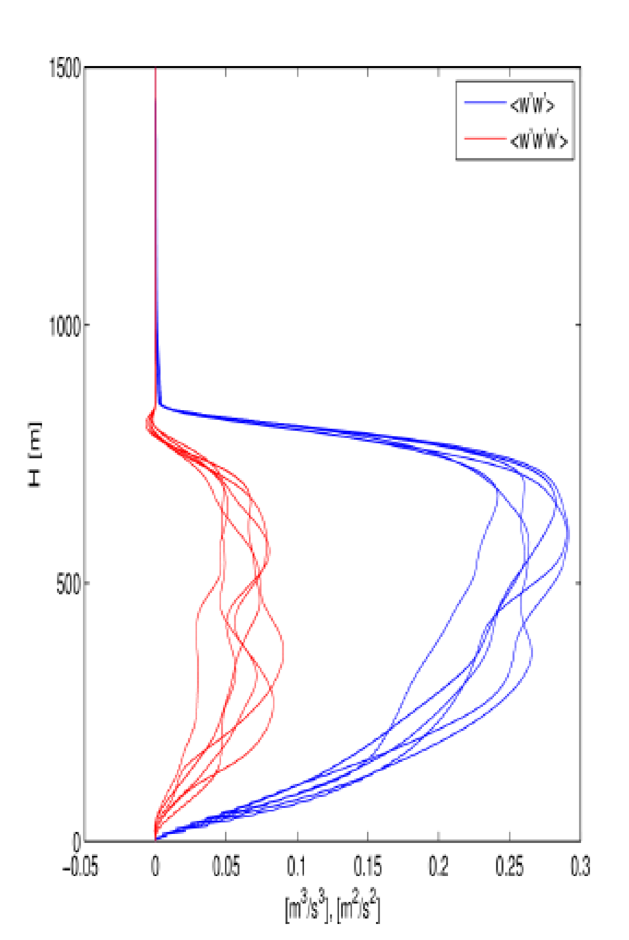
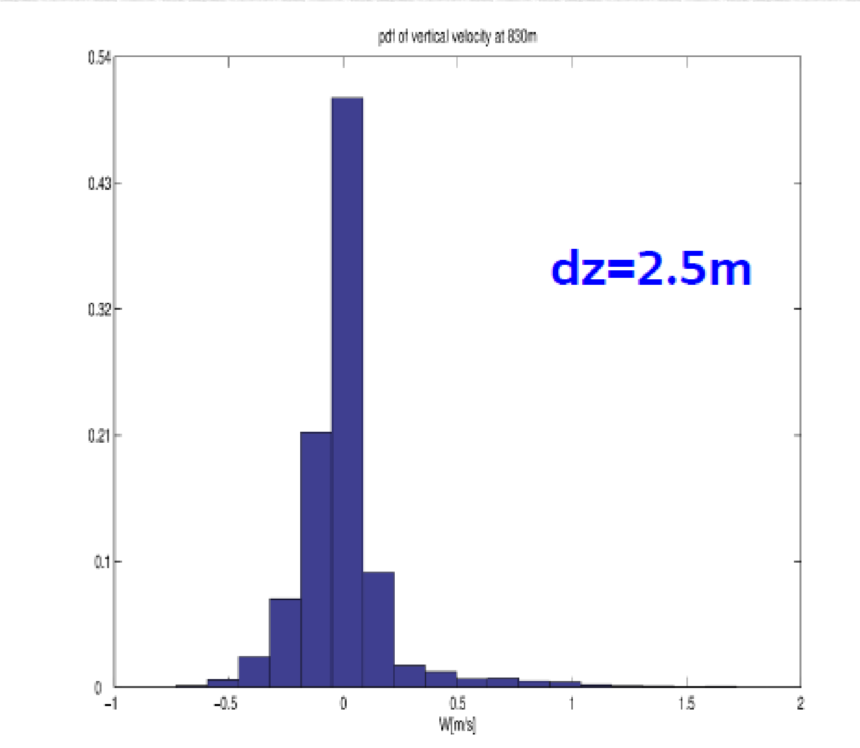
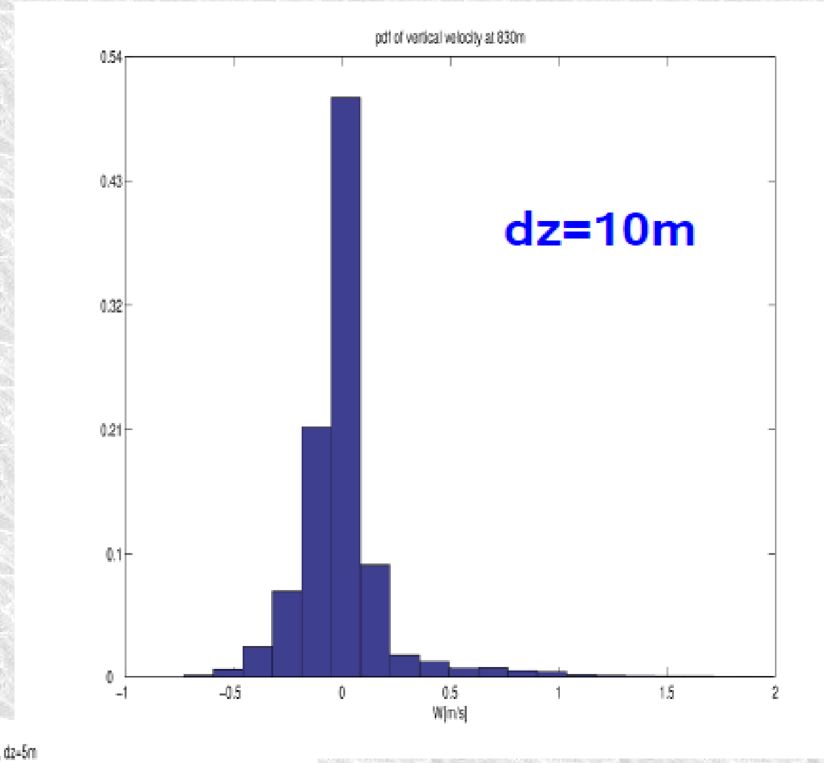
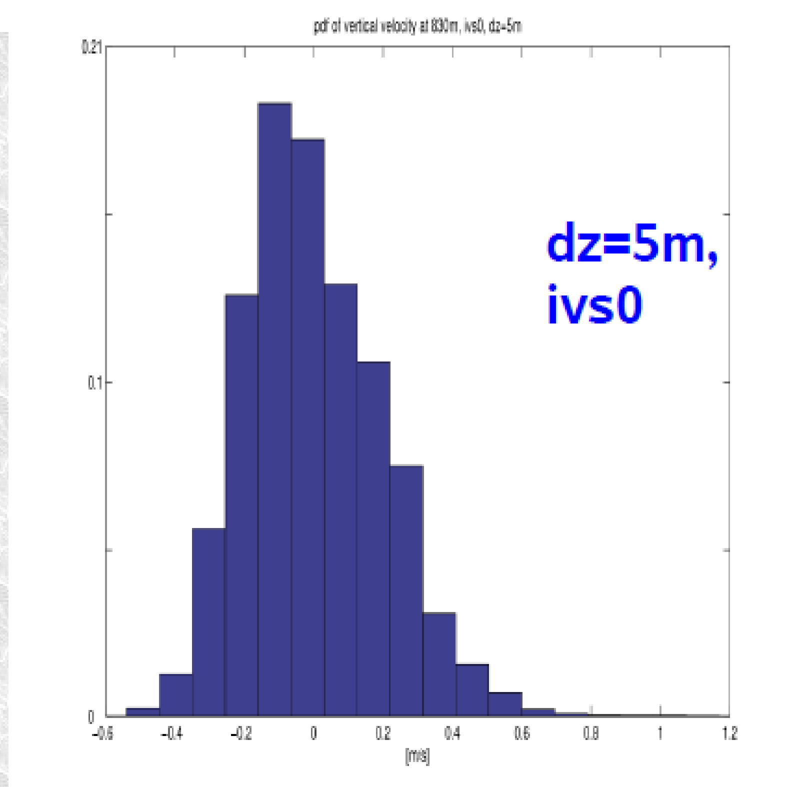


Table 4: Selected statistics of QS and TS surfaces at $t = 3$ hr. The "inviscid" simulation is marked as "ivs 5m". Units are meters except for skewness.

dz		mean	std	skewness	min	max
2.5m	TS	864.3	5.9	-0.3	840	885
	QS	850.7	11.3	-0.6	788	877
10m	TS	875.3	5.3	-0.3	860	890
	QS	855.2	9.2	0.0	820	882
ivs 5m	TS	853.0	2.5	-0.4	845	860
	QS	845.4	7.1	-1.6	790	857

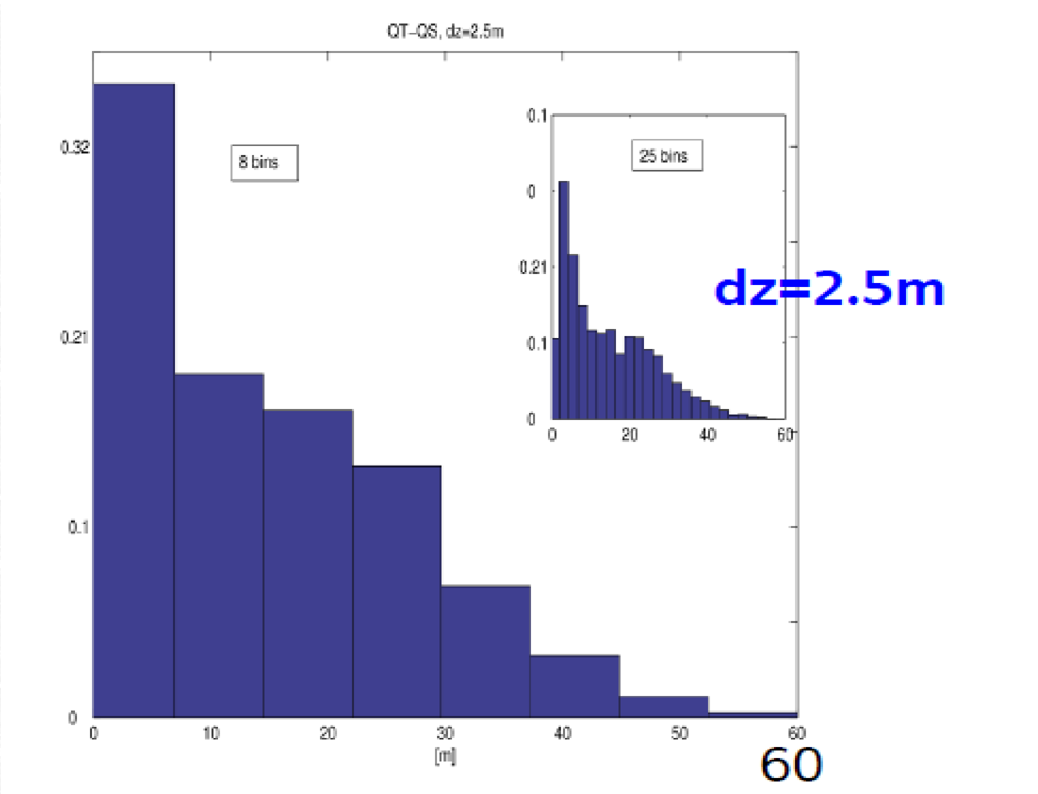


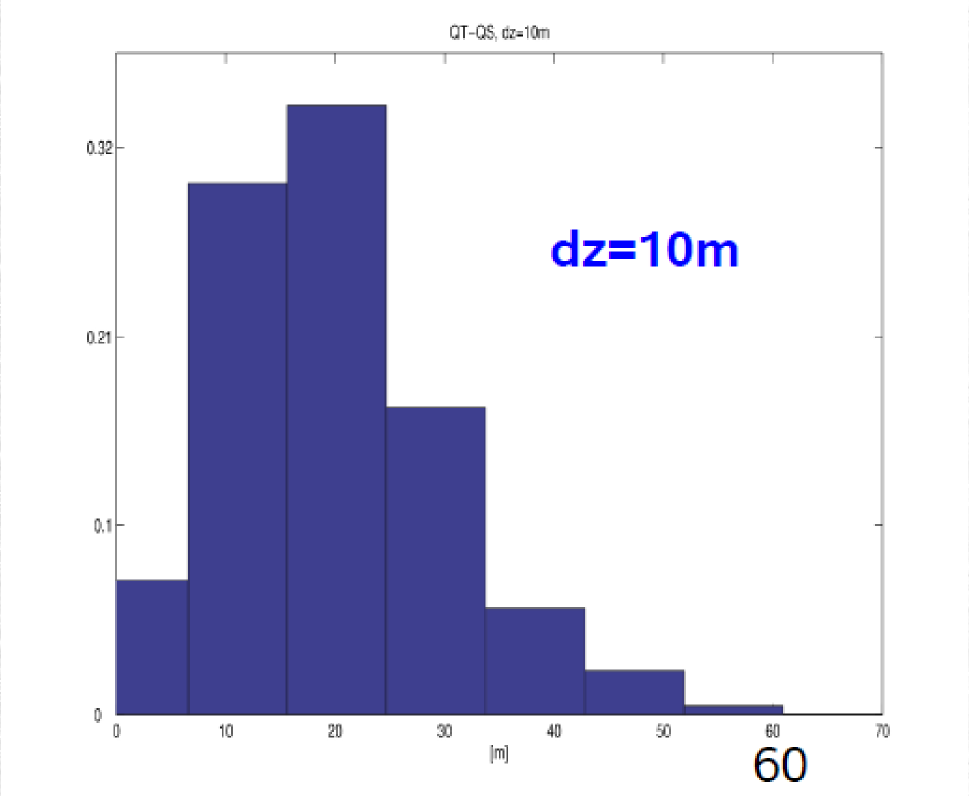


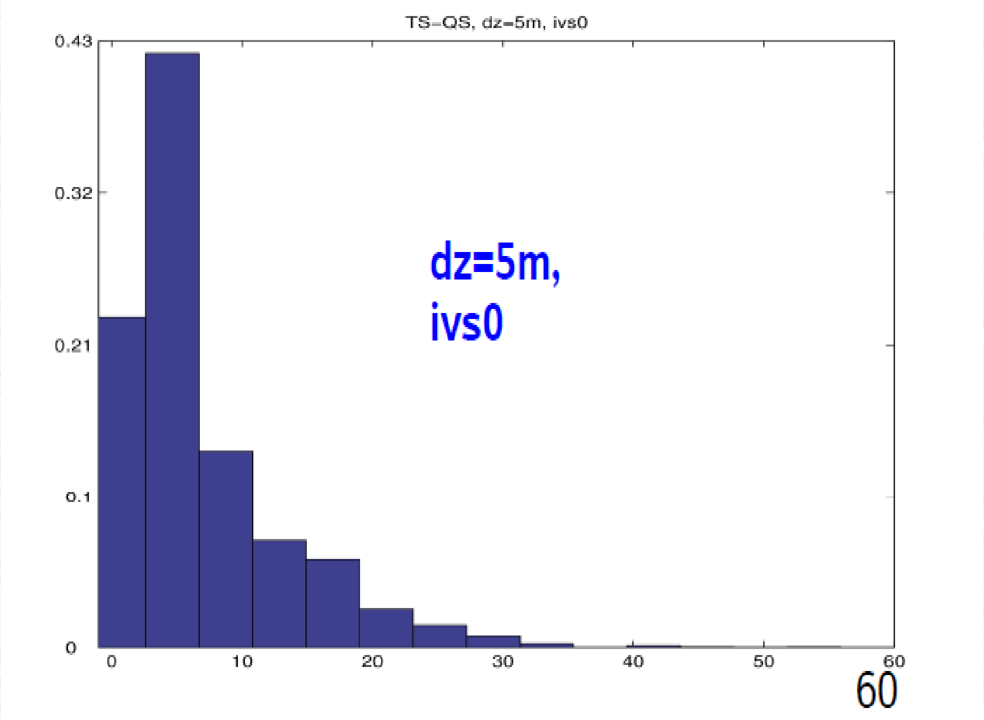


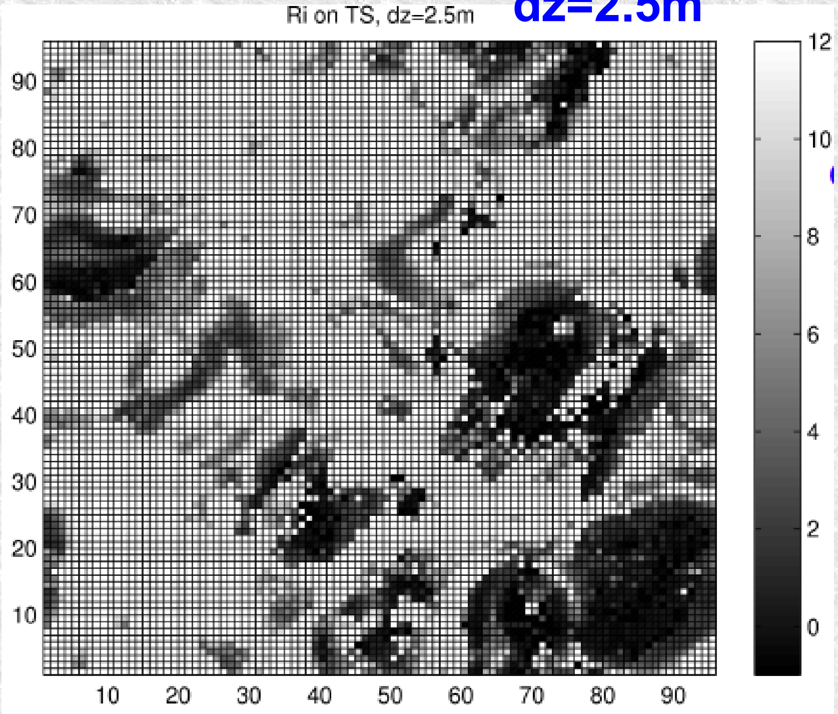
Typical pdf of vertical velocity at z=830m

(just below the top of STBL)

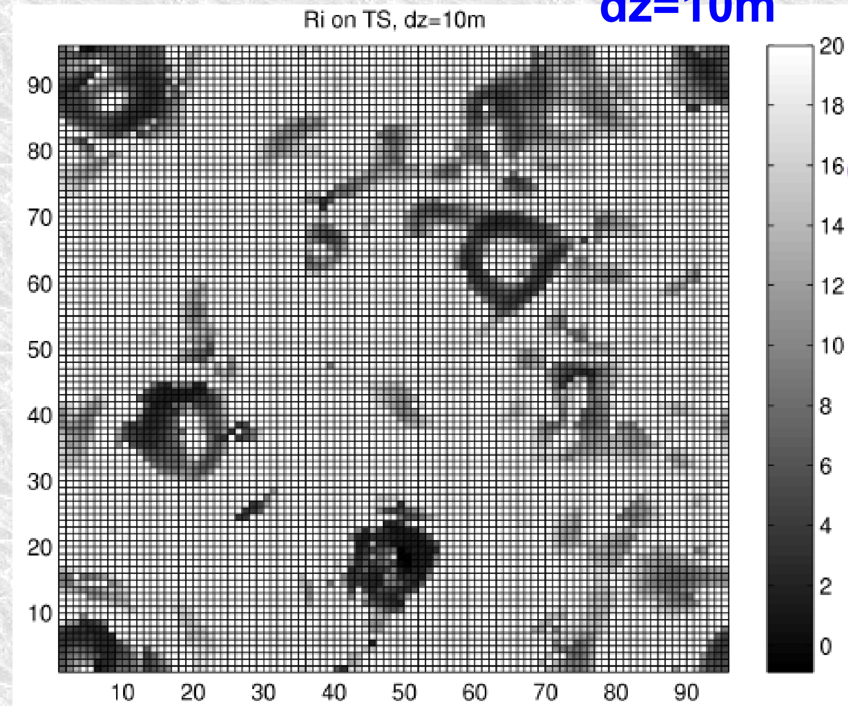

QT-QS, dz=2.5m
8 bins
25 bins
dz=2.5m
[m]
60


QT-QS, dz=10m
dz=10m
[m]
60

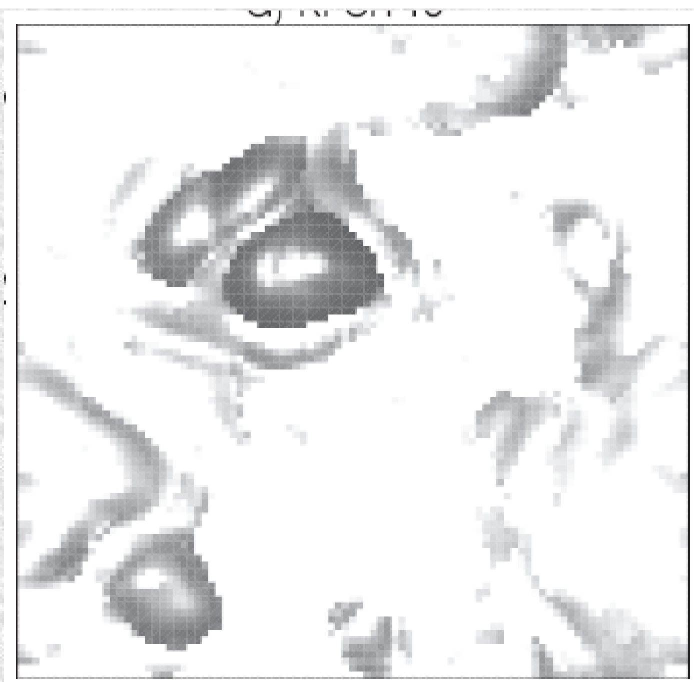

TS-QS, dz=5m, ivs0
dz=5m,
ivs0
60



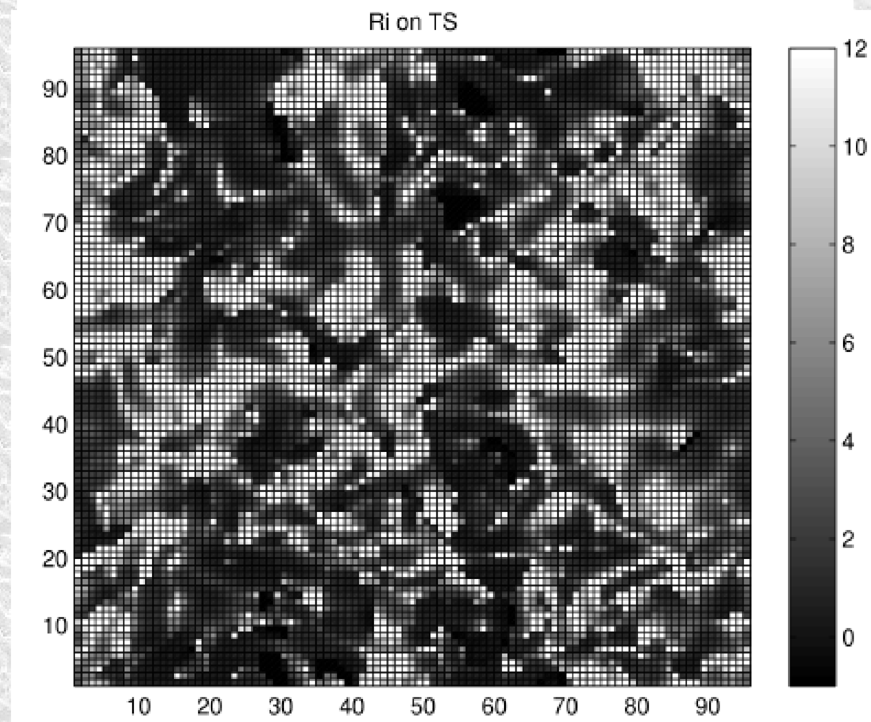
dz=2.5m



dz=10m

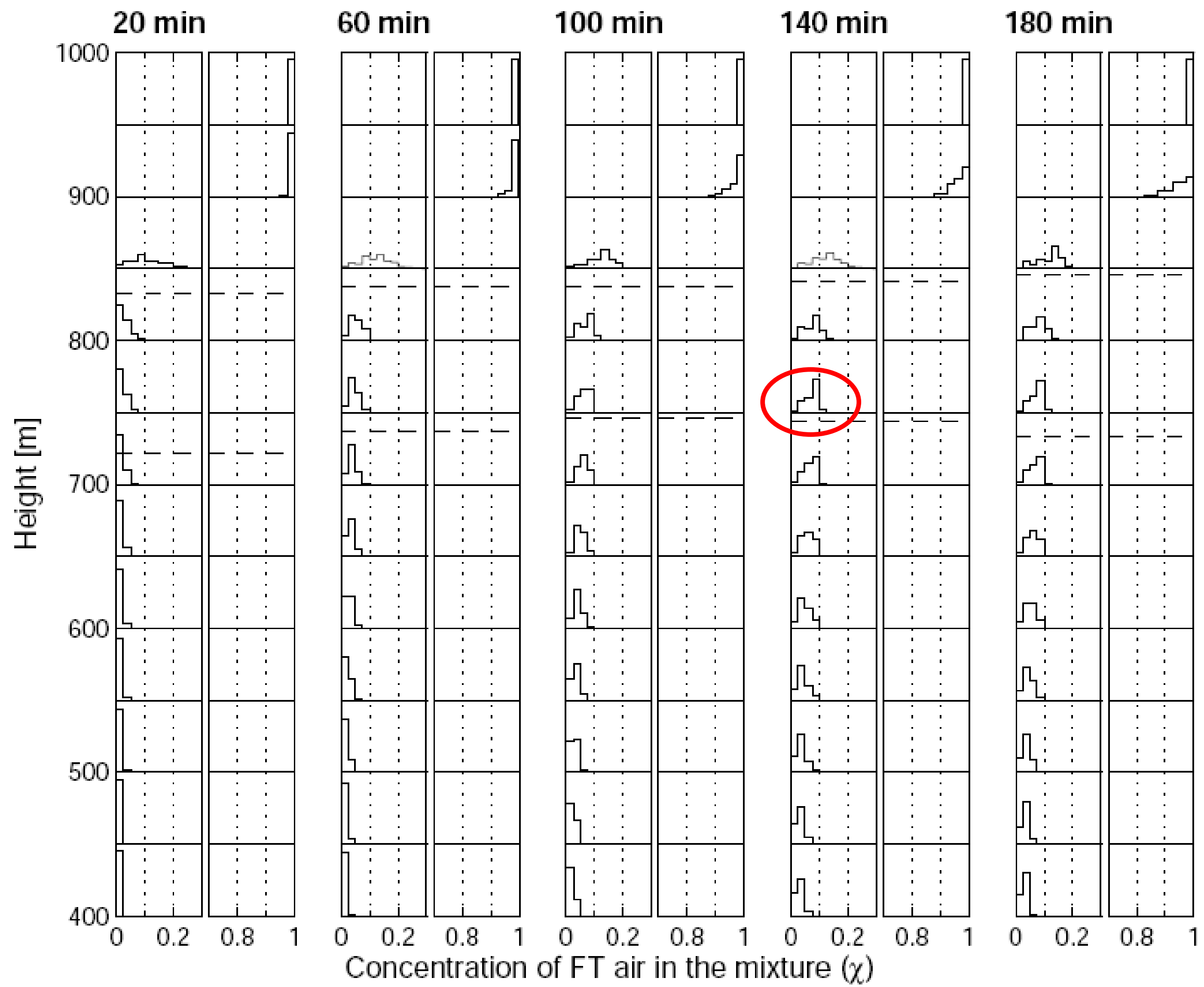


dz=5m



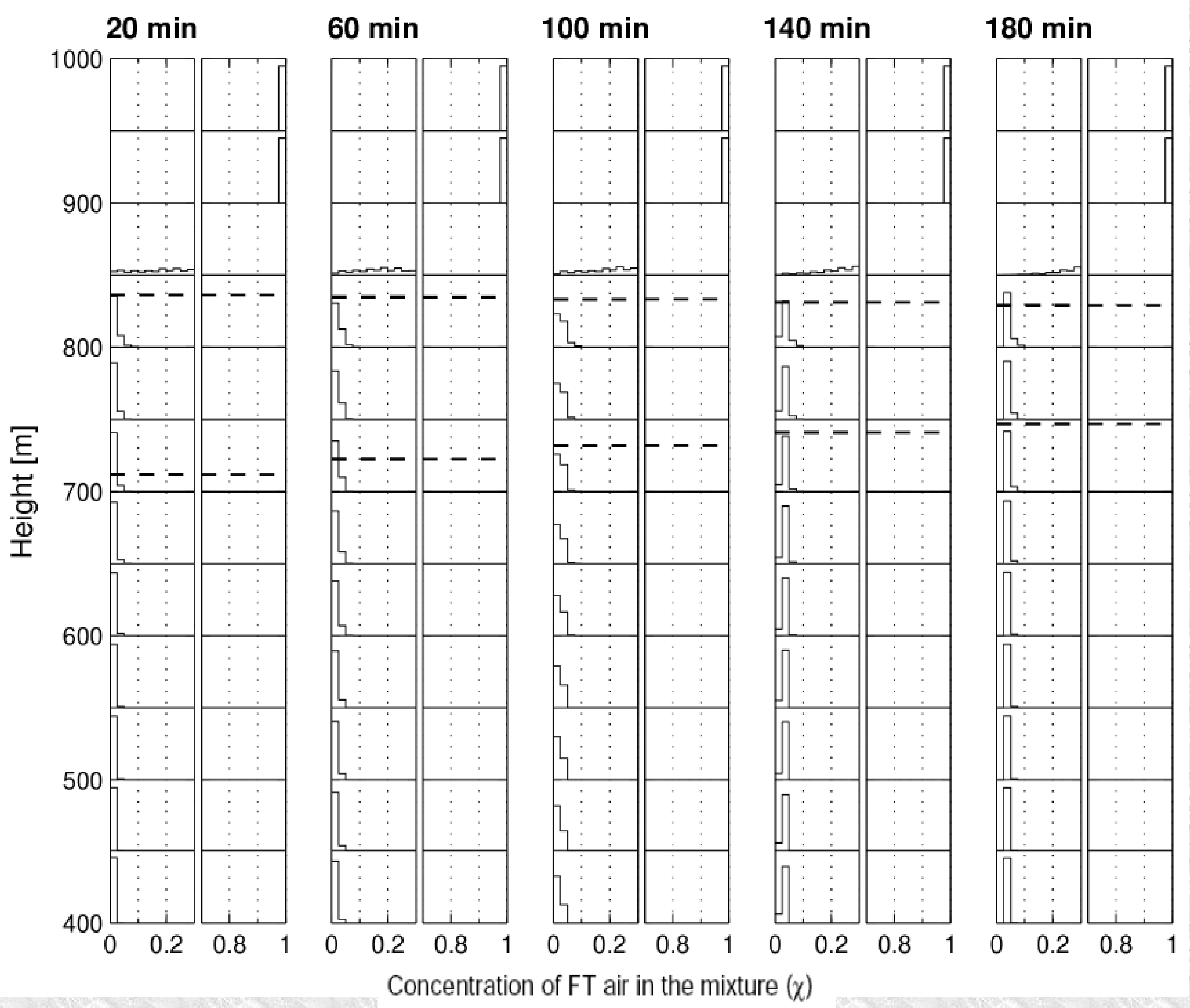
dz=5m
ivs0

dz=2.5m

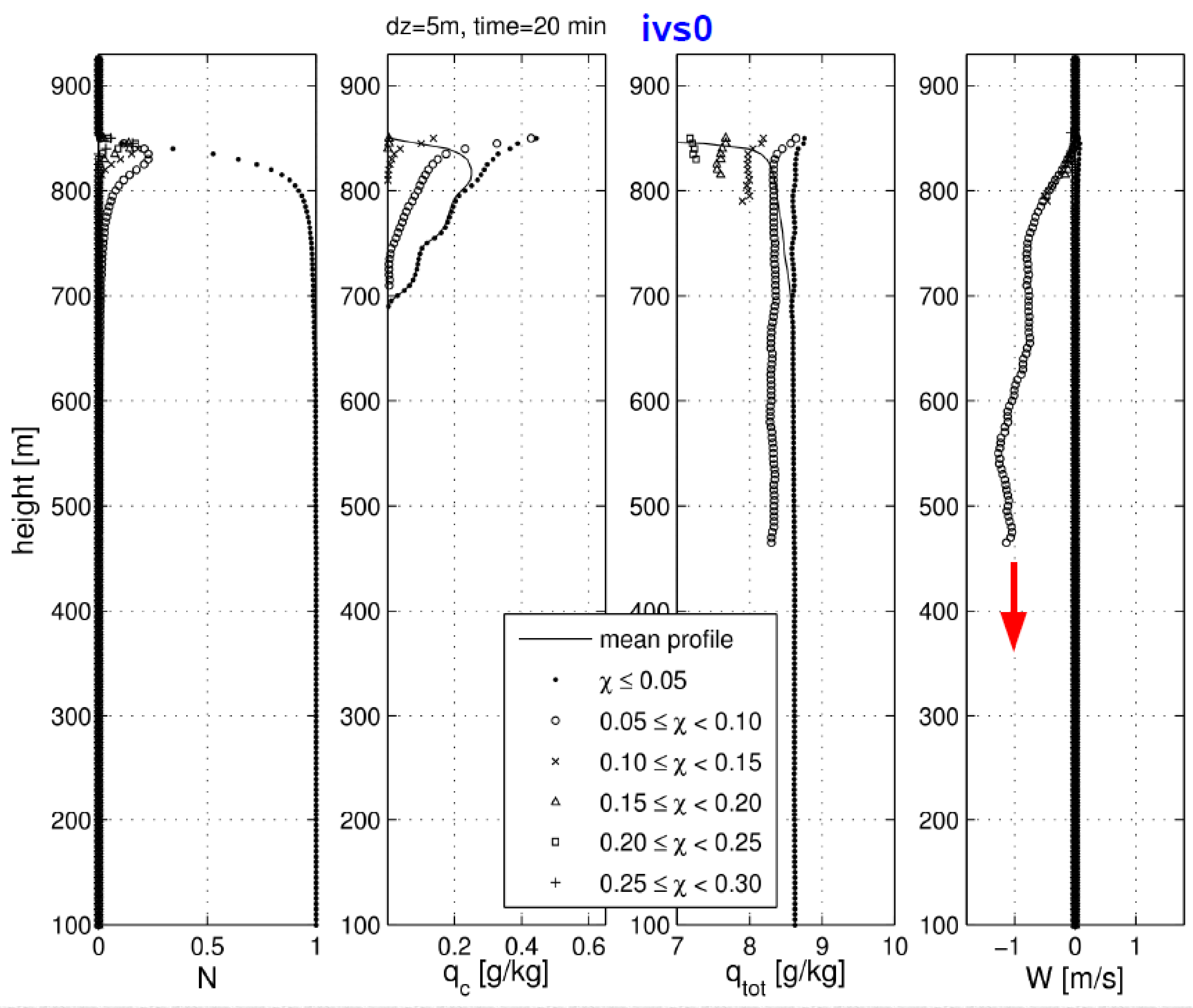


20 min
60 min
100 min
140 min
180 min
Height [m]
1000
900
800
700
600
500
400
0
0.2
0.8
1
Concentration of FT air in the mixture (χ)

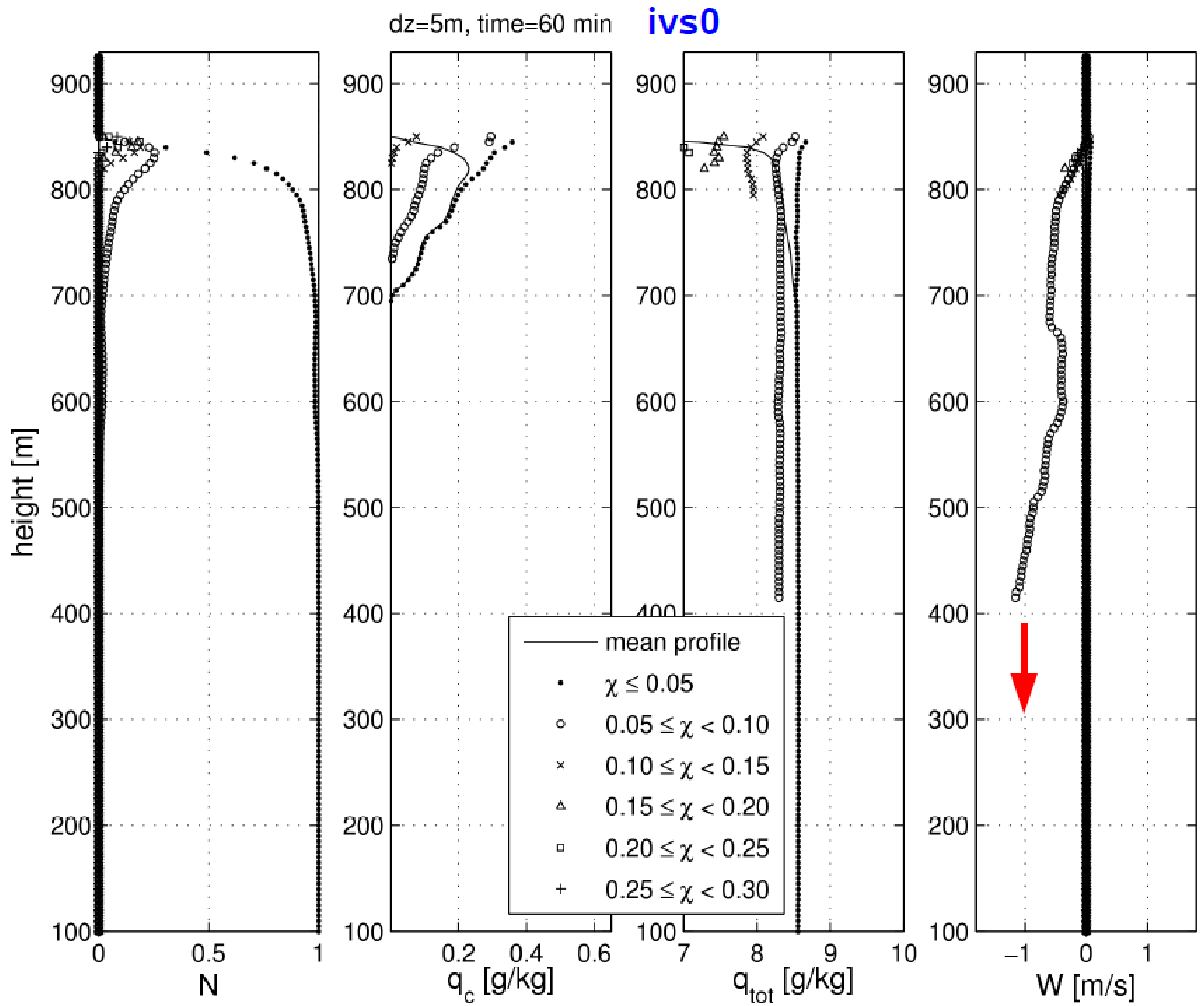
dz=5m, ivs0



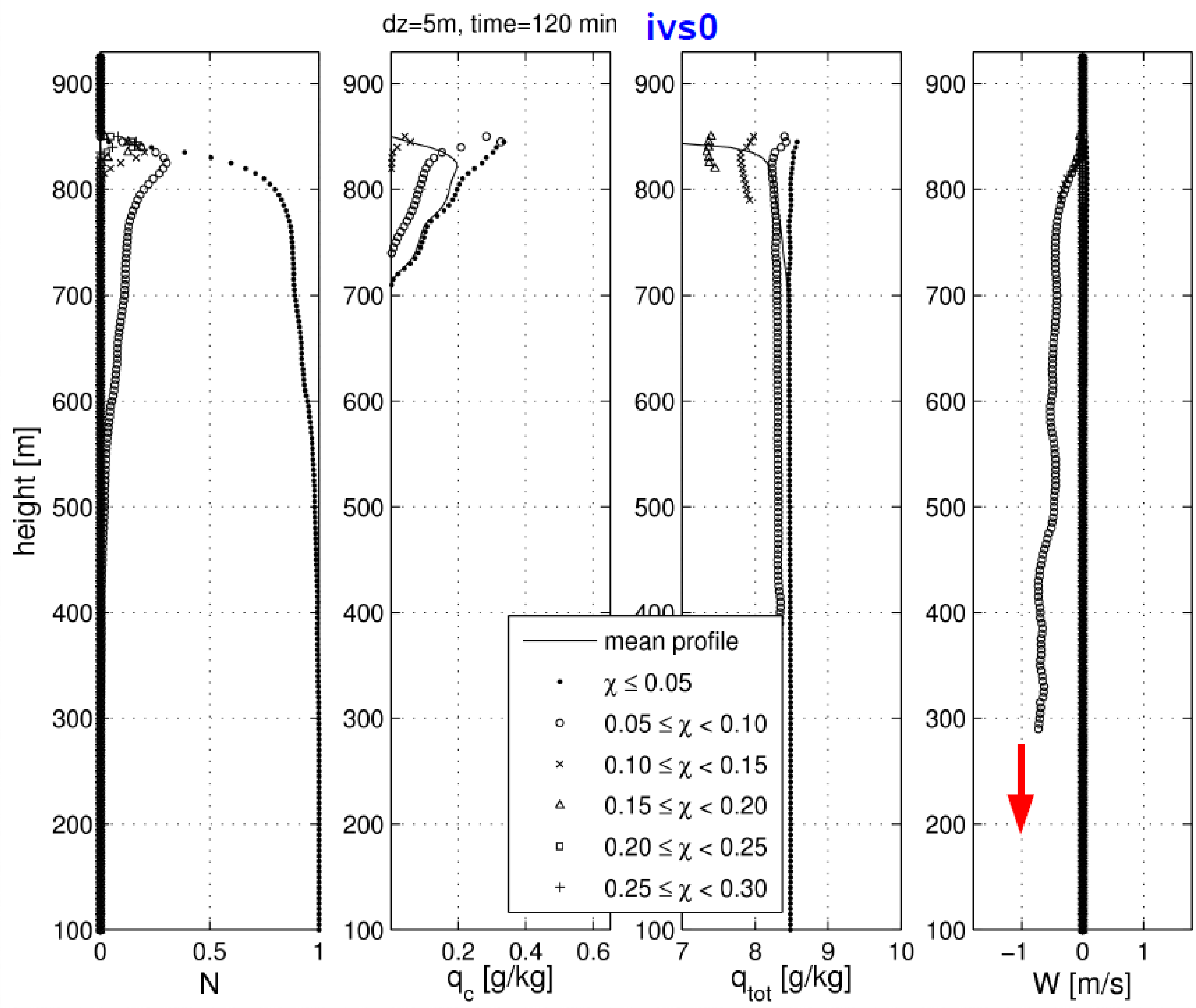
20 min
60 min
100 min
140 min
180 min
Height [m]
1000
900
800
700
600
500
400
0
0.2
0.8
1
Concentration of FT air in the mixture (χ)

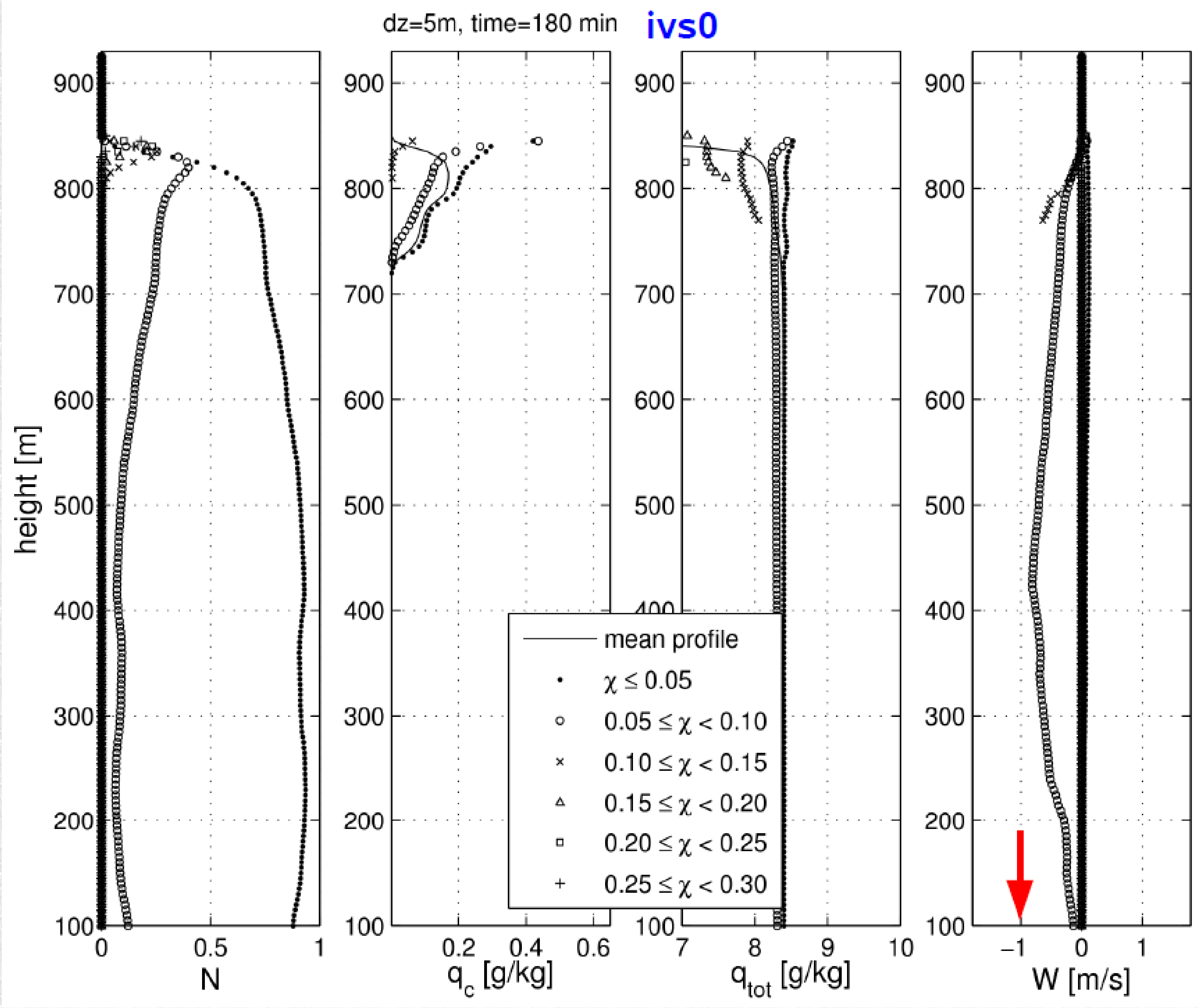


dz=5m, time=20 min
ivs0
height [m]
N
q_c [g/kg]
q_tot [g/kg]
W [m/s]
mean profile
χ ≤ 0.05
0.05 ≤ χ < 0.10
0.10 ≤ χ < 0.15
0.15 ≤ χ < 0.20
0.20 ≤ χ < 0.25
0.25 ≤ χ < 0.30



dz=5m, time=60 min
ivs0
height [m]
N
q_c [g/kg]
q_{tot} [g/kg]
W [m/s]
mean profile
$\chi \leq 0.05$
$0.05 \leq \chi < 0.10$
$0.10 \leq \chi < 0.15$
$0.15 \leq \chi < 0.20$
$0.20 \leq \chi < 0.25$
$0.25 \leq \chi < 0.30$


dz=5m, time=120 min
ivs0
height [m]
N
q_c [g/kg]
q_{tot} [g/kg]
W [m/s]
mean profile
χ ≤ 0.05
0.05 ≤ χ < 0.10
0.10 ≤ χ < 0.15
0.15 ≤ χ < 0.20
0.20 ≤ χ < 0.25
0.25 ≤ χ < 0.30


dz=5m, time=180 min
ivs0
height [m]
N
q_c [g/kg]
q_tot [g/kg]
W [m/s]
mean profile
χ ≤ 0.05
0.05 ≤ χ < 0.10
0.10 ≤ χ < 0.15
0.15 ≤ χ < 0.20
0.20 ≤ χ < 0.25
0.25 ≤ χ < 0.30

Summary:

The following mechanistic picture of the entrainment emerges from the simulations:

- Rising STBL impinges upon the inversion and forms “cloud domes”;
- EIL forms as a consequence of diverging flow, which increases shear and thus mixing ('preconditioned' air);
- The flow at the peripheries of these domes becomes unstable and mixing between STBL and FT air takes place;
- Resulting buoyancy reversal leads to a preferential entrainment of negatively-buoyant parcels with FT air fraction between 0.1 and 0.2; positively-buoyant parcels with higher fractions are left within EIL (selective process)
- Penetration of STBL goes through the 'cloud holes'
- Sinking air can be wrapped around the cloud edges and recirculated into its core, what results in an increased level of cloud base; the rest of it slowly dilutes STBL;