Turbulent effects on cloud microstructure and precipitation of deep convective clouds as seen from simulations with a 2-D spectral microphysics cloud model

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Parameters characterizing cloud turbulence

a) Turbulent kinetic energy: $E = (\langle u'^2 + w'^2 \rangle)/2$

b) Dissipation rate ε

c) Reynolds number Re_λ

d) Mixing length l

e) External turbulent scale L

f) Turbulent coefficient K

Collision enhancement factor (*Pinsky et al 2008*)

$$\frac{d\langle f\rangle}{dt} = \int_0^{m/2} \langle f(m')\rangle \langle f(m-m')\rangle P_{col} K_g(m-m')dm' -$$

$$-\int_0^{\infty} \langle f(m)\rangle \langle f(m')\rangle P_{col} K_g(m,m')dm'$$

Collision enhancement factor

$$P_{col} = P_{kern} P_{clust}$$

P_{kern} Is the enhancement factor due to the increase in relative velocity between droplets and the increase in the collision efficiency

P_{clust} is the enhancement factor due to the droplet clustering.

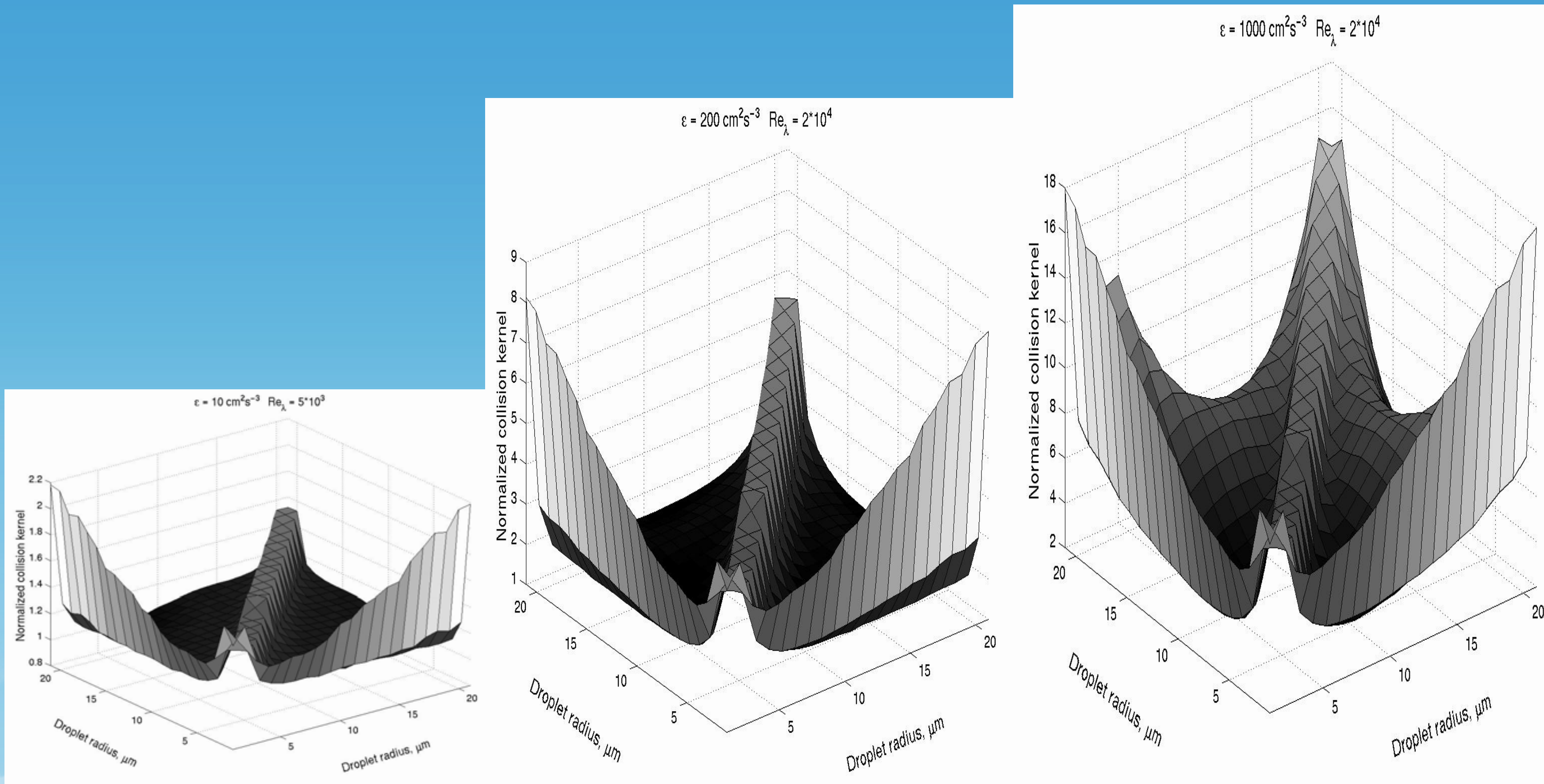


Figure 1. Mean normalized collision kernel in turbulent flow for three cases: stratiform clouds (left panel), cumulus clouds (middle) and cumulonimbus (right panel). Pressure is equal to 1000mb.(After Pinsky et al, 2008)

P_{clust} is calculated as (Pinsky and Khain 2003; Pinsky et al 2008) :

$$P_{clust}(St_1, St_2) = \frac{\langle N_1 N_2 \rangle}{\langle N_1 \rangle \langle N_2 \rangle} = 1 + 0.333 \cdot (St_1 St_2)^{0.317}$$

St_1 and St_2 are the Stokes numbers of colliding droplets and

N_1 and N_2 are the droplet concentrations

$$P_{clust} \sim 1 - 2$$

Relative contribution of different mechanisms to the collision rate enhancement:

Transport effect: ~20%

Clustering effect: ~20%

Collision efficiency: ~60%

Hebrew University Cloud Model (HUCM) with spectral (bin) microphysics (*Khain et al 2004, 2008*)

- **8 types of hydrometeors:**
  a) water drops, b) plate crystals; c) columnar crystals;
  d) dendrites; e) snow; f) graupel; g) hail; h) aerosols

- **Each distribution function is defined on mass grid containing 43 bins.**

- **The minimum size corresponds to a 2 micron drop. The maximum size corresponds to hail of 6 cm in diameter.**

- **Computational area: 25 km x 16 km.**

- **Model resolution: 50 m x 50 m**

- **Time steps range from 0.5 to 5 s.**

The K-epsilon theory (1.5 order closure) (*Skamarock et al., 2005*)

$$\frac{\partial E}{\partial t}+U\frac{\partial E}{\partial x}+W\frac{\partial E}{\partial z}=K\left[2\left(\frac{\partial U}{\partial x}\right)^2+2\left(\frac{\partial W}{\partial z}\right)^2+2\left(\frac{\partial U}{\partial z}+\frac{\partial W}{\partial x}\right)^2\right]-\alpha KN^2-\varepsilon$$

$$K=C_k lE^{0.5}$$

the turbulent coefficient

$$\varepsilon=\frac{CE^{3/2}}{l}$$

dissipation rate

$$l=\begin{cases}\sqrt{\Delta x\Delta z} & if \quad N^2\le 0\\ \min\left(\sqrt{\Delta x\Delta z},0.76\frac{\sqrt{E}}{N}\right) & if \quad N^2\rangle 0\end{cases}$$

mixing length

$$N^2=\frac{g}{\theta}\frac{\partial\theta}{\partial z}$$

The Brunt-Vaisala frequency

$$C=1.9C_k+\frac{(0.93-1.9C_k)l}{\sqrt{\Delta x\Delta z}}$$

$$C_k=0.2$$

coefficient

Evaluation of Re_λ

$$L = \min\left\{ l, \frac{1}{15} S_{cl}^{1/2} \right\}$$

L is the external turbulent scale (*Grabowski and Clark, 1993*)

$$TKE_{tot} = (\varepsilon L)^{2/3}$$

Total kinetic energy of turbulence

$$u' = \sqrt{TKE_{tot}}$$

Characteristic velocity fluctuation

$$\lambda = u' \sqrt{\frac{15\nu}{\varepsilon}}$$

Taylor microscale

$$\mathrm{Re}_\lambda = \frac{u'\lambda}{\nu}$$

Taylor microscale Reynolds number

Turbulent effects on precipitation

Model calculates in each grid point and at each time step:

a) dissipation rate ε

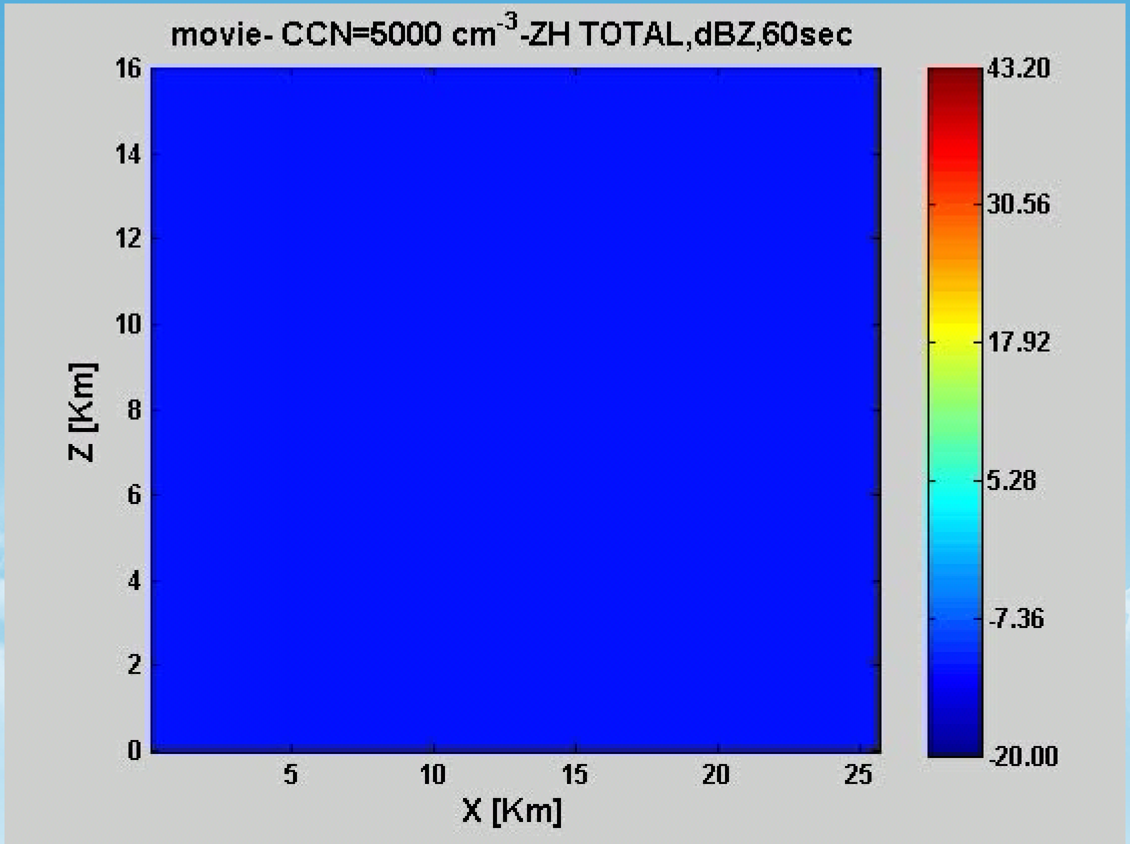
b) Reynolds number Re_{λ}

c) Collision enhancement factor

This procedure makes it possible to investigate effects of turbulence on precipitation formation.

Simulations of single clouds in LBA-SMOCC experiment

Cloud type :	CCN concentration(1%S) cm^{-3}	: stratification	: freezing level
Blue ocean:	200; 700	Andeae et al (2004)	4.1 km
Green-Ocean :	900, 1200, 1700	Andeae et al (2004)	4.1 km
Smoky :	5000, 10000	Andeae et al (2004)	4.1 km


movie- CCN=5000 cm-3-ZH TOTAL,dBZ,60sec
Z [Km]
X [Km]
16
14
12
10
8
6
4
2
0
5
10
15
20
25
43.20
30.56
17.92
5.28
-7.36
-20.00

TURBULENT CLOUD STRUCTURE AND ITS TIME EVOLUTION

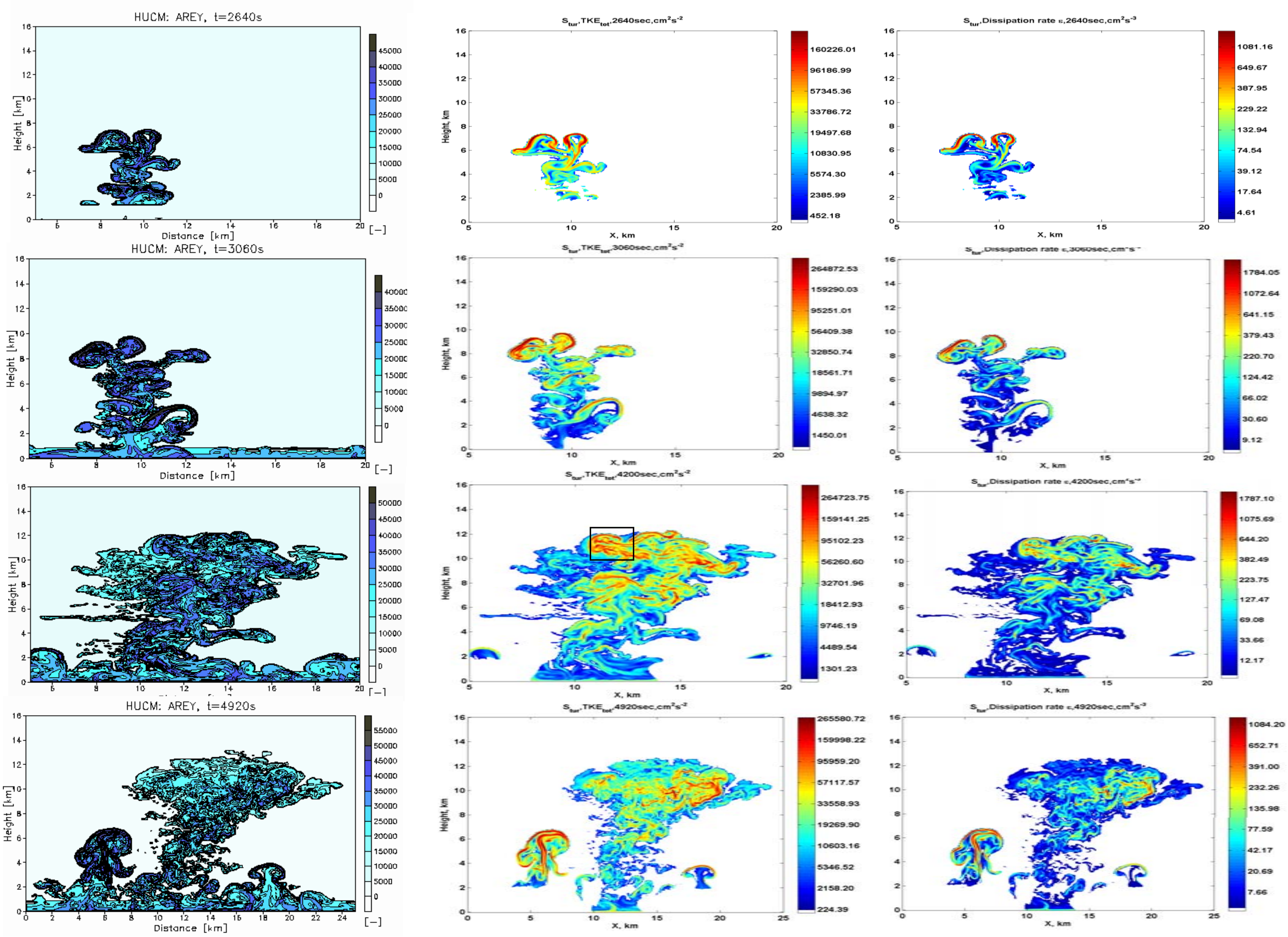


Figure 1. Fields of Re_{λ} (left), Total turbulent kinetic energy (middle) and dissipation rate (right) at different time instances during development of smoky cloud (with turbulent collision kernel)

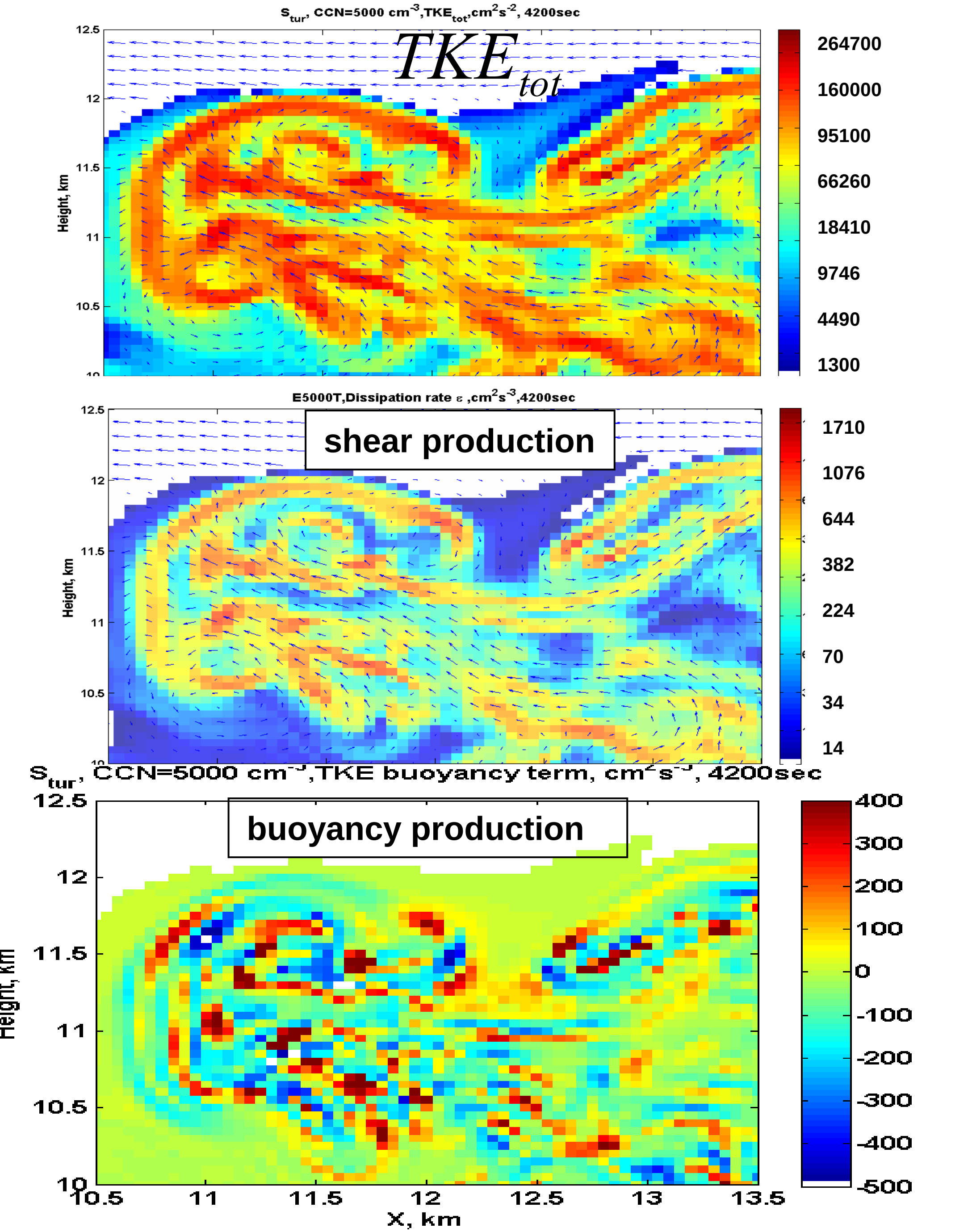


Figure 2 . Fields of total kinetic energy (upper), wind shear production (middle) and buoyancy production term in the rectangle area marked in Figure 4 in panel b

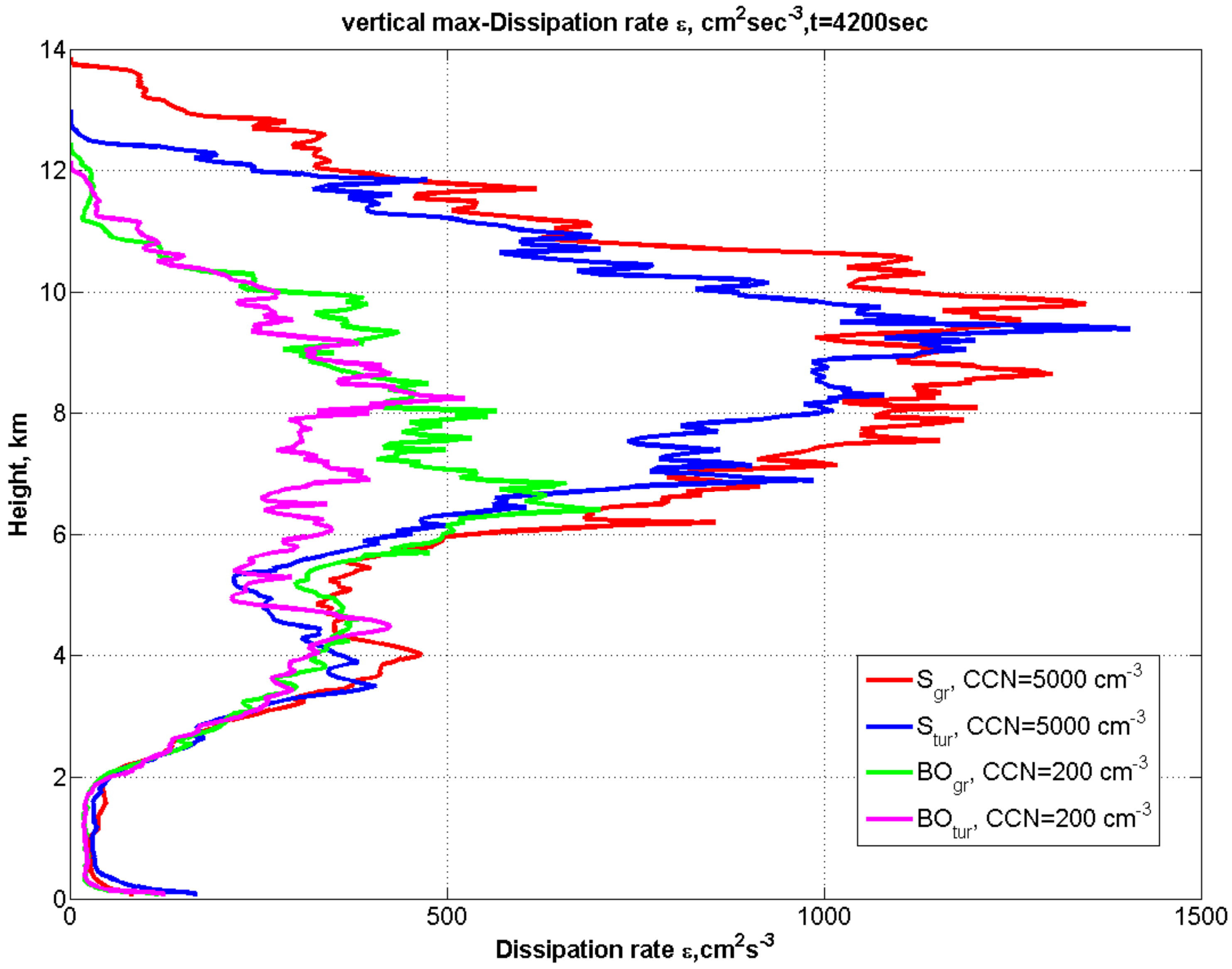


Figure 3. **Vertical profiles of time averaged maximum values of the dissipation rates in S_{gr}, S_{tur}, BO_{gr} and Bo_{tur} (averaging within the period 3600 s to 4800 s)**

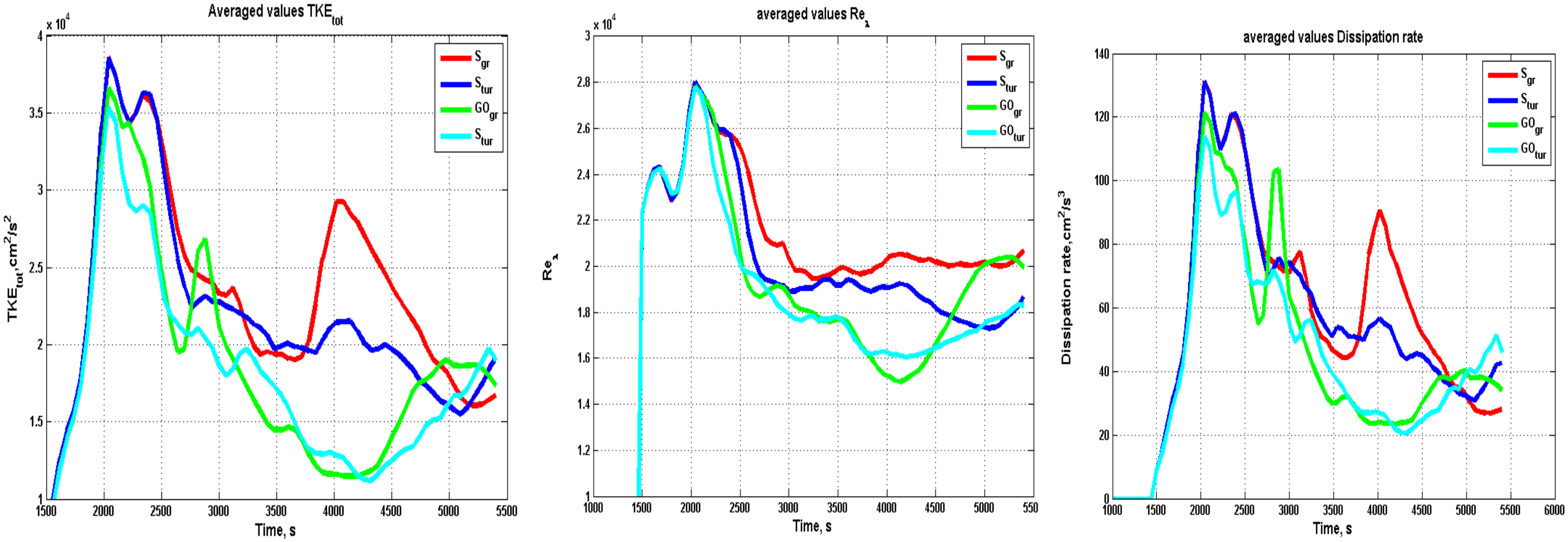


Figure 4. Shows time dependencies of cloud averaged total kinetic energy (left), Reλ (middle) and dissipation rate (right) in all experiments

Conclusions concerning turbulent cloud structure:

a) Turbulent structure of clouds is highly inhomogeneous

b) Cloud averaged turbulent parameters agree well with measurements (Panchev 1971; Mazin et al, 1989; Weil et al, 1993; Pinsky and Khain 2003)

c) Aerosols invigorate clouds and cloud turbulence

d) In case the turbulent kernel is used cloud turbulence is slightly weaker than in case of gravitational kernel

e) Effects of aerosols and of turbulent kernel on cloud turbulence are opposite. It seems that aerosol effects are stronger.

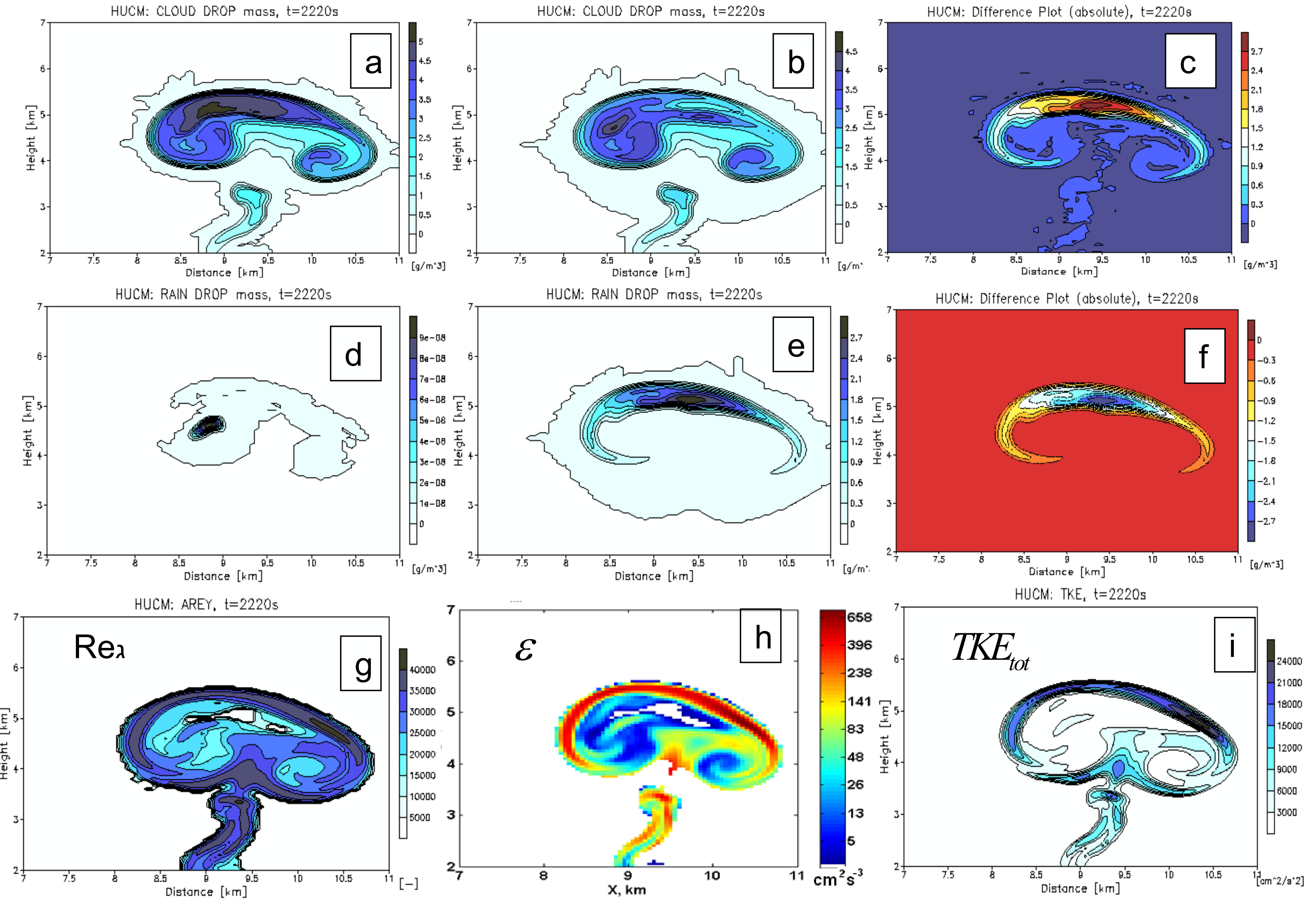


Figure 5. Fields of CWC, RWC in GO_gr (left) and in GO_tur (right) at t=2220 s and turbulent parameters (Reλ ε and TKE_{tot}) in the GO_tur case(bottom row).

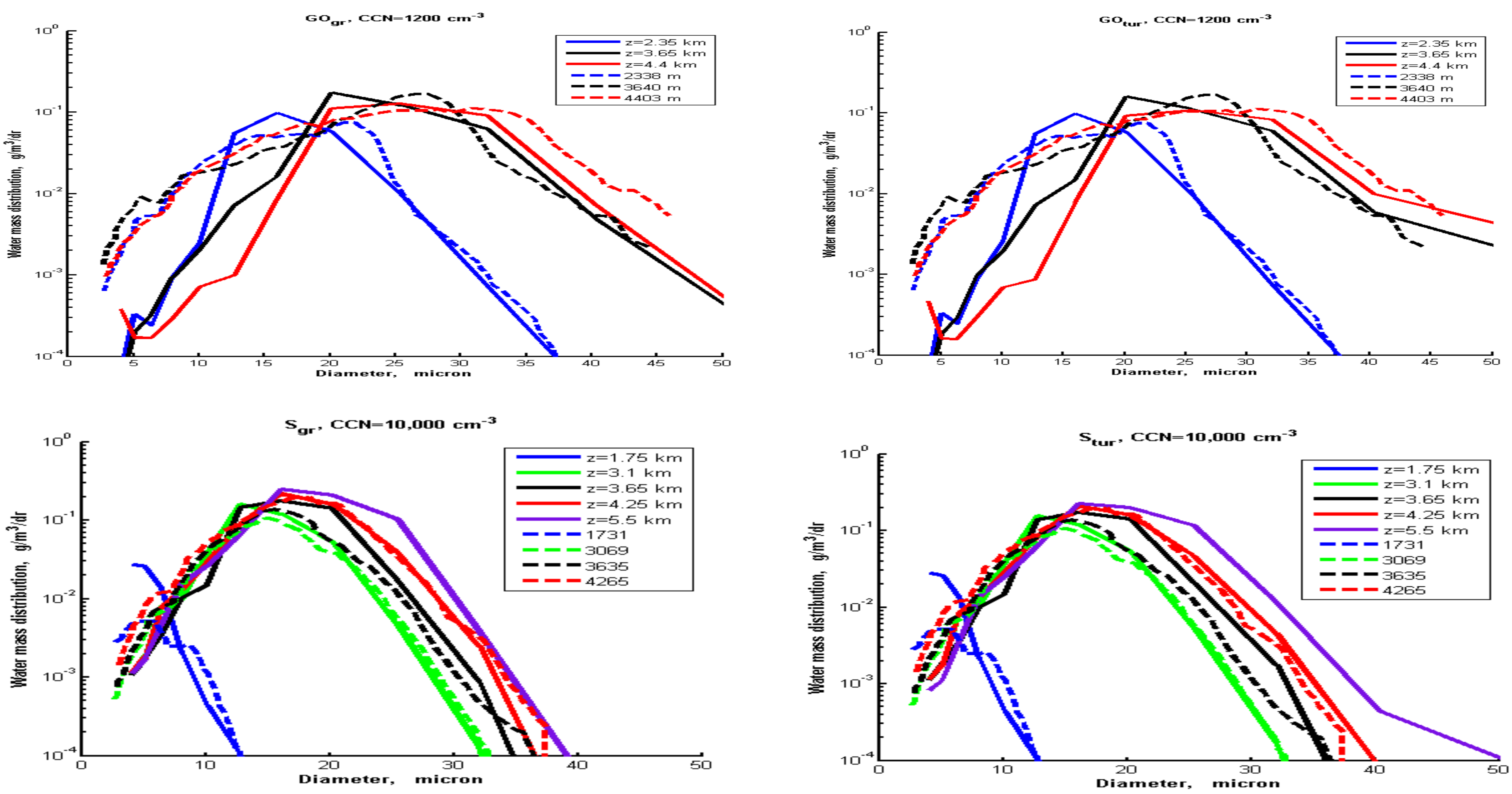


Figure 6. Mass distribution functions at different heights calculated in the GO/S_gr (left) and GO/S_tur (right) simulations (solid lines). The distributions measured in situ at 5/4 Oct 2002 in the green –ocean clouds at nearly the same height levels are plotted by dashed lines (after Andreae et al 2004). CCN concentration is 1500/8000 cm^{-3}

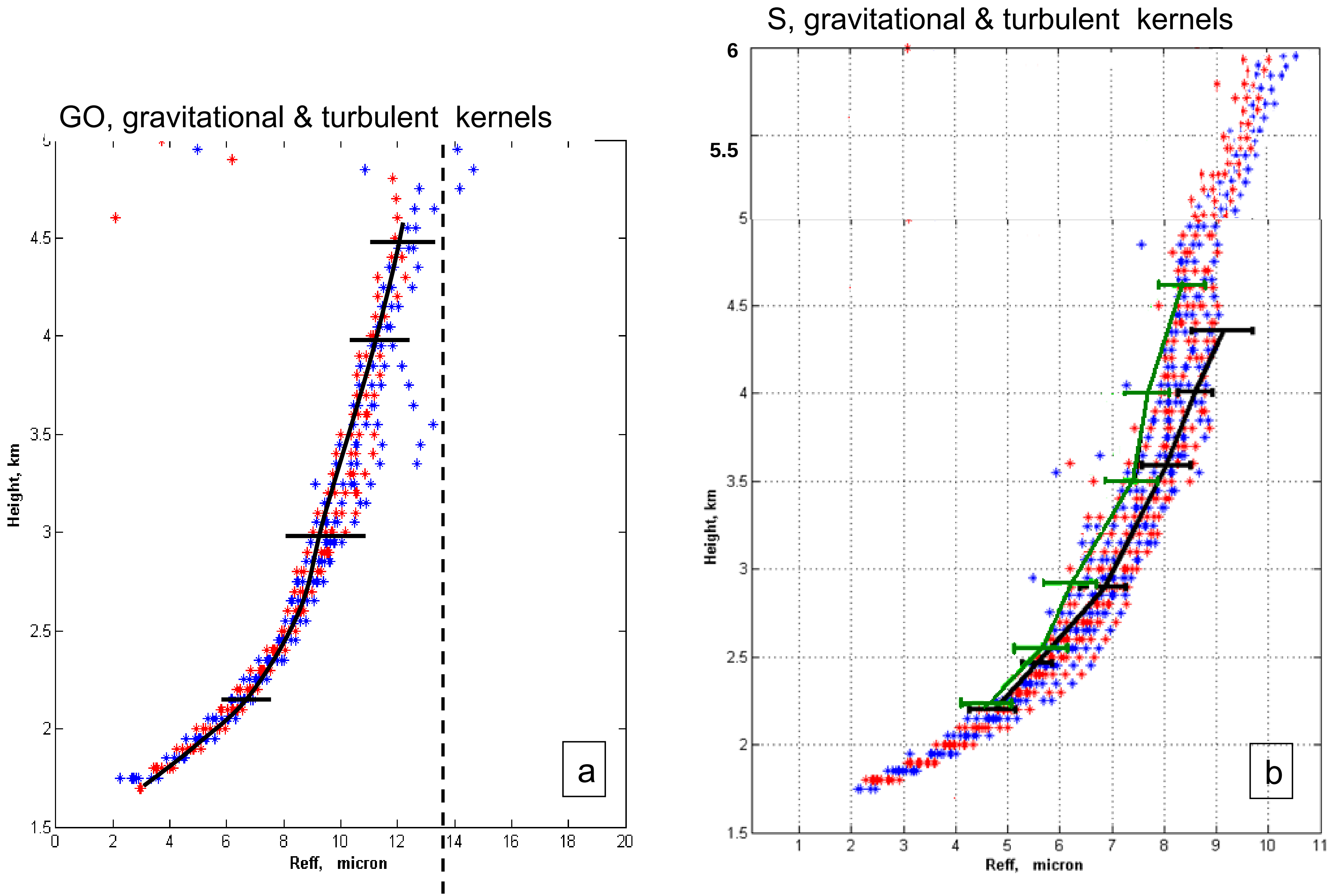


Figure 7. Vertical profiles of effective radius in (a) the GO clouds and (b) S-clouds. Red and blue dots denote gravitational and turbulent kernels. The profile (z) plotted according to in-situ observations is presented according to Freud et al (2008). In Panel b green line corresponds to “polluted period” and black line corresponds to “transition” period.

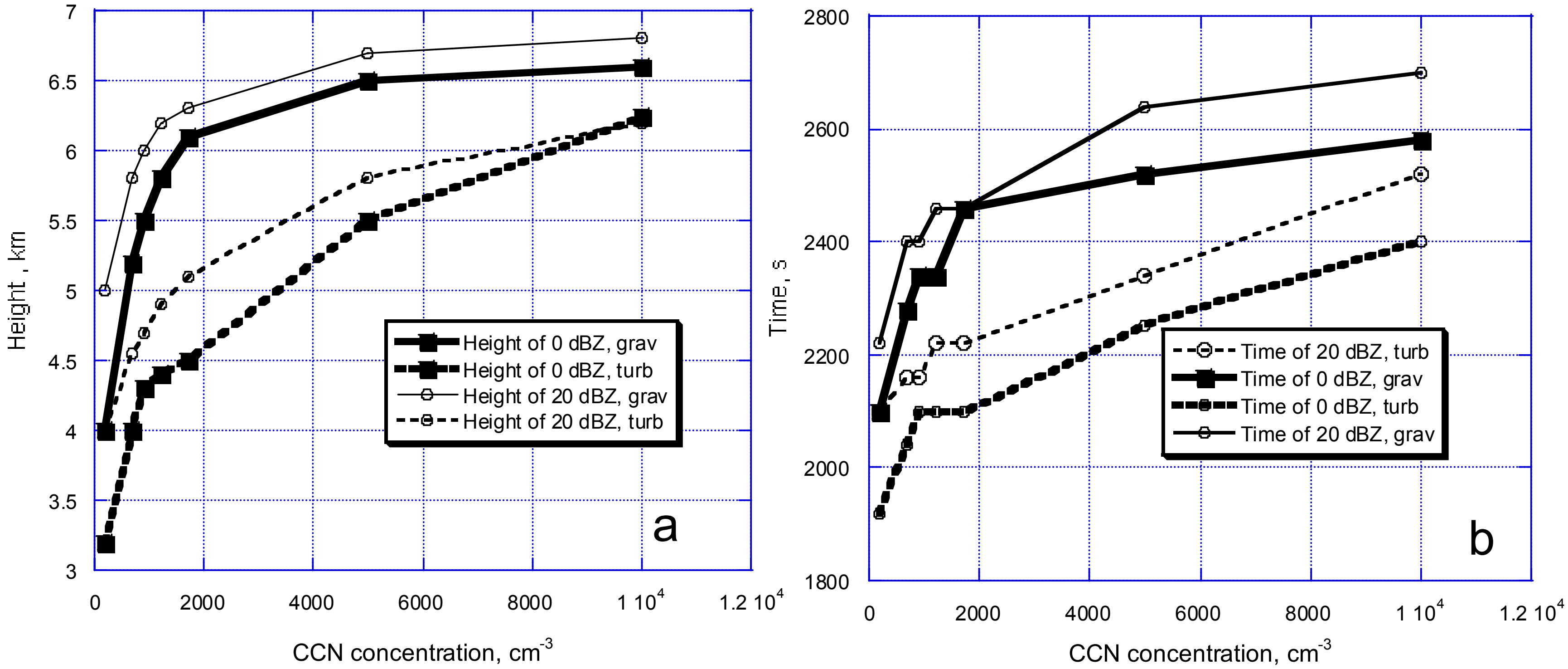


Figure 8. (a) Dependence of height of the formation of radar reflectivity of 0 dBZ and 20 dBZ on the CCN concentration in cases of utilization of gravitational and turbulent collision kernels. (b) Dependence of time of the formation of radar reflectivity of 0 dBZ and 20 dBZ on the CCN concentration in cases of utilization of gravitational and turbulent collision kernels. The time of cloud formation is 1800 s.

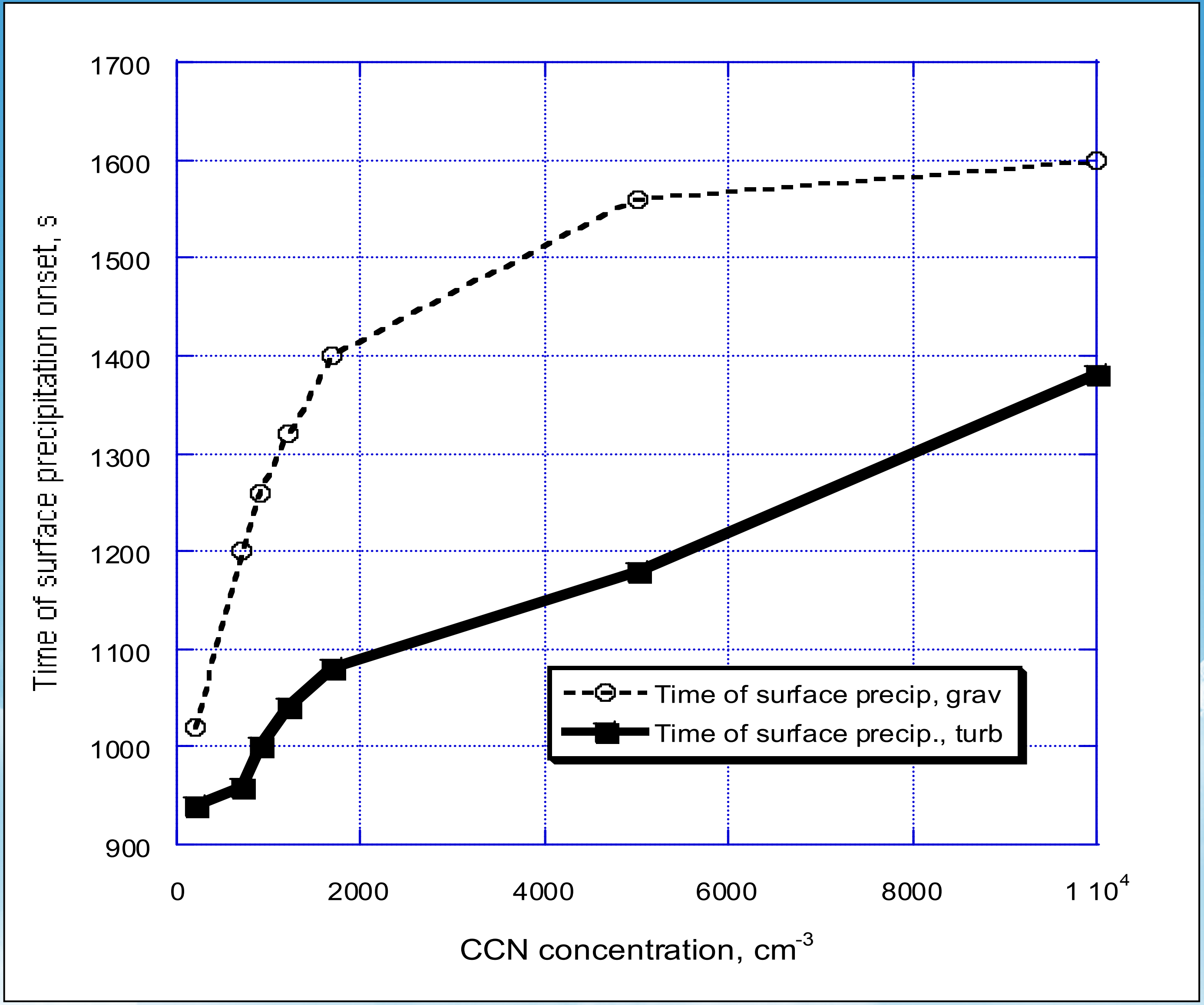
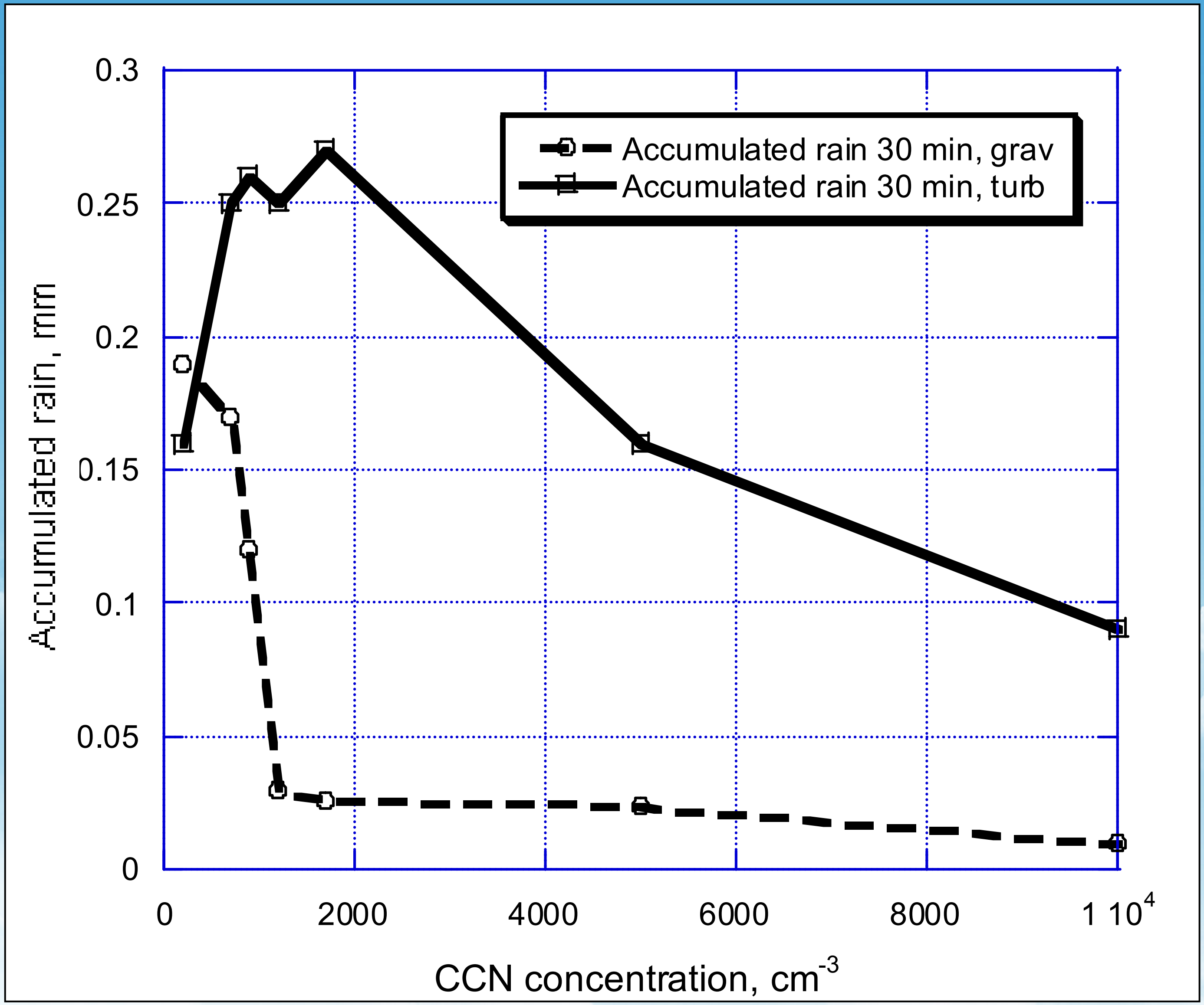


Figure 10. Dependence of the time of surface precipitation onset on the CCN concentration in cases of utilization of gravitational and turbulent collision kernels. The time is counted from the beginning of the cloud formation (t=1800s)



Accumulated rain 30 min, grav
Accumulated rain 30 min, turb
Accumulated rain, mm
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2000
4000
6000
8000
1 10^4
CCN concentration, cm^-3

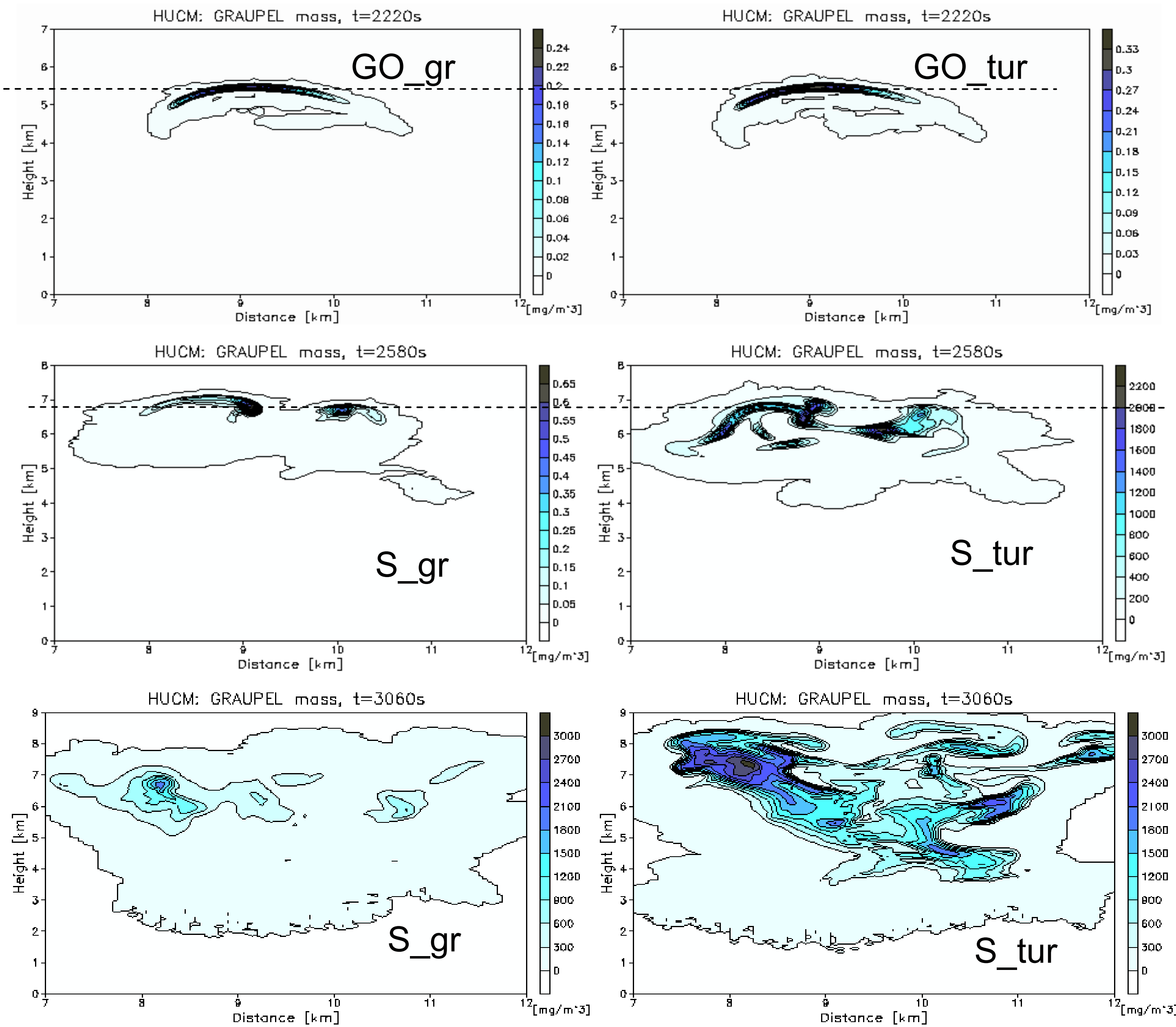


Figure 9. The fields of graupel contents in GO_gr (left) and GO_tur (right) (upper row) and in S_gr (left) and S_tur (right) (middle row) at time instances corresponding to the formation of the first graupel in cases when gravitational kernels were used. Bottom: The fields of graupel contents in S_gr (left) and S_tur (right) in 8 minutes after formation of first graupel.

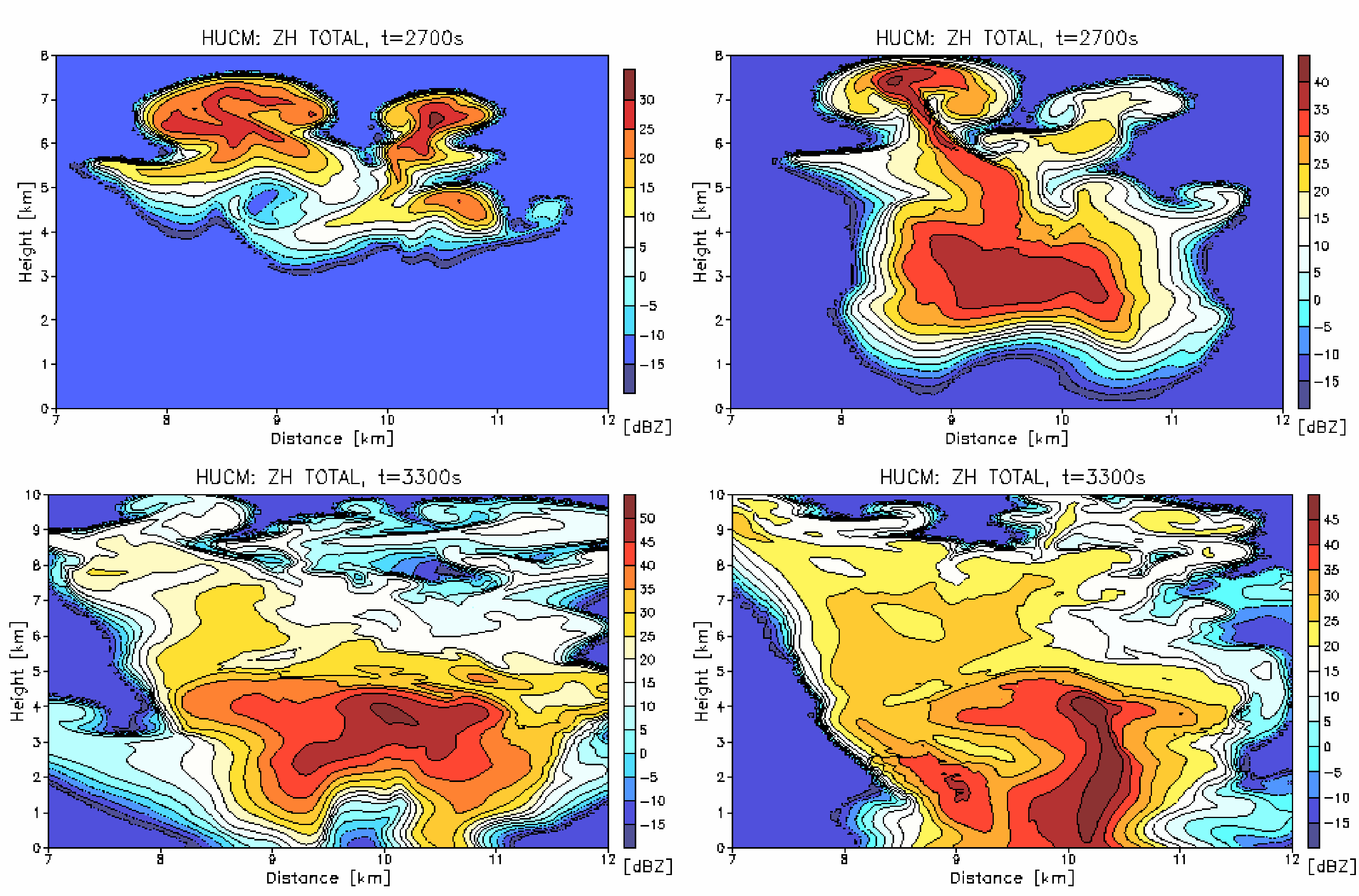


Figure 12. The fields of radar reflectivity in GO_gr (left) and GO_tur (right) during fall of warm rain.

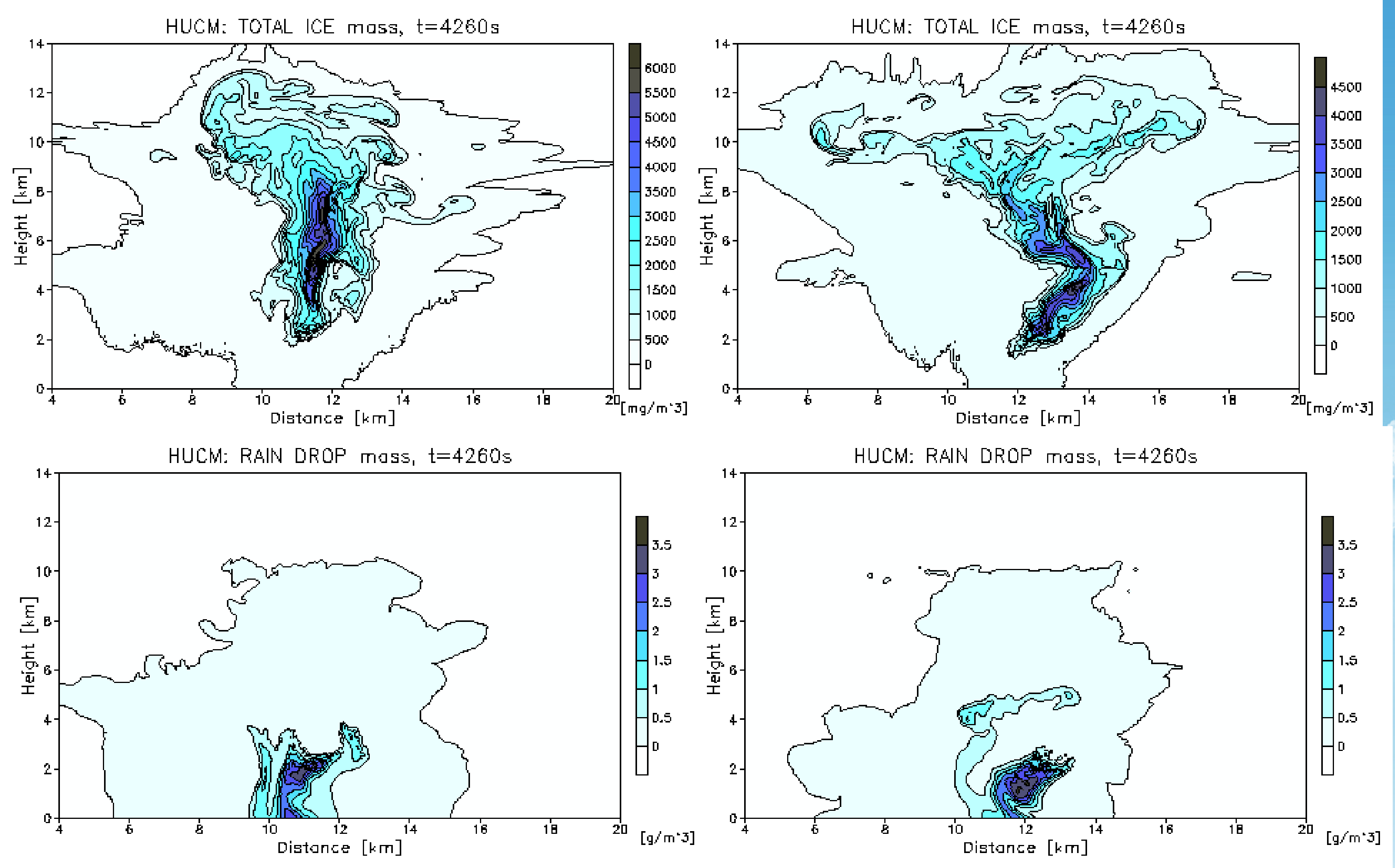


Figure 13. Fields of total ice content and RWC in S-gr (left panels) and S_tur (right panels)

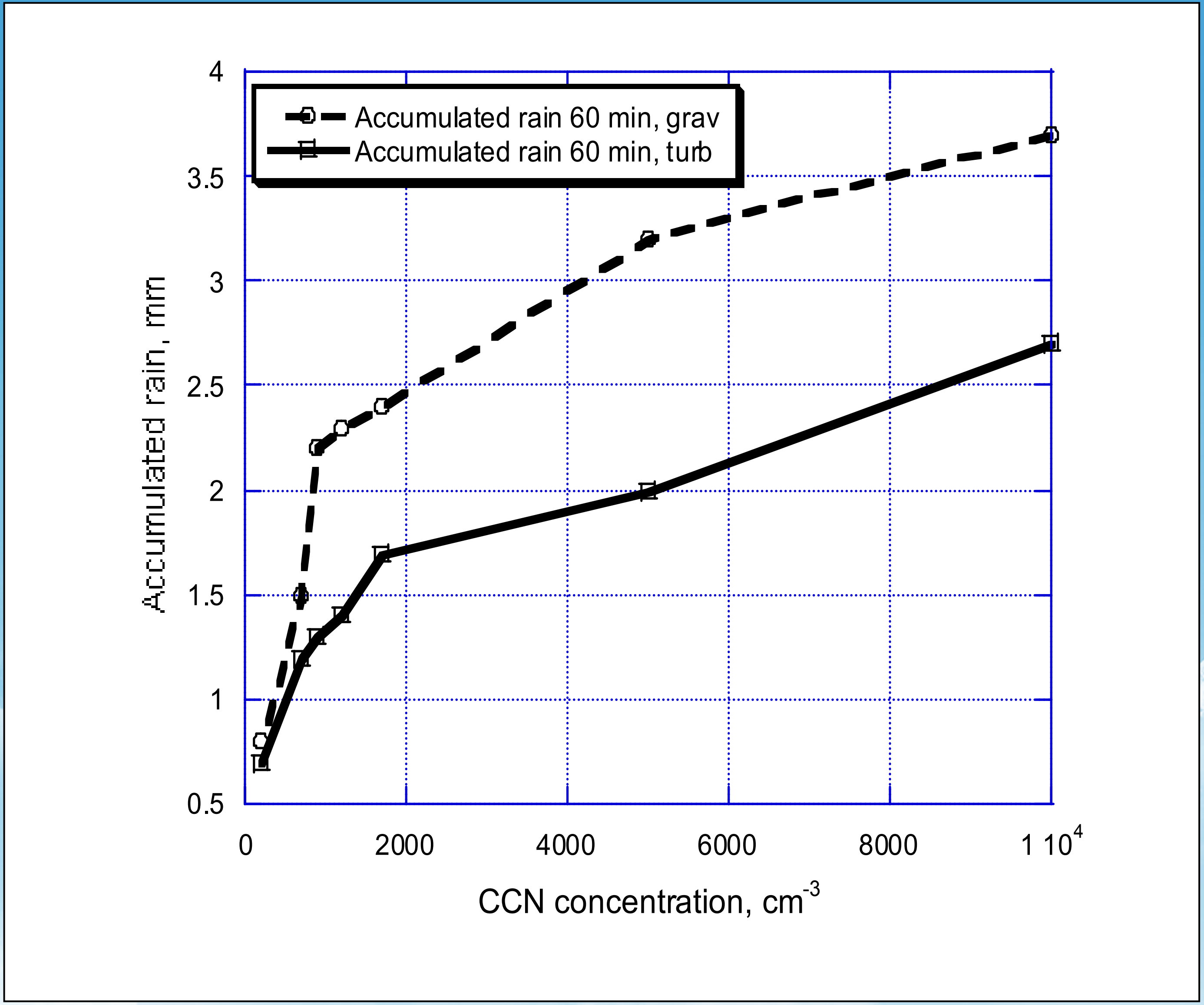


Figure 14. Dependence of accumulated rain at the surface on the CCN concentration obtained using gravitational and turbulent collision kernels 60 min after cloud formation.

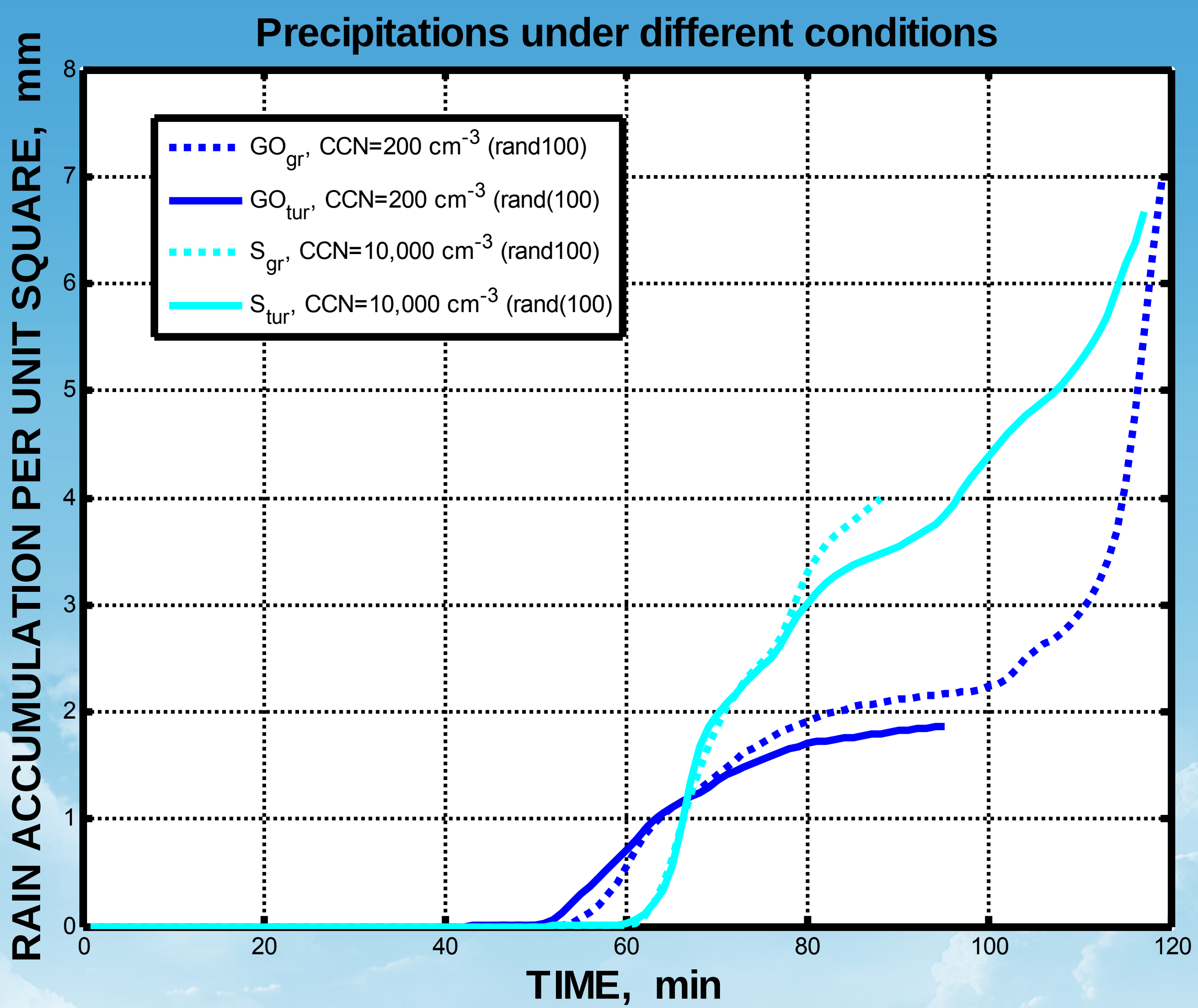


Figure 15. Accumulated rain at the surface in GO and S clouds, gravitational and turbulental

CONCLUSIONS

1) The turbulent structure of mixed-phase convective clouds observed in the LBA-SMOC field experiment was simulated with the CCN concentration varying from 200 to 10000 cm-3.

2) The simulations have been carried out using 2-D Hebrew University cloud model with spectral (bin) microphysics (HUCM) with uniform resolution of 50 m within the computational area 25.6 x 16 km.

3) Collision kernels were calculated in each grid point and at each time step.

Cloud turbulence:

4) Turbulence in clouds turned out to be highly inhomogeneous so that maximum values of dissipation rate and may be by order of magnitude higher than the values averaged over the entire cloud. The elongated zones of enhanced turbulence are located at the edges of ascending bubbles. They represent large scale turbulent intermittency in clouds.

5) Turbulence in polluted clouds turned out to be more intense than that in clouds developing in the clean atmosphere.

Rain drop formation:

6) The model reproduces accurately the DSD shapes in blue-ocean, green-ocean and smoky clouds measured in situ during the LBA-SMOC field experiment, as well as the vertical profiles of effective radius in these clouds.
7) The observed DSDs are reproduced better in simulations when the turbulent collision kernels were used.
8) It is shown that first raindrops form when the effective radius reaches 13.5-14 um.
9) It is shown that turbulence leads to acceleration of raindrop formation by 30-100%, which is a very significant effect. The turbulence decreases the height of the first raindrop formation from several hundred meters to ~1 km.

Surface rain:

10)Turbulence is the one of the main mechanism causing warm rain at the surface, especially for the CCN concentrations exceeding 700 cm-3.
11) The effect of turbulence-induced enhancement of drop collisions on the cold precipitation is just opposite: in polluted air turbulence decreases surface rain by about **30%-40%** as compared with the cases when the gravitational kernels are used.
12) Thus, the role of turbulent –induced collision rate enhancement is somehow opposite to that of small aerosols playing the role of CCNs.


THANK YOU!