Turbulence-microphysics interactions in boundary layer clouds

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with contributions from D. Jarecka[2], H. Morrison[1], H. Pawlowska[2], J.Slawinska[3], L.-P. Wang[4] A. A. Wyszogrodzki[1]

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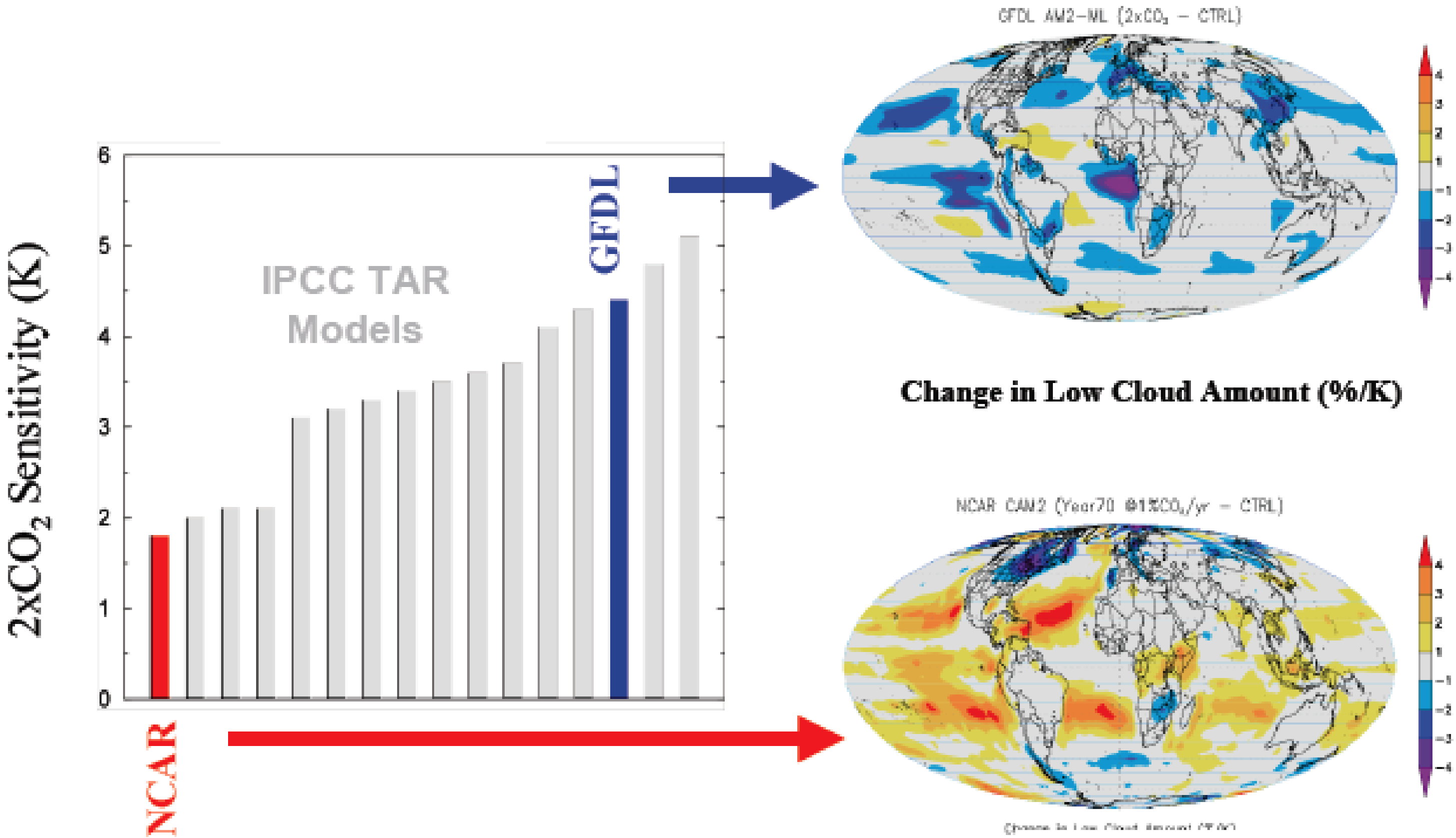
Why shallow convection?

1. Because it plays a critical role in the climate system (together with St)….
2. Because this is where radiative sensitivity to microphysics might be the largest…
3. Because it will remain parameterized in GCMs for any foreseeable future…

Brian Soden, U. of Miami

Climate Sensitivity and Low Cloud Feedback



Resolving macroscopic processes associated with shallow convection requires gridlengths between 10 and 100 m (the Large Eddy Simulation approach). Since such resolutions are unlikely to be used in atmospheric GCMs any time soon, development of sophisticated parameterizations, guided by observations and modeling studies, is badly needed…

Turbulence-microphysics interactions in shallow ice-free convective clouds (cumulus, stratocumulus):

- Turbulent entrainment affects spectrum of cloud droplets (mean size, concentrations); relevant processes concern in-cloud activation, homogeneity of parameterized subgrid-scale mixing, etc.

- Turbulence affects growth of cloud droplets and formation of drizzle/rain.

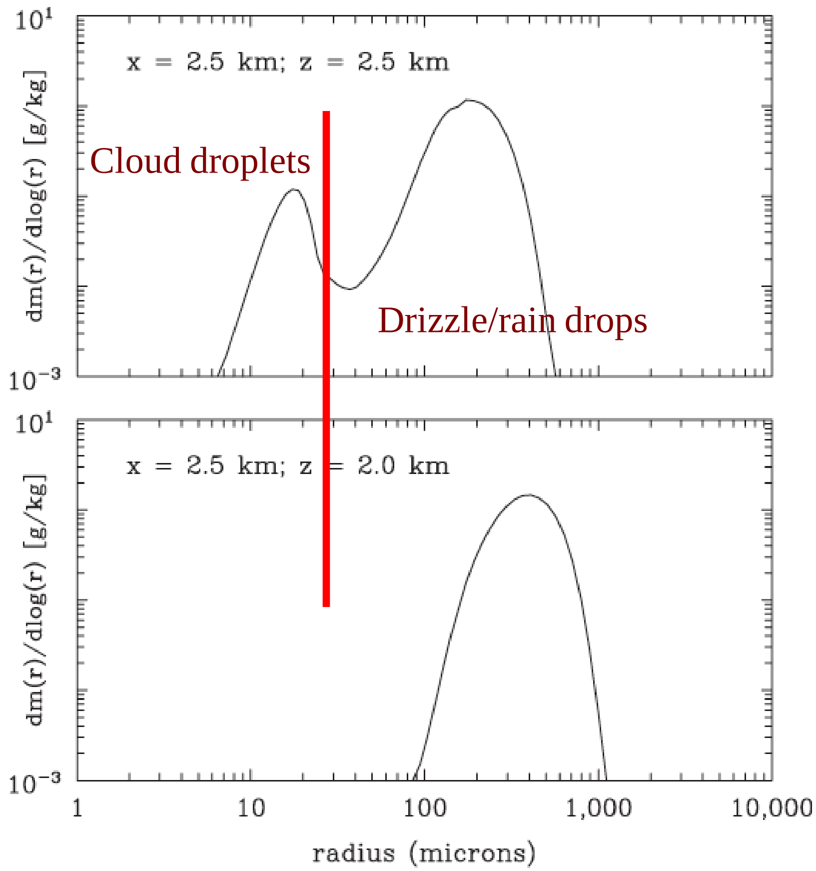
Warm-rain microphysics:
- double-moment scheme (Morrison and Grabowski, *JAS* 2007, 2008)
-bin microphysics (Grabowski et al. *Atoms. Res*. 2011)

Double-moment warm-rain microphysics of Morrison and Grabowski (2007, 2008):

- Prediction of concentrations and mass of cloud droplets and rain drops (4 variables);

- Prediction of in-cloud supersaturation and thus relating the concentration of activated cloud droplets to local value of the supersaturation; additional variable (concentration of activated CCN) needed;

- Allows various mixing scenarios for subgrid-scale mixing (from homogeneous to extremely inhomogeneous).



Bin warm-rain microphysics of Grabowski et al. (2011):

- Prediction of the spectral shape of cloud droplets and drizzle/rain; 112 bins

- Prediction of supersaturation and thus relating the concentration of activated cloud droplets to local value of the supersaturation; additional variable (concentration of activated CCN) needed;

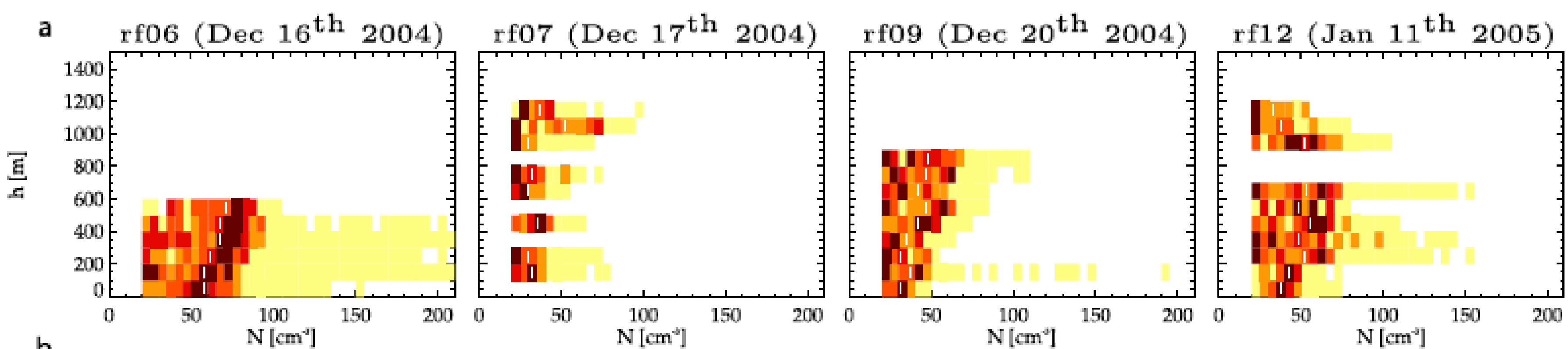
Gerber et al. *JMSJ* 2008

Table 3. Microphysics of the seven Cu at five different levels shown in Fig. 2, with mean values of LWC (liquid water content) and its sample standard deviation for three horizontal data resolutions, total droplet concentration N, and mean volume radius r_v. The latter two parameters correspond to 10-m resolution data. The subscript a indicates expected adiabatic values.

Level	LWC_a (g/m^3)	LWC (g/m^3)	s (10 cm) (g/m^3)	s (50 cm) (g/m^3)	s (1000 cm) (g/m^3)	N (No/cc)	s [N] (No/cc)	r_{va} (µm)	r_v (µm)	s (r_v) (µm)
1	.605	.284	.084	.078	.063	95	12	11.4	9.2	2.0
2	1.00	.427	.142	.136	.128	97	22	13.5	10.6	3.1
3	1.42	.520	.160	.153	.145	112	25	15.2	10.2	1.7
4	2.11	.536	.196	.184	.173	116	11	17.3	10.6	2.4
5	2.46	.331	.142	.135	.125	54	35	18.2	11.9	3.7

Arabas et al. *GRL* 2009

ARABAS ET AL.: OBSERVATIONS OF CU MICROPHYSICS



RICO (Rain in Cumulus over Ocean) field project observations

A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

A. Pier Siebesma,[a] Christopher S. Bretherton,[b] Andrew Brown,[c] Andreas Chlond,[d] Joan Cuxart,[e] Peter G. Duynkerke,[f*] Hongli Jiang,[g] Marat Khairoutdinov,[h] David Lewellen,[i] Chin-Hoh Moeng,[j] Enrique Sanchez,[k] Bjorn Stevens,[l] and David E. Stevens[m]

JAS
2003

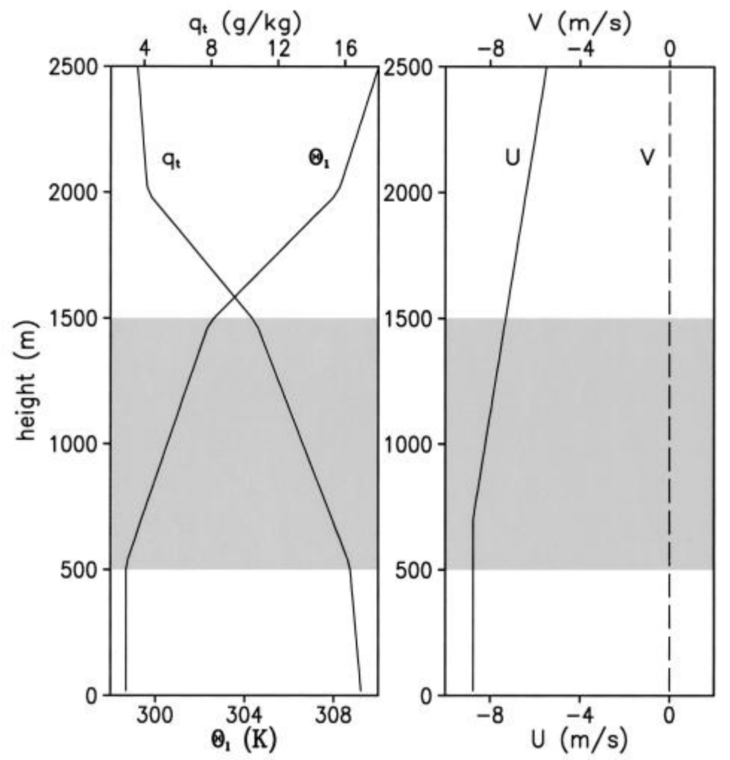
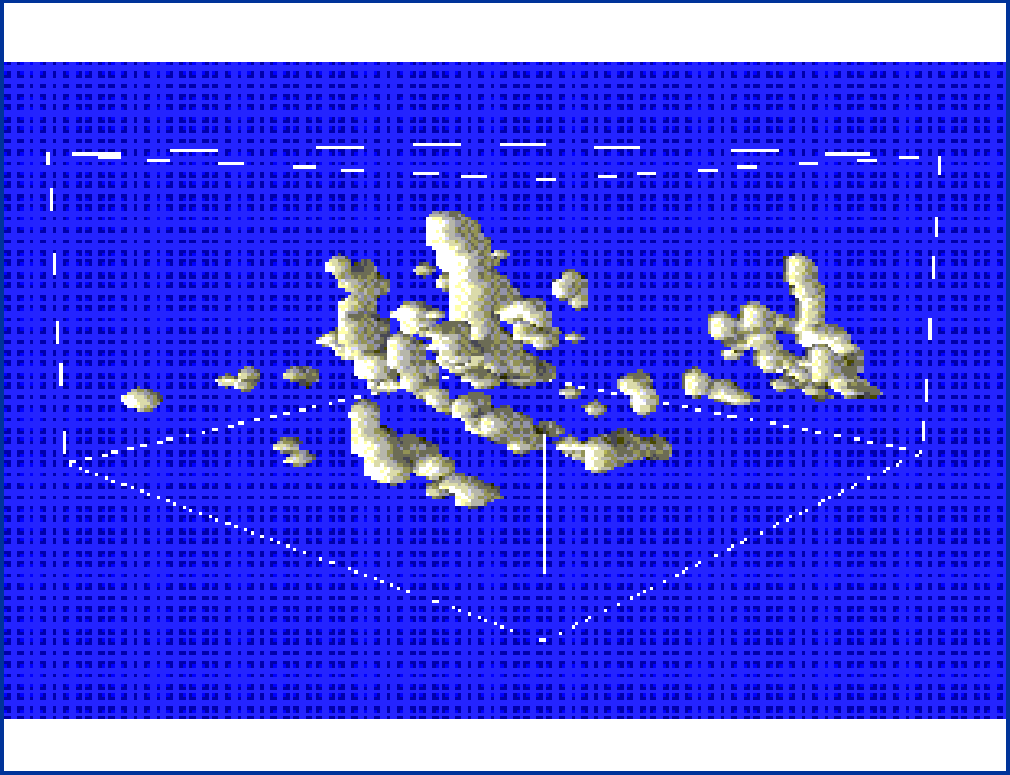
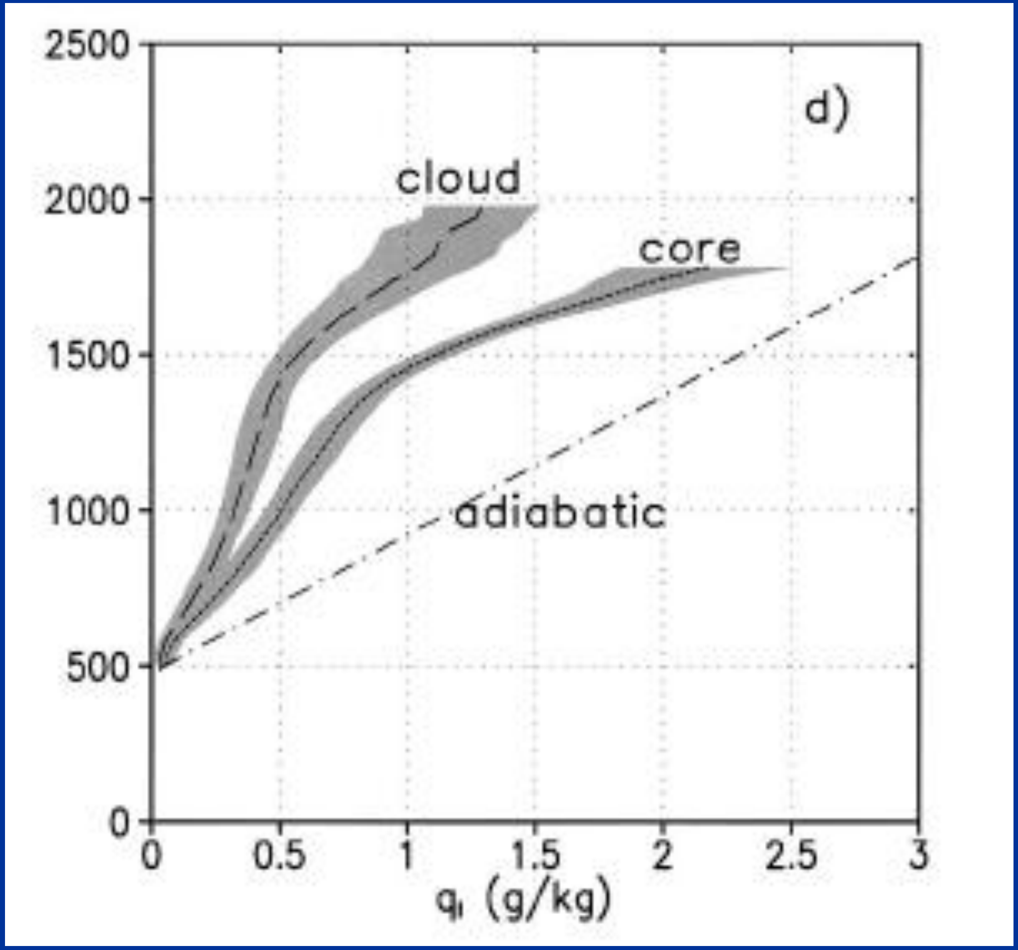


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.



The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

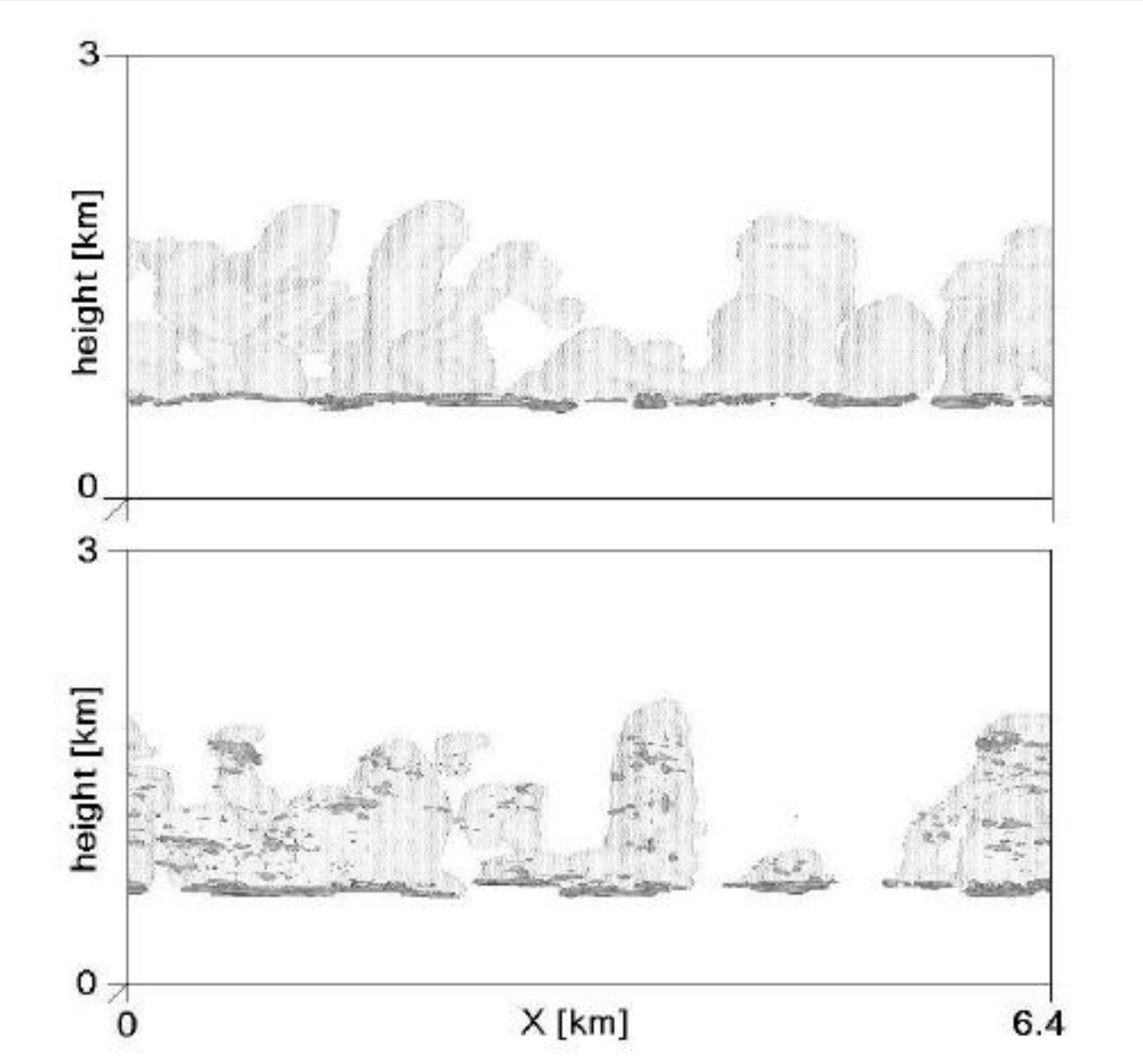
How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?



How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?

In-cloud activation (i.e., activation above the cloud base)!

gray – cloud water; dark gray – positive activation tendency

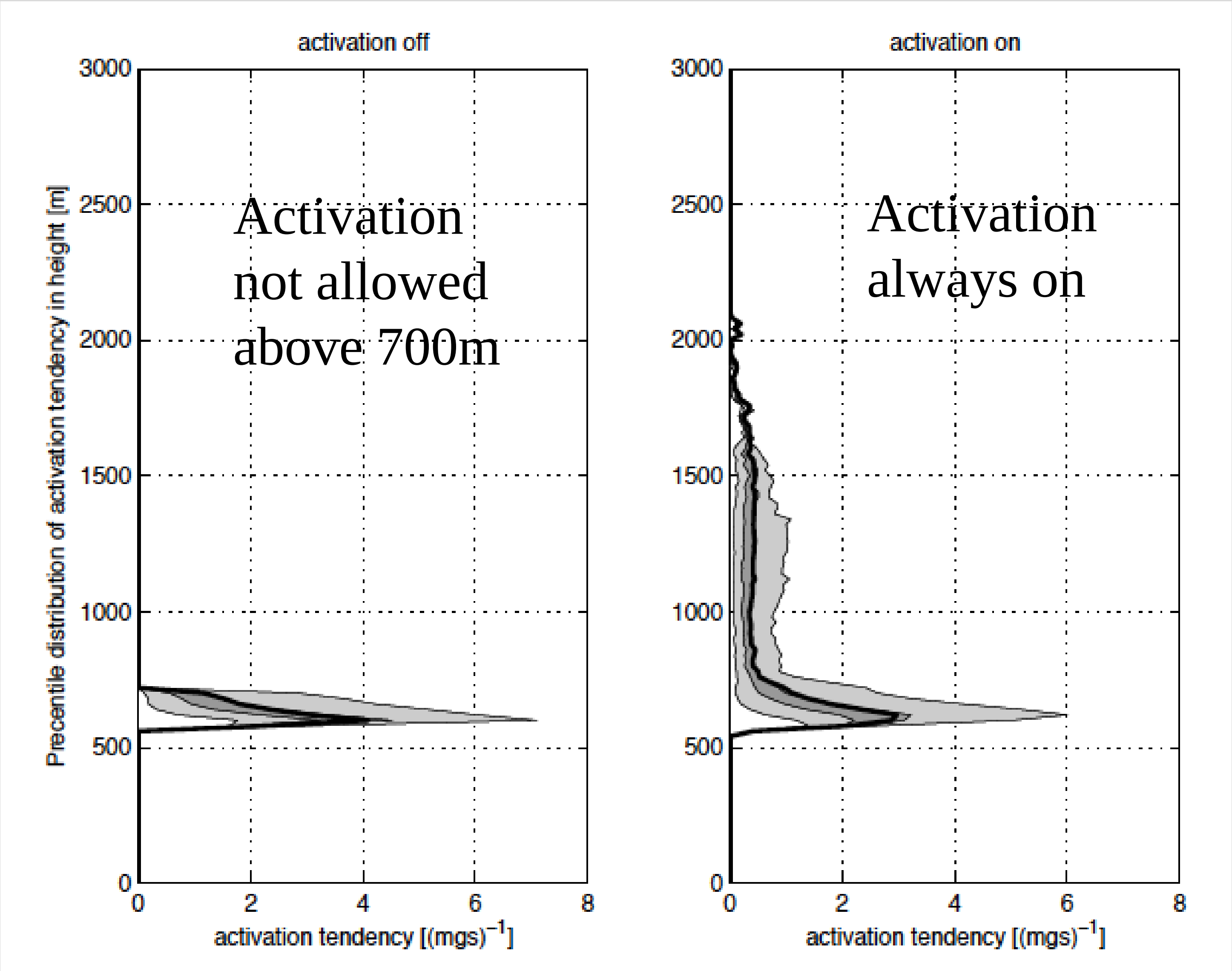


Activation not allowed above 700m

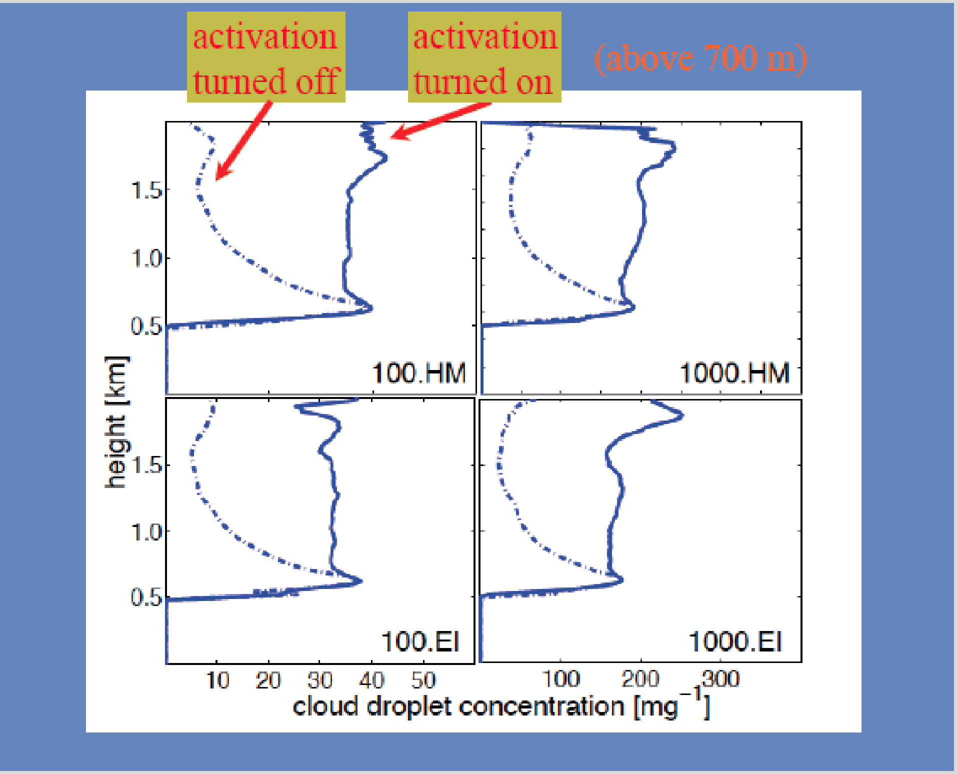
Activation always on

Wyszogrodzki et al. (*Acta Geophysica* 2012)

Conditionally-sampled activation tendency



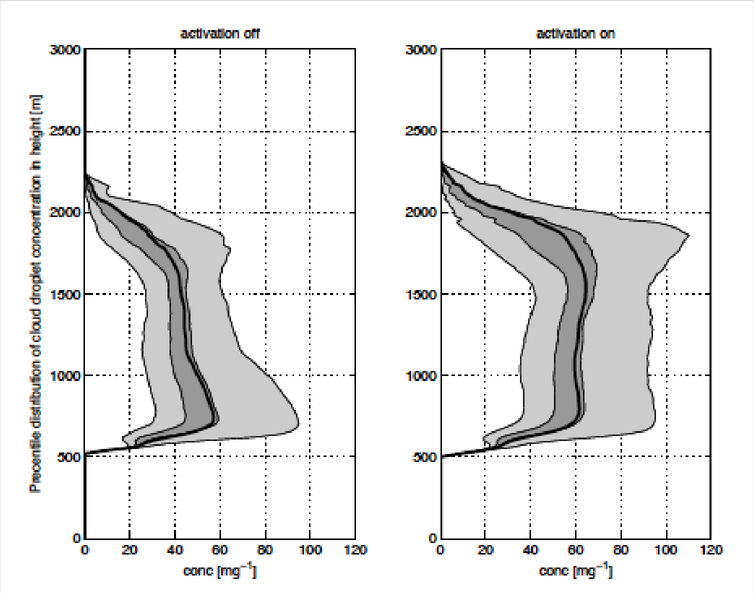
Wyszogrodzki et al. (*Acta Geophysica* 2012)



Slawinska et al. (*J. Atmos. Sci*. 2012)

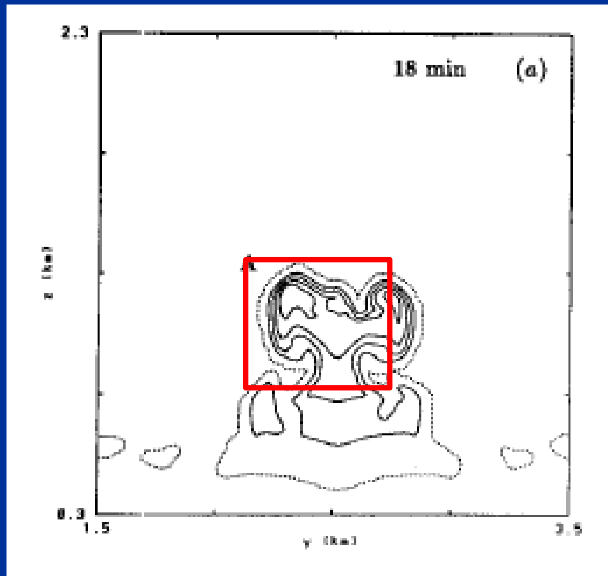
Activation not allowed above 700m

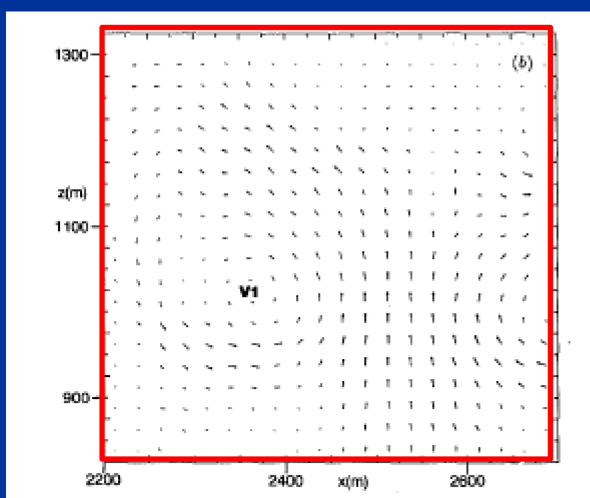
Activation always on

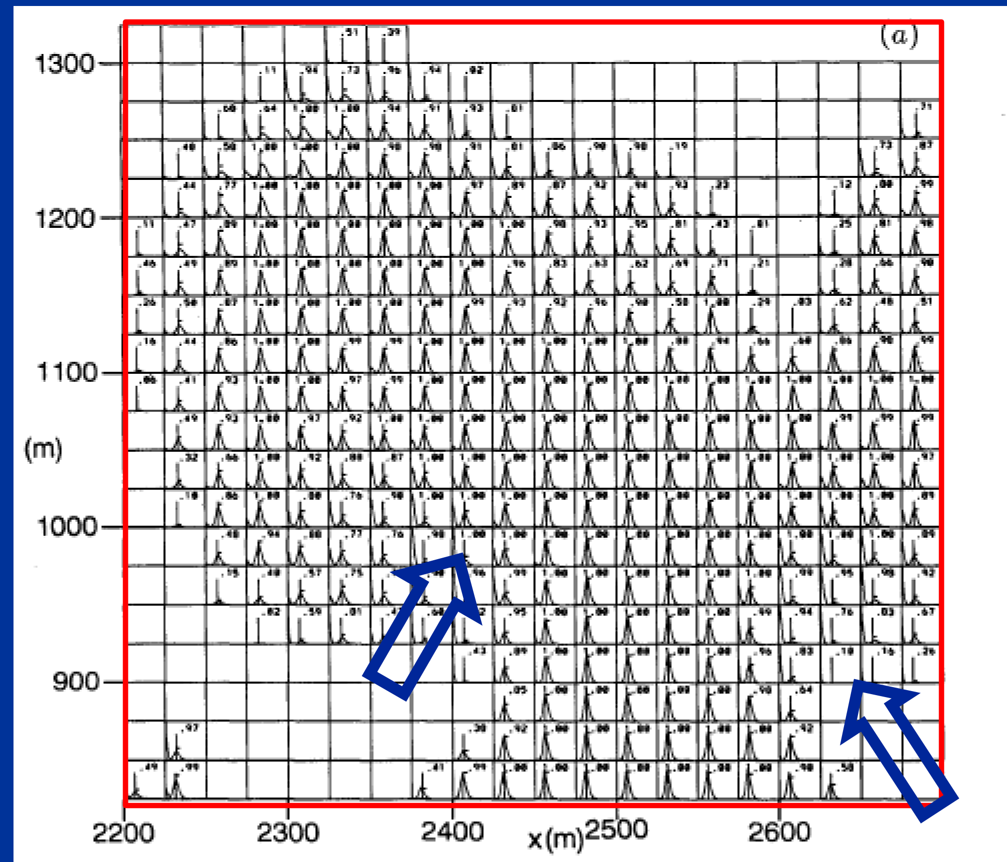


Wyszogrodzki et al. (*Acta Geophysica* 2012)

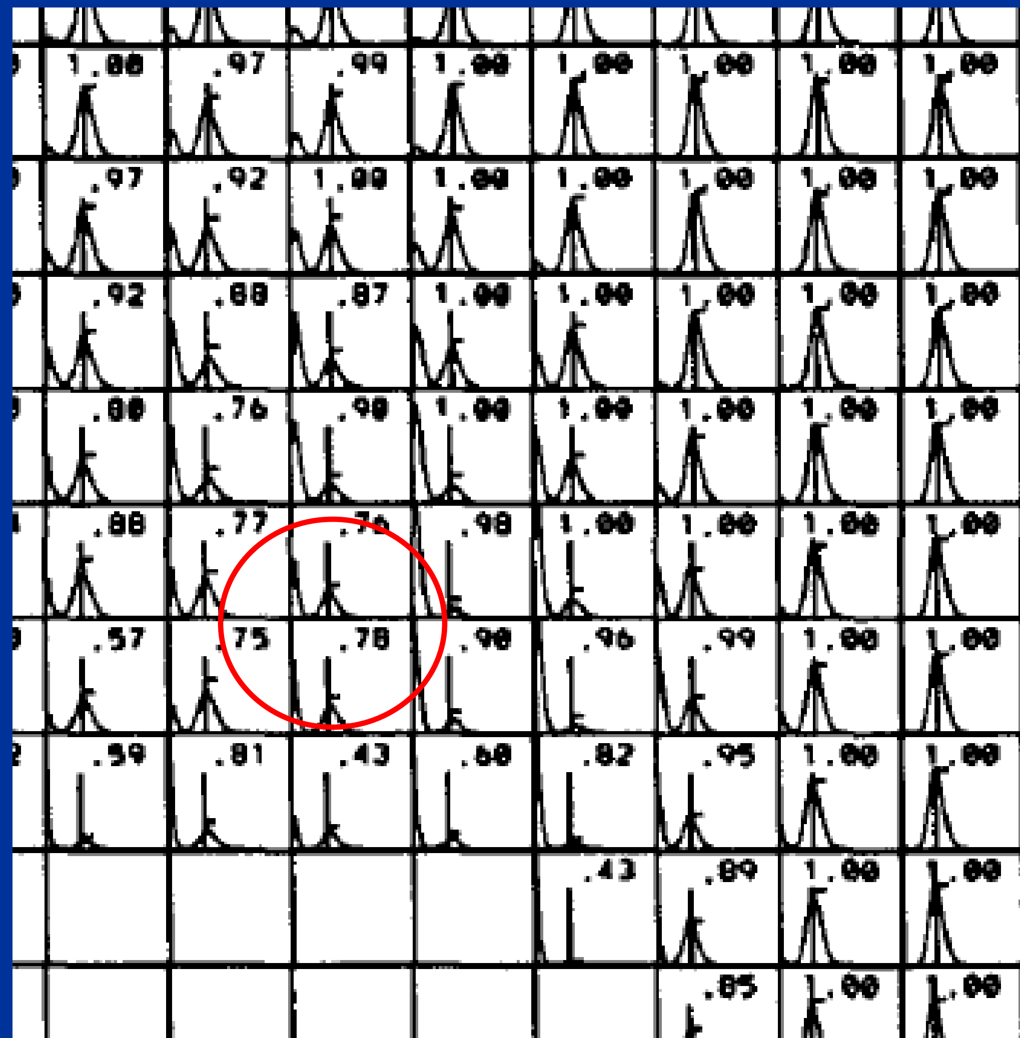
Droplet concentrations with and without in-cloud activation





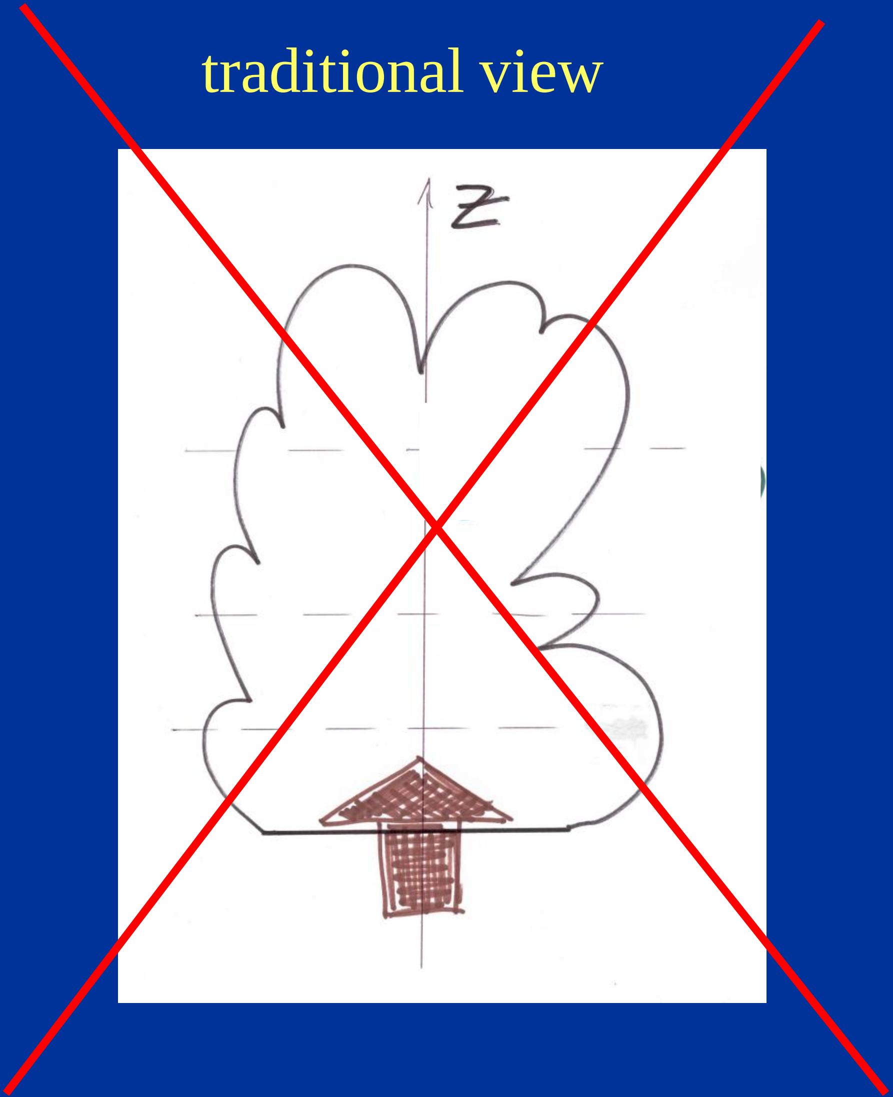


Brenguier and Grabowski (JAS 1993)

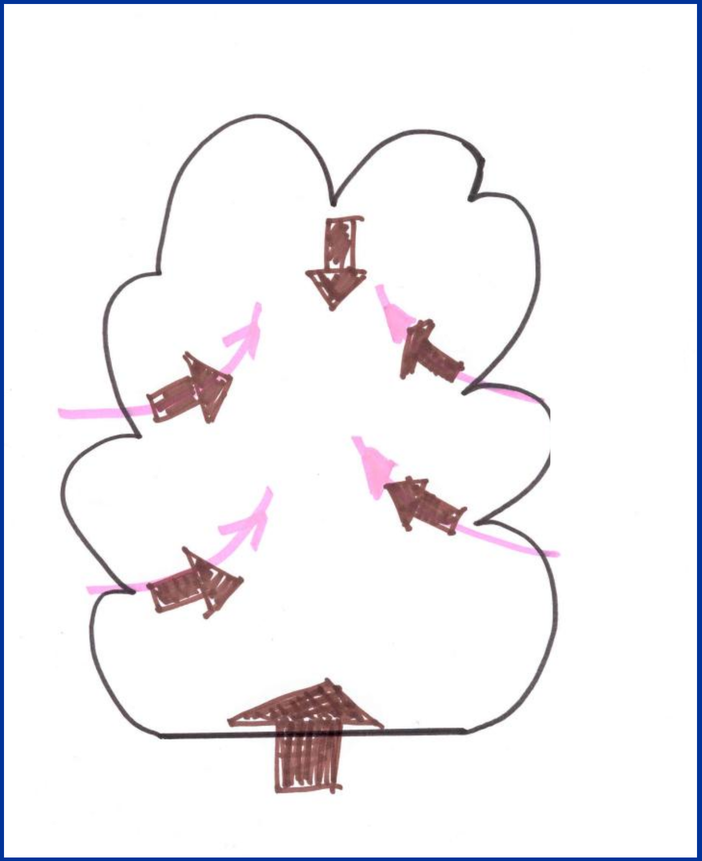


Brenguier and Grabowski (JAS 1993)

traditional view



view suggested by
model simulations



Conclusions (for the 1st part):

Activation of cloud droplets above the cloud base is essential for realistic simulation of cloud microphysics. In simulations reported here, about 40% of cloud droplets is activated above the cloud base. Only with in-cloud activation, key features of observed shallow cumuli can be simulated (e.g., constant or increasing mean concentration of cloud droplets with height)

Activation seems to mimic entrainment-related activation observed in higher-resolution cloud simulation.

Towards the assessment of the role of cloud turbulence in warm-rain processes

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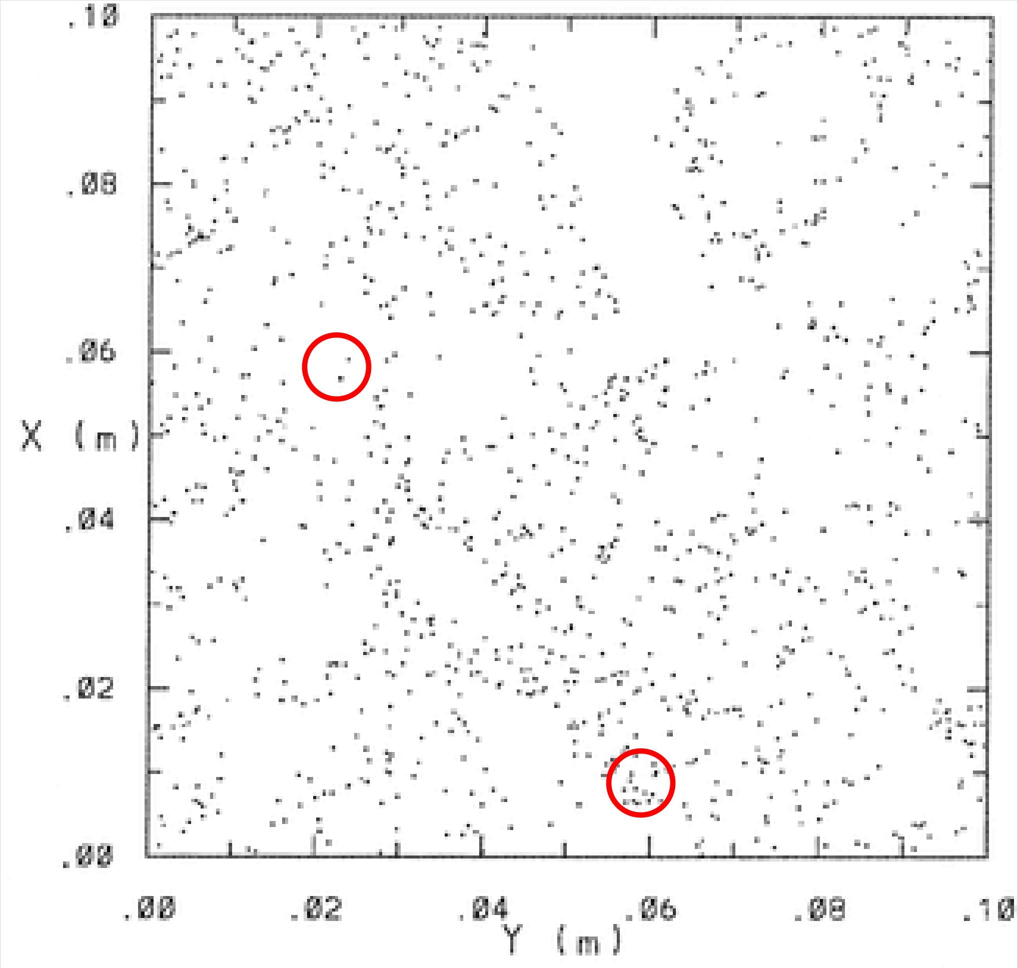
Growth by collision/coalescence: nonuniform distribution of droplets in space affects droplet collisions…



NB: insignificant impact on growth by the diffusion of water vapor ; reversible vs irreversible growth (Grabowski and Wang; ARFM 2013).

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence:

-Turbulence modifies local droplet concentration (preferential concentration effect)

-Turbulence modifies relative velocity between colliding droplets (e.g., small-scale shears, fluid accelerations)

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence:

geometric collisions
(no hydrodynamic interactions)

-Turbulence modifies local droplet concentration (preferential concentration effect)

-Turbulence modifies relative velocity between colliding droplets (e.g., small-scale shears, fluid accelerations)

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence:

-Turbulence modifies local droplet concentration (preferential concentration effect)

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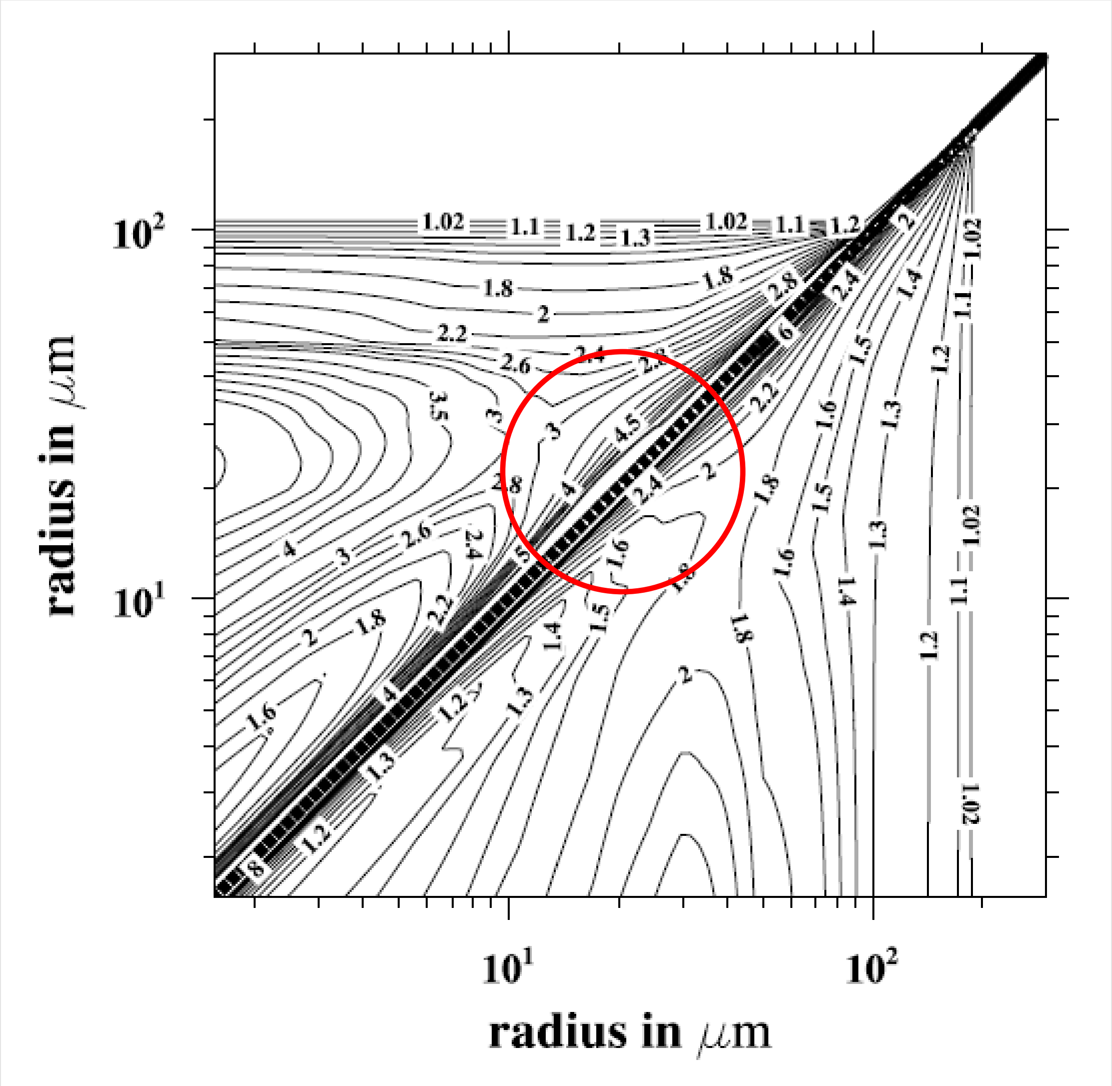
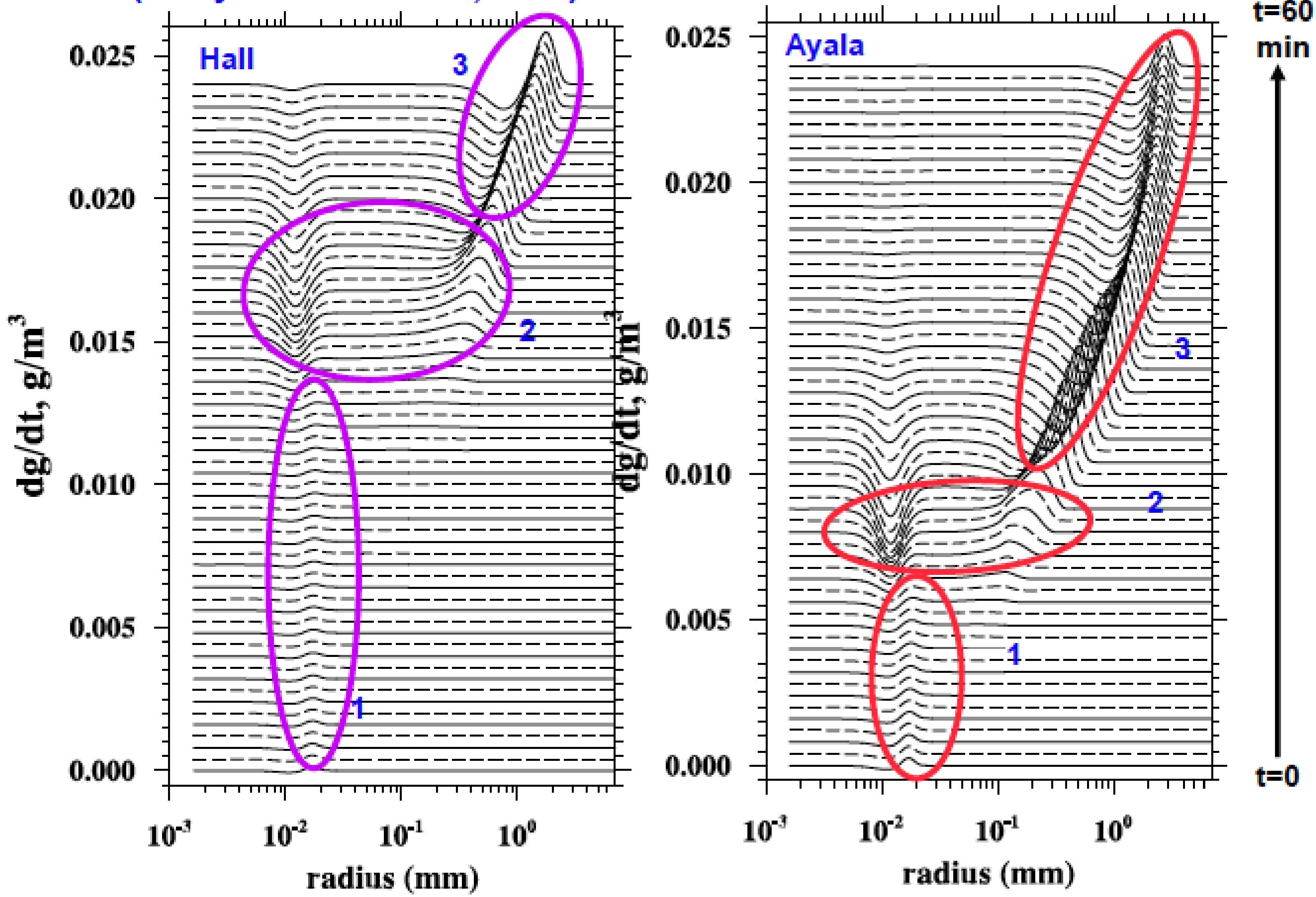
- Turbulence modifies hydrodynamic interactions when two droplets approach each other

collision efficiency



Enhancement factor for the collision kernel (the ratio between turbulent and gravitation collision kernel in still air) including turbulent collision efficiency; ε = 100 and 400 $cm^2\ s^{-3}$.

1. Autoconversion; 2. Accretion; 3. Hydrometeor self-collection (Berry and Reinhardt, 1974)



without turbulence

with turbulence, ε = 400 cm^{2}s^{-3}

A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

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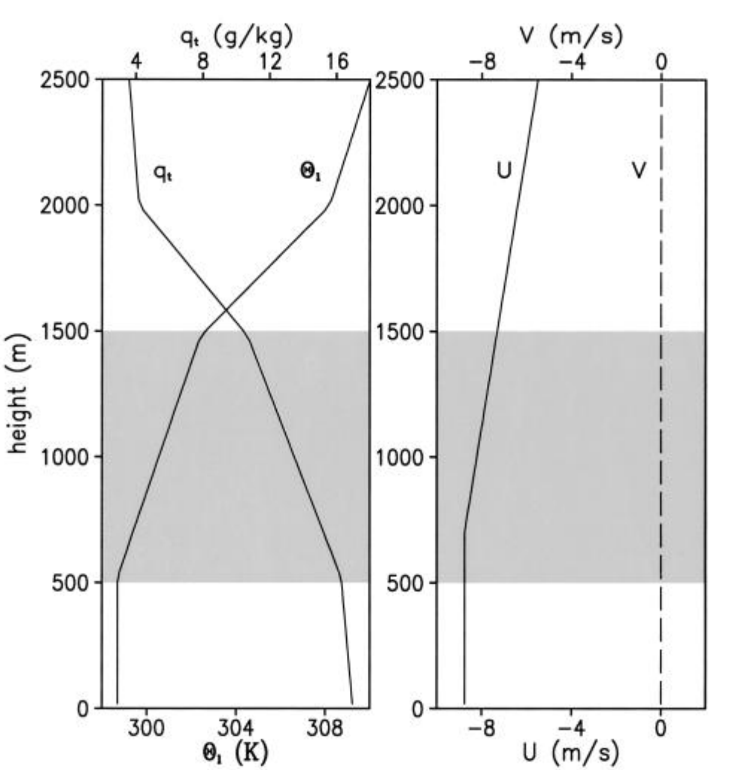
JAS
2003



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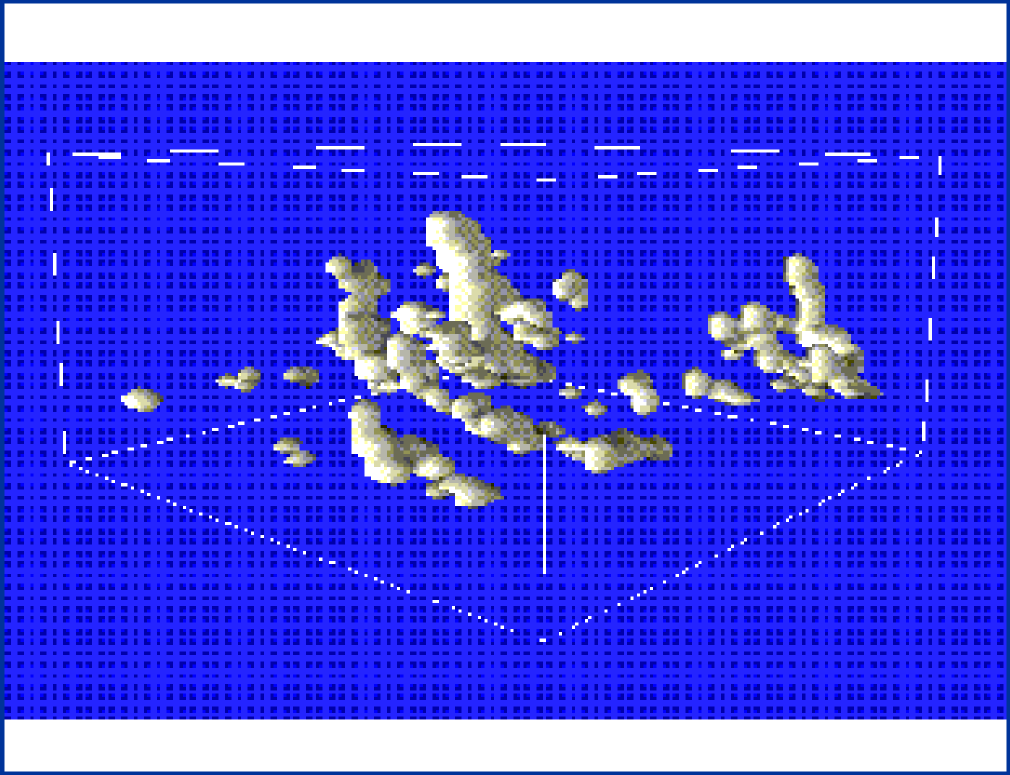


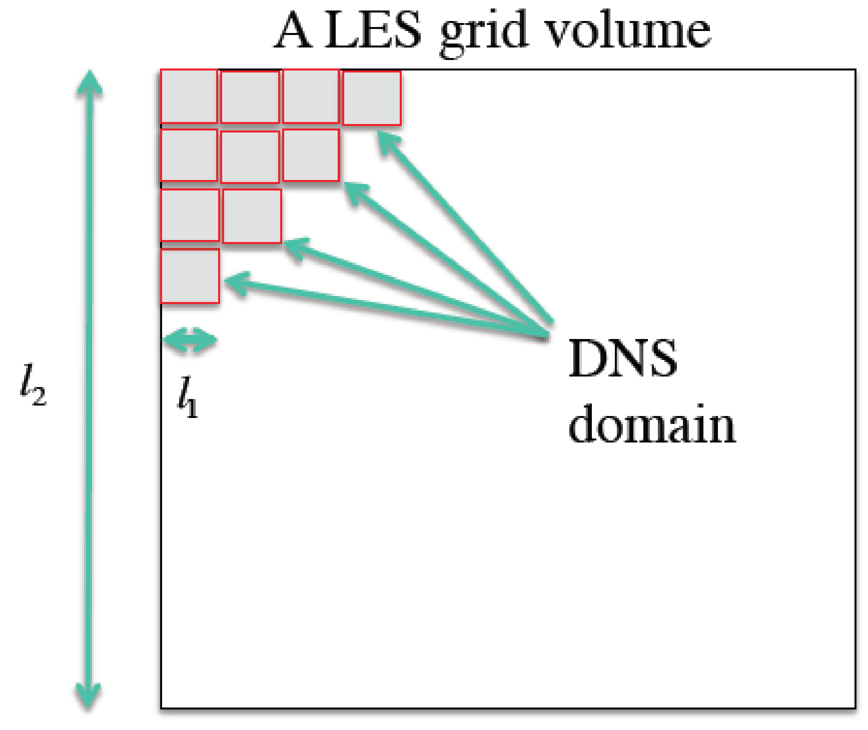
The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973)

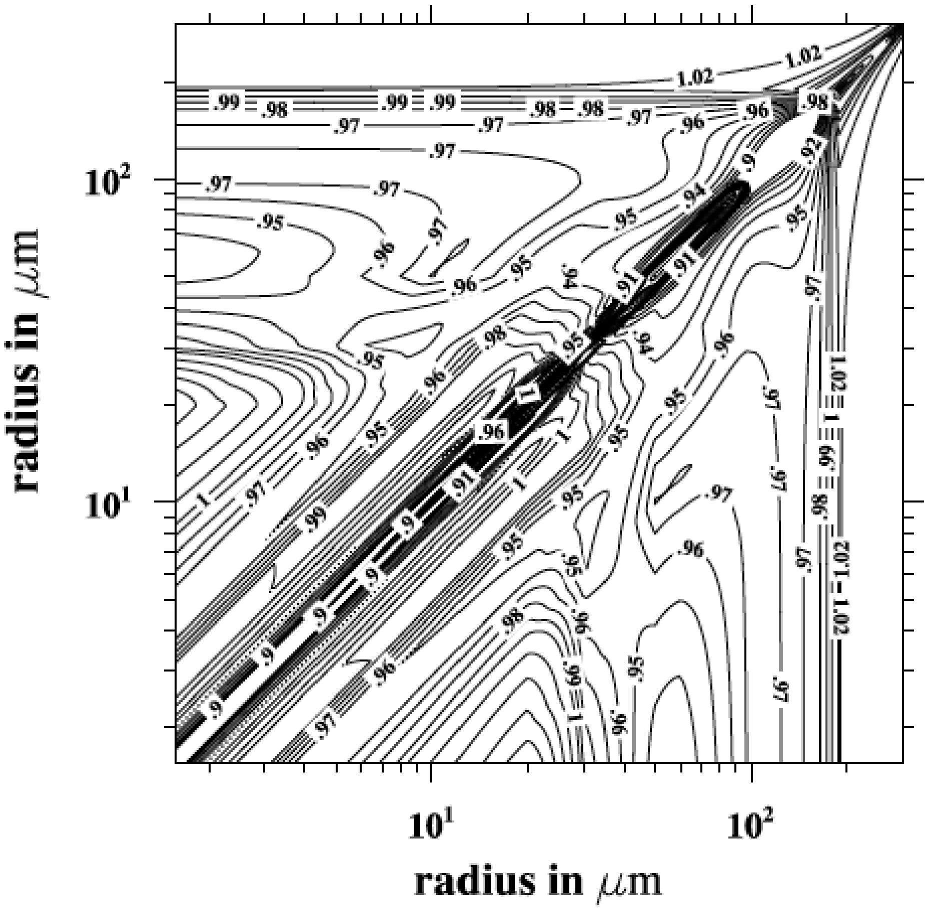
The size gap between LES and DNS

Current DNS domain size $= l_1 \sim 0.5$ m

Current LES grid length $= l_2 \sim 10$ m to 100 m

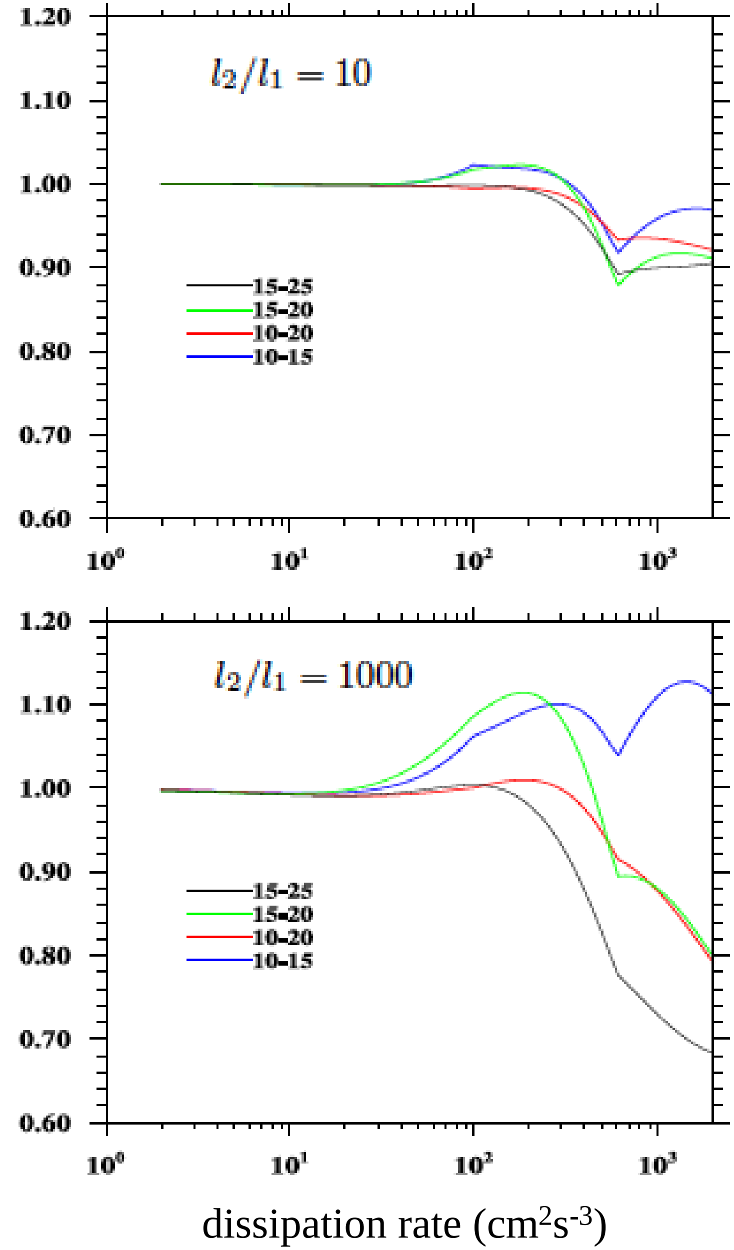
$$20 < \frac{l_2}{l_1} < 200$$





$$\langle \varepsilon \rangle = 100 \text{ cm}^2/\text{s}^3$$

$$l_2/l_1 = 100$$



Rain formation depends critically on the CCN concentration, so we consider a range …

$$N_{CCN} = \begin{cases} N^0_{CCN} & \text{if } S > 1 \\ N^0_{CCN}\ S^{0.4} & \text{if } 0.1 < S < 1 \\ N^0_{CCN}\ (0.1)^{-3.6} S^4 & \text{if } S < 0.1 \end{cases}$$

N^0_{CCN} : 30, 60, 120, 240 mg^{-1}

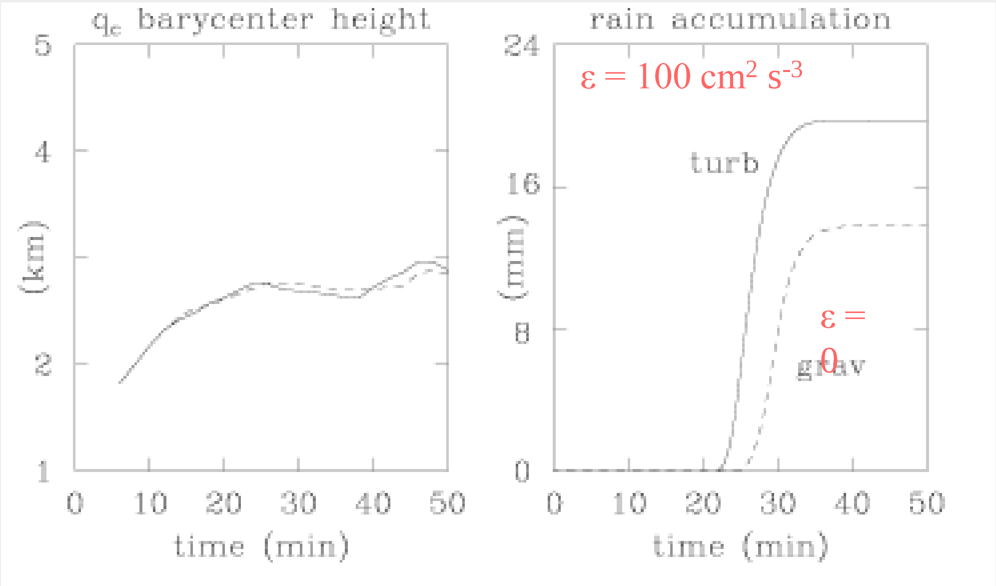
Before considering LES of a cloud field, lets consider a simple (2D, idealized) single cloud simulation: a bubble (thermal) rising in a stratified environment using the same EULAG bin model…

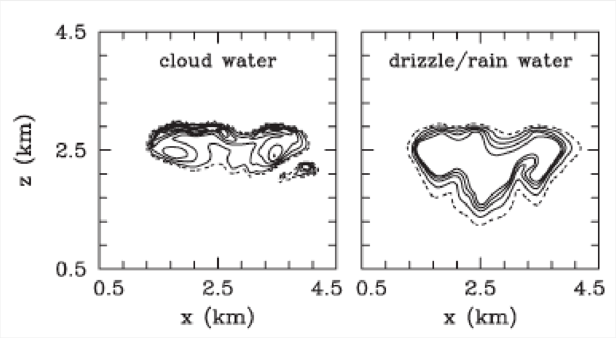
For reasons that will become obvious in the discussion, lets consider two cases:

- 2-layer system: bubble's rise is stopped by an inversion;
- 1-layer system: bubble can rise unobstructed towards the upper boundary.

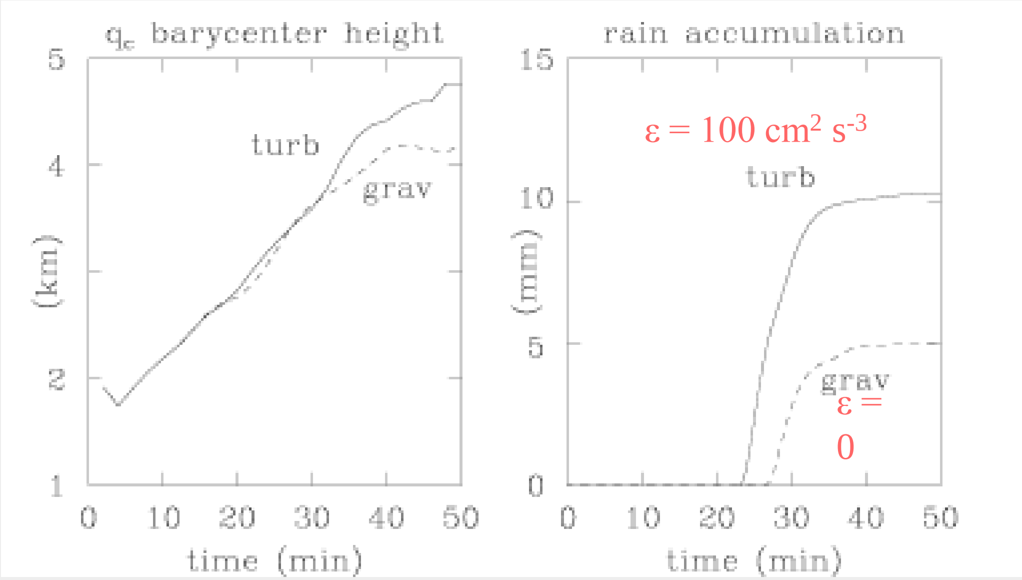
Compare simulations with a gravitation collection kernel and with a turbulent kernel assuming $\varepsilon = 100\ cm^2s^{-3}$.

Rising bubble simulation with an inversion at 2.5 km (2 layers)

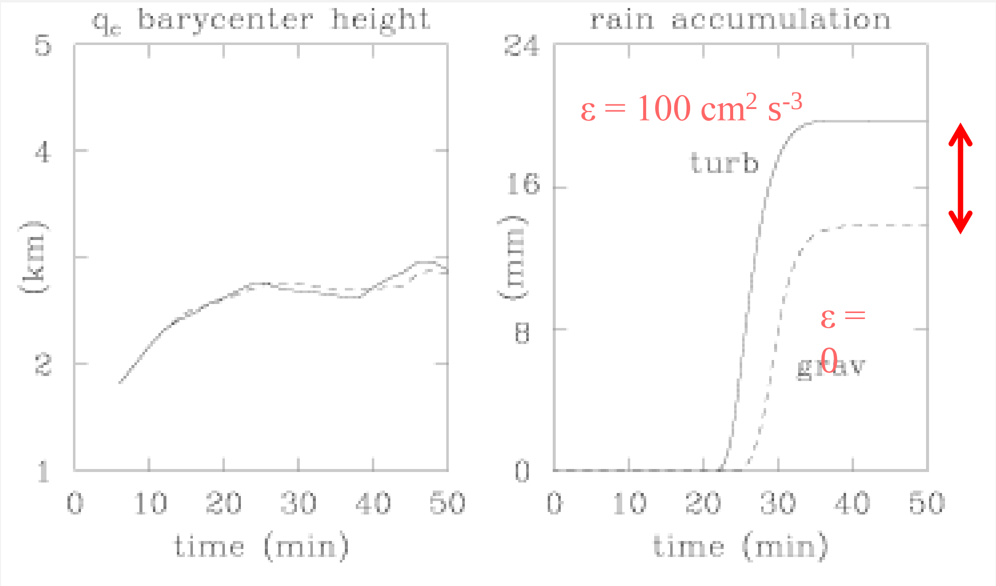




Rising bubble simulation without an inversion (1 layer)



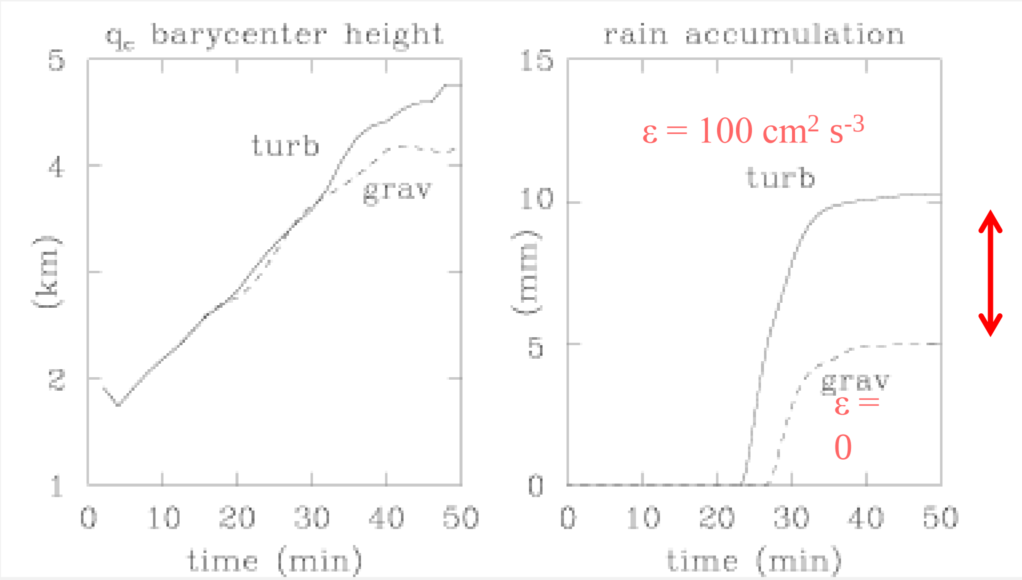
Rising bubble simulation with an inversion at 2.5 km (2 layers)



Microphysical enhancement

~40%

Rising bubble simulation without an inversion (1 layer)



Dynamical enhancement

~100%

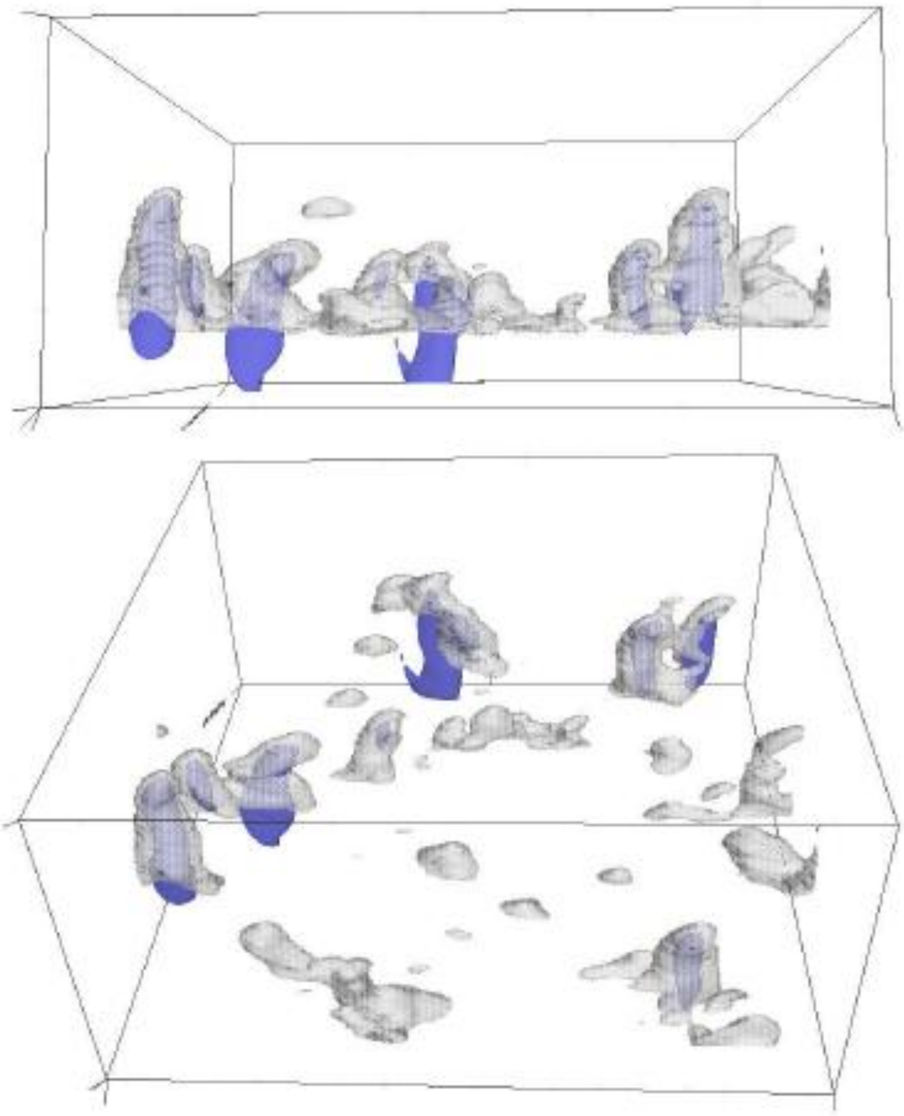
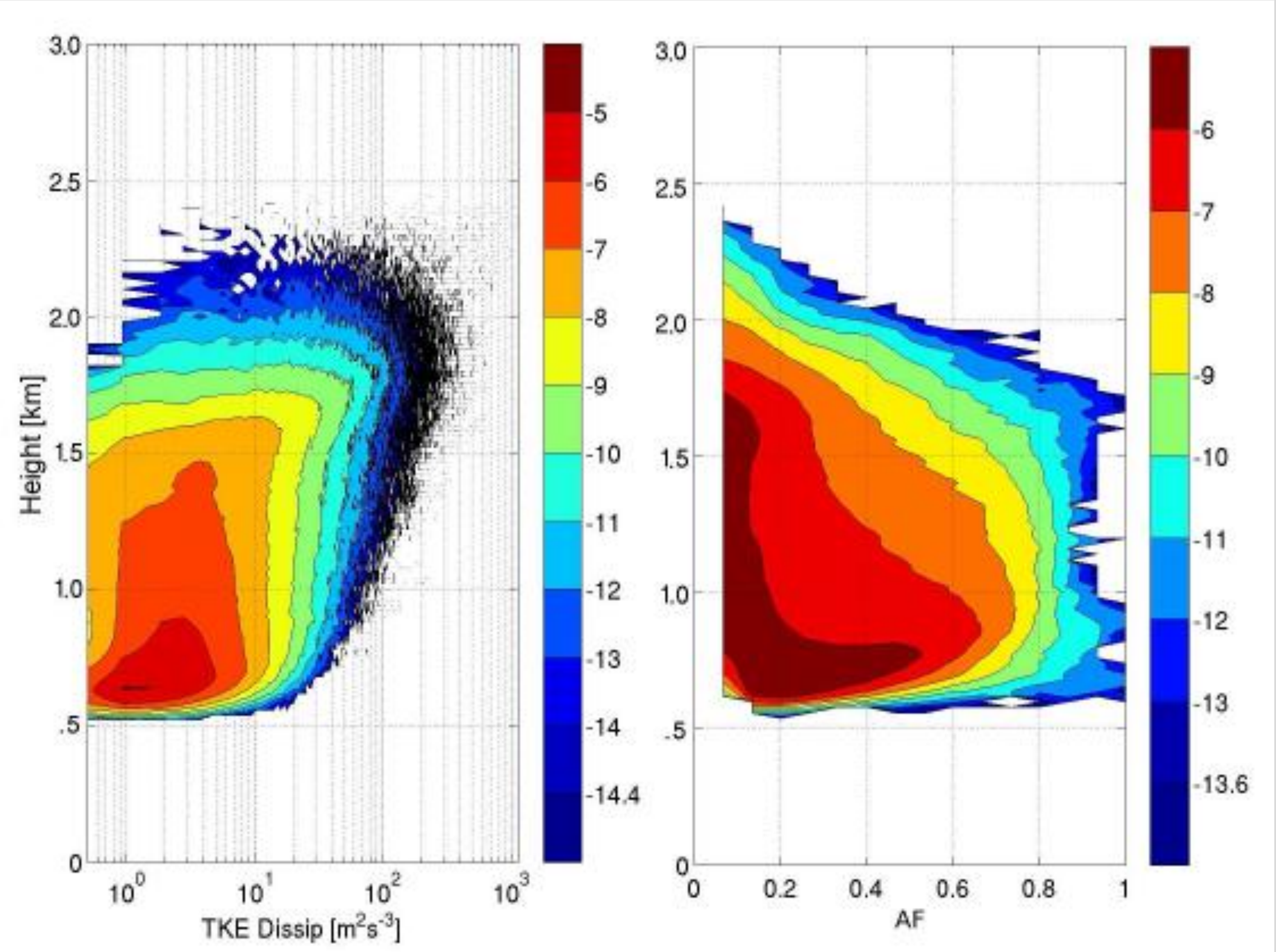


Fig. 4. Snapshots of cloud water mixing ratio (transparent gray) and rain water mixing ratio (solid blue) at the 6th hour of the simulation. The isosurfaces show values $q_c = 0.05\ \mathrm{g\,kg^{-1}}$ and $q_r = 0.02\ \mathrm{g\,kg^{-1}}$.



3.0
2.5
2.0
1.5
1.0
.5
0
Height [km]
10^0
10^1
10^2
10^3
TKE Dissip [m^2s^-3]
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-14.4
0
0.2
0.4
0.6
0.8
1
AF
-6
-7
-8
-9
-10
-11
-12
-13
-13.6

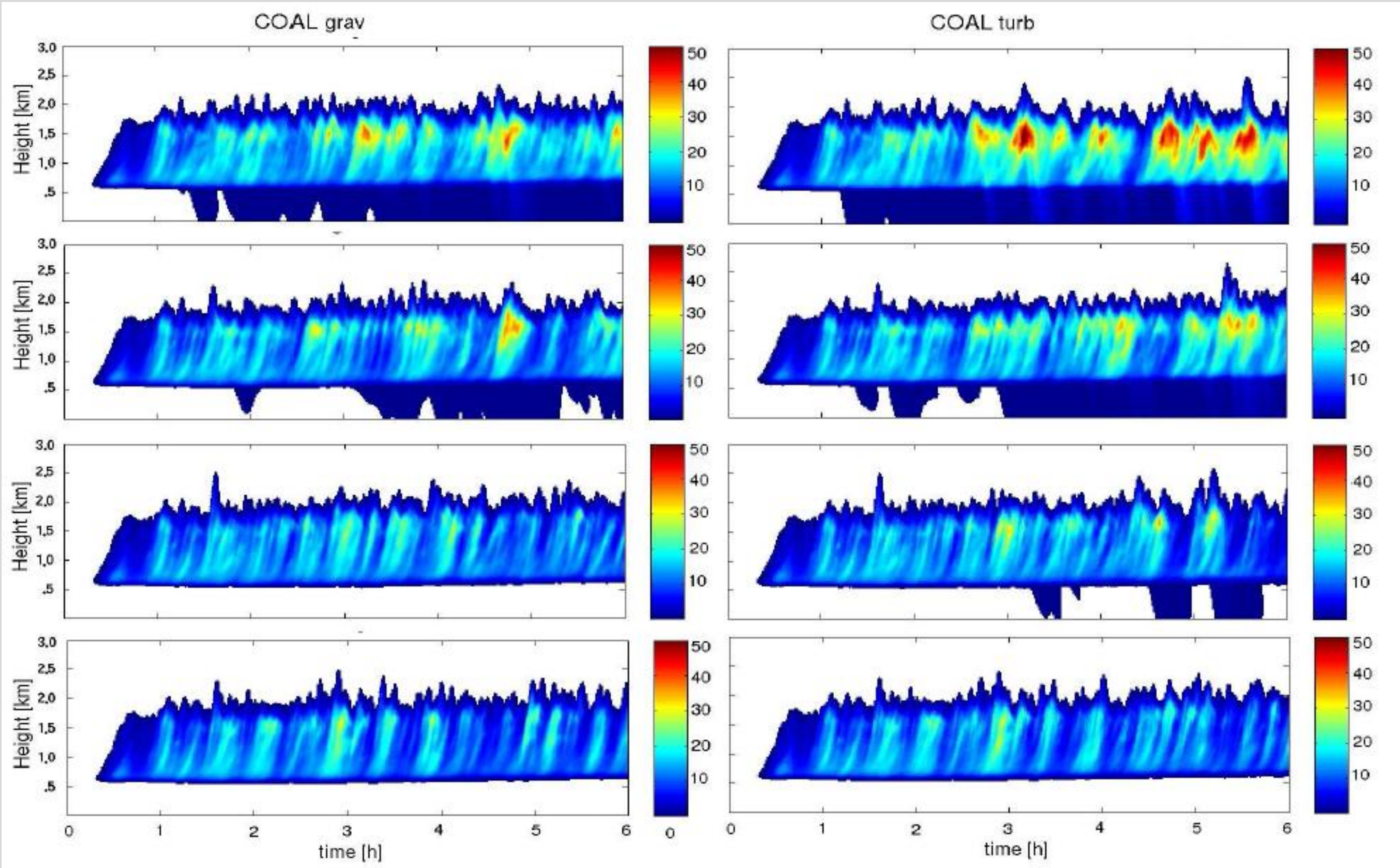
Domain-averaged cloud water mixing ratio

30

60

120

240



Gravitational kernel

Turbulent kernel

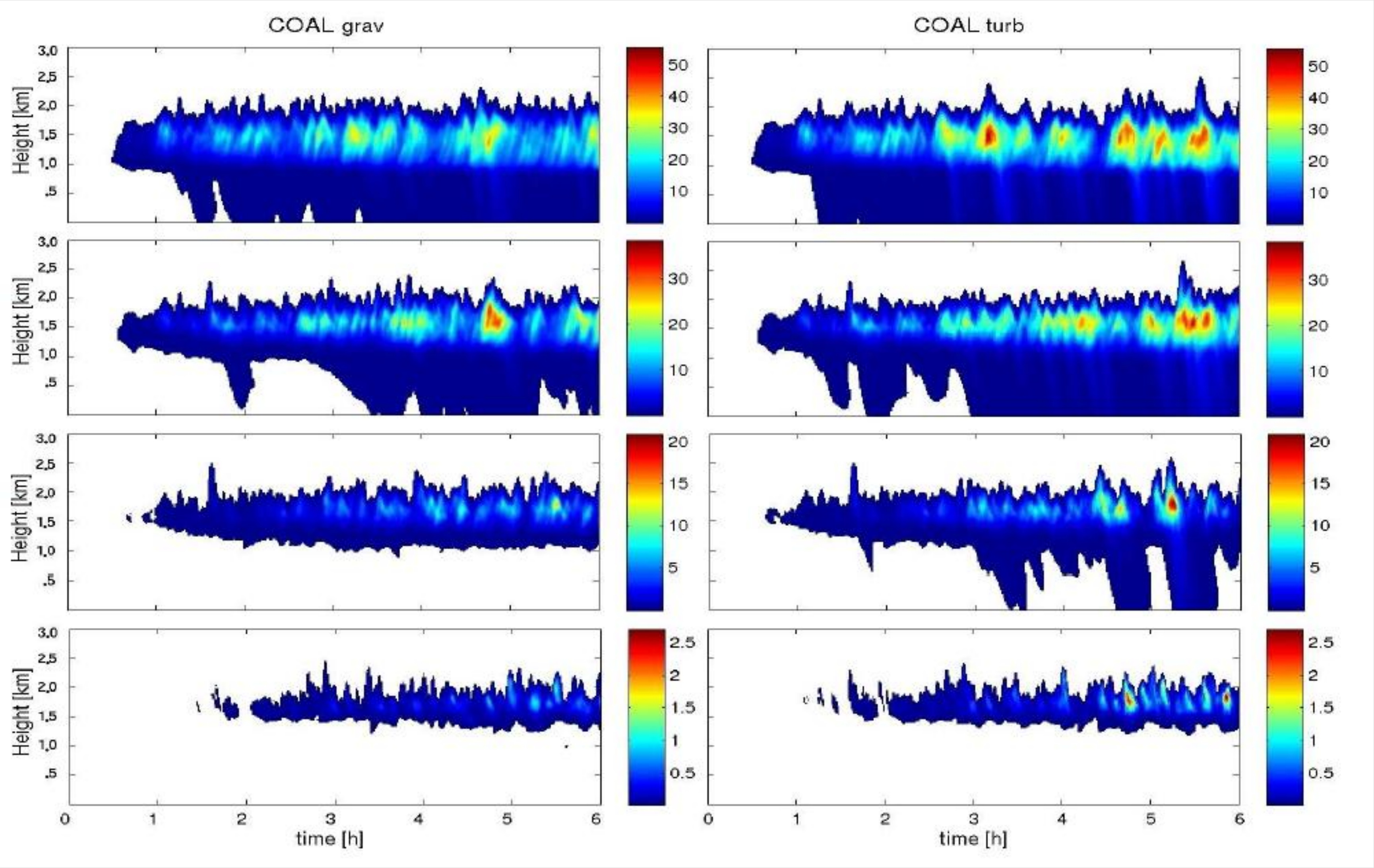
Domain-averaged rain water mixing ratio

30

60

120

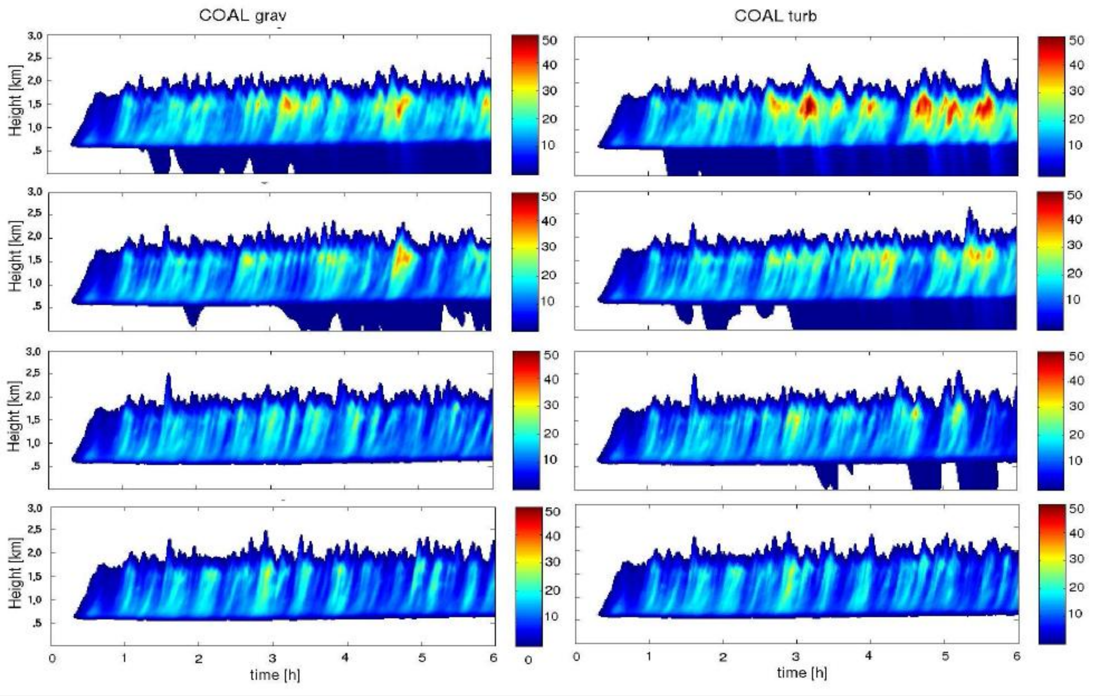
240



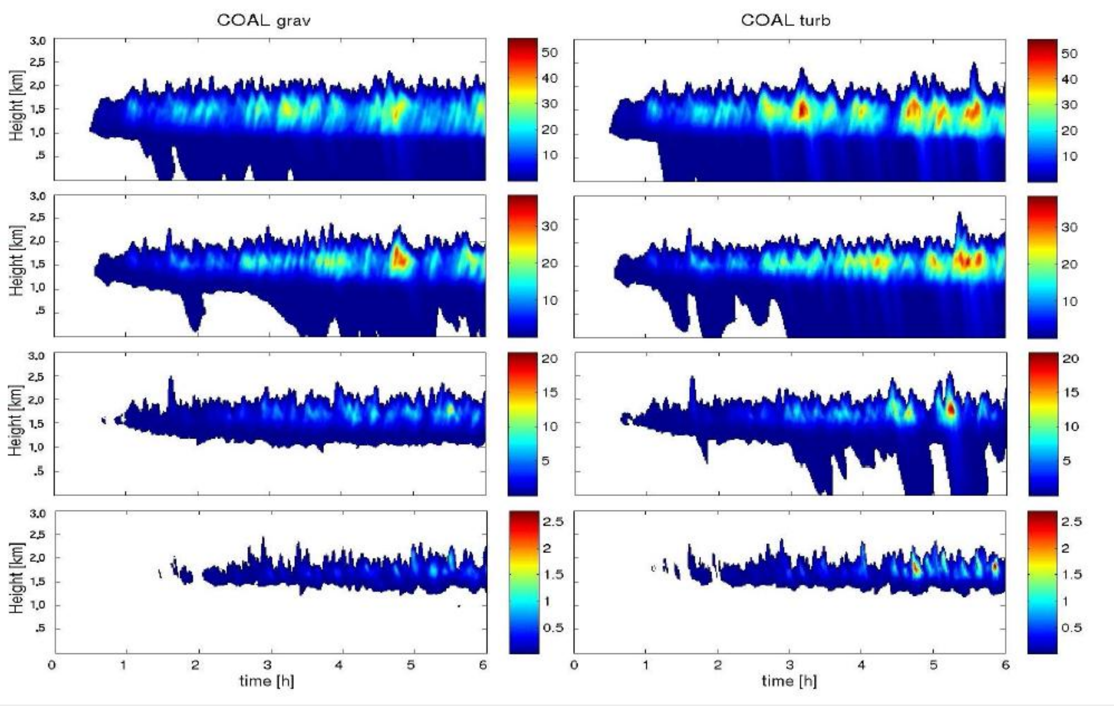
Gravitational kernel

Turbulent kernel

Cloud water



Rain water



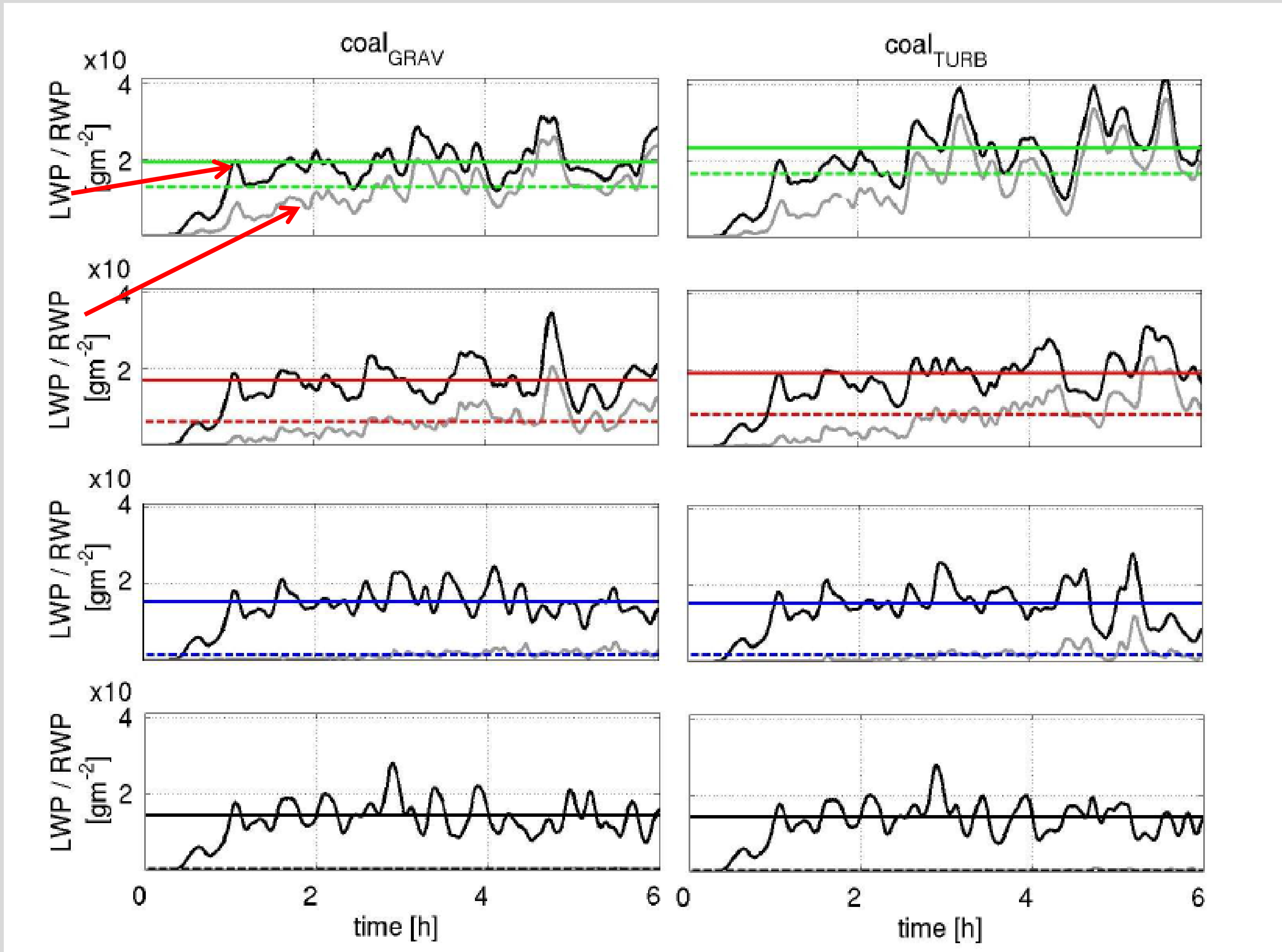
Domain-averaged liquid water path (LWP, cloud water only) and rain water path (RWP)

30

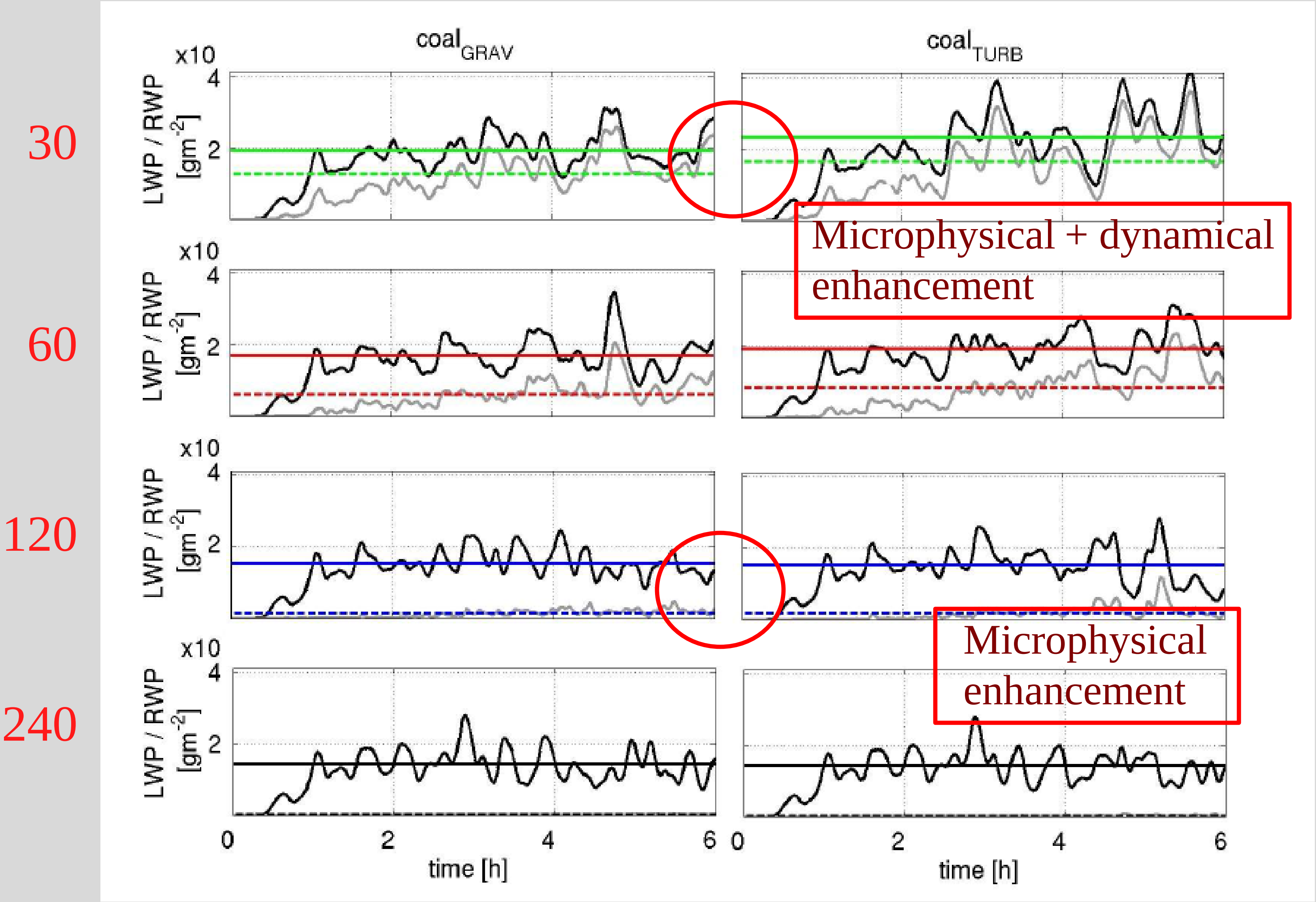
60

120

240

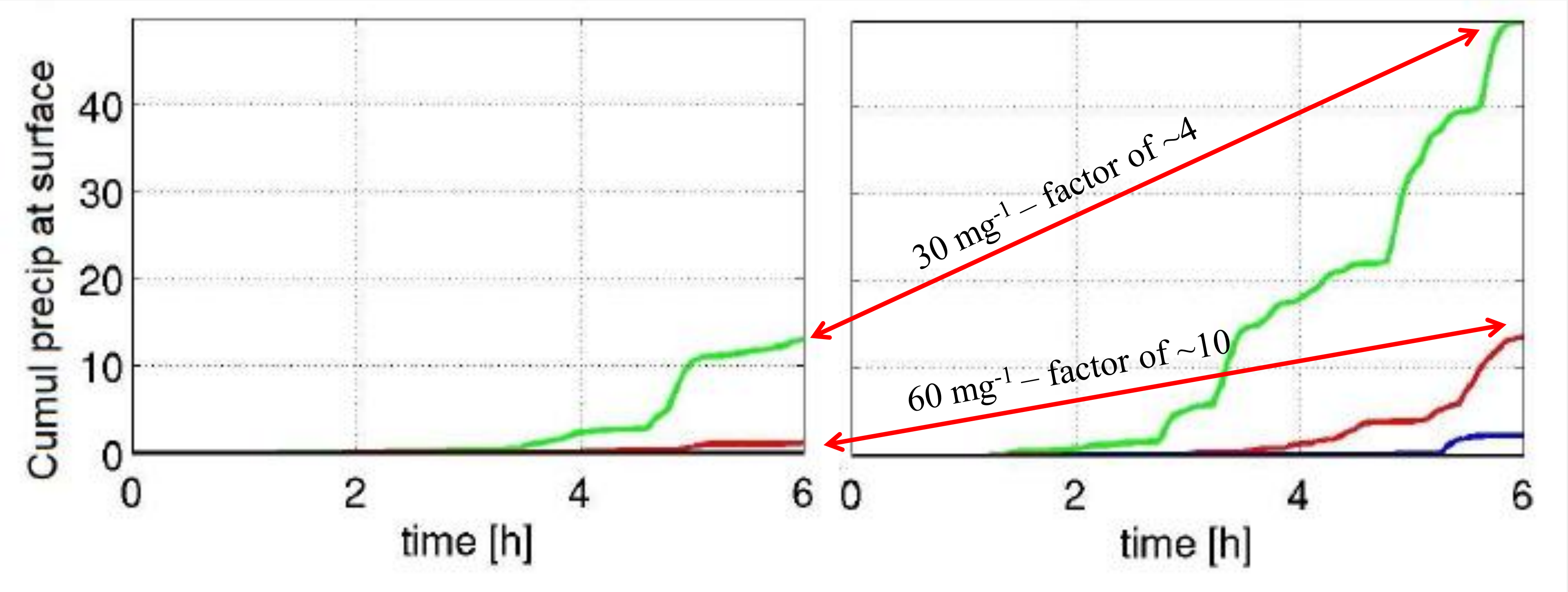


Domain-averaged liquid water path(LWP, cloud water only) and rain water path (RWP)



Surface rain accumulation from cloud field:

Gravitational kernel | Turbulent kernel



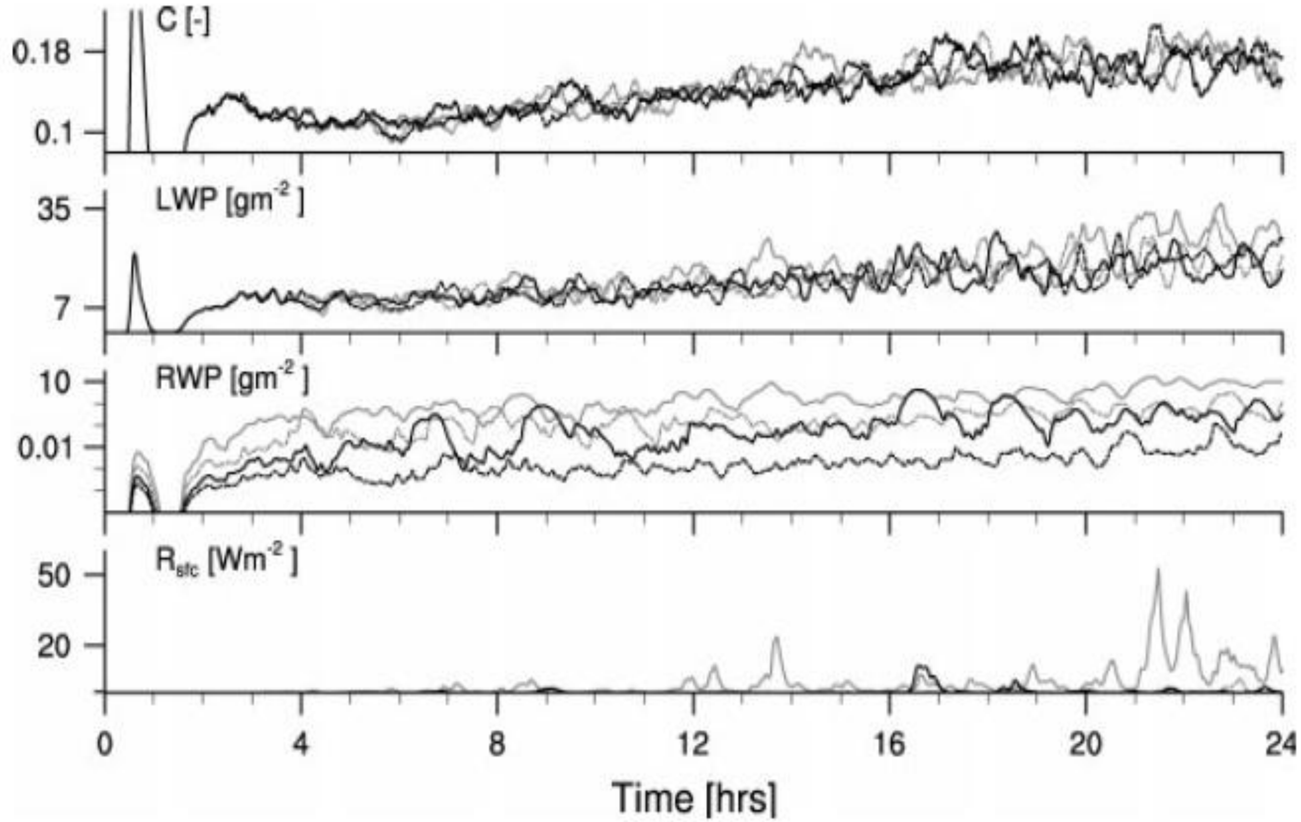


Figure 5. Time series of the number of cloudy columns (cloud cover) C, liquid (cloud + rain) water path L, rain water path R, and surface rain-rate R_{sfc} for simulations with cloud droplet number concentrations N_c of 140 cm^{-3} (grey) and 300 cm^{-3} (black), with (solid line) and without (dashed line) turbulence-enhanced coalescence.

Seifert et al. *QJRMS* 2010
(double-moment microphysics)

Table II. Sensitivity to turbulence-enhanced coalescence (T), versus no turbulence enhancement (NT), for cloud droplet number concentrations N_c = 70, 140 and 300 mg^{-1}. NT-140-hr and T-140-hr represent simulations with doubled horizontal resolution (grid spacing of 50 m).

Run	L (gm^{-2})	R (gm^{-2})	z_i (m)	C	R_{sfc} (W m^{-2})	R_{max} (W m^{-2})	N_r (dm^{-3})
NT-70	18.6	7.0	2418	0.17	8.6	16.6	19.7
T-70	19.3	22.2	2358	0.15	43.3	51.6	26.6
NT-140	18.9	0.8	2449	0.17	0.8	2.0	8.7
T-140	19.7	8.3	2422	0.17	13.2	18.8	14.9
NT-140-hr	21.1	1.0	2422	0.21	1.1	2.6	8.9
T-140-hr	21.9	3.9	2399	0.21	4.9	9.9	10.9
NT-300	20.2	0.0	2442	0.17	0.0	0.0	4.7
T-300	18.3	0.4	2438	0.16	0.4	0.9	6.4

Variables are cloud (liquid) water path L, rain water path R, inversion height z_i, fraction of cloudy columns C, rain-drop number concentrations averaged over raining regions N_r, surface rain rate R_{sfc}, and the maximum rain-rate R_{max} within the (domain-averaged) profile of rain-rate.
All variables are averaged over the last four hours of each simulation.
A rain rate of 29 W m^{-2} corresponds to 1 mm day^{-1}.

Seifert et al. *QJRMS* 2010
(double-moment microphysics)

Summary (for the 2nd part):

Small-scale turbulence appears has a significant effect on collisional growth of cloud droplets and delopment of warm rain in shallow cumuli. Not only rain tends to form earlier in a single cloud, but also turbulent clouds seem to rain more. This is a combination of microphysical and dynamical effects. The (perhaps surprising) magnitude of this effect calls for further observational and modeling studies to provide more support for these findings.