Modeling of warm-rain microphysics and dynamics-microphysics interactions with EULAG-based Large Eddy Simulation model

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Microphysics of shallow convective clouds (cumulus, stratocumulus):

- Factors affecting cloud droplet sizes and concentrations (in-cloud activation, homogeneity of parameterized subgrid-scale mixing, etc.)

- Formation of drizzle/rain.

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

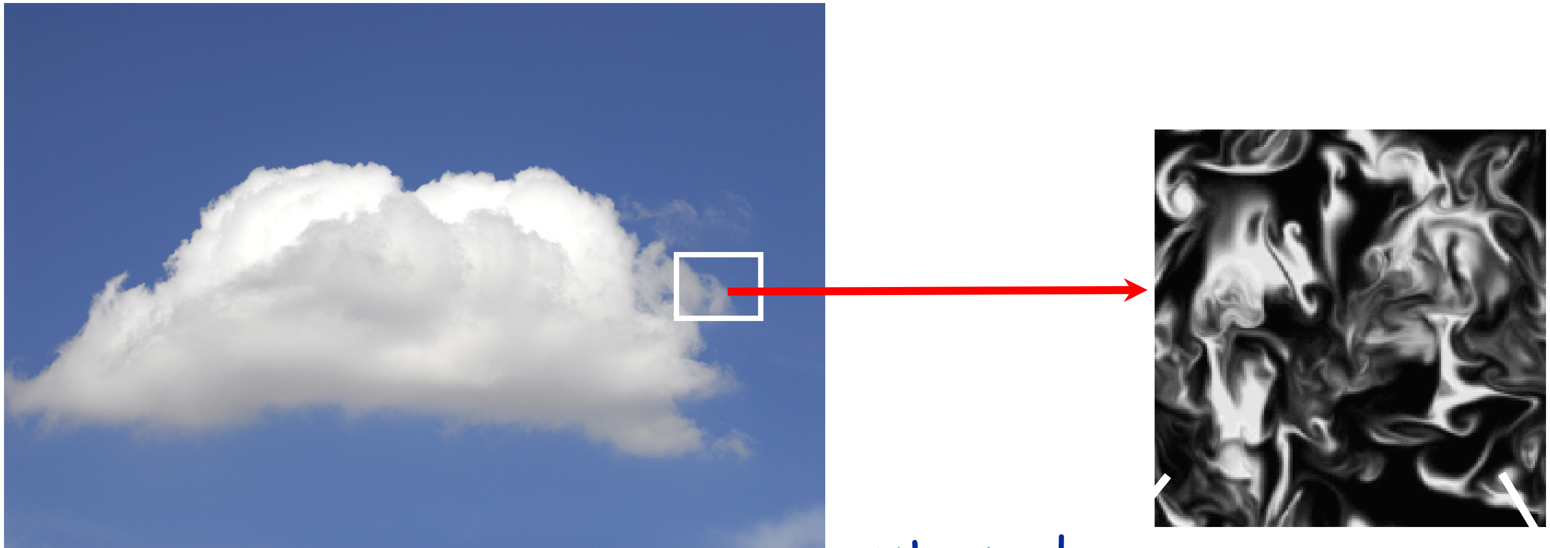
Double-moment warm-rain microphysics of Morrison and Grabowski (2007, 2008):

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

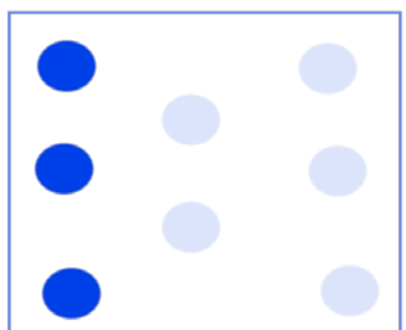
- Prediction of in-cloud supersaturation and thus relating the concentration of activated cloud droplets to local value of the supersaturation; additional variable (concentration of activated CCN) needed;

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

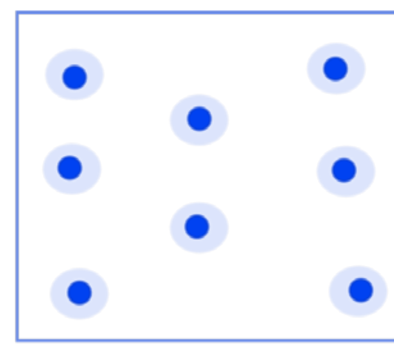
Turbulent cloud-environment mixing: impact on cloud microphysics



extremely inhomogeneous mixing



homogeneous mixing



Microphysical transformations due to subgrid-scale mixing may cover a wide range of mixing scenarios.

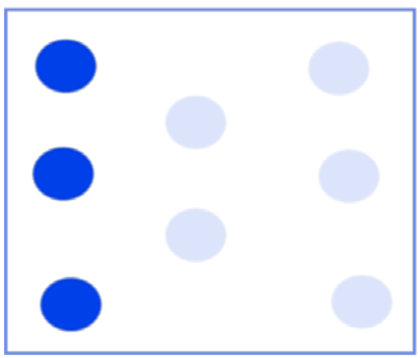
2-moment microphysics - mixing scenarios

$$N_f = N_i \left(\frac{q_f}{q_i} \right)^{\alpha}$$

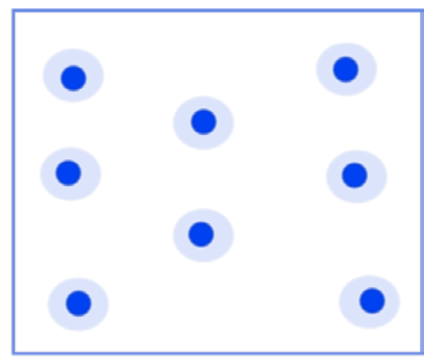
i – initial (before microphysical adjustment)

f – final (after the adjustment)

α = 1
extremely inhomogeneous mixing



α = 0
homogeneous mixing



Previews study (Slawinska et al. *JAS* 2011): α=const for entire simulation to contrast results with different mixing scenarios.

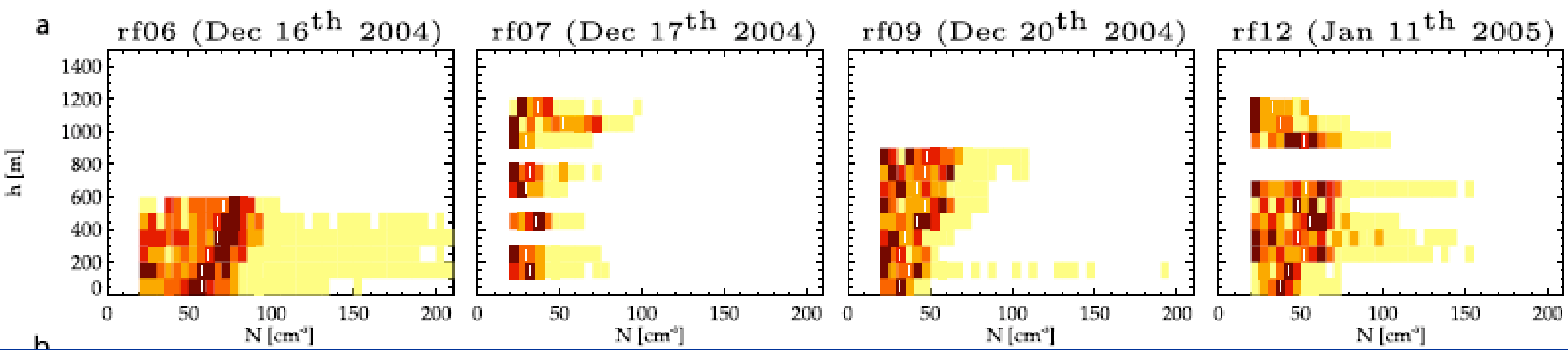
Gerber et al. *JMSJ* 2008

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



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

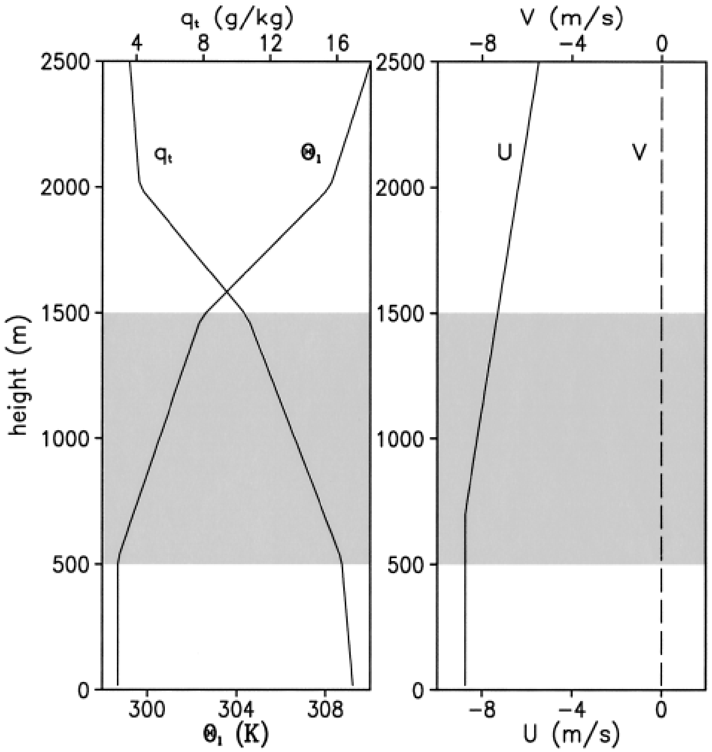
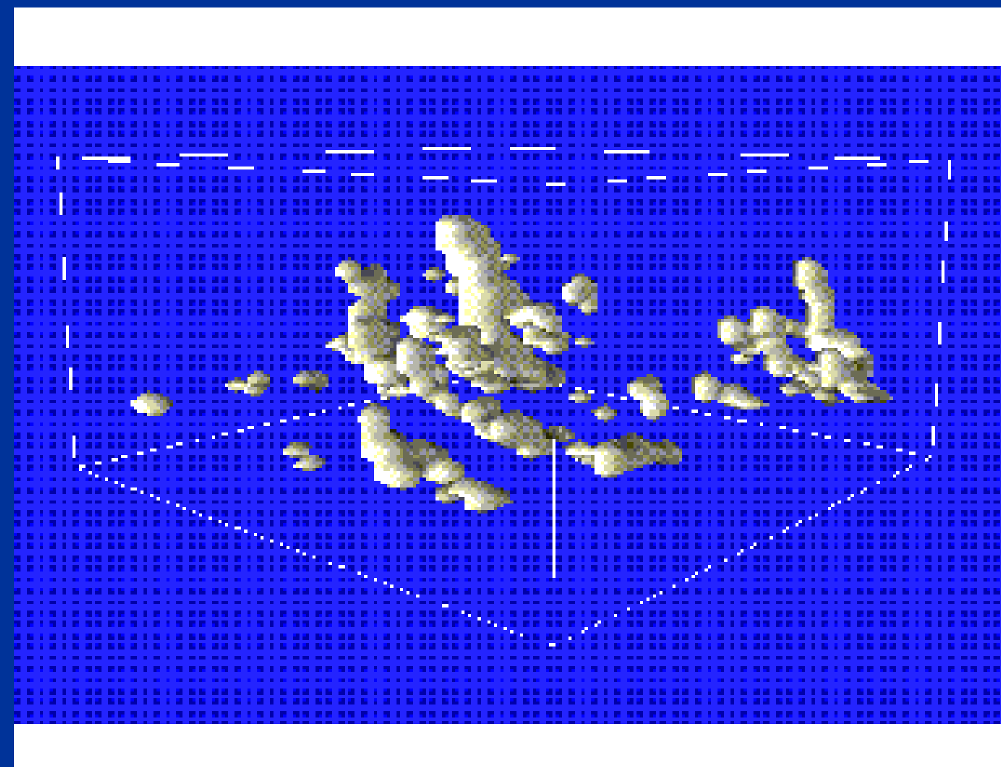
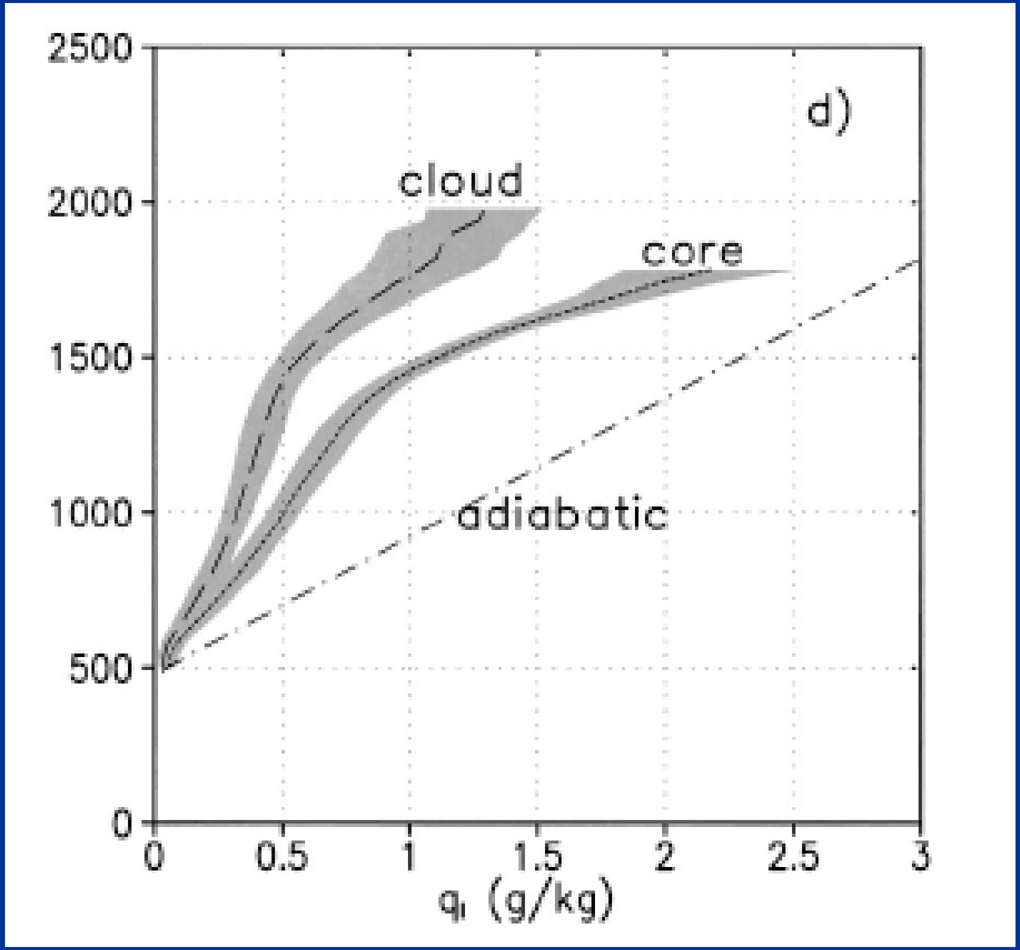


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.



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

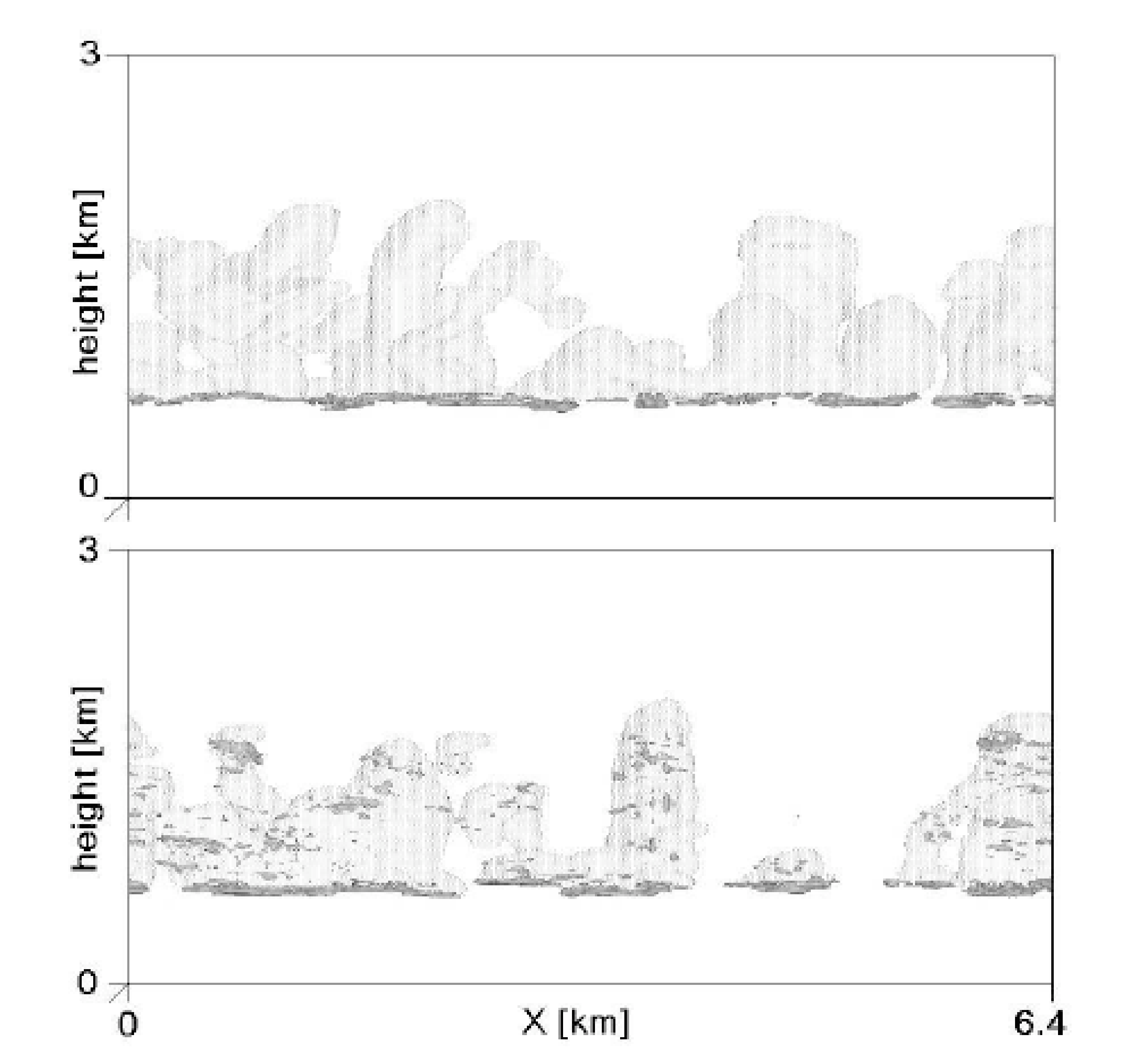
How is it possible that the dilution of the cloud water content is NOT accompanied by the dilution of the droplet concentration?



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

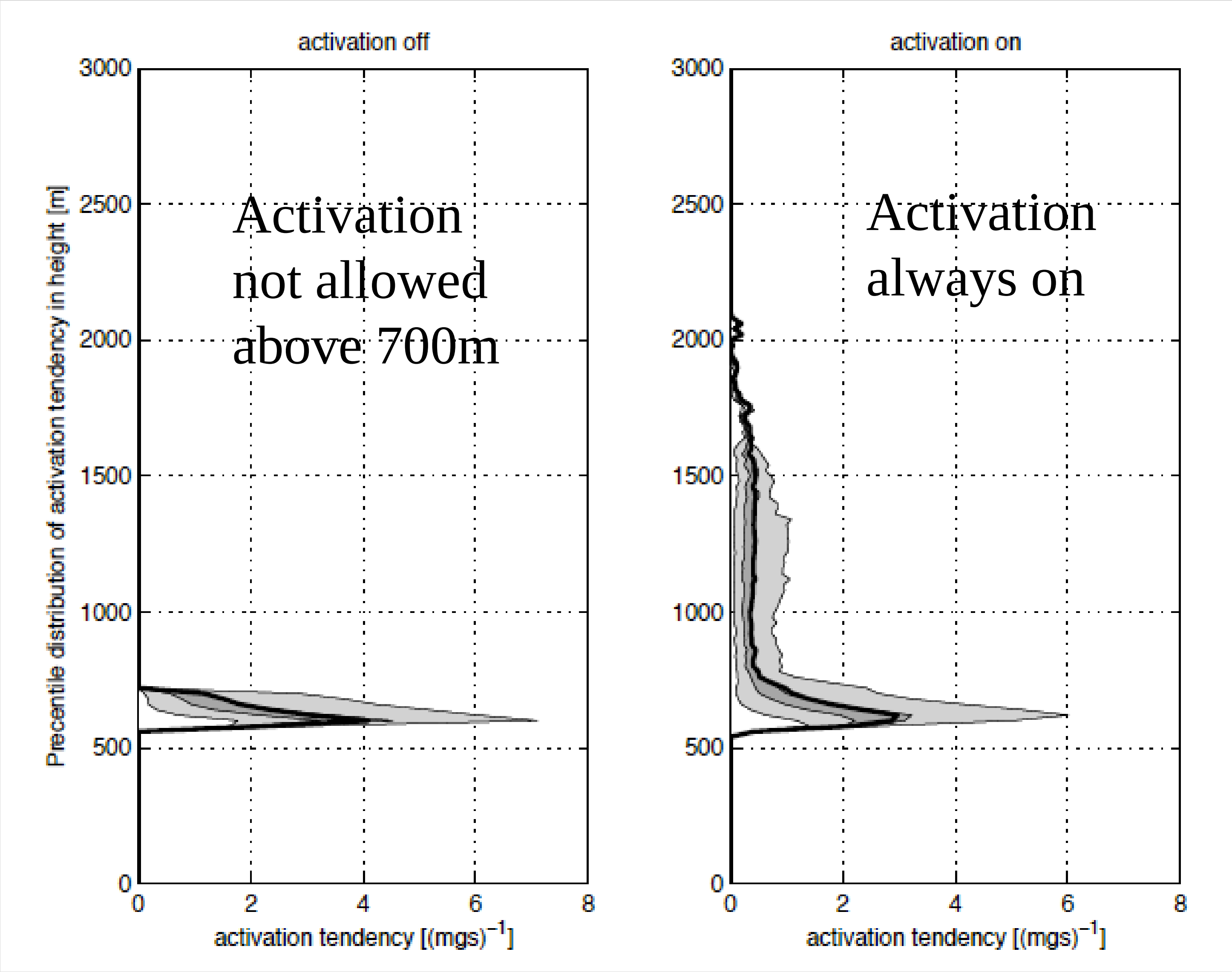


Activation not allowed above 700m

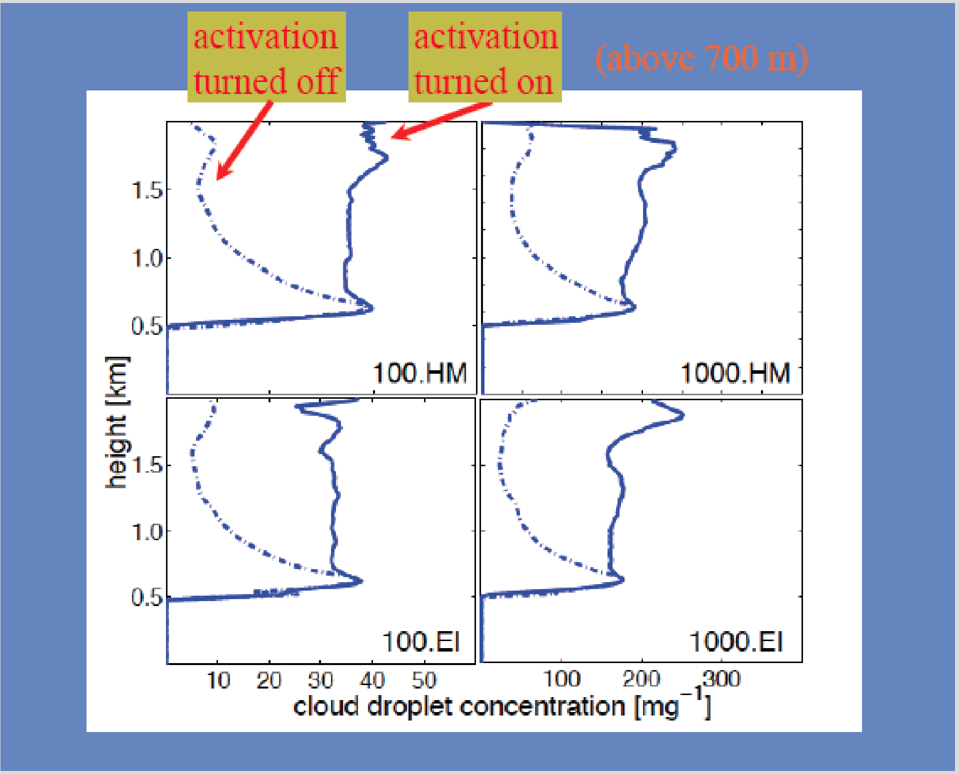
Activation always on

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

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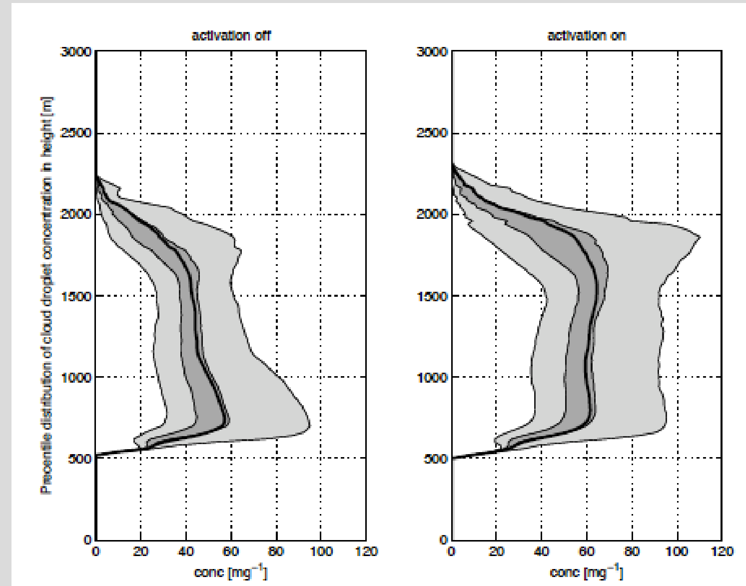
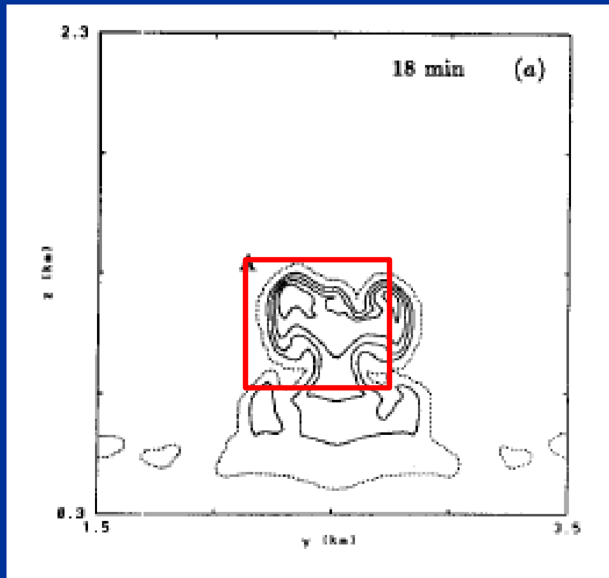
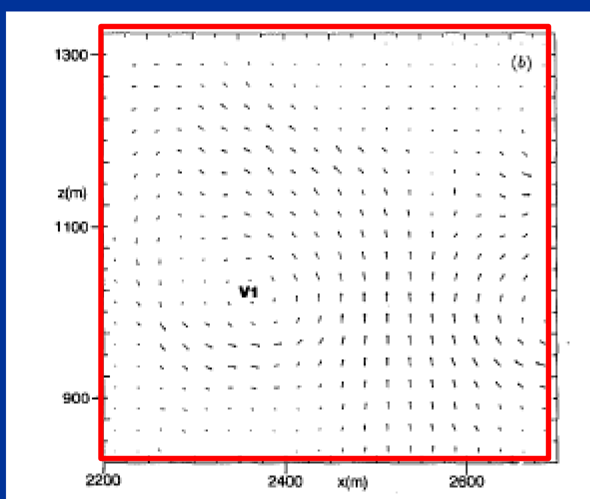
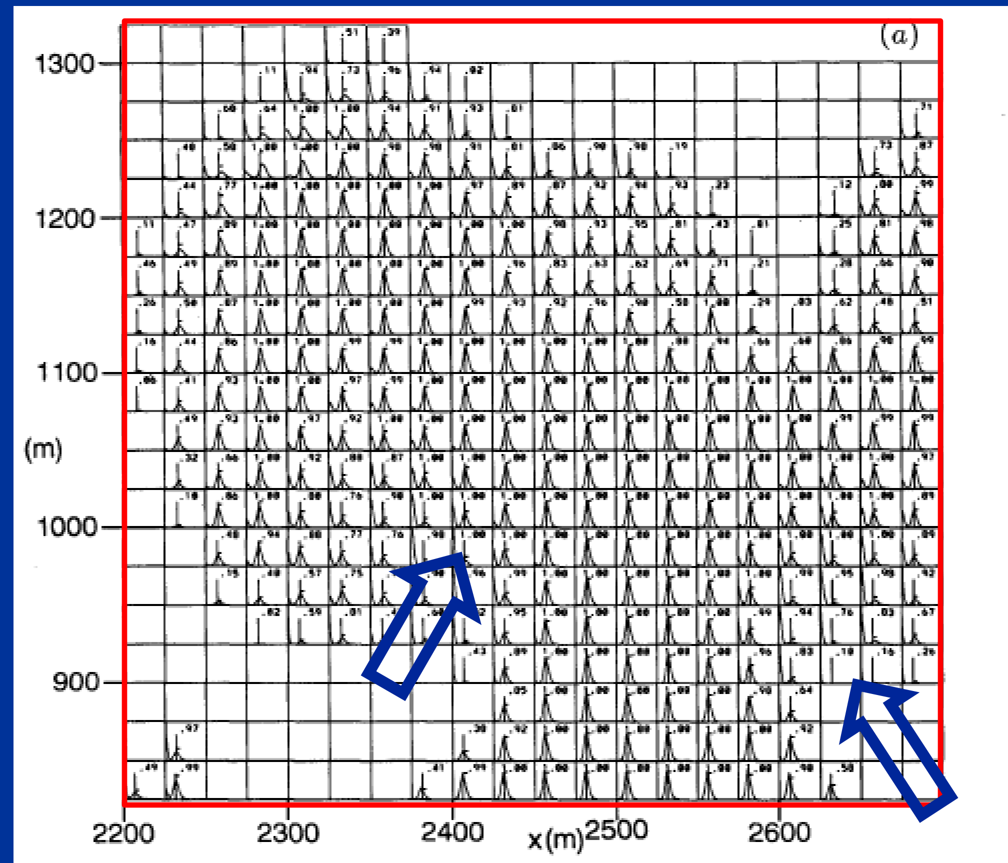


Wyszogrodzki et al. (*Acta Geophysica* 2012)

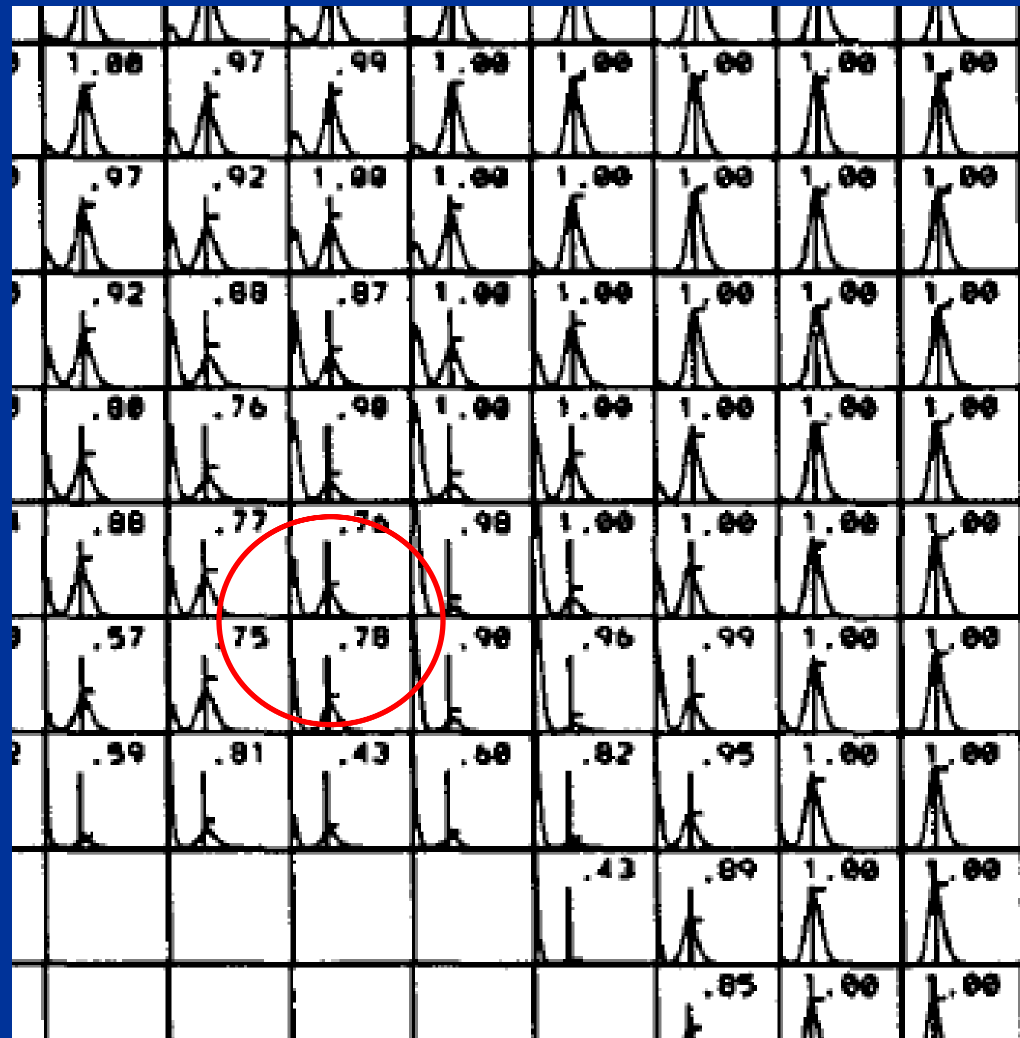
Droplet concentrations with and without in-cloud activation





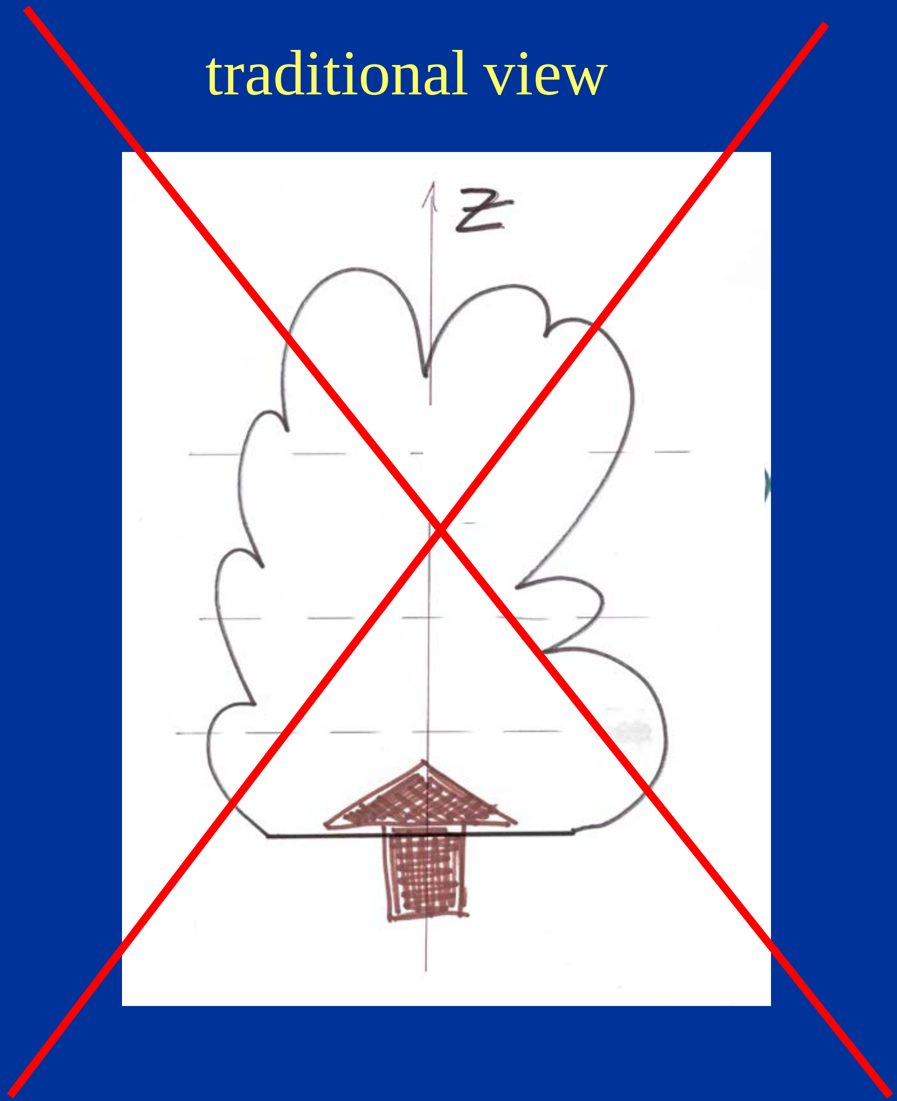


Brenguier and Grabowski (JAS 1993)

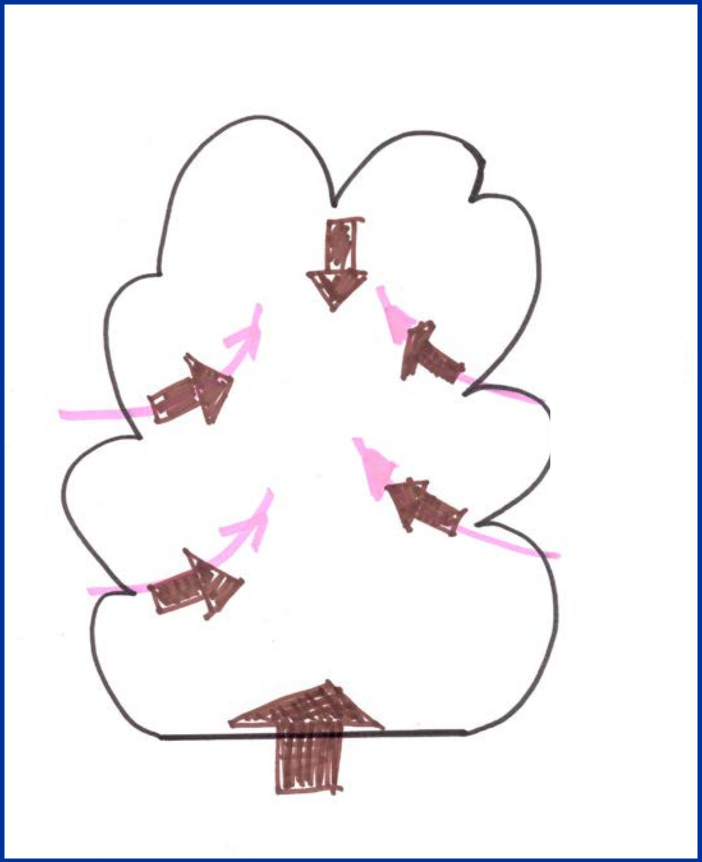


Brenguier and Grabowski (JAS 1993)

traditional view



view suggested by
model simulations

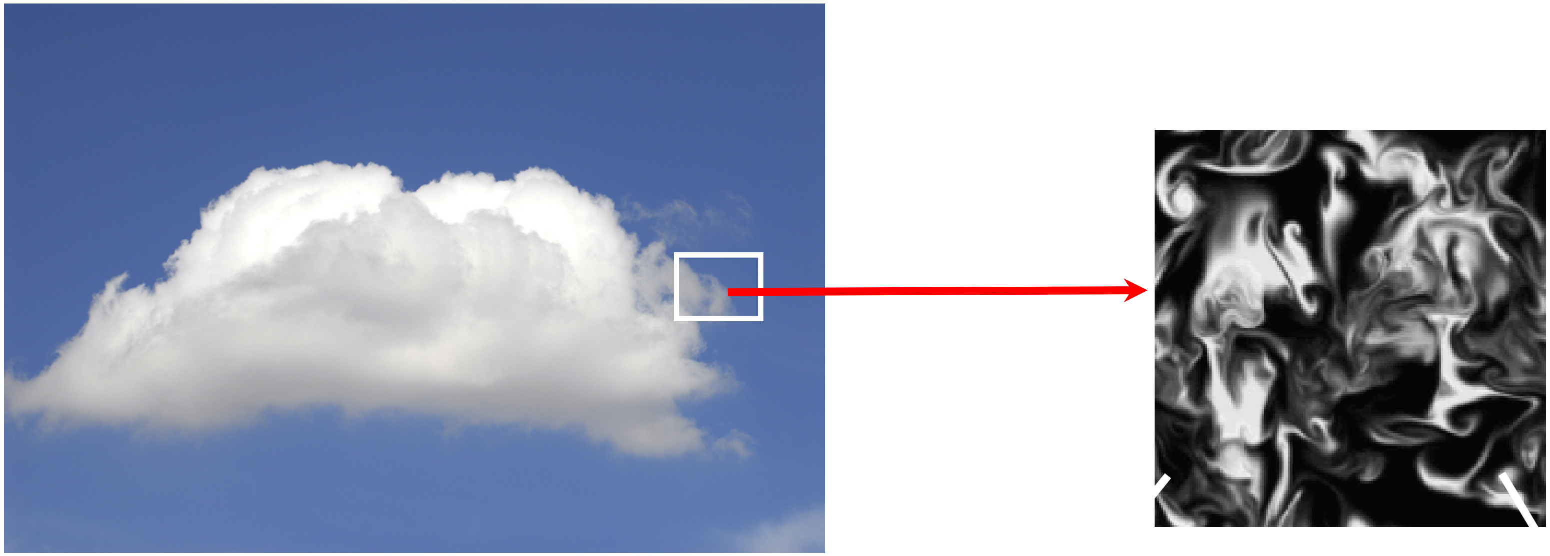


Conclusions:

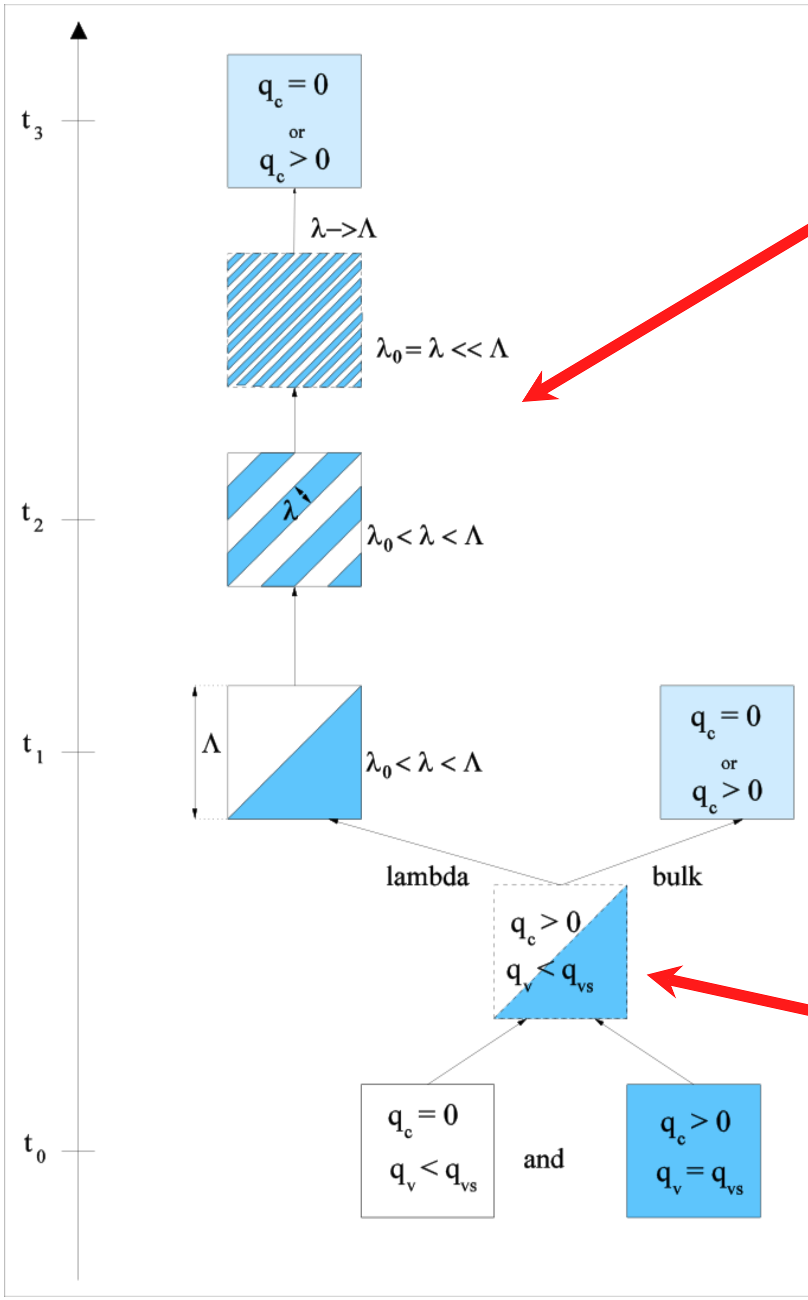
Activation of cloud droplets above the cloud base is essential for realistic simulation of cloud microphysics. In simulations reported here, about 40% of cloud droplets is activated above the cloud base. Only with in-cloud activation, key features of observed shallow cumuli can be simulated (e.g., constant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

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

Turbulent cloud-environment mixing



Microphysical transformations due to subgrid-scale mixing are not instantaneous...

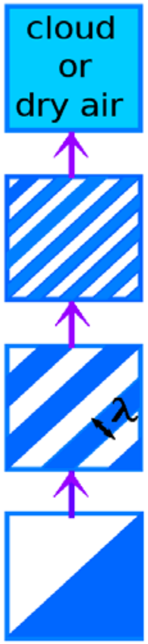


Modified model with λ approach: homogenization delayed until turbulent stirring reduces the filament width λ to the value corresponding to the microscale homogenization scale λ_0

Bulk model: immediate homogenization

mixing event

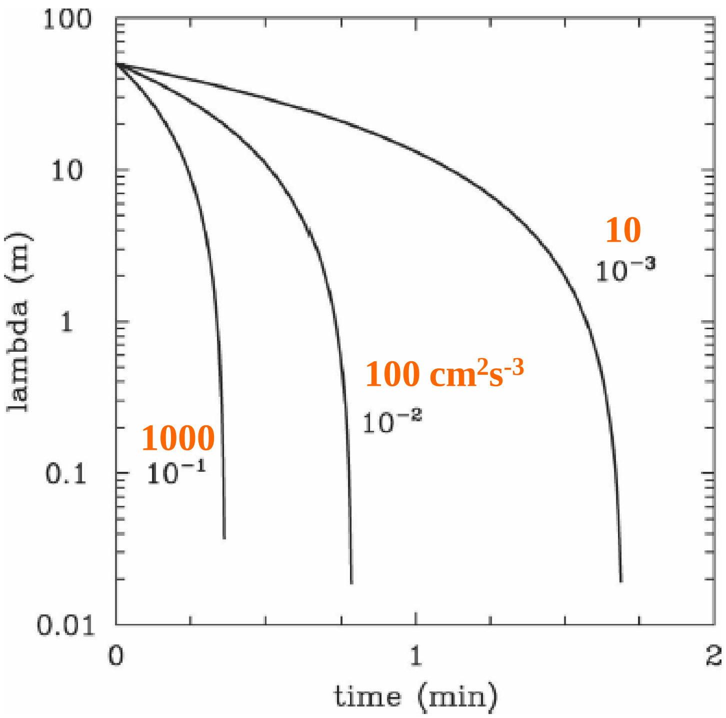
Grabowski (2007), Jarecka et al. (2009)



λ - spatial scale of the cloudy filaments during turbulent mixing

$$\frac{d\lambda}{dt} = -\gamma\epsilon^{\frac{1}{3}}\lambda^{\frac{1}{3}}$$

$$\lambda_0 \leq \lambda \leq \Lambda$$



Λ - model gridlength;

λ_0 - homogenization scale (~ 1 mm).

γ ~ 1

ε – dissipation rate of turbulent kinetic energy

Broadwell and Breidenthal (1982); Grabowski (2007)

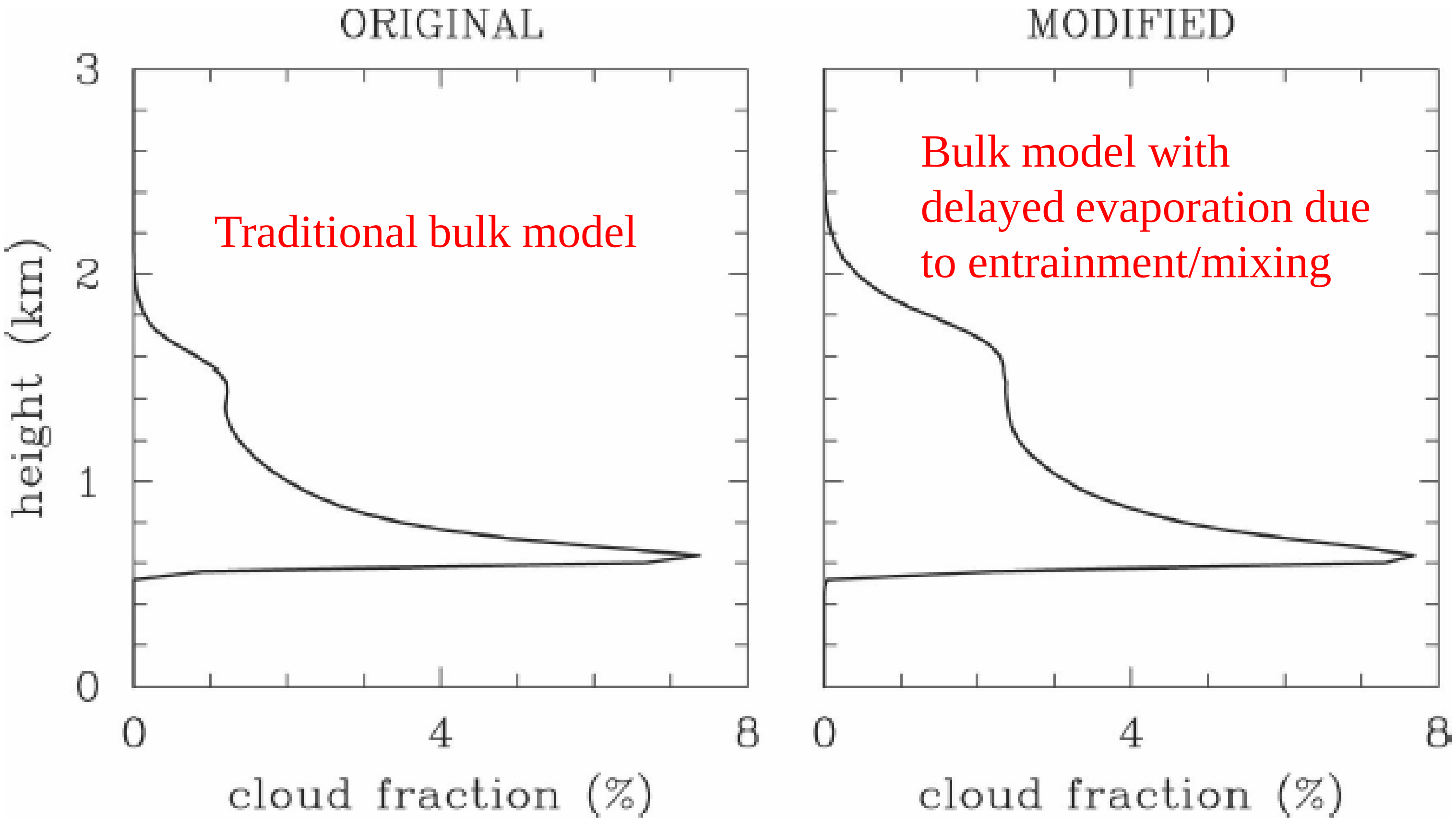


FIG. 9. Profiles of the cloud fractions (4-h averages) in BOMEX simulations using either the (left) original or (right) modified approaches.

Simulation of a field of shallow non-precipitating convective clouds (Grabowski, *JAS* 2007)

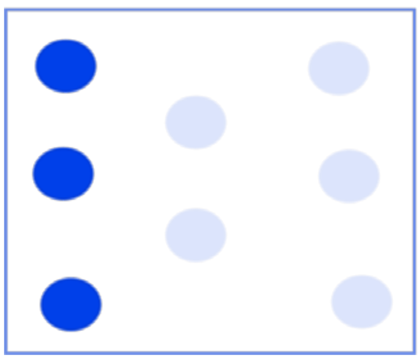
2-moment microphysics - mixing scenarios

$$N_f = N_i \left(\frac{q_f}{q_i} \right)^\alpha$$

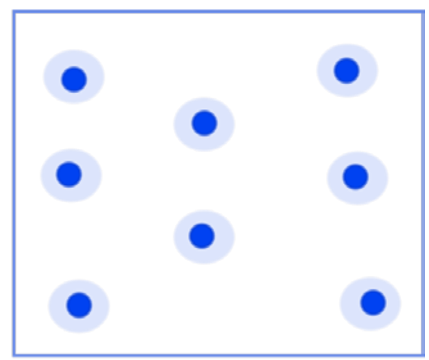
i – initial (before microphysical adjustment)

f – final (after the adjustment)

α = 1
extremely inhomogeneous mixing



α = 0
homogeneous mixing



Previews study (Slawinska et al. *JAS* 2011): α=const for entire simulation to contrast results with different mixing scenarios.

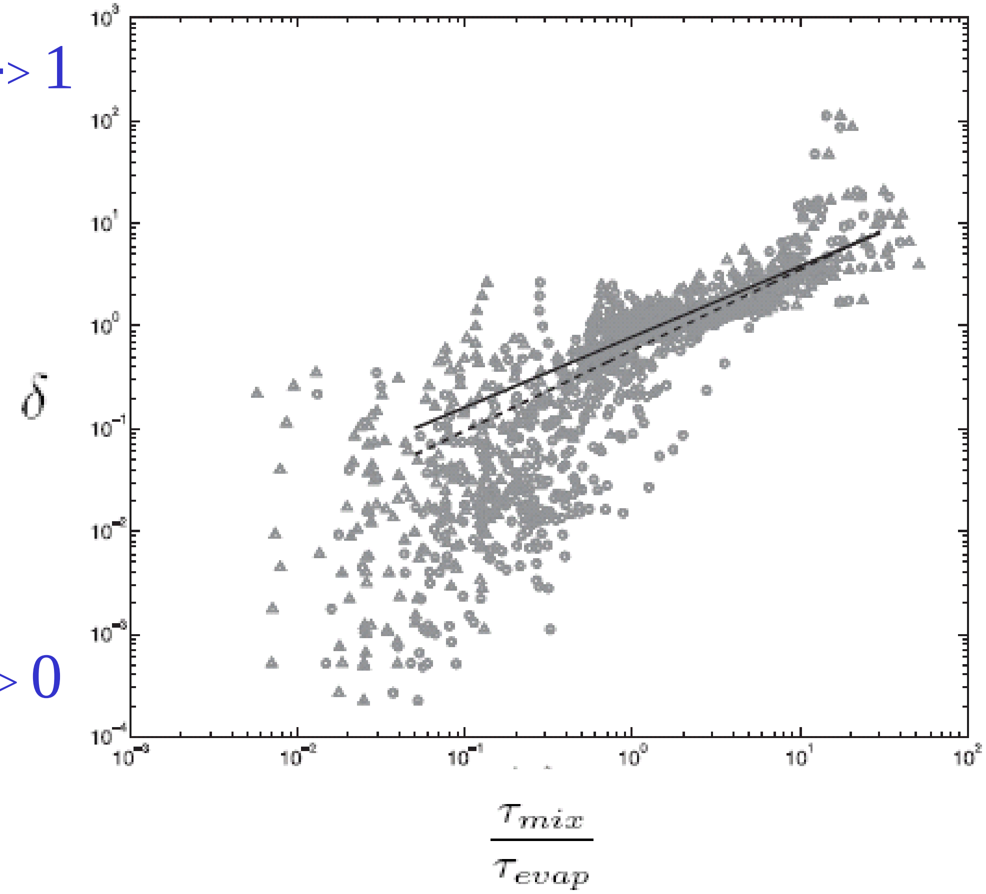
Using DNS results to predict α

Andrejczuk et al. (*JAS* 2009)

$$\tau_{mix} = \frac{\lambda}{u(\lambda)} = \frac{\lambda^{\frac{2}{3}}}{TKE^{\frac{1}{2}} * \Lambda^{\frac{1}{3}}}$$

$$\tau_{evap} = \frac{r^2}{A * (1 - RH_d)}$$

α -> 1



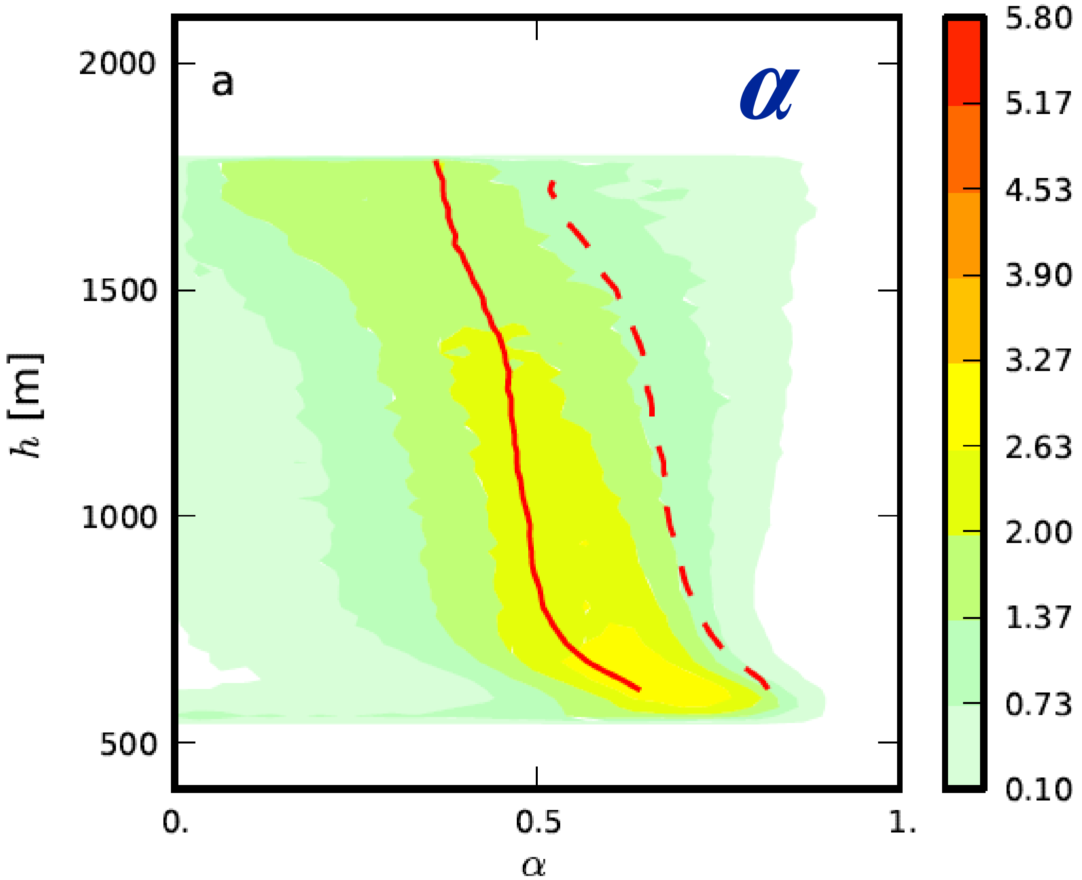
α -> 0

$\alpha = f(\lambda, TKE, RH_d, r)$

We can calculate α locally as a function of these parameters !!

Changes of the parameter α with height: sampling all cloudy points with $\lambda_0 < \lambda < \Lambda$

Shallow Cu:
BOMEX

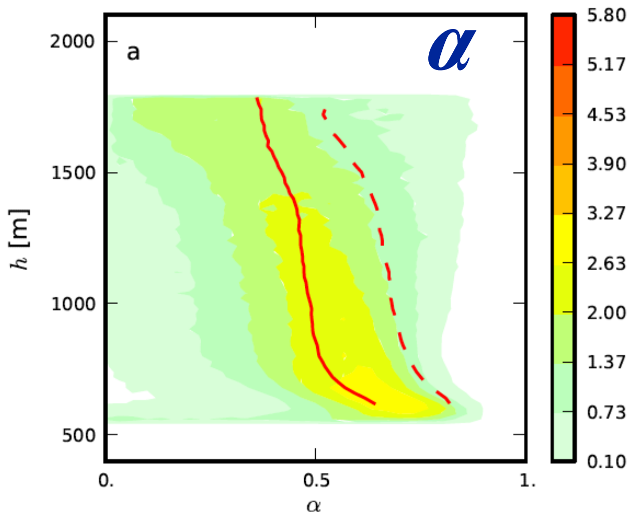


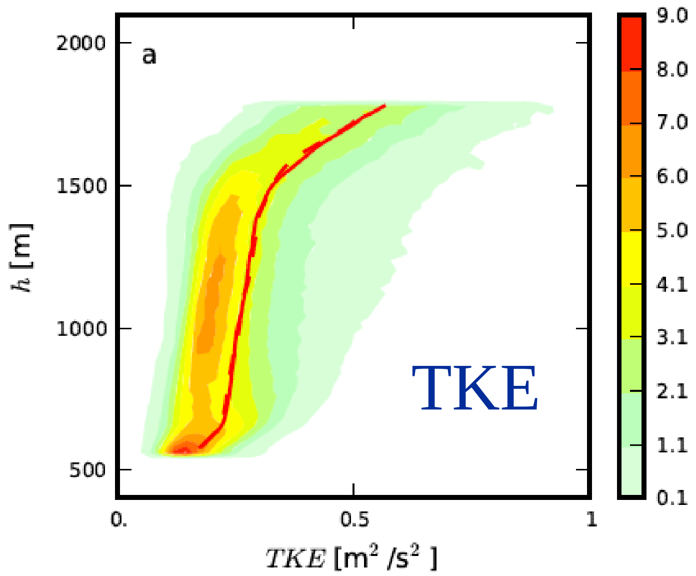
homogeneous mixing

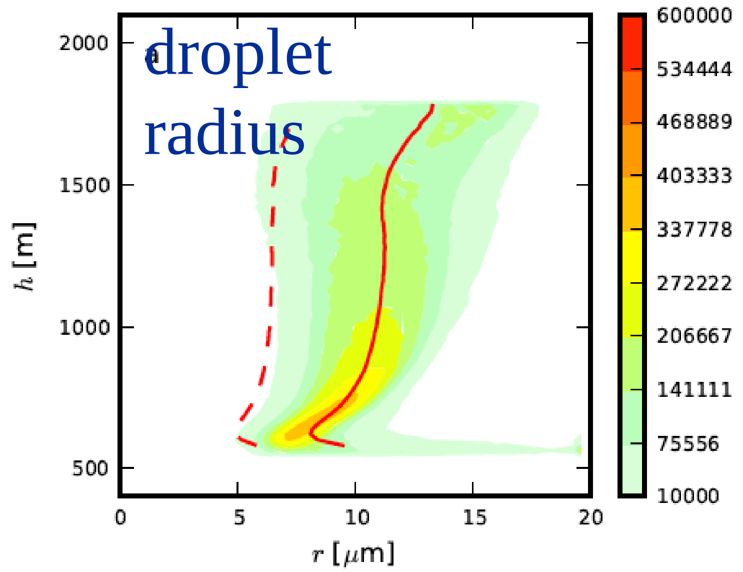
extremely inhomogeneous mixing

Vertical profiles of α , droplet radius and TKE

Shallow Cu:
BOMEX







Predicting scale of cloudy filaments λ allows representing in a simple way progress of the turbulent mixing between cloudy air and dry (cloud-free) environmental air.

Parameter α (and thus the mixing scenario) can be predicted as a function of λ, TKE, RH, and droplet radius r.

In BOMEX simulations, α decreases with height on average, i.e., mixing becomes more homogeneous. This is consistent with both TKE and droplet radius increasing with height.

In IMPACT simulations, mixing is close to extremely inhomogeneous across most of the cloud depth, and wide range is simulated near the cloud top.

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

W. W. Grabowski[1], A. A. Wyszogrodzki[1], L.-P. Wang[2], and O. Ayala[2]

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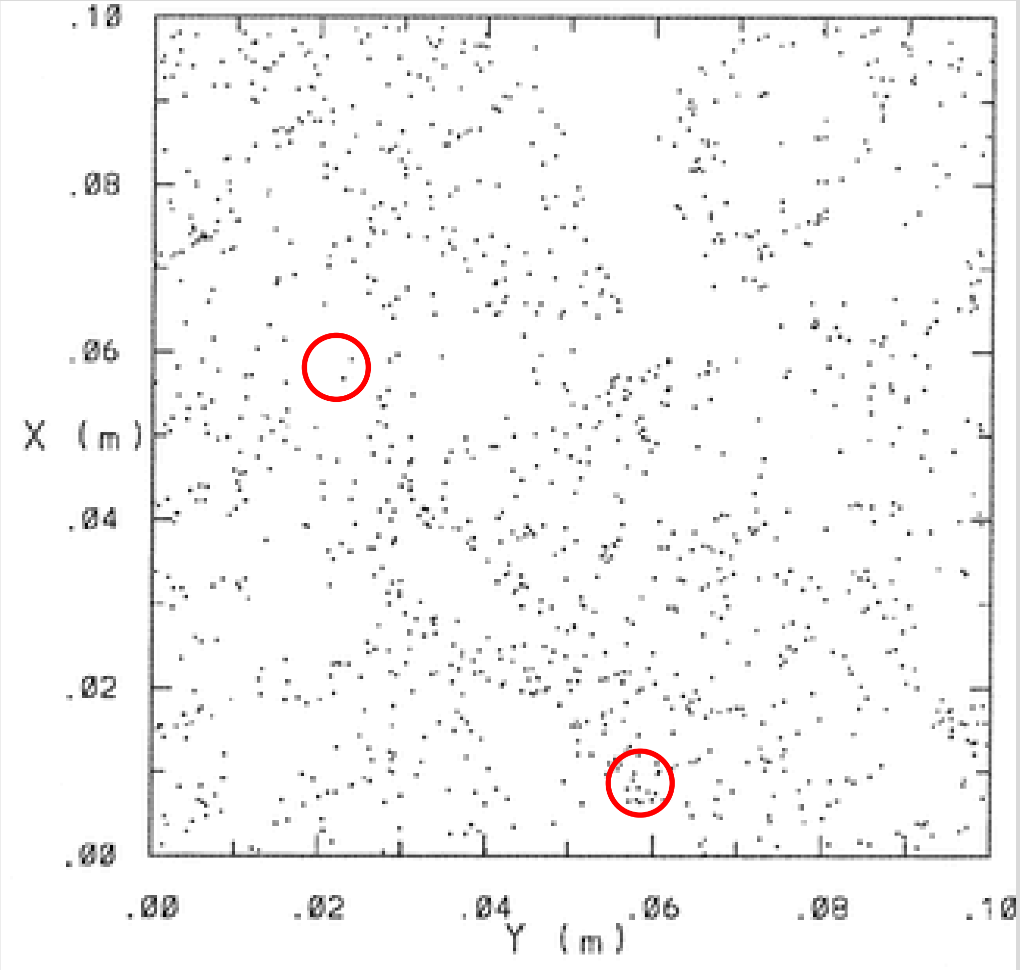
[2]University of Delaware, Newark, Delaware

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



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

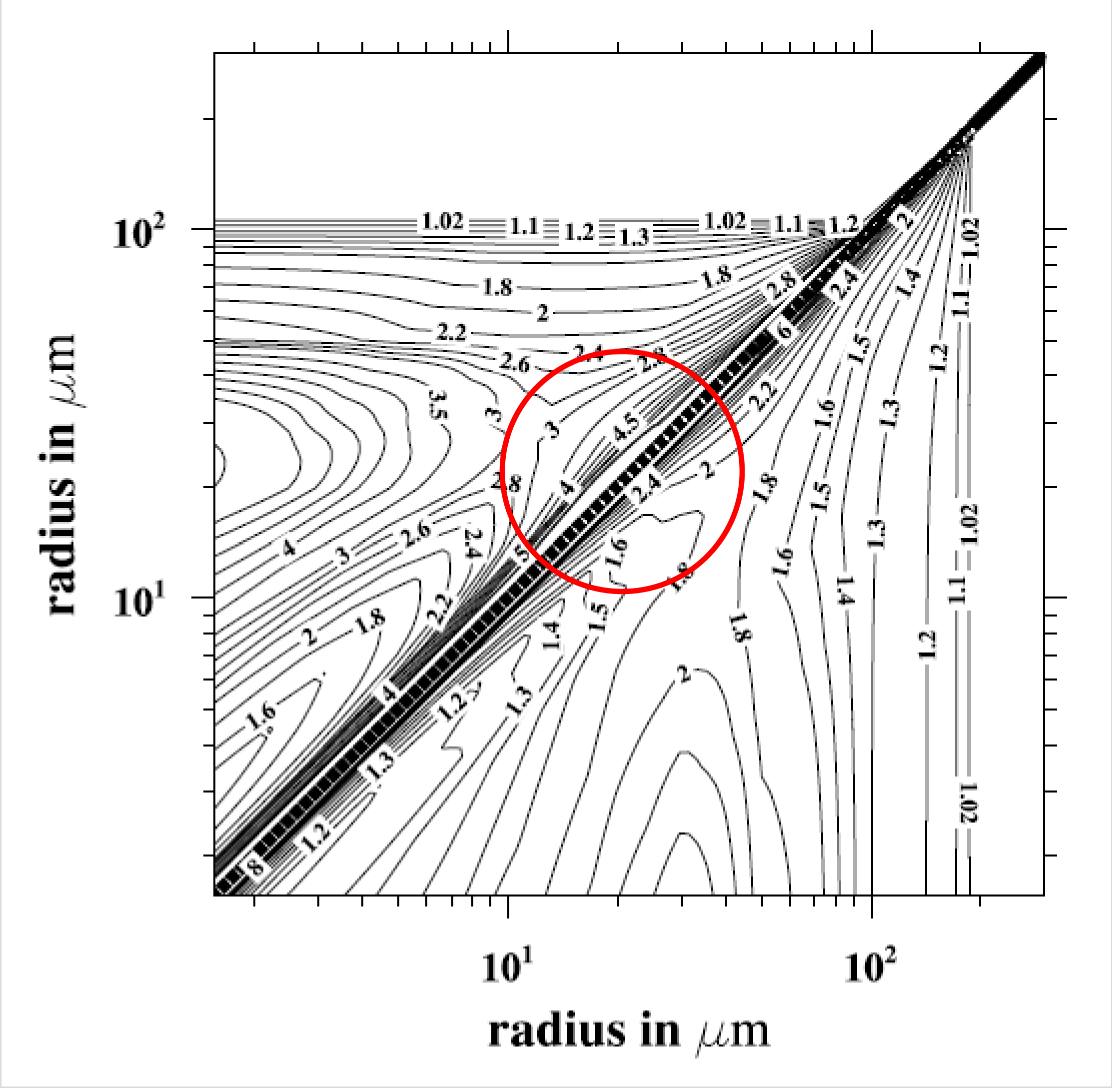
Three basic mechanisms of turbulent enhancement of gravitational collision/coalescence:

-Turbulence modifies local droplet concentration (preferential concentration effect)

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

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

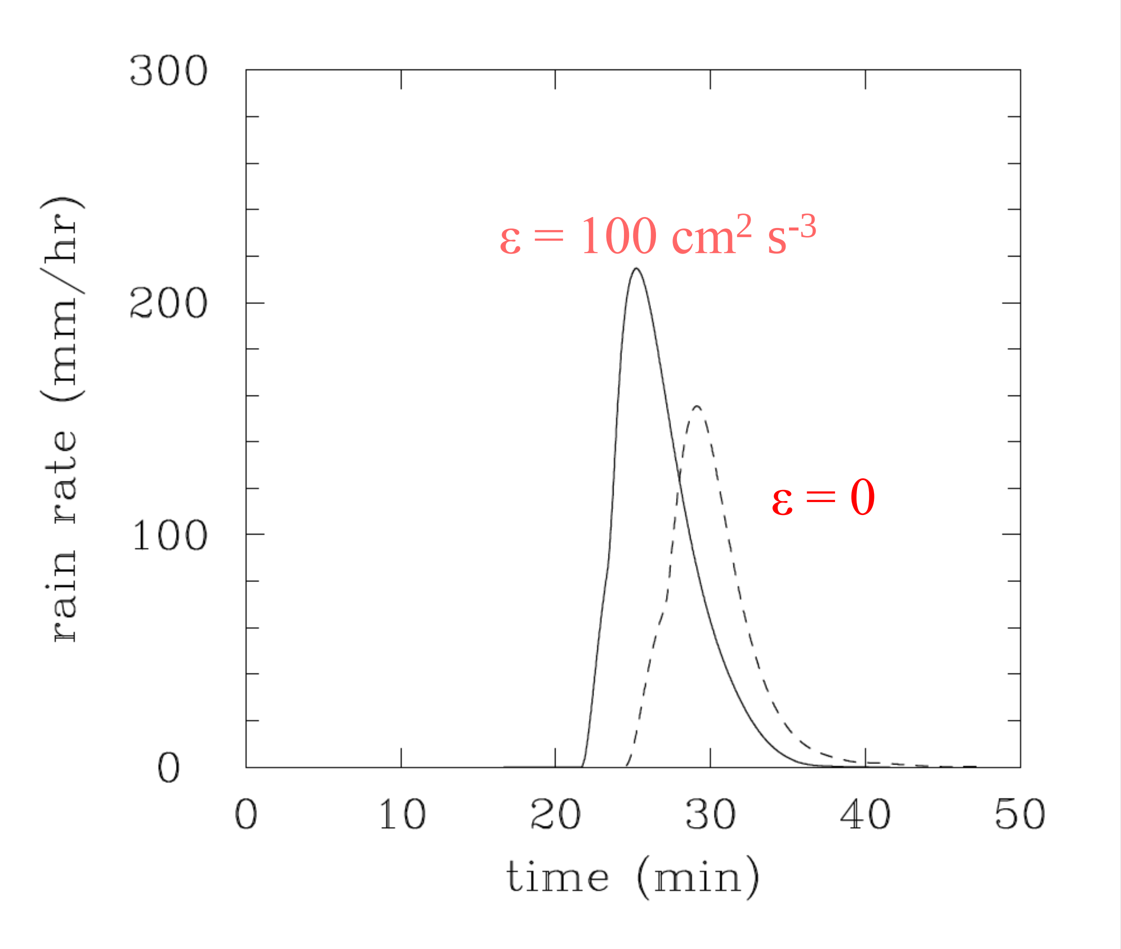
collision efficiency



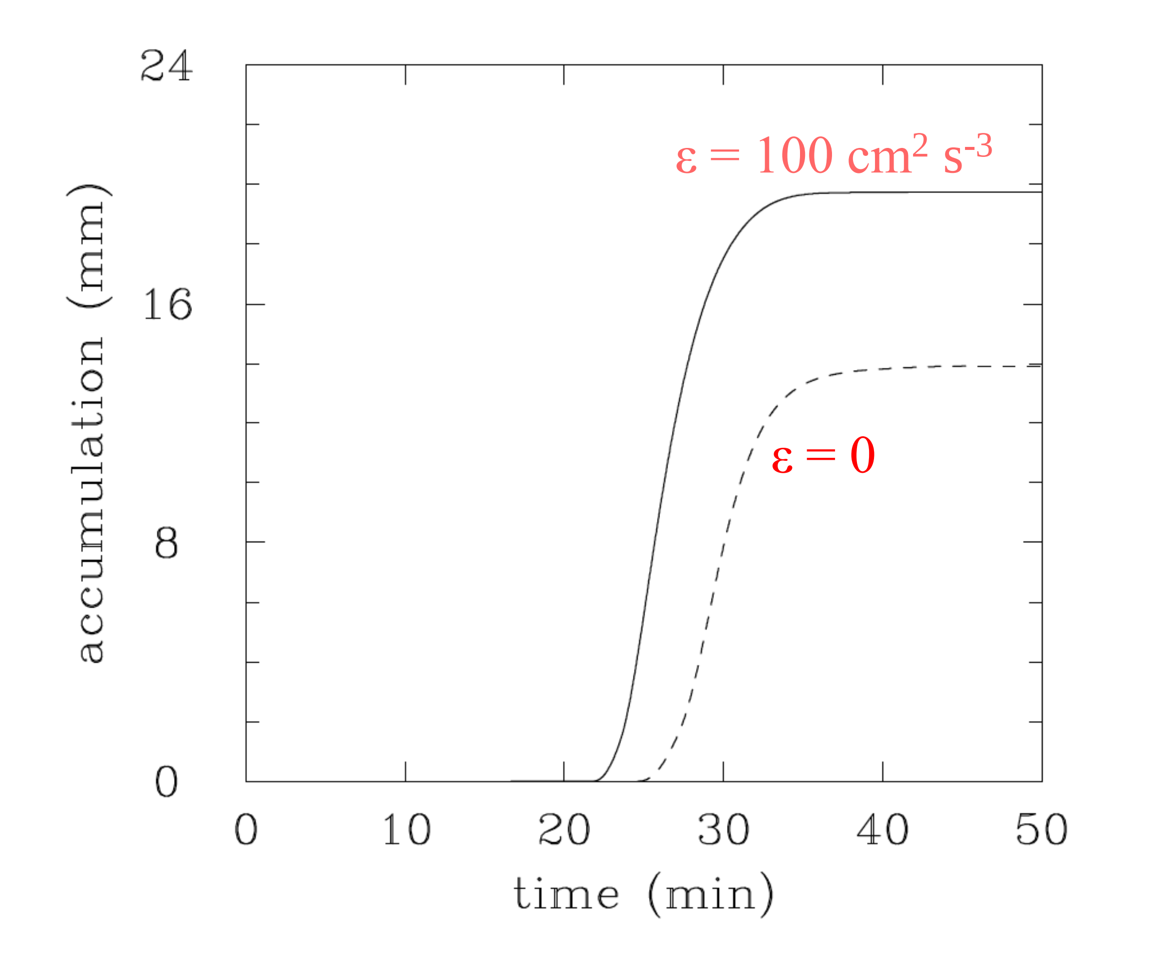
Enhancement factor for the collision kernel (the ratio between turbulent and gravitation collision kernel in still air) including turbulent collision efficiency; ε = 100 and 400 $cm^2\ s^{-3}$.

Time evolution of the surface precipitation intensity in an idealized simulation of a small precipitating cloud:

Turbulent collisions lead to earlier rain at the ground and higher peak intensity…

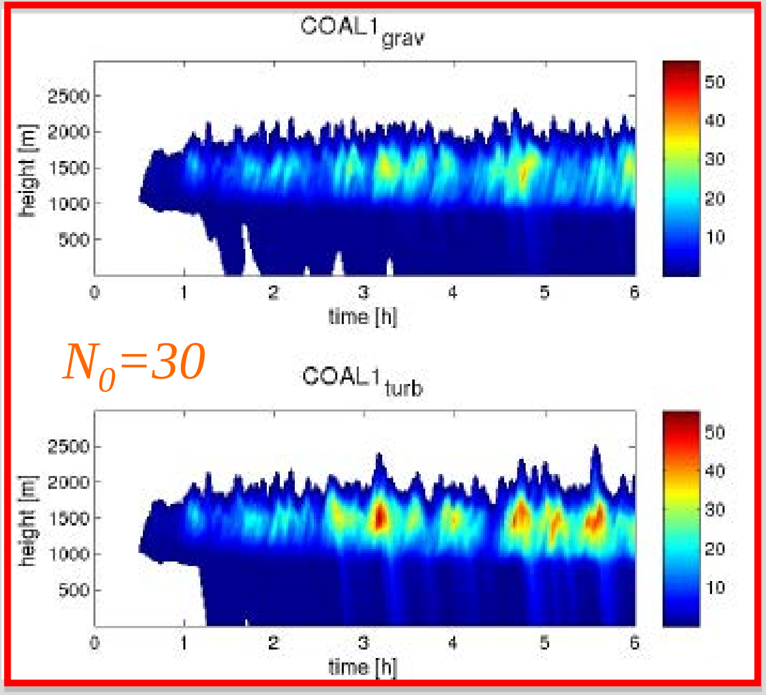


…but also to more rain at the surface. This implies higher precipitation efficiency!



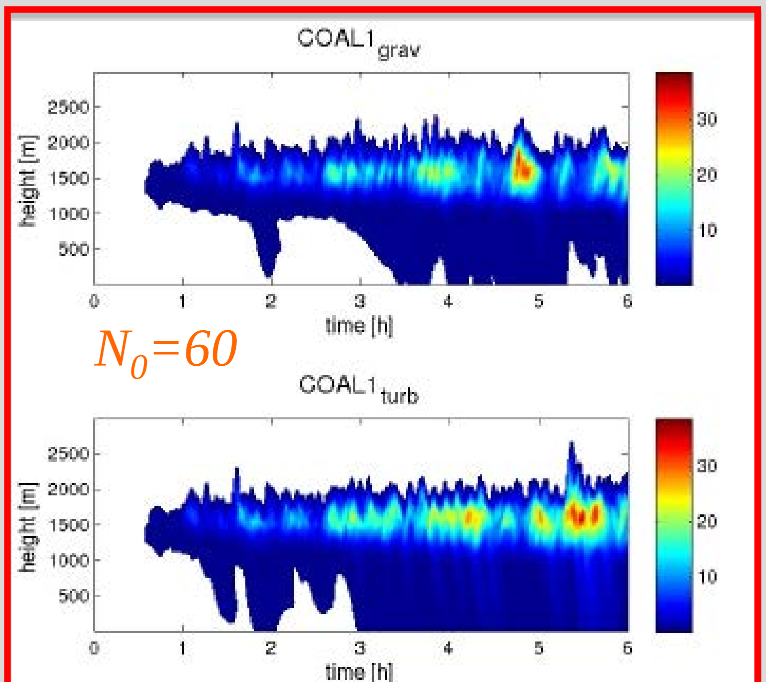
Simulations of a shallow cumulus field – the BOMEX case

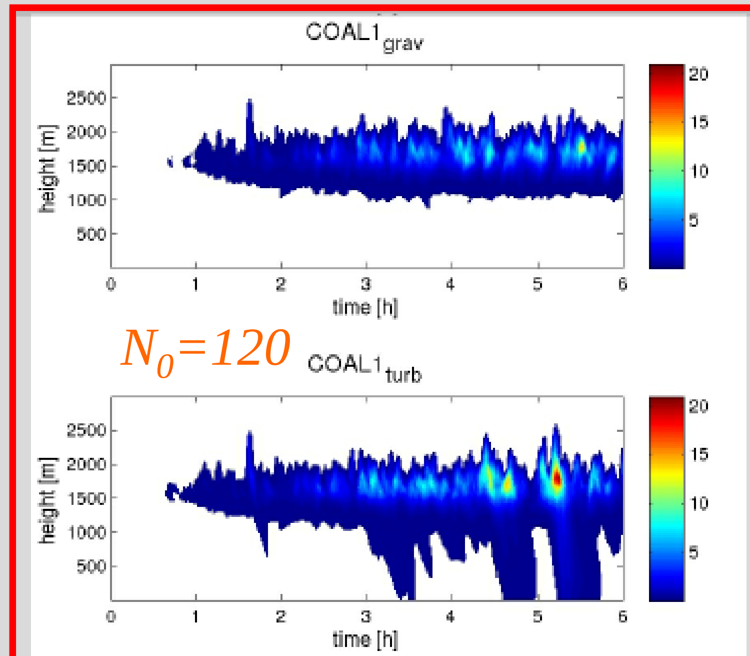
Activation: $N_{act} = N_0 S^b$, $b=.5$



gravity only

gravity + turbulence





Summary:

Small-scale turbulence appears to have a significant effect on collisional growth. Not only rain tends to form earlier in a single cloud, but also turbulent clouds seem to rain more. Analysis of more realistic numerical studies are underway to quantify this aspect.