Growth of cloud droplets and raindrops in turbulent clouds

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Droplet growth in warm turbulent clouds

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Cloud droplets grow by the diffusion of water vapor (i.e., by condensation) and by collision/coalescence.

For both cloud turbulence is thought to play some role.

Turbulent entrainment and mixing affects the spectrum of cloud droplets as well.

Elementary facts about cloud droplets:

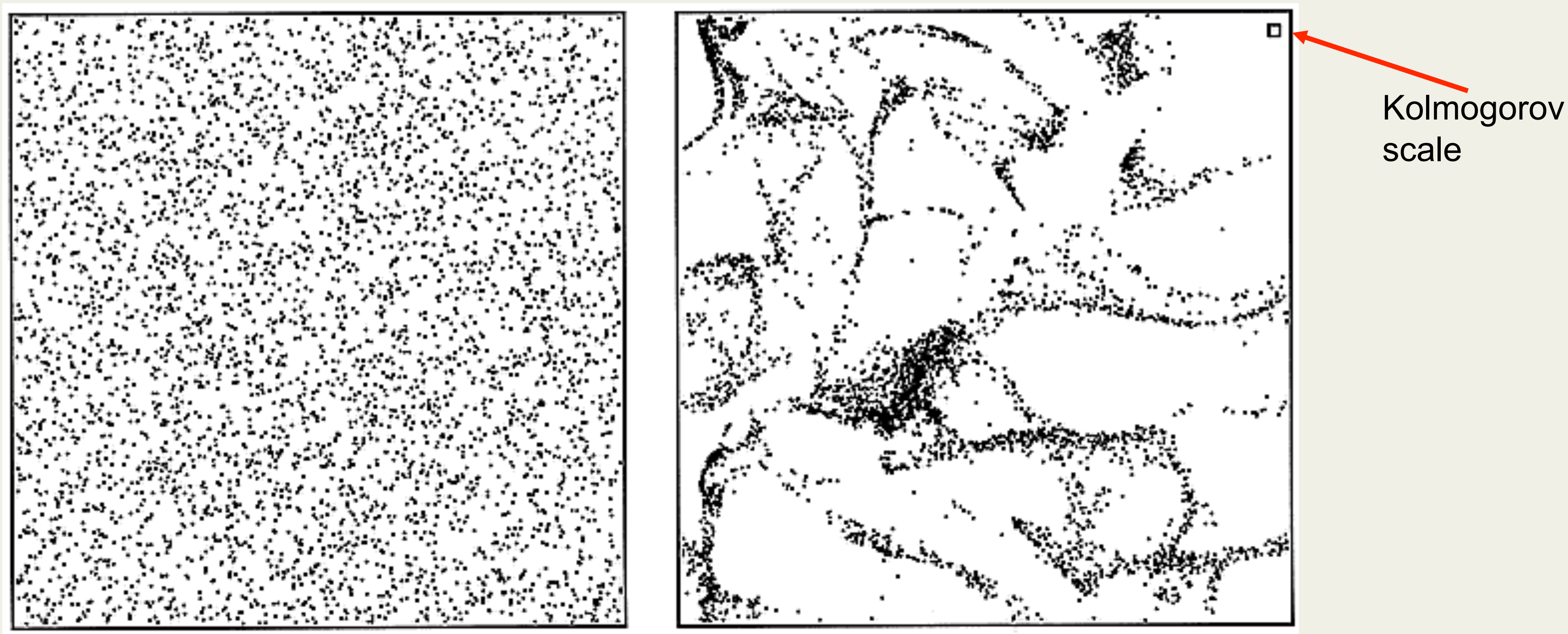
Radius r : 5-30 microns (r << Kolmogorov length scale)

Concentration: 50-2,000 cm^{-3} (mean separation distance >> r)

Mass loading: 0.5-5 g kg^{-1} (<< 1; no effects on turbulence)

Fall terminal velocity v_t: $v_t \sim r^2$; $v_t \approx 1$ cm/s for $r = 10\ \mu m$

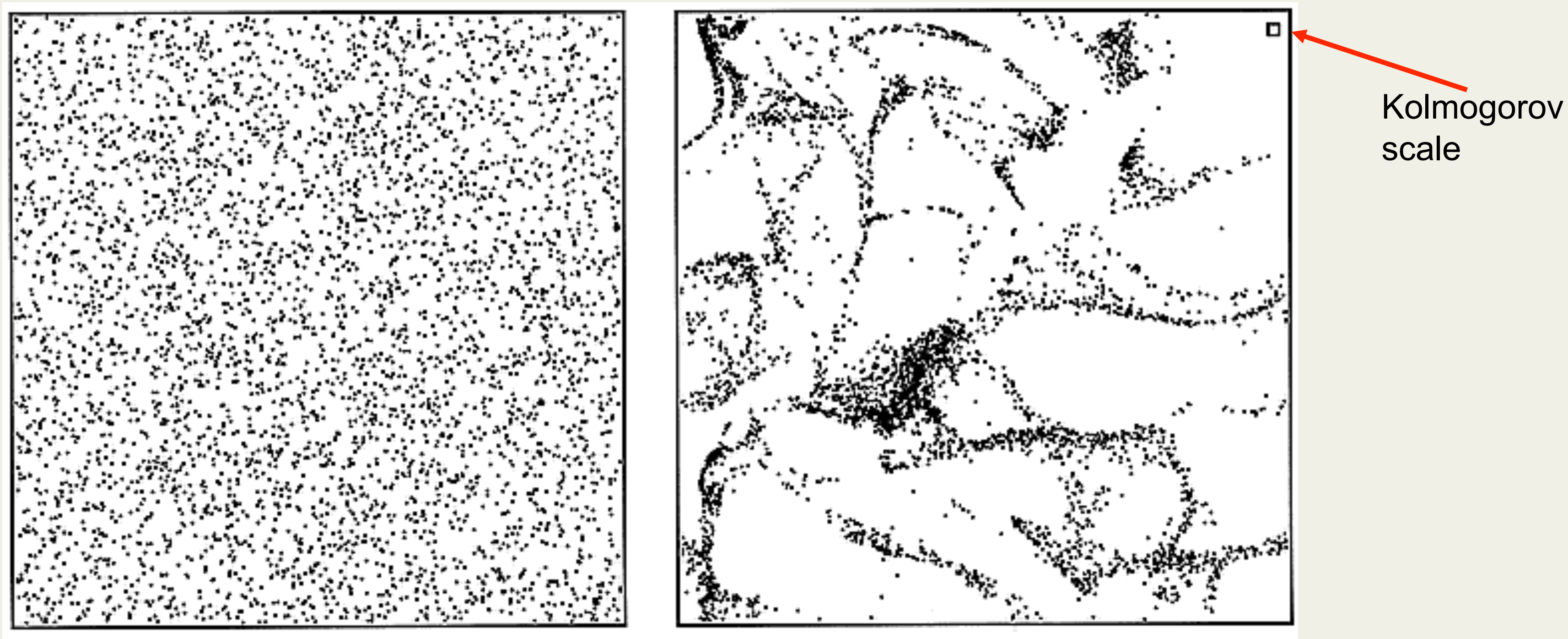
initial conditions solution at a later time



Clustering of nonsedimenting particles for St ~ 1

Shaw et al. JAS 1998

initial conditions solution at a later time



Clustering of nonsedimenting particles for St ~ 1

Is this how cloud microscale looks like?

Not really!....

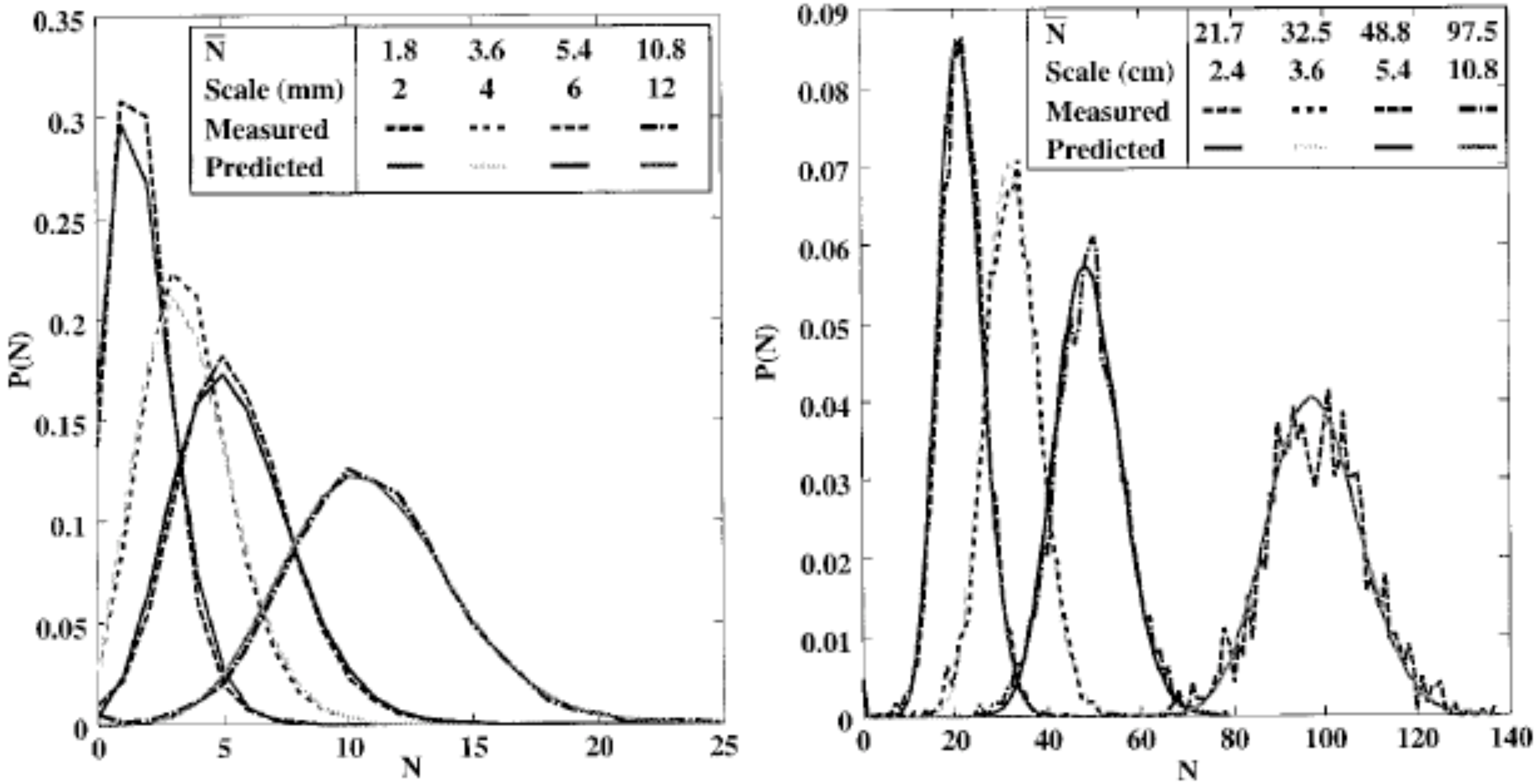


FIG. 1. Probability distribution of the number of counts in actual subsamples (dashed lines), compared to the Poisson distribution (solid lines), for various values of subsample sizes, i.e., of $\overline{N}$. The corresponding spatial scale is indicated in the legend. SCMS sample, at 1542:18.6 UTC 10 Aug 1995 (duration: 1.6 s): $z = 2188$ m, $C = 329$ cm^{-3}, $\overline{\phi} = 25.7$ μm.

Analysis of aircraft observations; Chaumat and Brenguier JAS 2001.

Parameters describing interaction of cloud droplets with turbulence for the case with gravity:

Stokes number: $St = \tau_p / \tau_\eta$

τ_p **- droplet response time**

τ_η **– Kolmogorov timescale**

Nondimensional sedimentation velocity: $Sv = v_p / v_\eta$

v_p **- droplet sedimentation velocity (**$g\tau_p$ **for small droplets)**

v_η **– Kolmogorov velocity scale**

Nondimensional parameters (*St and Sv*) for typical cloud conditions: *St << Sv*

Dissipation rate

Kologorov velocity scale

Kolmogorov time scale

R	v_t	t_p	ϵ m^2 s^{-3}	10^{-4}	10^{-3}	10^{-2}
			υ_η cm s^{-1}	0.64	1.10	2.00
μm	cm s^{-1}	s	t_η s	0.41	0.13	4.1×10^{-2}
5	0.32	3.3×10^{-4}	St	8.0×10^{-4}	2.5×10^{-3}	8.0×10^{-3}
			S_v	0.50	0.28	0.16
15	2.7	2.9×10^{-3}	St	7.0×10^{-3}	2.2×10^{-2}	7.0×10^{-2}
			S_v	4.2	2.4	1.3
25	7.5	8.2×10^{-3}	St	2.0×10^{-2}	6.3×10^{-2}	0.20
			S_v	12	6.6	3.7

droplet radius

sedimentation velocity

response time

Grabowski and Vaillancourt JAS 1999

Nondimensional parameters (*St and Sv*) for typical engineering applications: *St >> Sv*

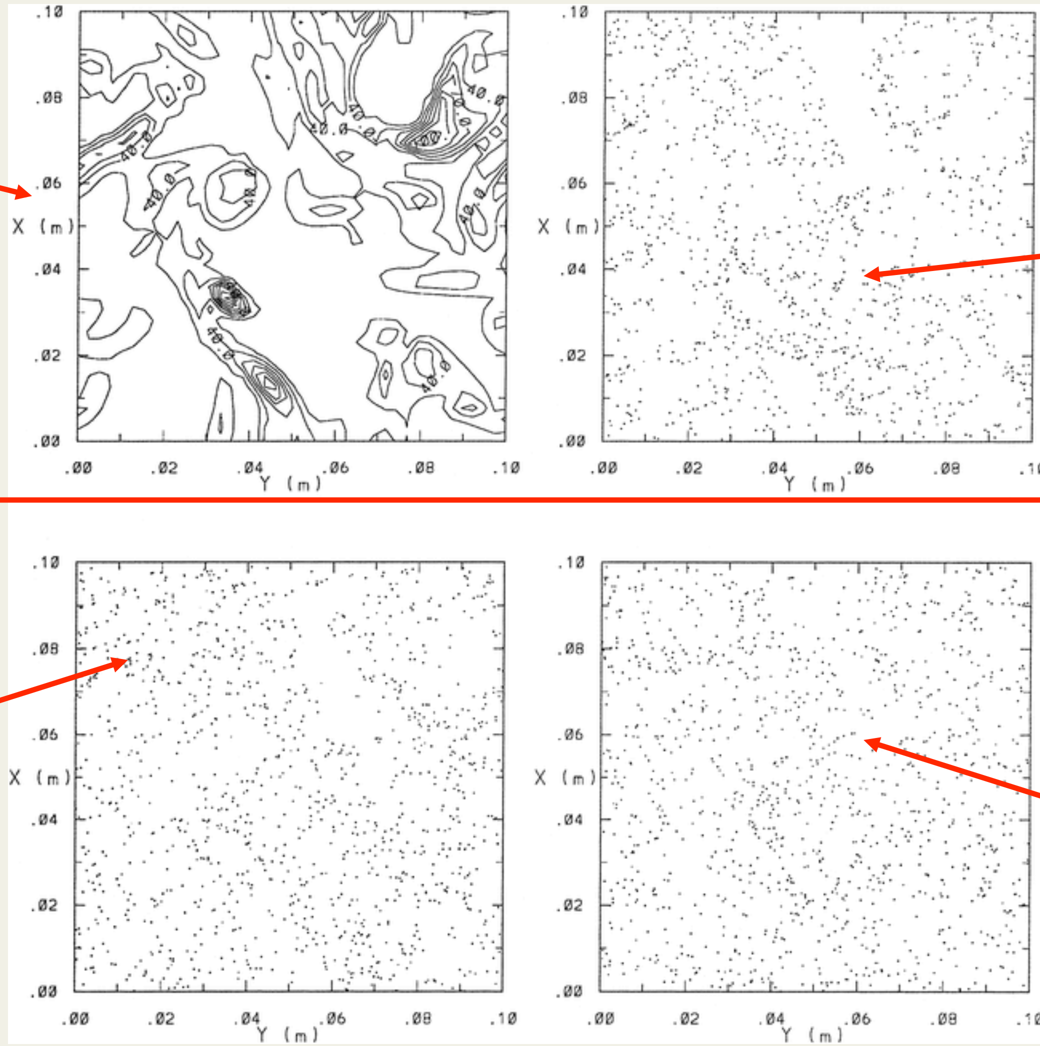
R μm	v_t cm s^{-1}	t_p s		
			ϵ m^2 s^{-3}	10
			v_η cm s^{-1}	11.00
			t_η s	1.3×10^{-3}
5	0.32	3.3×10^{-4}	St	0.25
			S_v	2.8×10^{-2}
15	2.7	2.9×10^{-3}	St	2.2
			S_v	0.24
25	7.5	8.2×10^{-3}	St	6.3
			S_v	0.66

$St / Sv \sim \varepsilon^{3/4}$ (for Stokes limit: $v_p = g\tau_p$)

Grabowski and Vaillancourt JAS 1999

The key point: turbulence in clouds is significantly weaker than in laboratory experiments. This makes droplet sedimentation significantly more important.

DNS simulations with sedimenting droplets for conditions relevant to cloud physics (ε=160 cm^2s^{-3})



Vorticity

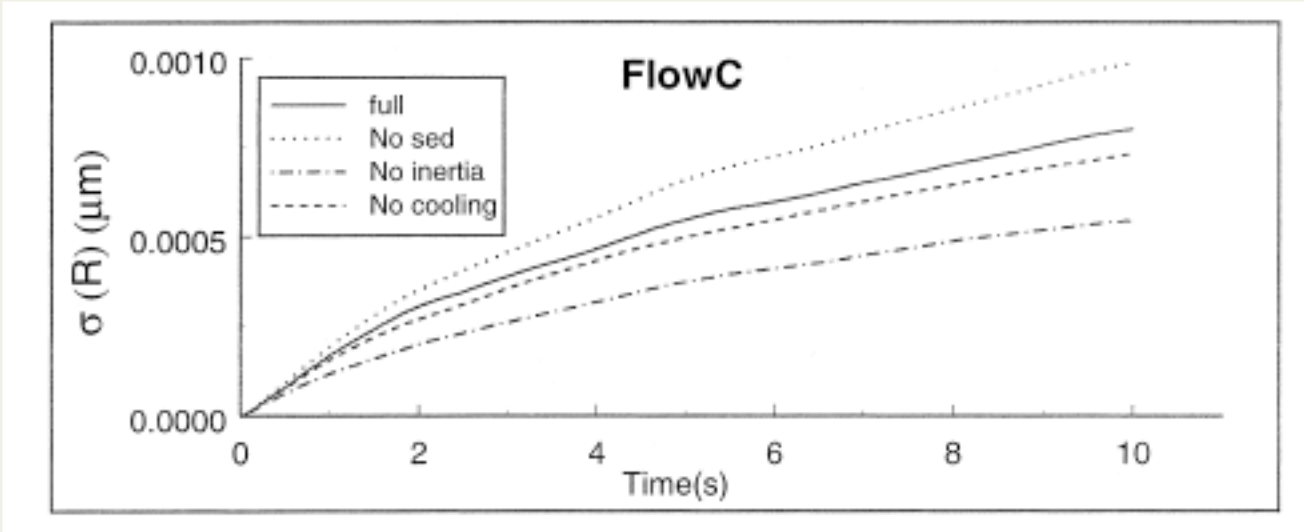
(contour 15 s^{-1})

r=20 micron

r=15 micron

r=10 micron

Vaillancourt et al. JAS 2002



Main conclusion: small-scale turbulence has a very small effect…

Vaillancourt et al. JAS 2002

What about those DNS limitations?

Argument: if Re increases (i.e., the range of scales involved increases), can supersaturation fluctuation increase as well?

Yes, but only to some point…

The brake on supersaturation fluctuations:

$$\frac{dS}{dt} = \alpha w - \frac{S}{\tau_{qe}}$$

TABLE 1. Time constant characterizing supersaturation. (Values of $\tau = 1/(a_2 I)$ s for $p = 771$ mb, $T = 4.3°C$)

Radius (μm)	Droplet concentration (cm^{-3}) 100	300	500	1000
2	14.1	4.7	2.8	1.4
3	8.7	2.9	1.7	0.87
5	4.9	1.6	0.98	0.49
10	2.3	0.77	0.46	0.23

Politovich and Cooper, JAS 1988

$$\tau_{qe} \sim 1\,\mathrm{sec}$$

$$\frac{dS}{dt} \equiv 0 \rightarrow S_{qe} = \alpha w \tau_{qe}$$

For eddies with time-scale larger than τ_{qe}, S is limited to S_{qe} !!!

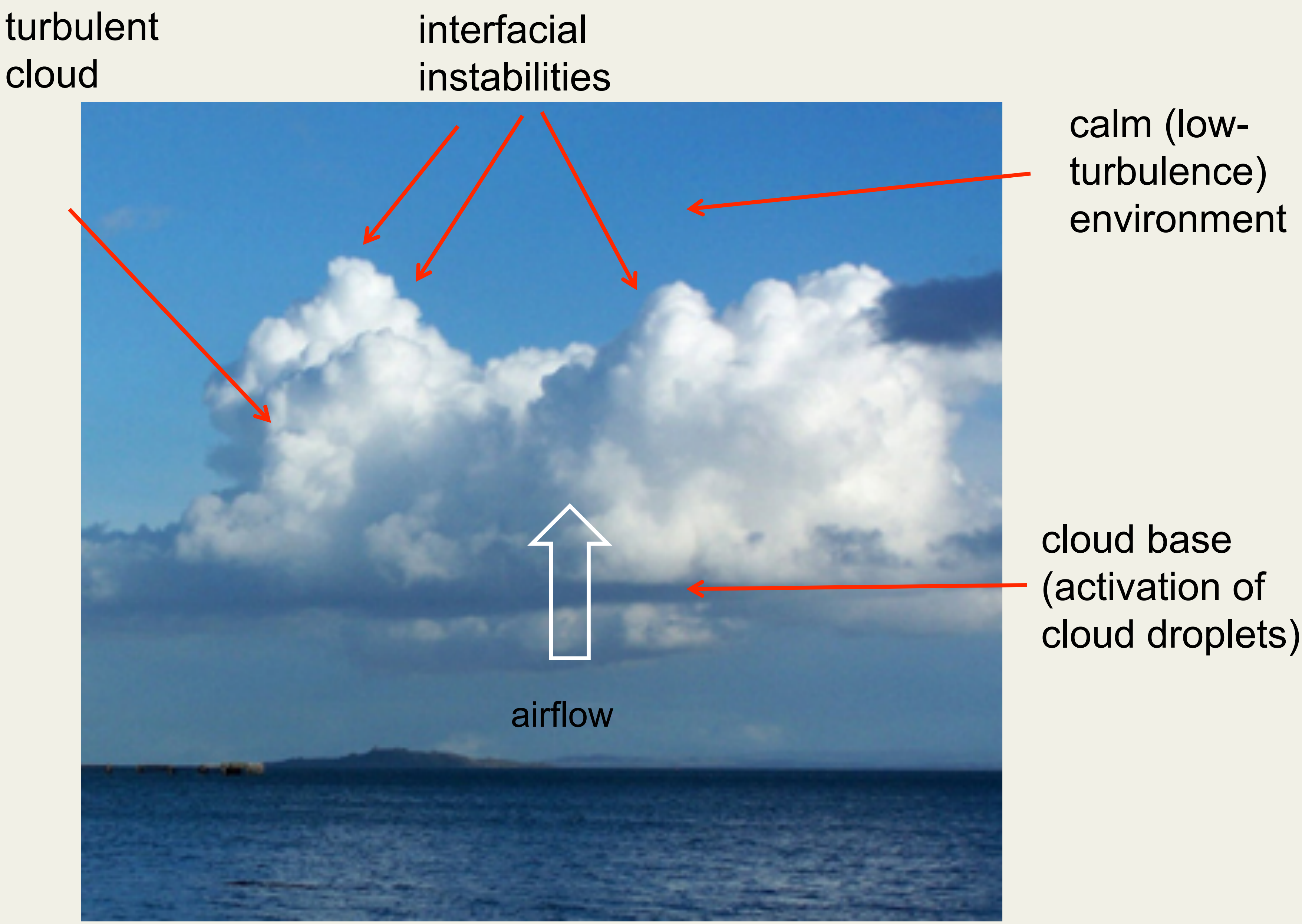
So within a uniform cloud (e.g., the adiabatic core), fluctuations of the supersaturation have a small effect.

Another way to think about this problem:

Condensational growth is reversible: droplets grow more in higher S, and then less in lower S, and the two situations change rapidly…

But if you think about the collisional growth, then the story is different: growth is not reversible…

So within a uniform cloud (e.g., the adiabatic core), fluctuations of the supersaturation have a small effect. But what about the impact of mixing with the dry air from cloud environment (entrainment)?


turbulent cloud
interfacial instabilities
calm (low-turbulence) environment
cloud base (activation of cloud droplets)
airflow

Entrainment/mixing and the cloud droplet spectra:

1. Entrainment/mixing typically leads to partial evaporation of cloud water. How this evaporation affects the spectrum of cloud droplets?

2. Entrainment/mixing may lead to activation of cloud droplets above the cloud base.

3. Entrainment/mixing provides large-scale source of cloud turbulence (this may seem irrelevant…).

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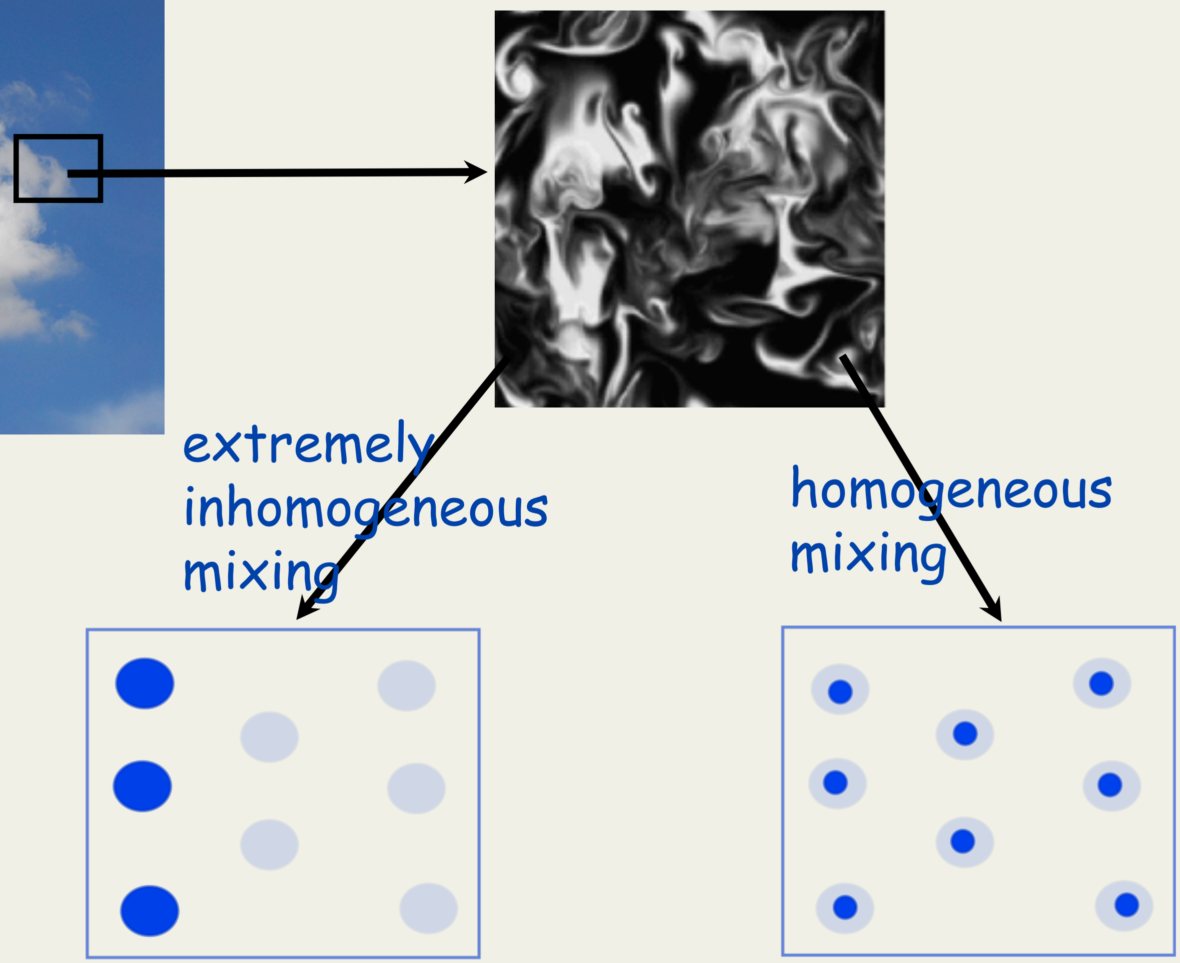
Turbulent mixing



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

Homogeneity of mixing depends on the ratio of two relevant time scales:

-Droplet evaporation time scale:

$$\tau_{\mathrm{evap}} \equiv r\left(\frac{dr}{dt}\right)^{-1} = \frac{r^2}{A(1-\mathrm{RH})},$$

$$A \approx 10^{-10}\ \mathrm{m}^2\ \mathrm{s}^{-1}$$

-Turbulent mixing time scale

$$\tau_{\mathrm{mix}} \equiv \frac{L}{U(L)} \sim \left(\frac{L^2}{\epsilon}\right)^{1/3},$$

$$U(L) \sim (\epsilon L)^{1/3}$$

droplet spectra

vertical and along-track velocity

liquid water content

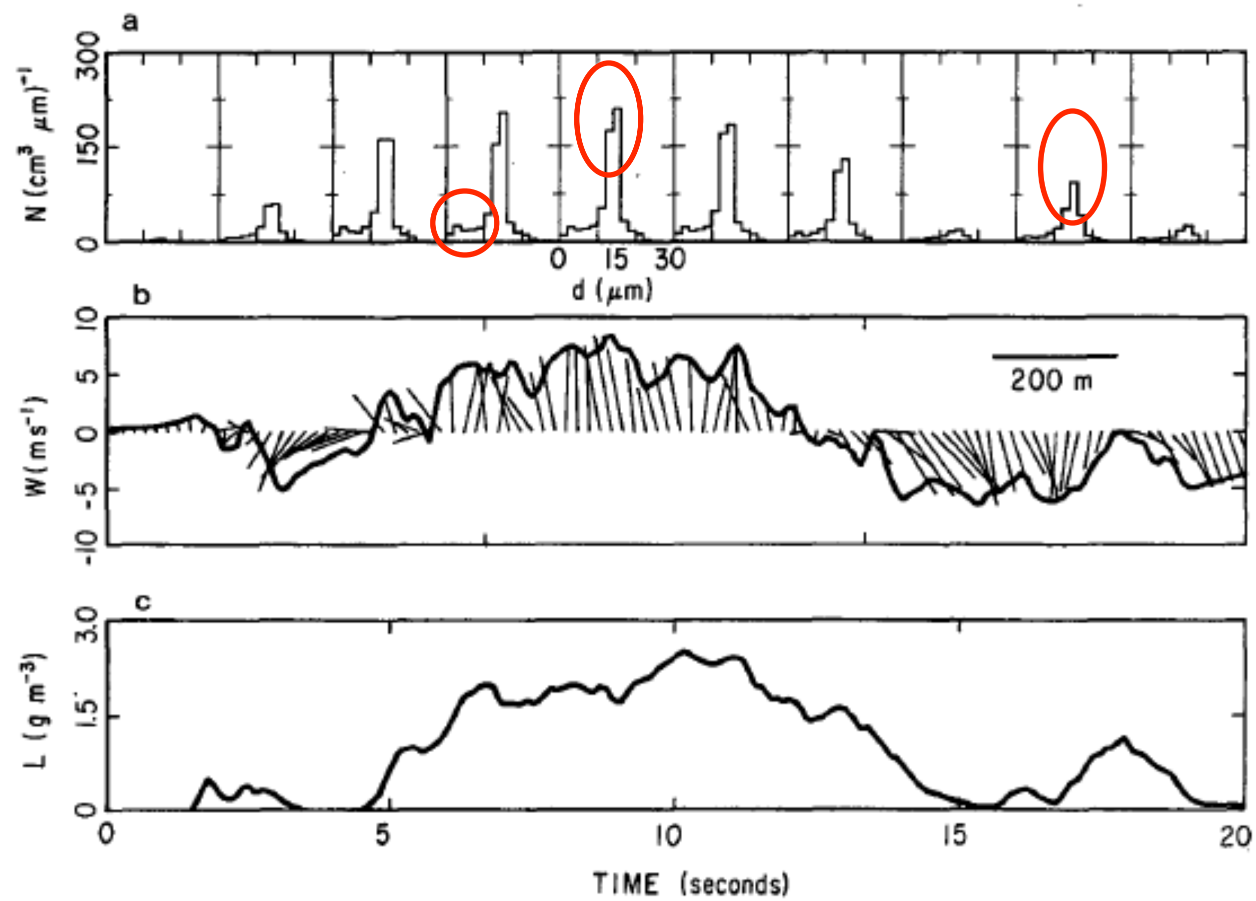
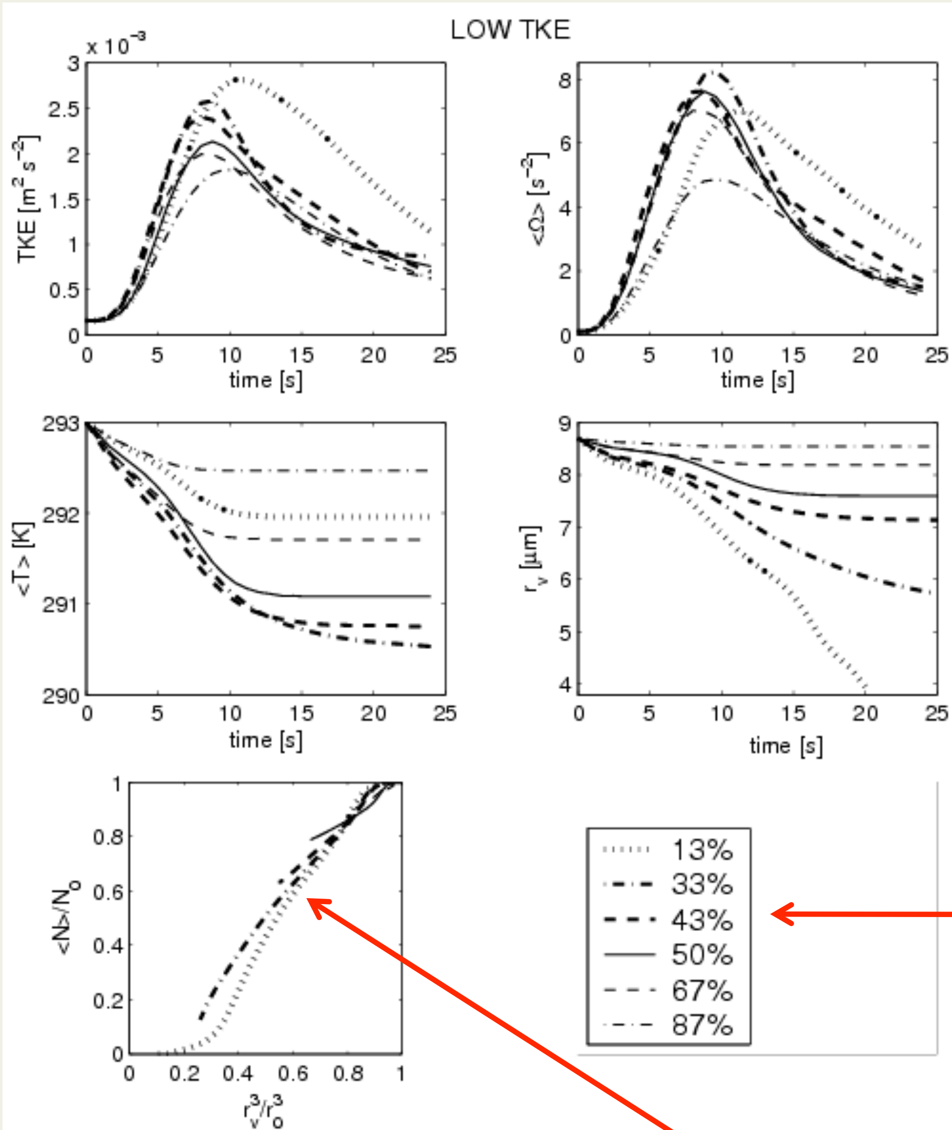


FIG. 3. Penetration at 600 mb, 6 June: (a) two-second averaged droplet spectra (sizes for diameter bins are those given by the manufacturer); (b) wind velocity, the lines represent wind vectors formed from the vertical wind and the wind along the flight path; (c) liquid water density measured by the Johnson-Williams device. All H-2 measurements.

(Austin et al. JAS 1985)

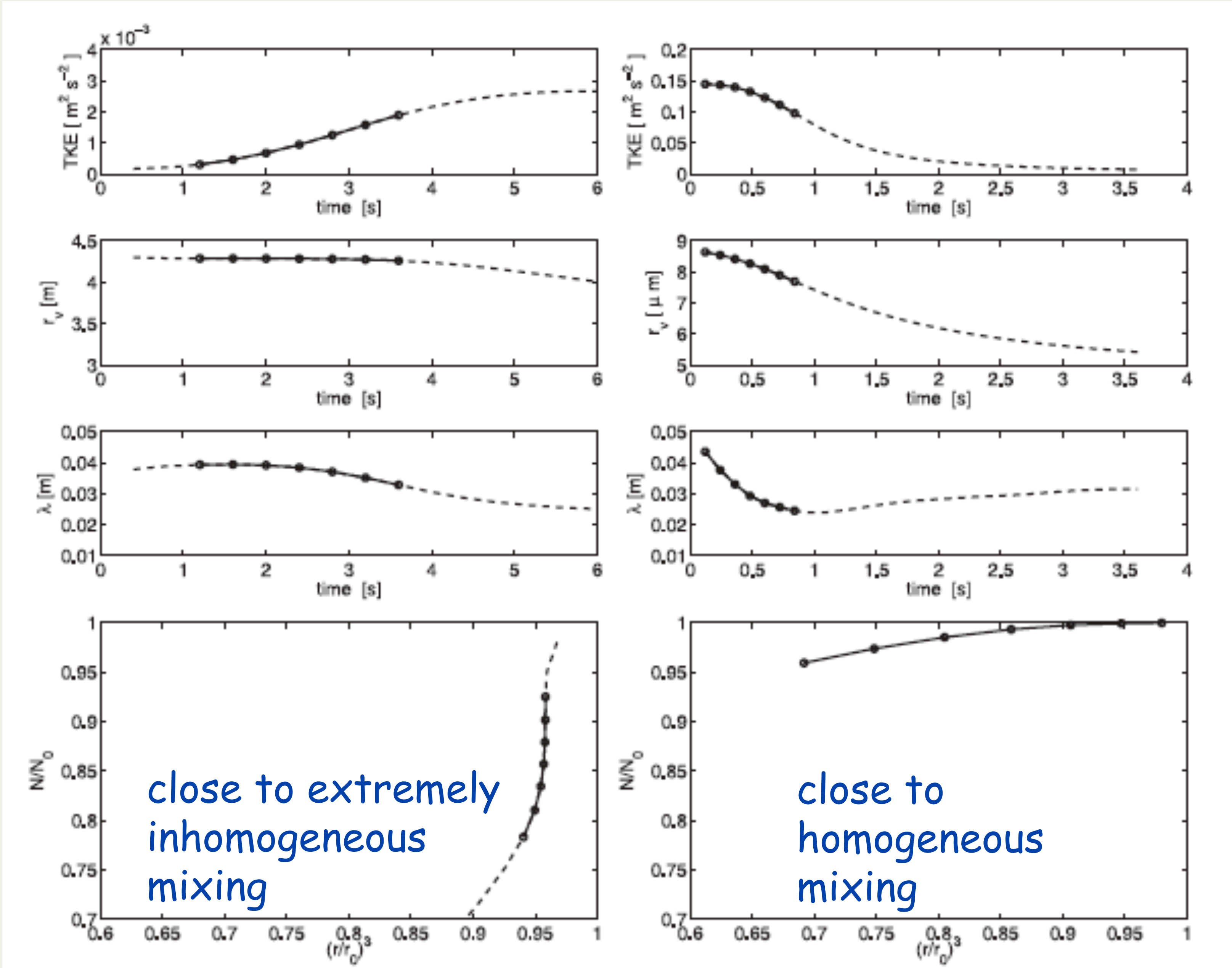
DNS simulations of microscale homogenization of initially separate filaments of cloudy and cloud-free air (decaying turbulence setup).



Andrejczuk et al JAS 2006

The percentage represents the initial volume fraction of cloudy air.

Evolution of the number of droplets N and their mean volume radius r_v, both normalized by the initial values



Andrejczuk et al JAS 2009

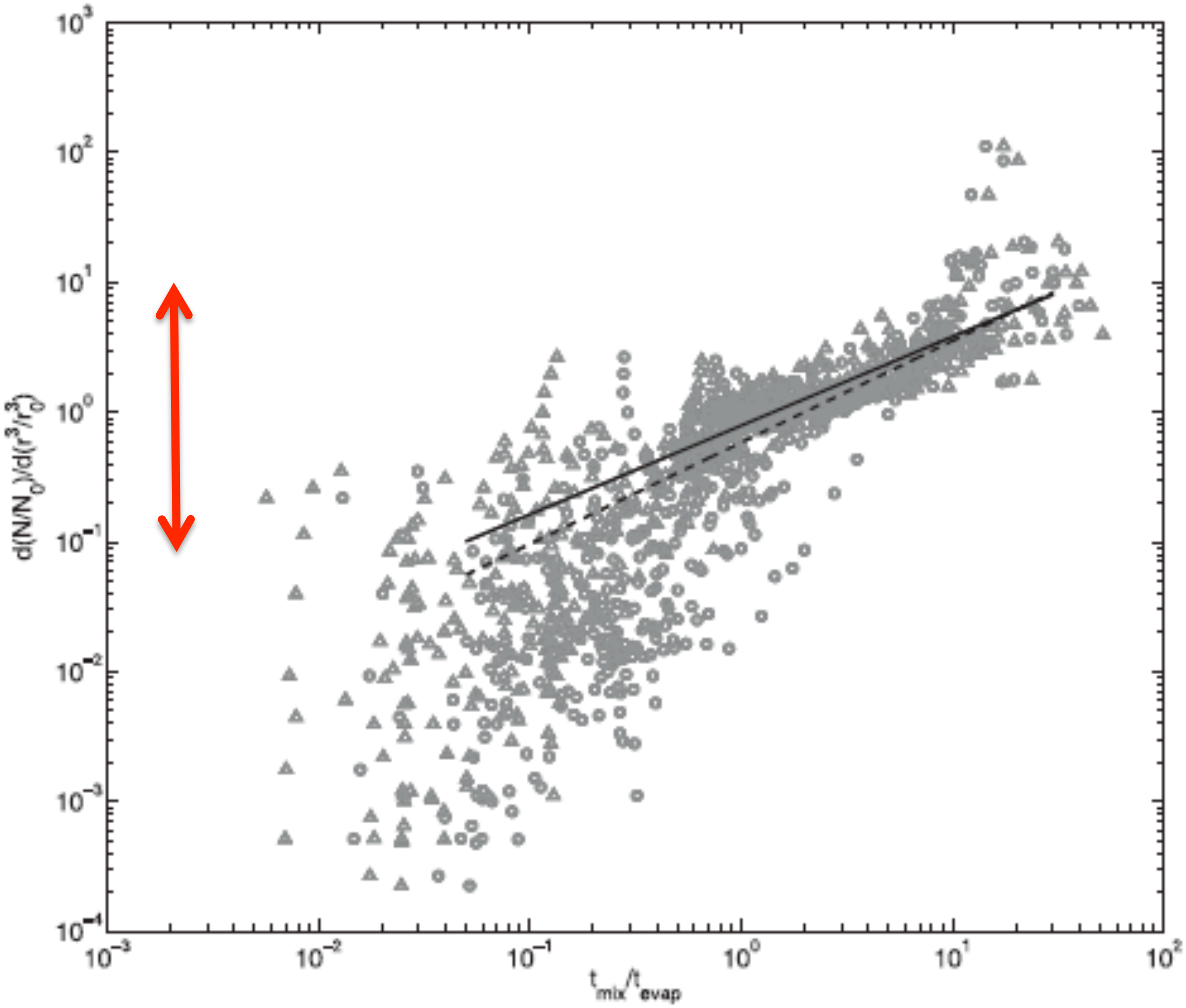


FIG. 2. Scatterplot of the slope of the mixing line on the *r*–*N* diagram vs the ratio between the turbulent mixing and the droplet evaporation time scales. Each data point represents analysis of instantaneous DNS data as explained in text, with triangles (circles) depicting data points with the mixing time scale calculated using TKE (enstrophy). The solid and dashed lines represent linear fits for either triangles or circles. See text for details.

Andrejczuk et al JAS 2009

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3. Entrainment/mixing provides large-scale source of cloud turbulence (this may seem irrelevant…).

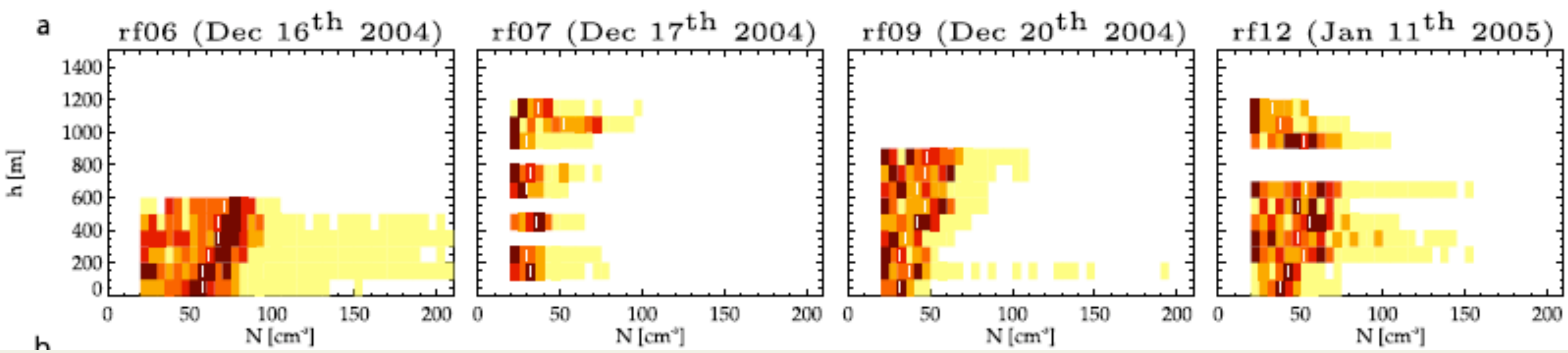
Gerber et al. *JMSJ* 2008

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.

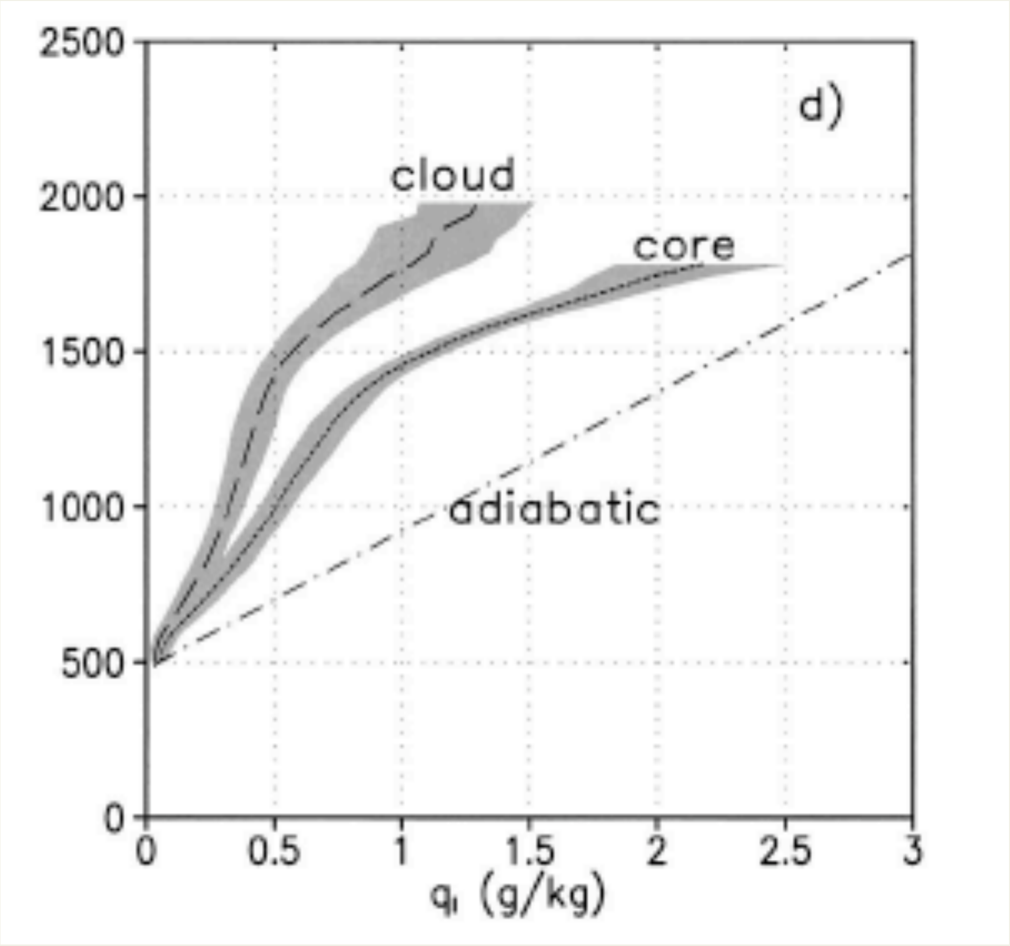
Level	LWC_a (g/m³)	LWC (g/m³)	s (10 cm) (g/m³)	s (50 cm) (g/m³)	s (1000 cm) (g/m³)	N (No/cc)	s [N] (No/cc)	r_{va} (μm)	r_v (μm)	s (r_v) (μm)
1	.605	.284	.084	.078	.063	95	12	11.4	9.2	2.0
2	1.00	.427	.142	.136	.128	97	22	13.5	10.6	3.1
3	1.42	.520	.160	.153	.145	112	25	15.2	10.2	1.7
4	2.11	.536	.196	.184	.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



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)!

Slawinska et al. (*J. Atmos. Sci*.; in review)
Wyszogrodzki et al. (*Acta Geophysica*; in review)

JAS
2003

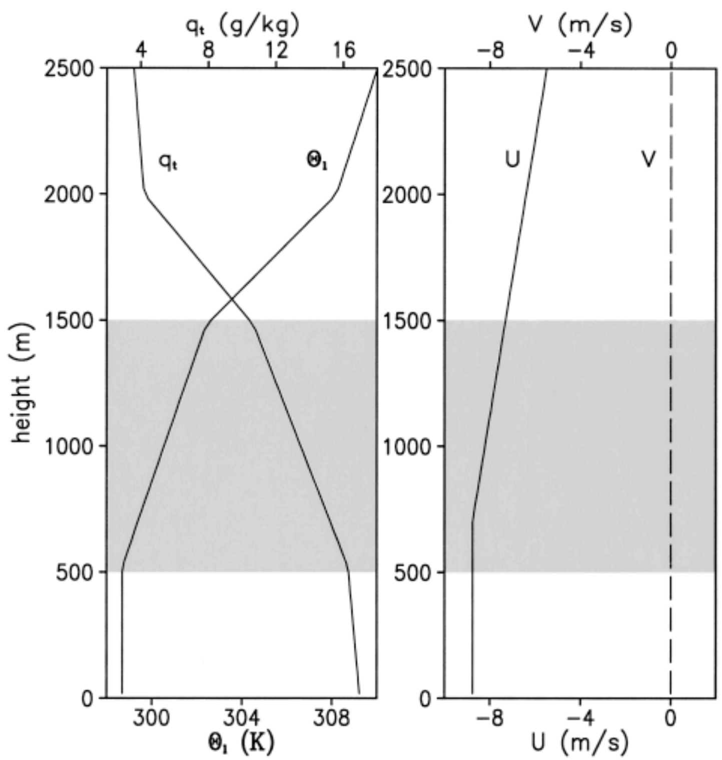
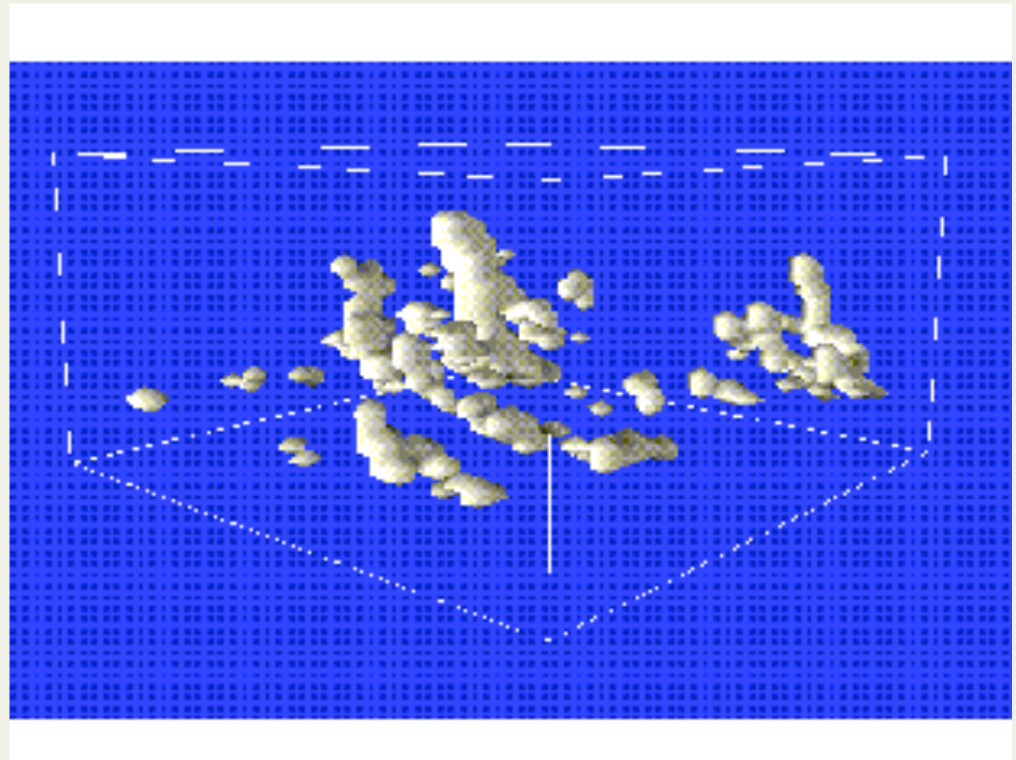
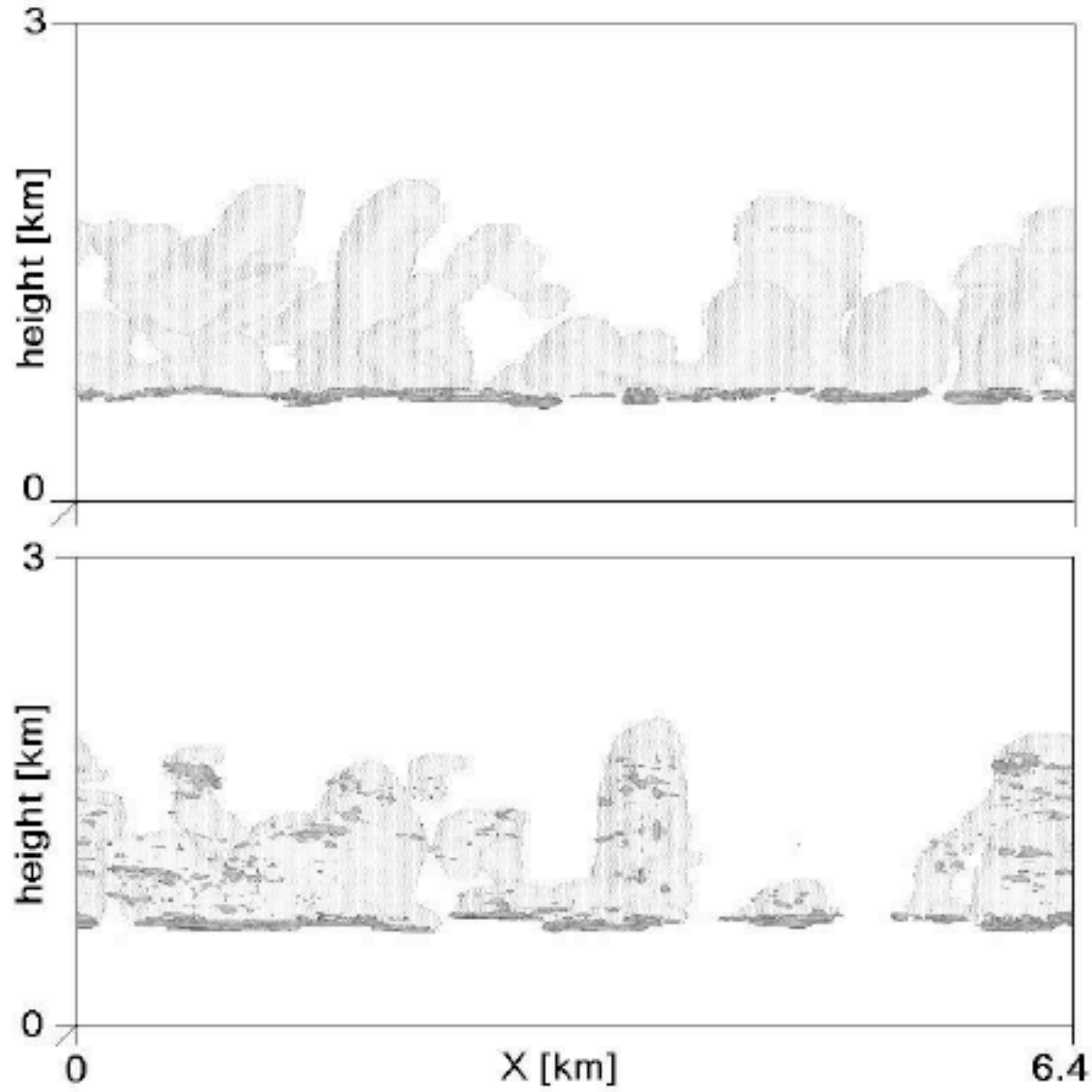


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.



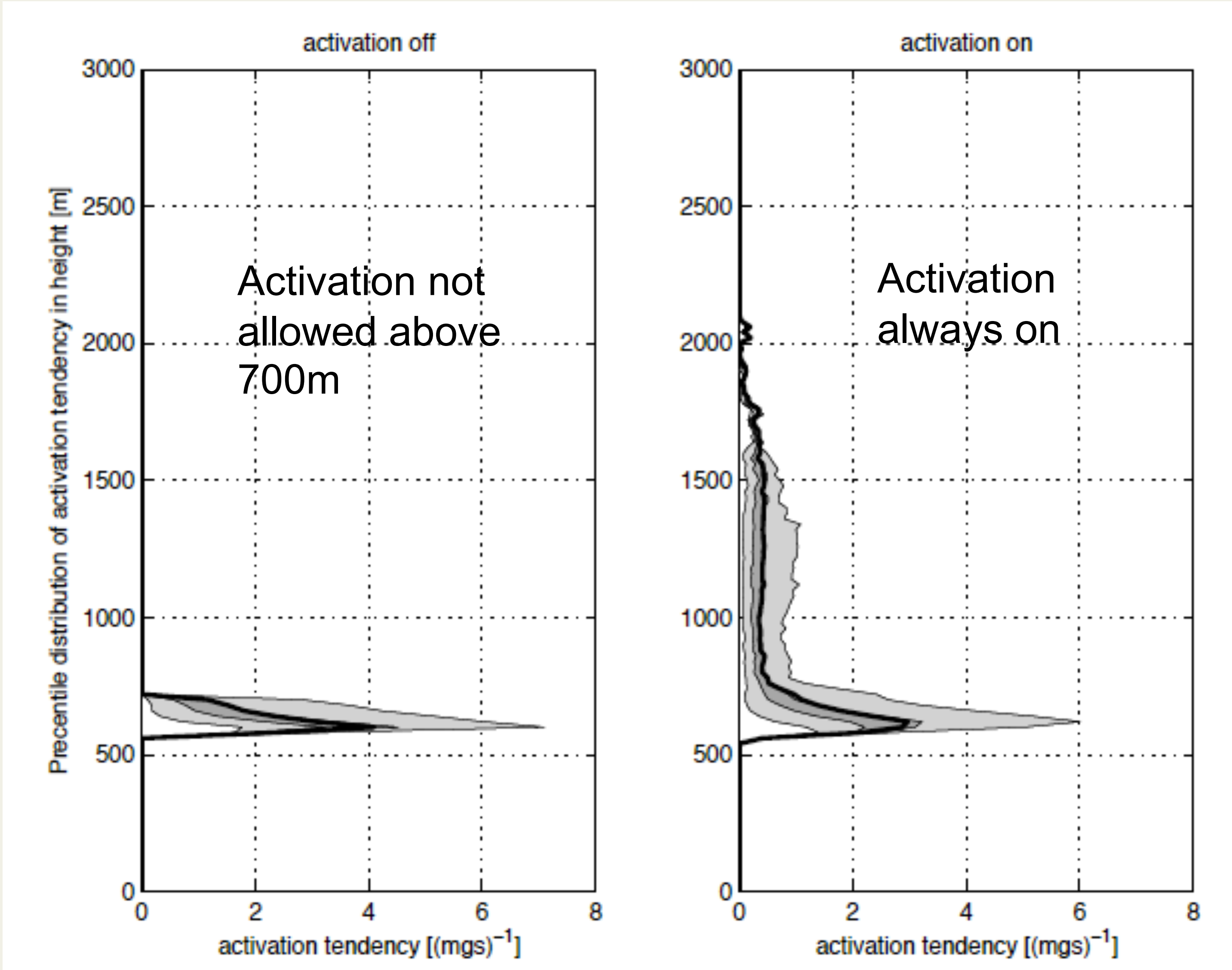
The Barbados Oceanographic and Meteorological Experiment (BOMEX) case (Holland and Rasmusson 1973) gray – cloud water; dark gray – positive activation tendency

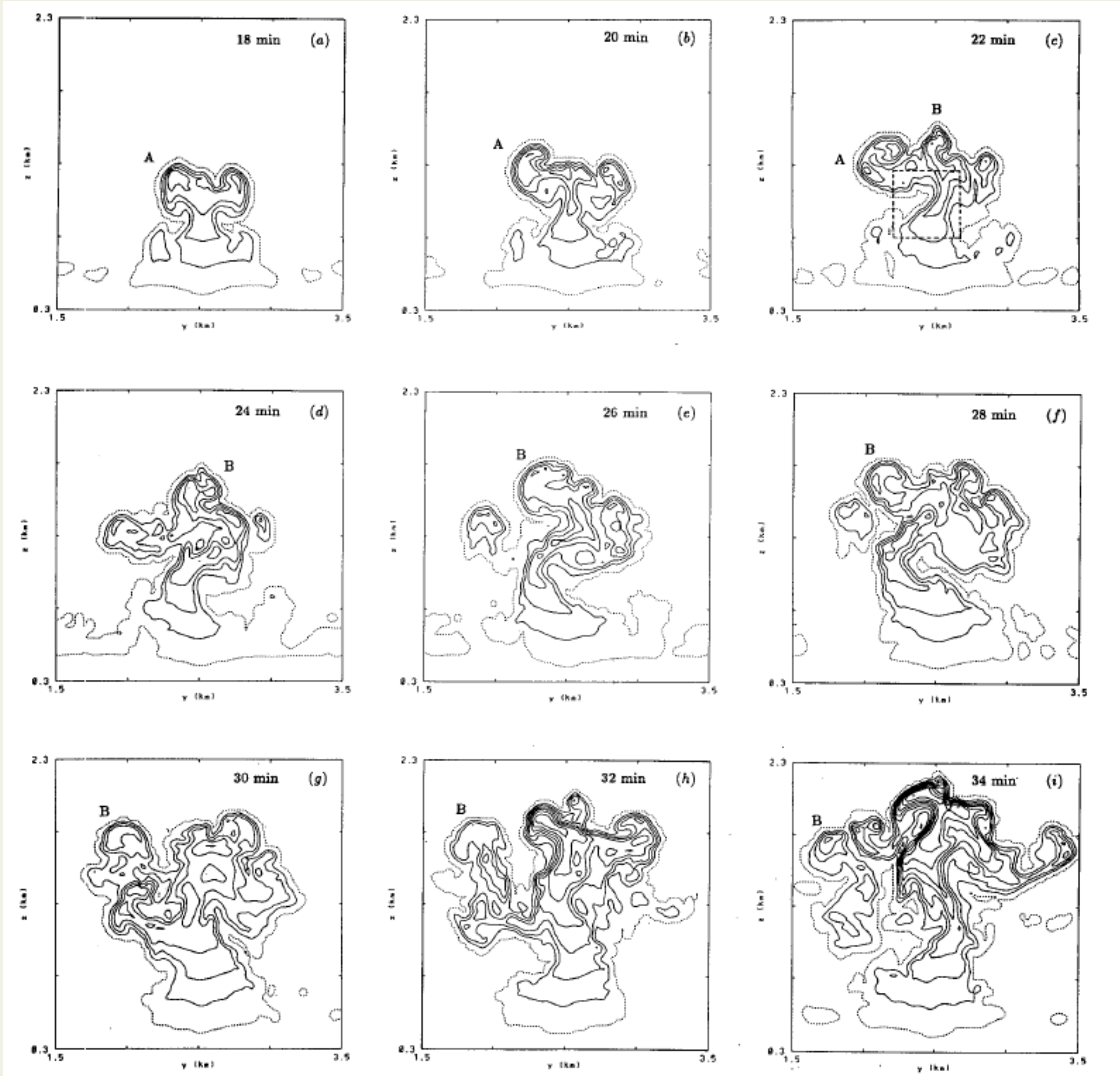


Activation not allowed above 700m

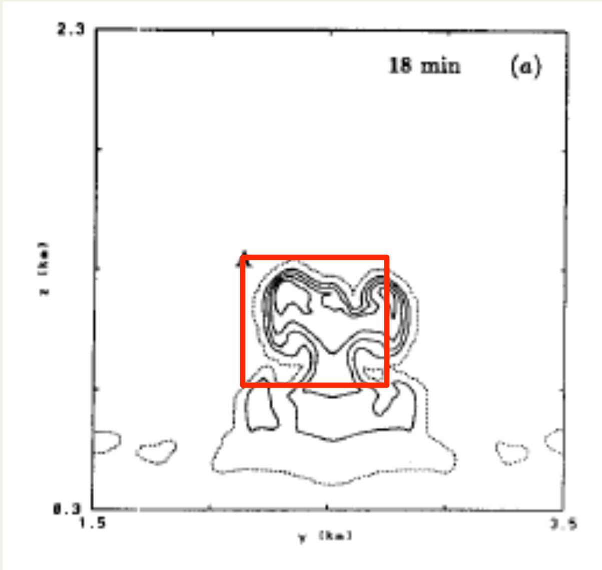
Activation always on

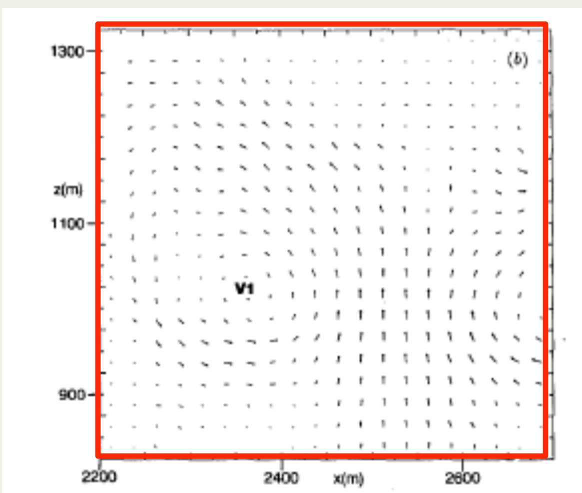
Conditionally-sampled activation tendency

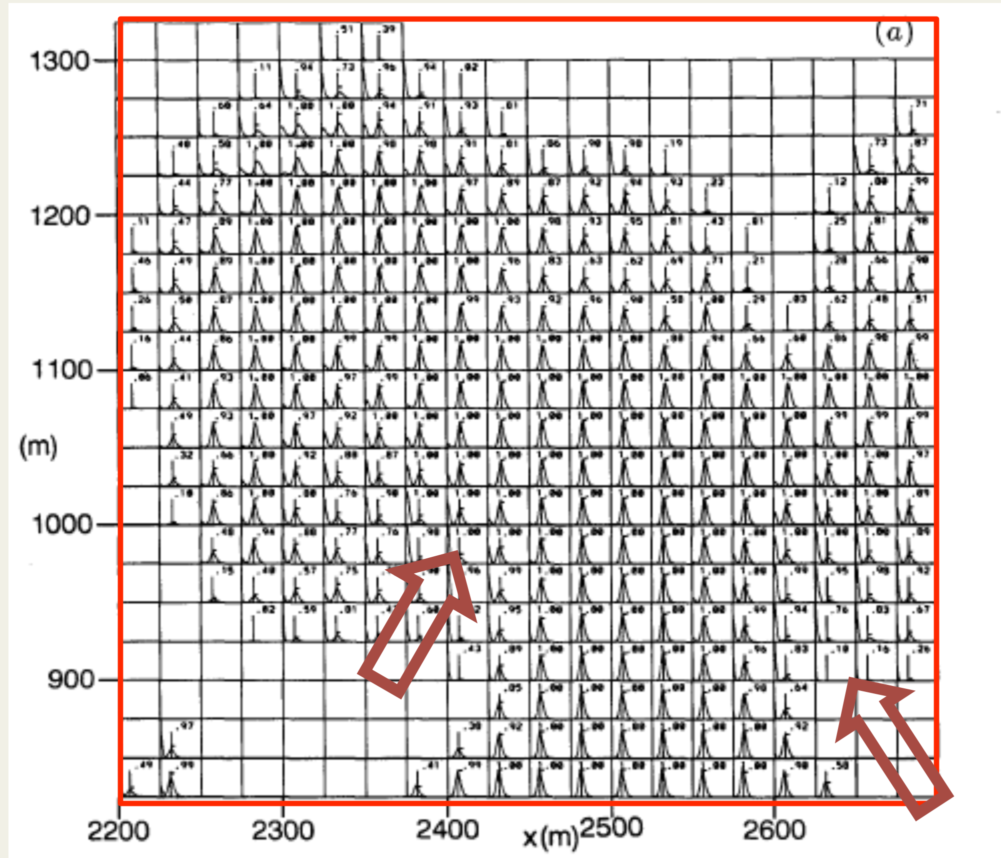




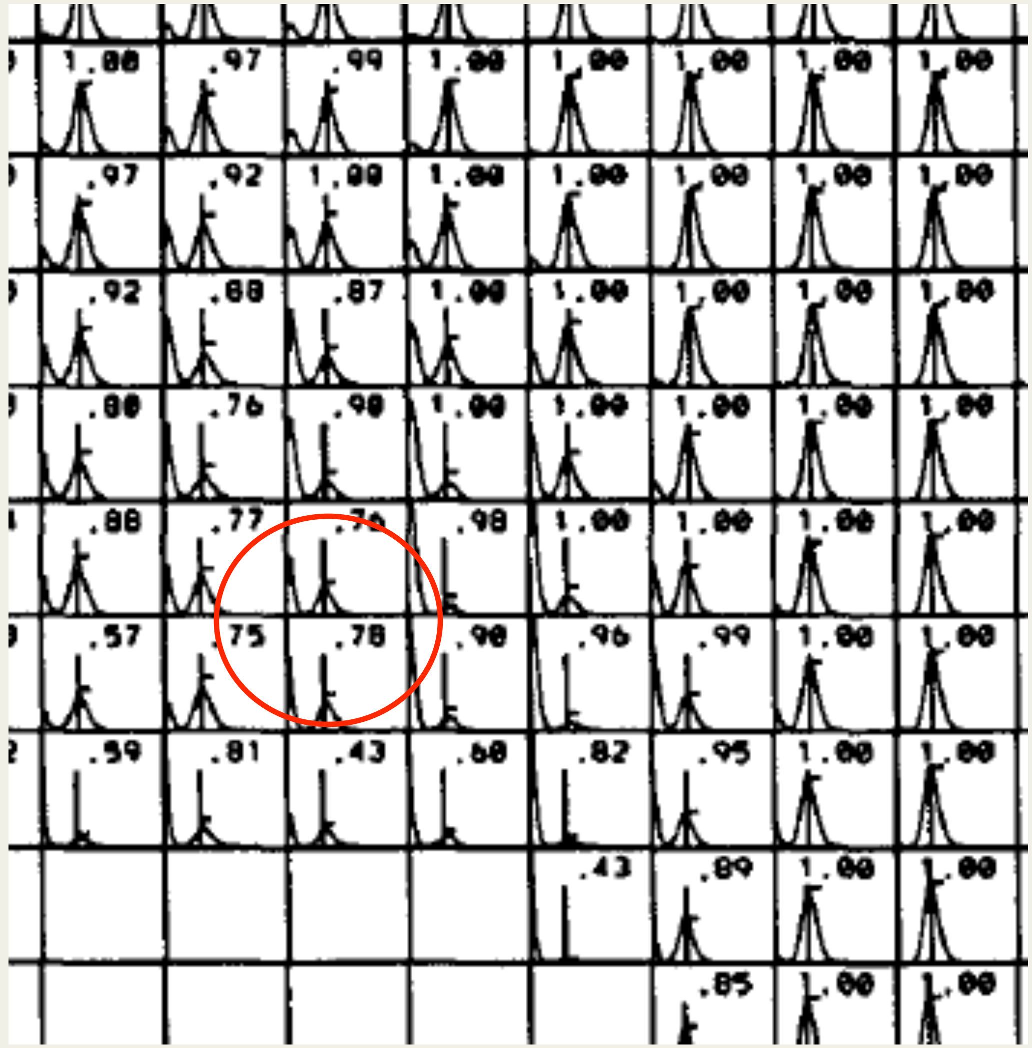
Brenguier and Grabowski (JAS 1993)



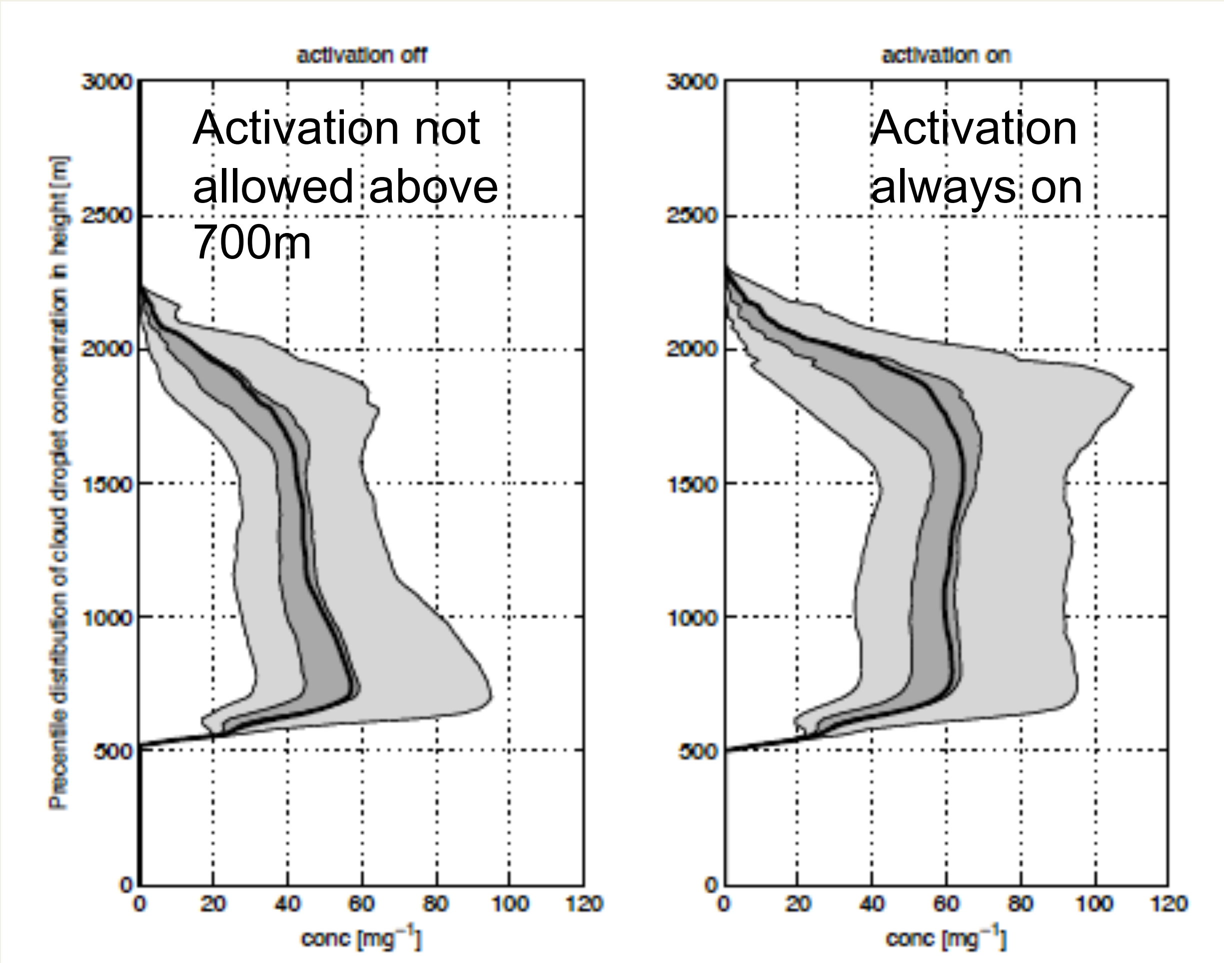




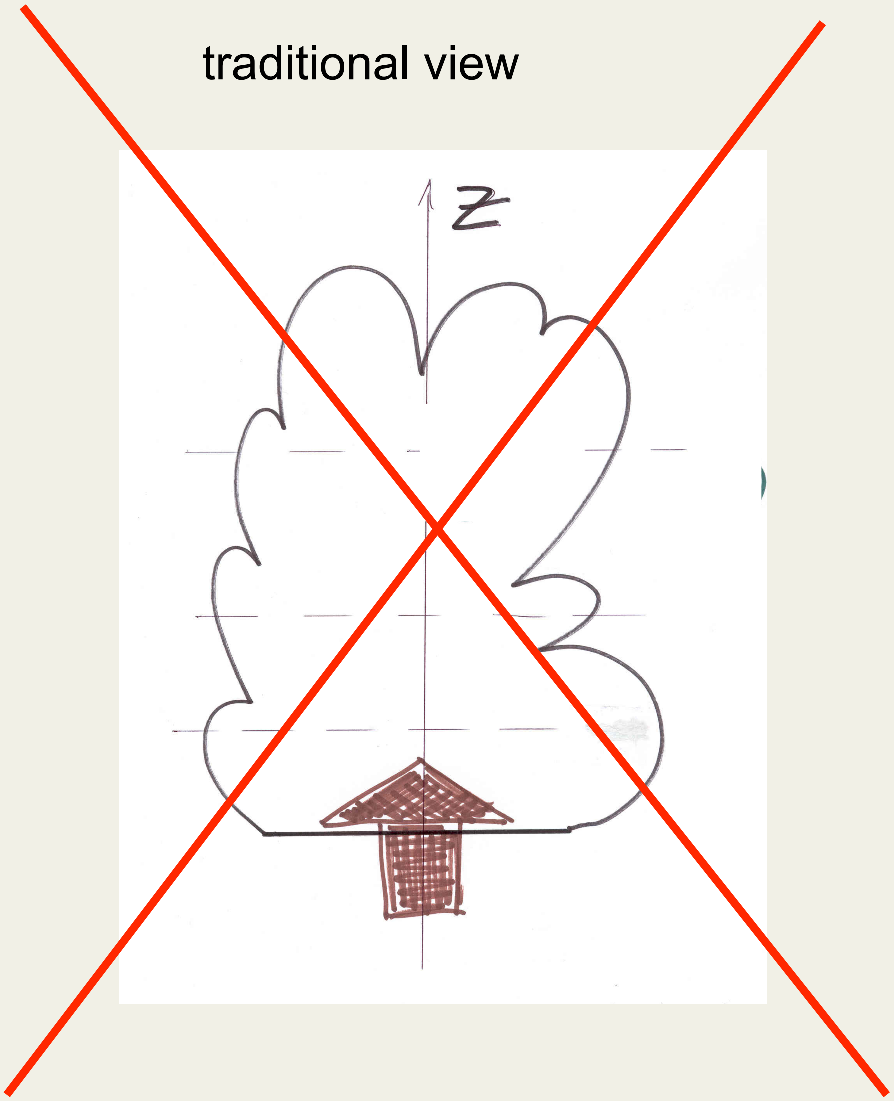
Brenguier and Grabowski (JAS 1993)



Brenguier and Grabowski (JAS 1993)


activation off
activation on
Activation not allowed above 700m
Activation always on
Precentile distribution of cloud droplet concentration in height [m]
conc [mg^{-1}]
conc [mg^{-1}]
0
500
1000
1500
2000
2500
3000
0
20
40
60
80
100
120

traditional view



view suggested by model simulations

Entrainment/mixing and the cloud droplet spectra:

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3. Entrainment/mixing provides large-scale source of cloud turbulence (this may seem irrelevant…).

"Large-eddy hopping"

(Al Cooper, NCAR; Sonia Lasher-Trapp, Purdue; Alan Blyth, Leeds):

Droplets observed in a single location within a cloud arrive along variety of fluid trajectories:

- large scales are needed to provide different droplet activation/growth histories;

- small scales needed to allow hopping from one large eddy to another.

[see also Sidin et al. (*Phys. Fluids* 2009) for idealized 2D synthetic turbulence simulations]

The Initiation of Coalescence in a Cumulus Cloud

A Beneficial Influence of Entrainment and Mixing

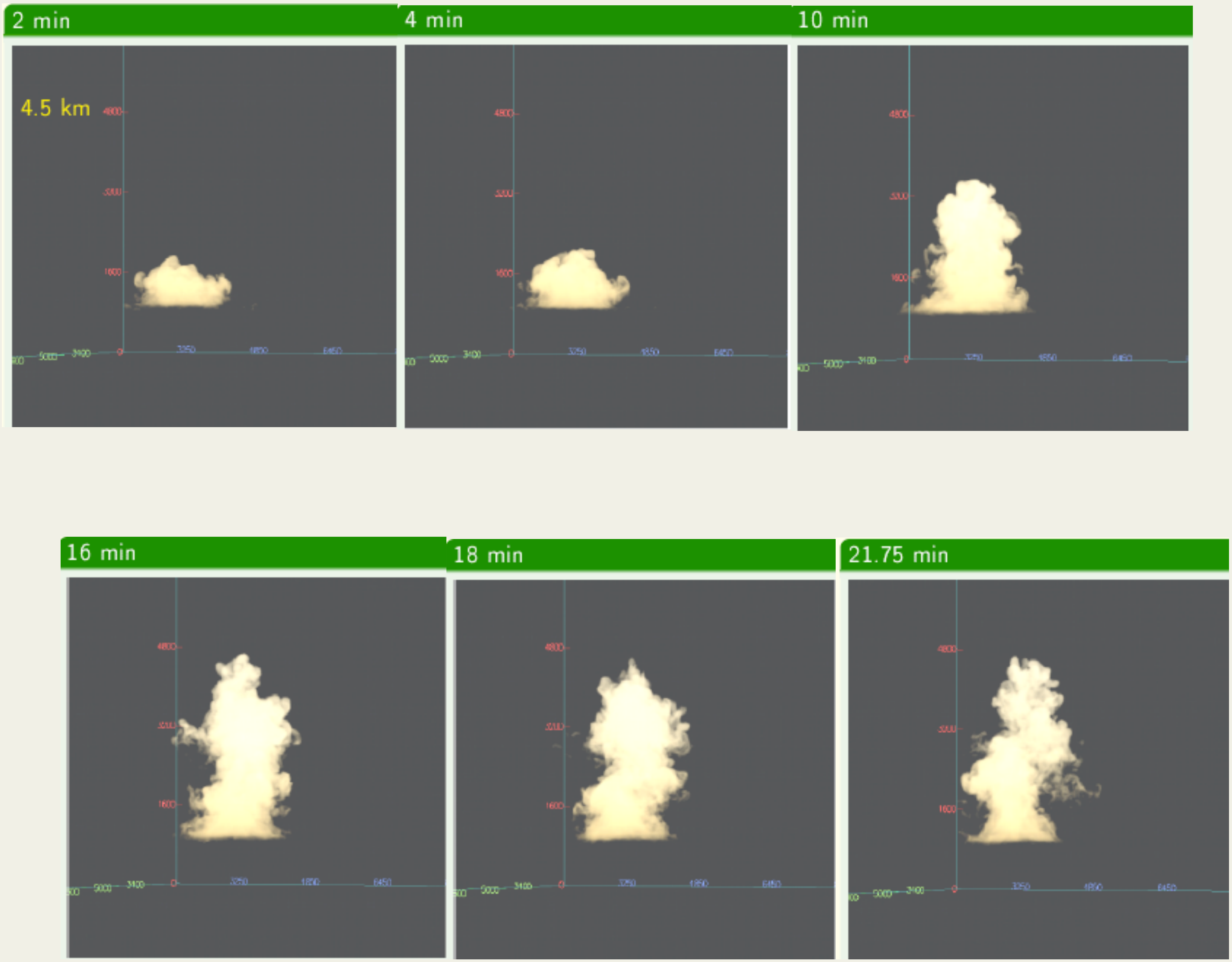
Al Cooper

NCAR EOL

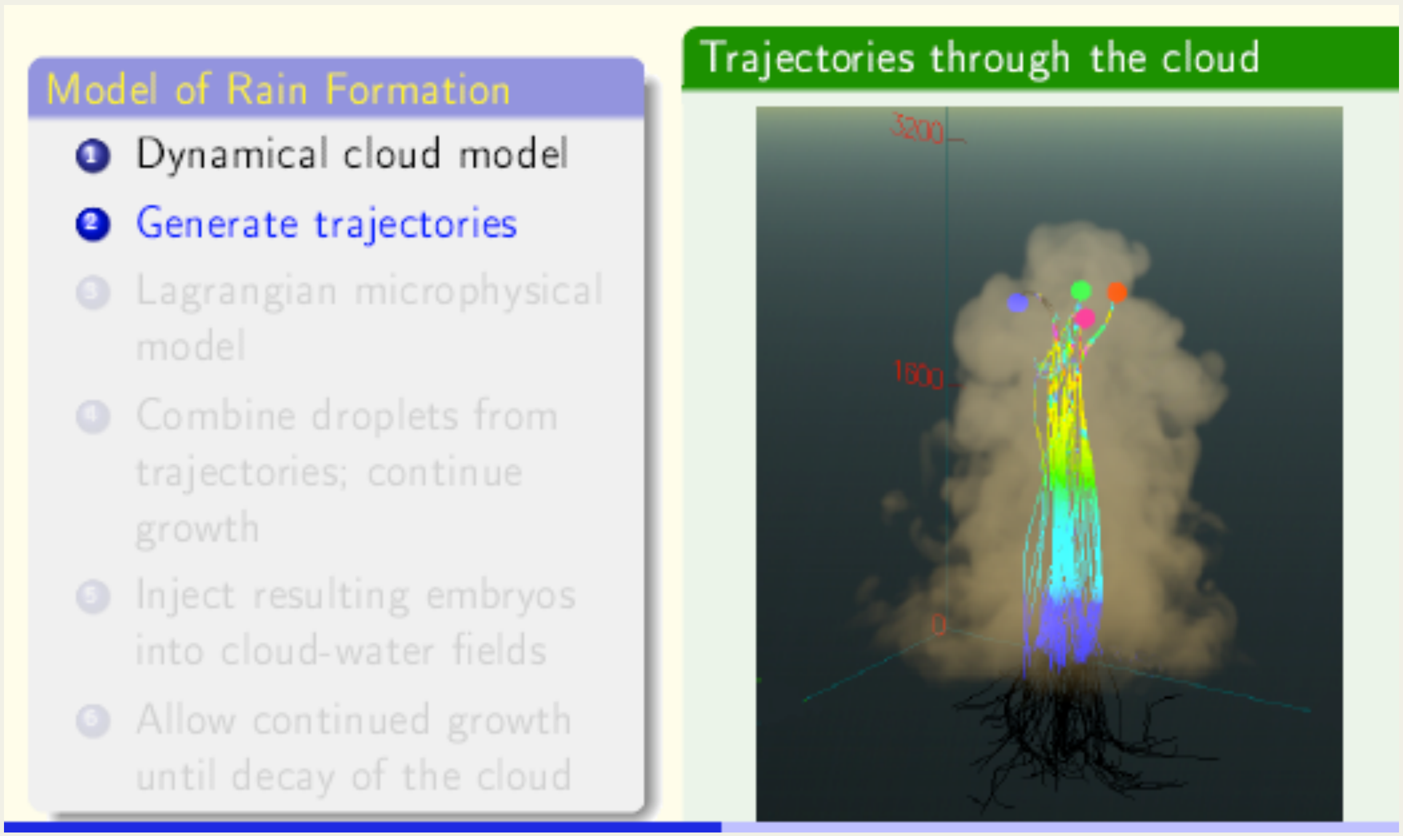
Collaborators:
Sonia Lasher-Trapp, Purdue University
Alan Blyth, University of Leeds

April 21, 2011: EOL/MMM Seminar

courtesy of Al Cooper, NCAR



courtesy of Al Cooper, NCAR



courtesy of Al Cooper, NCAR

ADIABATIC ASCENT

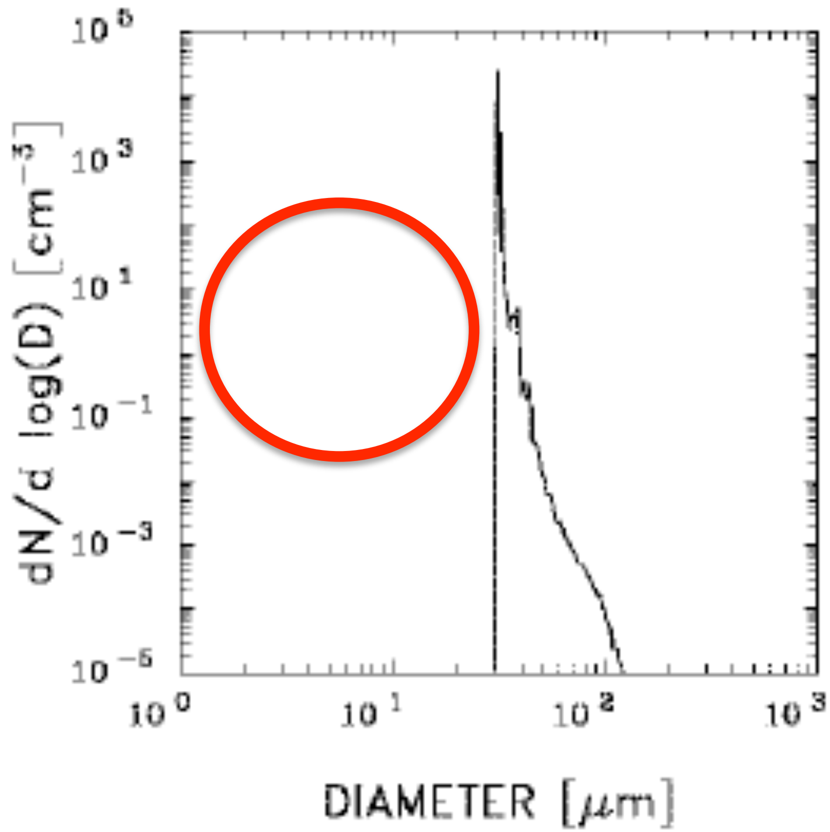
Test Case For Comparison

Results

ascent to 3 km (254 s)
$N = 272\ cm^{-3}$
$LWC = 4.31\ g\,m^{-3}$
$\bar{d} = 31.2\,\mu m$, $\sigma = 0.30\,\mu m$

Noteworthy Aspects:

1. very narrow: $\sigma/d < 0.01$
2. peaks, multiples of modal mass



courtesy of Al Cooper, NCAR

ENSEMBLE CONTRIBUTIONS

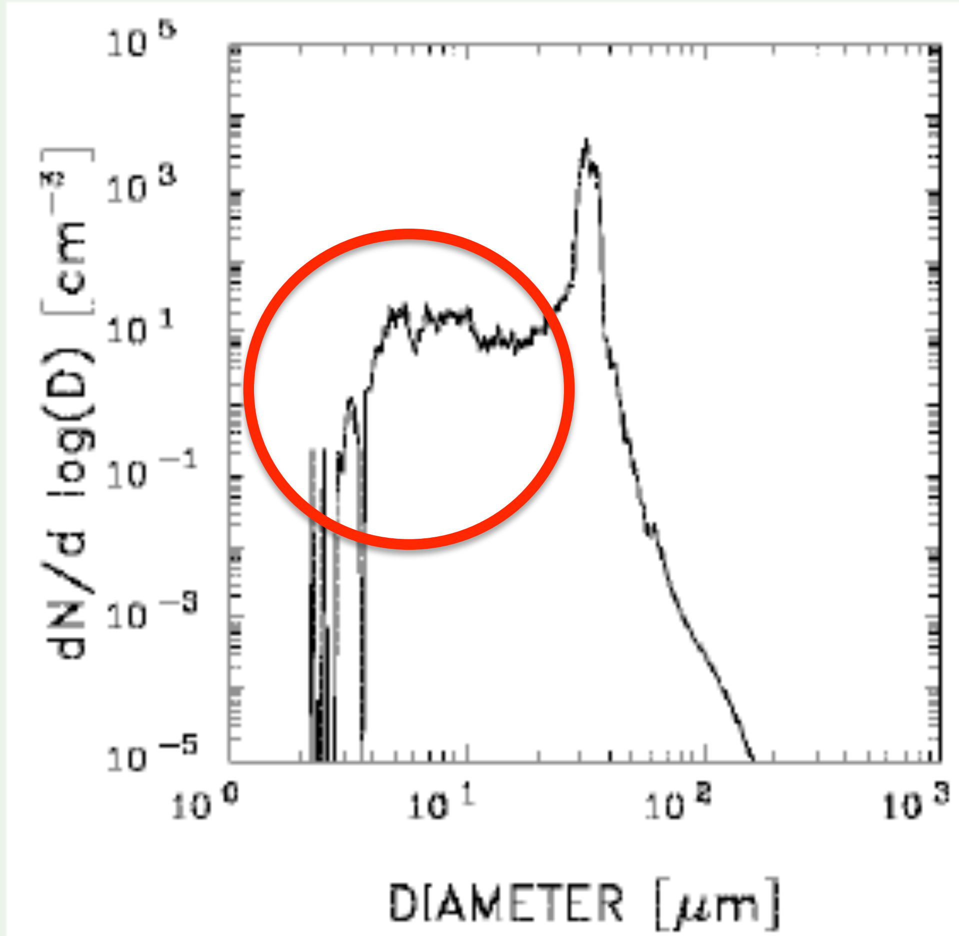
Result of Variability Along Trajectories

Results (vs. adiabatic)

$N = 220\ cm^{-3}$ [80%]
LWC: 78%
$\bar{d} = 29.4\,\mu m$, $\sigma = 7.0\,\mu m$

Noteworthy Aspects:

1. Realistic shape:
   - broad, bimodal
   - dispersion $\simeq 0.24$
2. many more large drops



courtesy of Al Cooper, NCAR

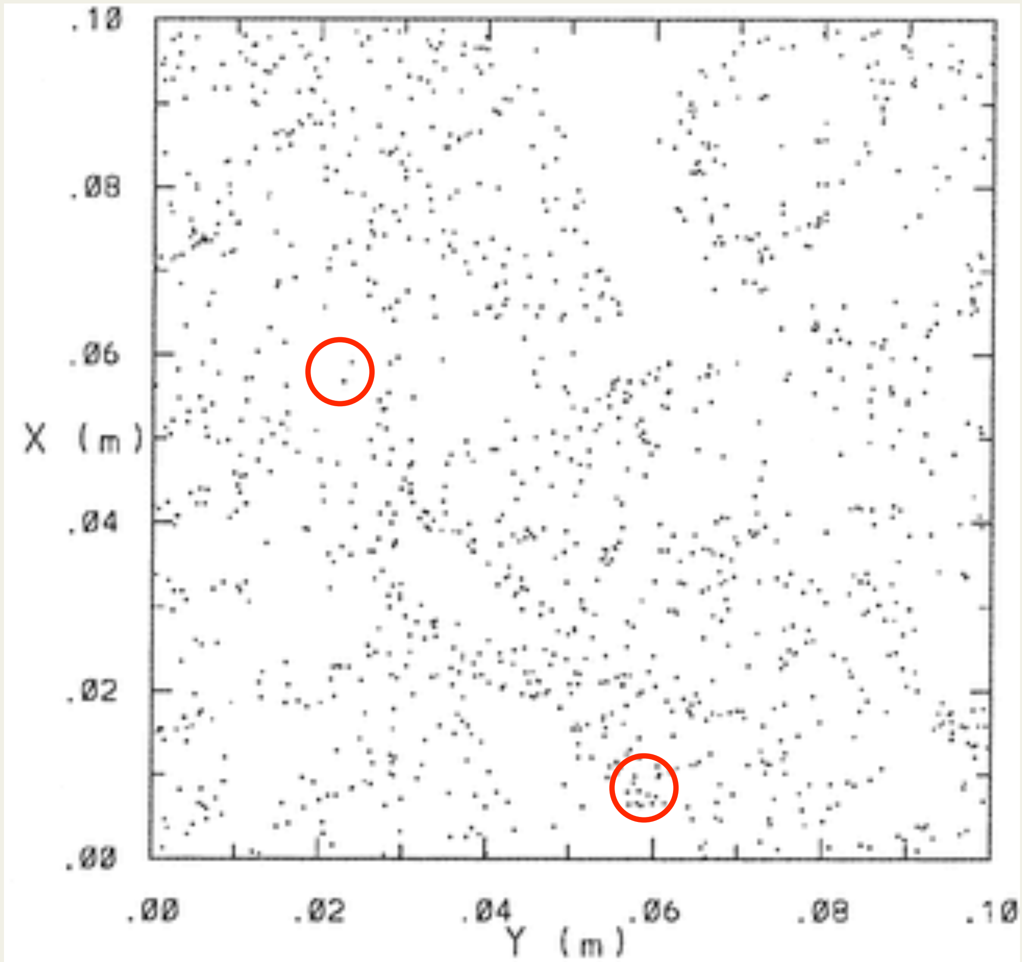
Condensational growth is reversible: droplets grow more in higher S, and then less in lower S, and the two situations change rapidly…

… *but entrainment/mixing and the "large-eddy hopping" provides additional effects contributing to spectral width.*

But if you think about the collisional growth, then the story is different: growth is not reversible…

The impact on collisional growth is being studied in a joint project with Prof. Lian-Ping Wang (U. of 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:

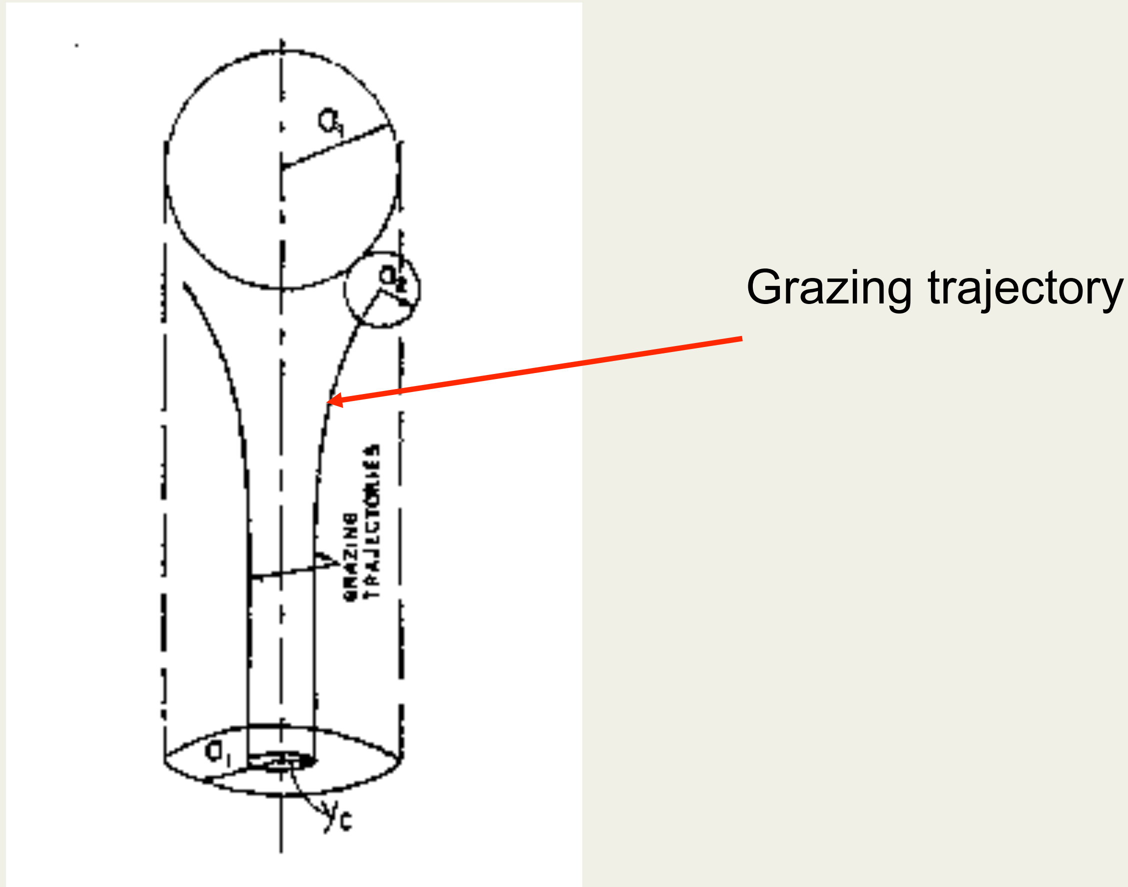
-*Turbulence modifies local droplet concentration (preferential concentration effect)*

-*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

Collision efficiency E_c for the gravitational case:



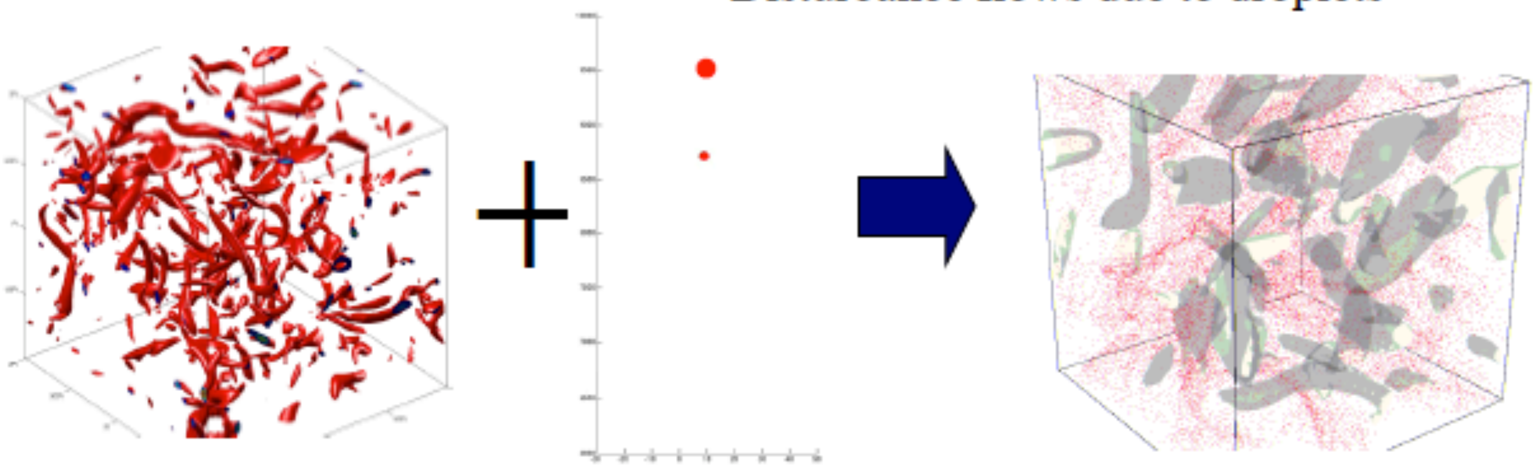
$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$

The hybrid DNS approach: including disturbance flows due to droplets

$$\vec{U}(\vec{x},t)+\sum_{k=1}^{N_p}\vec{u}_s(\vec{r}_k;a_k,\vec{V}_k-\vec{U}(\vec{Y}_k,t)-\vec{u}_k)$$

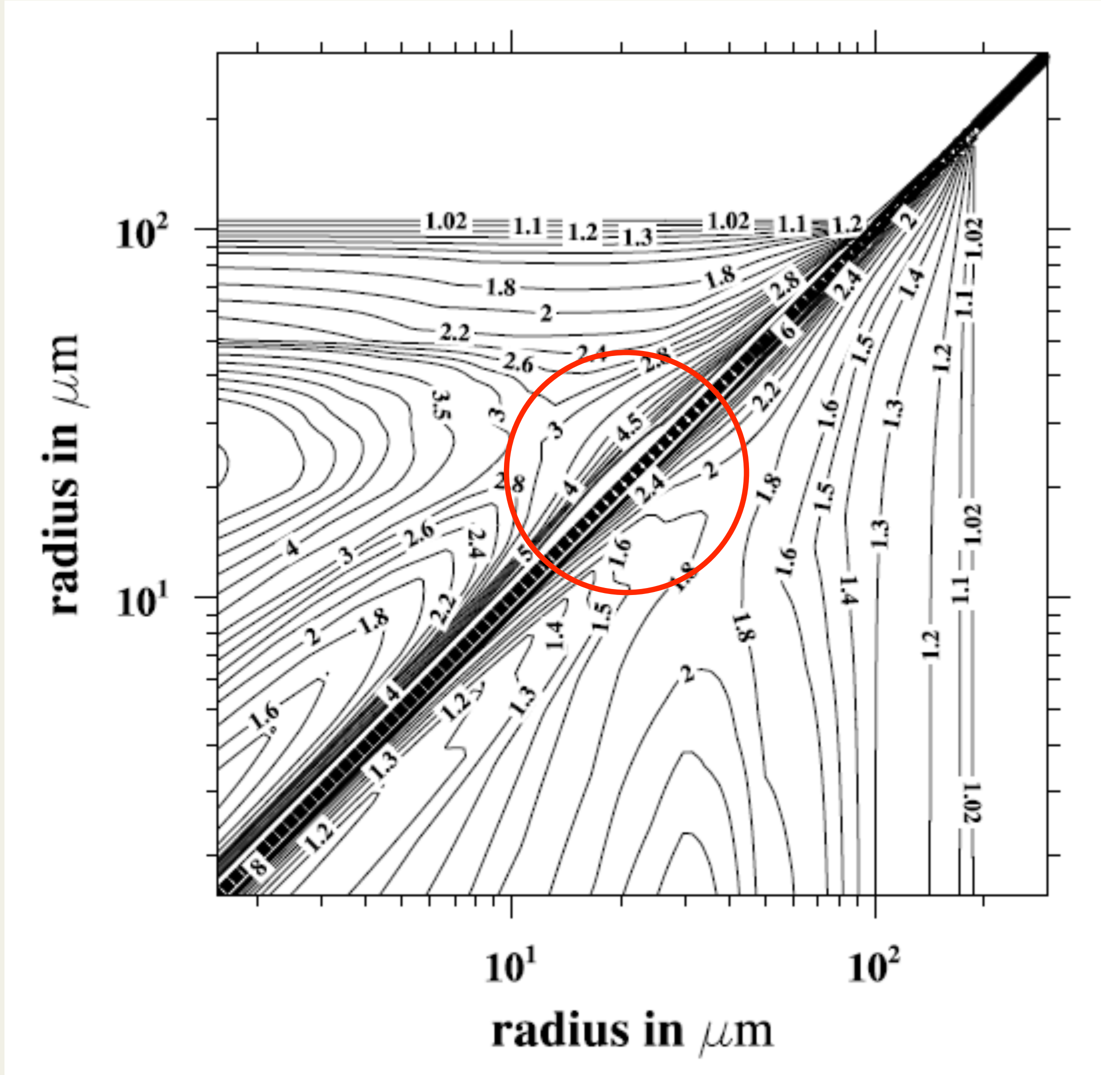
Background turbulent flow

Disturbance flows due to droplets



Features: Background turbulent flow can affect the disturbance flows;
No-slip condition on the surface of each droplet is satisfied on average;
Both near-field and far-field interactions are considered.

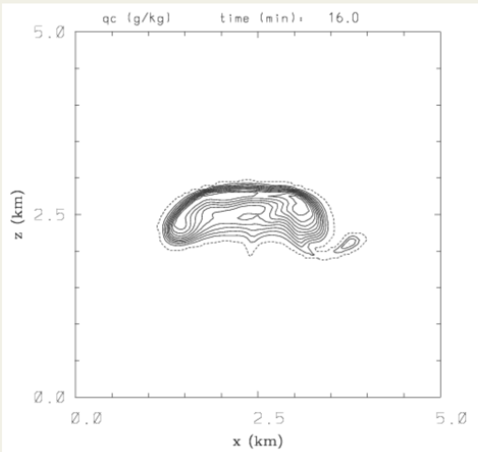
Wang, Ayala, and Grabowski, J. Atmos. Sci. **62**: 1255-1266 (2005).
Ayala, Wang, and Grabowski, J. Comp. Phys. **225**: 51-73 (2007).

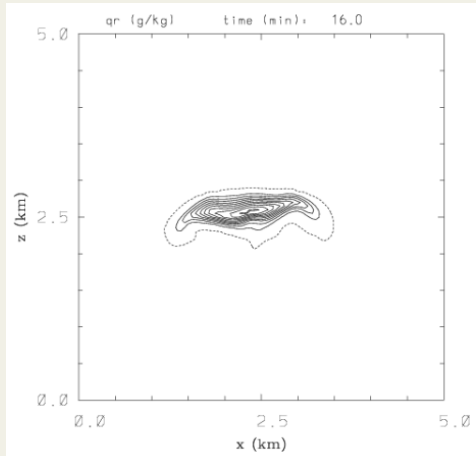


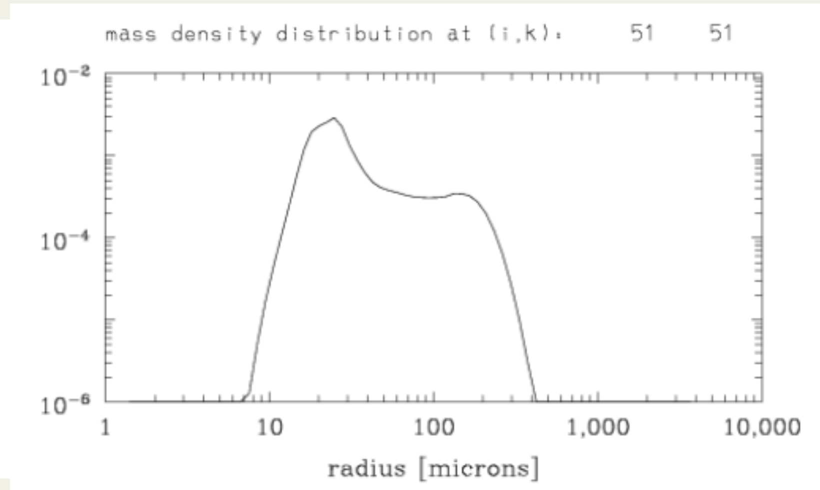
Enhancement factor for the collision kernel (the ratio between turbulent and gravitation collision kernel in still air) including turbulent collision efficiency; ε = 100 and 400 cm^2 s^{-3}.

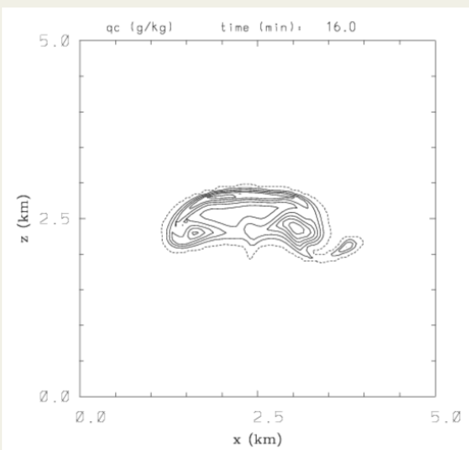
2D simulation of a small precipitating cloud: t=16 min

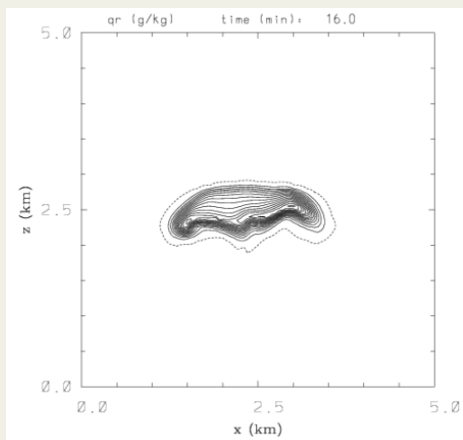
no turbulence

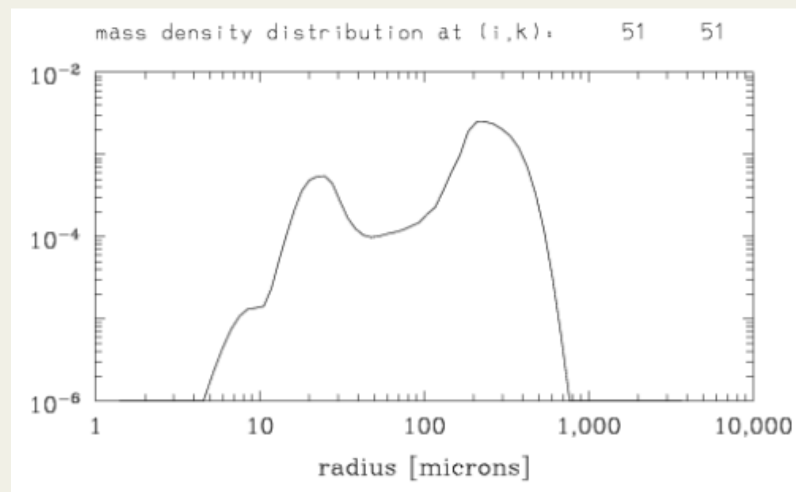








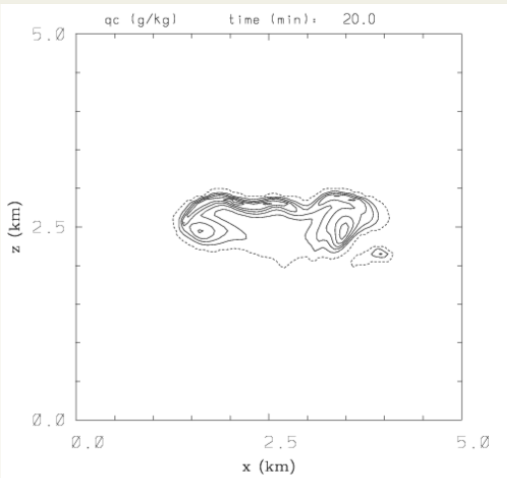


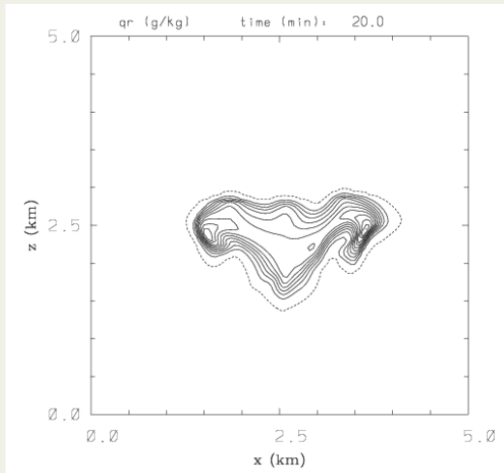


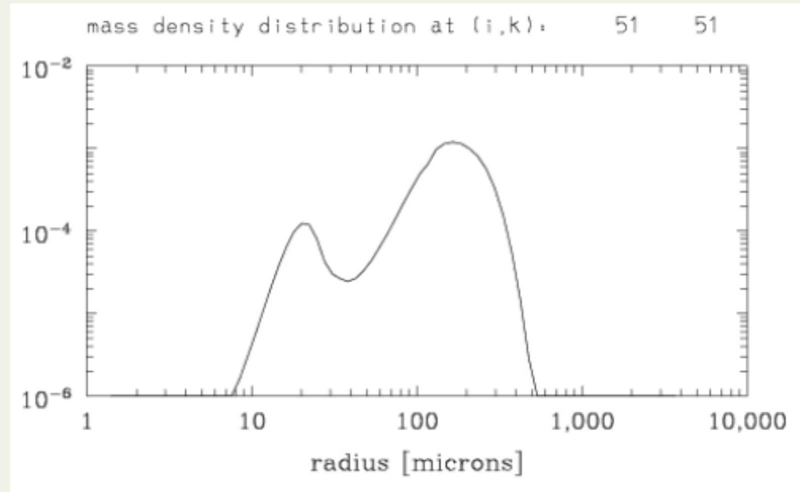
with turbulence – Ayala kernel with 100 cm^2s^{-3}

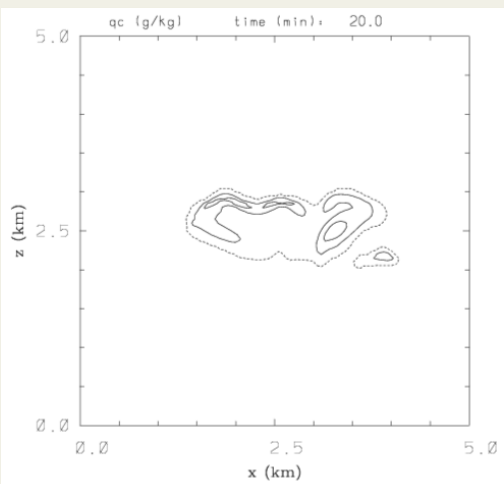
2D simulation of a small precipitating cloud: t=20 min

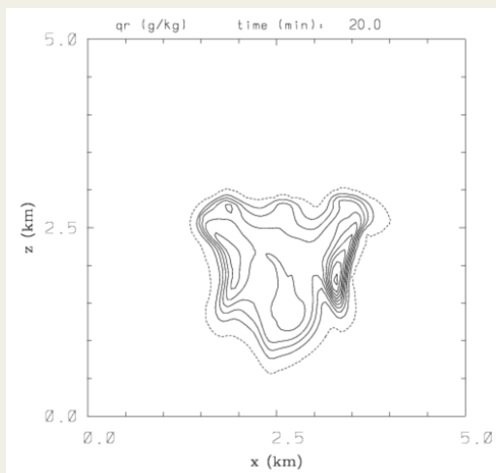
no turbulence

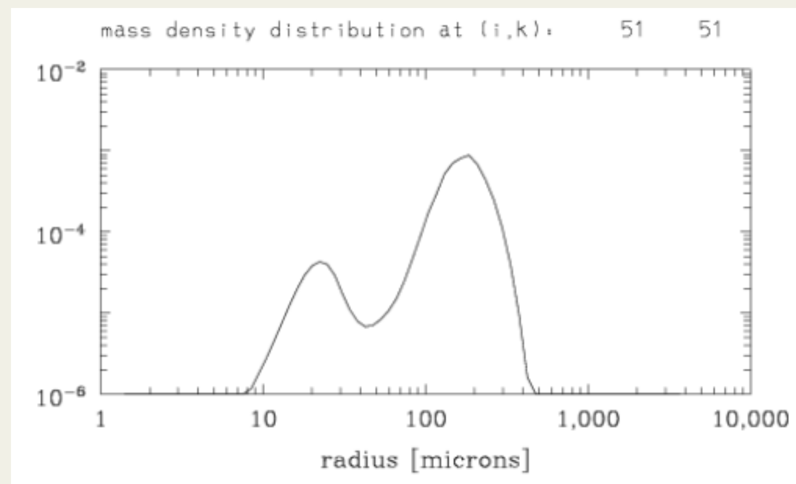








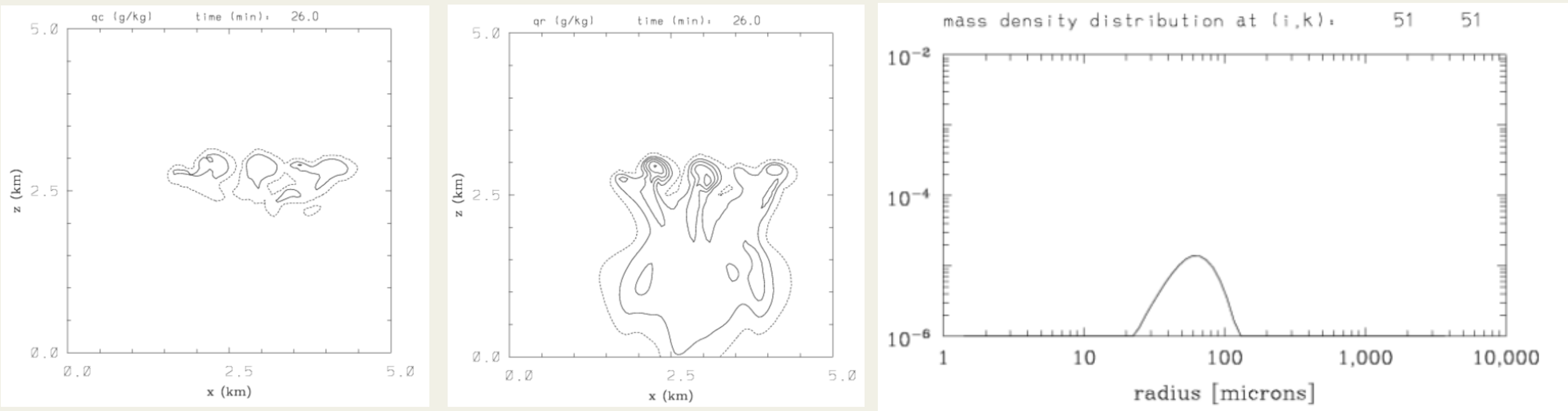


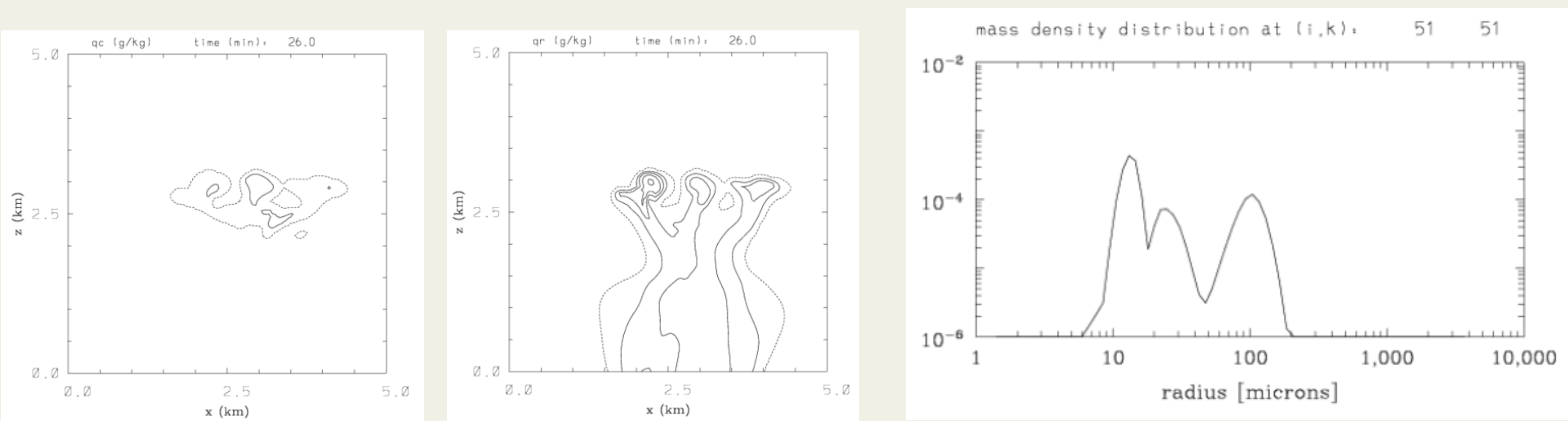


with turbulence – Ayala kernel with 100 cm^2s^{-3}

2D simulation of a small precipitating cloud: t=26 min

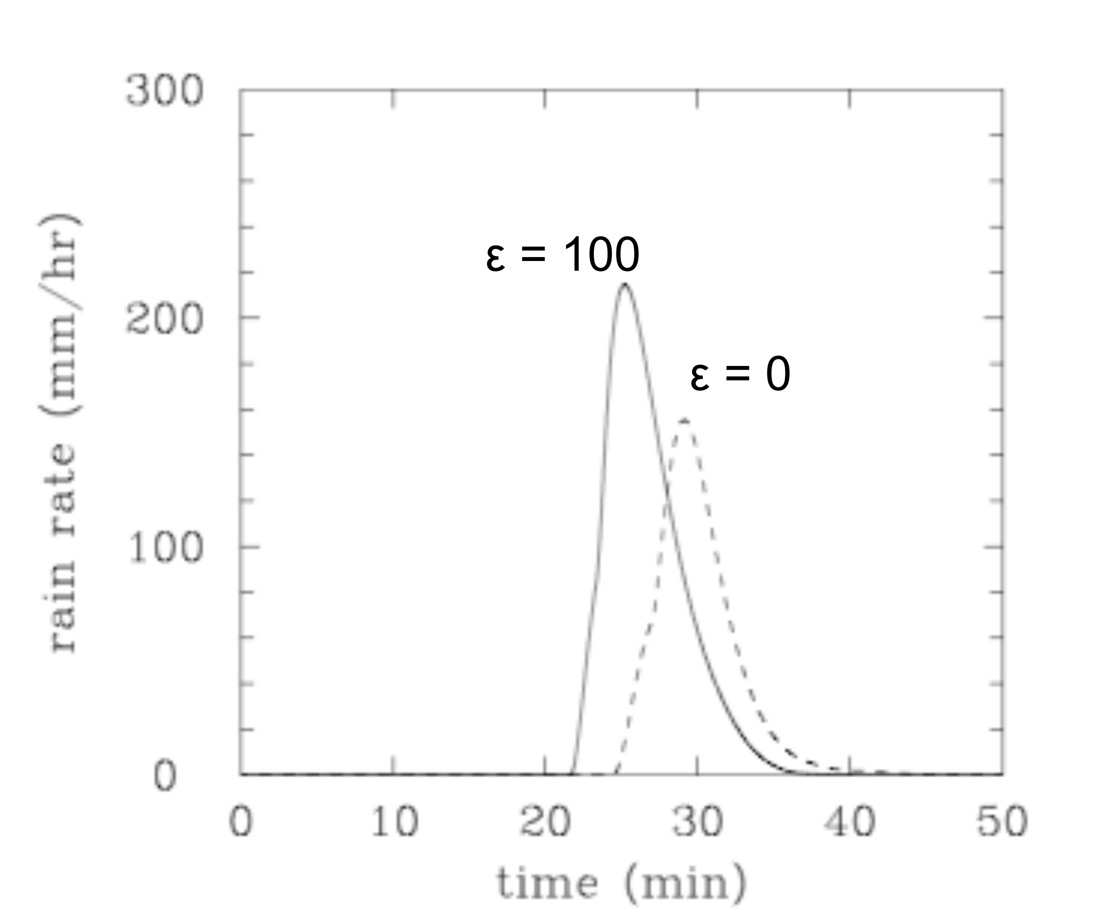
no turbulence



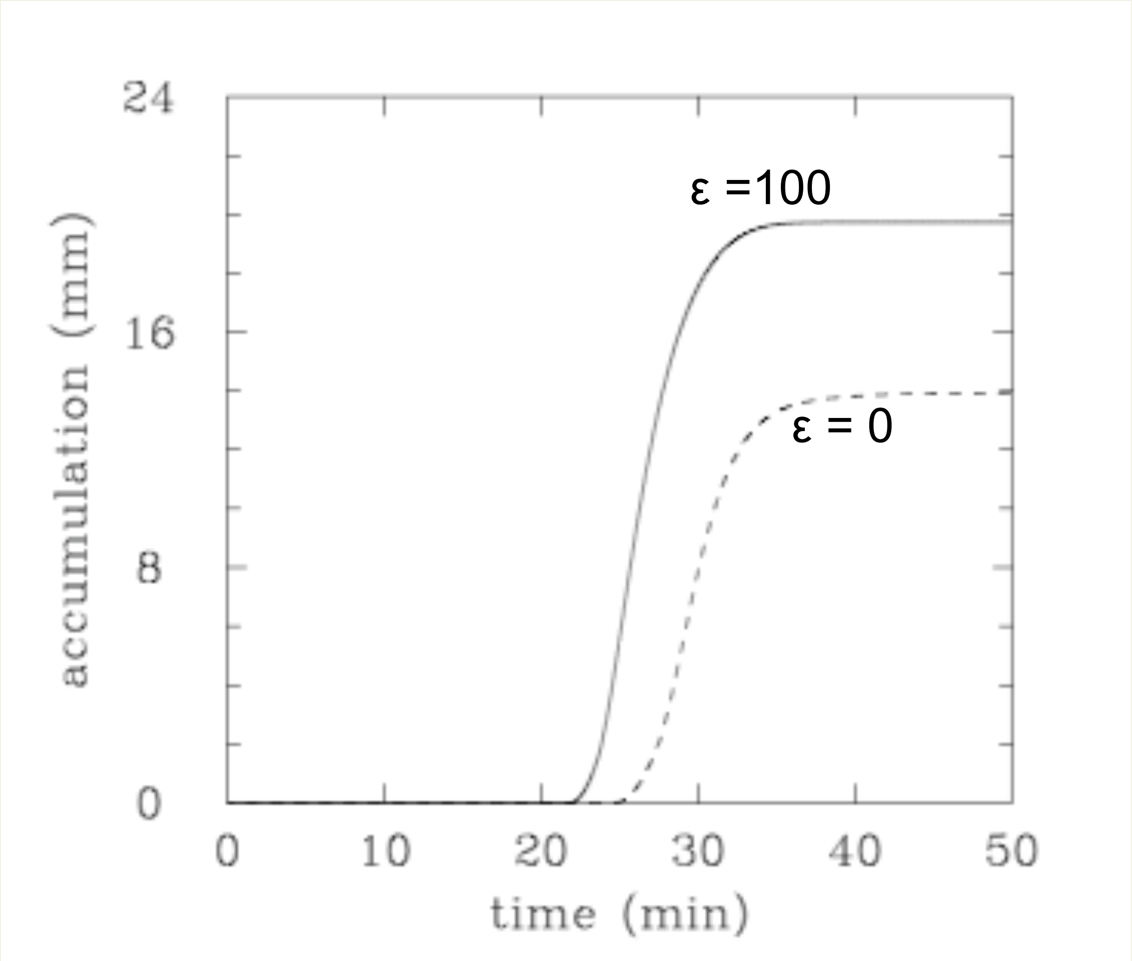


with turbulence – Ayala kernel with 100 cm^{2}s^{-3}

Time evolution of the surface precipitation intensity: 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!



Summary:

Small-scale turbulence seems to have an insignificant effect on diffusional growth of cloud droplets.

Turbulence seems to plays a significant role when entrainment and mixing is considered through “large-eddy hopping”, local heterogeneity of mixing, and in-cloud activation.

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. More realistic numerical studies are needed to quantify this aspect.