Impact of entrainmnet and mixing on trade-wind shallow convection: homogeneous versus inhomogeneous mixing

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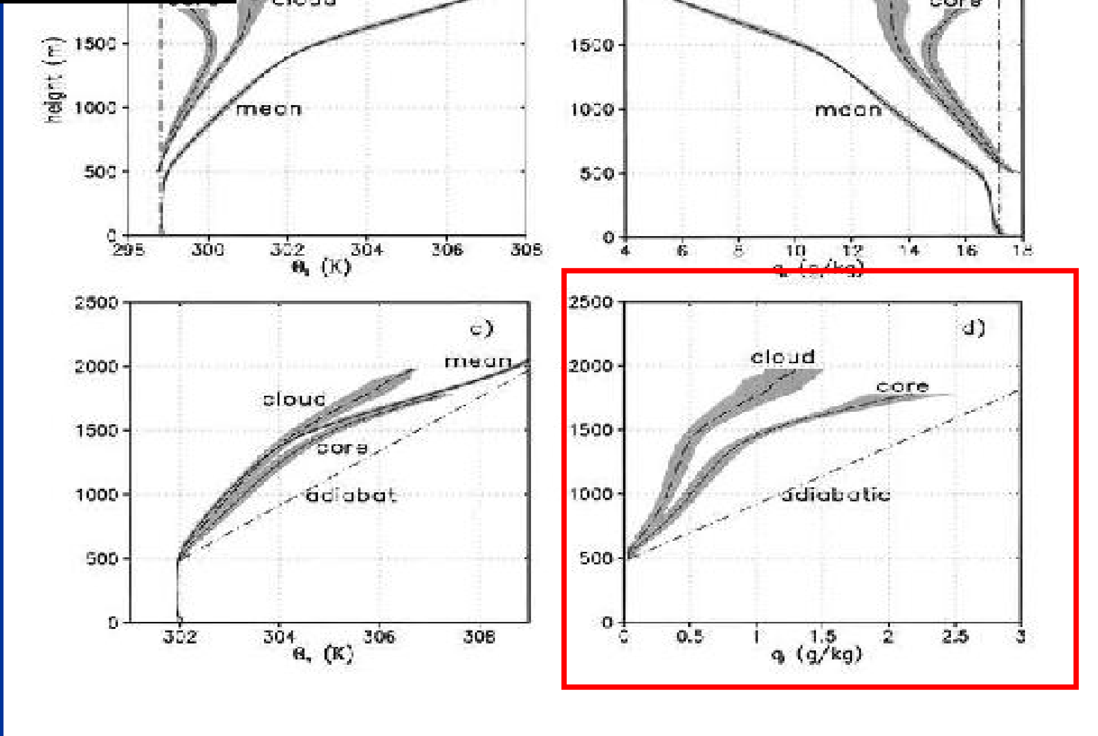
Shallow convective clouds are strongly diluted by entrainment…

Siebesma et al. JAS 2003



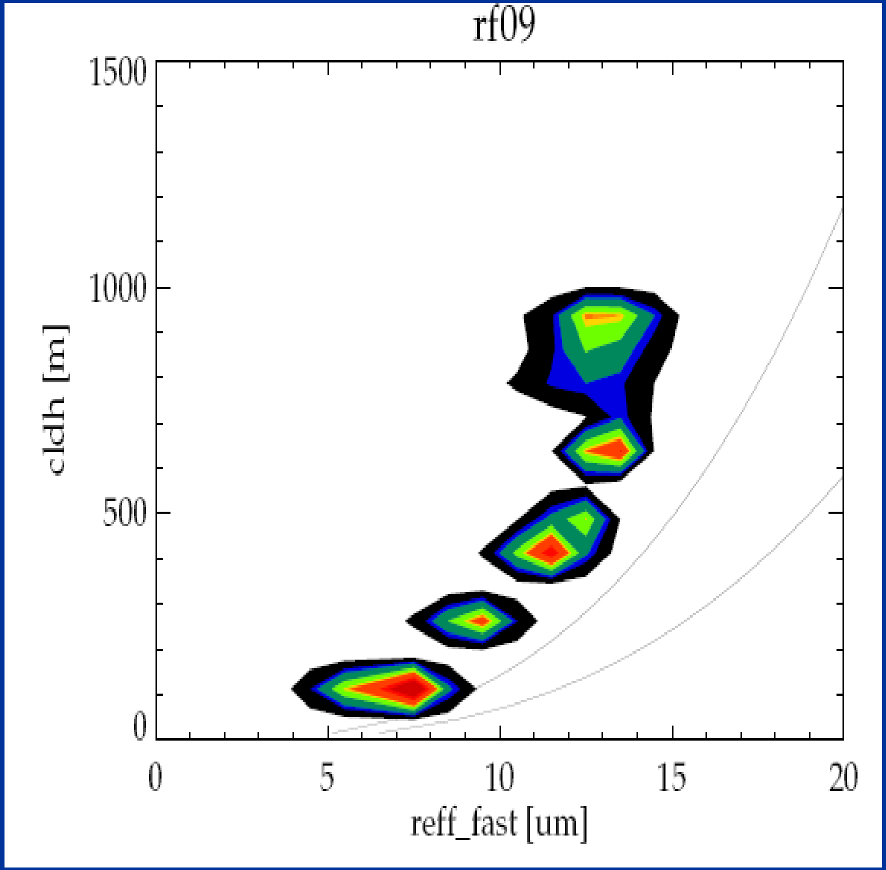
…but the effects of entrainment and mixing on the spectrum of cloud droplets is far from being understood (the homogeneous versus inhomogeneous mixing).

The assumptions concerning homogeneity of mixing has been shown to have a significant impact on the 1st indirect effect (the Twomey effect).

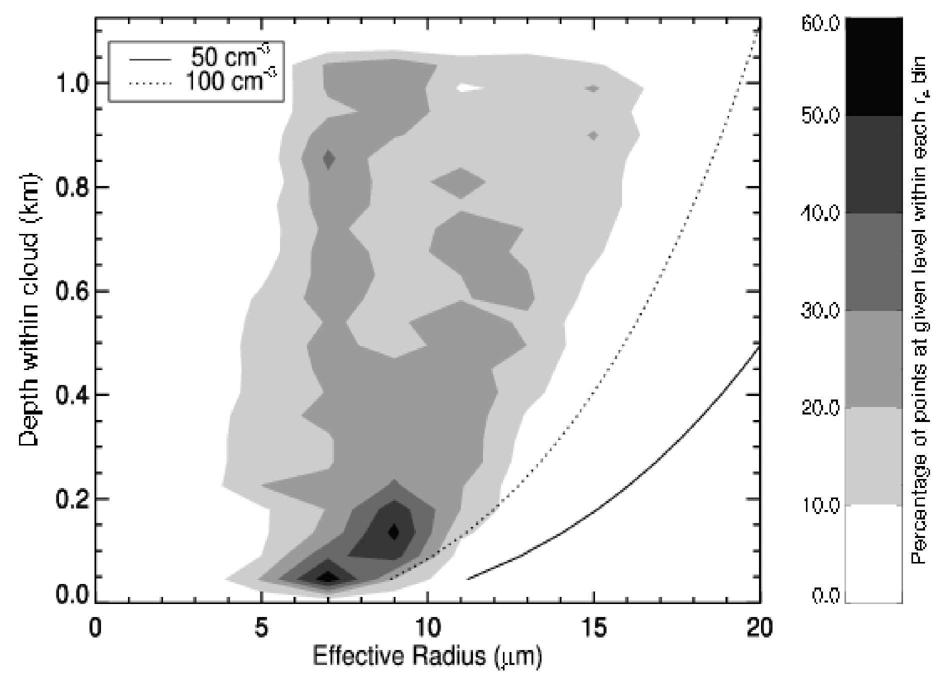
Chosson et al JAS 2007;
Grabowski JClimate 2006;
Slawinska et al. JClimate 2008.

Observations...

In-situ data from one flight during RICO (Sylwester Arabas i Hanna Pawlowska)



Remotely sensed data from ARM Tropical Western Pacific Nauru site (McFarlane and Grabowski, GRL 2007)



Morrison and Grabowski 2008

Microphysical transformations during sub-grid mixing with 2-moment bulk microphysics

- Flexibility to treat any mixing scenario from homogeneous to extremely inhomogeneous.

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

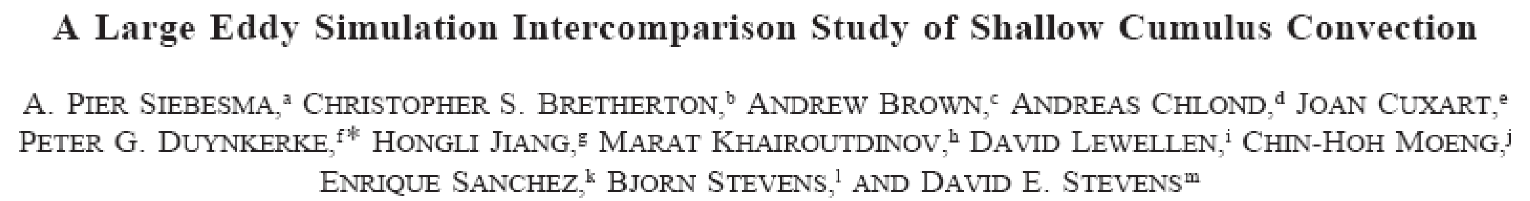
N – droplet concentration

q – cloud water mixing ratio

- α = 1: extremely inhomogeneous
- α = 0: homogeneous

N_i, q_i – initial (i.e., after mixing)

N_f, q_f – final (i.e., after mixing and microphysical adjustment)



A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

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ENRIQUE SANCHEZ,[k] BJORN STEVENS,[l] AND DAVID E. STEVENS[m]

Journal of the Atmospheric Sciences, 2003

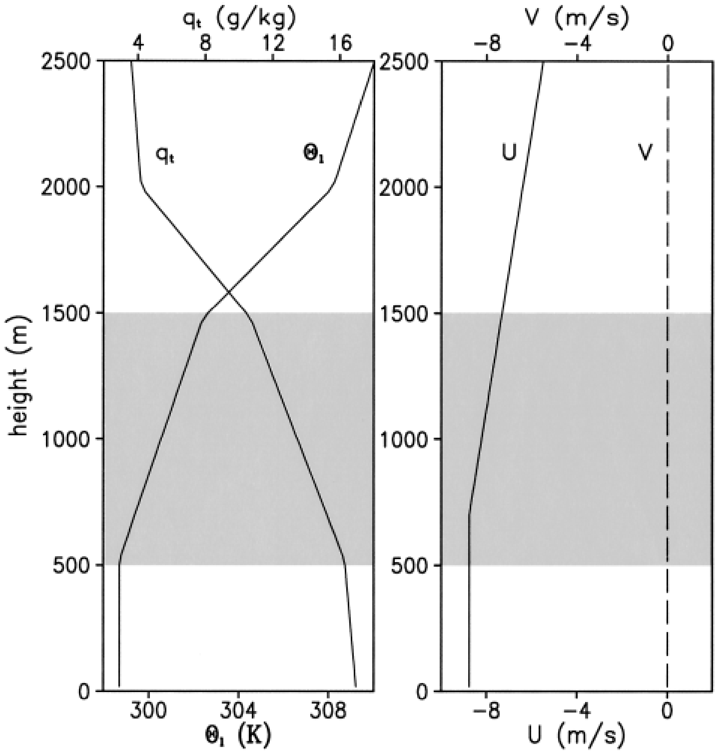
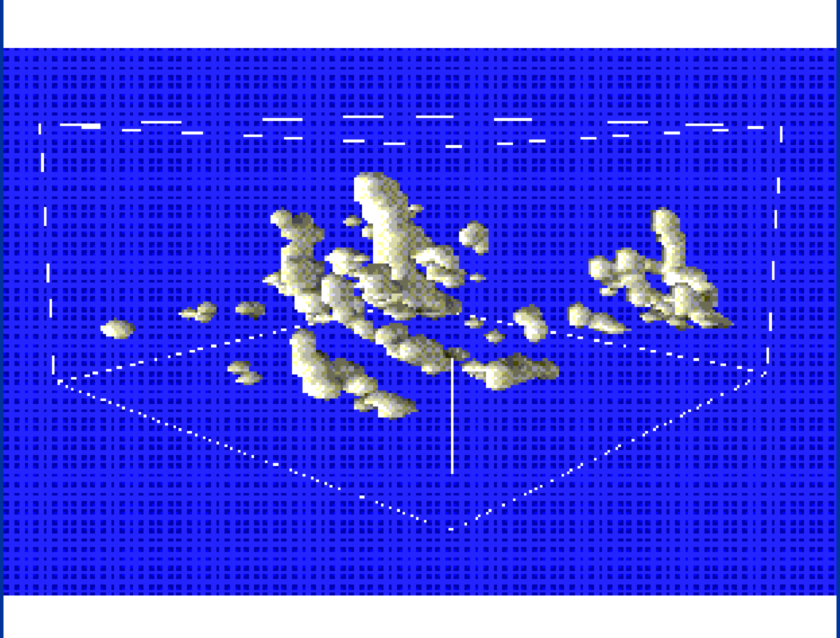


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.

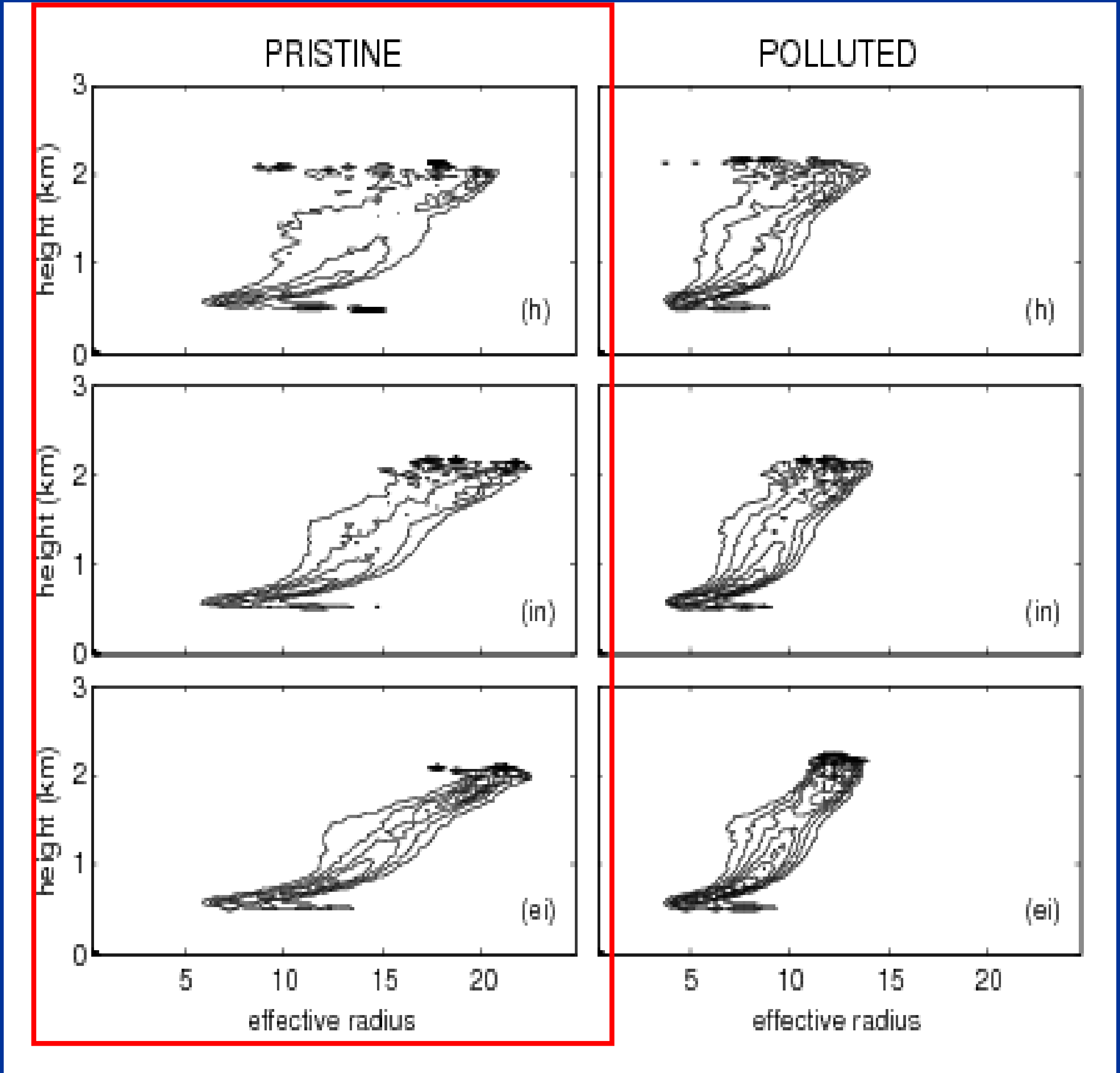


BOMEX two-moment scheme

homogeneous mixing

intermediate mixing

extremely inhomogeneous mixing



time-scale for cloud droplet evapotation τ_d:

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

r - droplet radius, $A \approx 10^{-10}$ m^{2}s^{-1}, RH - relative humidity

$\tau_d \approx 1$ s for RH=0.1
$\tau_d \approx 10$ s for RH=0.9

time-scale for turbulent homogenzation τ_t:

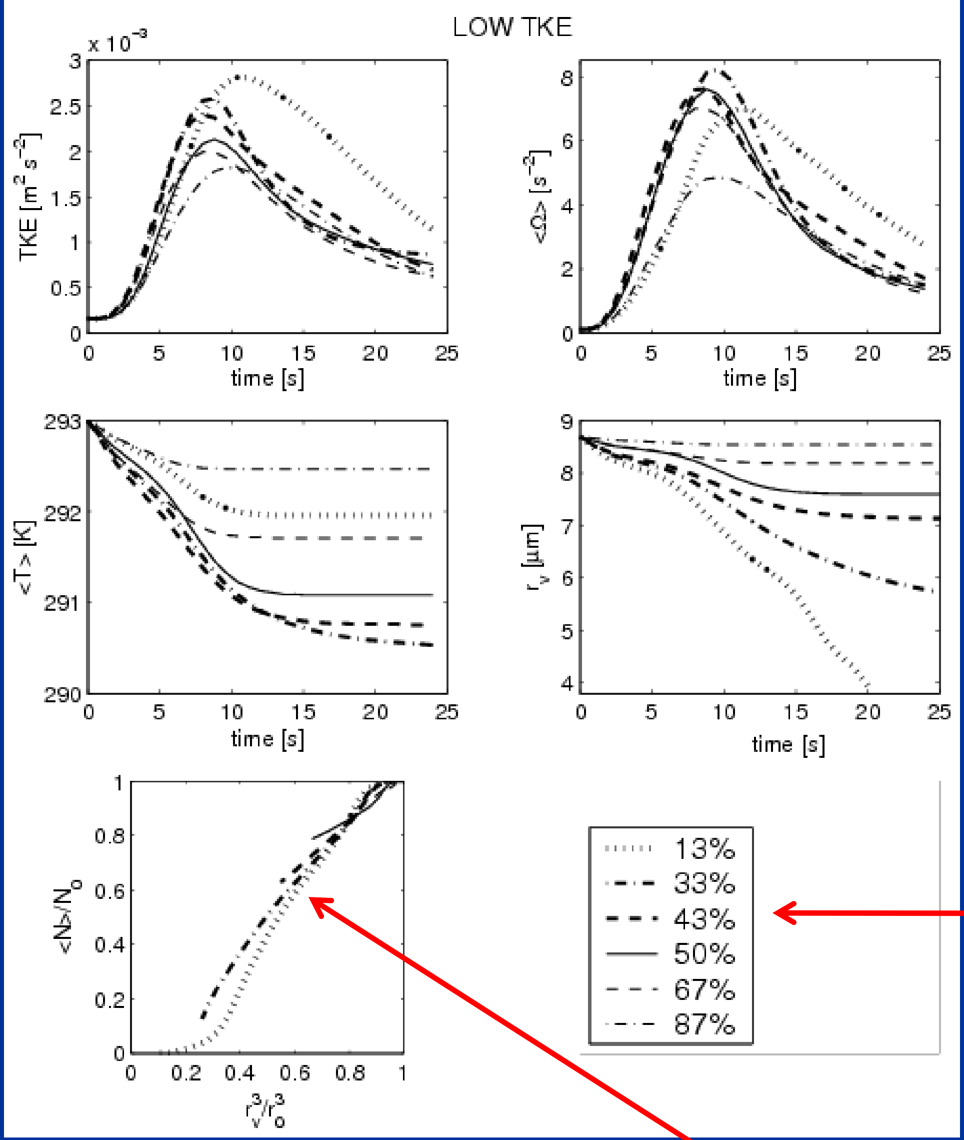
$$\tau_t \equiv \frac{L}{U} \sim \left(\frac{L^2}{\epsilon}\right)^{1/3}$$

L, U - eddy length scale and velocity, ϵ - turbulence dissipation rate

for $\epsilon = 100$ cm^{2}s^{-3}:

$\tau_t \approx 0.2$ s for $L = 1$ cm
$\tau_t \approx 5$ s for $L = 1$ m
$\tau_t \approx 100$ s for $L = 100$ m

DNS simulations of microscale homogenization of initially separate filaments of cloudy and cloud-free air.

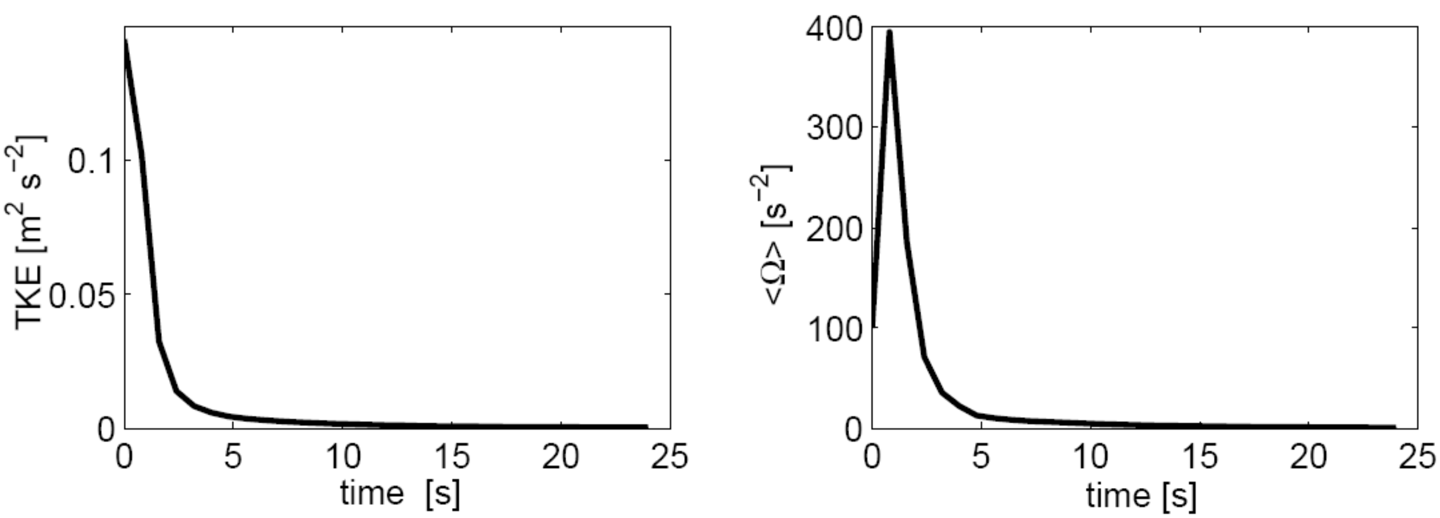


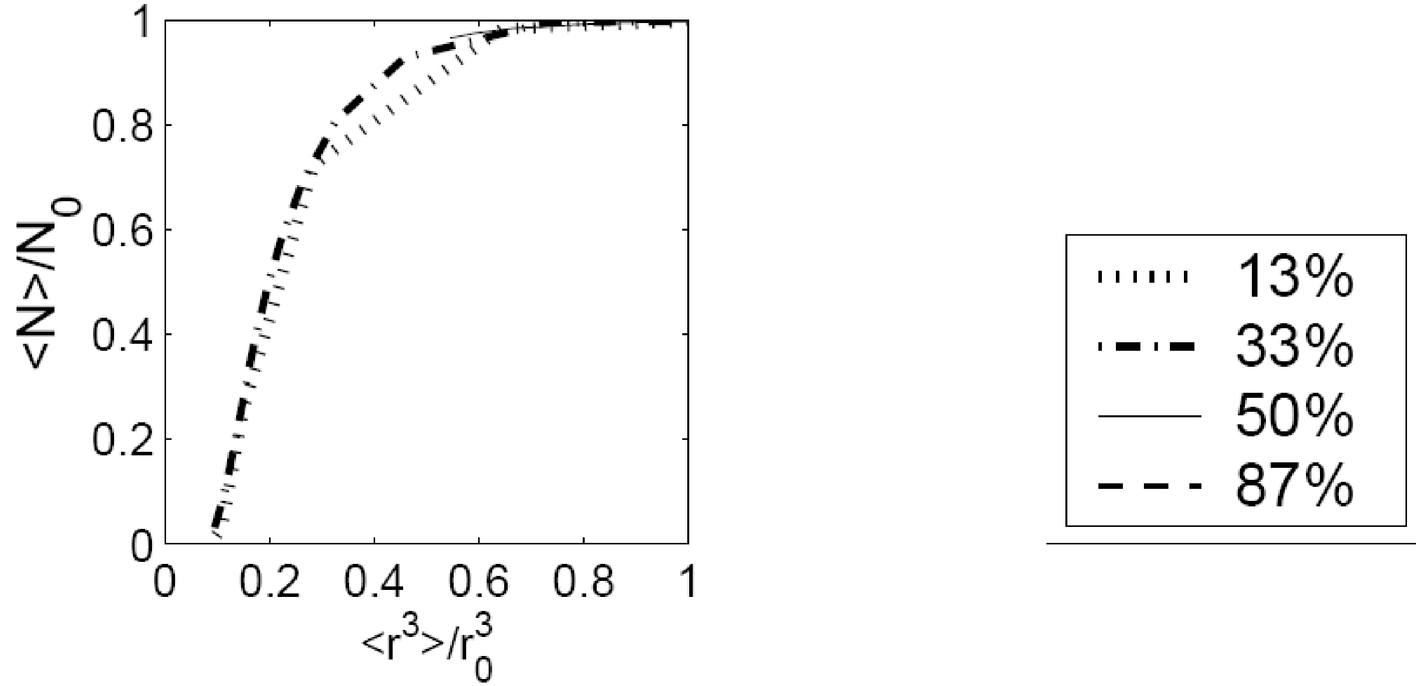
Andrejczuk et al JAS 2006

The percentage represents the initial volume fraction of cloudy air.

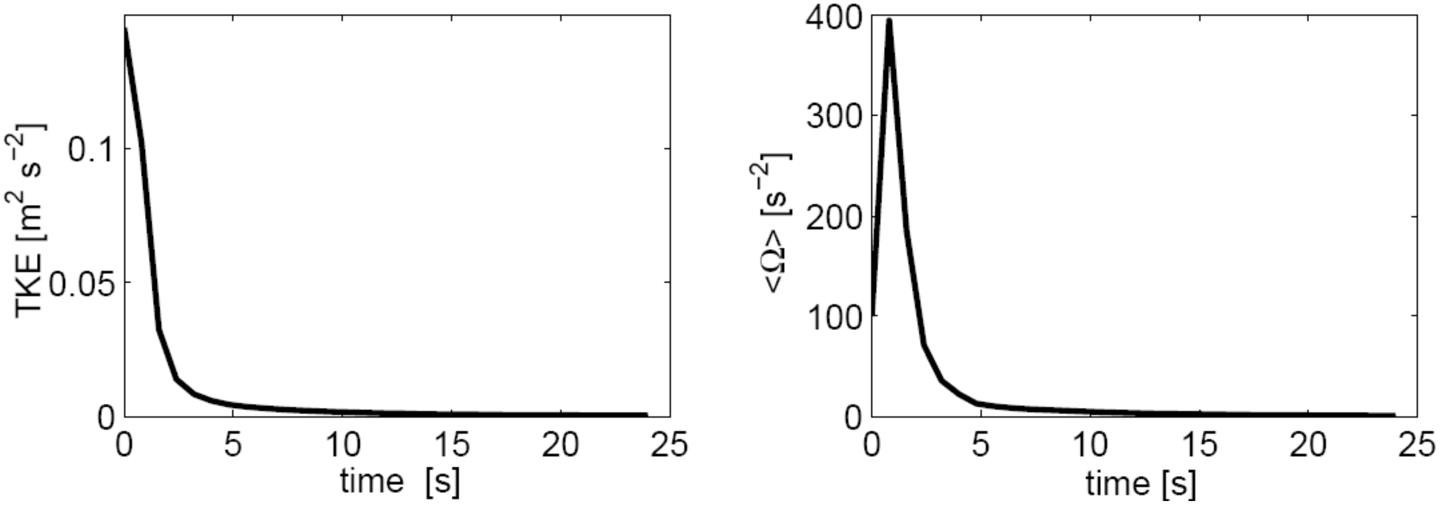
Evolution of the number of droplets N and their mean volume radius r_v, both normalized by the initial values

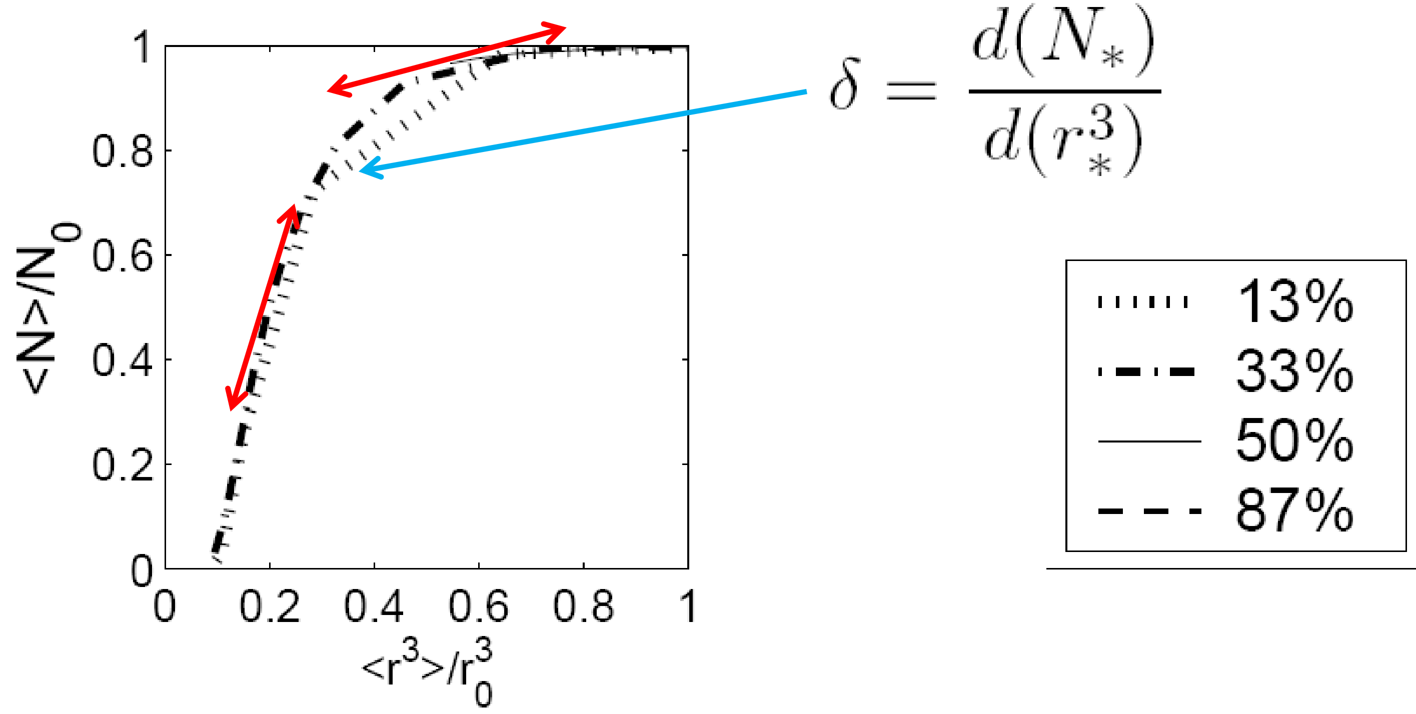
HIGH TKE


TKE [m^2 s^{-2}]
0.1
0.05
0
0
5
10
15
20
25
time [s]
<Ω> [s^{-2}]
400
300
200
100
0
0
5
10
15
20
25
time [s]


<N>/N$_0$
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
<r^3>/r$_0^3$
13%
33%
50%
87%

HIGH TKE





$$\delta = \frac{d(N_*)}{d(r_*^3)}$$

slope of the mixing line on the $N - r$ diagram:

$$\delta = \frac{d(N_*)}{d(r_*^3)}$$

$\delta = 0$ - homogeneous mixing

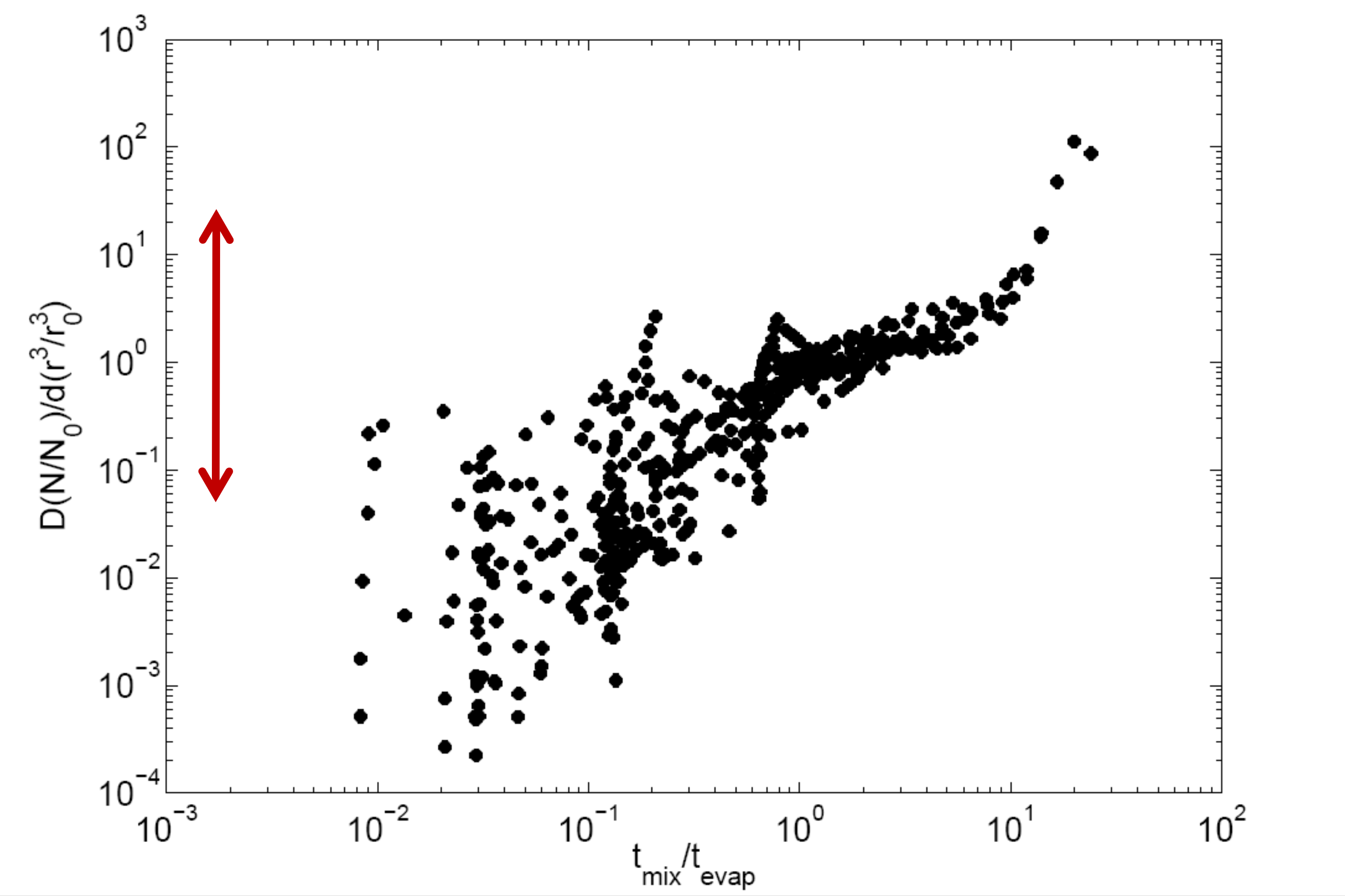
$\delta \rightarrow \infty$ - extremely inhomogeneous mixing

relationship between parameter α (homogeneity of mixing in the two-moment bulk schmeme of Morrison and Grabowski 2008) and δ:

$$\alpha = \frac{\delta}{\delta + 1}$$

$\alpha = 0$ - homogeneous mixing

$\alpha = 1$ - extremely inhomogeneous mixing



homogeneous

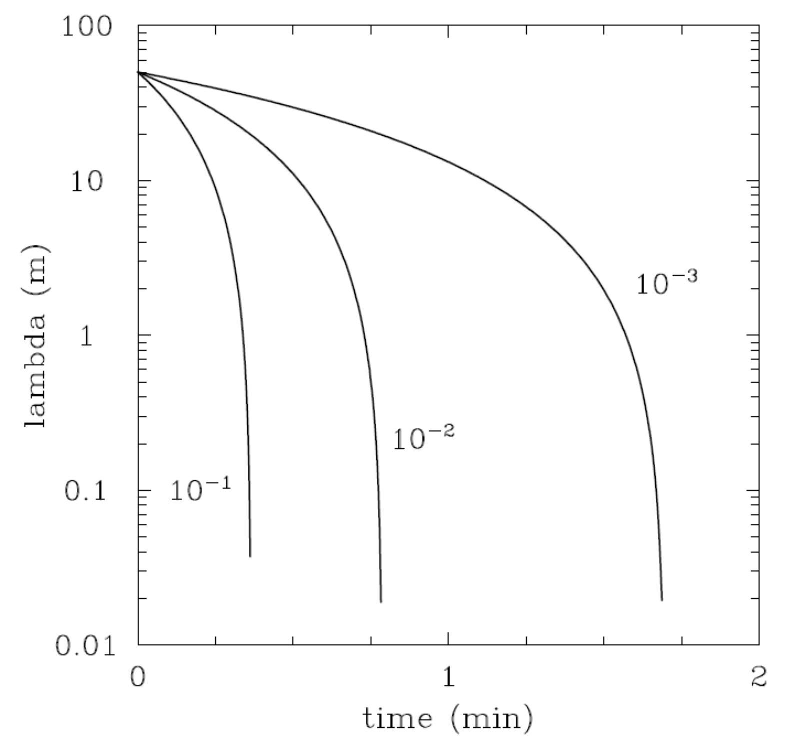
extremely inhomogeneous

Mirek Andrejczuk, work in progress…

Evolution of spatial scale λ of the filaments of a passive scalar during turbulent mixing (Broadwell and Breidenthal 1982):

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

$\alpha \sim 1$



DNS simulation of cloud-clear air interfacial mixing (decaying turbulence setup; Andrejczuk et al. JAS 2006)

Application of the λ equation into LES model:

$$\frac{\partial \lambda}{\partial t} + \frac{1}{\rho_o} \nabla \cdot (\rho_o \mathbf{u} \lambda) = -\alpha \epsilon^{1/3} \lambda^{1/3} + S_\lambda + D_\lambda$$

$$\epsilon = c_\epsilon \frac{E^{3/2}}{\Lambda}$$

E is the model-predicted TKE, $\Lambda = (\Delta x \ \Delta y \ \Delta z)^{1/3}$, and c_ϵ is a constant

Outside cloud: $\lambda=0$

Inside homogeneous cloud: $\lambda=\Lambda$

S_λ ensures transitions between cloud-free to cloudy (initial condensation) or between inhomogeneous to homogeneous cloudy volume (see Grabowski 2007 for details).

2-moment scheme and $\boldsymbol{\lambda} - \boldsymbol{\beta}$ approach

λ - "filament width"

β - "cloud fraction" within a gridbox

$$RH = \beta \cdot 1 \;+\; (1-\beta)\; RH_d$$

$RH \;=\; \dfrac{q_v}{q_{vs}(p,T)}$ - mean relative humidity; RH_d - relative humidity of the dry part of the grisbox

$$RH_d = \frac{RH - \beta}{1 - \beta}$$

$$\boxed{\begin{gathered} \tau_{mix} \sim \lambda\;(TKE)^{-1/2} \\[2em] \tau_{evap} \sim \frac{r^2}{A(1 - RH_d)} \end{gathered}}$$

if τ_{mix}/τ_{evap} provides δ, then $\alpha = \dfrac{\delta}{1+\delta}$

Conclusions:

Representation of microphysical transformations due to entrainment and mixing (essentially, homogeneous versus inhomogeneous mixing) has significant impact on the evaluation of the 1st indirect effect (the Twomey effect) in shallow convective clouds.

Aircraft observations and ground-based remote sensing suggest a complicated (and to some extent inconsistent) picture of the entrainment-related microphysical processes in these clouds.

A new approach is being developed to represent locally homogeneity of mixing based on the predicted scale of subgrid-scale filaments λ, mean droplet size, grid-averaged relative humidity, and TKE.