Exploring Use of Z-LWC Relationships to Study Entrainment-Mixing-Processes

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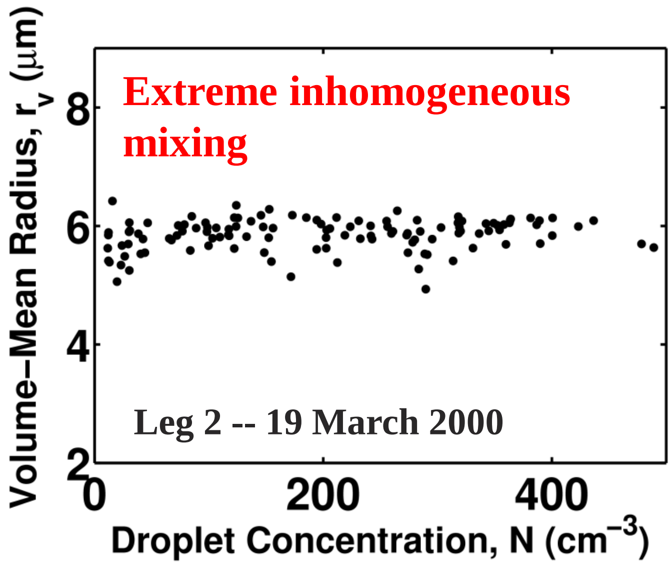
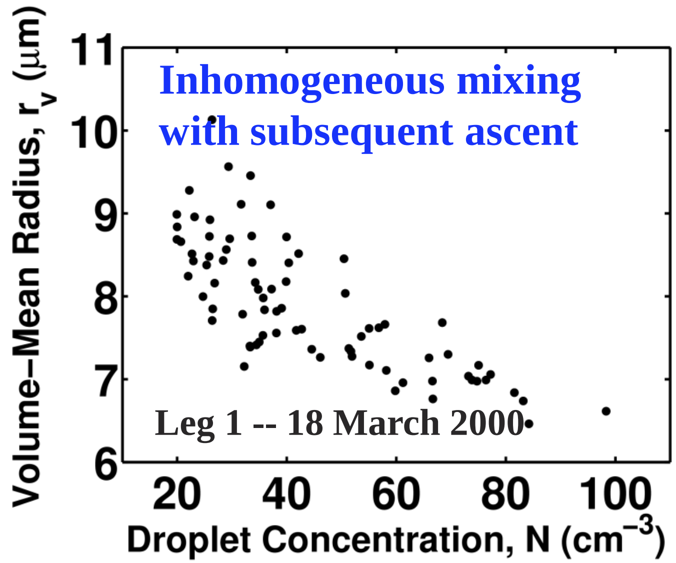
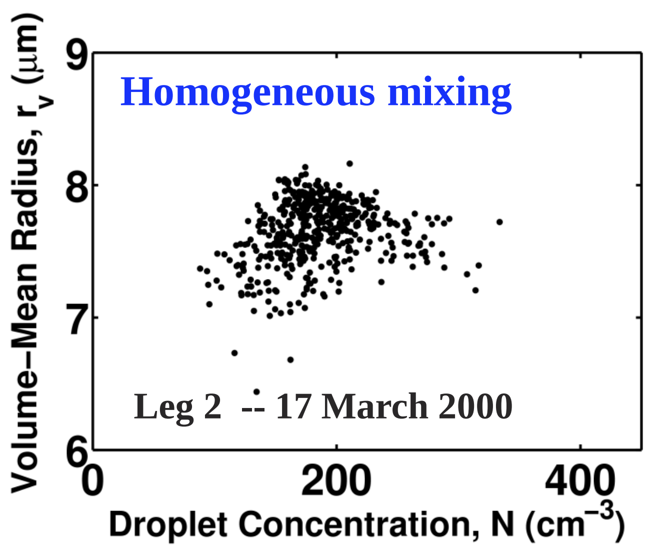
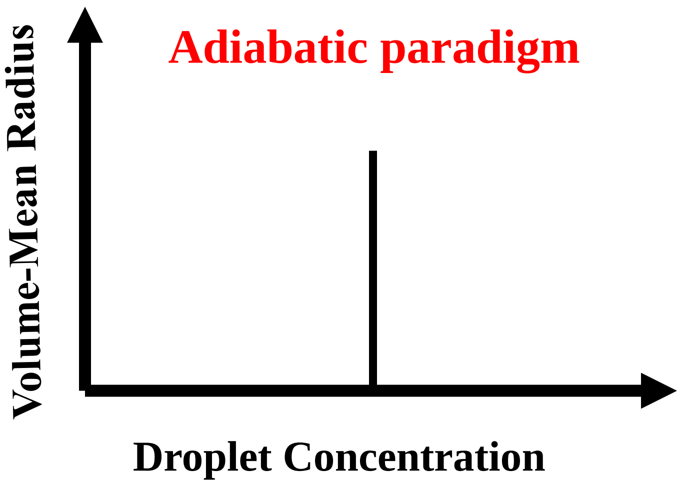
Entrainment-Mixing Paradigm: Examples

March 2000 Cloud IOP at SGP



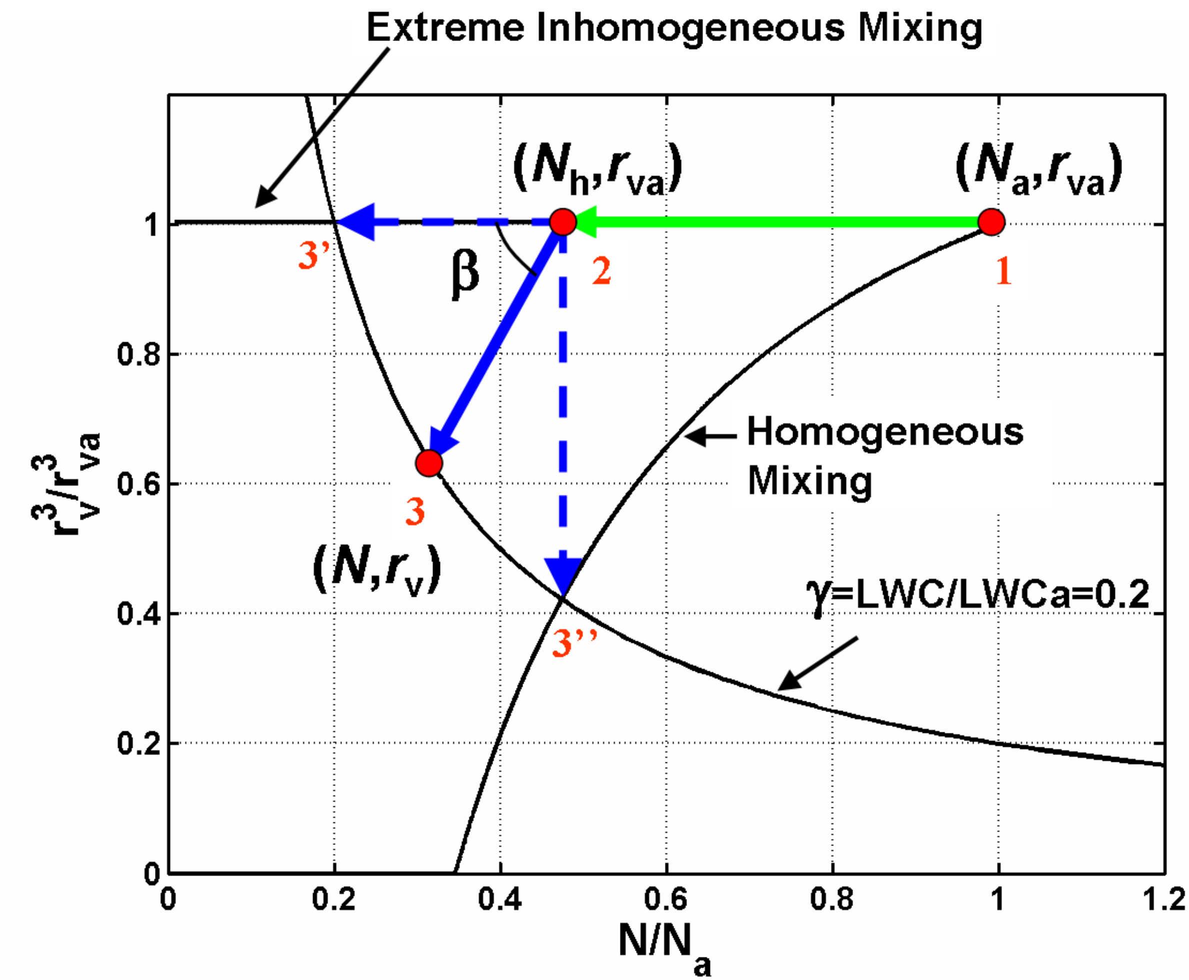






Reality is more diverse (Lu et al, JGR, 2011)

Microphysical Measure for Homogeneous Mixing Degree -- ψ_1



$$\psi_1 = \frac{\beta}{\pi/2}$$

Ψ_1= 0 for extreme inhomogeneous

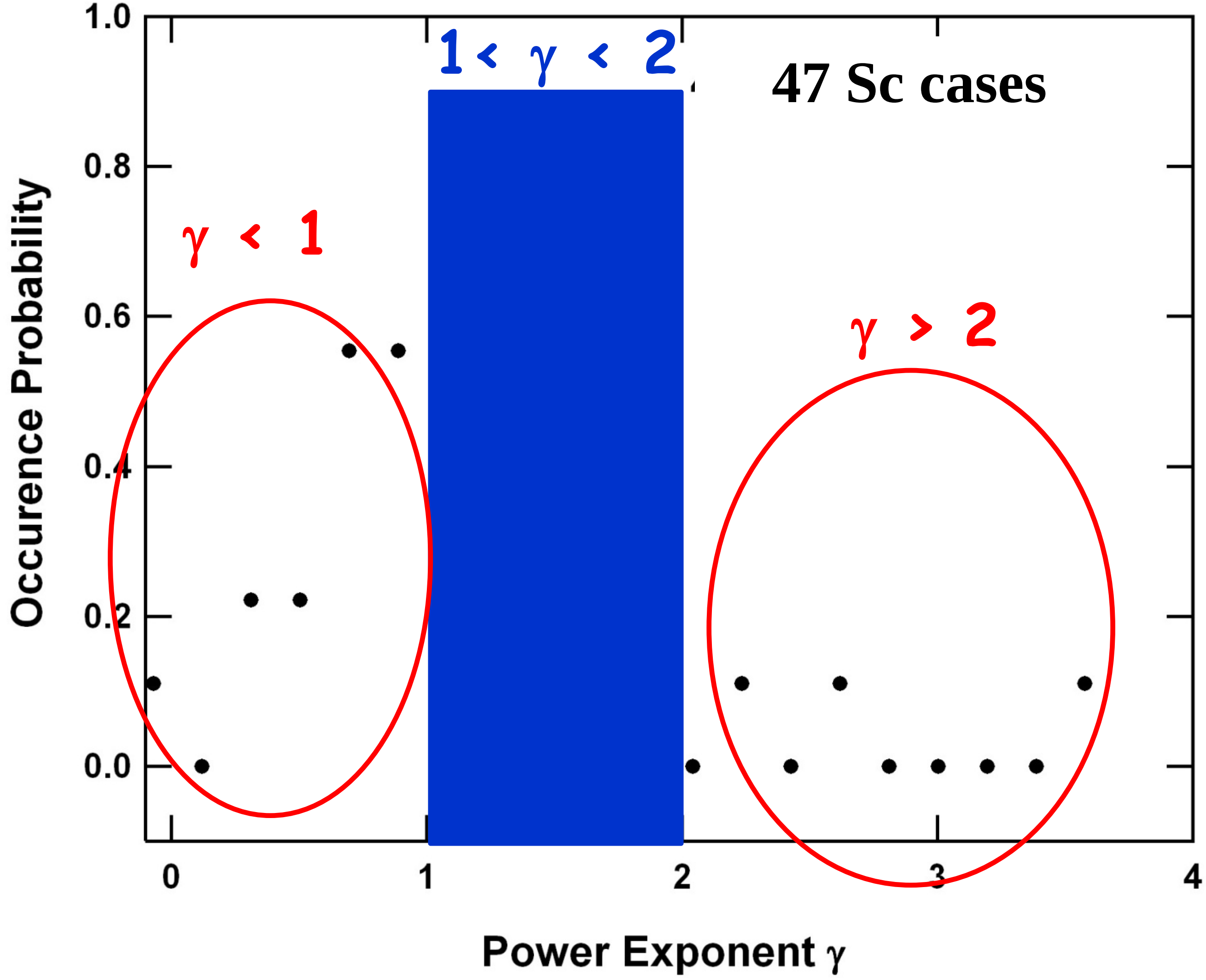
Ψ_1= 1 for extreme homogeneous

(Lu et al, JGR, 2013)

However, the approach is difficult for remote sensing, esp., retrieving droplet concentration $\longrightarrow$ approach based on Z-LWC relation

Frequency of γ during MASE

$$Z = \alpha L^{\gamma}$$



Z-LWC Approach: Theoretical Analysis

$$\mathbf{Z = 64\int r^6 n(r)dr = 64Nr_6^6} \qquad \mathbf{r}_p = \left[\frac{\int \mathbf{r^p n(r)dr}}{\mathbf{N}}\right]^{\mathbf{1/p}}$$

Case1: Constant r_3, β_6 and A (extreme inhomogeneous mixing)

$$\mathbf{Z = \frac{3\times 64}{4\pi\rho_w}\beta_6^6 r_3^3 L = AL}$$

Case 2: Constant N, β_6 and B ("adiabatic")

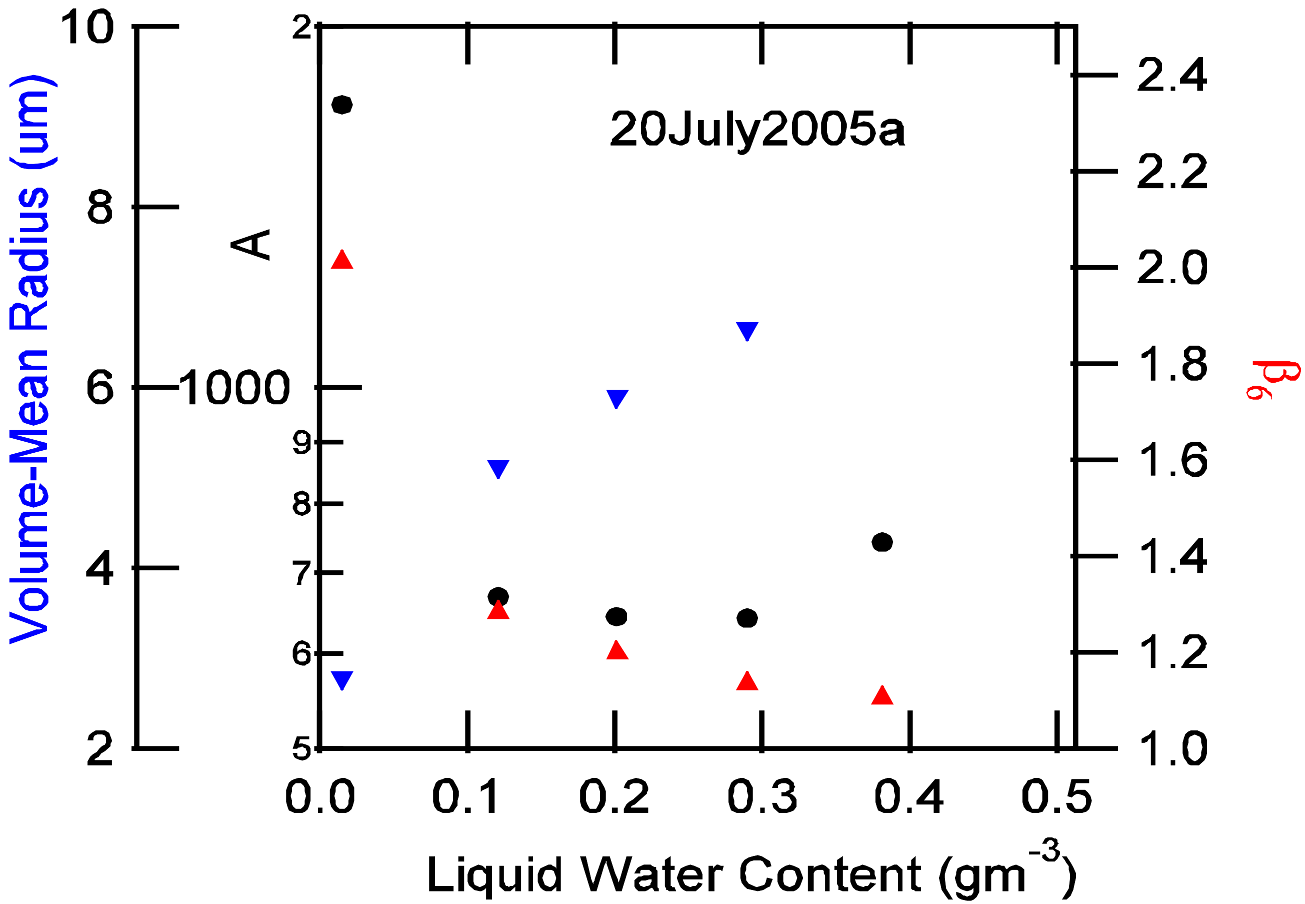
$$\mathbf{Z = \frac{36}{\pi^2}\frac{\beta_6^6}{N}L^2 = BL^2}$$

$$\beta_6 = \frac{r_6}{r_3}$$

$$A = BL$$

How about the other types?

Type 1: γ < 1



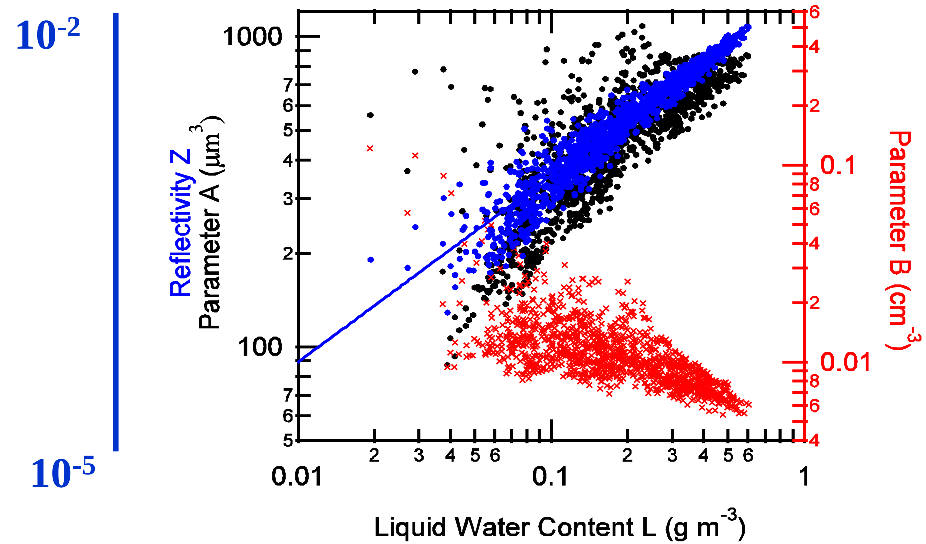
- ***The value of γ < 1 is caused by a relative faster decrease of β_6 with LWC than the increase of volume mean radius with LWC (vertical profile);***
- ***Both volume mean radius and β_6 decrease with LWC (broadening toward large sizes)*** — *inhomogeneous mixing with ascent ?*

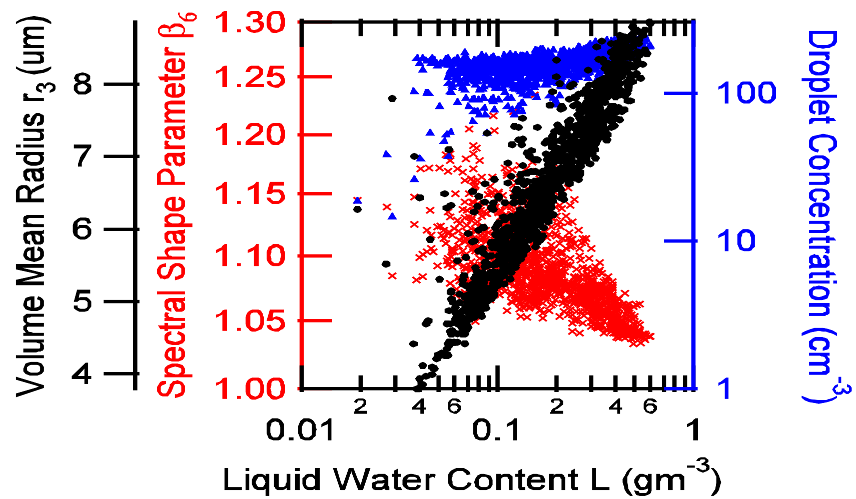
Type 2: $1 < \gamma < 2$

- **Type 2 $1 < \gamma < 2$ corresponds to A increasing but B decreasing with LWC;**

- **This type is likely associated with increasing droplet concentration and volume mean radius increase, but decreasing β_6, with increasing LWC ---- spectral broadening toward small droplet sizes**

- **Indication of homogeneous mixing**





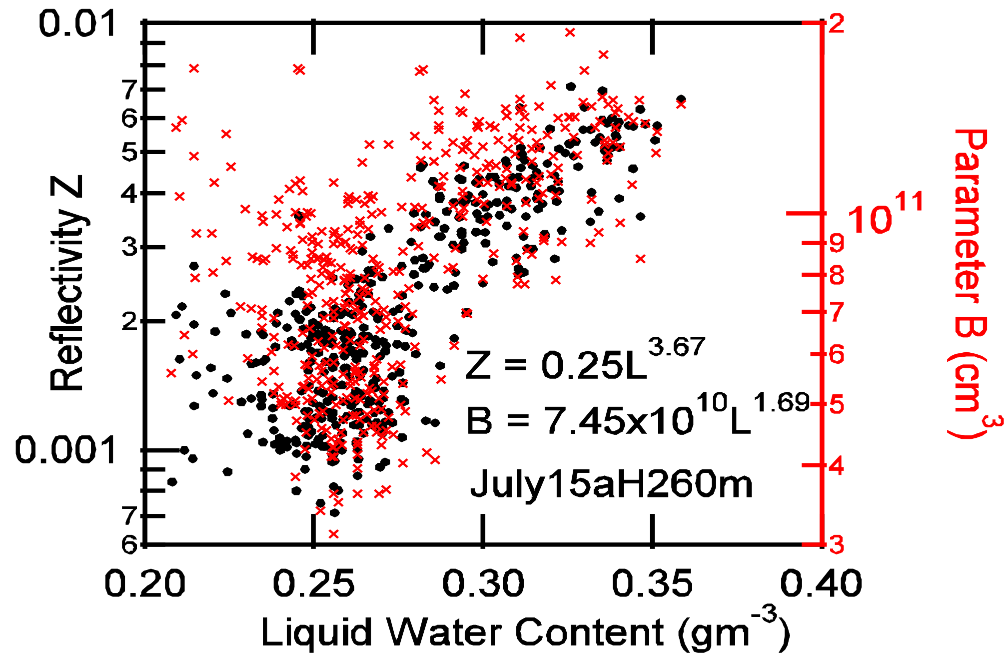
Type 3: γ > 2

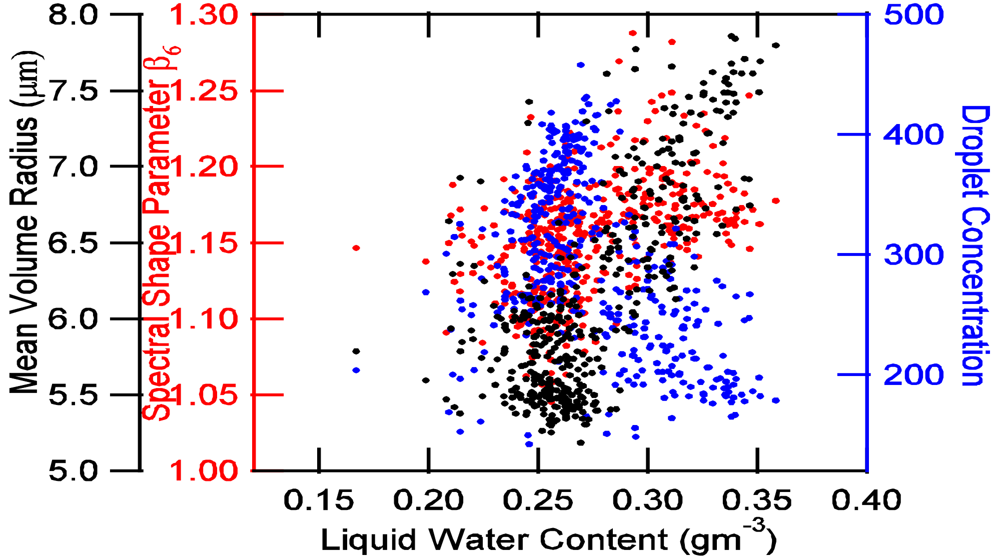
•This type features an increase of B with increasing LWC;

• The increase of B with LWC is caused by increase of β_6 and decrease of droplet concentration with LWC;

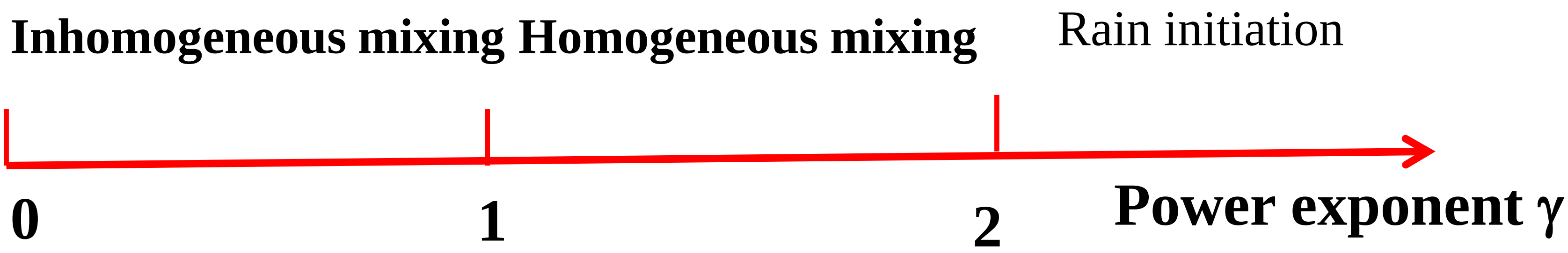
• Indication of collection process

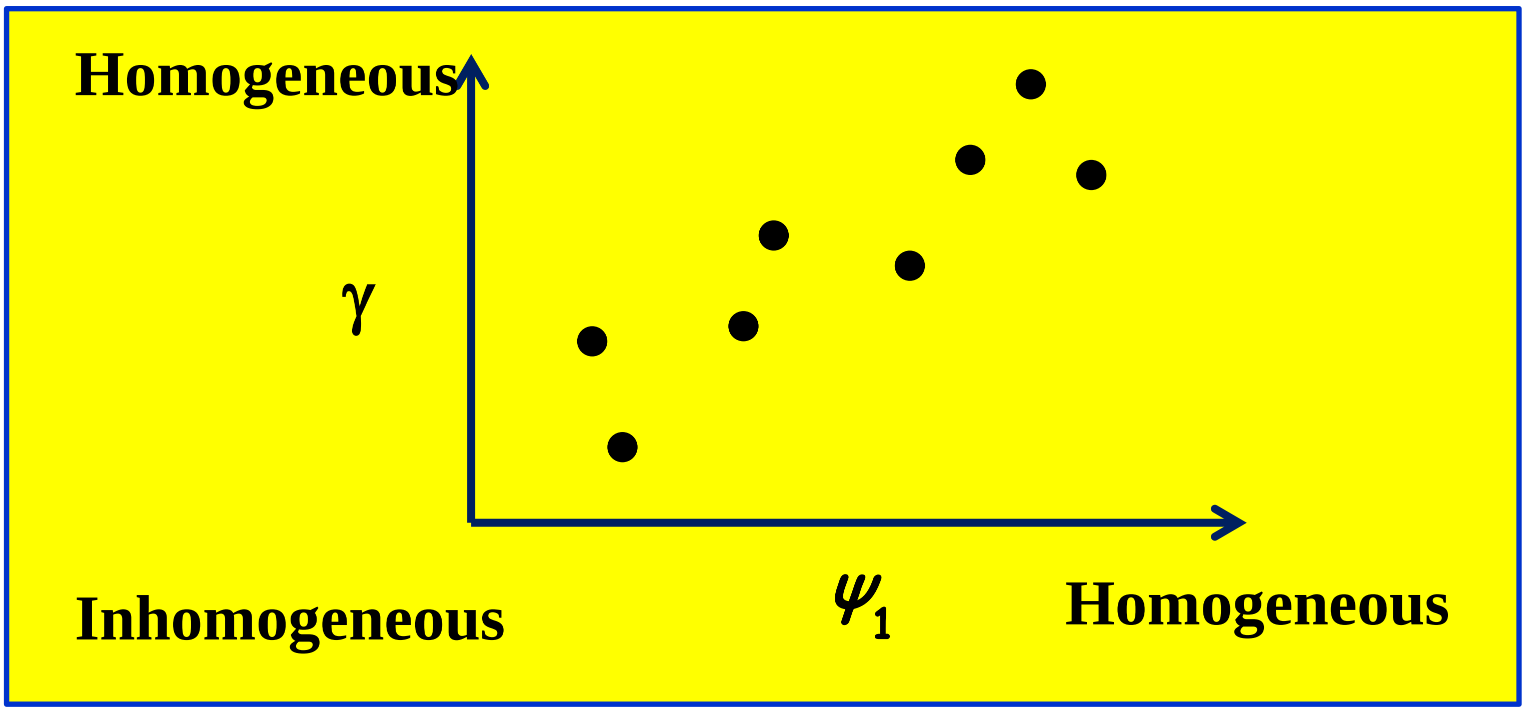
$$Z = \frac{36}{\pi^2}\frac{\beta_6^6}{N}L^2 = BL^2$$





γ as Another Measure of Homogeneous Degree ?

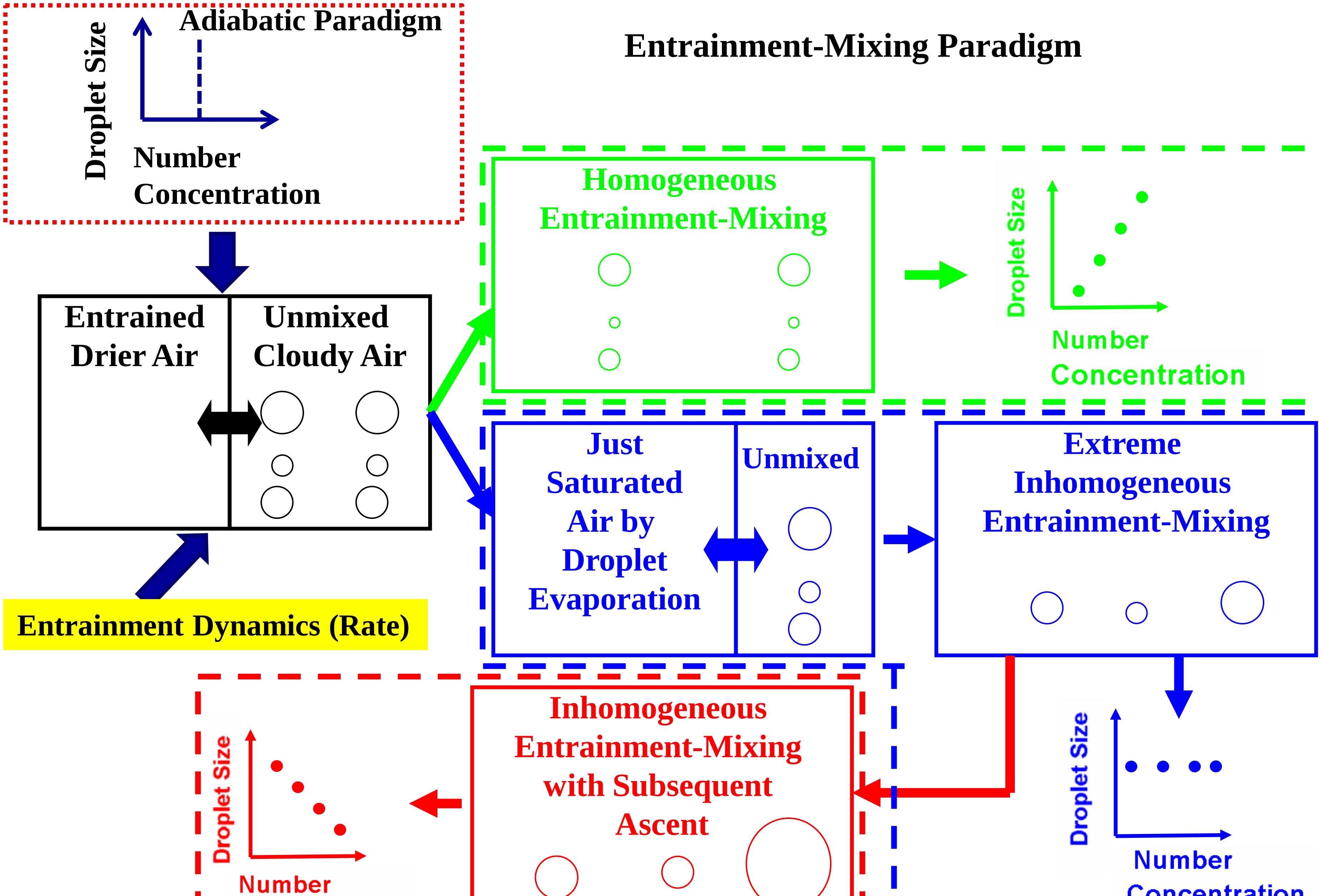




Pathways forwward

- Verify with in-situ (aircraft) measurements
- Dual frequency radar (Huang et al, GRL, 2009) for LWC
- Radar-Lidar combination (extinction to replace LWC)
- Others
- Effect of prefactor α (Khain et al, JAMC, 2008) in $\mathbf{Z} = \alpha \mathbf{L}^{\gamma}$

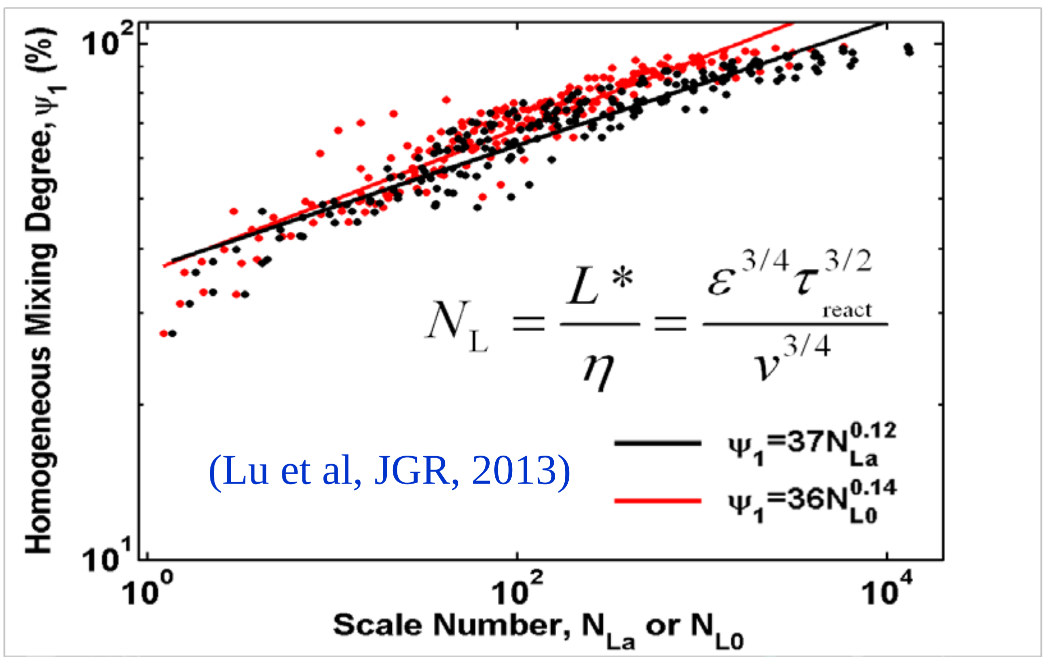
Entrainment-Mixing and Microphysics



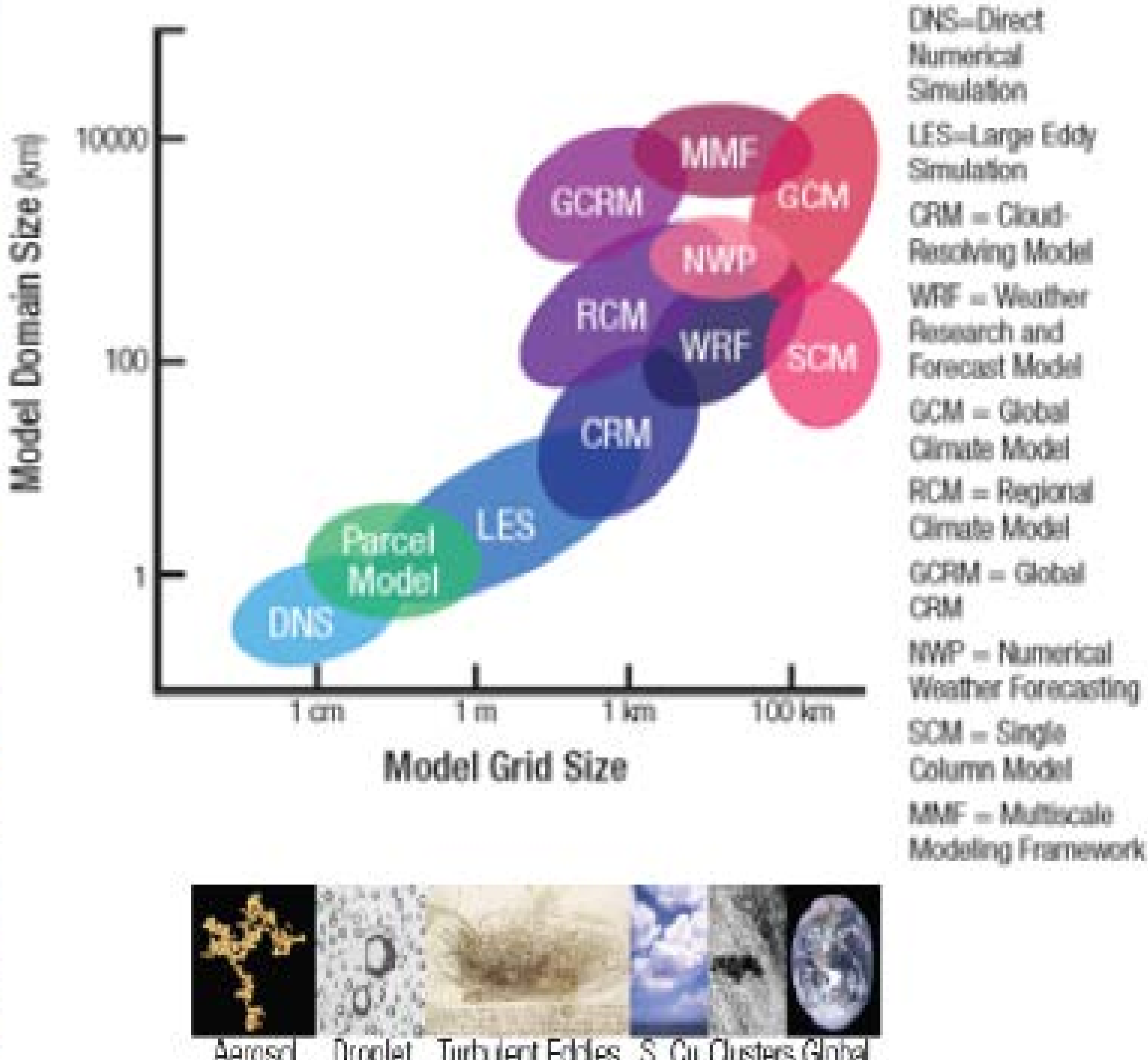
γ as a another measure of homogeneous degree ?

Inhomogeneous mixing **Homogeneous mixing** Rain initiation

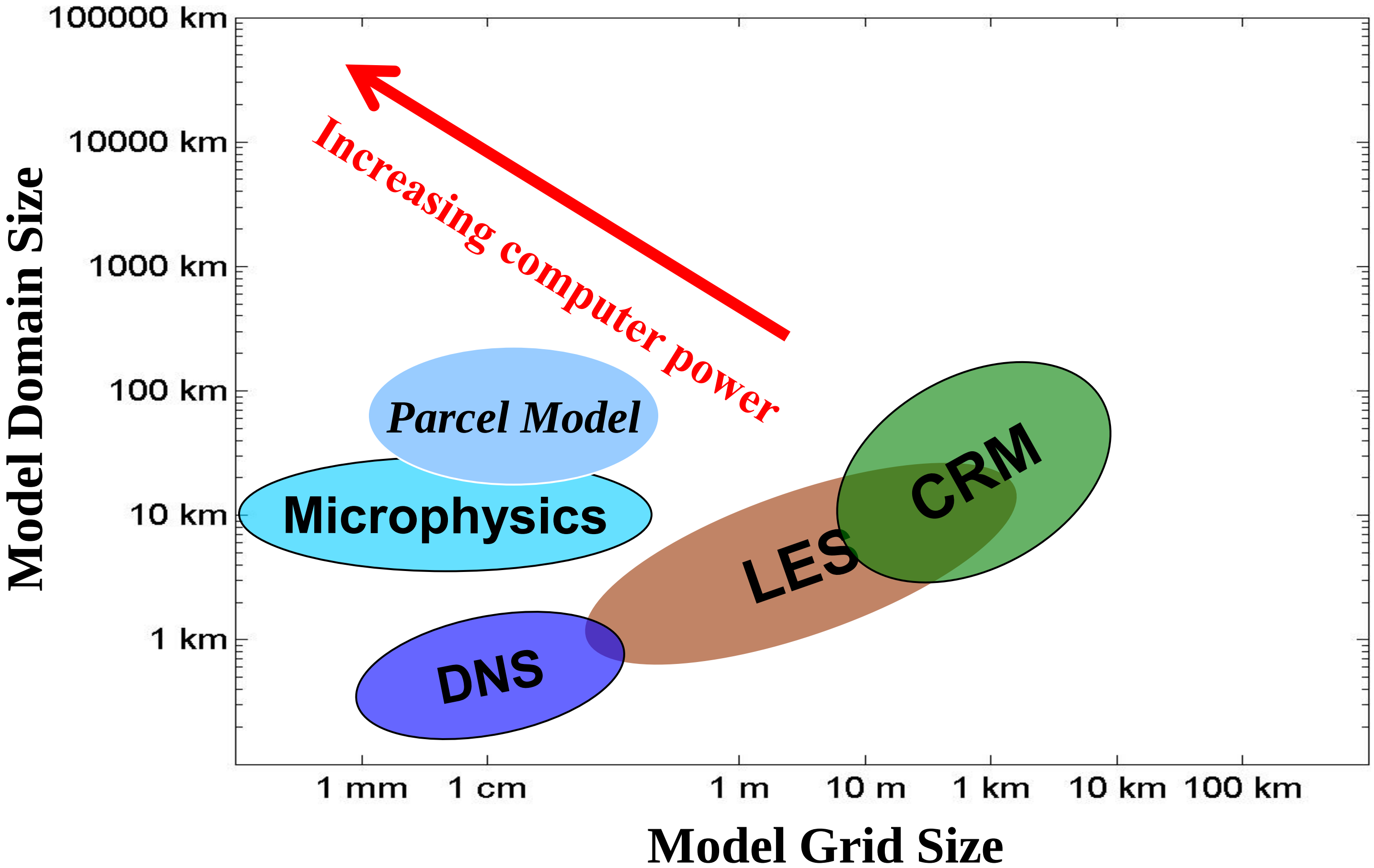
0 **1** **2** **Power exponent γ**



Understanding Fast Physics Calls for Multiscale Model Simulation & Evaluation



Multiscale Model Hierarchy



Aerosol Droplet Turbulent Eddies S. Cu Clusters Global

DNS = Direct Numerical Simulation

LES = Large Eddy Simulation

CRM = Cloud-Resolving Model

WRF = Weather Research and Forecast Model

GCM = Global Climate Model

RCM = Regional Climate Model

GCRM = Global CRM

NWP = Numerical Weather Forecasting

SCM = Single Column Model

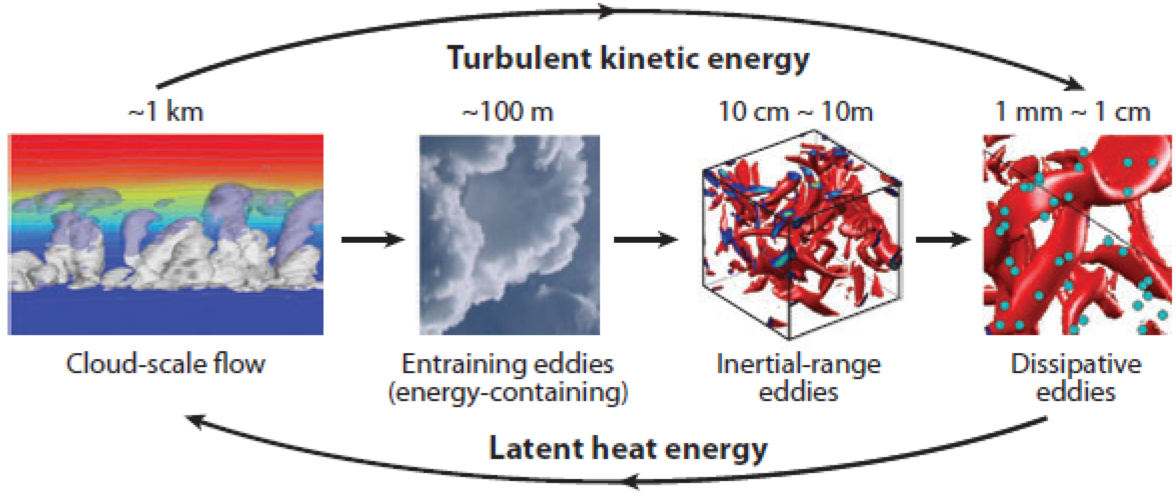
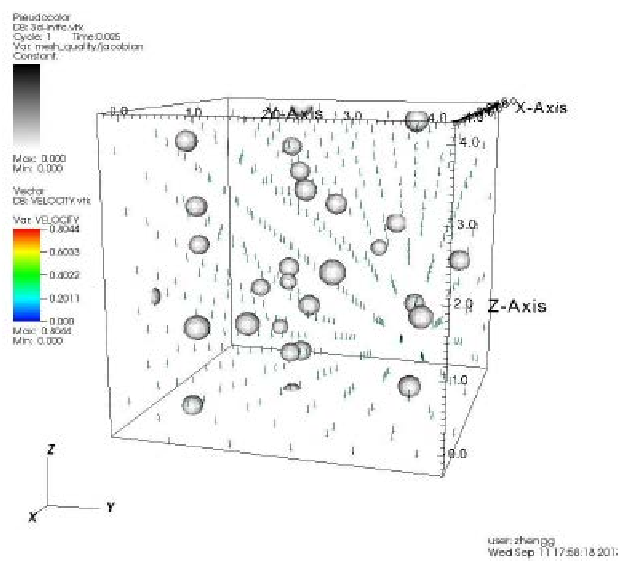


Figure 1

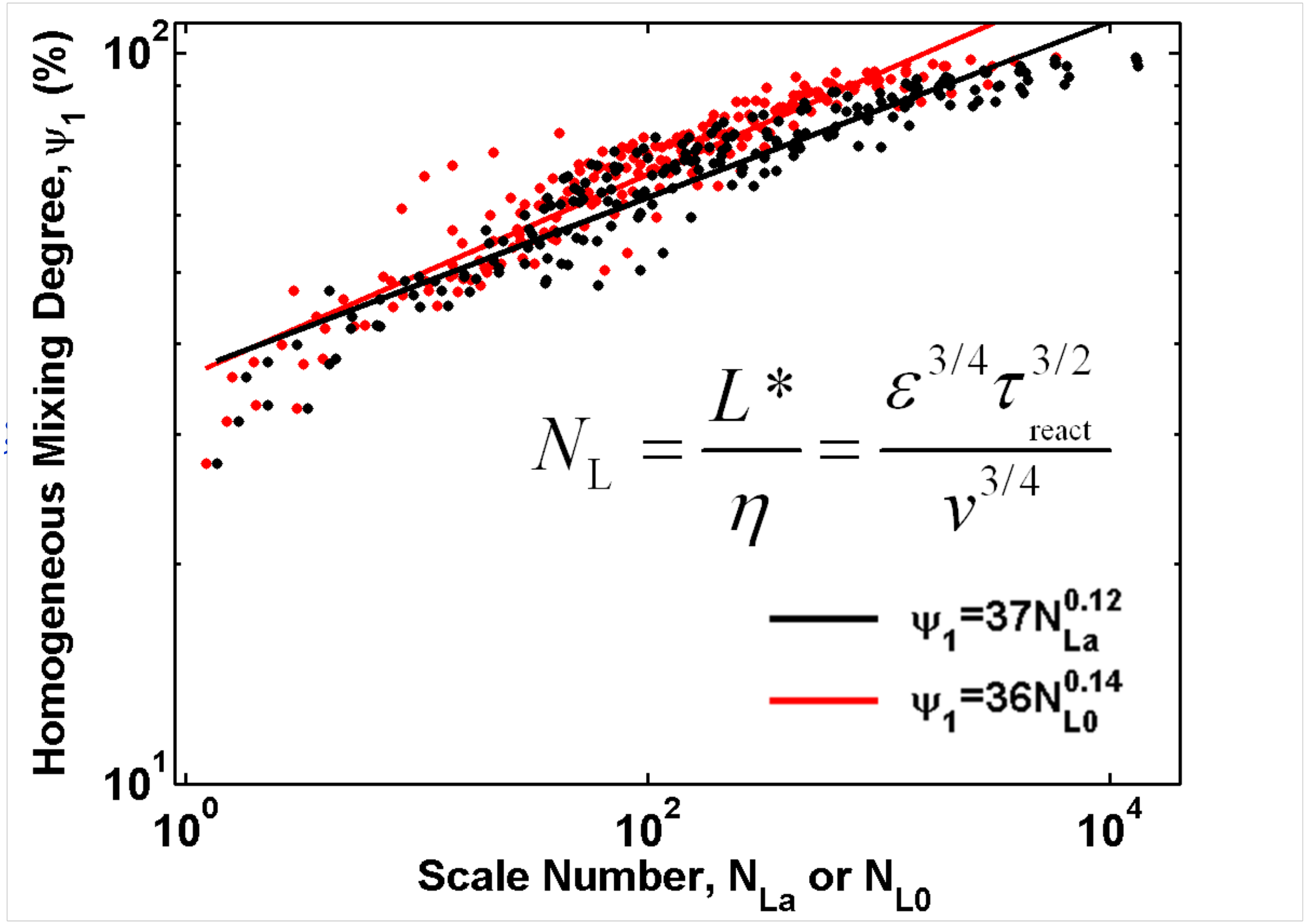
Multiscale interactions in atmospheric clouds. The turbulent kinetic energy flows from cloud-scale motion to dissipative eddies. Latent heat energy flows from individual droplets to cloud-scale motion.



DNS

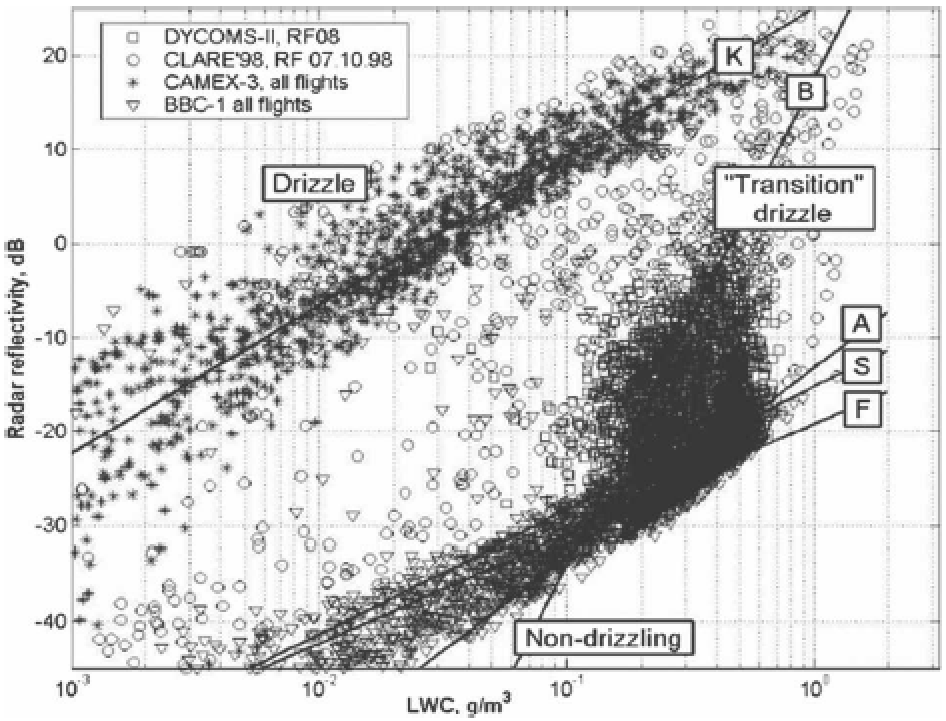
New Parameterization for Homogeneous Mixing Degree

- Eliminate the need for assuming extreme inhomogenous or homogenous mixing;
- Work best for models with 2-moment schemes;
- Testing with SCM and CRM/LES in FASTER
- Integrating with entrainment rate



A new parameterization that unifies entrainment rate and mixing effects on cloud microphysics is on the horizon.

Rain Initiation and Drizzling



Khain et al, 2008, JAMC, 47, 591-606

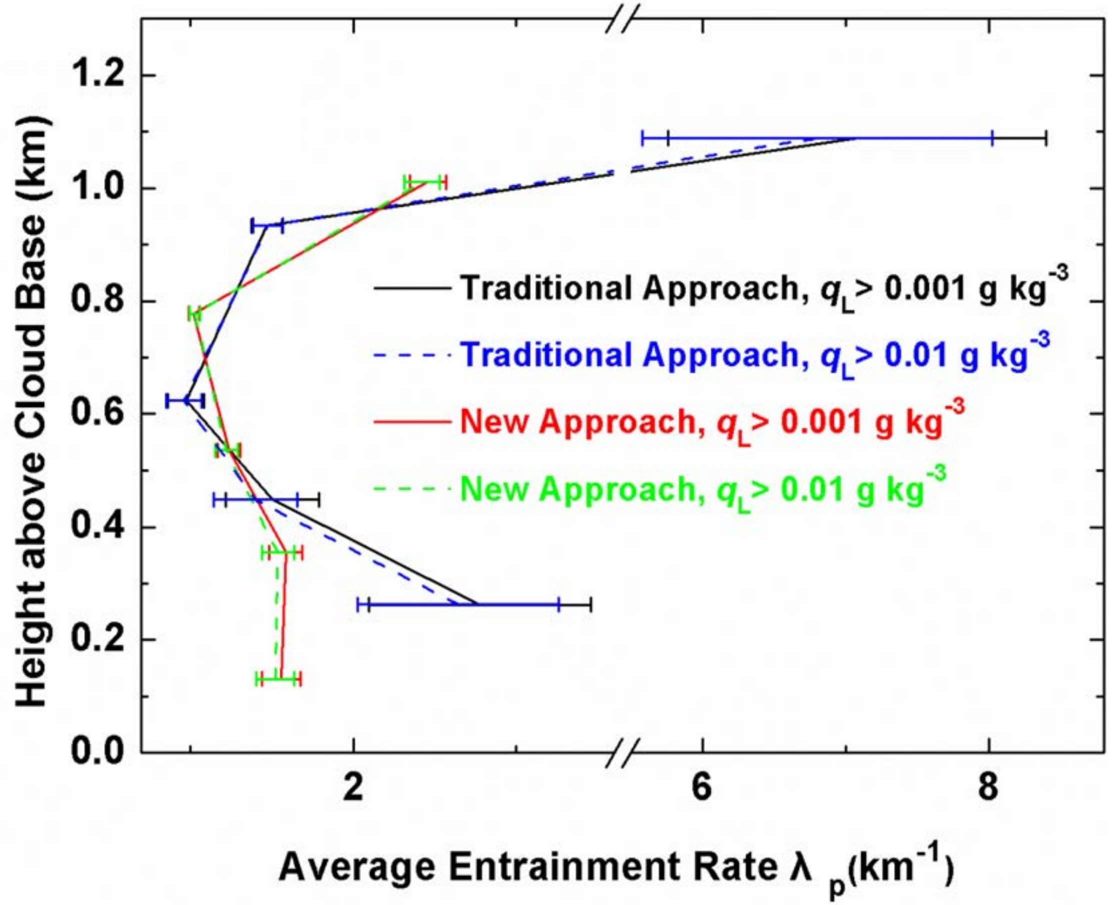
New Approach for Estimating Entrainment Rate

• Eliminate need for in-cloud measurements of temperature and water vapor

• Have smaller uncertainty

• Have potential for linking entrainment dynamics to microphysical effects

• Have potential for remote sensing technique (underway)



Lu et al 2012: Geophys. Res. Lett. 39, L04862

New Parameterization for Homogeneous Mixing Degree

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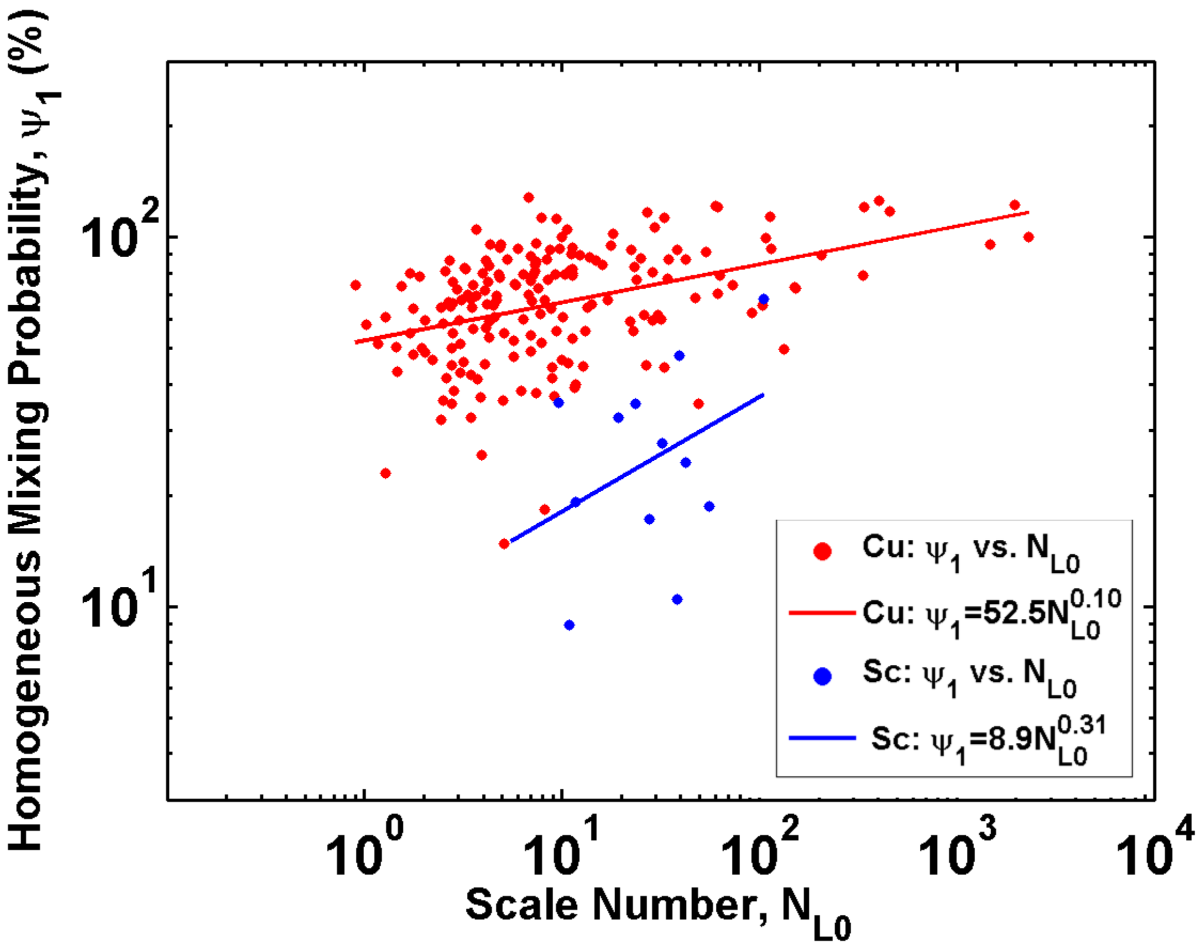

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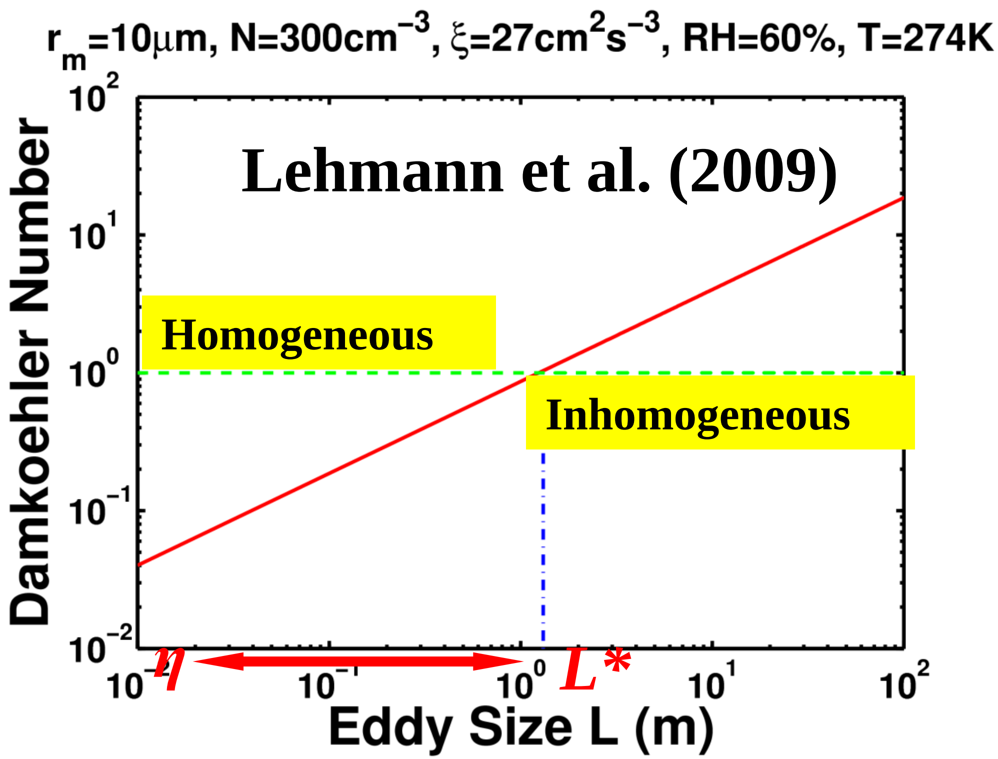
Transition Scale Number: Dynamical Measure of Homogeneous Mixing Degree



- **Transition length L^* is the eddy size of Da =1.**

$$Da = \tau_{\mathrm{mix}} / \tau_{\mathrm{react}} = 1$$

$$\tau_{\mathrm{mix}} \sim (L^2/\xi)^{1/3}$$

$$L^* = \xi^{1/2} \tau_{\mathrm{react}}^{3/2}$$

- **Transition scale number:**

$$N_L = \frac{L^*}{\eta} = \frac{\xi^{1/2}\tau_{\mathrm{react}}^{3/2}}{\eta}$$

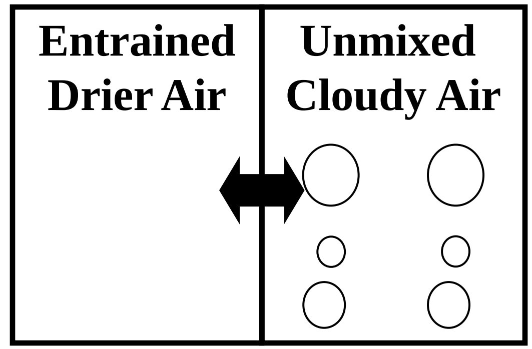
η: Kolmogorov scale

A larger N_L indicates a higher degree of homogeneous mixing.

Dynamics: Damkoehler Number

- Damkoehler number:

$$Da = \tau_{\text{mix}} / \tau_{\text{react}}$$



- τ_{mix}: the time needed for complete turbulent homogenization of an entrained parcel of size *L* (Baker et al., 1984):

$$\tau_{\text{mix}} \sim (L^2 / \xi)^{1/3}$$

ξ: dissipation rate

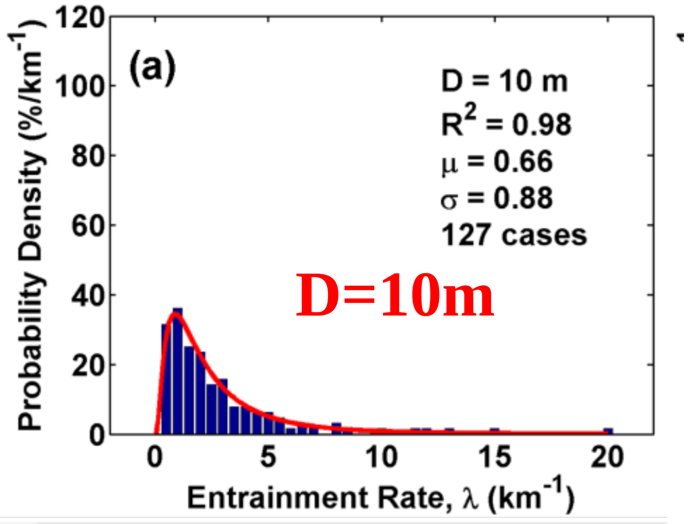
- τ_{react}: the time needed for droplets to evaporate in the entrained dry air or the entrained dry air to saturate (Lehmann et al 2009):

$$\begin{cases} \dfrac{dr_{\text{m}}}{dt} = A \cdot \dfrac{s}{r_{\text{m}}} \\ \dfrac{ds}{dt} = -B \cdot s \end{cases}$$

r_m: mean radius

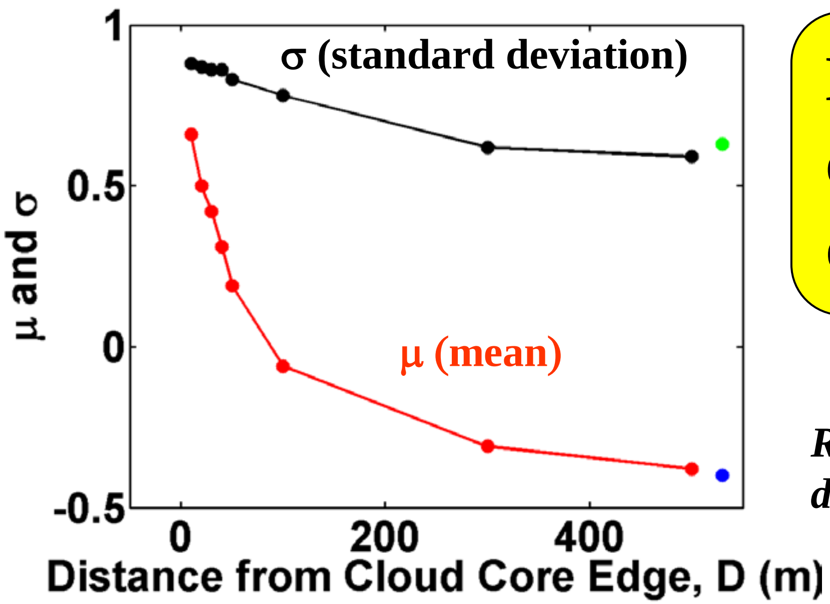
s: supersaturation

PDF and Distance Dependence



All the PDFs can be well fitted by lognormal distributions; $R^2 > 0.91$.

$$f_X(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, \quad x > 0$$

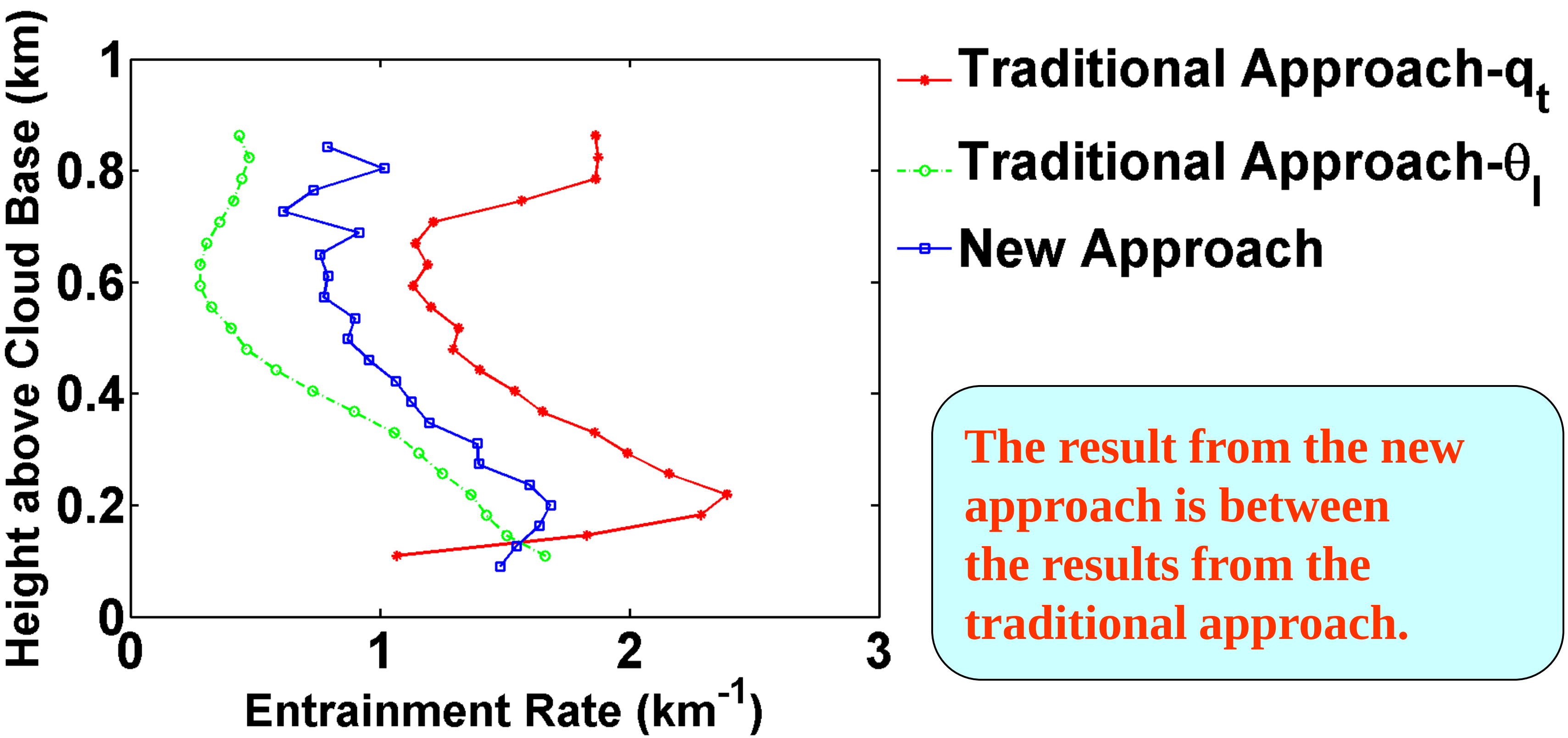


Both mean and standard deviation of ln (λ) decrease with increasing distance from cloud core D.

Ref: Lu et al 2012: Entrainment rate in cumuli: PDF and dependence on distance. Geophys. Res. Lett. (in press)

Validation with LES Results

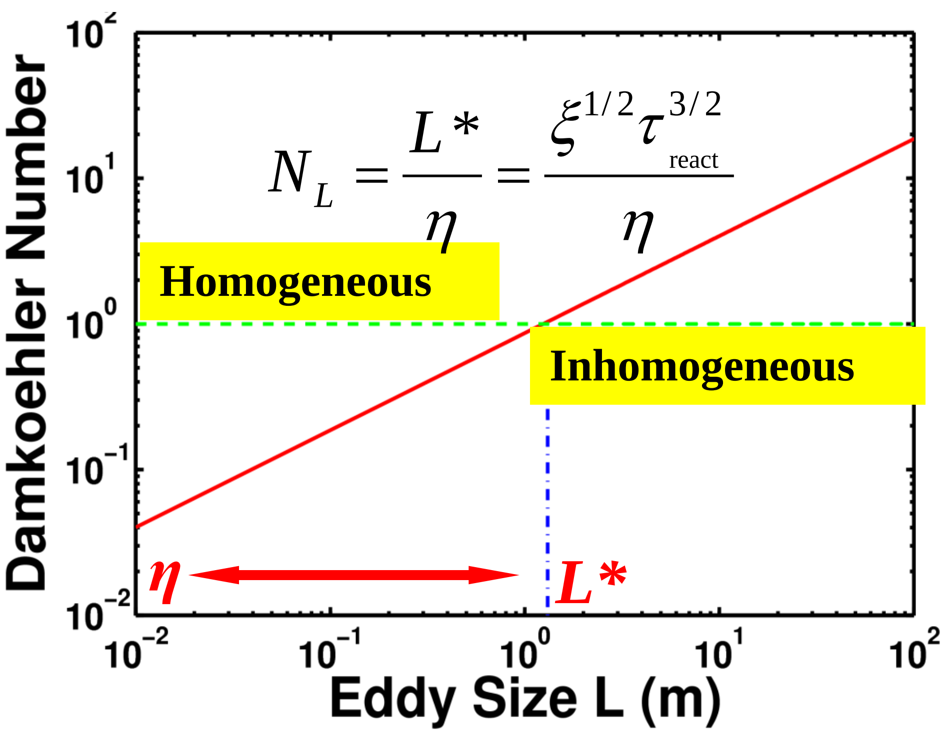
A benchmark case over the SGP site simulated by WRF-FASTER

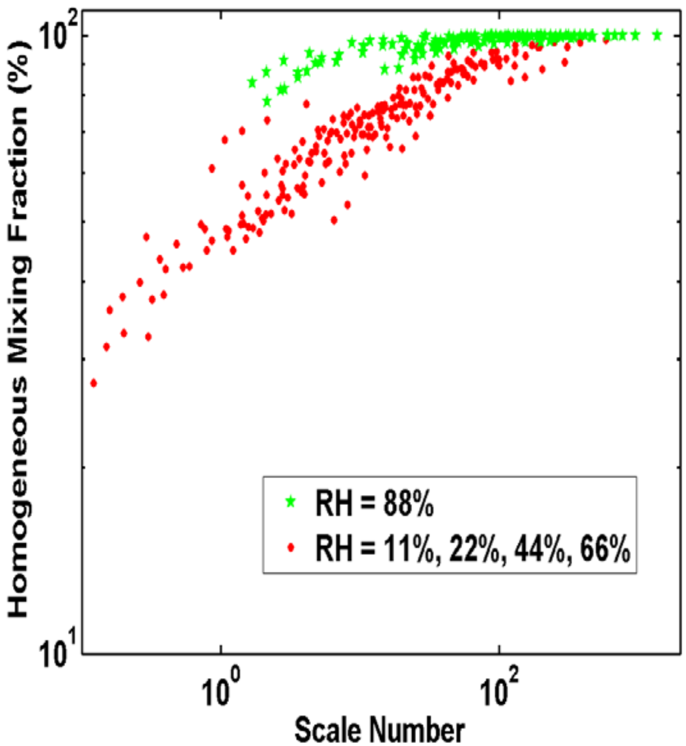


The result from the new approach is between the results from the traditional approach.

Homogeneous Mixing Fraction

η: Kolmogorov scale; L* transition scale; N_L transition scale number





Further parameterization of the scale number leads to a much needed parameterization for homogeneous mixing fraction.

Lu et al 2011: Examination of turbulent entrainment-mixing mechanisms using a combined approach. J. Geophys. Res.; 2012: Relationship between homogeneous mixing fraction and transition scale number, Environ. Res. Lett. (to be submitted)

Task of convection parametrisation

in practice this means:

Determine occurrence/localisation of convection

→ Trigger

Determine vertical distribution of heating, moistening and momentum changes

→ Cloud model

Determine the overall amount of the energy conversion, convective precipitation=heat release

→ Closure

The “Kuo” scheme

Closure: Convective activity is linked to large-scale moisture convergence

$$P = (1-b)\int_0^{\infty}\left(\frac{\partial \rho q}{\partial t}\right)_{ls} dz$$

Vertical distribution of heating and moistening: adjust grid-mean to moist adiabat

Main problem: here convection is assumed to consume water and not energy -> …. Positive feedback loop of moisture convergence

Adjustment schemes

e.g. Betts and Miller, 1986, QJRMS:

When atmosphere is unstable to parcel lifted from PBL and there is a deep moist layer - adjust state back to reference profile over some time-scale, i.e.,

$$\left(\frac{\partial T}{\partial t}\right)_{conv.} = \frac{T_{ref} - T}{\tau} \qquad \left(\frac{\partial q}{\partial t}\right)_{conv.} = \frac{q_{ref} - q}{\tau}$$

T_{ref} is constructed from moist adiabat from cloud base but no universal reference profiles for q exist. However, scheme is robust and produces “smooth” fields.

Adjustment schemes:

The Next Step is an *Enthalpy* Adjustment

First Law of Thermodynamics:

$$dH = C_p dT + L_v dq_v$$

With Parameterized Convection, each grid-point column is treated in isolation. Total column latent heating must be directly proportional to total column drying, or **dH = 0.**

$$\int_{P_b}^{P_t} C_p \left(T_{ref} - T\right) dp = -\int_{P_b}^{P_t} L_v (q_{vref} - q_v) dp$$

The mass-flux approach

$$Q_{1C} \equiv L(\overline{c} - \overline{e}) - \frac{\partial \overline{\omega' s'}}{\partial p}$$

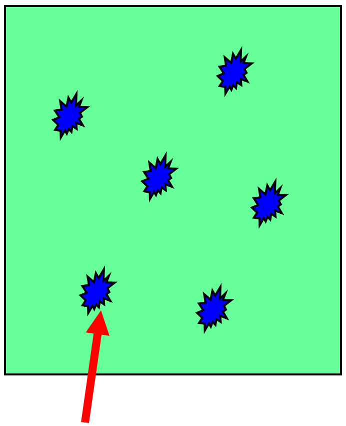
Condensation term

Eddy transport term

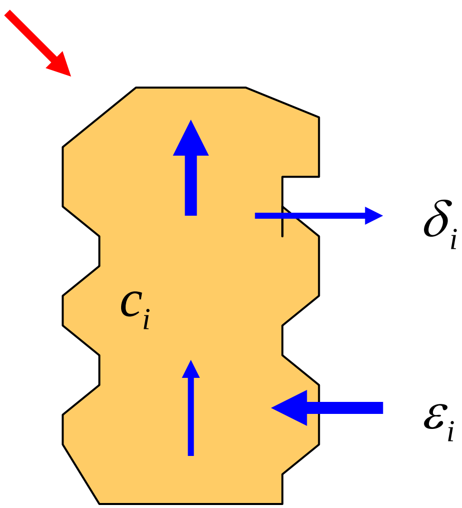
Aim: Look for a simple expression of the eddy transport term

$$\overline{\omega' \Phi'} = ?$$

Mass-flux entraining plume cloud models



Cumulus element i



Entraining plume model

Continuity:

$$\frac{\partial \sigma_i}{\partial t} + D_i - E_i - g\frac{\partial M_i}{\partial p} = 0$$

Heat:

$$\frac{\partial\left(\sigma_i s_i\right)}{\partial t} + D_i s_i - E_i \overline{s} - g\frac{\partial\left(M_i s_i\right)}{\partial p} = L c_i$$

Specific humidity:

$$\frac{\partial\left(\sigma_i q_i\right)}{\partial t} + D_i q_i - E_i \overline{q} - g\frac{\partial\left(M_i q_i\right)}{\partial p} = -c_i$$

Mass-flux entraining plume cloud models

Simplifying assumptions:

1. Steady state plumes, i.e., $\frac{\partial X}{\partial t} = 0$

Most mass-flux convection parametrizations today still make that assumption, some however are prognostic

2. Bulk mass-flux approach Sum over all cumulus elements, e.g.

$$\frac{1}{M}\frac{dM}{dz} = \varepsilon - \delta \Rightarrow -g\frac{\partial M_c}{\partial p} = E - D \quad \text{with} \quad M_c = \sum_i M_i, \quad \varepsilon = \sum_i \varepsilon_i, \quad \delta = \sum_i \delta_i$$

$$E = M / \rho\ \varepsilon; \quad D = M / \rho\ \delta$$

ε,δ [m^{-1}] denote fractional entrainment/detrainment, E,D [s^{-1}] entrainment/detrainment rates

3. Spectral method

$$M_c(p) = \int_0^{\varepsilon_D} m_B(\varepsilon)\eta(p,\varepsilon)d\varepsilon$$

e.g., Arakawa and Schubert (1974) and derivatives

Important: No matter which simplification - we always describe a cloud ensemble, not individual clouds (even in bulk models)

Large-scale cumulus effects deduced using mass-flux models

$$Q_{1C} \equiv -gM_c \frac{\partial \overline{s}}{\partial p} + D(\overline{s}^c - \overline{s}) - Le$$

Physical interpretation (can be dangerous after a lot of maths):

Convection affects the large scales by

Heating through compensating subsidence between cumulus elemen

The detrainment of cloud air into the environment (term 2)

Evaporation of cloud and precipitation (term 3)

Note: The condensation heating does not appear directly in Q_1. It is however a crucial part of the cloud model, where this heat is transformed in kinetic energy of the updrafts.

Similar derivations are possible for Q_2.

Summary (1)

- Convection parametrisations need to provide a physically realistic forcing/response on the resolved model scales and need to be practical
- a number of approaches to convection parametrisation exist
- basic ingredients to present convection parametrisations are a method to trigger convection, a cloud model and a closure assumption
- the mass-flux approach has been successfully applied to both interpretation of data and convection parametrisation

Summary (2)

- The mass-flux approach can also be used for the parametrization of shallow convection.

It can also be directly applied to the transport of chemical species

- The parametrized effects of convection on humidity and clouds strongly depend on the assumptions about microphysics and mixing in the cloud model --> uncertain and active research area

- ………… Future we already have alternative approaches based on explicit representation (Multi-model approach) or might have approaches based on Wavelets or Neural Networks

Development of Parameterization

- **Turbulent entrainment-mixing processes**

- **Three-moment-based microphysics**

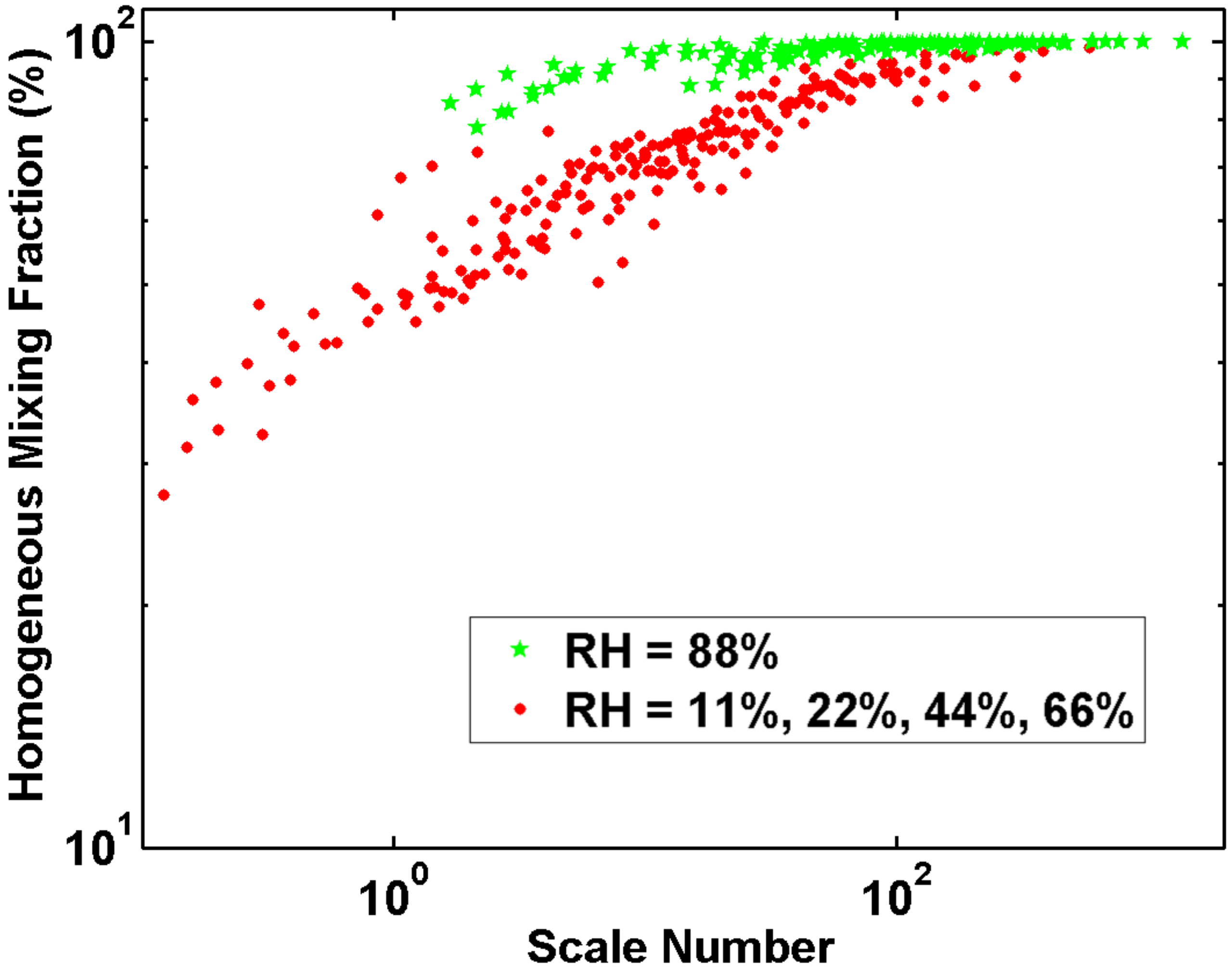
- **Convection**

- **Implementation of CLUBB (multi-variate PDF approach)**

- **Consideration of cloud structure**

- **Coupling between convection and microphysics**

Dependence of Homogeneous Mixing Fraction on Transition Scale Number



Three Definitions of Homogeneous Mixing Fraction --- Ψ_3

$$\boxed{\psi_3 = \frac{\ln N - \ln N_i}{\ln N_h - \ln N_i} = \frac{\ln r_v^3 - \ln r_{vi}^3}{\ln r_{vh}^3 - \ln r_{vi}^3}}$$

This definition, Ψ_3, turns out to be related to α:

$$\psi_3 = 1 - \alpha$$

where α was defined by Morrison and Grabowski (2008):

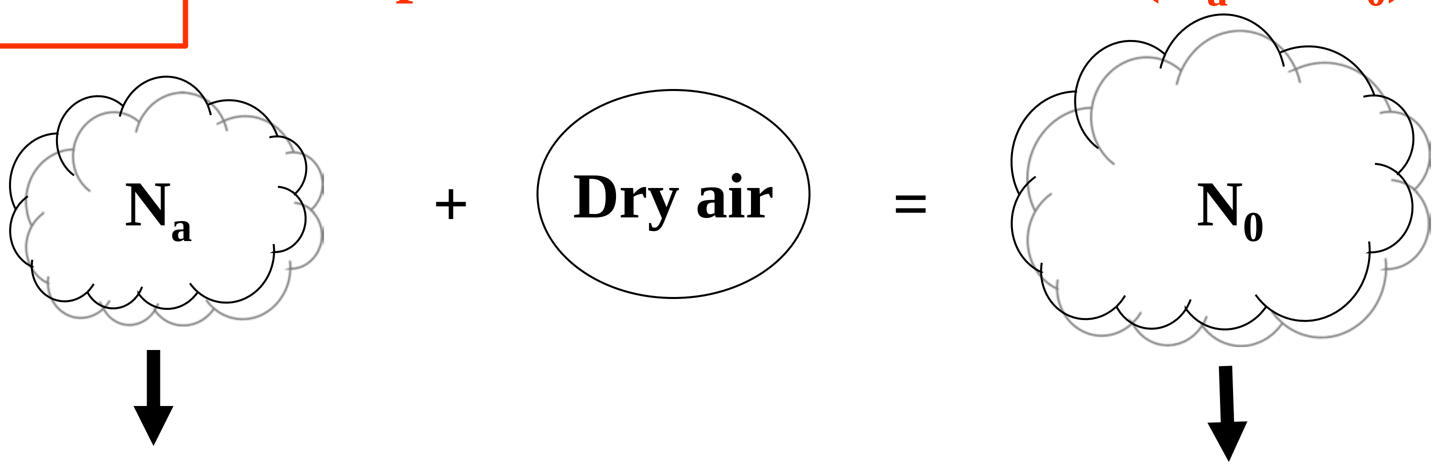
$$N = N_0 \left(\frac{q}{q_0}\right)^{\alpha}$$

Two Transition Scale Numbers (2)

τ_{react} is based on:

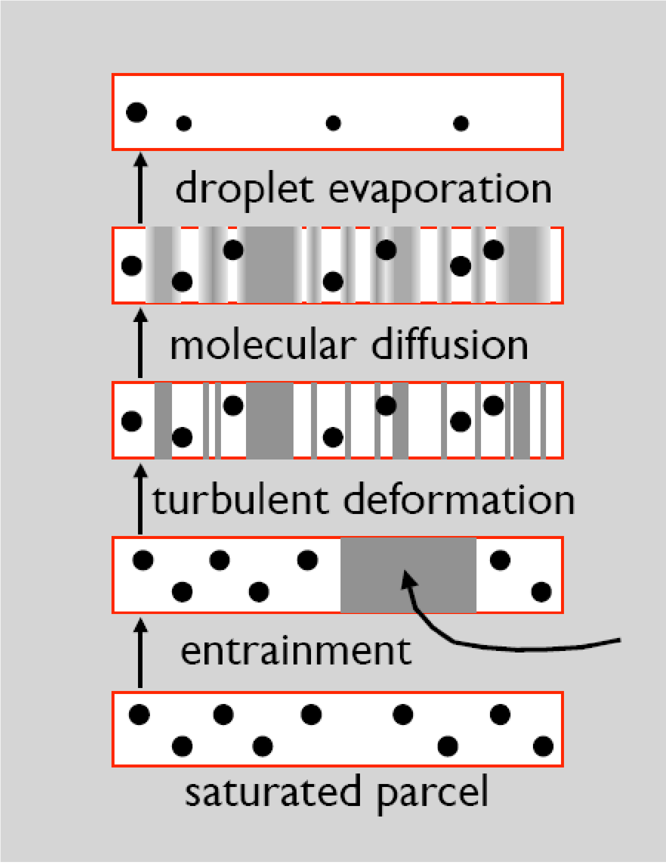
$$\boxed{\begin{cases} \dfrac{dr}{dt} = A\dfrac{s}{r} \\[2ex] \dfrac{ds}{dt} = -Brs \end{cases}}$$

***r*: droplet radius;**
***s*: supersaturation;**
***A*: a function of pressure and temperature;**
***B*: a function of pressure, temperature and droplet number concentration (N_a or N_0).**



Scale Number N_{La} **N_{L0}**

Explicit Mixing Parcel Model (EMPM)



Krueger (2008)

Domain size:

20 m× 0.001 m × 0.001 m ;

Adiabatic Number Concentration:

102.7, 205.4, 308.1, 410.8, 513.5 c

Relative humidity:

11%, 22%, 44%, 66%, 88%;

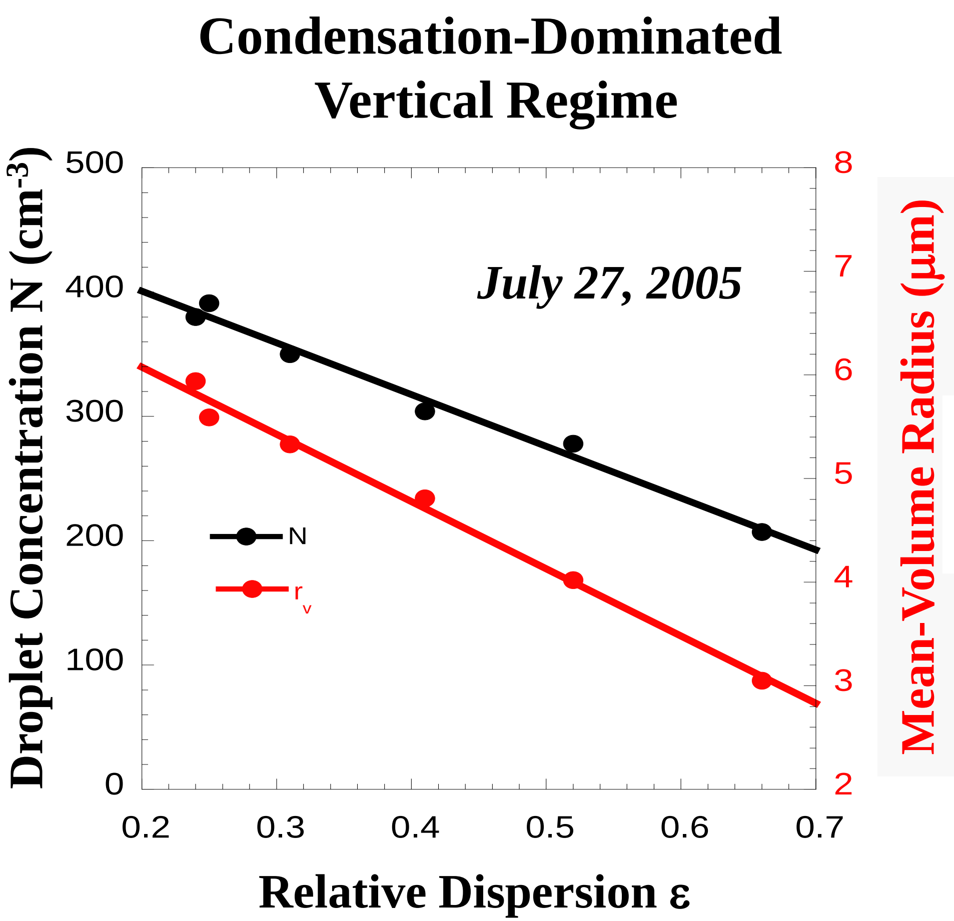
Dissipation rate:

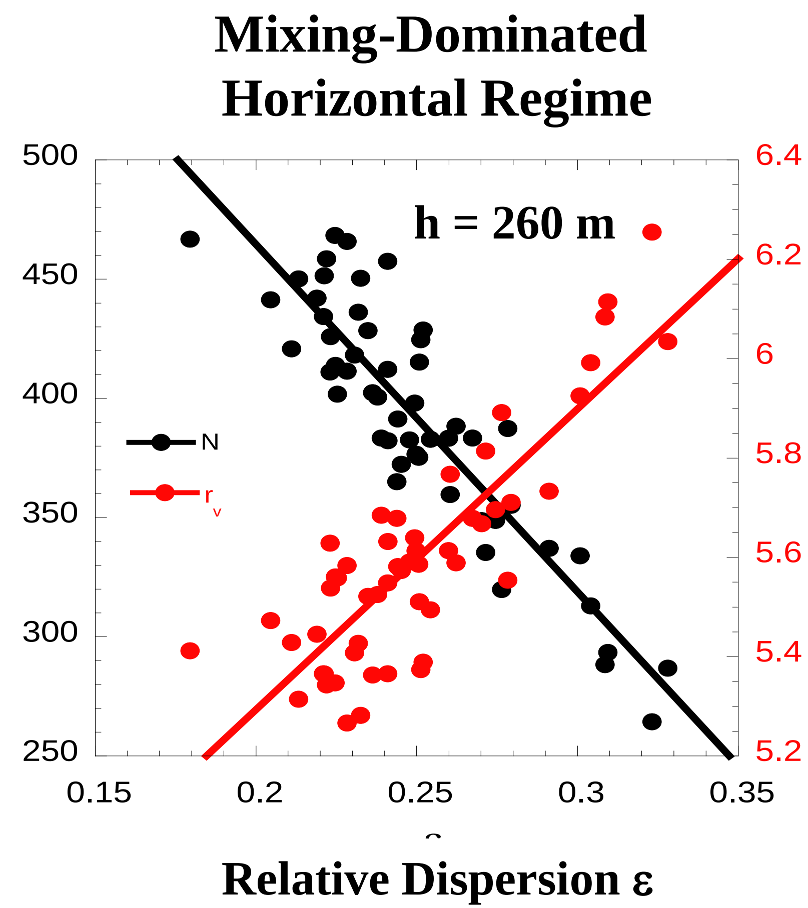
1e-5, 5e-4, 1e-3, 5e-3, 1e-2, 5e-2 m

Mixing fraction of dry air:

0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.

Entrainment-mixing processes complicate the dispersion effect as well.





Note the opposite relationships of mean-volume radius to relative dispersion in the two figures. The left panel is largely consistent with the adiabatic condensation theory whereas the right one with entrainment-mixing processes.

Atmospheric Modeling Background

1950s - : Beginning (Charney and von Neumann)

"To von Neumann, meteorology stood the most to gain from high speed computation"

1960-1990s: Expansion Phase

1990- Consolidation and Application