Numerical modeling of multiscale atmospheric flows: From cloud microscale to climate

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This presentation includes results from collaborative work between myself and several people:

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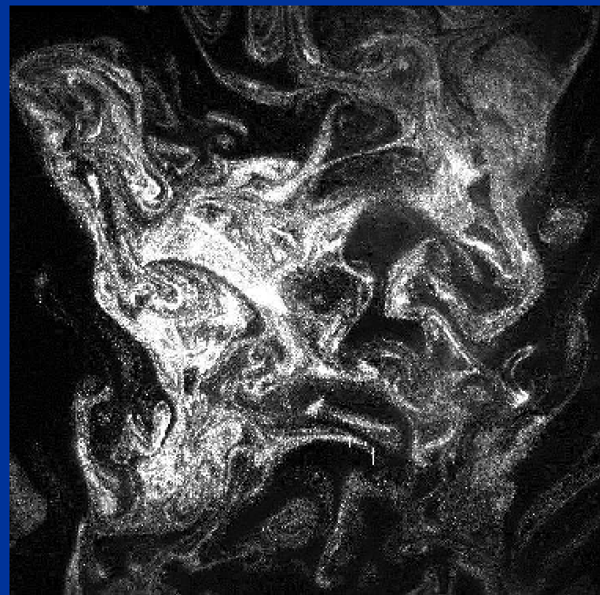
Cloud processes span tremendous range of scales, from *thousands of kilometers* down to a *fraction of a cm*…

Earth
in visible light

1,000 km

Small cumulus
clouds

Mixing in laboratory
cloud chamber



10 cm

Resolving such a range of scales in numerical models will never be possible…

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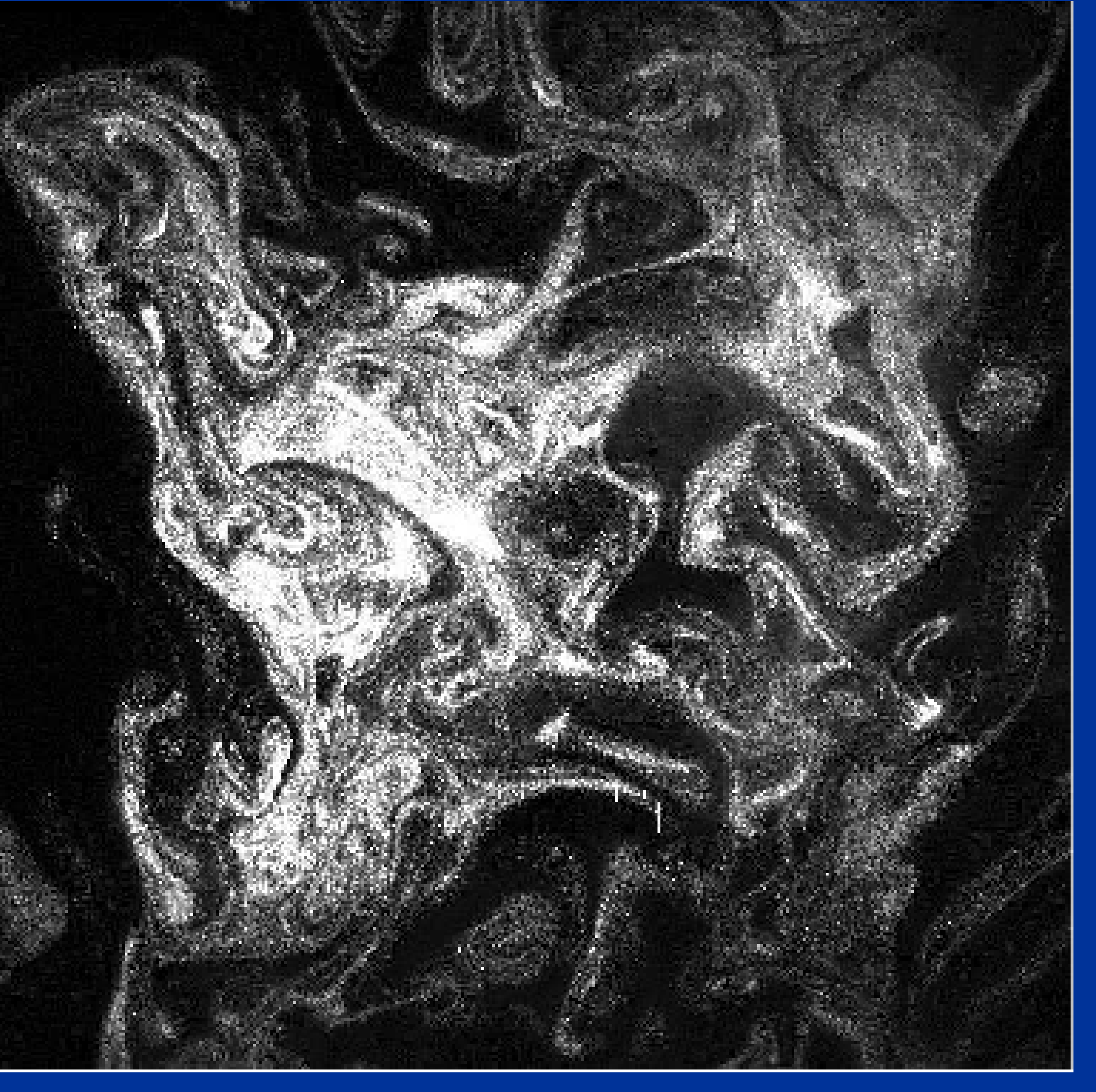
Even for processes near each of the scale illustrated above, there are multiscale interactions that cannot be resolved by the “direct numerical simulation” approach…

Significant progress may still be achieved using “multiscale” approaches.

NB. “Multiscale” is used here in a loose sense: extending the range of scales directly simulated by the model…

Modeling effects of turbulence on growth of cloud droplets by collision/coalescence



Elementary facts about cloud droplets:

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

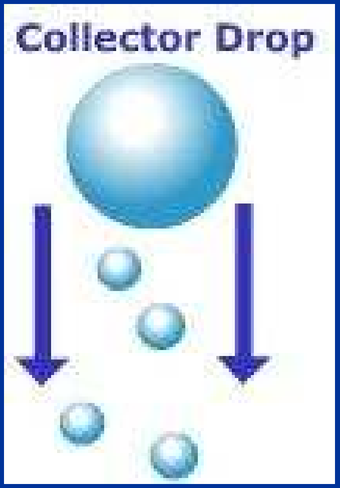
Concentration: 50-2,000 cm^{-3} (mean separation distance >> *r*)

Mass loading: 0.5-5 g kg^{-1} (<< 1; negligible effects on turbulence)

Growth of cloud droplets:

by diffusion of water vapor --- only efficient for r < 15 µm

by collision/coalescence --- only efficient for r > 15 µm



Droplet inertial response time:

$$\tau_p = 2\rho_w r^2/9\mu$$

ρ_w – water density (~10^3 kg m^{-3})

μ – air dynamic viscosity (~$1.5 \cdot 10^{-5}$ kg m^{-1} s^{-1})

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

Stokes number: $St = \tau_p / \tau_\eta$ **(typical values: 0.001 – 0.3)**

τ_p **- droplet response time**

τ_η **– Kolmogorov timescale**

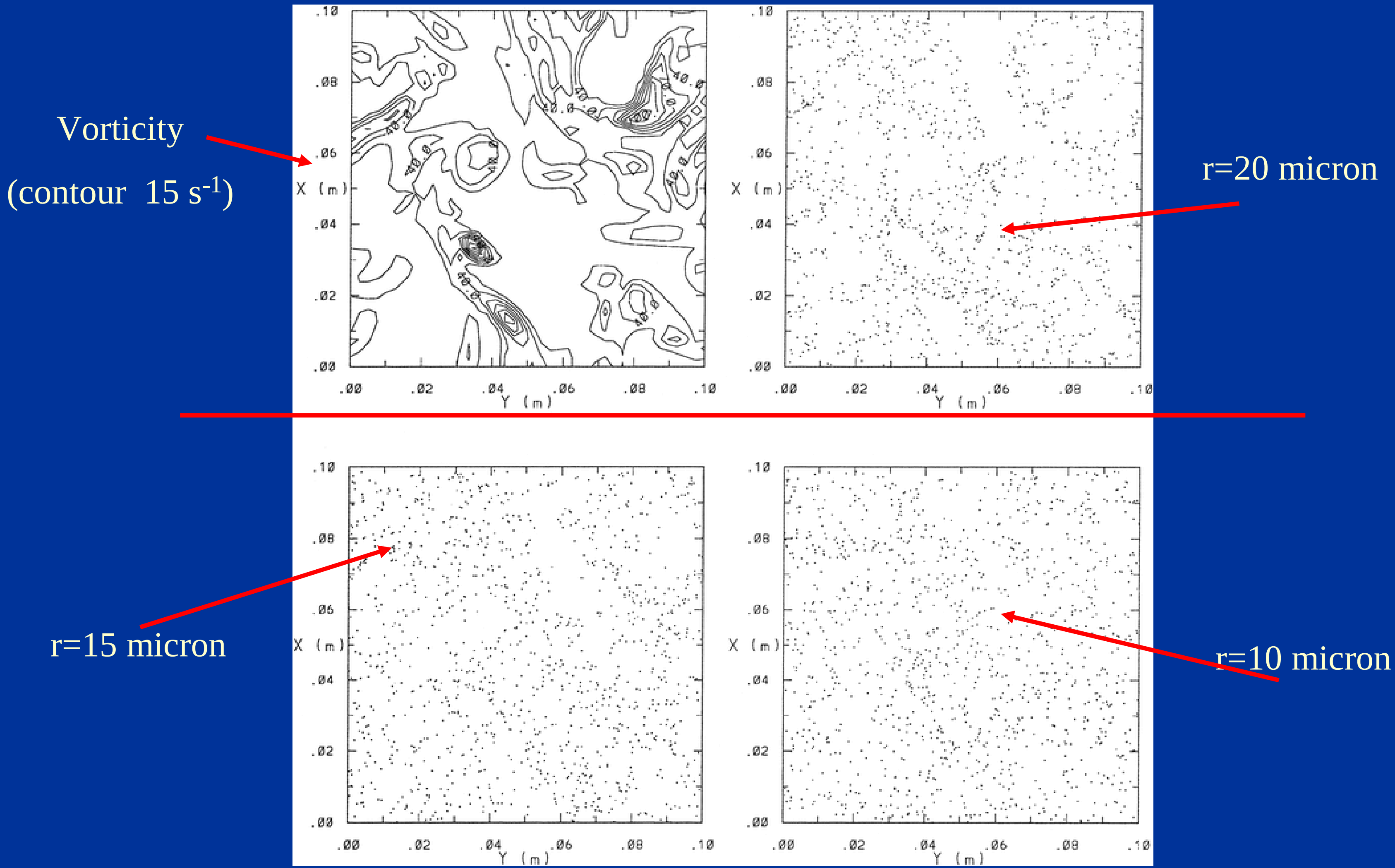
Nondimensional sedimentation velocity: $Sv = v_p / v_\eta$

(typical values: 0.1 – 10)

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

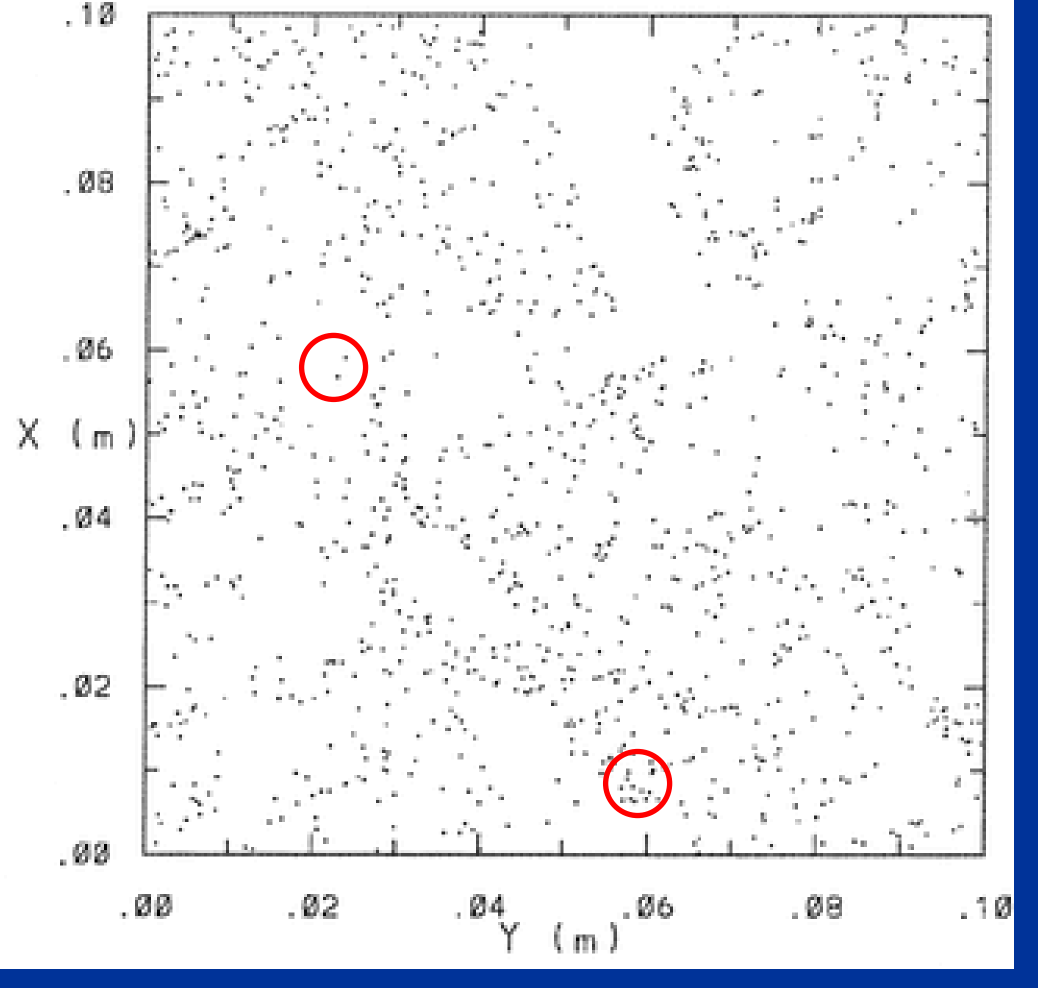
v_η **– Kolmogorov velocity scale**

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



Vaillancourt et al. JAS 2002

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

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geometric collisions

(no hydrodynamic interactions)

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

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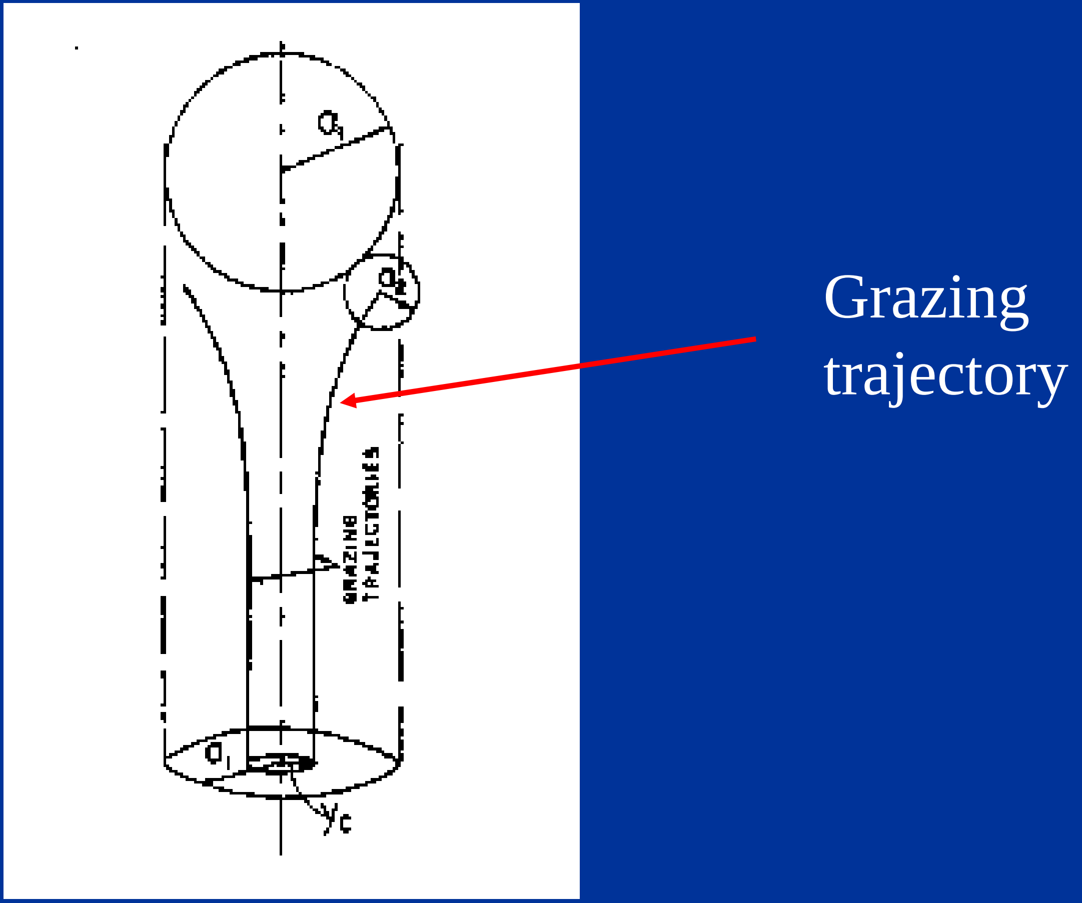
collision efficiency

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

Collision efficiency E_c for the gravitational case:



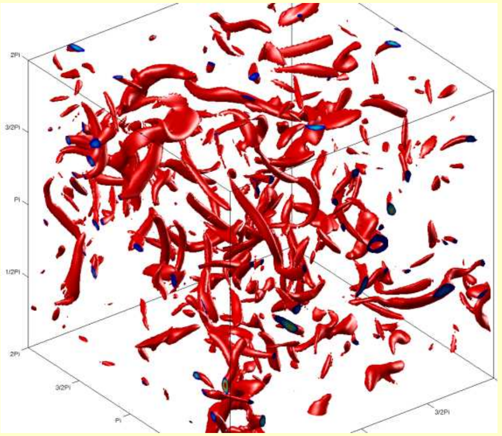
$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$

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



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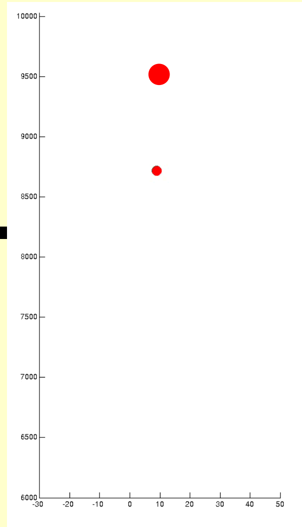
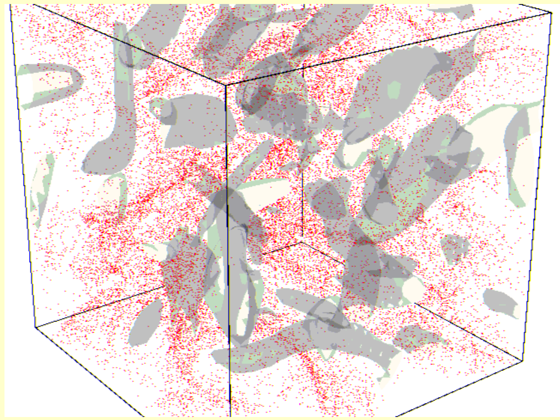




Features: Background turbulent flow can affect the disturbance flows;
No-slip condition on the surface of each droplet is satisfied on average;
Both near-field and far-field interactions are considered.

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

gravitational and turbulent collision kernels, Γ^g_{12} and Γ_{12}, with amd without hydrodynamic intercations (HI, no HI):

$$\Gamma_{12}(\mathrm{HI}) \;=\; E_{12} \;\; \Gamma_{12}(\mathrm{No\ HI})$$

$$\Gamma_{12}(\mathrm{HI}) \;=\; \frac{E_{12}}{E^g_{12}} \; \frac{\Gamma_{12}(\mathrm{No\ HI})}{\Gamma^g_{12}(\mathrm{No\ HI})} \; E^g_{12} \;\; \Gamma^g_{12}(\mathrm{No\ HI})$$

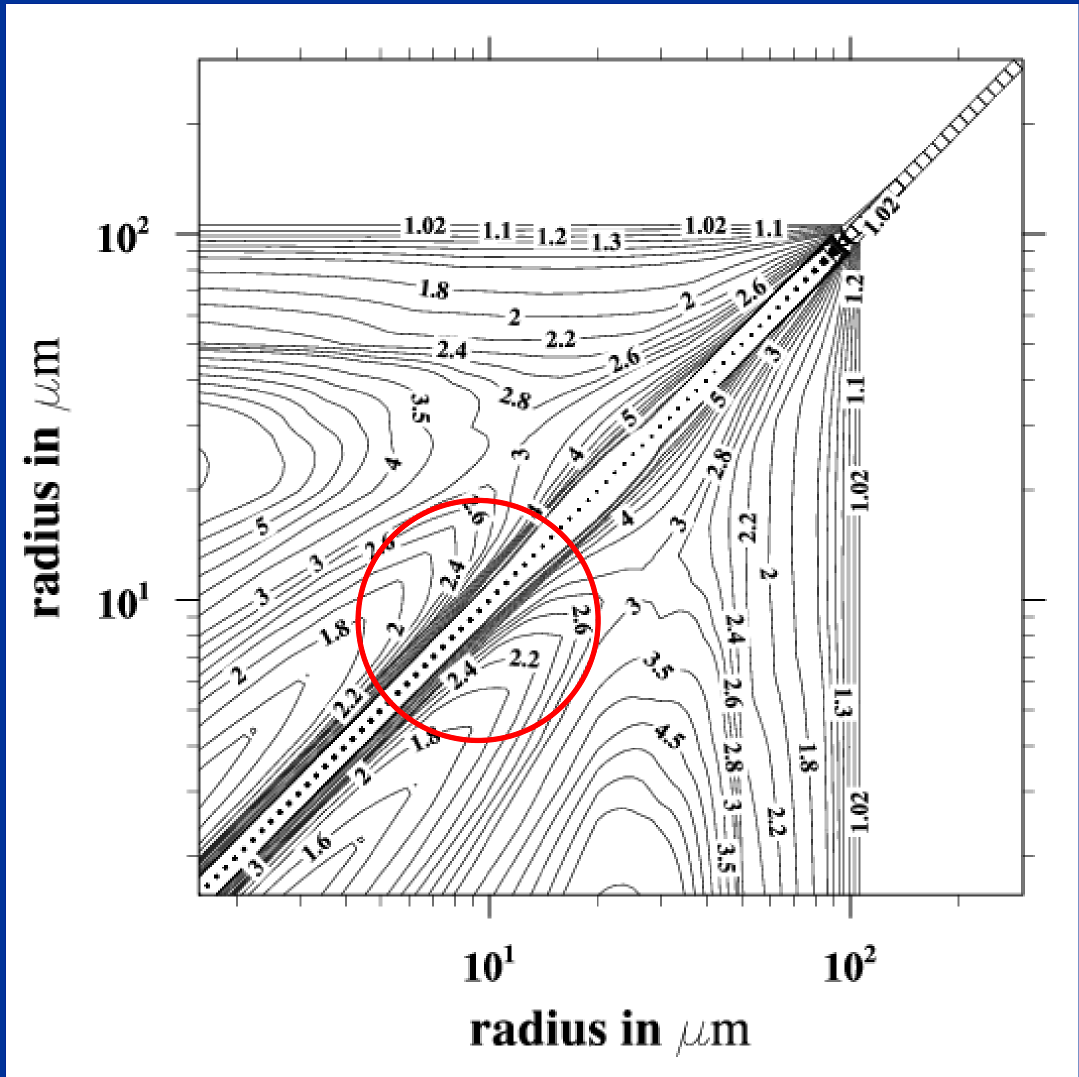
(strictly valid for droplets of unequal sizes only)

$$\Gamma_{12}(\mathrm{HI}) \;=\; \eta_E \;\; \eta_G \;\; \Gamma^g_{12}(\mathrm{HI})$$

$$\eta_E = \frac{E_{12}}{E^g_{12}} \qquad \eta_G = \frac{\Gamma_{12}(\mathrm{No\ HI})}{\Gamma^g_{12}(\mathrm{No\ HI})} \qquad \Gamma^g_{12}(\mathrm{HI}) = E^g_{12} \;\; \Gamma^g_{12}(\mathrm{No\ HI})$$

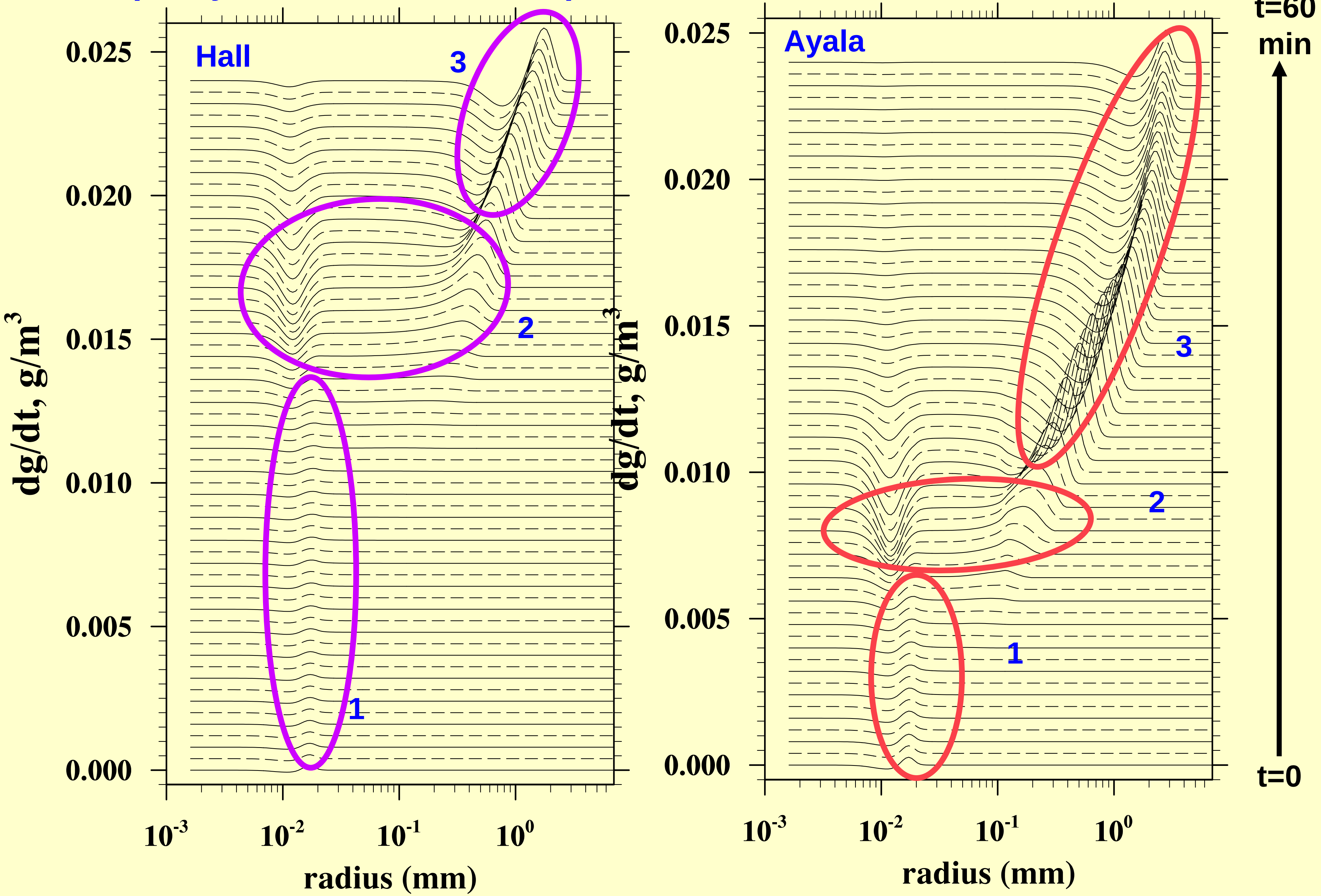
Table 1: $a_1 = 20\ \mu\mathrm{m}$, $a_2 = 25\ \mu\mathrm{m}$

ϵ ($\mathrm{cm^2 s^{-3}}$)	η_E	η_G	$\eta = \eta_E \eta_G$
100	1.10	1.12	1.23
400	1.60	1.42	2.27



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

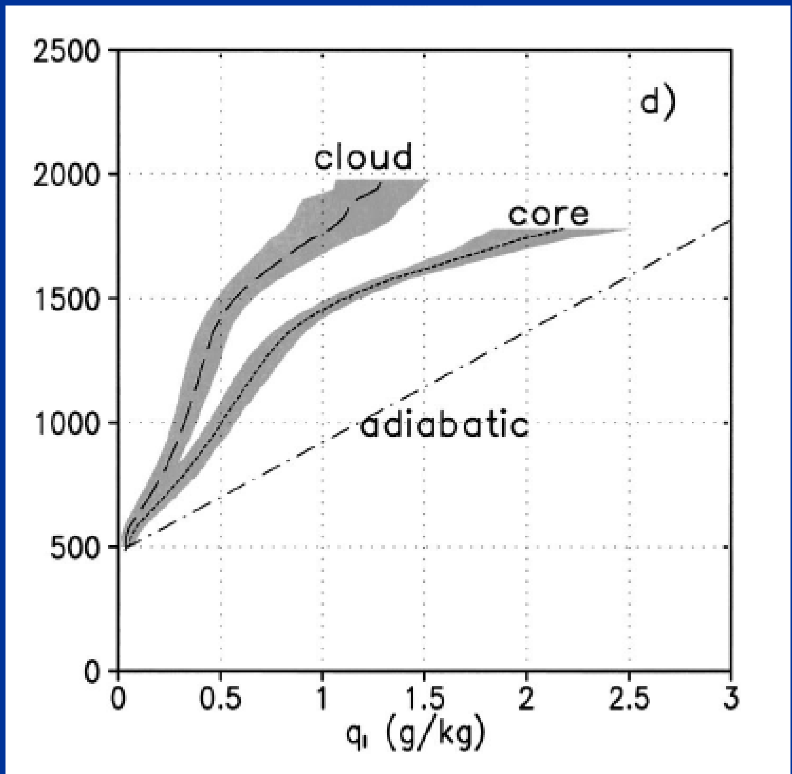
1. Autoconversion; 2. Accretion; 3. Hydrometeor self-collection
(Berry and Reinhardt, 1974)



Cloud turbulence seems to have appreciable effect on droplet growth by collision/coalescence. This is a combination of the impact on the number of geometric collisions and on the collision efficiency.

Siebesma et al. JAS 2003

Gerber et al, AMS Cloud Physics Conference, 2006



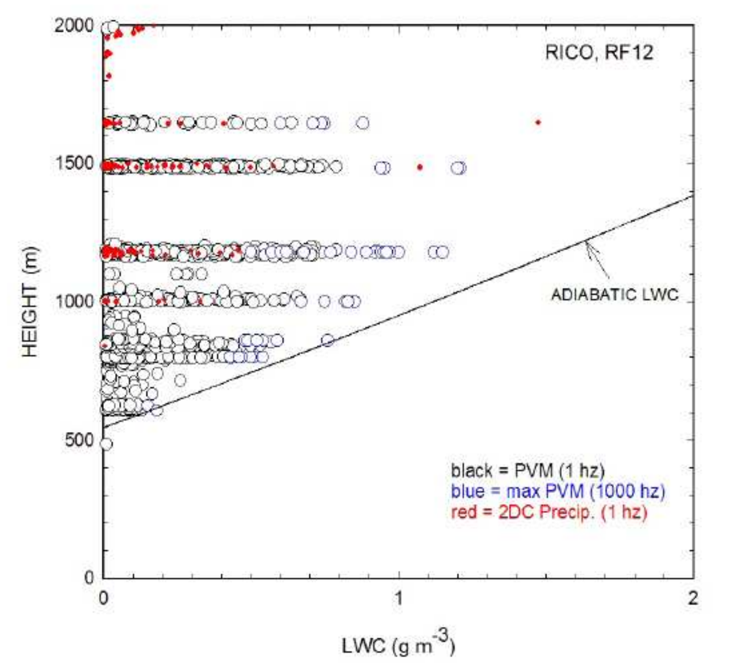
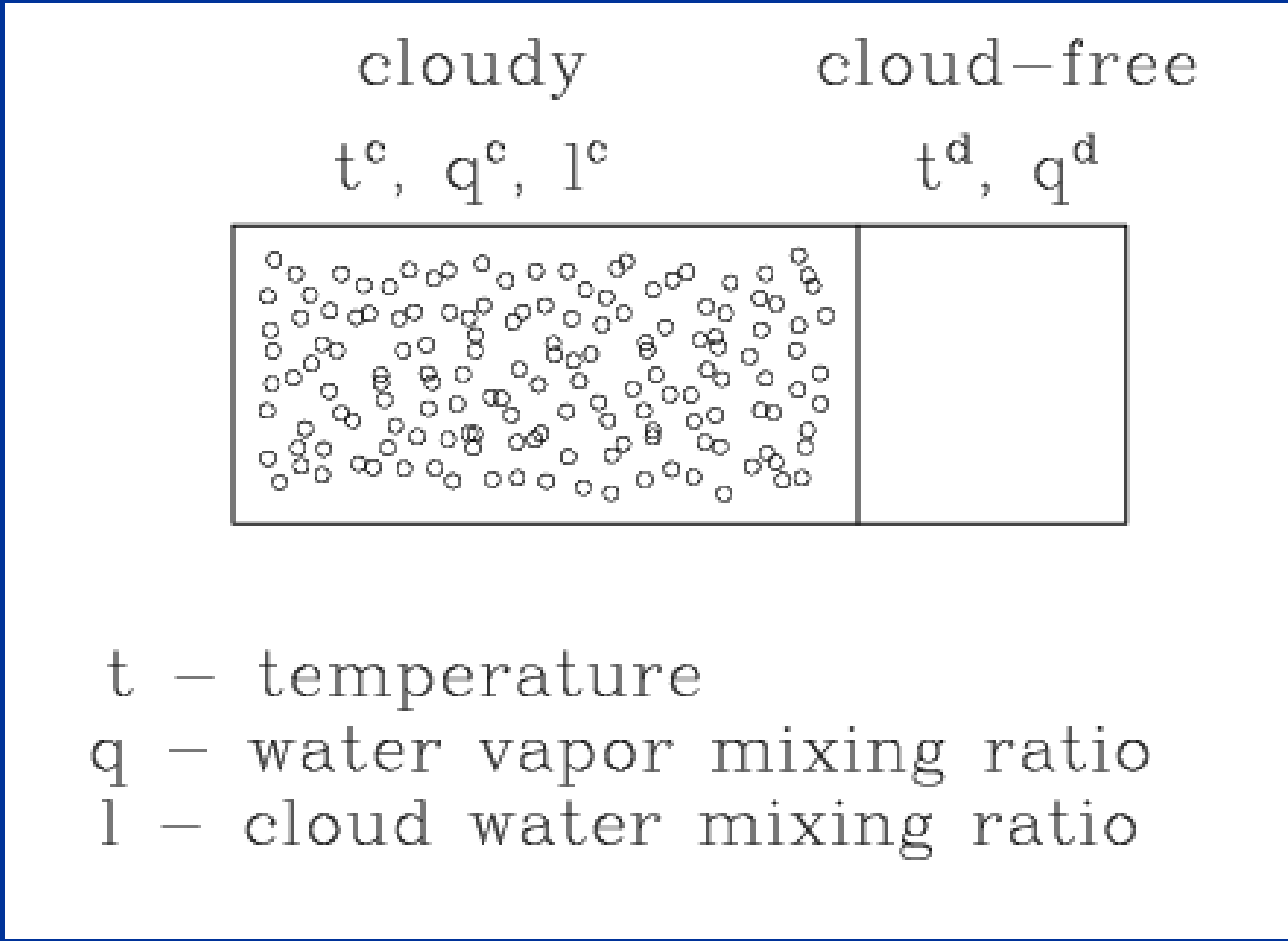


Figure 1 - 100-m resolution (1Hz), maximum 10-cm resolution (1000 Hz),and 2DC LWC for all ~ 200 Cu aircraft passes for flight RF12.

Shallow convective clouds are strongly diluted by entrainment

Bulk mixing between cloudy and cloud-free air (adiabatic, isobaric)



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

For atmospheric large-eddy simulation (LES) models (spatial gridlength between 10 and 100 meters), subgrid-scale mixing should cover wide range of situations, from extremely inhomogeneous at scales close to model gridlength, to homogeneous at scales close to the Kolmogorov scale (typically around 1 mm).

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(NB: This problem is similar to modeling turbulent combustion.)

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However, this is not how subgrid-scale mixing and homogenization are represented in current LES models.

For bulk models, a pdf-based subgrid scheme of Sommeria and Deardorff , JAS 1977, is sometimes used...

Possible approaches:

-Simple approach: a subgrid scheme based on Broadwell and Breidenthal (JFM 1982) scale collapse model (Grabowski 2007);

- Sophisticated approach: embedding Kerstein's Linear Eddy Model (LEM) in each LES gridbox ("One-Dimensional Turbulence", ODT; Steve Krueger, U. of Utah).

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Bulk model for nonprecipitating clouds:

Turbulent transport

$$\frac{\partial \theta}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u}\theta) = \frac{L_v \theta_e}{c_p T_e} C + D_\theta$$

$$\frac{\partial q_v}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u} q_v) = -C + D_v$$

$$\frac{\partial q_c}{\partial t} + \frac{1}{\rho_o}\nabla \cdot (\rho_o \mathbf{u} q_c) = C + D_c$$

C **– condensation rate, defined by a constraint that cloudy air is always at water saturation (instantaneous adjustment).**

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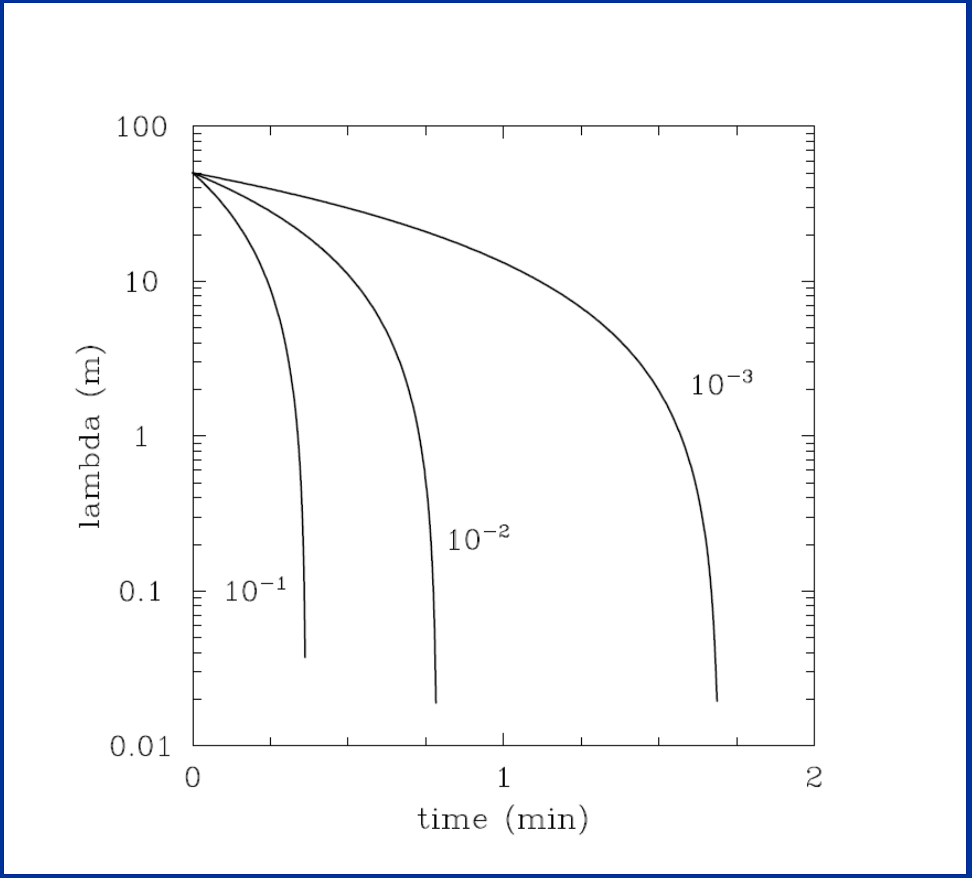
Instantaneous adjustment is questionable for the cloud-environment mixing…

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

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

α ~ 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:

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

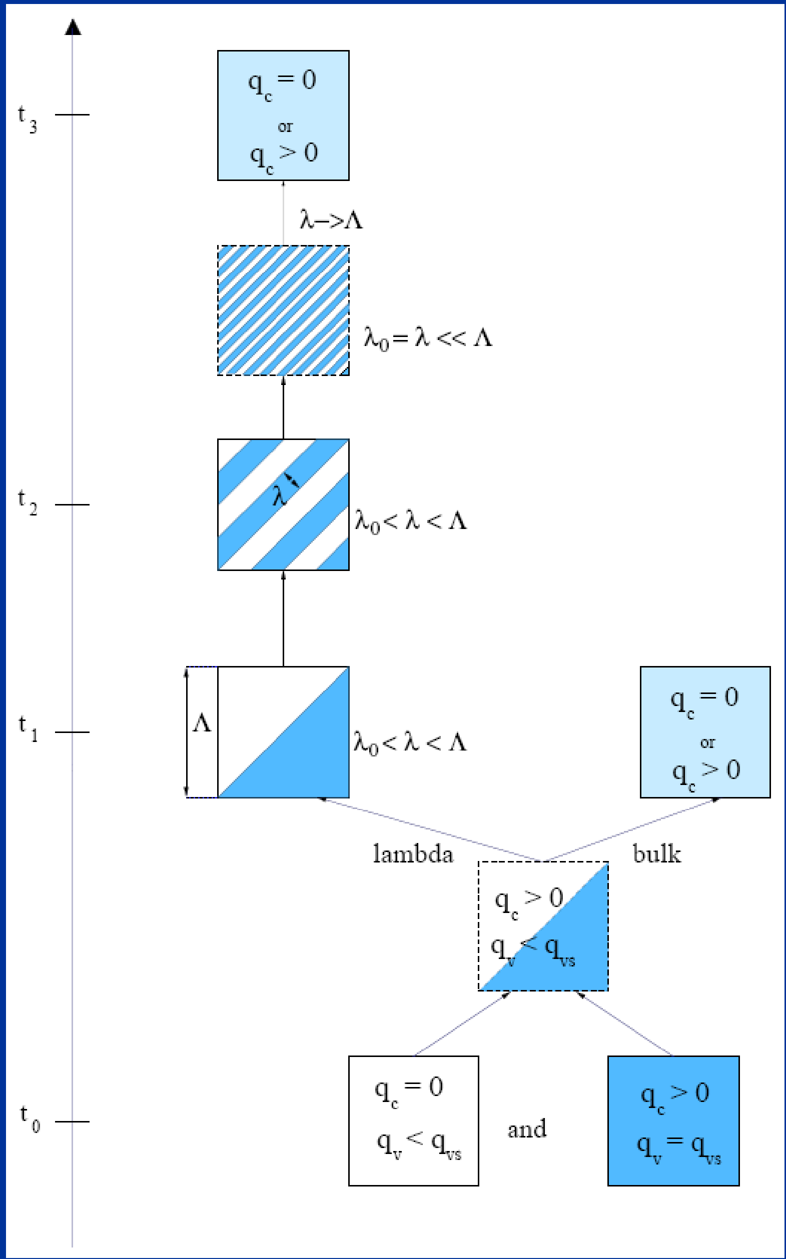
$$\epsilon = c_\epsilon \frac{E^{3/2}}{\Lambda}$$

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).



(Jarecka et al., *J. Atmos. Sci.*, submitted)

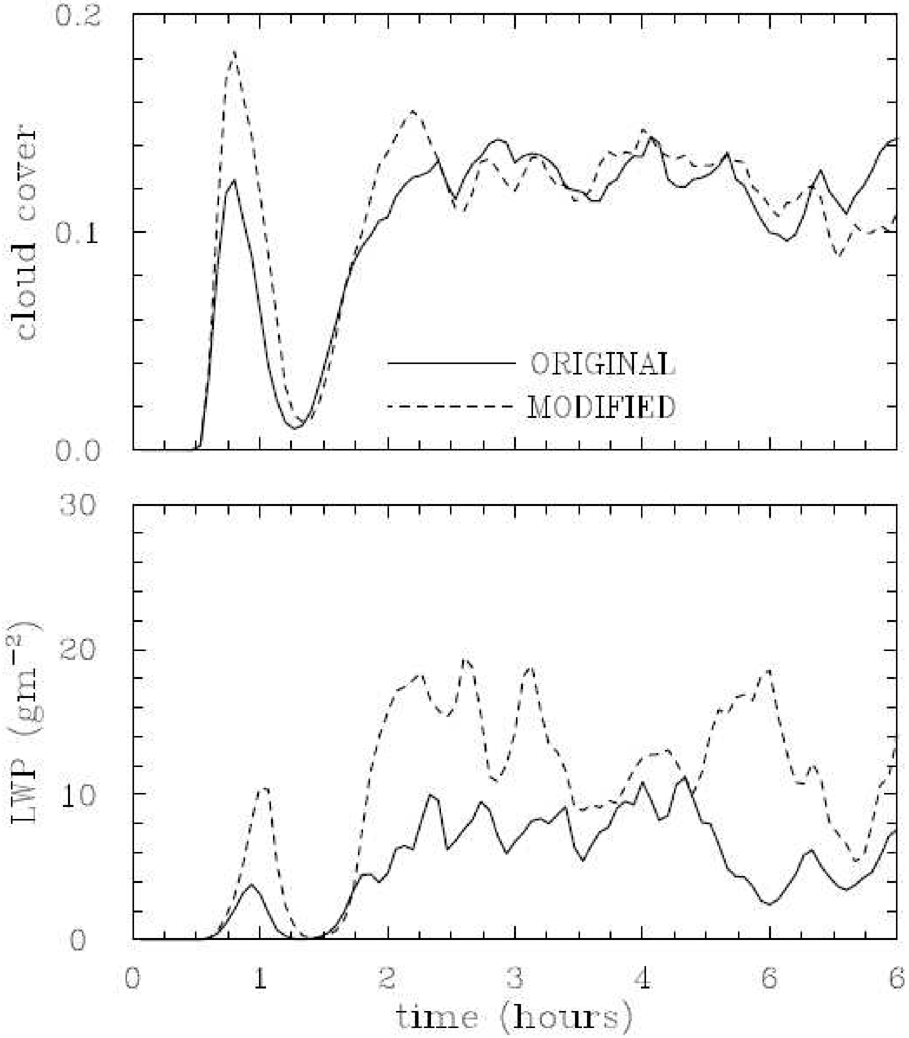


Figure 8: Evolutions of the cloud cover and liquid water path in BOMEX simulations using either the original (solid lines) or the modified (dashed lines) approaches.

Simulation of a field of shallow convective clouds; Grabowski JAS 2007

This is work in progress…

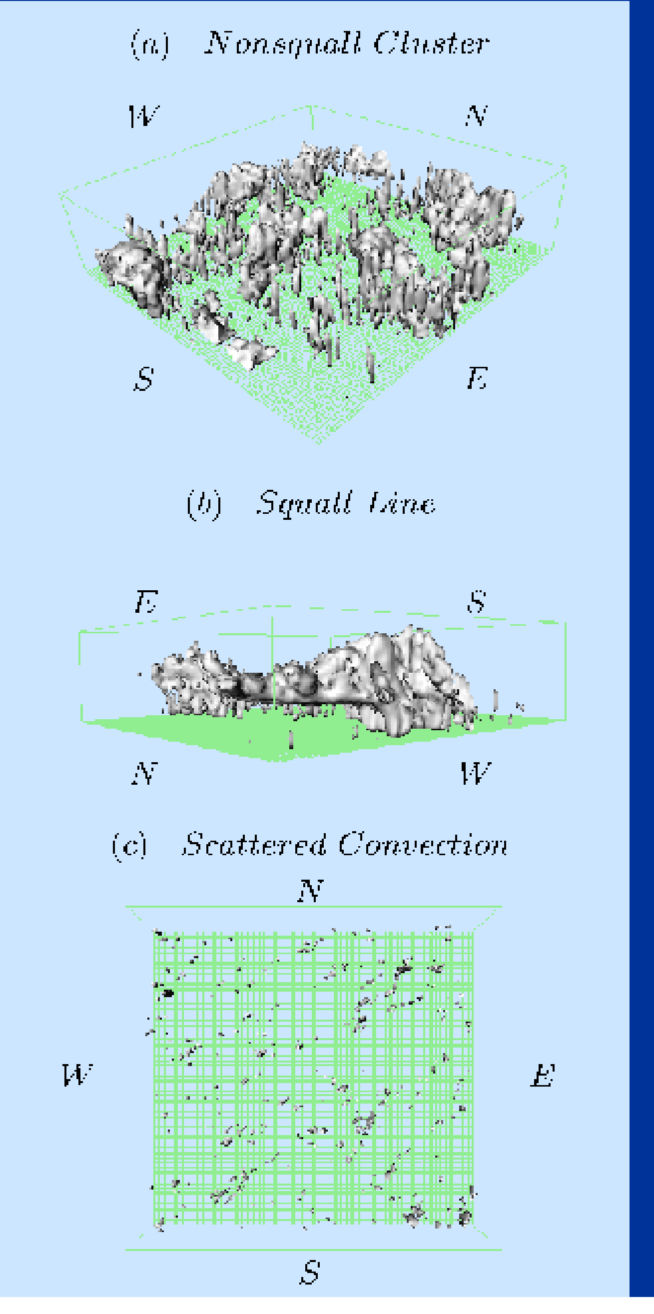
The idea is to apply such a subgrid-scale model with more sophisticated representation of cloud microphysics to locally predict cloud droplet sizes (the homogeneous versus inhomogeneous mixing).

Cloud-resolving modeling of GATE cloud systems (Grabowski et al. JAS 1996)

2 Sept, 1800 Z

4 Sept, 1800 Z

7 Sept, 1800 Z



400 x 400 km horizontal domain, doubly-periodic, 2 km horizontal grid length

Driven by observed large-scale conditions

Grabowski et al. JAS 1998:

"…low resolution two-dimensional simulations can be used as realizations of tropical cloud systems in the climate problem and for improving and/or testing cloud parameterizations for large-scale models…"

- *Can we use 2D cloud-resolving model (CRM) in all columns of a climate model to represent deep convection?*

- *Can we move other parameterizations (radiative transfer, land surface model, etc) into 2D CRM?*

Cloud-Resolving Convection Parameterization (CRCP)
(super-parameterization, SP)

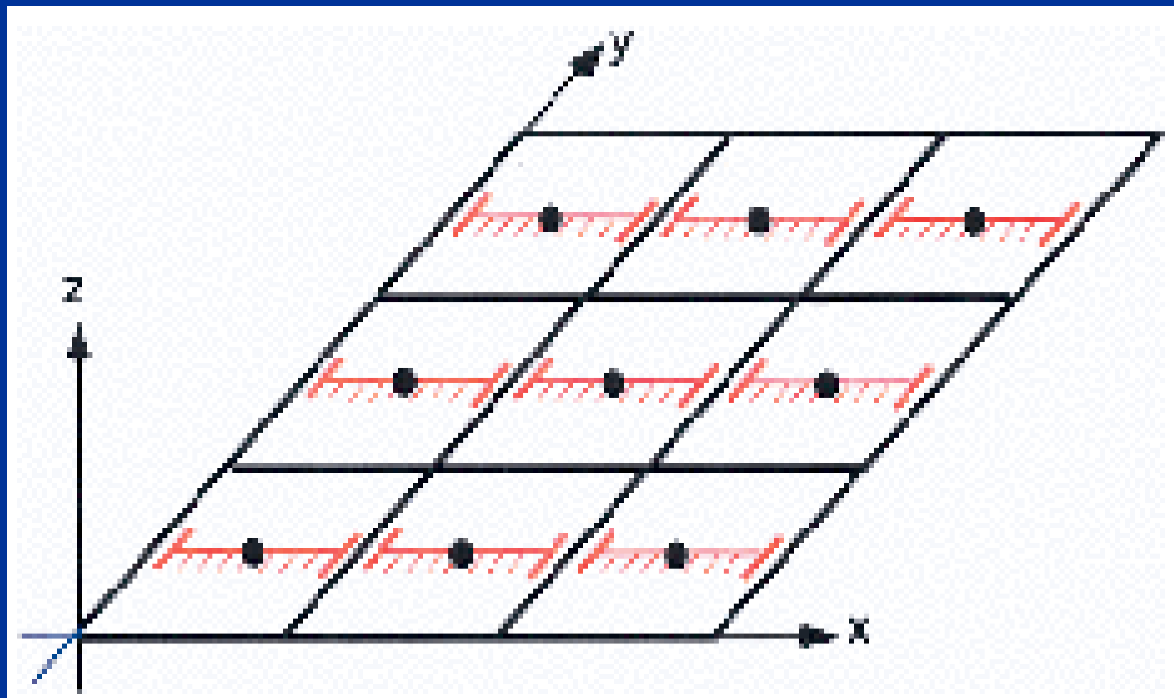
Grabowski and Smolarkiewicz, Physica D 1999

Grabowski, JAS 2001

The idea is to represent subgrid scales of the 3D large-scale model (horizontal resolution of 100s km) by embedding periodic-domain 2D CRM (horizontal resolution around 1 km) in each column of the large-scale model

Another (better?) way to think about CRCP: CRCP involves hundreds or thousands of 2D CRMs interacting in a manner consistent with the large-scale dynamics

Original CRCP proposal

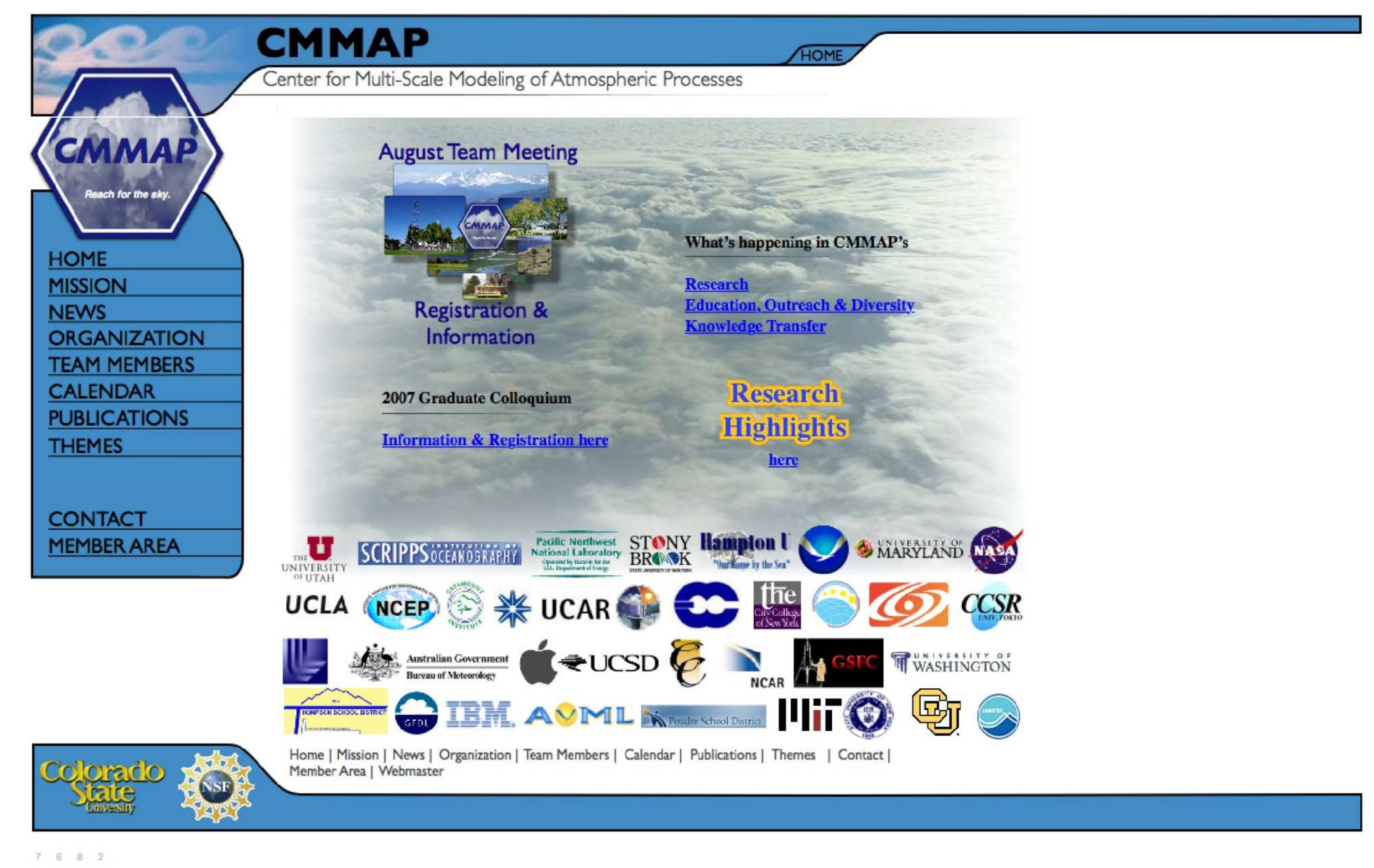


- CRCP is a “parameterization” because scale separation between large-scale dynamics and cloud-scale processes is assumed; cloud models have periodic horizontal domains and they communicate only through large scales.

- CRCP is “embarrassingly parallel”: a climate model with CRCP can run efficiently on 1000s of processors.

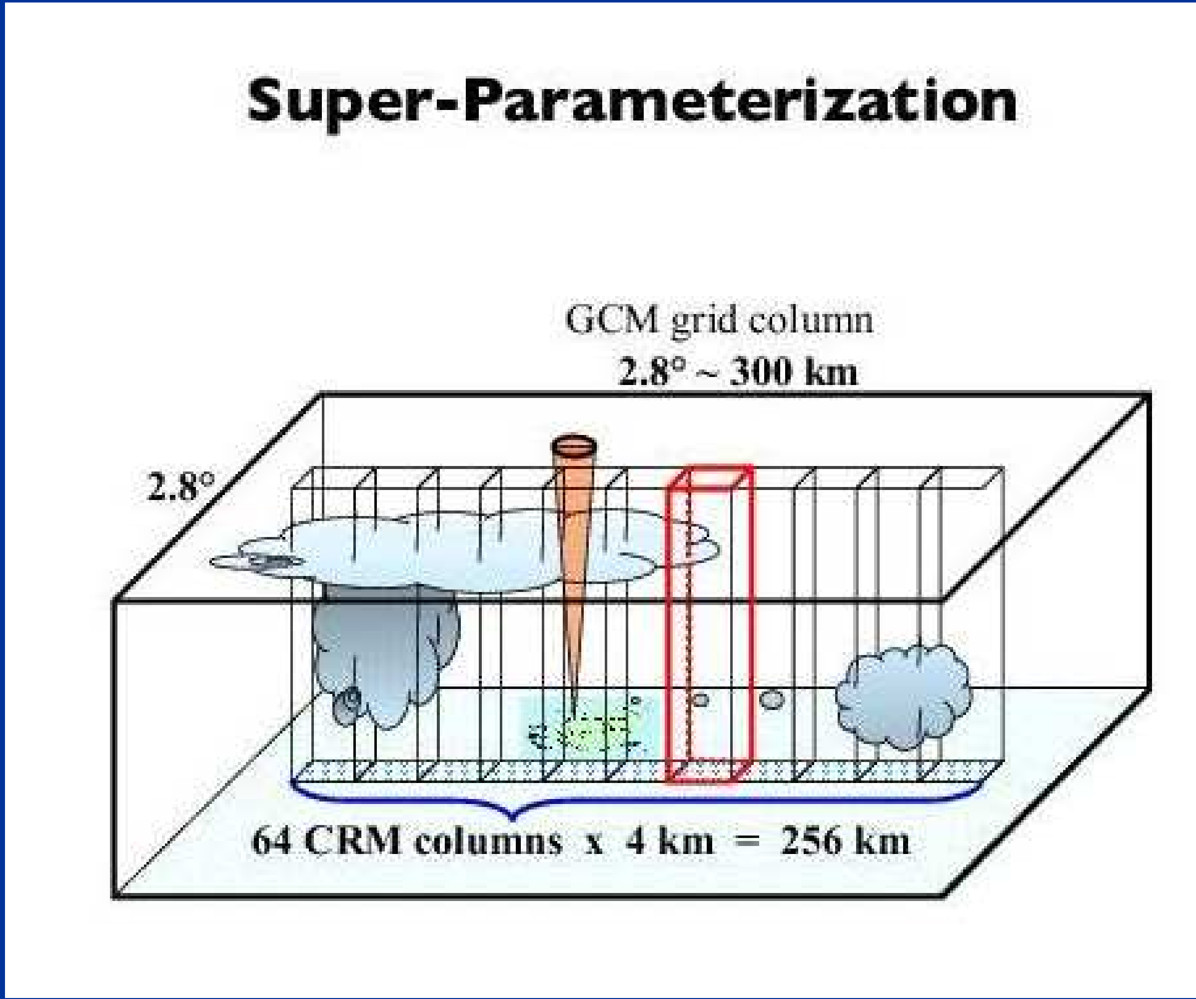
- CRCP is a physics coupler: most (if not all) of physical (and chemical, biological, etc.) processes that are parameterized in the climate model can be included into CRCP framework.

NSF Science and Technology Center was created in 2006…



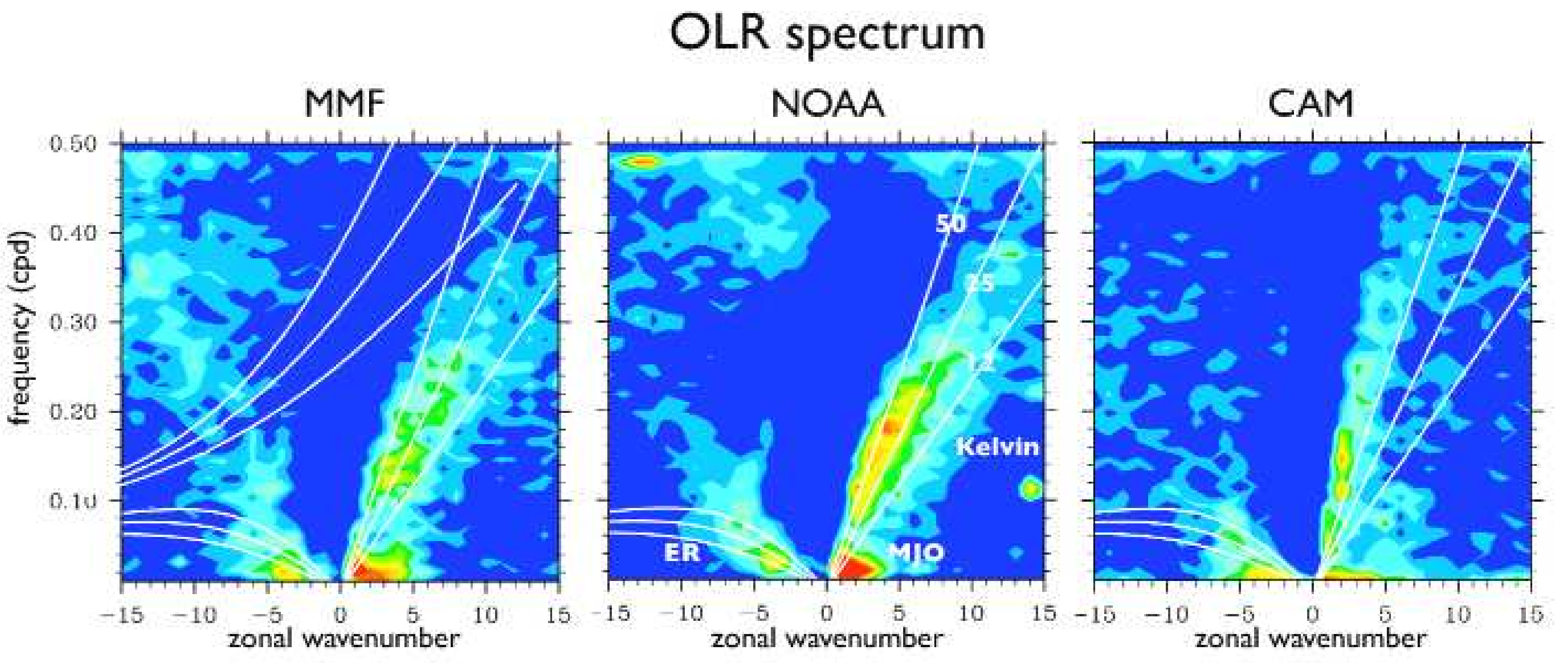
http://cmmap.colostate.edu

Multiscale Modeling Framework (MMF): SP (Super-Parameterized) CAM (Community Atmospheric Model, part of NCAR's Community Climate System Model (CCSM)



(Khairoutdinov and Randall, 2001; Khairoutdinov et al. 2005, 2007; Wyant et al. 2006)

Tropical disturbances in MMF and standard CAM compared to observations on the Wheeler-Kiladis diagram



(Khairoutdinov et al. JAS 2007)

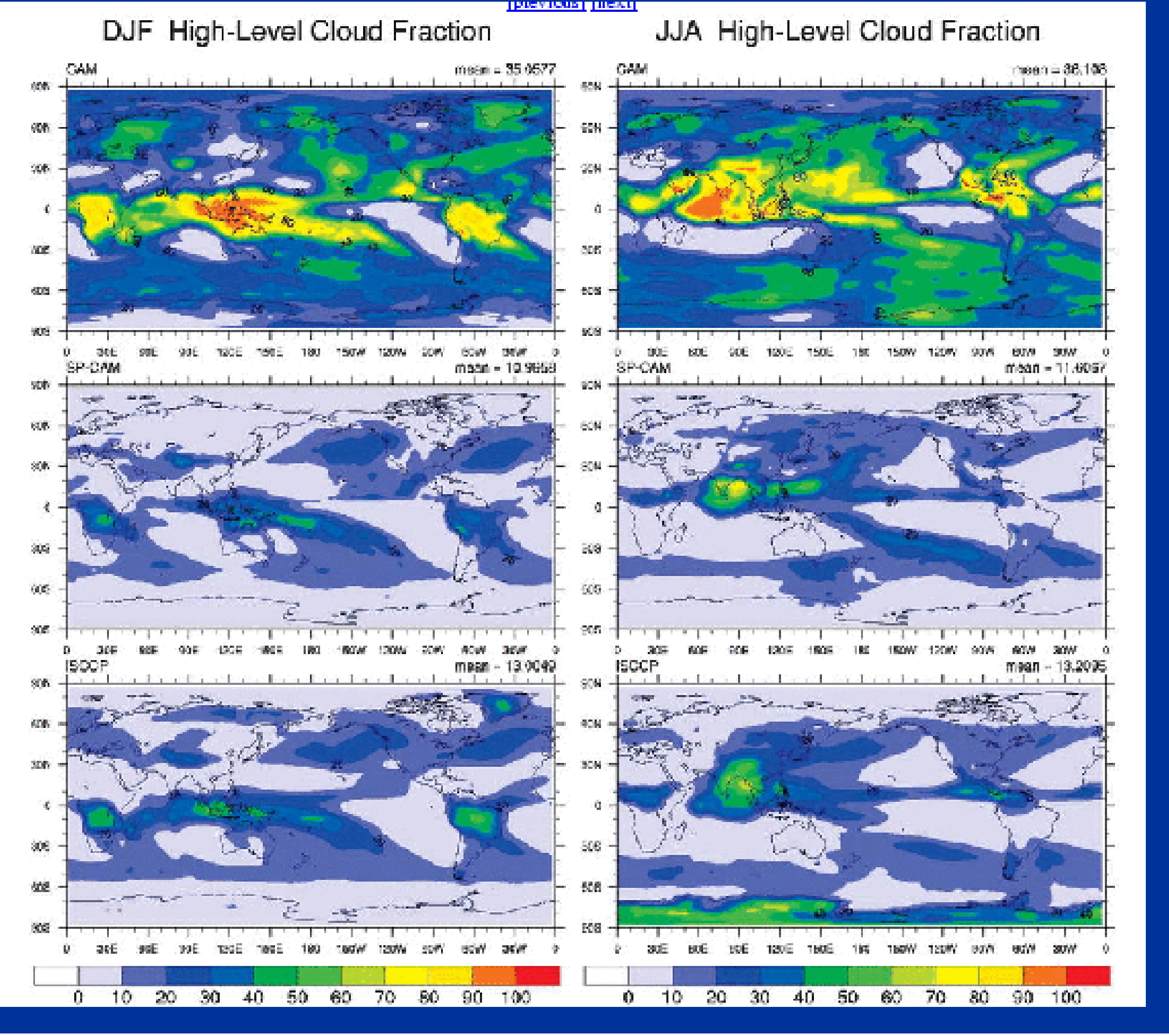
Results from a traditional climate model versus MMF

Khairoutdinov et al. JAS 2005

Traditional

MMF

Observations



SUMMARY:

Resolving entire range of scales from cloud microscale to climate in numerical models will never be possible.

For processes near each of the scale discussed here, there are multiscale interactions that cannot be resolved by the “direct numerical simulation” approach.

Knowledge developed at one scale can subsequently be used in modeling larger scales. For instance, the impact of small-scale turbulence on droplet growth can be parameterized in LES models, where small-scale turbulent motions are nor resolved. This is the concept of “hierarchical” approach, the only hope to cover the entire range of scales relevant to climate.