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

Wojciech W. Grabowski

(reporting on collaborative research)

National Center for Atmospheric Research

Boulder, Colorado, USA

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7th WMO Cloud Modeling Workshop

23-27 July 2012 (the week before ICCP in Leipzig)

Warsaw, Poland

Cases are being finalized,
info will send out once finished

Interested? If so, please email me (grabow@ucar.edu)

NCAR GTP Workshop

Multiphase turbulent flows in the atmosphere and ocean

13-17 August 2012

Boulder, Colorado

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

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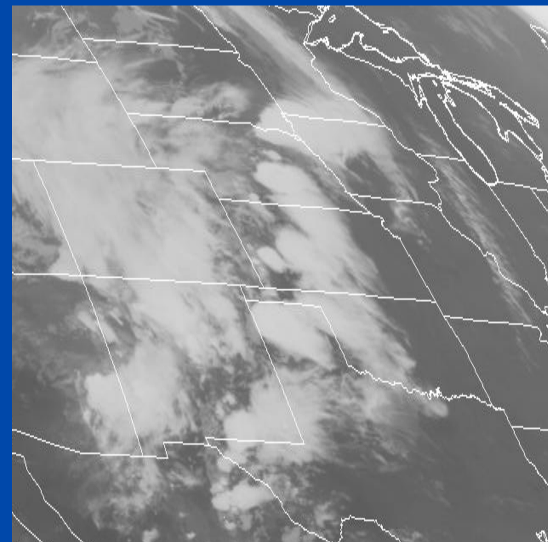
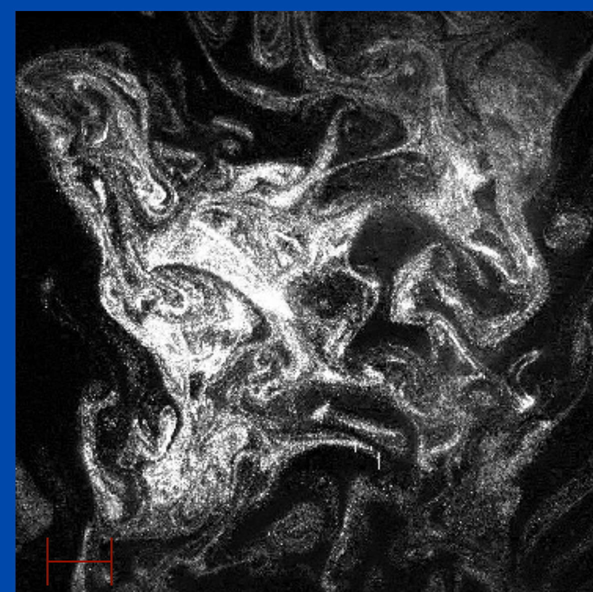
Mesoscale convective systems over US



1,000 km

Mixing in laboratory cloud chamber



10 cm

Clouds and climate: the range of scales...

Small cumulus clouds

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…

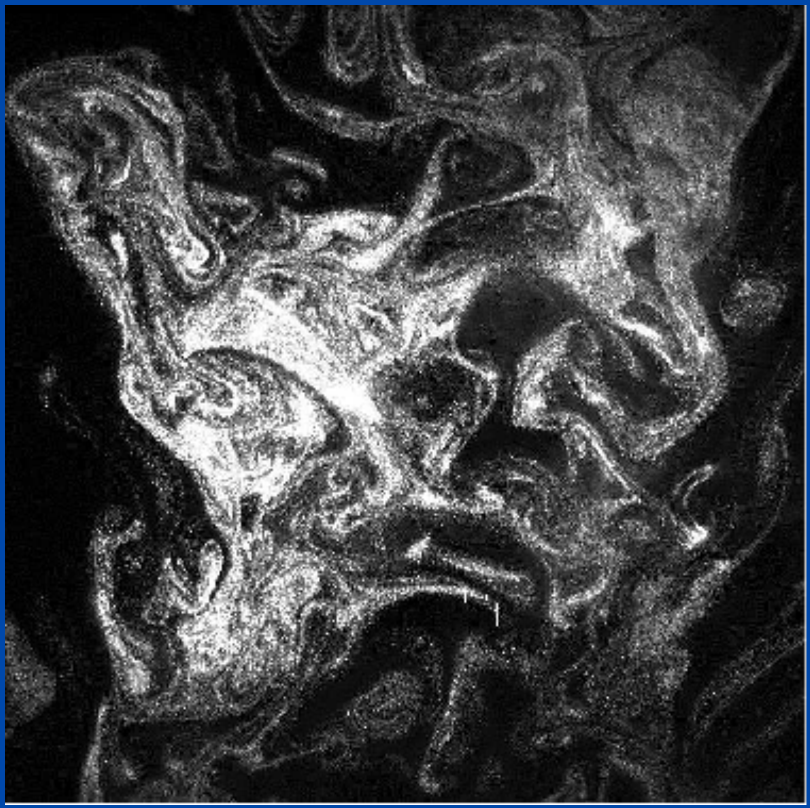
Resolving such a range of scales in numerical models will never be possible…

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 (e.g., sophisticated subgrid-scale parameterizations?)…

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



with Prof. Lian-Ping Wang

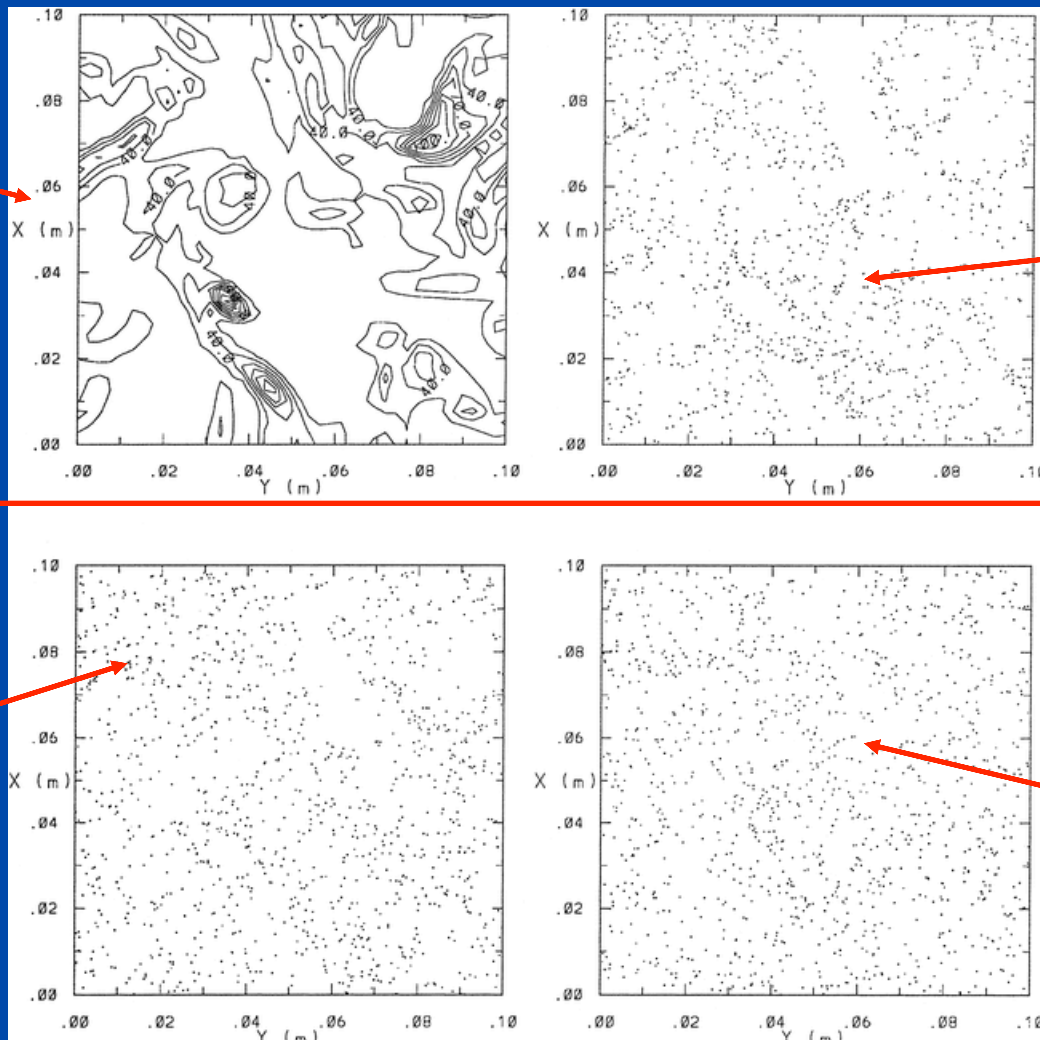
Department of Mechanical Engineering,
University of Delaware,
Newark, Delaware, USA

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

Vorticity

(contour 15 s^{-1})

r=20 micron

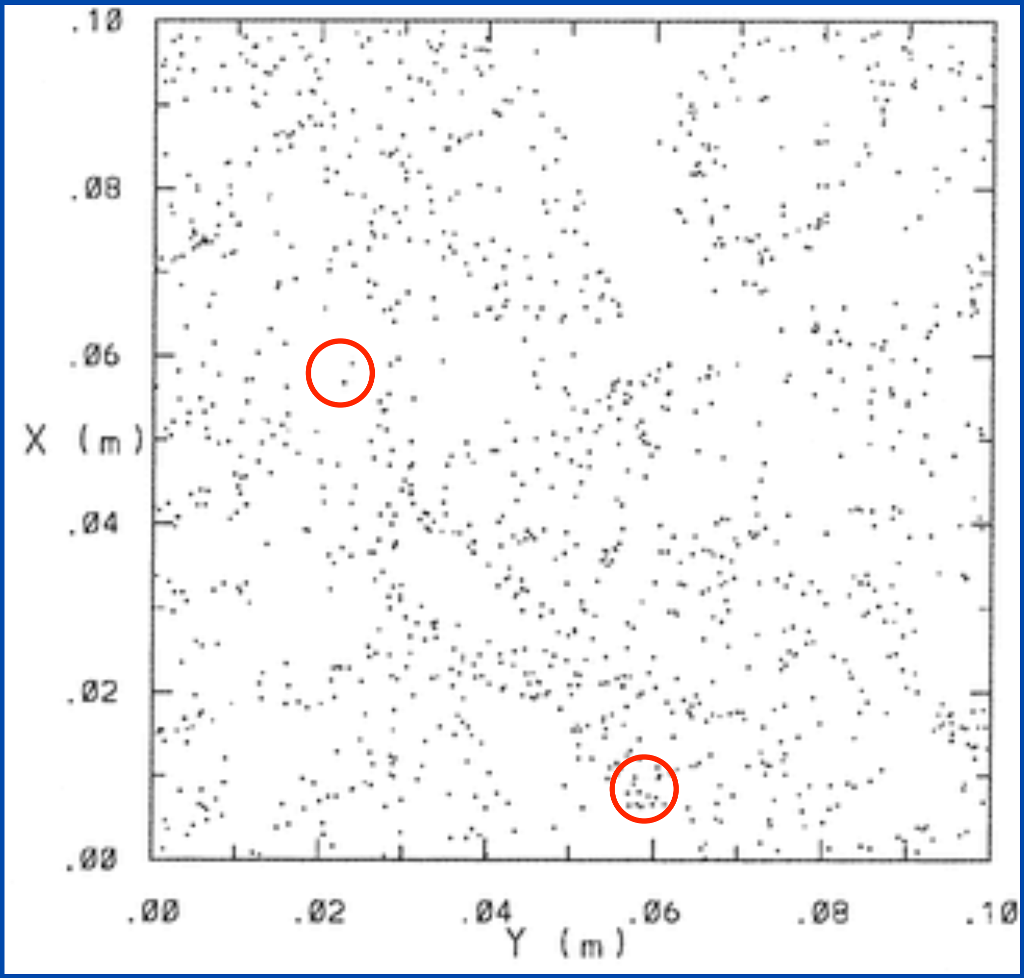


r=15 micron

r=10 micron

Vaillancourt et al. JAS 2002

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:

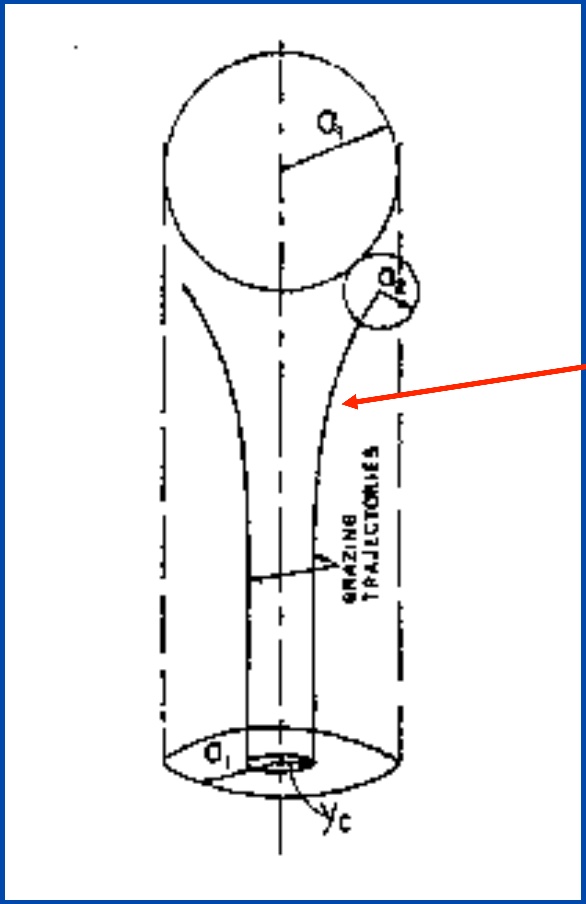
-Turbulence modifies local droplet concentration (preferential concentration effect)

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

collision efficiency

- Turbulence modifies hydrodynamic interactions when two droplets approach each other

Collision efficiency E_c for the gravitational case:



Grazing trajectory

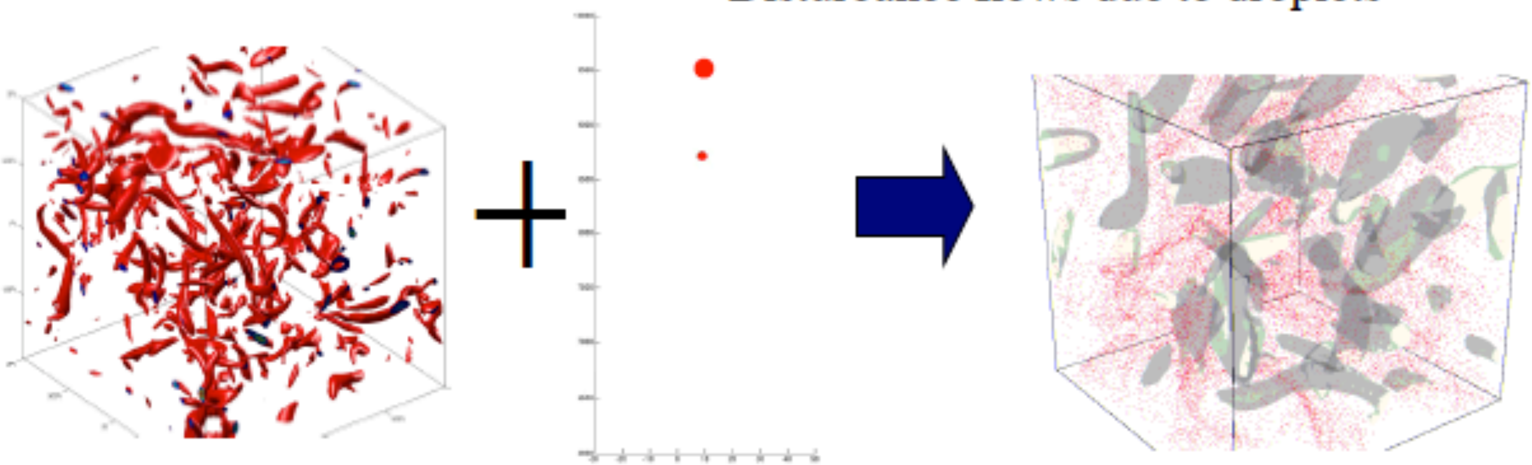
$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$

The hybrid DNS approach: including disturbance flows due to droplets

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

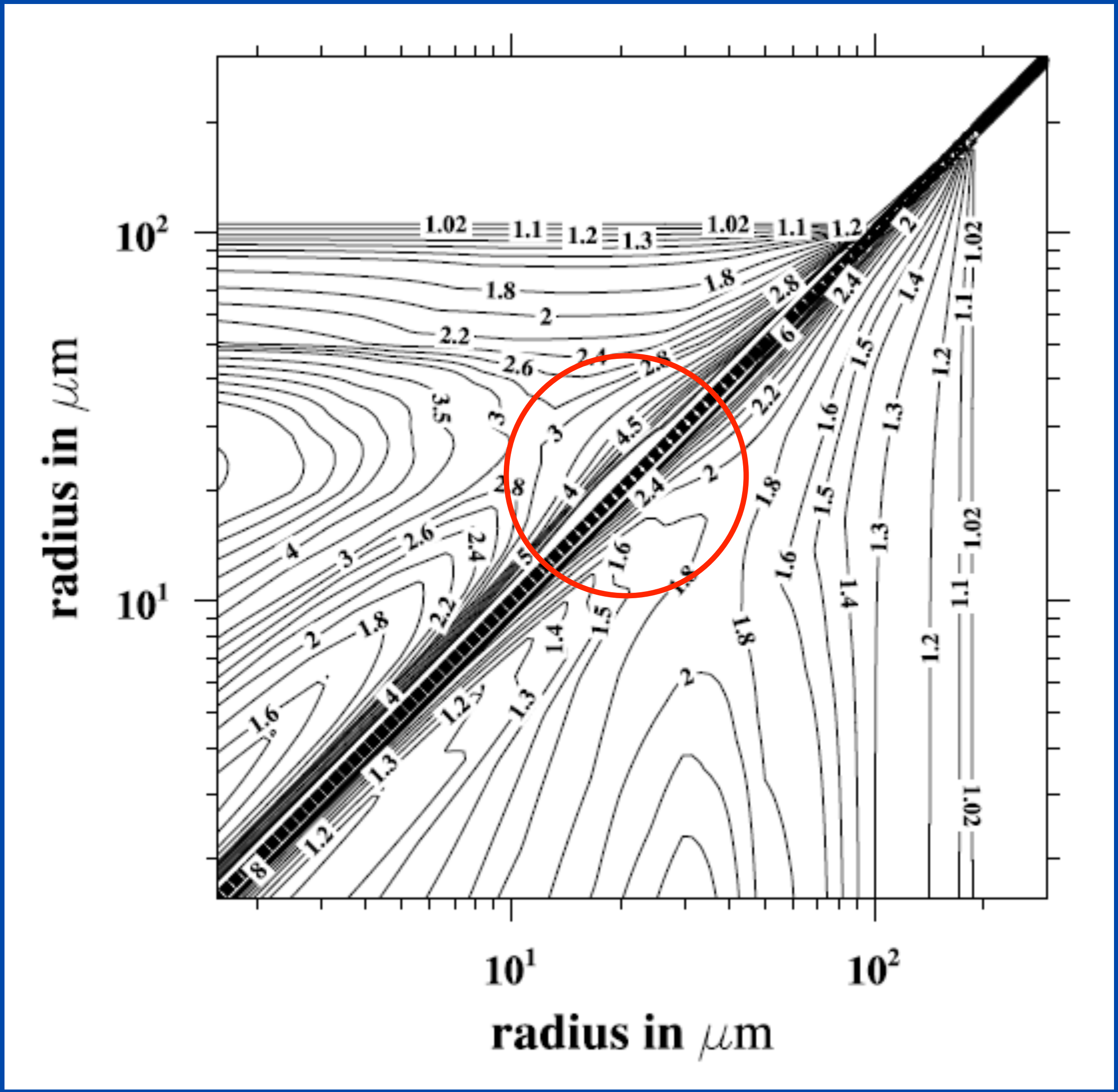
Background turbulent flow

Disturbance flows due to droplets



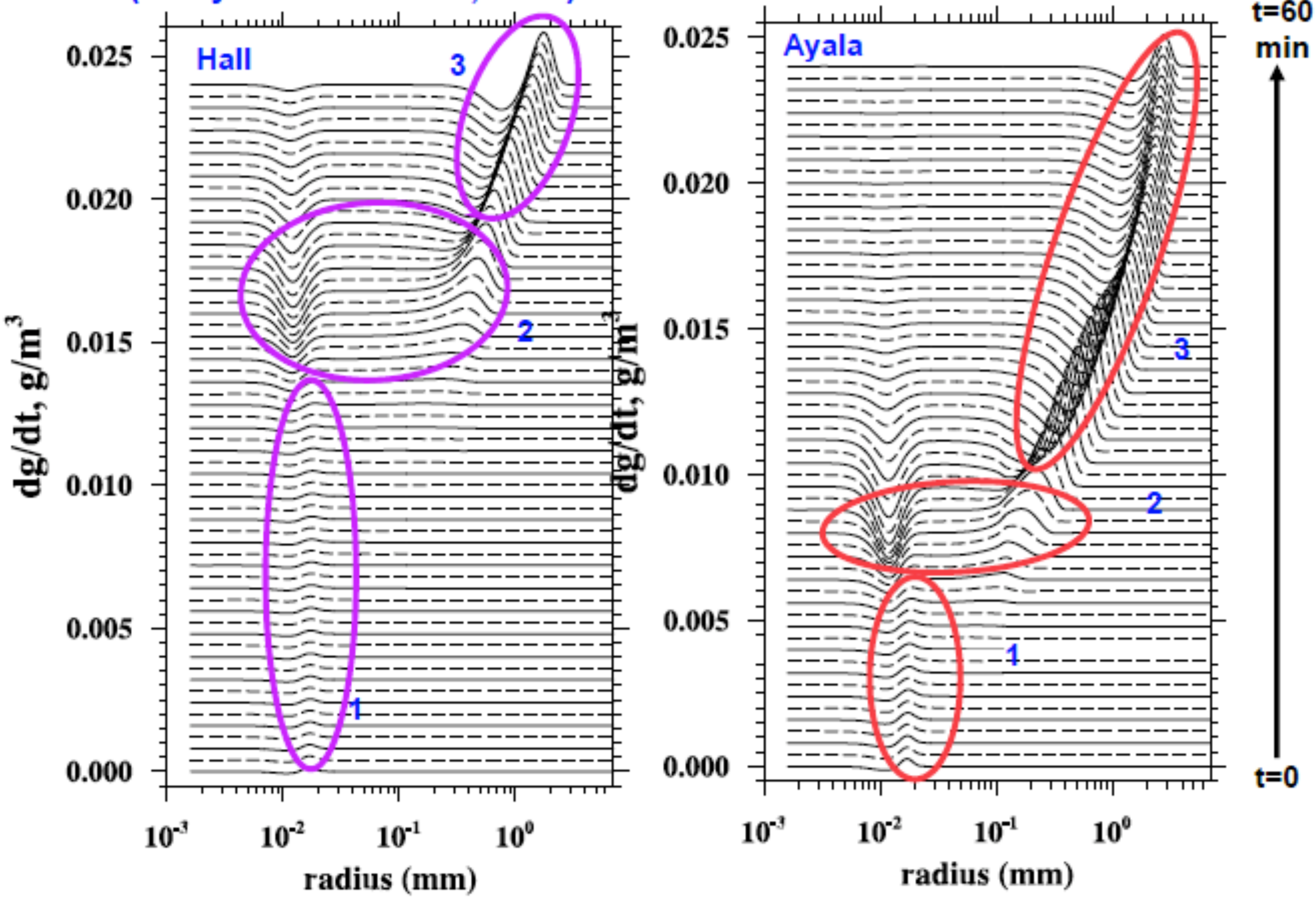
Features: Background turbulent flow can affect the disturbance flows;
No-slip condition on the surface of each droplet is satisfied on average;
Both near-field and far-field interactions are considered.

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



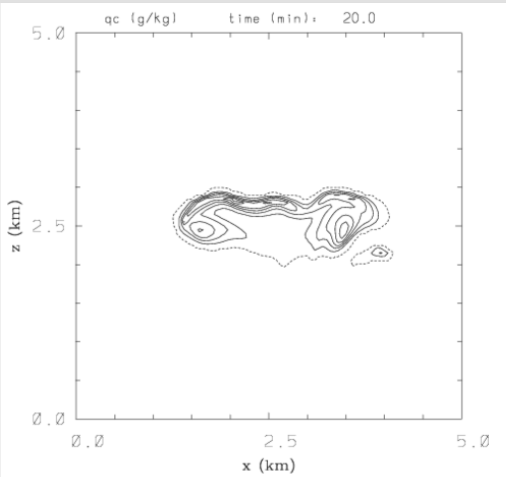
Enhancement factor for the collision kernel (the ratio between turbulent and gravitation collision kernel in still air) including turbulent collision efficiency; ε = 100 and 400 $cm^2\ s^{-3}$.

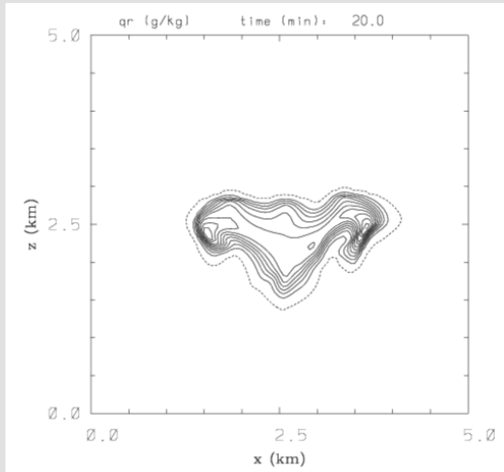
1. Autoconversion; 2. Accretion; 3. Hydrometeor self-collection
(Berry and Reinhardt, 1974)

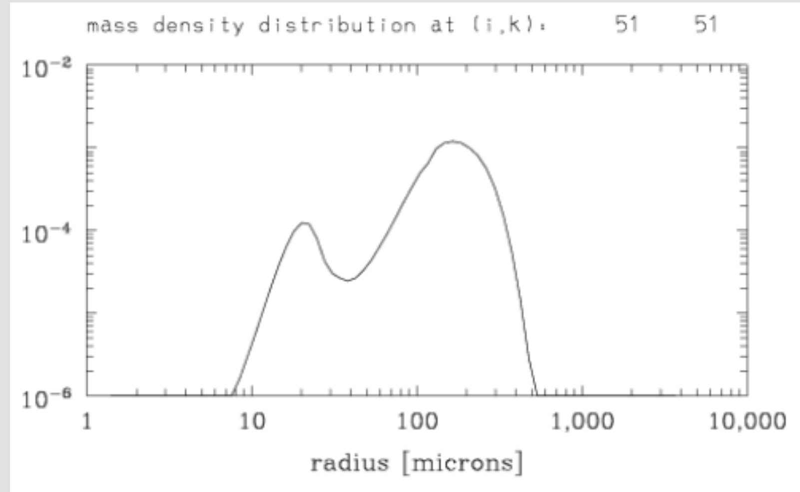


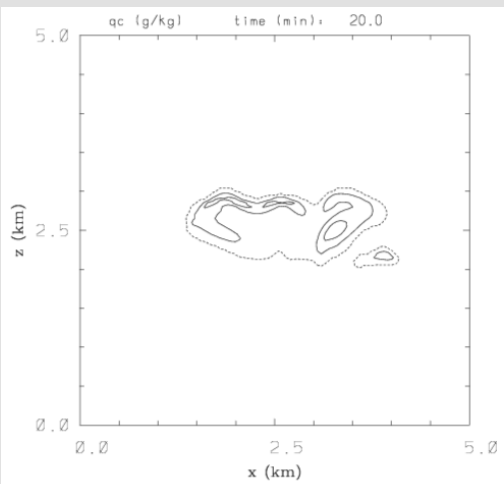
2D simulation of a small precipitating “cloud”: t=20 min

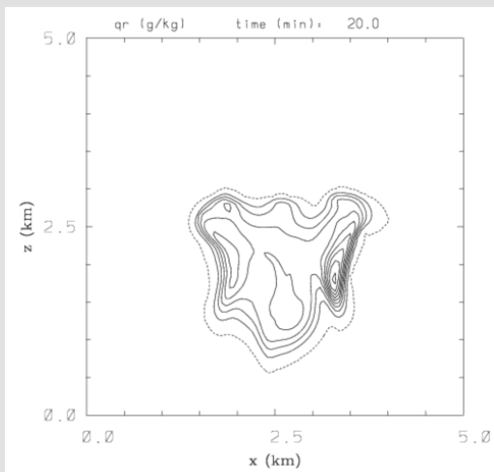
no turbulence

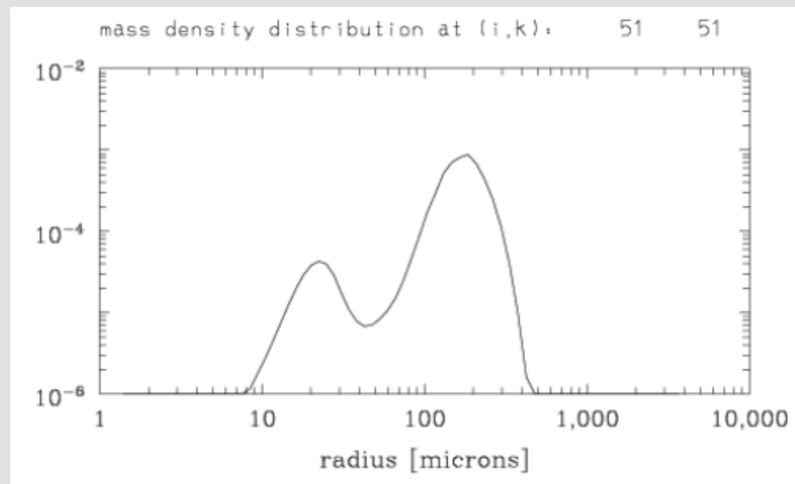






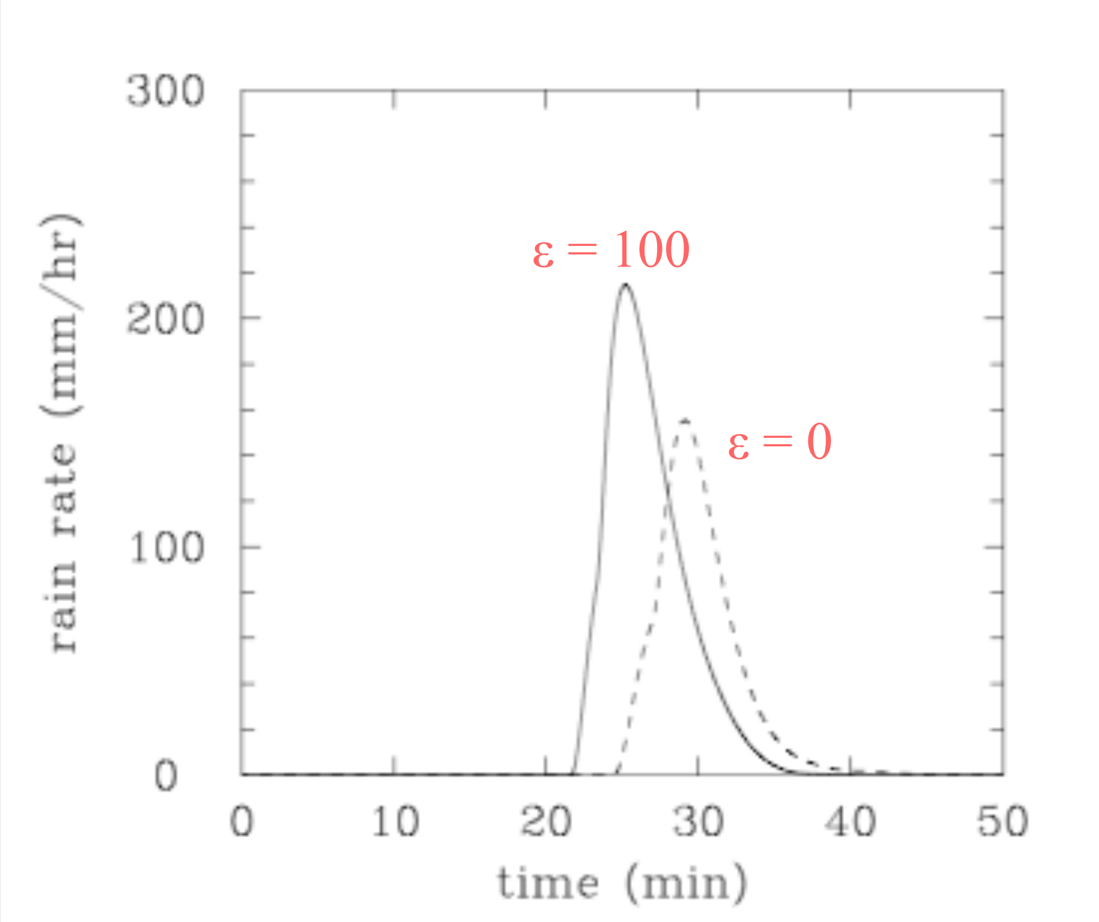




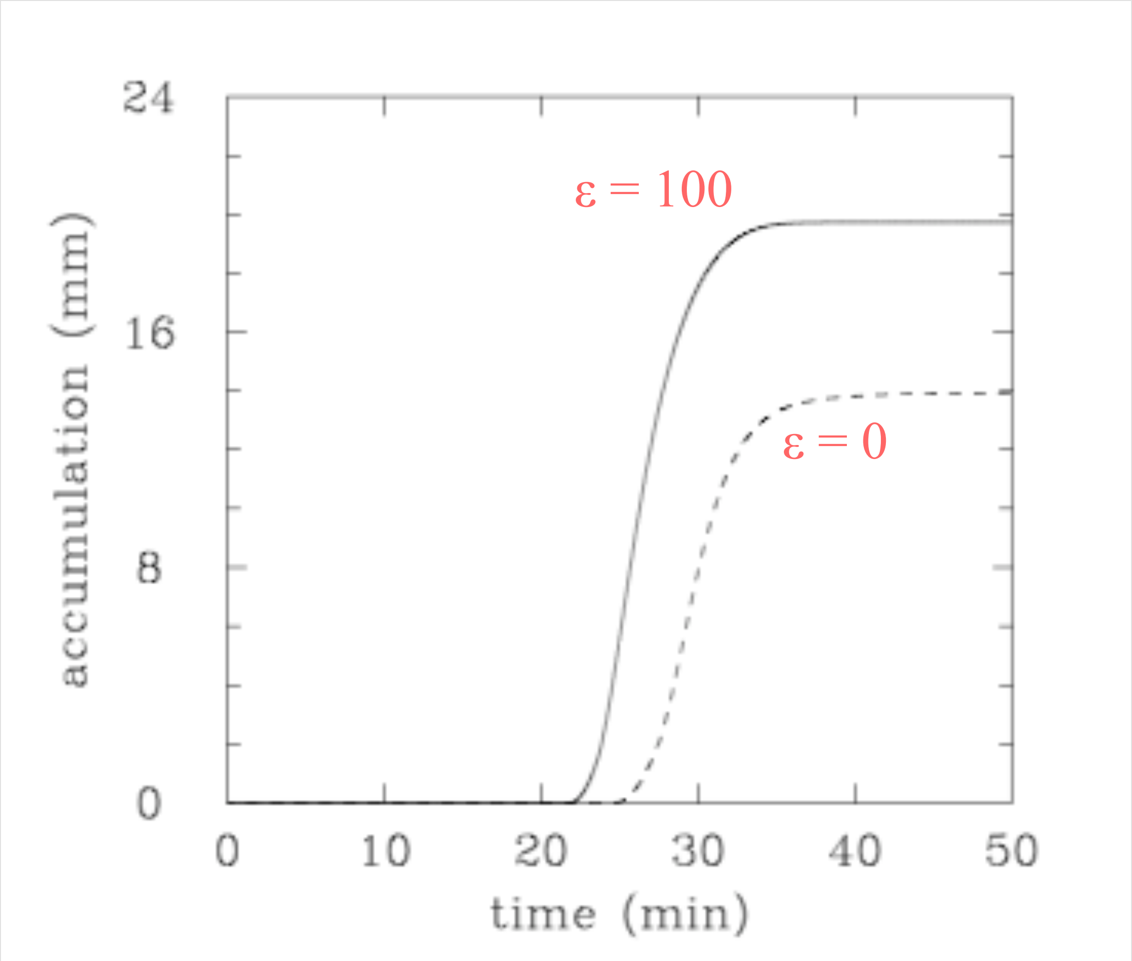


with turbulence – Ayala kernel with 100 cm^2s^{-3}

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!



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.

In a single cloud, not only rain tends to form earlier, but also a turbulent cloud seem to rain more. More realistic numerical studies are needed to quantify this aspect – work in progress.

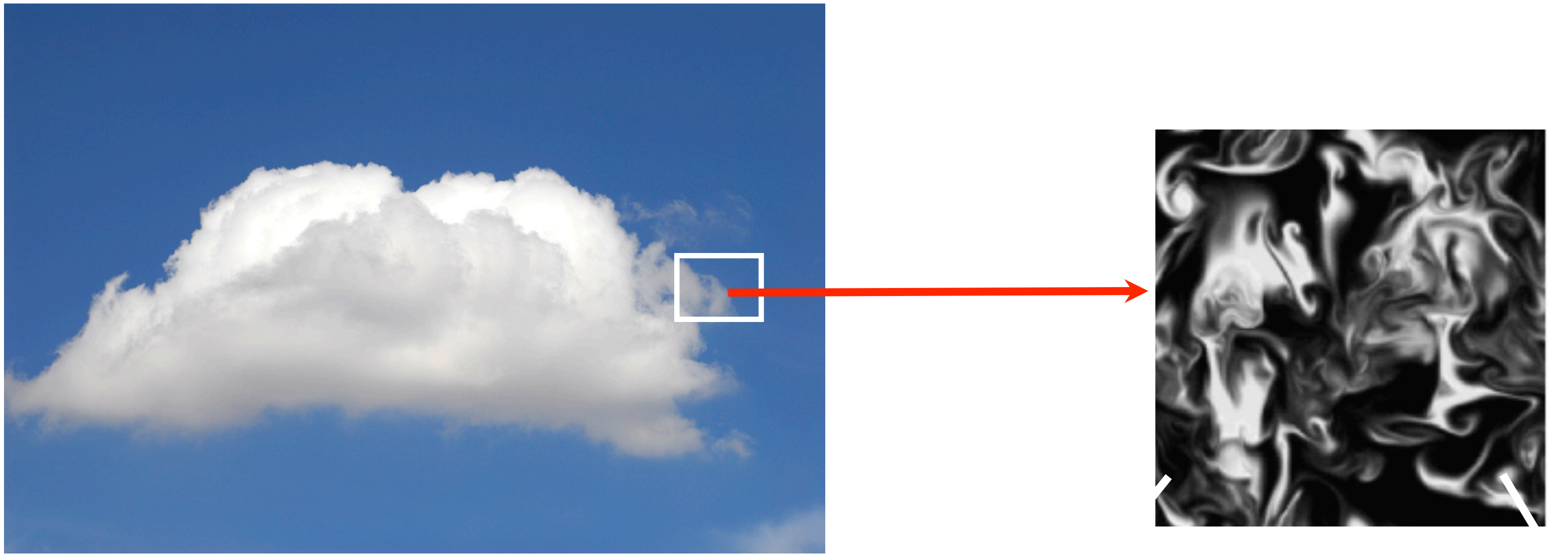
Simulation of boundary layer clouds with double-moment microphysics and microphysics-oriented subgrid-scale modeling

Dorota Jarecka[1], W. W. Grabowski[2], H. Morrison[2], H. Pawlowska[1]

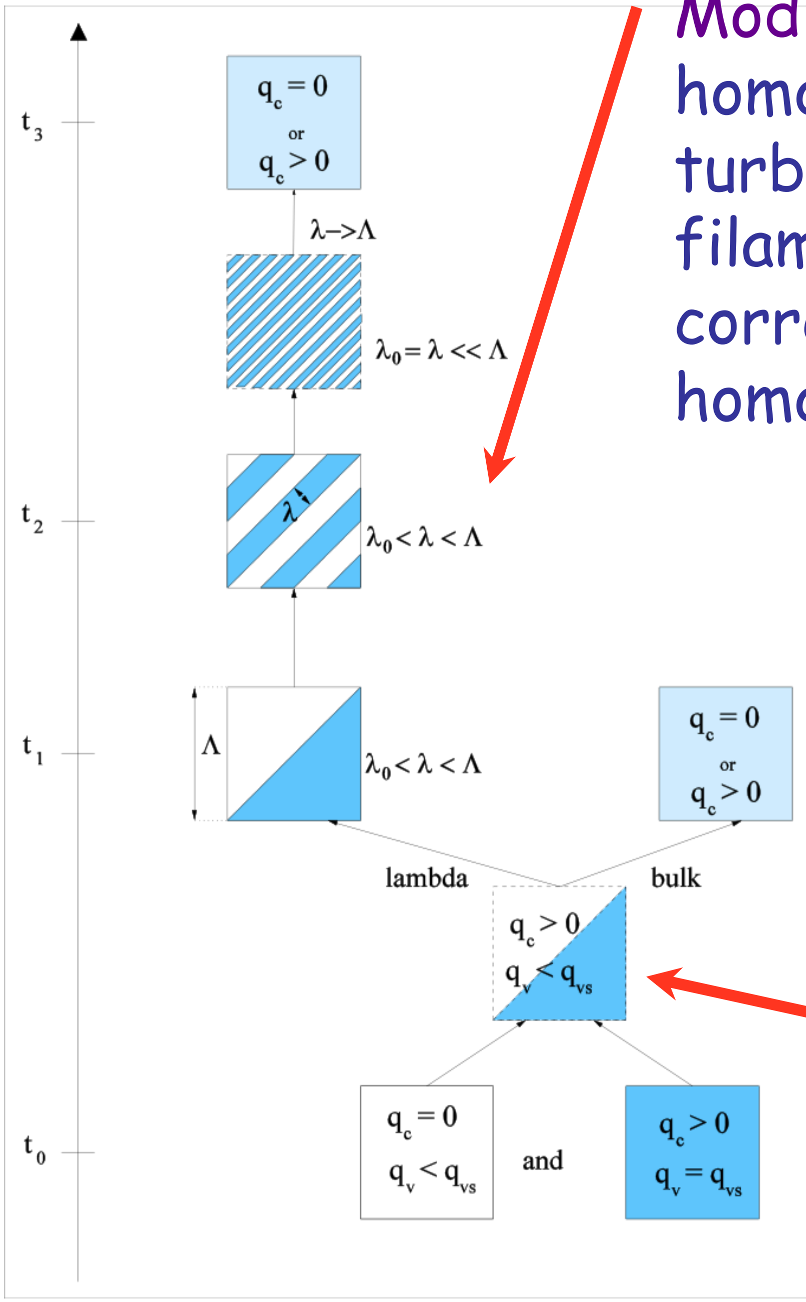
[1] Institute of Geophysics, Faculty of Physics, University of Warsaw, Poland

[2] National Center for Atmospheric Research, USA

Turbulent cloud-environment mixing



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

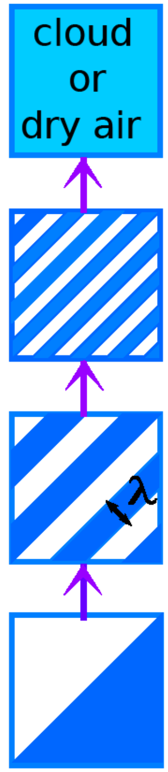


Modified model with λ approach:
homogenization delayed until turbulent stirring reduces the filament width λ to the value corresponding to the microscale homogenization scale λ_0

Bulk model:
immediate homogenization

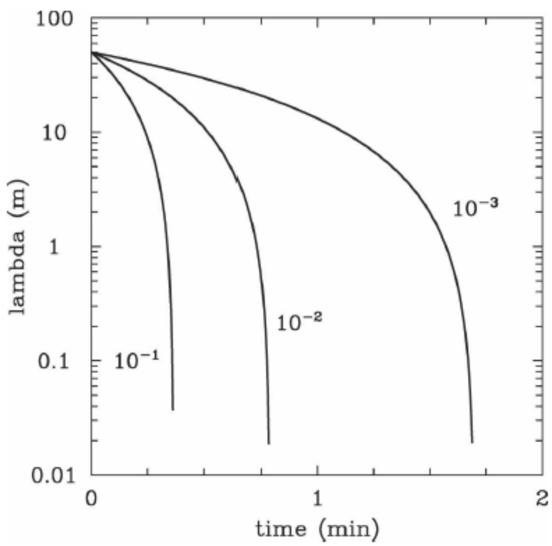
mixing event

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 - the model gridlength;
λ_0 - the homogenization scale (~ 1 mm).

γ ~ 1
ε – the dissipation rate of TKE

Broadwell and Breidenthal (1982); Grabowski (2007)

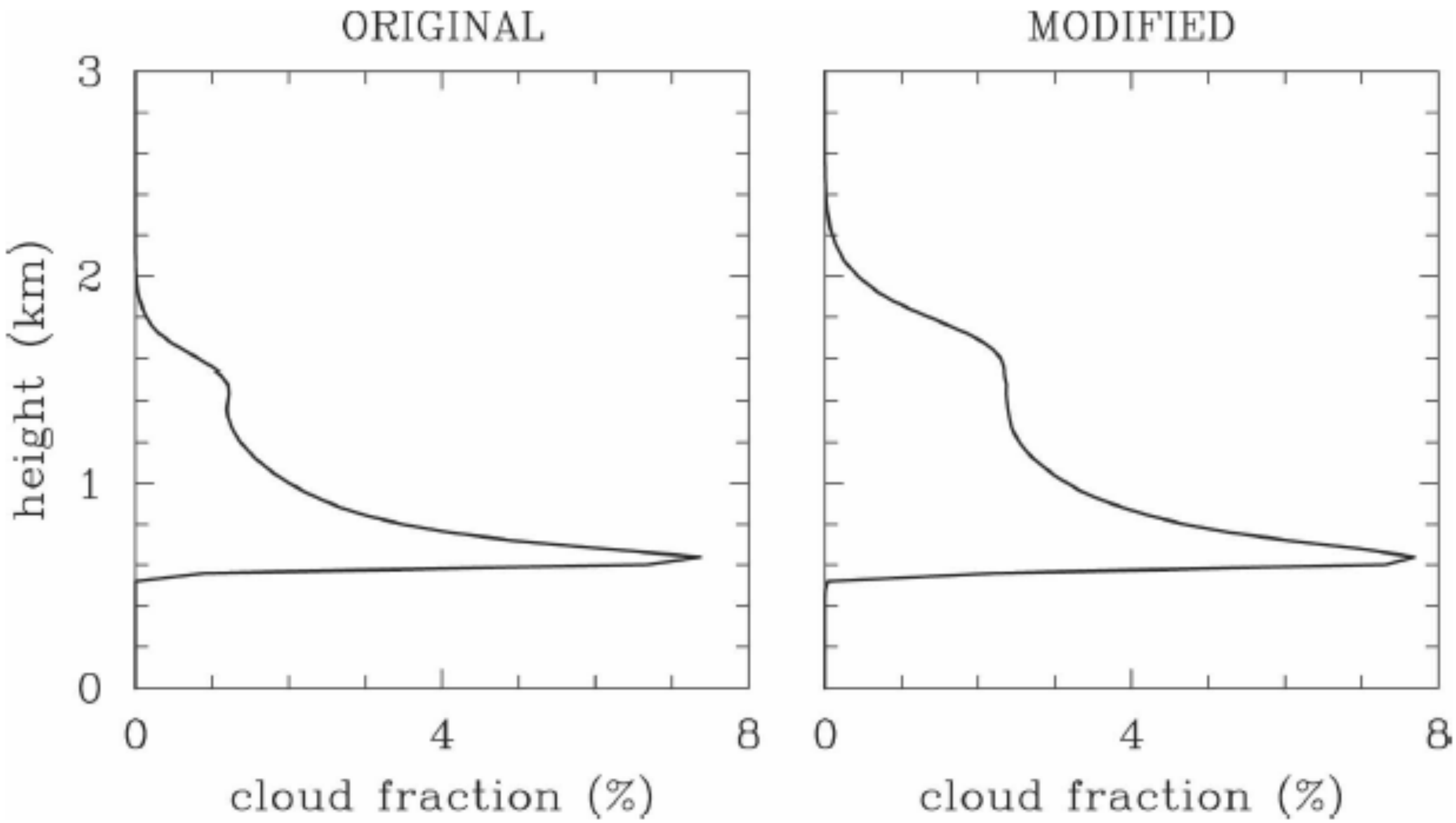
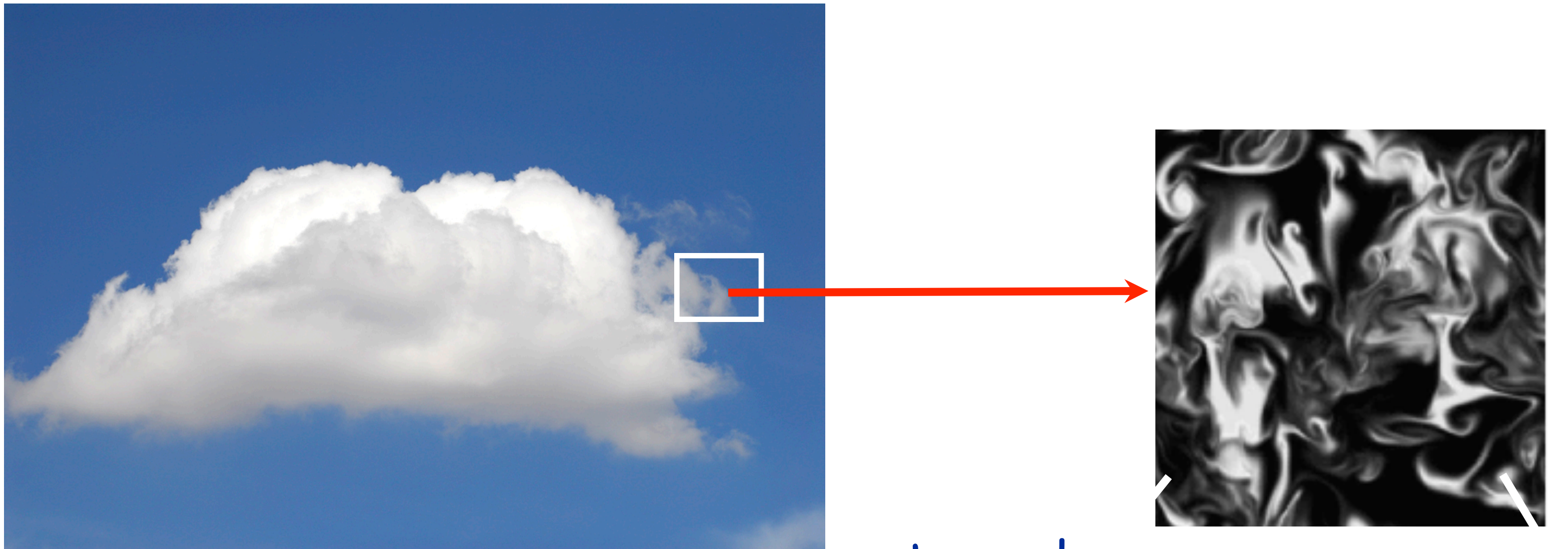


FIG. 9. Profiles of the cloud fractions (4-h averages) in BOMEX simulations using either the (left) original or (right) modified approaches.

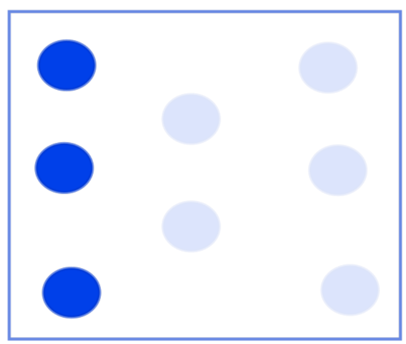
Grabowski (2007)

Turbulent cloud-environment mixing

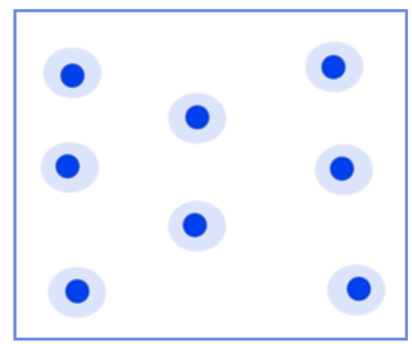


Microphysical transformations due to subgrid-scale mixing cover a wide range of mixing scenarios.

extremely inhomogeneous mixing



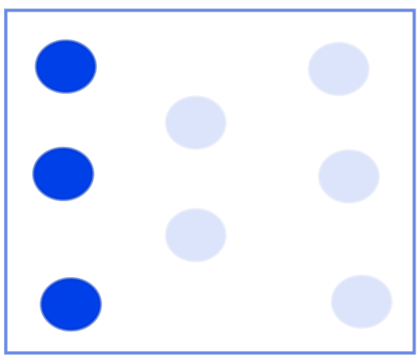
homogeneous mixing



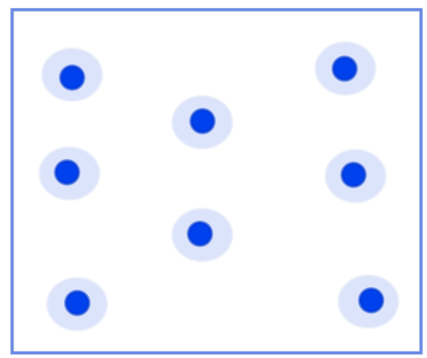
2-moment microphysics - mixing scenarios

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

$\alpha = 1$
extremely inhomogeneous mixing



$\alpha = 0$
homogeneous mixing



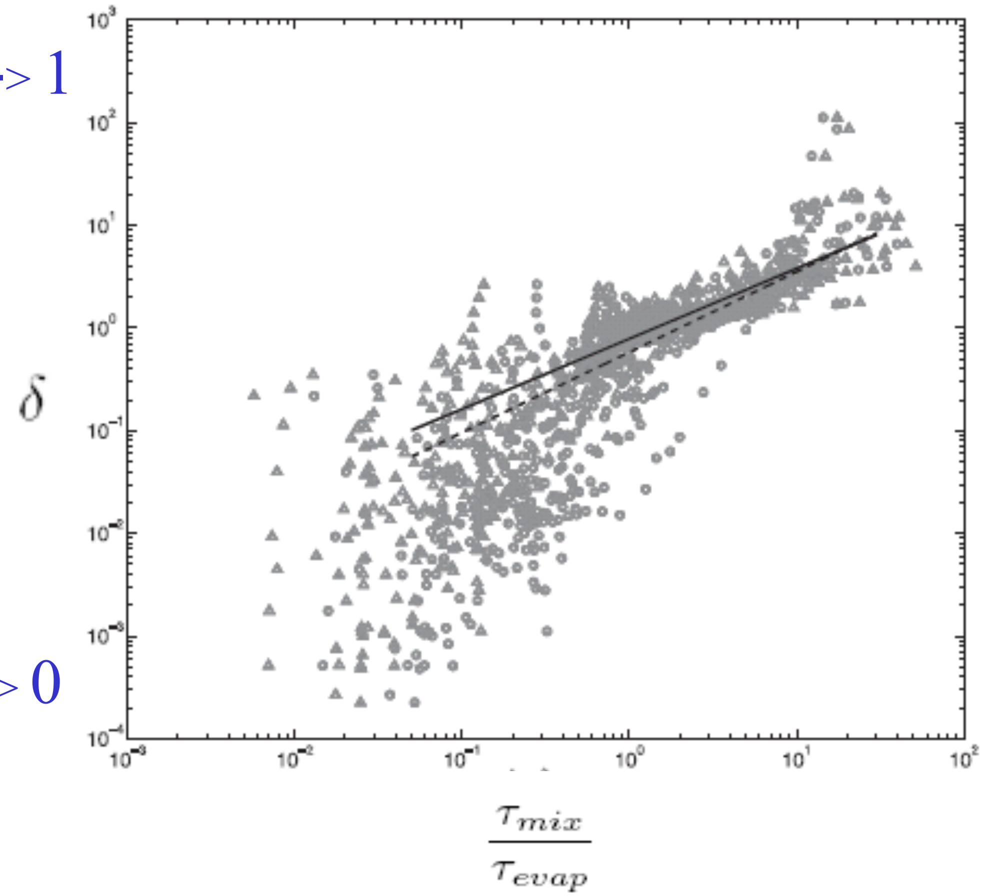
Previews studies (Slawinska et al. 2010): α=const for entire simulation to contrast results with different mixing scenarios.

Using DNS results for predicting α

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

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

α -> 1



α -> 0

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

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

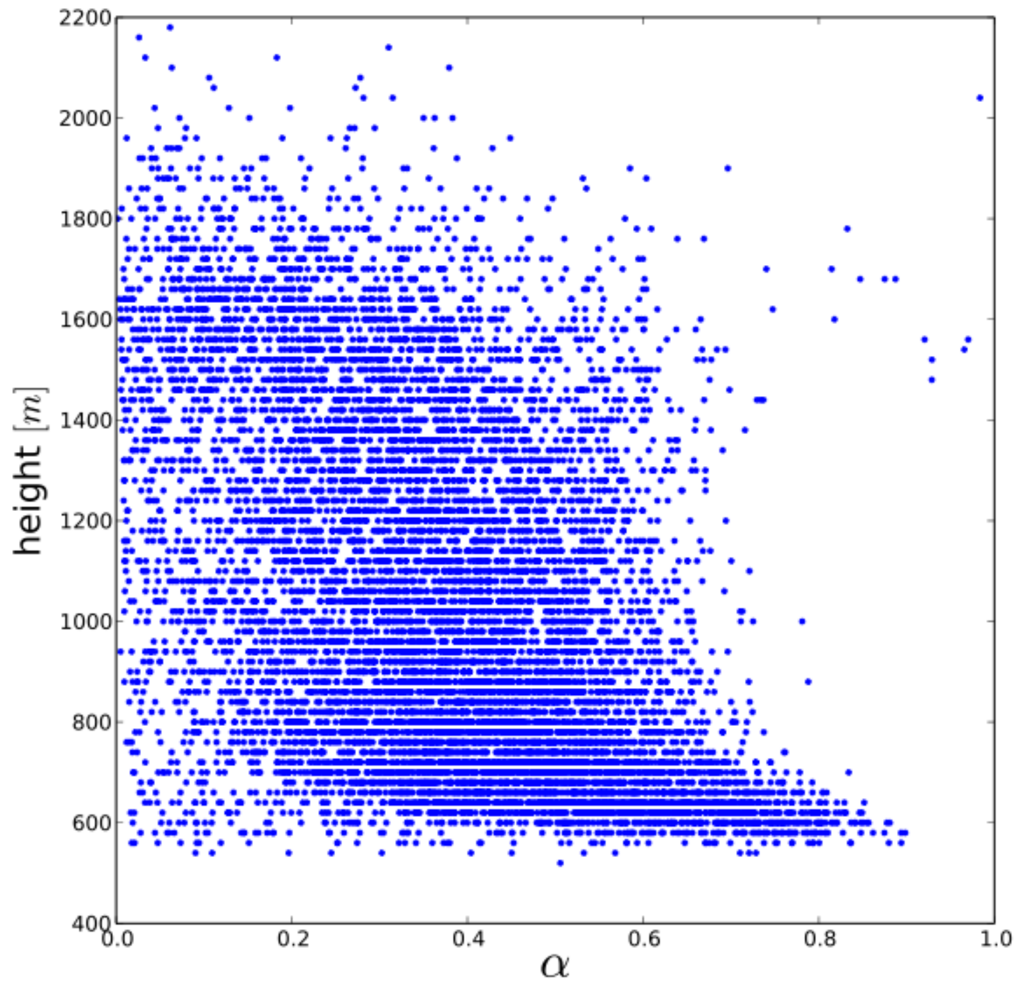
Model and model setup

3D numerical model EULAG www.mmm.ucar.edu/eulag/
with the 2-moment warm-rain microphysics scheme

Simulation setup - BOMEX (Siebesma et al. 2003)

- Domain: 6.4km, 6.4km, 3km
- Grid size: 50m, 50m, 20m
- Time step: 1s
- Initial profiles from Siebesma et al. 2003

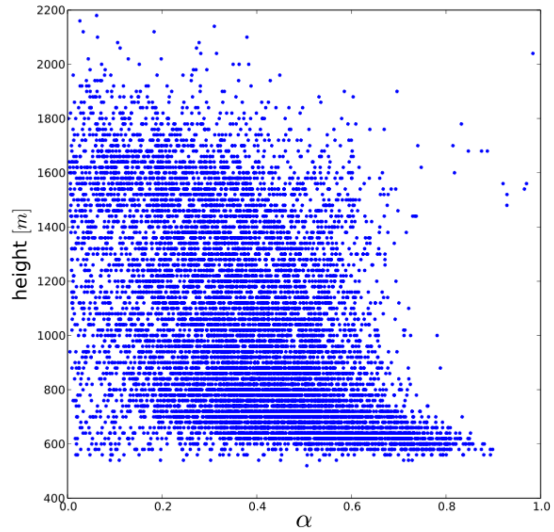
Changes of the parameter α with height

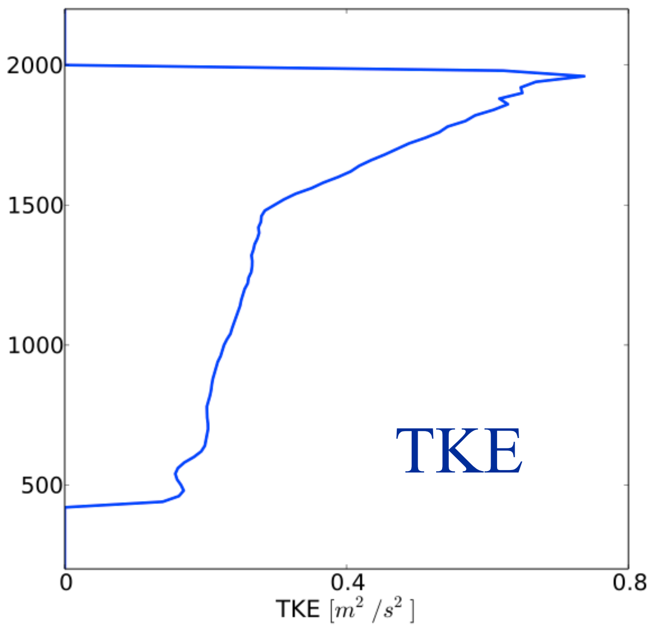


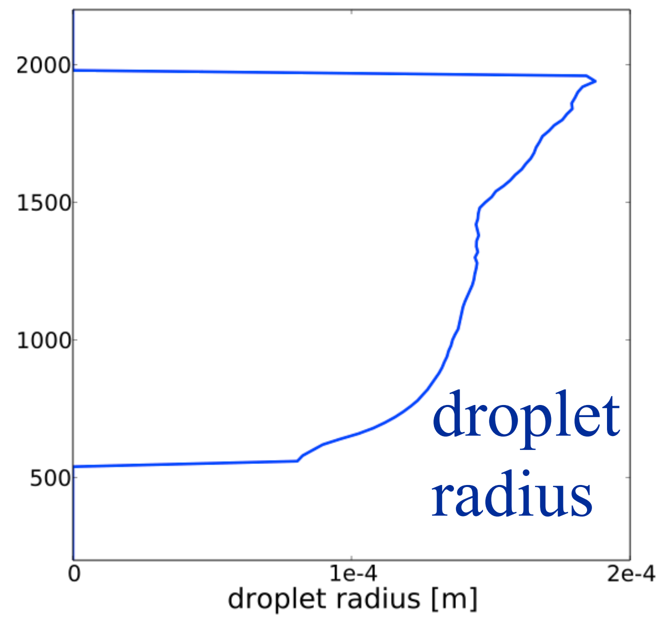
homogeneous mixing

extremely inhomogeneous mixing

Vertical profiles of α , droplet radius and TKE







Predicting scale of cloudy filaments λ allows representing in a simple way progress of the turbulent mixing between cloudy air and entrained dry 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., the mixing becomes more homogeneous. This is consistent with both TKE and droplet radius increasing with height.

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

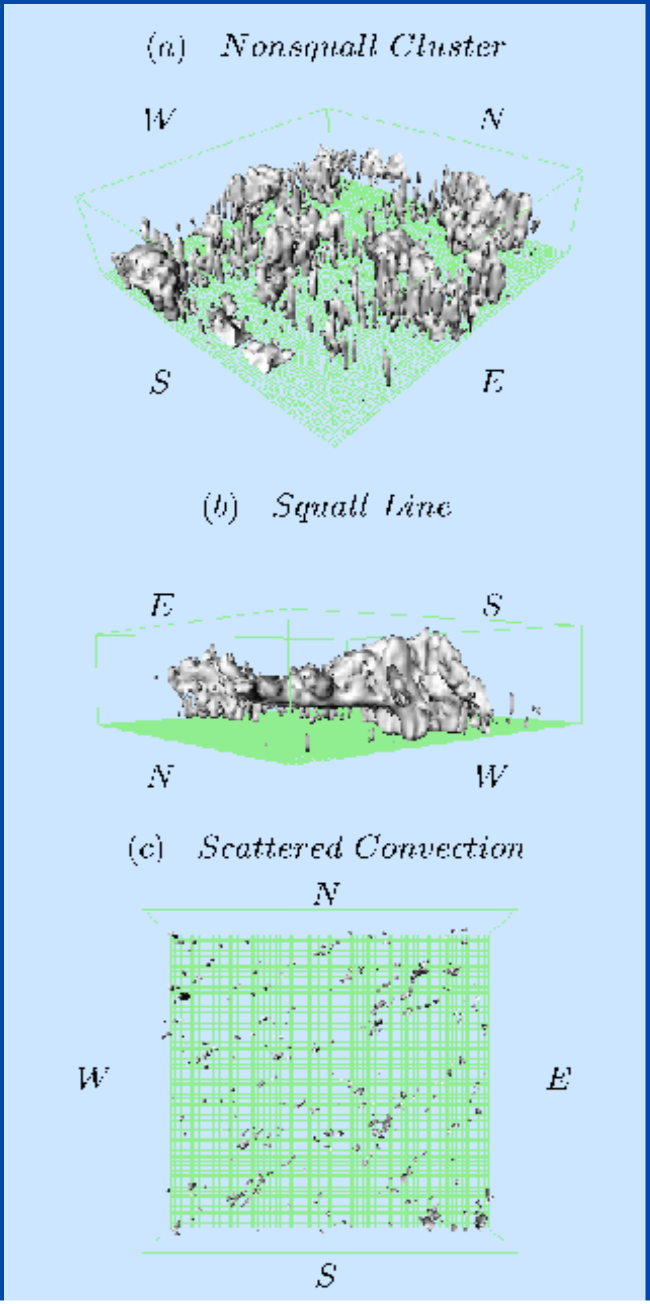
400 x 400 km horizontal domain, doubly-periodic, 2 km horizontal grid length

Driven by observed large-scale conditions

2 Sept, 1800 Z

4 Sept, 1800 Z

7 Sept, 1800 Z



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 to couple physical processes at their native scales?

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

Grabowski and Smolarkiewicz, *Physica D* 1999

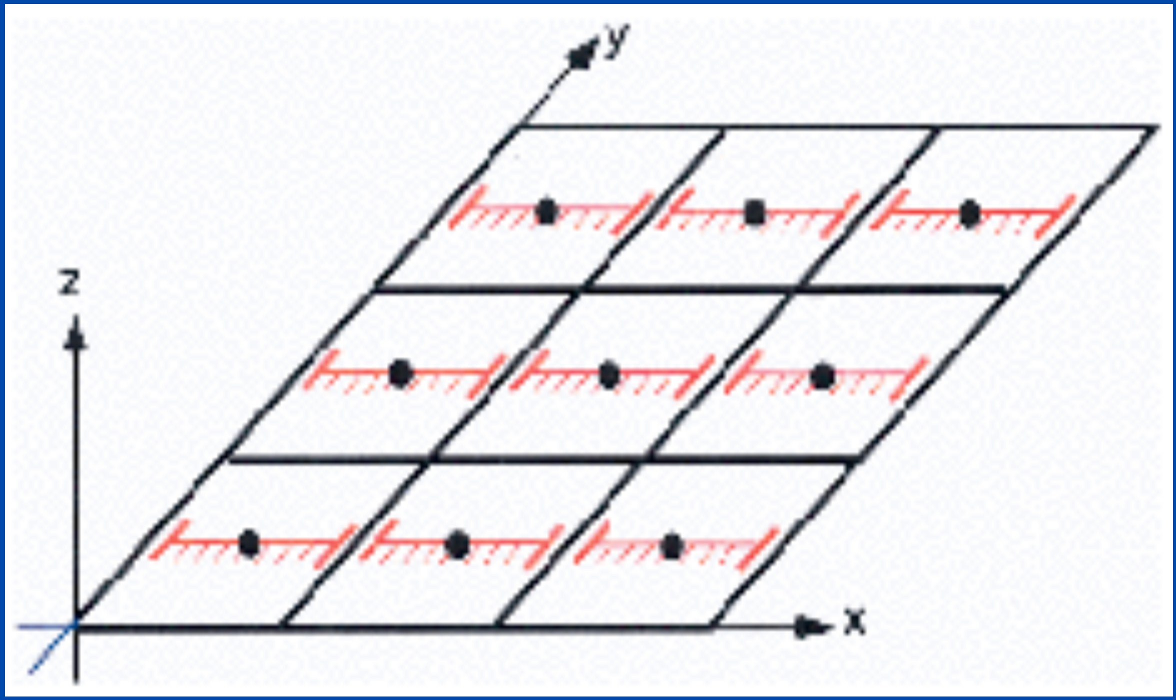
Grabowski, *JAS* 2001; Khairoutdinov and Randall *GRL* 2001;

Randall et al., *BAMS* 2003

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.

The effects of anthropogenic aerosols as simulated by the SP-CAM with two-moment microphysics

Marat Khairoutdinov

State University of New York @ Stony Brook
Long Island, New York

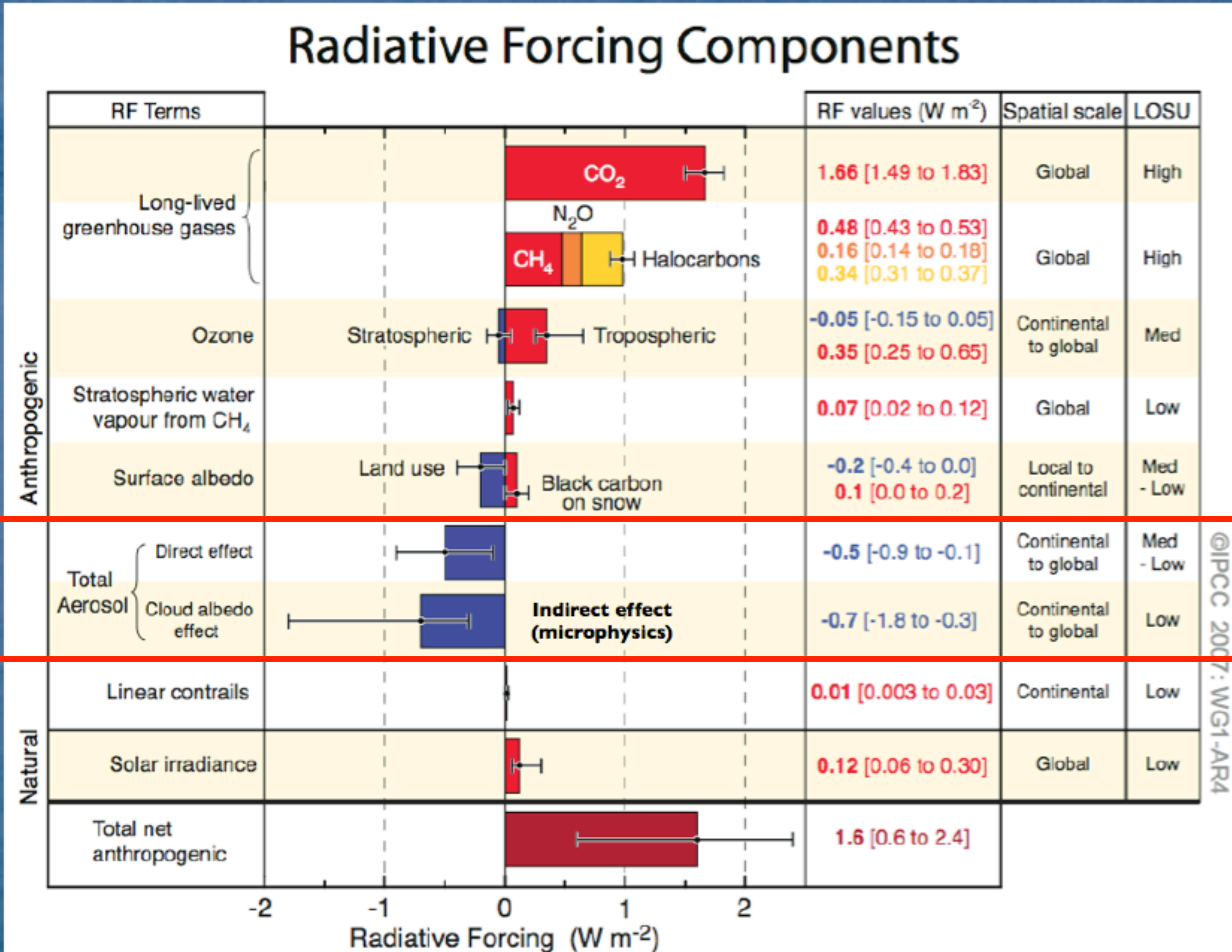
Wojciech Grabowski
Hugh Morrison

National Center for Atmospheric Research
Boulder, Colorado

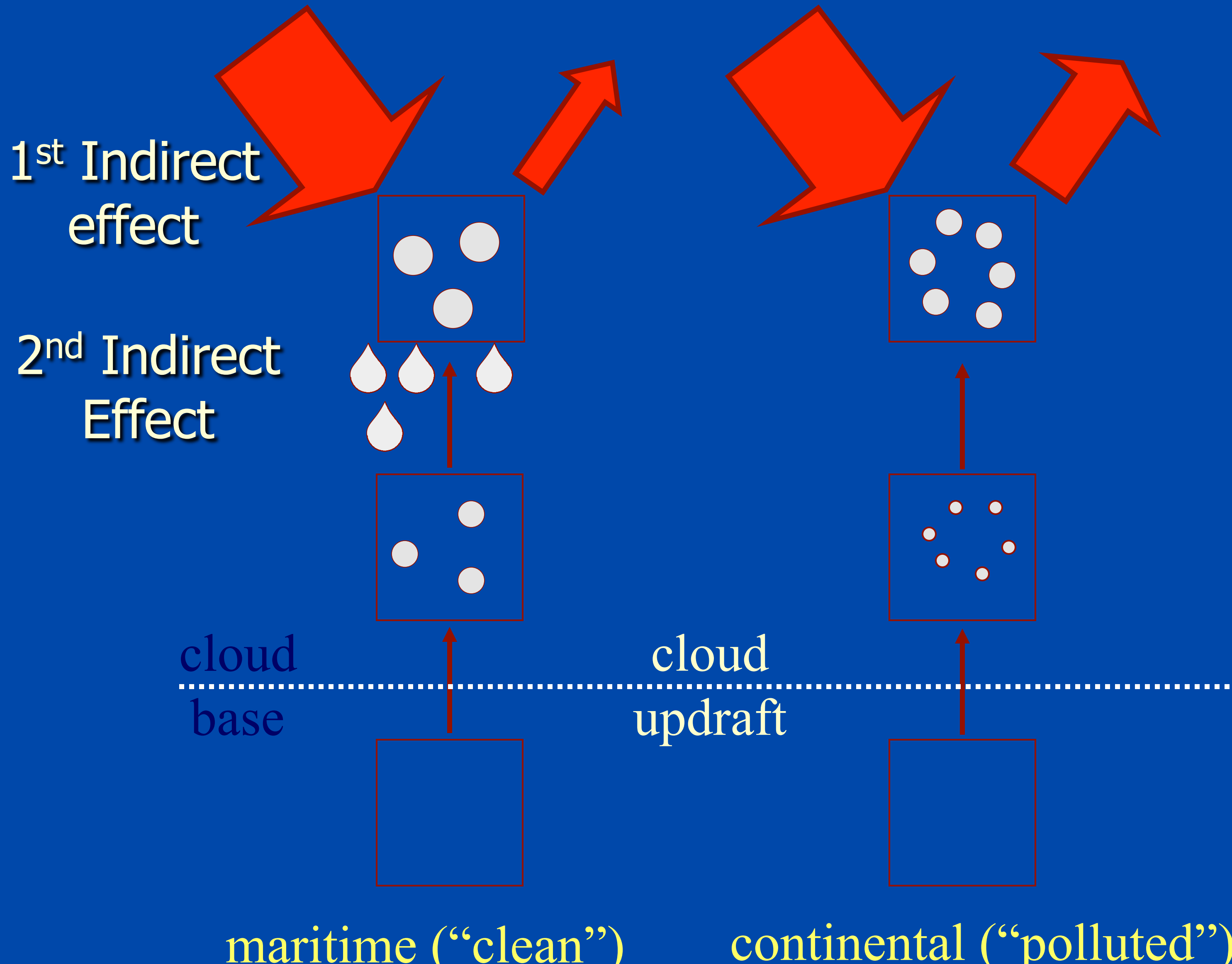
Center for Multiscale Modeling of Atmospheric Processes
CMMAP
Reach for the sky.

Industrial Era Climate Change

Source: IPCC 4th Assessment Report (AR4)



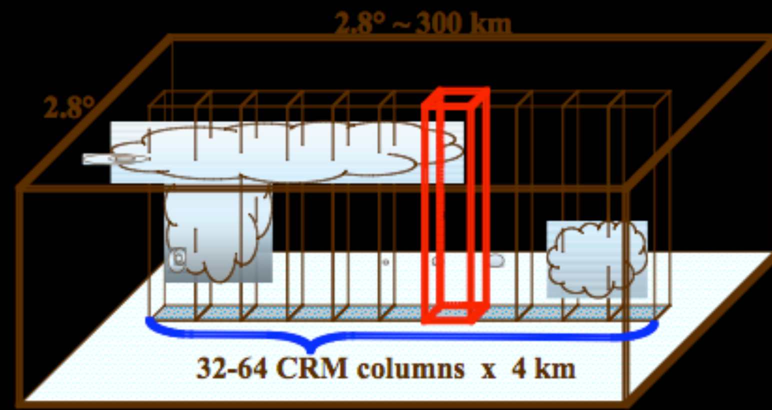
Indirect aerosol effects (warm rain only)

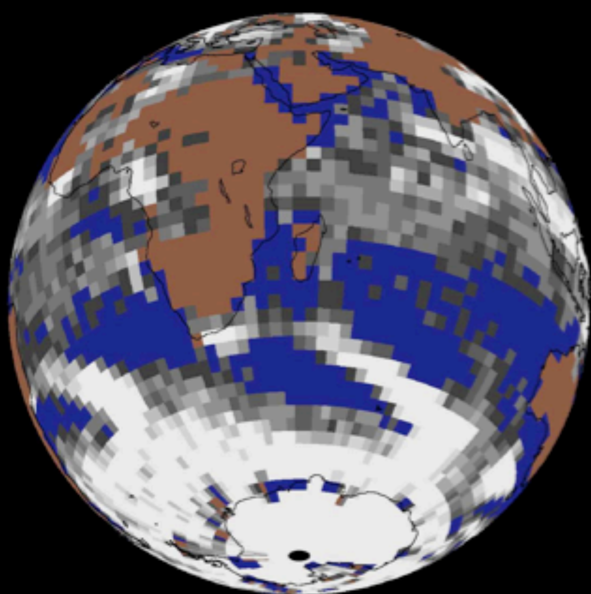


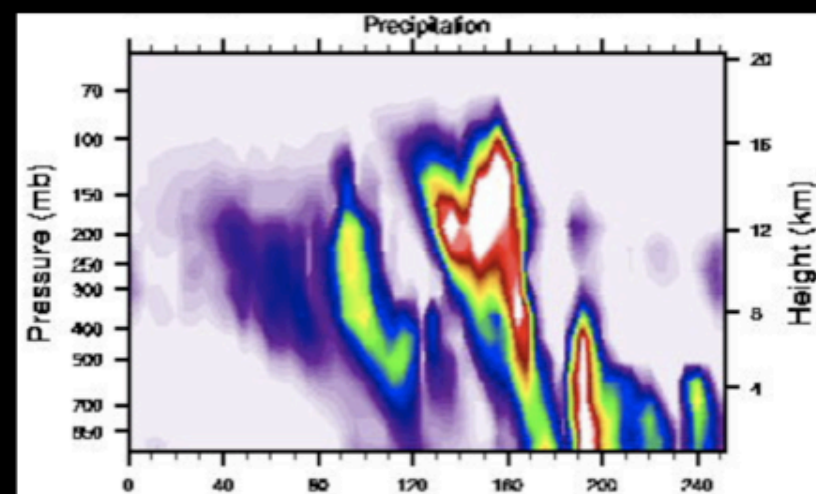
Super-parameterized CAM: SP-CAM

Multiscale Modeling Framework (MMF)

A copy of a CRM (a.k.a. “super-parameterization”) is run in each column of CAM GCM.







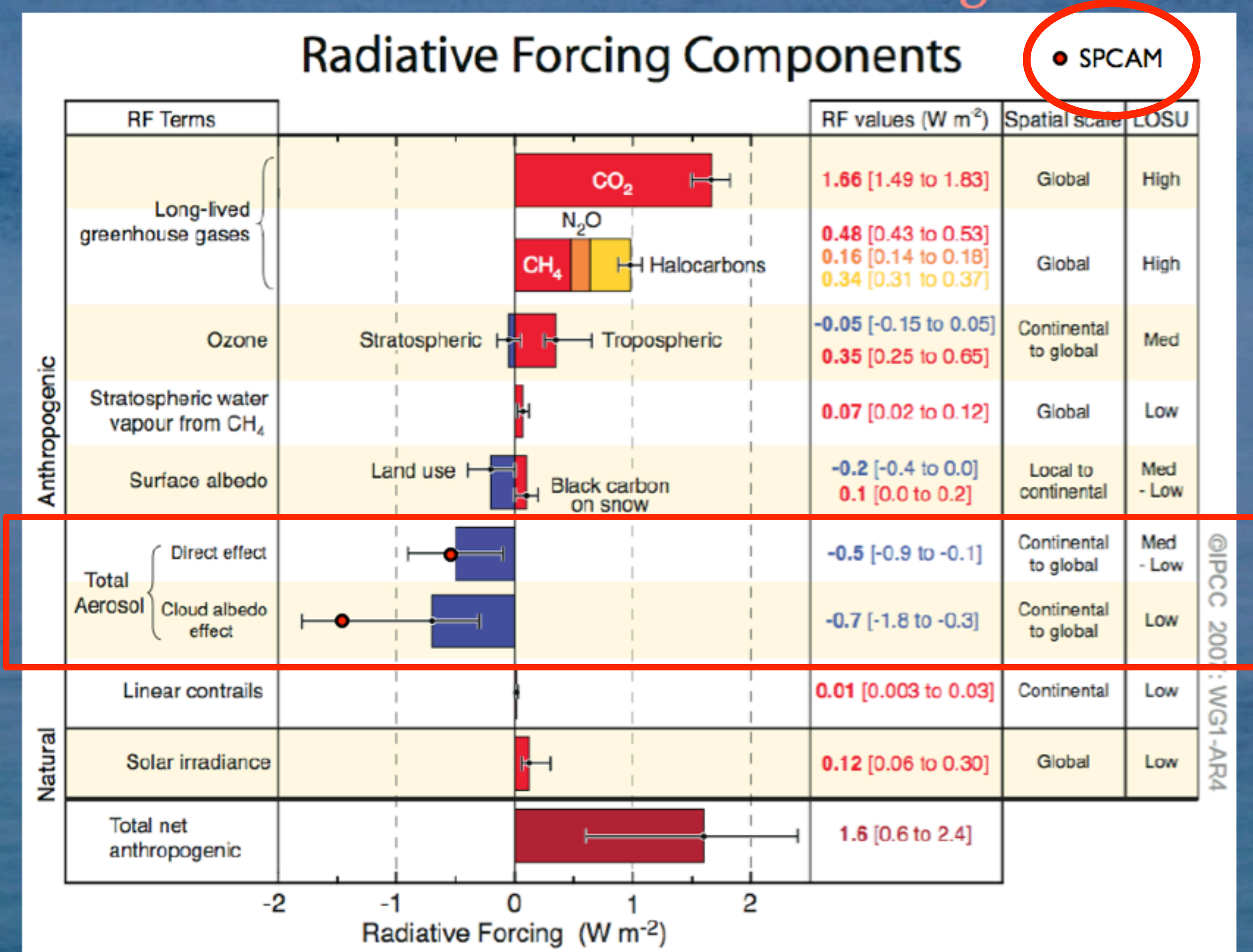
Each column of this has this

Bulk Microphysics Schemes in System for Atmospheric Modeling - SAM CRM used as super-parameterization in SP-CAM

Original One-Moment (Khairoutdinov and Randall 2003)	**Two-Moment** (Morrison et al. 2005) Thanks to Peter Blossey for implementing it in SAM
• 2 prognostic microphysics variables: total non-precipitating and precipitating water mixing ratios; • Cloud liquid and ice water, rain, graupel and snow are diagnosed as f(T); • Autoconversion to rain by simple Kessler formula; • Cloud drop effective radius is prescribed • No indirect aerosol effect is included.	• 10 prognostic microphysics variables; • Prognostic mixing ratio and concentration for 5 categories of water; • Autoconversion depends on water content and concentration (KK 2000); • Cloud Condensation nuclei (CCN) spectrum is prescribed; • Cloud droplet effective radius is computed; • Indirect aerosol effects are included.

IPCC 4th Assessment Report (AR4)

Industrial Era Climate Change



SUMMARY:

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

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

SUMMARY, cont:

Knowledge developed at one scale can be subsequently 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 not resolved. LES studies can guide development of subgrid-scale parameterizations that need to be included in lower-spatial-resolution models.

This is the concept of “hierarchical” approach, the only hope to cover the entire range of scales relevant to climate.