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:

Prof. **Lian-Ping Wang** (U. of Delaware)

Dr. **Hugh Morrison** (MMM/NCAR)

Profs. **Hanna Pawlowska** and **Szymon Malinowski** (U. of Warsaw)

PhD students: **Dorota Jarecka** and **Joanna Slawinska** (U. of Warsaw)

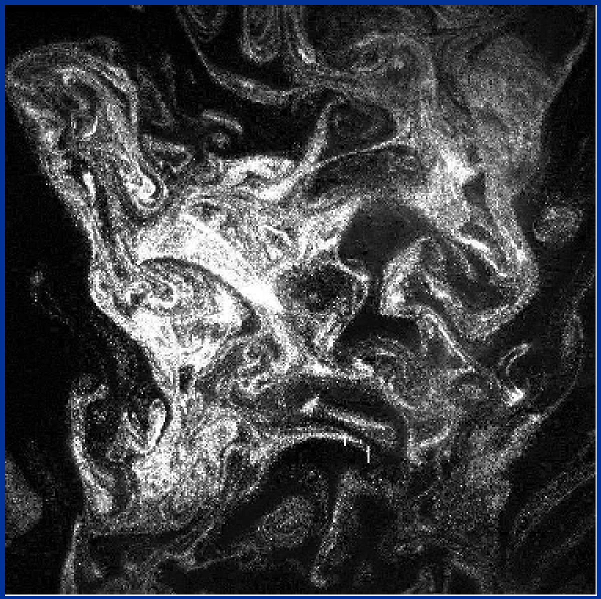
Cloud processes span tremendous range of scales, from *thousands of kilometers* to a *fraction of a cm*…

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…

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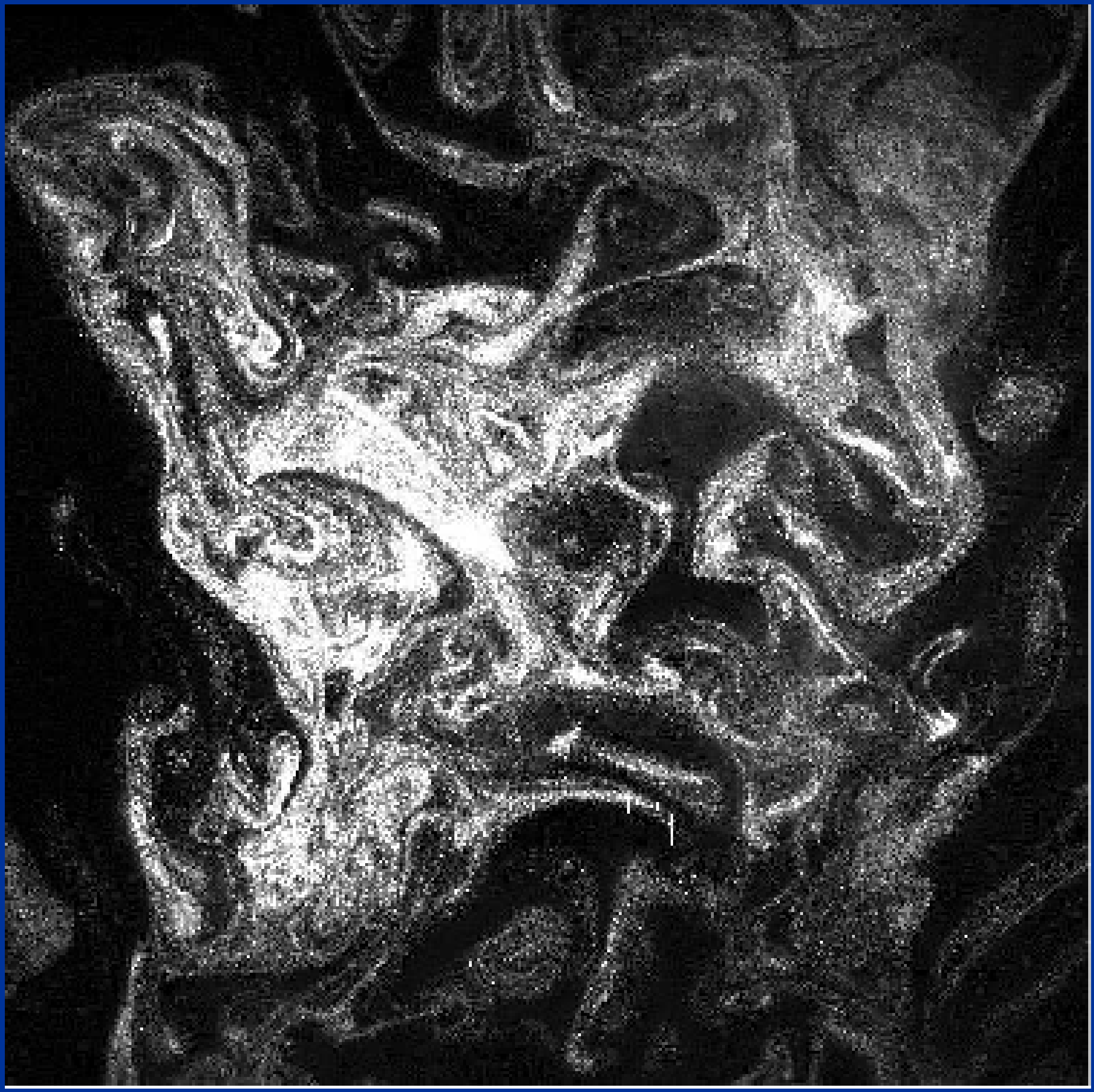
Even for processes near each of the scale illustrated above, there are multiscale interactions that cannot be resolved by the “direct numerical simulation” approach…

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



Collaborative project with Prof. Lian-Ping Wang from the Department of Mechanical Engineering, University of Delaware.

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)

Droplet inertial response time:

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

ρ_w – water density ($\sim 10^3$ kg m^{-3})

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

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

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

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 μm	v_t cm s^{-1}	t_p s	ϵ m^2 s^{-3}	10^{-4}	10^{-3}	10^{-2}
			u_η cm s^{-1}	0.64	1.10	2.00
			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

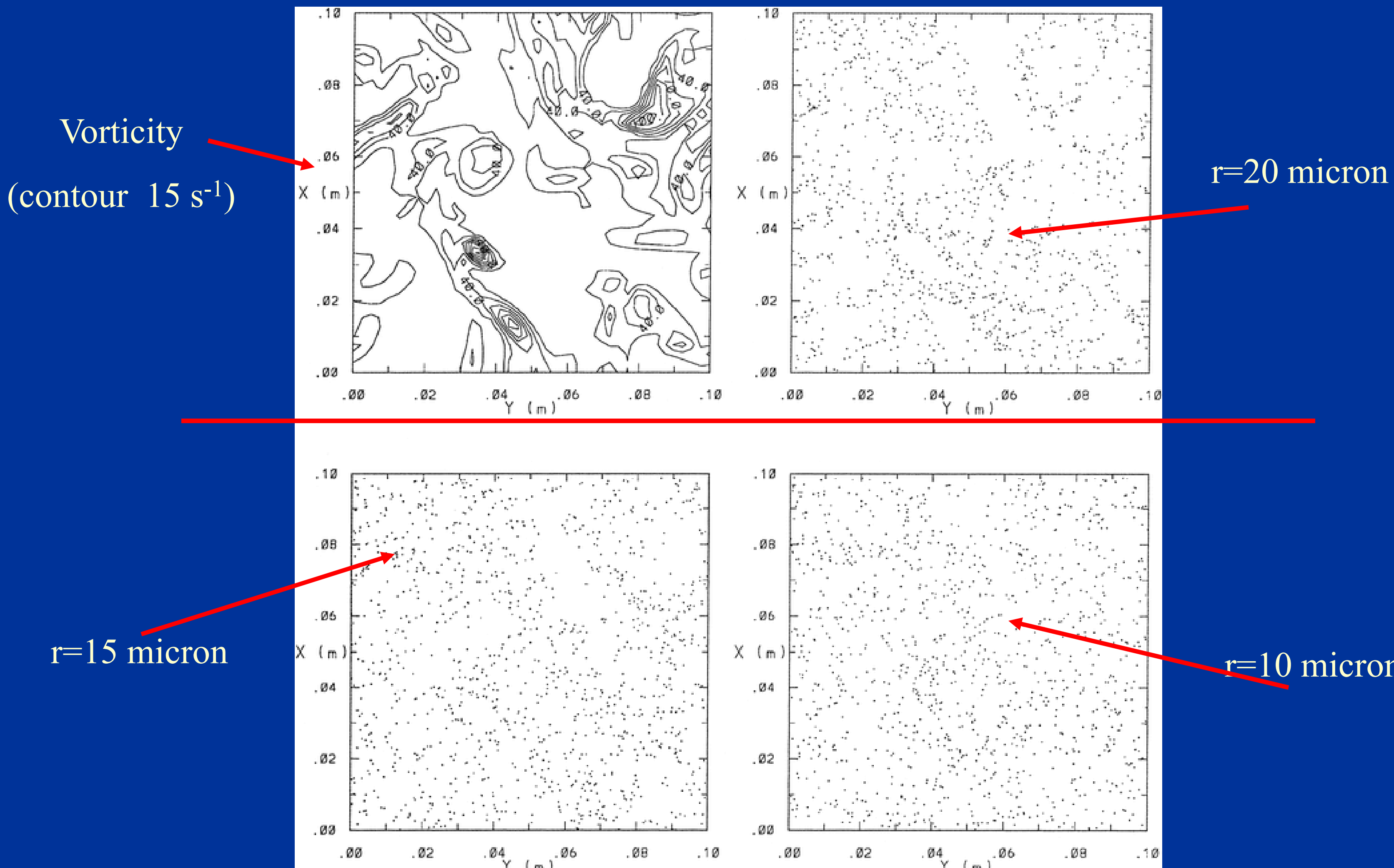
droplet radius

sedimentation velocity

response time

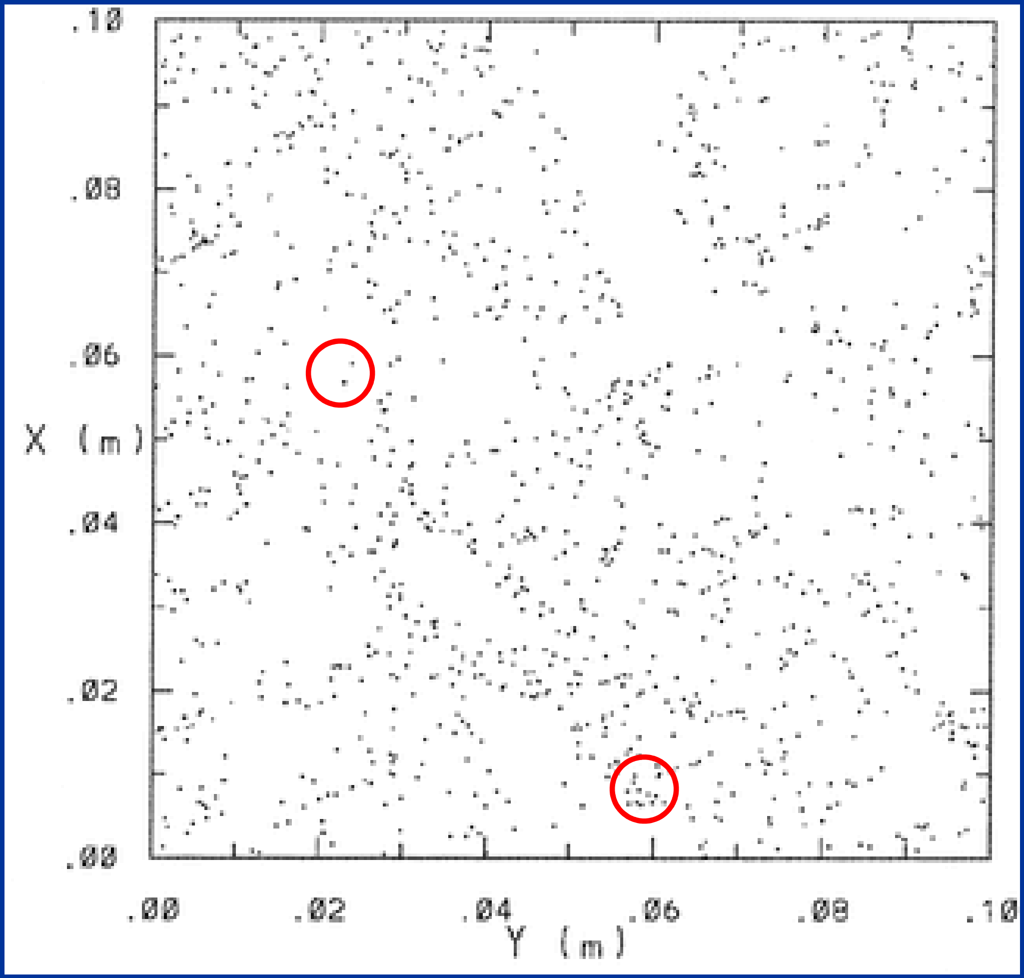
Grabowski and Vaillancourt JAS 1999

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

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

geometric collisions

(no hydrodynamic interactions)

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-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:

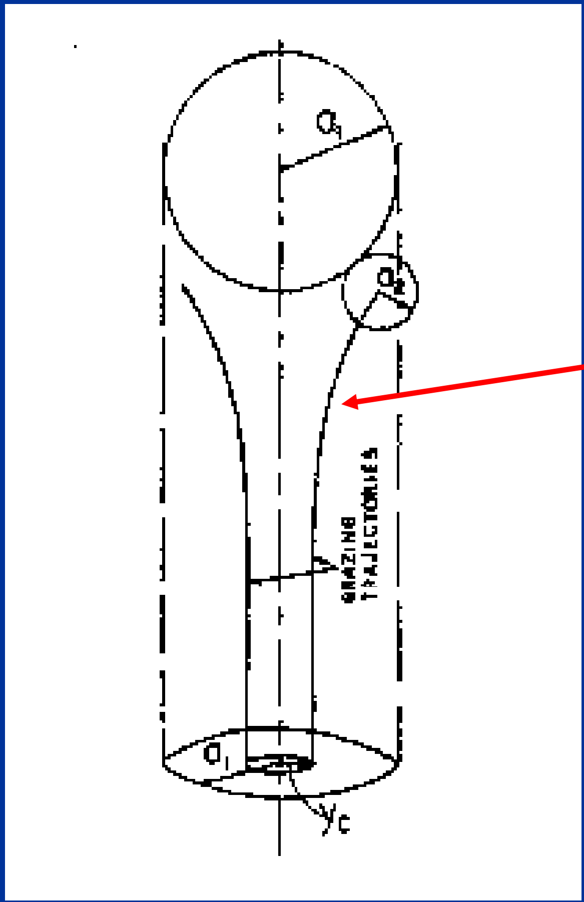
-Turbulence modifies local droplet concentration (preferential concentration effect)

-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

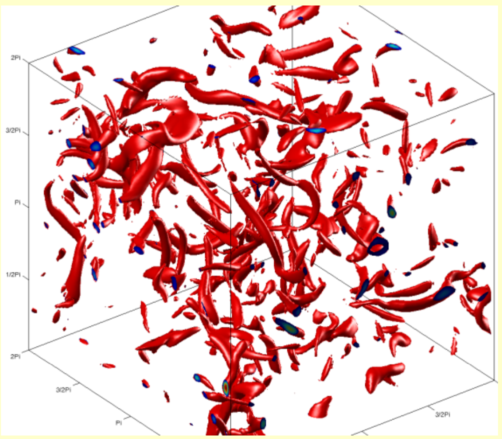
$$E_c = \frac{y_c^2}{(a_1 + a_2)^2}$$

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



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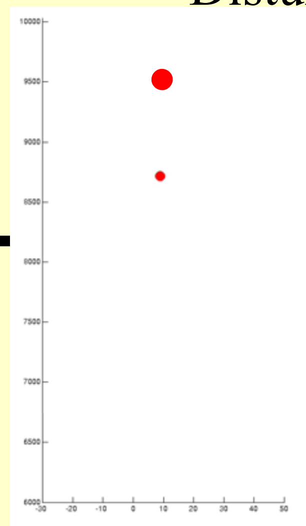
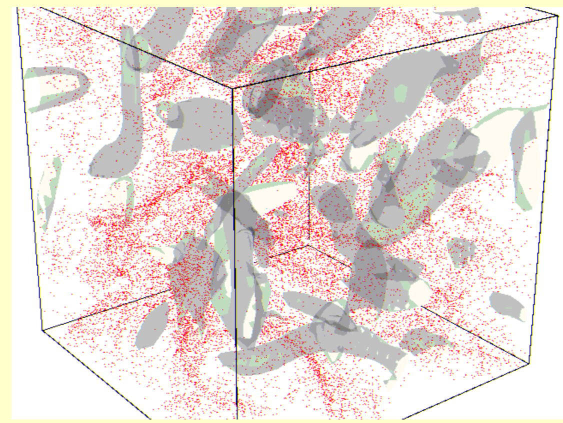




Features: Background turbulent flow can affect the disturbance flows;
No-slip condition on the surface of each droplet is satisfied on average;
Both near-field and far-field interactions are considered.

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):

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

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

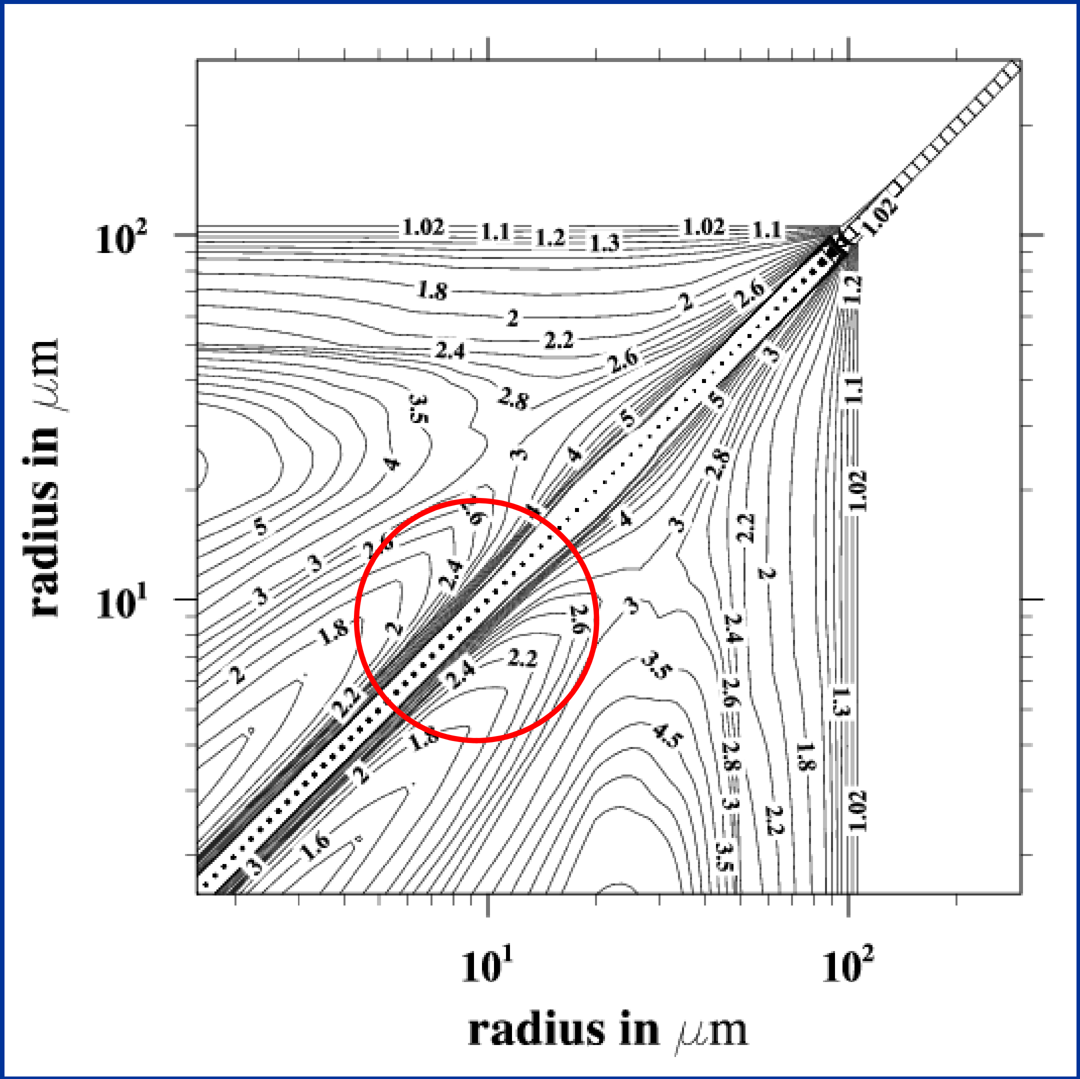
(strictly valid for droplets of unequal sizes only)

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

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

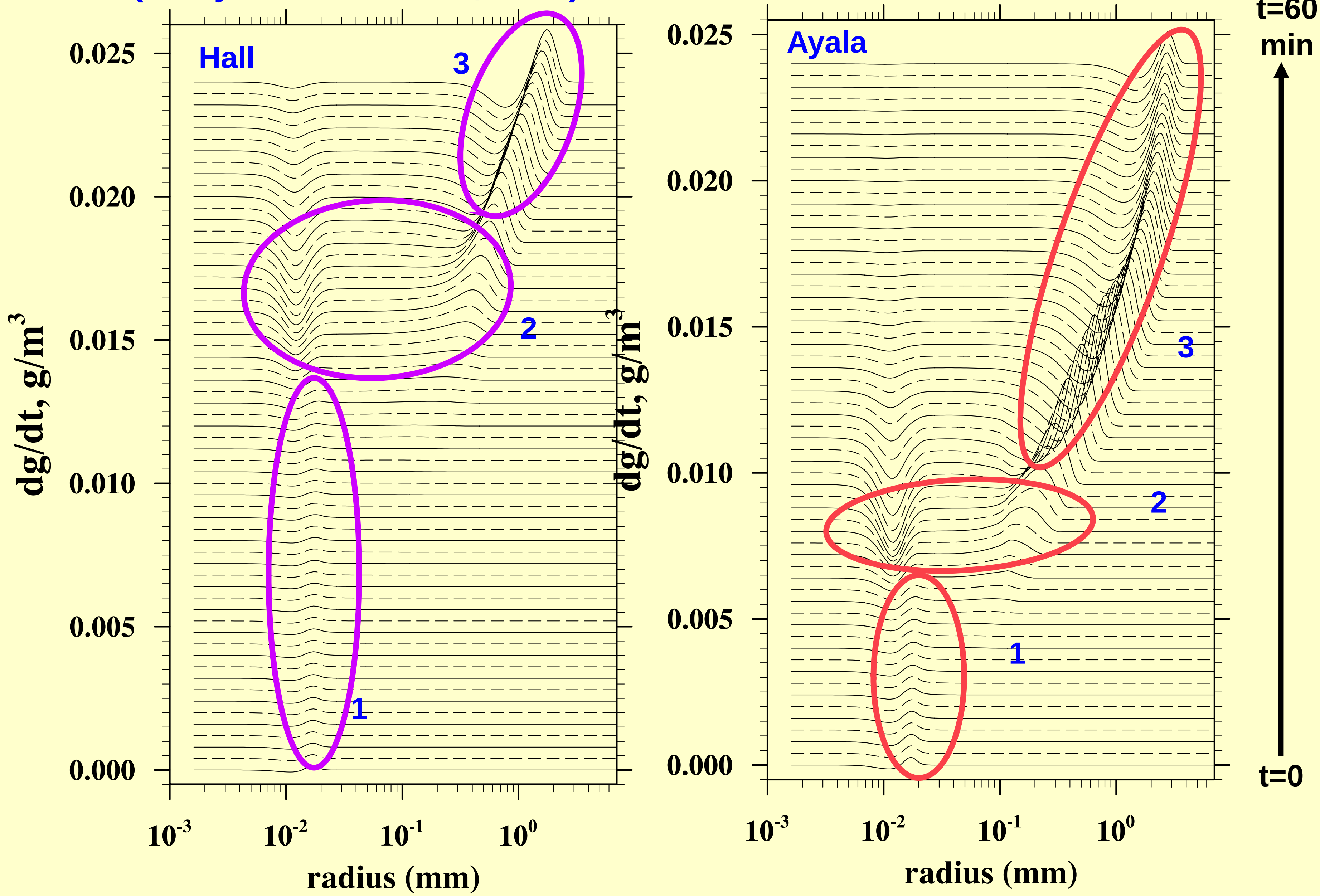
Table 1: $a_1 = 20\ \mu\mathrm{m}$, $a_2 = 25\ \mu\mathrm{m}$

$\epsilon\ (\mathrm{cm^2 s^{-3}})$	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; ε = 400 cm^2 s^{-3}.

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



Adiabatic parcel model

$$c_p \frac{dT}{dt} = -g\,w \; + \; L\,C$$

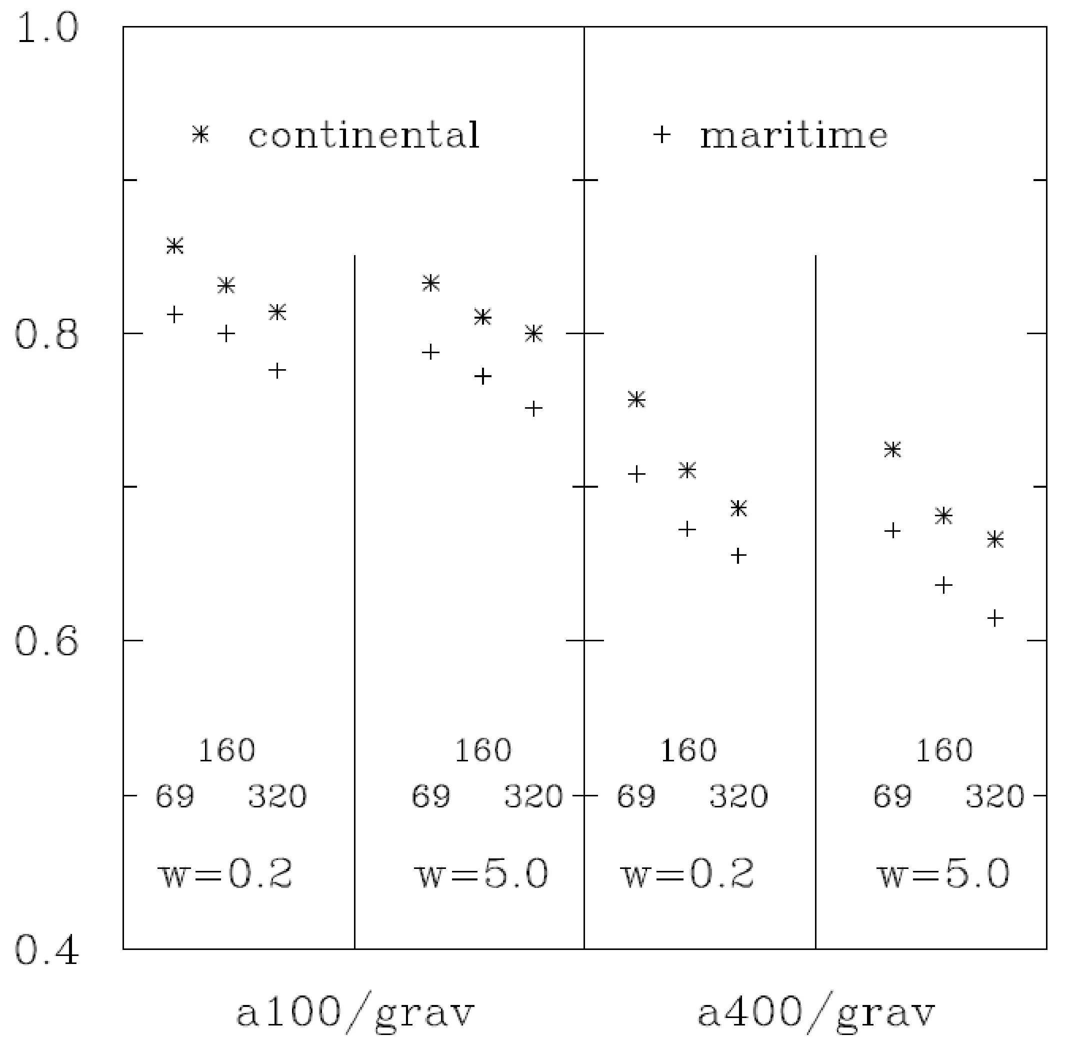
$$\frac{dq_v}{dt} = -C$$

$$\frac{dp}{dt} = -\rho_o w g$$

$$\frac{\partial \phi^{(i)}}{\partial t} = \left(\frac{\partial \phi^{(i)}}{\partial t}\right)_{cond} + \left(\frac{\partial \phi^{(i)}}{\partial t}\right)_{act} + \left(\frac{\partial \phi^{(i)}}{\partial t}\right)_{coal}$$

$$\text{for } i = 1, ..., \mathcal{N}$$

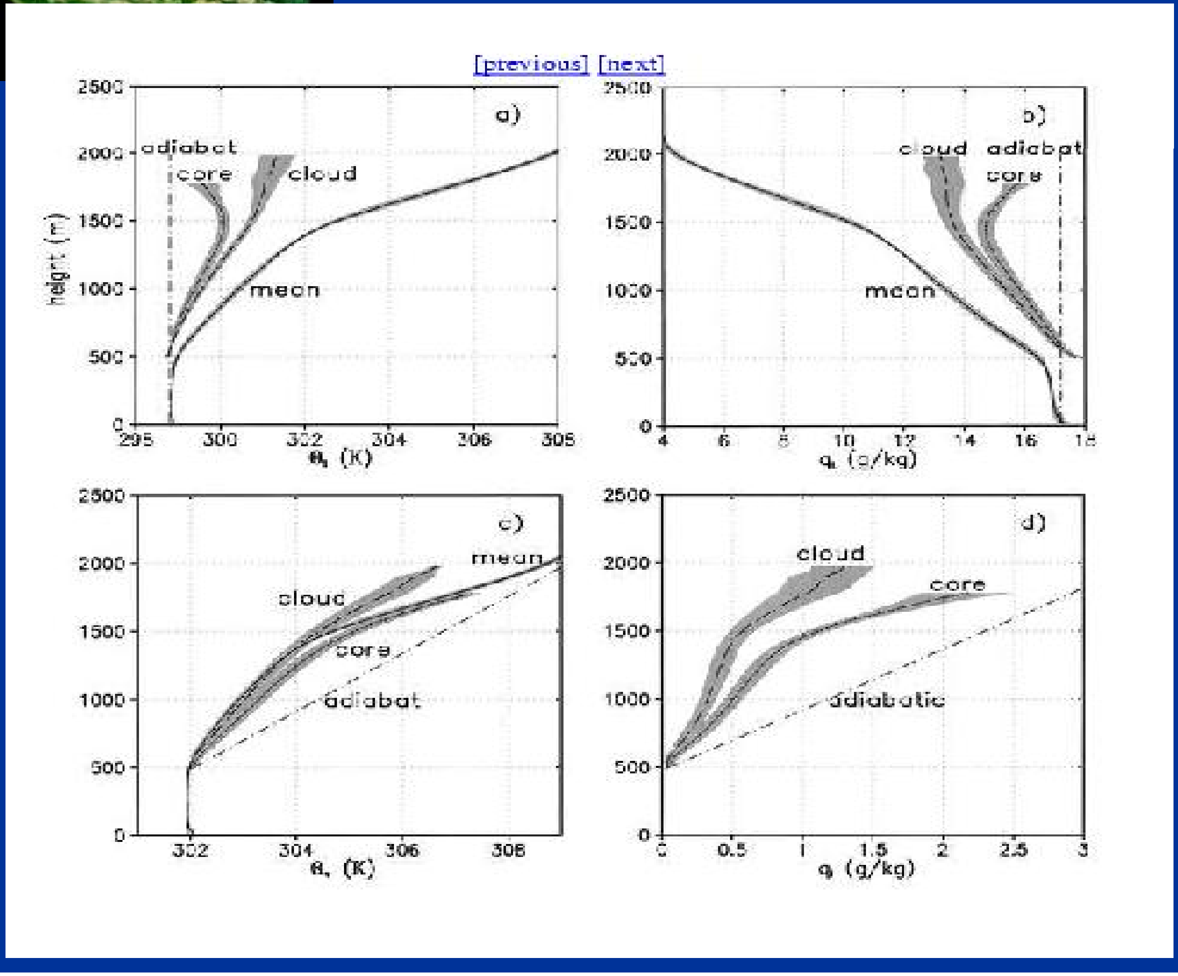
Grabowski and Wang (submitted to ACP)


1.0
0.8
0.6
0.4
* continental
+ maritime
160
69
320
w=0.2
w=5.0
a100/grav
a400/grav

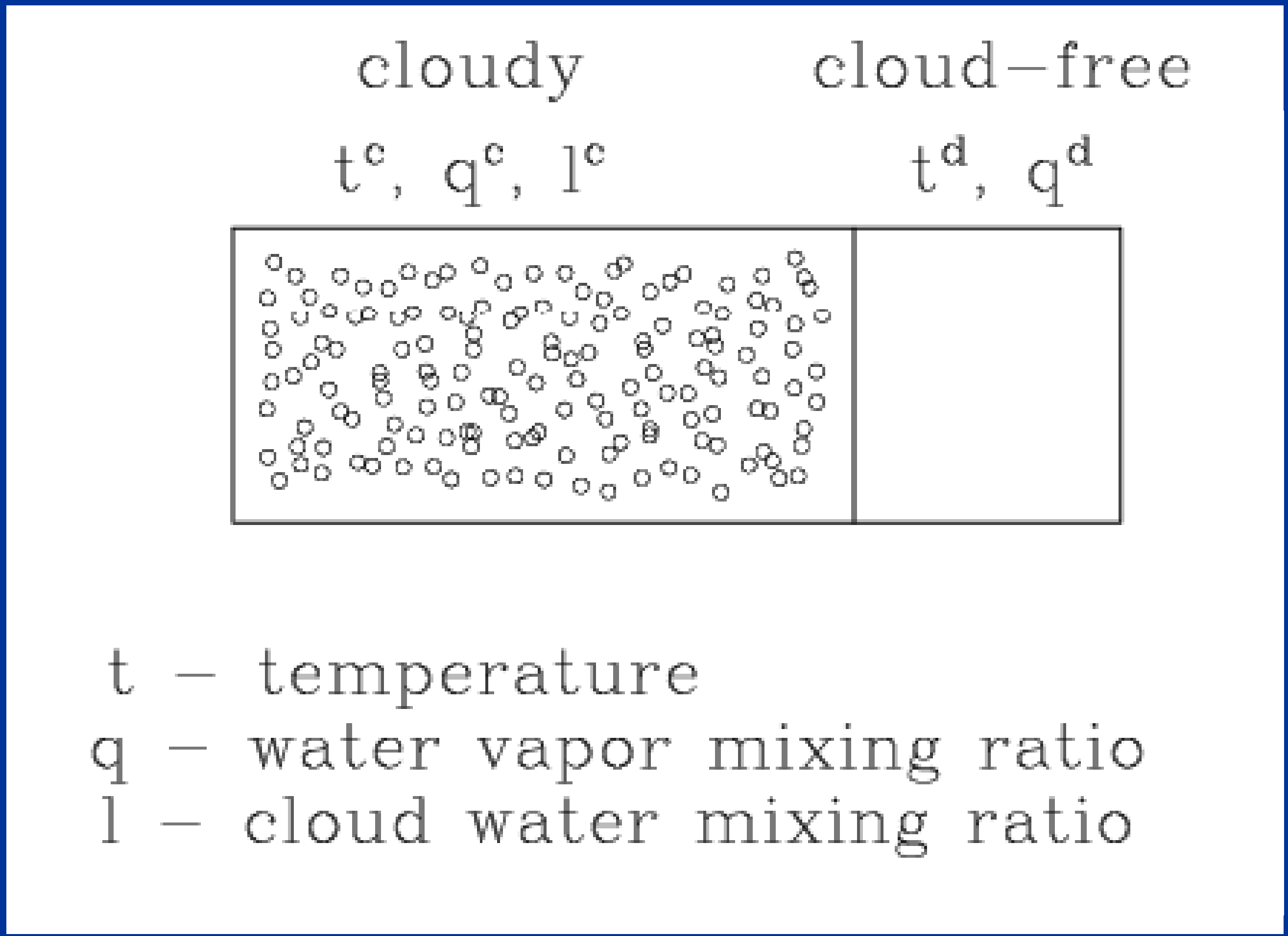
Cloud turbulence seems to have appreciable effect on droplet growth by collision/coalescence. This is a combination of the impact on the number of geometric collisions and on the collision efficiency.

Shallow convective clouds are strongly diluted by entrainment

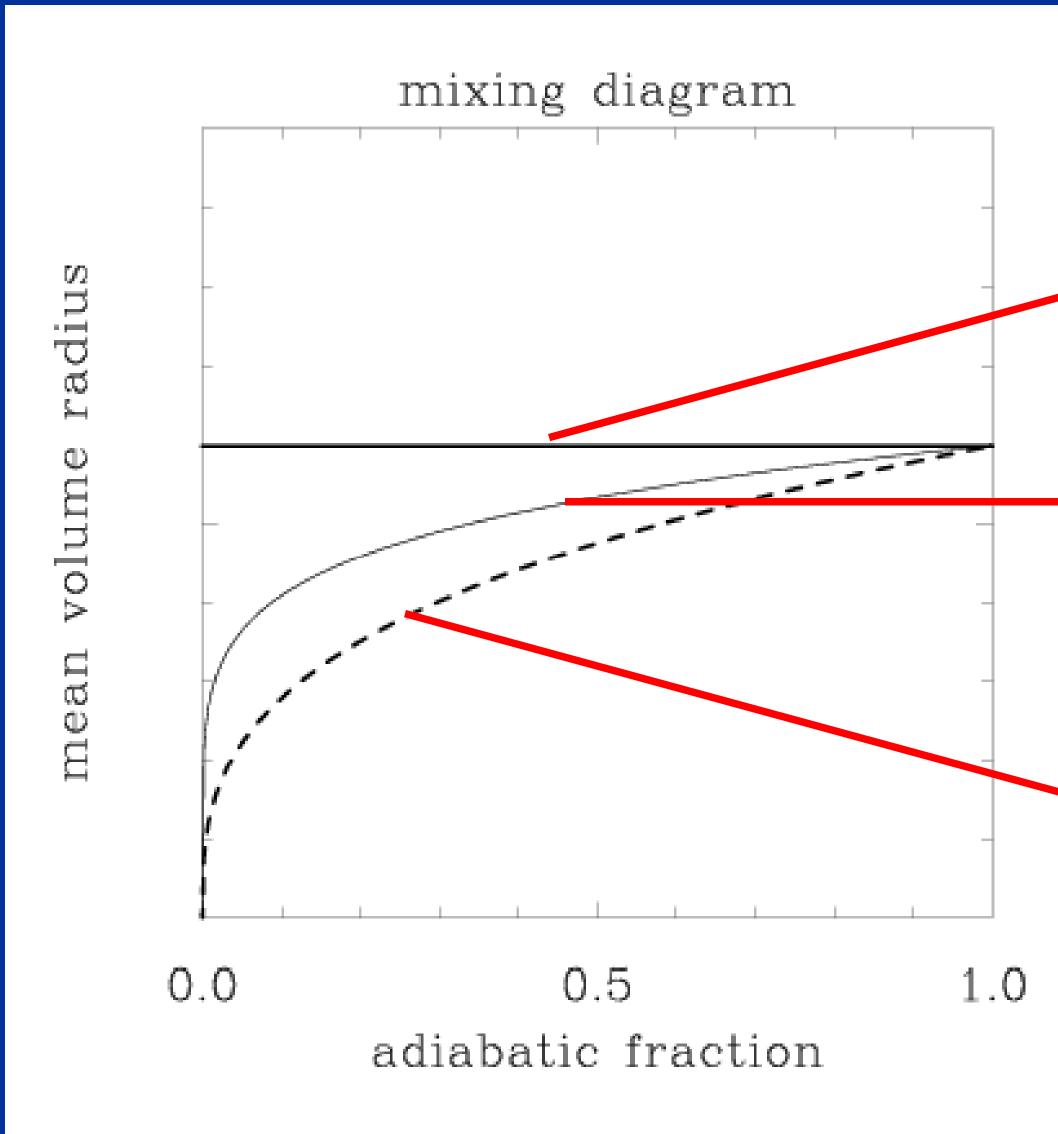
Siebesma et al. JAS 2003



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



What is wrong with this picture?



Extremely inhomogeneous: droplet evaporation much faster than turbulent mixing

Inhomogeneous; DNS simulations (Andrejczuk et al JAS 2004, 2006)

Homogeneous: turbulent mixing much faster than droplet evaporation

Does it matter for the mean albedo?

Assumptions about changes of cloud droplet spectra during entrainment and mixing have significant impact on mean scene albedo

Cloud scene	*CF* %	*LWP* g/m²	*H* m	N_{ad} cm^{-3}	Mixing scheme	A_{Vis} %	*PP bias* %
1	100	83	310	50	homogeneous	47	-2
					inhomogeneous	44	-8
				256	homogeneous	65	-2
					inhomogeneous	62	-7
				400	homogeneous	70	-2
					inhomogeneous	67	-6
2	63	8	130	50	homogeneous	11	-3
					inhomogeneous	9	-18
				256	homogeneous	17	-1
					inhomogeneous	13	-23
				400	homogeneous	20	-1
					inhomogeneous	15	-26
3	50	12	150	50	homogeneous	11	-3
					inhomogeneous	9	-23
				256	homogeneous	17	-4
					inhomogeneous	12	-31
				400	homogeneous	19	-3
					inhomogeneous	14	-31
4	17	12	230	50	homogeneous	8	-1
					inhomogeneous	7	-11
				256	homogeneous	10	-1
					inhomogeneous	8	-17
				400	homogeneous	11	-1
					inhomogeneous	9	-19

(Chosson et al. JAS 2007)

A Large Eddy Simulation Intercomparison Study of Shallow Cumulus Convection

A. Pier Siebesma,[a] Christopher S. Bretherton,[b] Andrew Brown,[c] Andreas Chlond,[d] Joan Cuxart,[e] Peter G. Duynkerke,[f*] Hongli Jiang,[g] Marat Khairoutdinov,[h] David Lewellen,[i] Chin-Hoh Moeng,[j] Enrique Sanchez,[k] Bjorn Stevens,[l] and David E. Stevens[m]

Journal of the Atmospheric Sciences, 2003

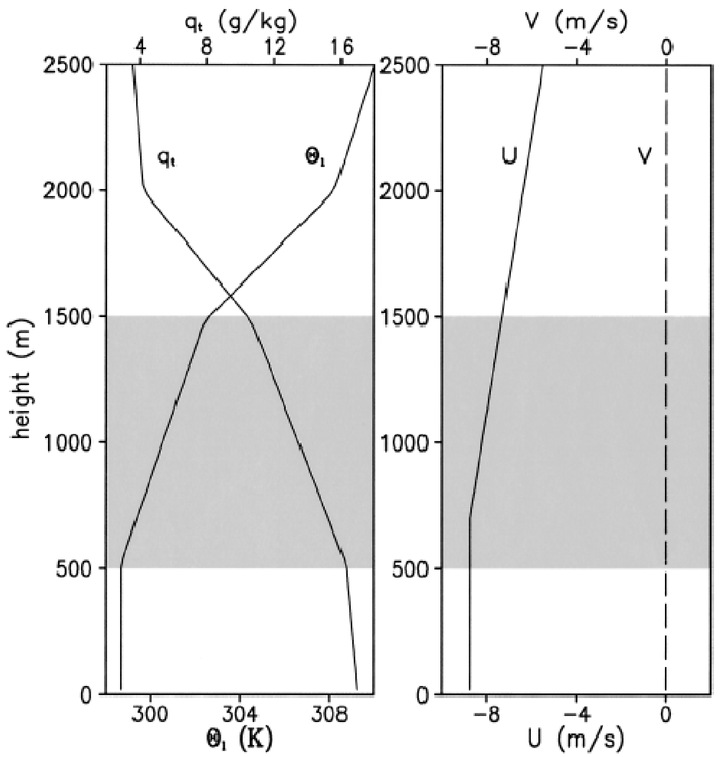
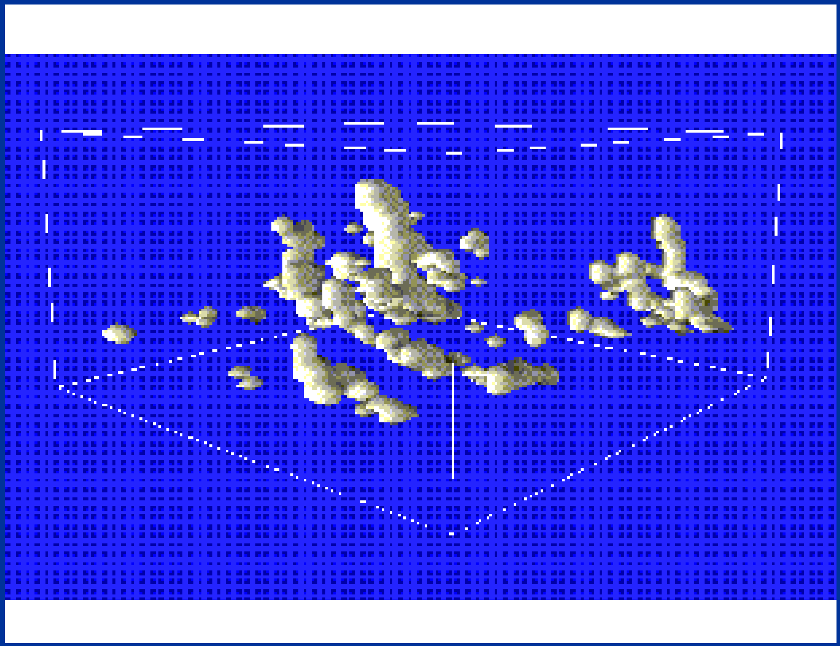


FIG. 1. Initial profiles of the total water specific humidity q_t, the liquid water potential temperature θ_ℓ, and the horizontal wind components u and v. The shaded area denotes the conditionally unstable cloud layer.



Slawinska et al. (J. Climate 2008)

Table 1: Mean values of the optical thickness τ, $\overline{r}_e$, TOA albedo A_{cloudy}, and net solar flux at the surface SF_{cloudy} for various mixing scenarios. Only model columns with LWP larger than 5×10^{-3} kg m^{-2} are included in the analysis. See text for details.

	PRISTINE				POLLUTED			
mixing scenario	(u)	(h)	(in)	(ei)	(u)	(h)	(in)	(ei)
τ (1)	11.5	10.4	9.0	7.7	23.5	21.2	18.3	15.8
$\overline{r}_e$ (μm)	8.1	9.1	11.1	13.6	4.0	4.4	5.4	6.7
A_{cloudy} (1)	0.332	0.320	0.292	0.270	0.454	0.441	0.409	0.381
SF_{cloudy} (W m^{-2})	229	234	245	255	177	182	196	208

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, $A \approx 10^{-10}\ \mathrm{m^2 s^{-1}}$, 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 $\epsilon = 100\ \mathrm{cm^2 s^{-3}}$:

$\tau_t \approx 0.2$ 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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(NB: This problem is similar to modeling turbulent combustion.)

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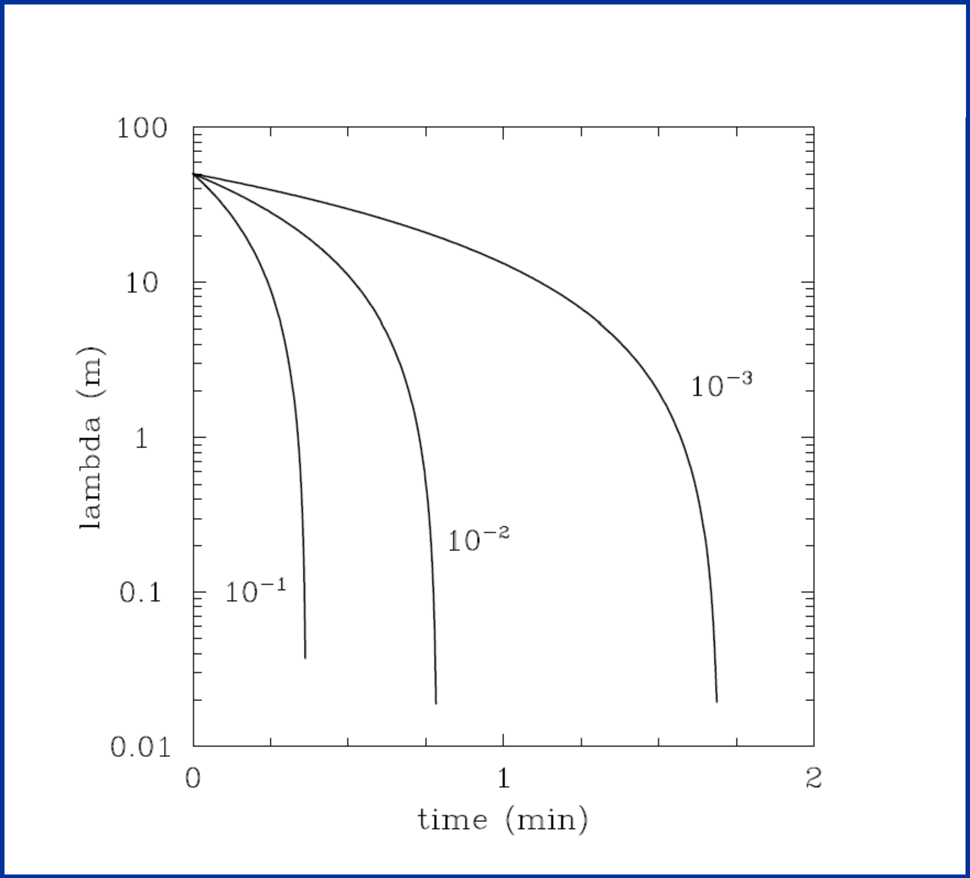
C **– condensation rate, defined by a constraint that cloudy air is always at water saturation (instantaneous adjustment).**

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:

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

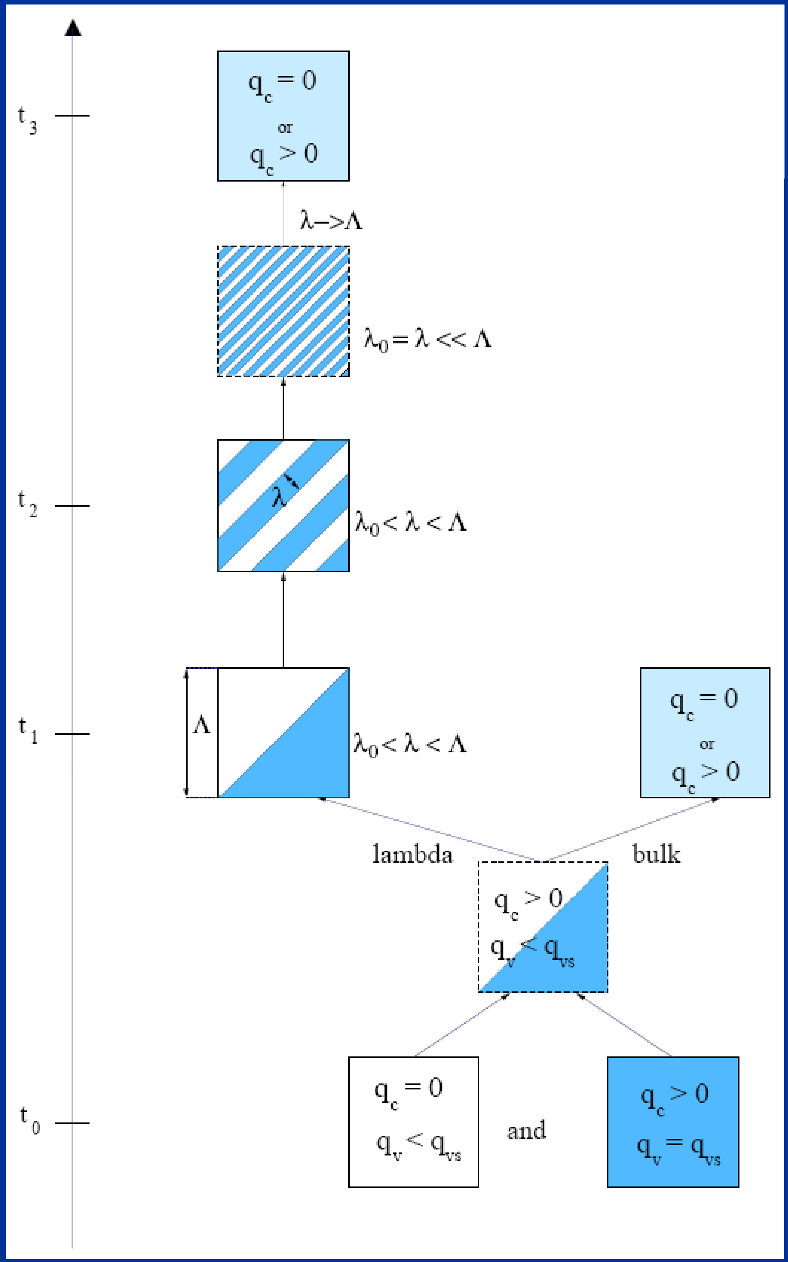
$$\epsilon = c_\epsilon \frac{E^{3/2}}{\Lambda}$$

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., Int. Conf. on Clouds and Precipitation, ICCP, 2008)

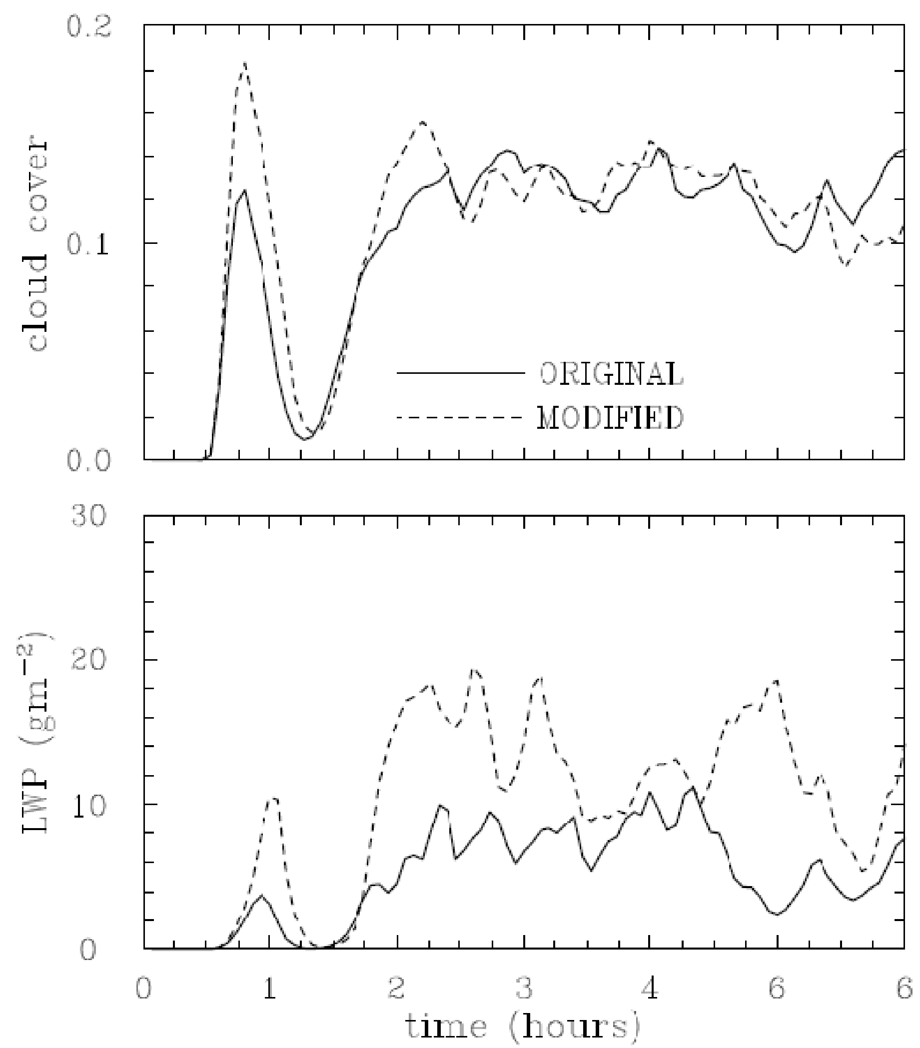


Figure 8: Evolutions of the cloud cover and liquid water path in BOMEX simulations using either the original (solid lines) or the modified (dashed lines) approaches.

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

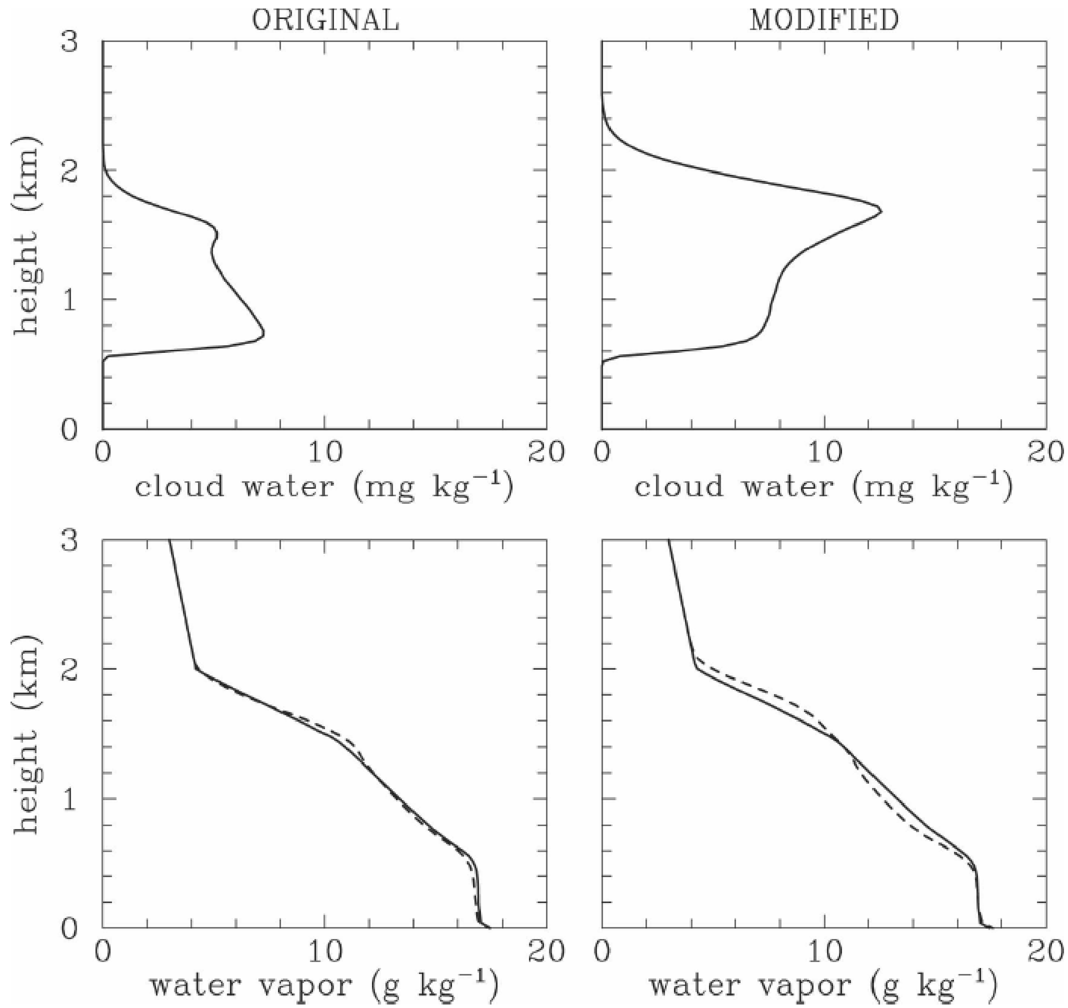
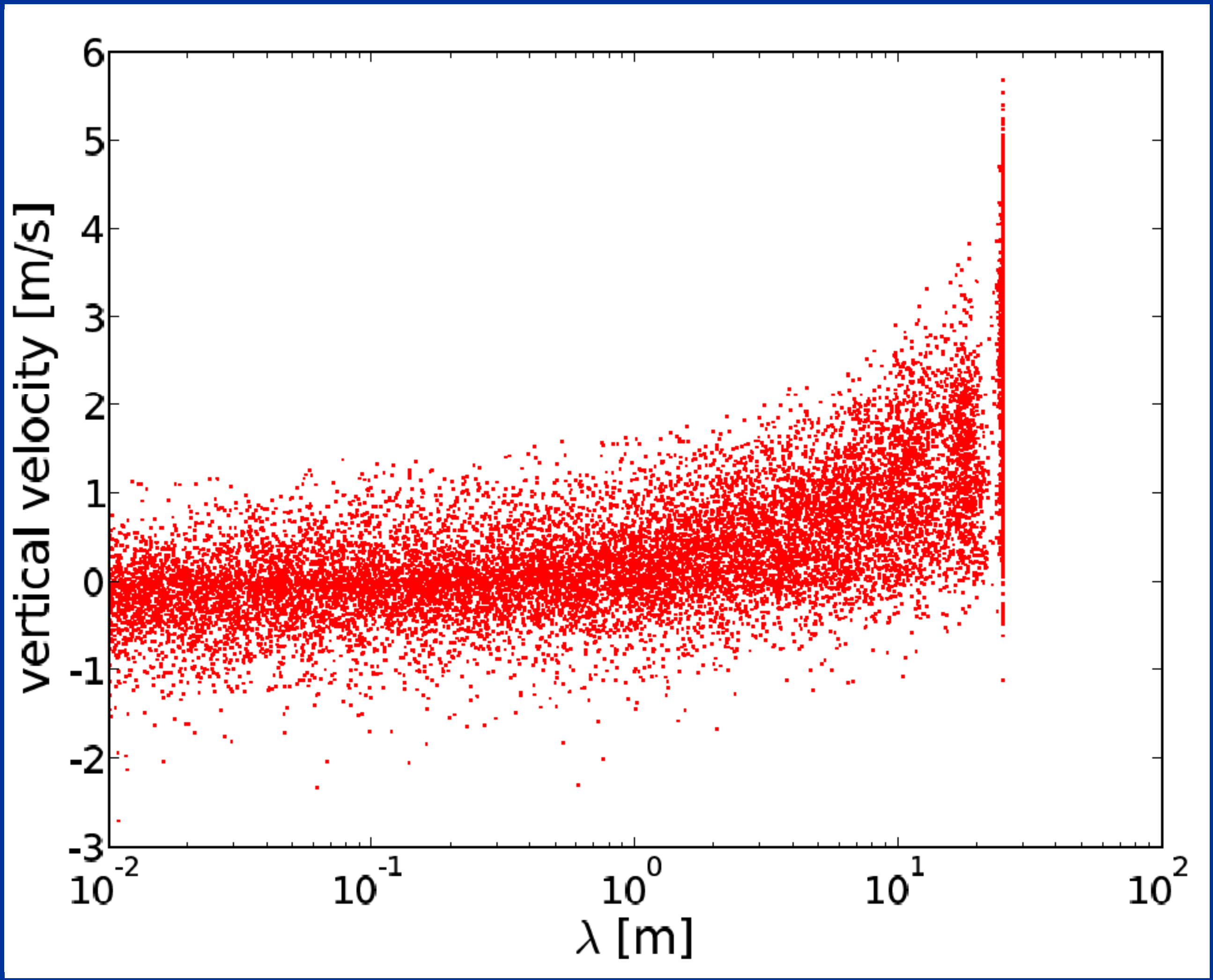


FIG. 10. Profiles of the (top) cloud water mixing ratio (4-h averages) and (bottom) water vapor mixing ratios at (solid lines) 2 h and (dashed lines) 6 h in BOMEX simulations using either the (left) original or (right) modified approaches.

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



Simulation of a field of shallow convective clouds; Jarecka et al. ICCP 2008

This is work in progress…

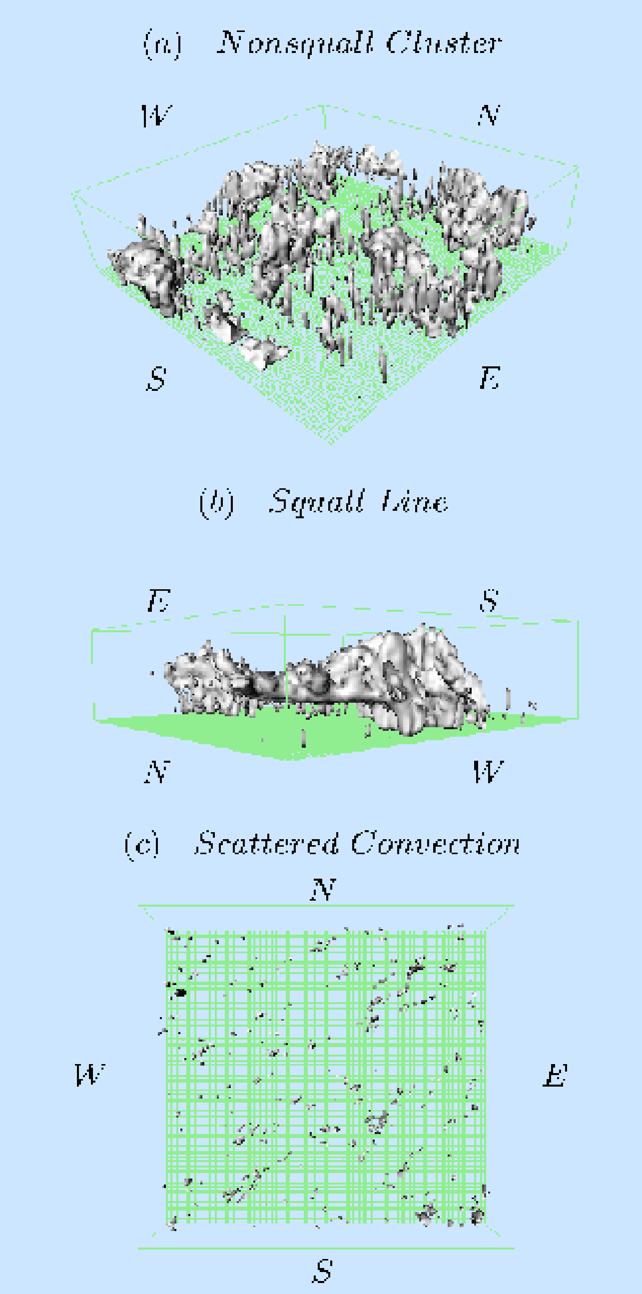
The idea is to apply such a subgrid-scale model with more sophisticated representation of cloud microphysics (a double-moment bulk scheme, bin microphysics, etc.) to locally predict cloud droplet sizes.

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)

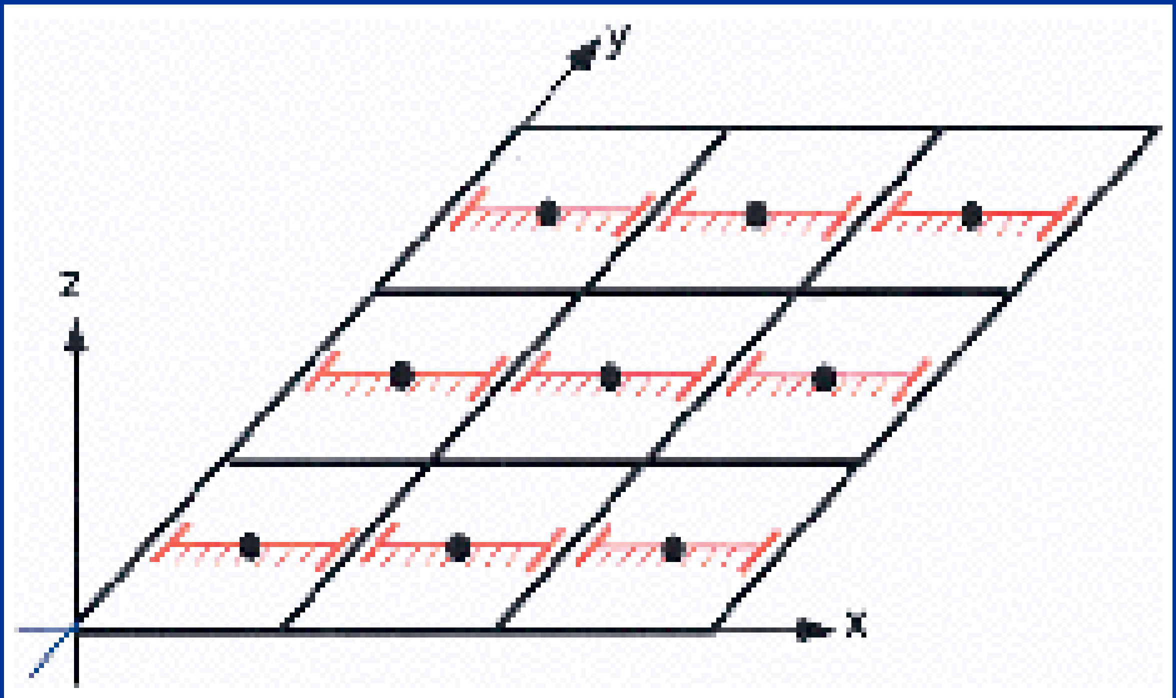
Grabowski and Smolarkiewicz, Physica D 1999

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:

“A day, a year, a millennium” paradigm

With the same amount of computer time, one can perform:

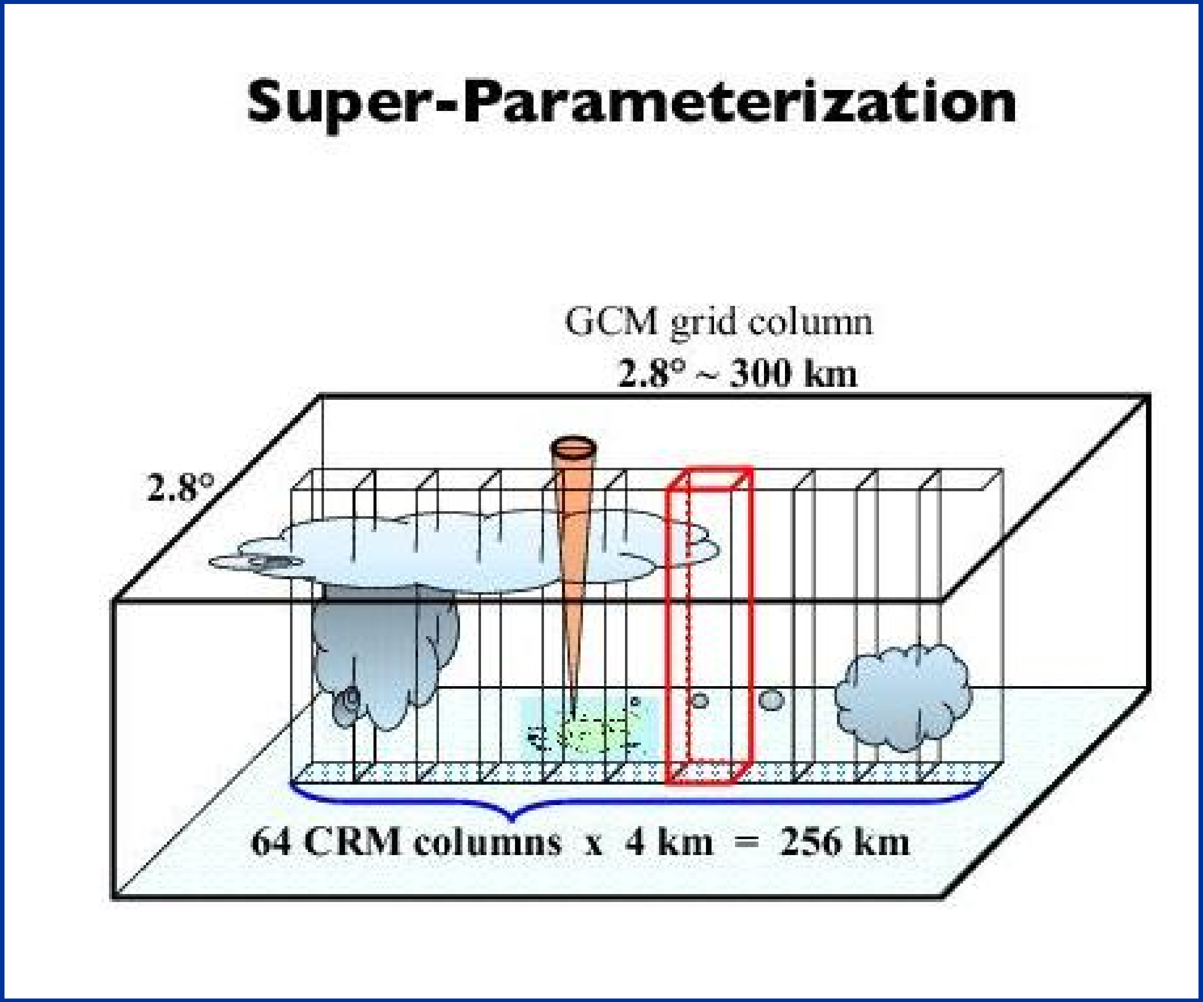
- about a day-long simulation using cloud-resolving AGCM
- about a year-long climate simulation using AGCM with super-parameterization
- about a millennium-long climate simulation using a traditional AGCM

Examples of applications:

- Atmospheric General Circulation Model (AGCM) simulations; …. using Community Atmosphere Model (atmospheric component of NCAR's Community Climate Model); Colorado State University's Multiscale Modeling Framework (Marat Khairoutdinov, Dave Randall, …), see http://cmmap.colostate.edu

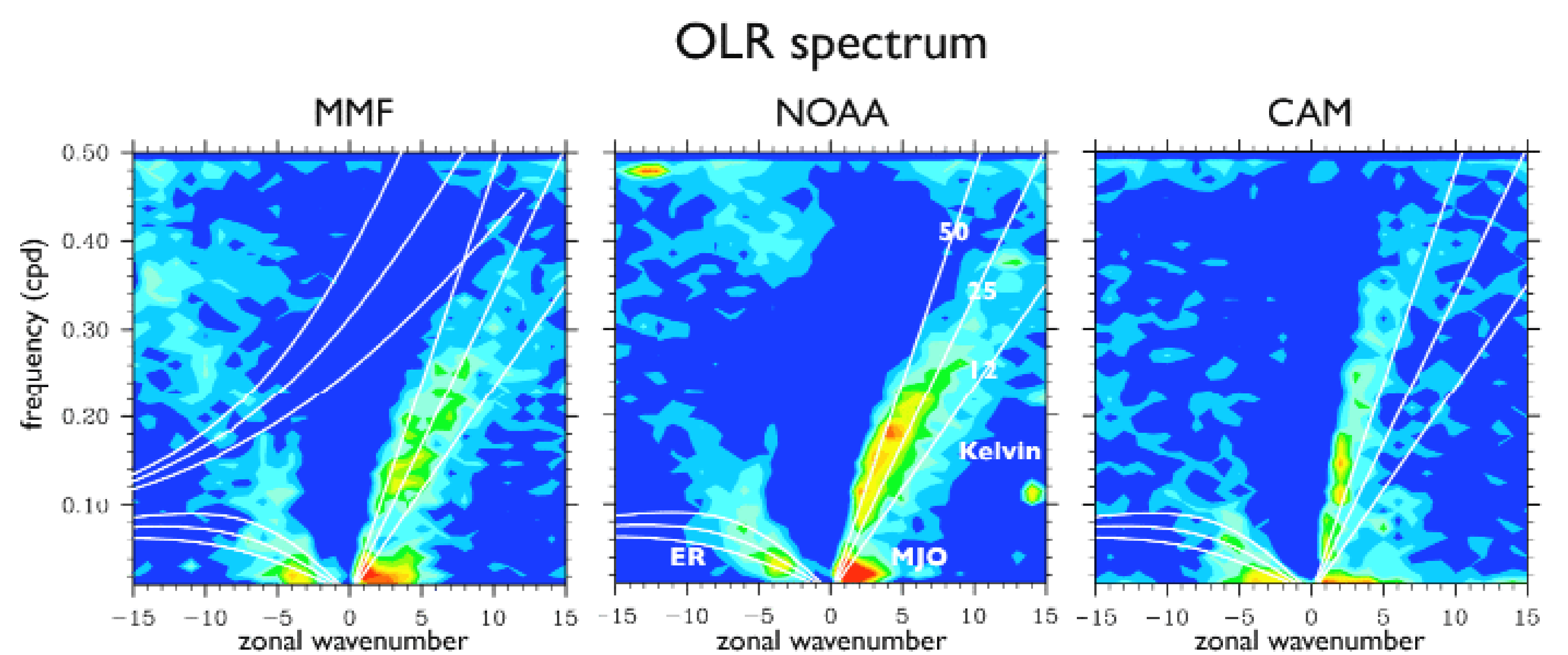
- Limited-area model simulations (possible application in a regional climate model)

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



(figure provided by M. Khairoutdinov)

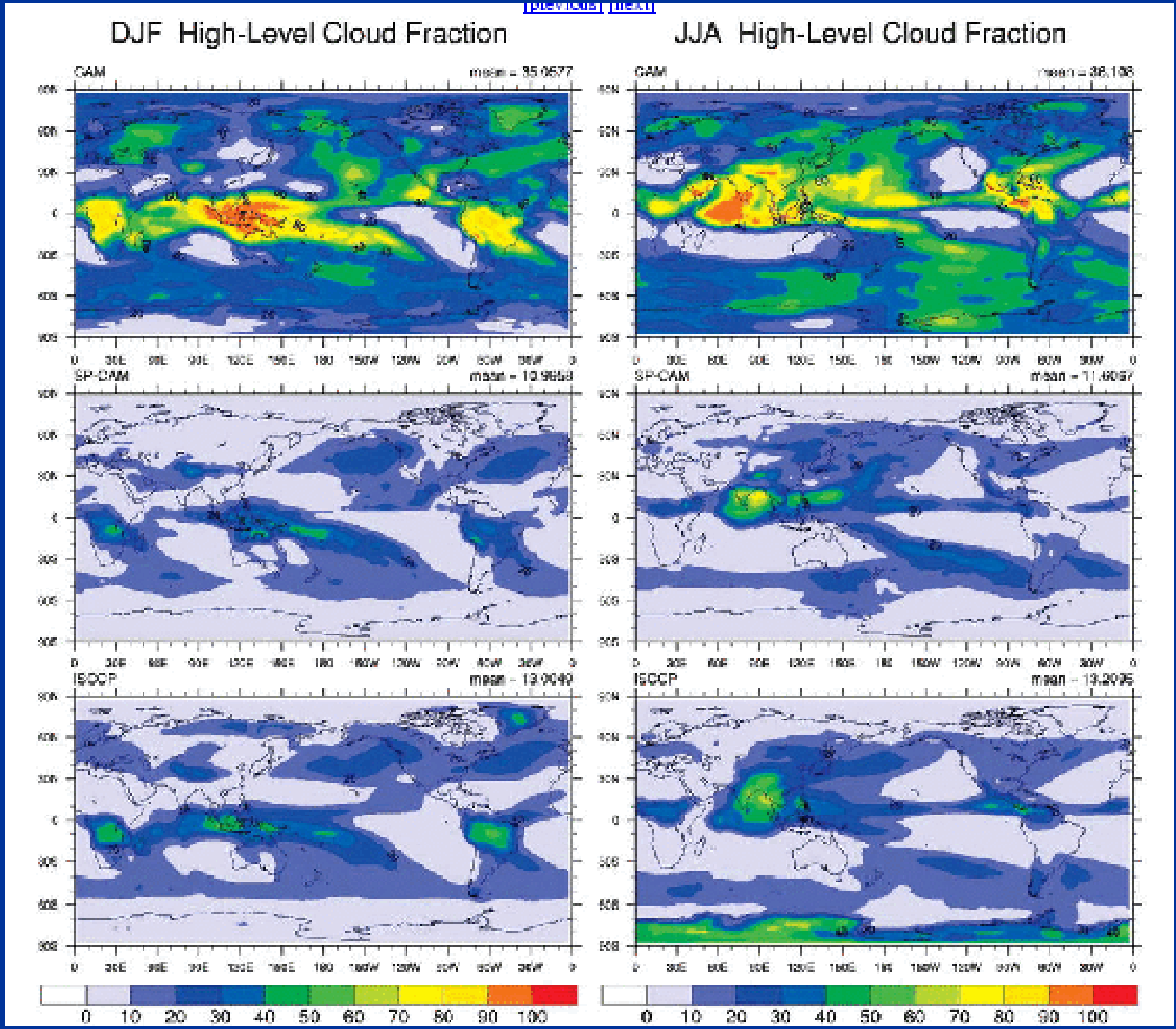
Results from a traditional climate model versus SP climate model

Khairoutdinov et al. JAS 2005

Traditional

SP

Observations



Examples of applications:

- Atmospheric General Circulation Model (AGCM) simulations; …. using Community Atmosphere Model (atmospheric component of NCAR's Community Climate Model); Colorado State University's Multiscale Modeling Framework (Marat Khairoutdinov, Dave Randall, …), see http://cmmap.colostate.edu

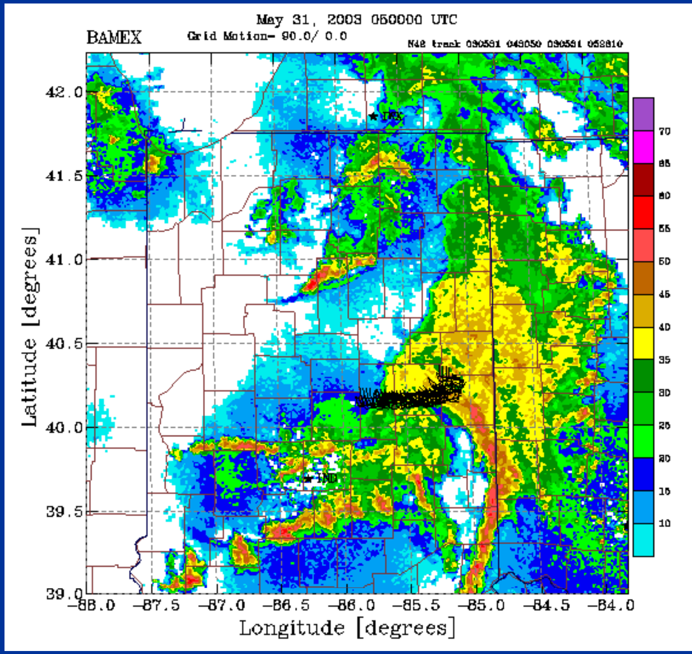
- Limited-area model simulations (possible application in a regional climate model)

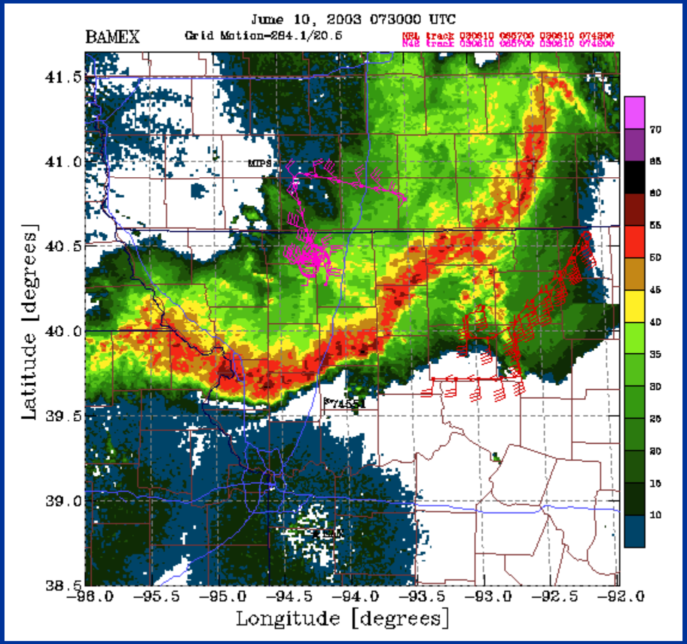
Can the super-parameterization approach be used in a mesoscale models (i.e., model with horizontal grid spacings in the range of 10-50 km)?

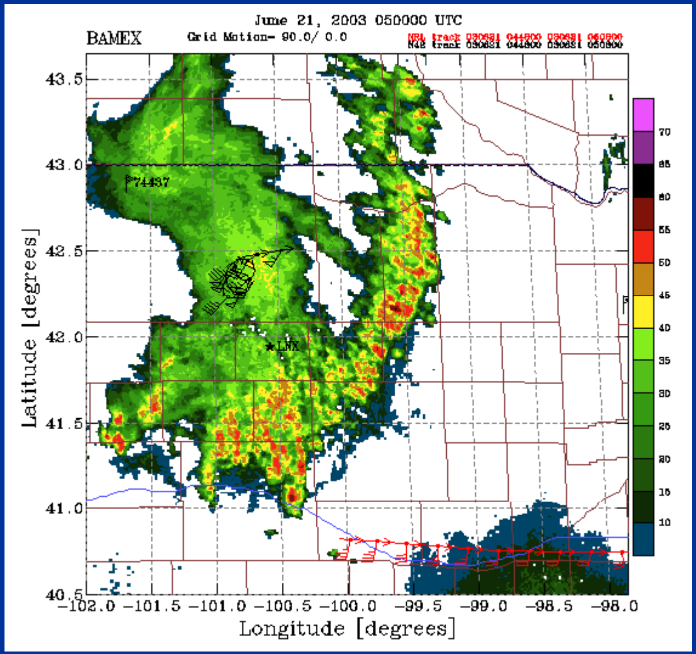
Compare idealized simulations using cloud-resolving model (CRM) and super-parameterization (SP)

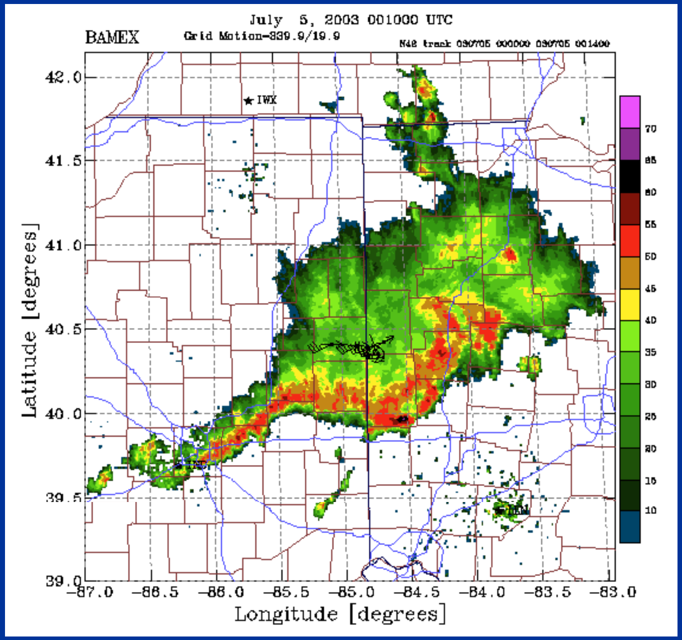
Grabowski MWR 2006 (comment to Jung and Arakawa MWR 2005)

Mesoscale Convective Systems – examples from BAMEX (Central US, May-July 2003)

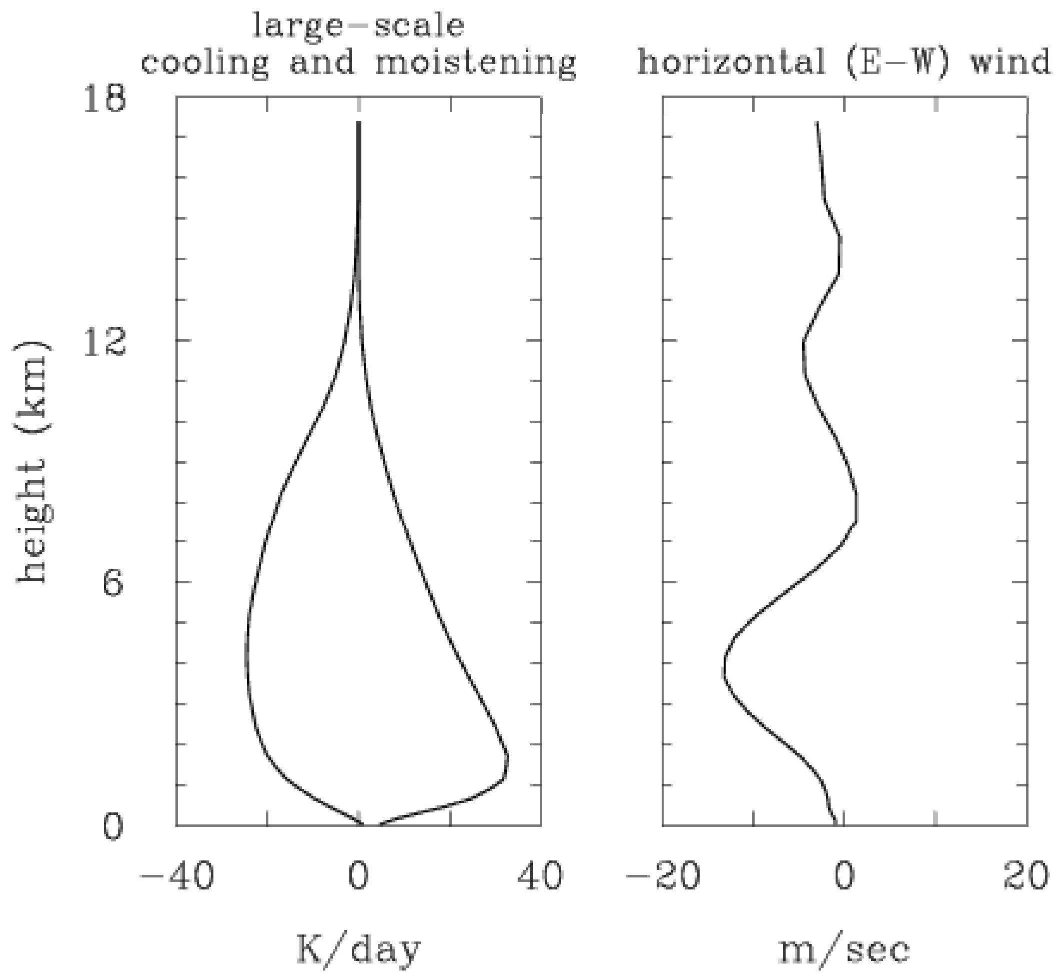




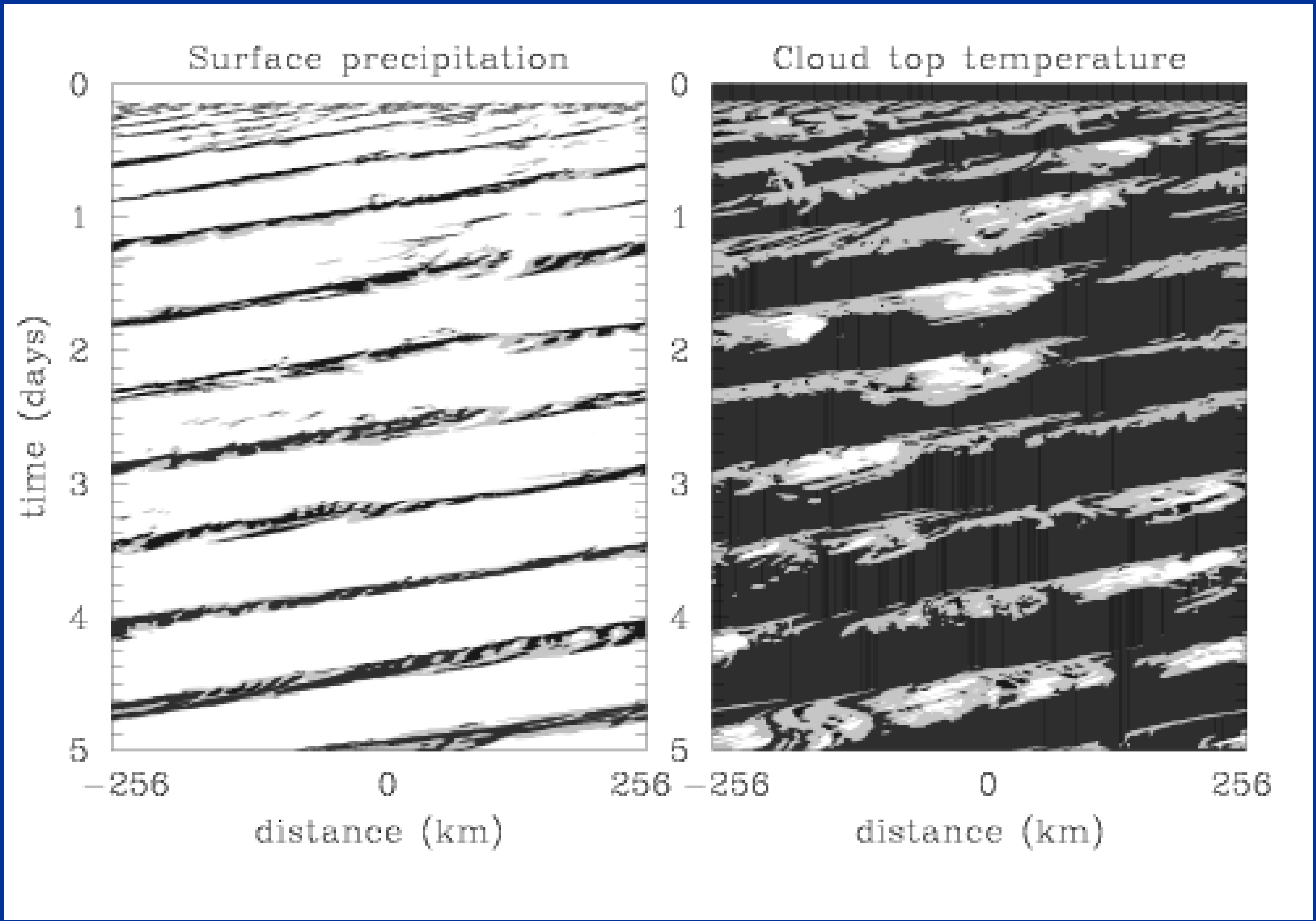




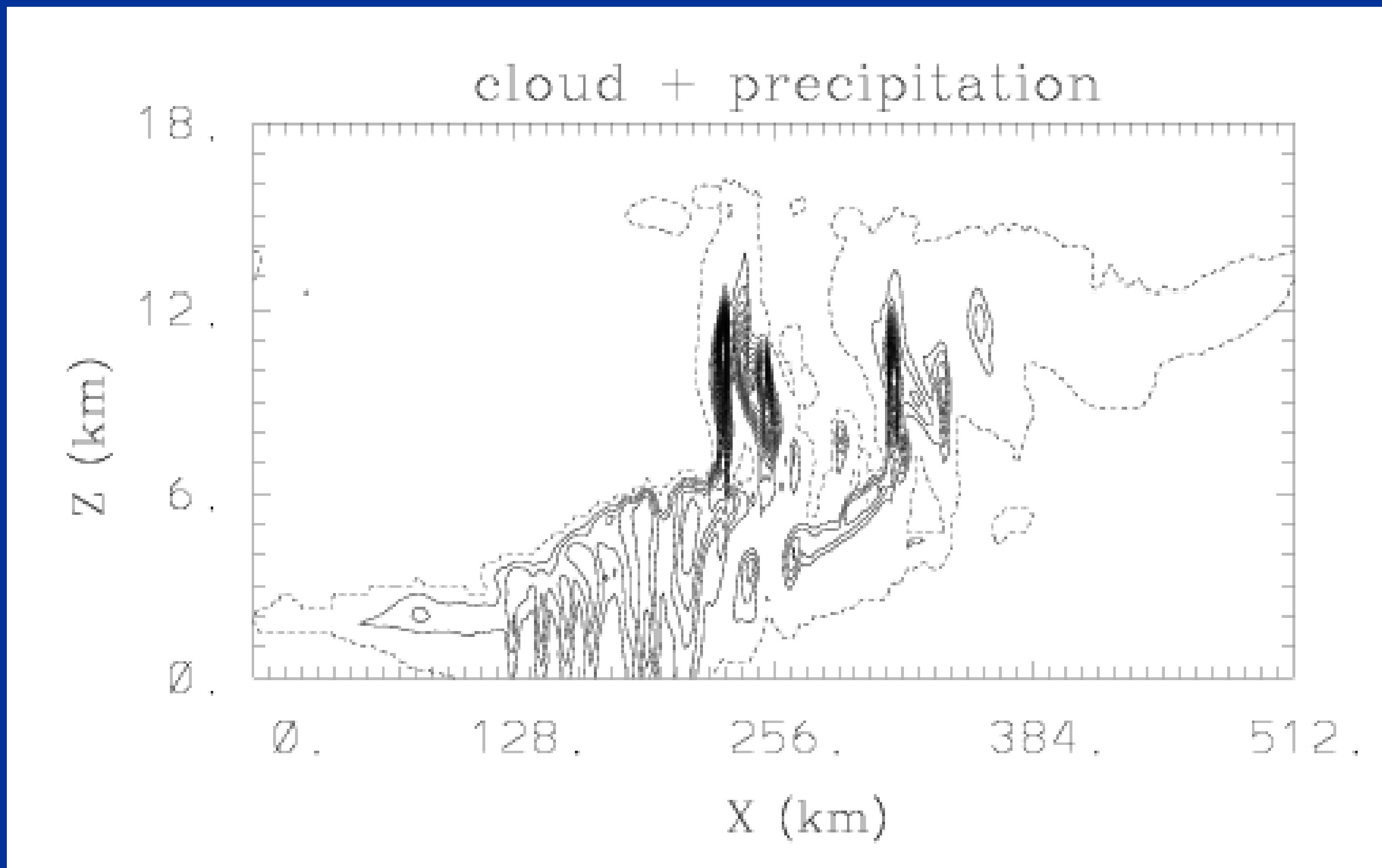
2D simulations of organized convection (a squall line) in the mean GATE environment (Jung and Arakawa MWR 2005)



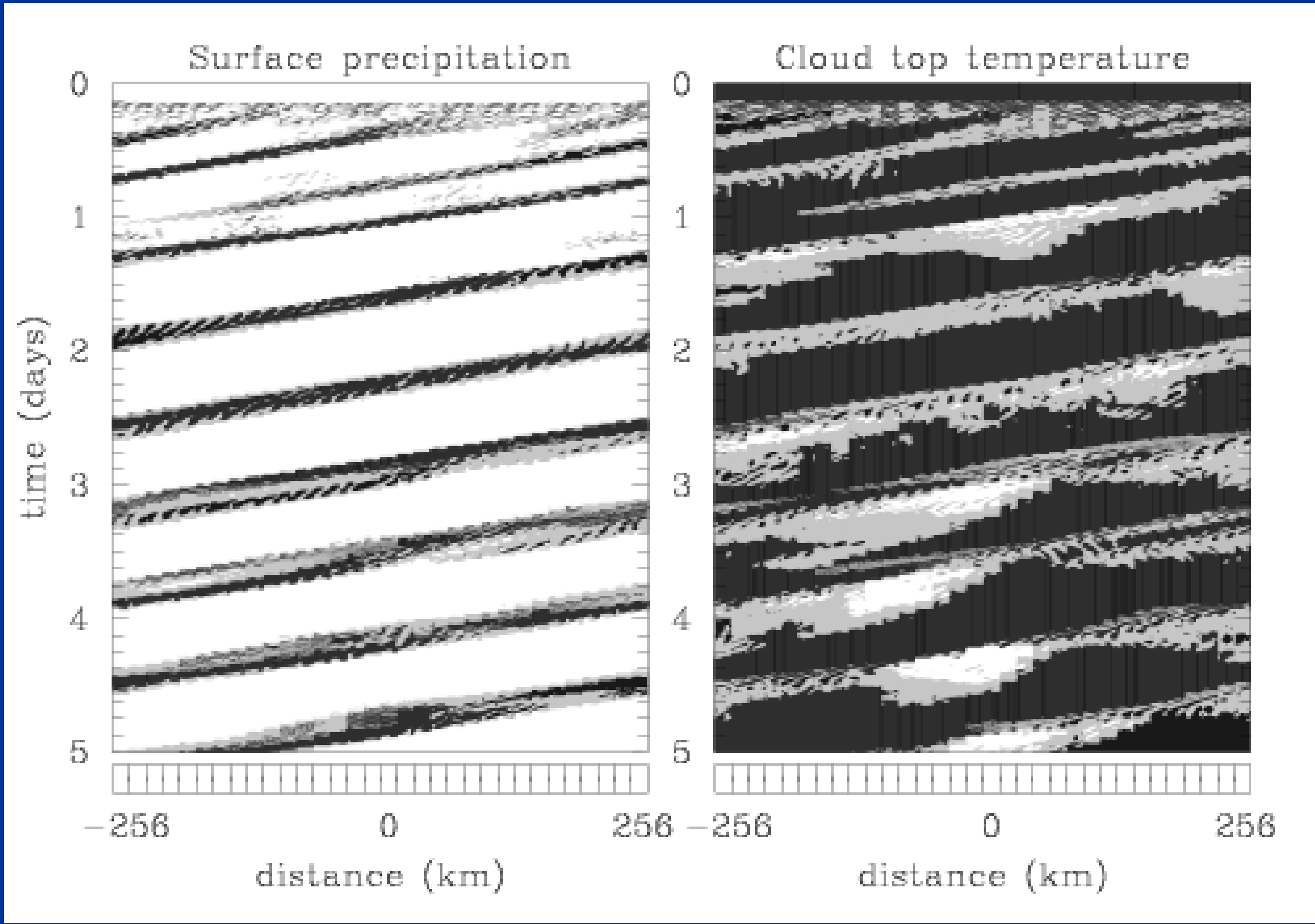
Cloud-resolving simulation (benchmark): Δx=2km



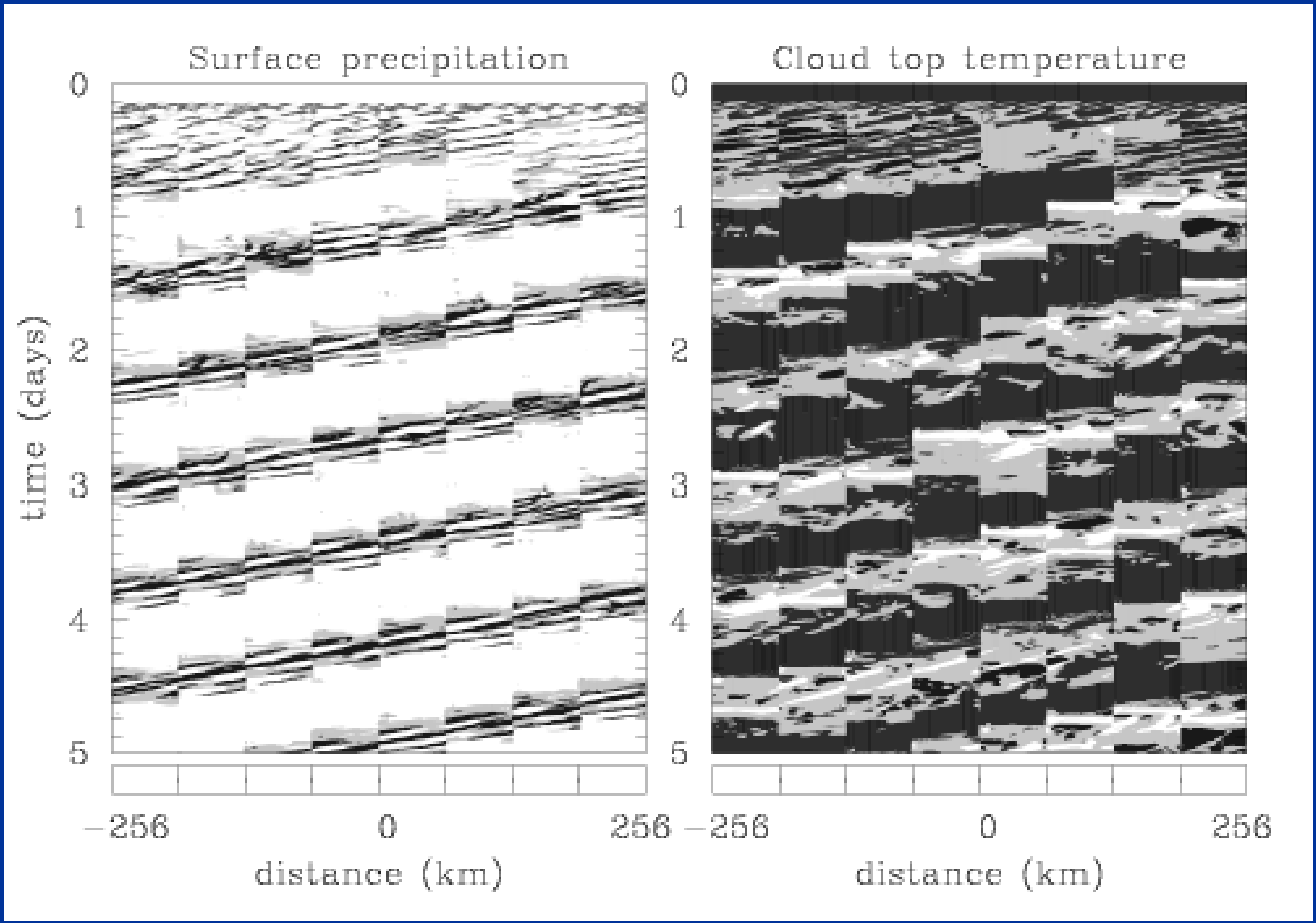
Cloud-resolving simulation (benchmark): Δx=2km



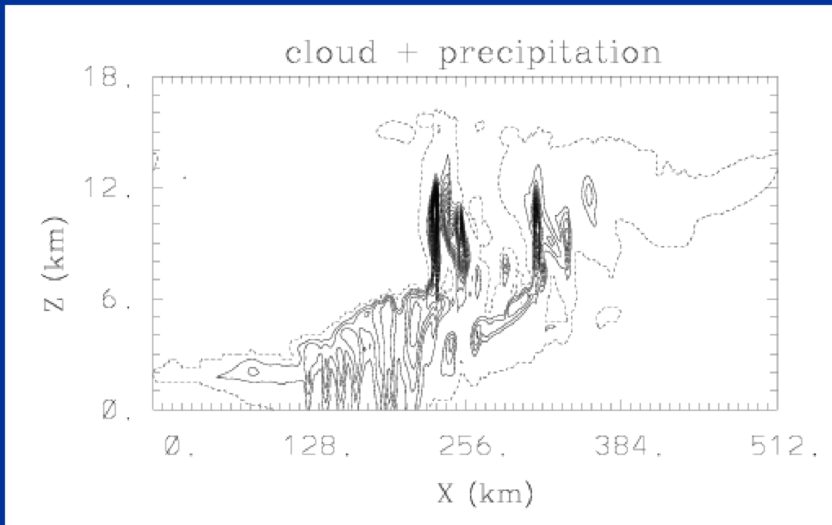
SP simulation: 32 columns with 16-km periodic small-scale models



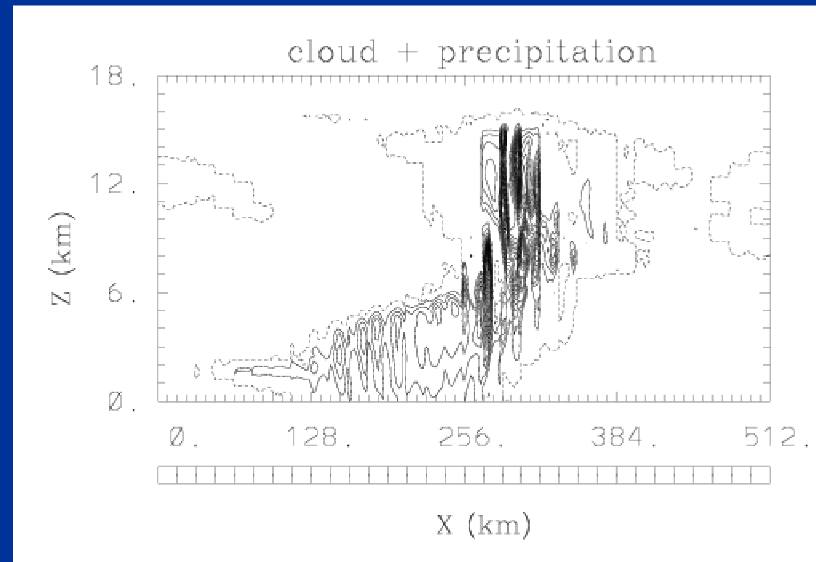
SP simulation: 8 columns with 64-km periodic small-scale models



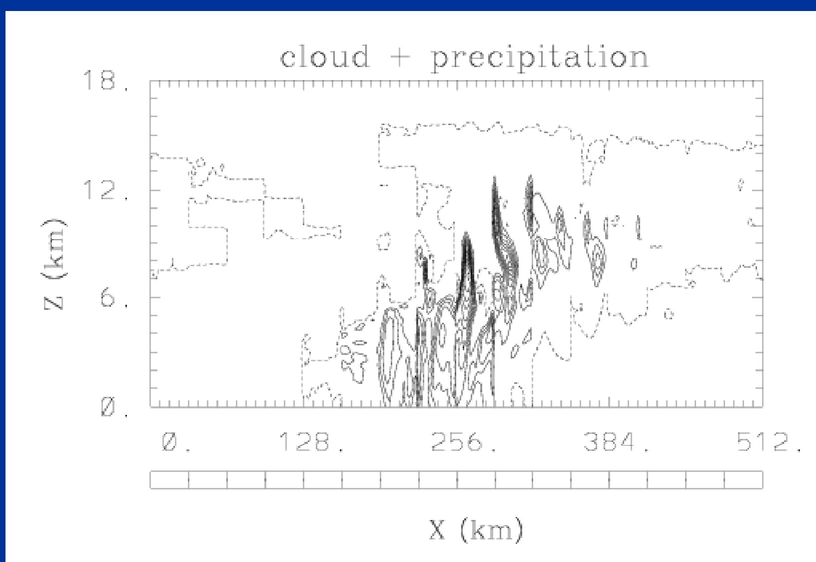
Cloud-resolving simulation (benchmark): Δx=2km



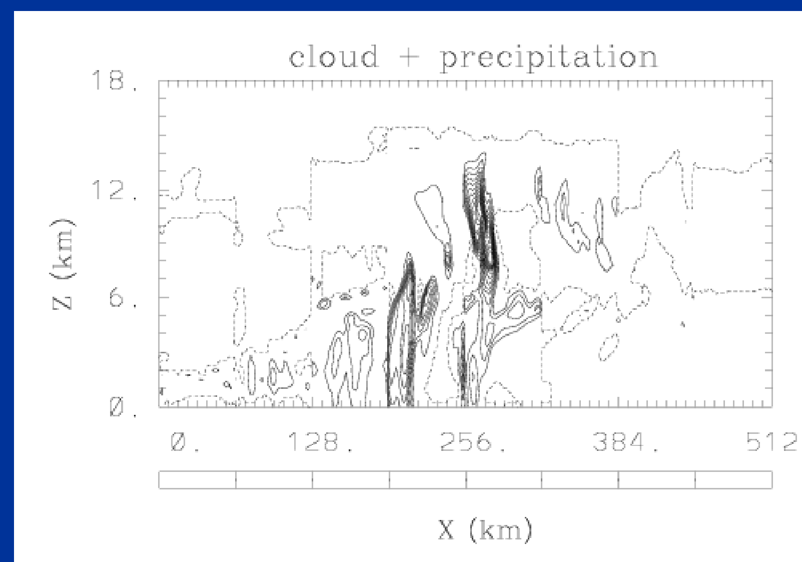
32 columns with 16-km periodic small-scale models



16 columns with 32-km periodic small-scale models



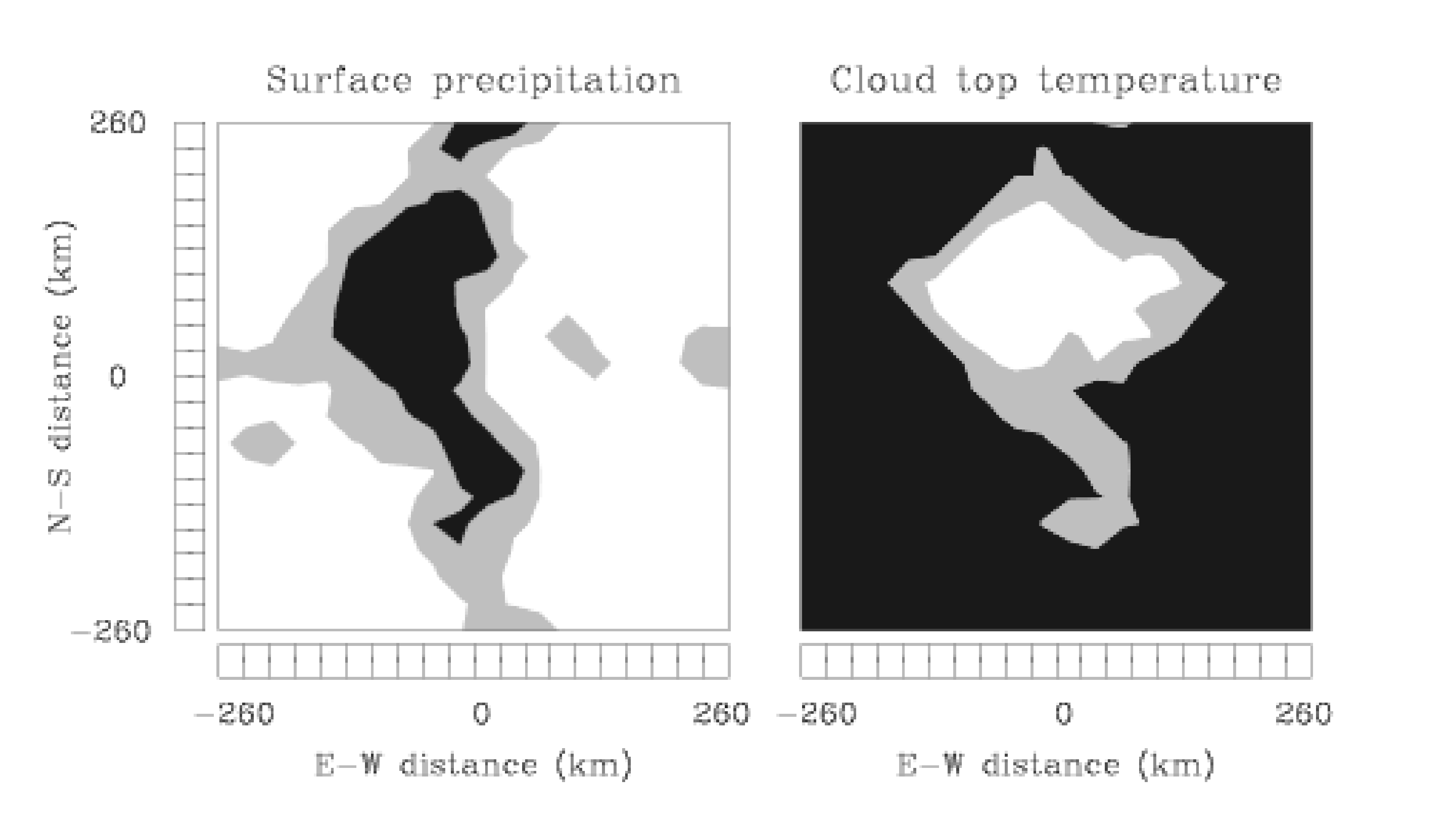
8 columns with 64-km periodic small-scale models



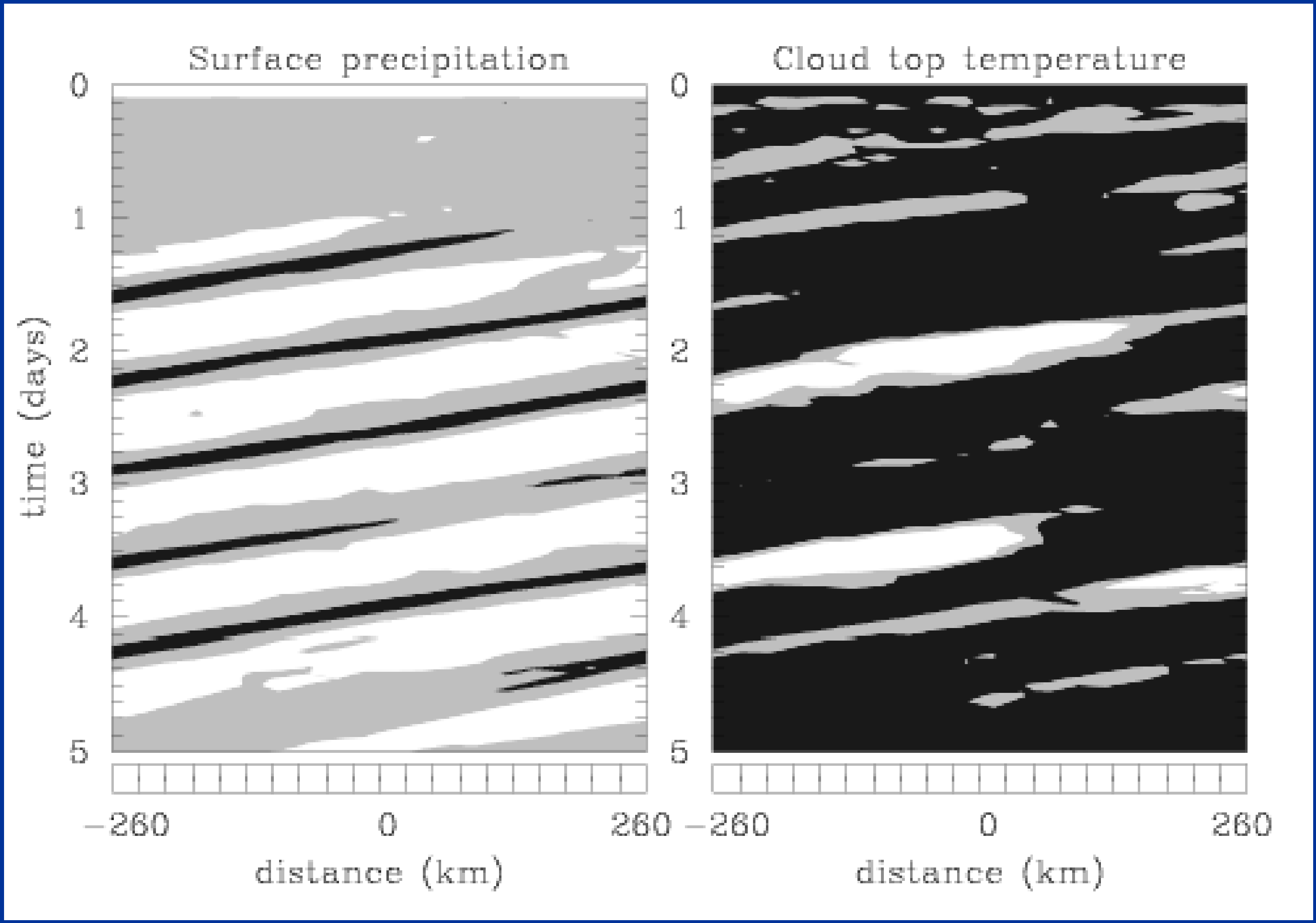
This approach extends naturally into 3D mesoscale model:

2D convective dynamics plus 3D mesoscale dynamics

Snapshots from a 3D simulation in the same setup as before, 520-km mesoscale domain, 26-km grid; 26-km SP domains aligned E-W



Hovmoeller diagrams of N-S averaged surface precipitation and cloud-top temperature from the 3D simulation



Superparameterization (SP) approach seems a better-posed problem for limited-area mesoscale models, such as regional climate models, than for temporary general circulation models.

SP model in a mesoscale model treats only convective-scale dynamics; mesoscale dynamics is them left for the 3D mesoscale model.

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.