Using Cloud-Resolving Models for Parameterization Development

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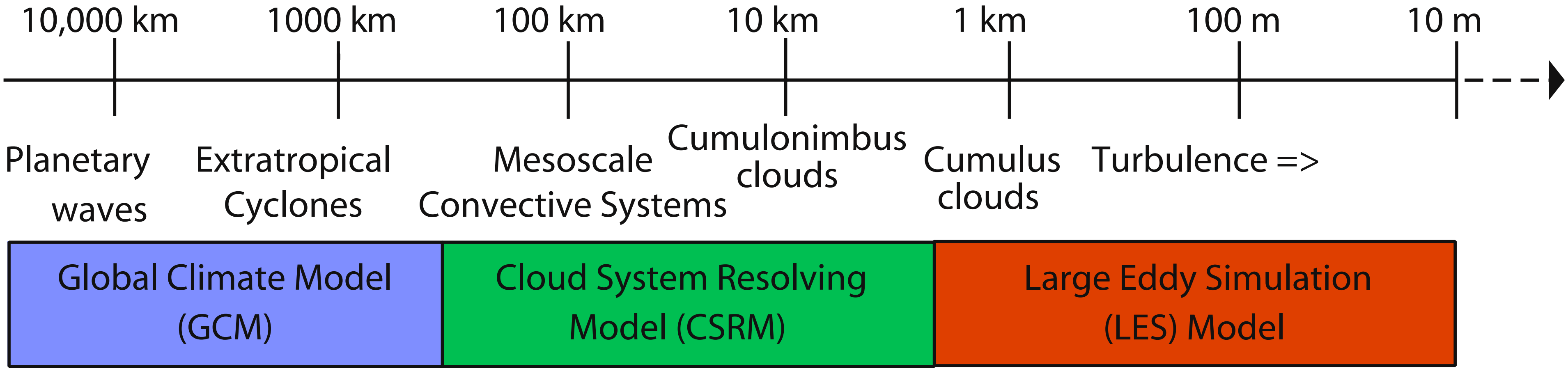
- What is are CRMs and why do we need them?
  - *Range of scales diagram*
  - (Define Cloud system resolving model)
- History of CRMs
  - *Yamasaki*:
    - **Yamasaki**, M. (1975). A **numerical experiment of the interaction between cumulus convection and larger scale motion**. Pap. Meteorol. Geophys. 26, 63-91.
  - Soong and Tao
  - Krueger and AA
- The UCLA CRM
  - Purpose: "cloud GCM"
  - Initial Design:
    - Origin was from Semtner's course
    - Vorticity-stream function: Arakawa Jacobian
    - Full 3d-moment turbulence closure (refer to Randall talk)
    - Warm-rain microphysics
    - Prescribed radiative heating

- Further development at U of Utah
  - Ice-phase microphysics (with Qiang Fu)
  - Interactive radiation (Qiang Fu)
- Applications to increased understanding of cloud systems
  - (list and select one or two for elaboration)
  - Two-dimensional cloud-resolving modeling of the atmospheric effects of Arctic leads based upon midwinter conditions at the Surface Heat Budget of the Arctic Ocean …
- Applications to parameterization development
  - (list and select several for elaboration)
  - UP
  - Luo studies
  - AA studies with his students
  - Jung & Arakawa

- Super parameterization and CSRMs
  - MMF uses embedded coarse-grid 2D CRMs for parameterization.
  - Shifted the focus to improving parameterization of physics that is SGS in CRMs.
  - This led to a return to turbulence parameterization in such CRMs, but now using the advances described by DR, and also extensive use of LESs for benchmarks.
  - Bogenschutz and Krueger: brief description of our approach.

- Giga LES
    - Is allowing us to examine the structures of deep convective cloud systems in unprecedented detail.
    - Resolves turbulence so produces accurate convective-scale vertical velocities.
    - Allows focus on microphysical processes which are still not resolved.
    - Also supports development of cumulus parameterizations that predict updraft vertical velocities and fractional area, not just updraft mass flux (e.g. UP).

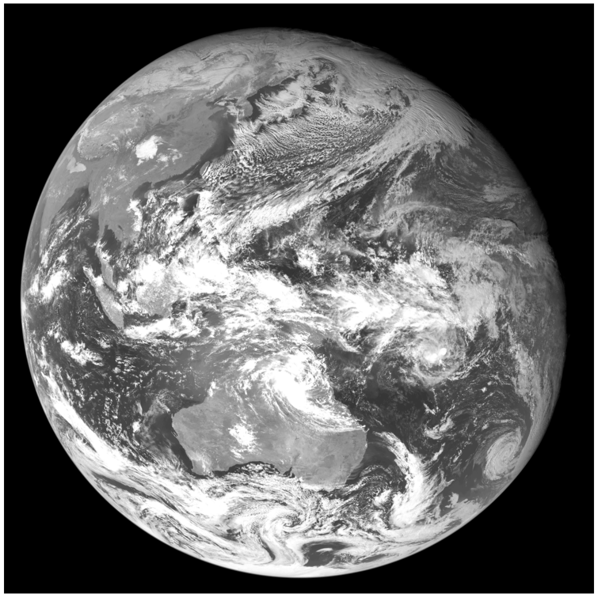
Scales of Atmospheric Motion

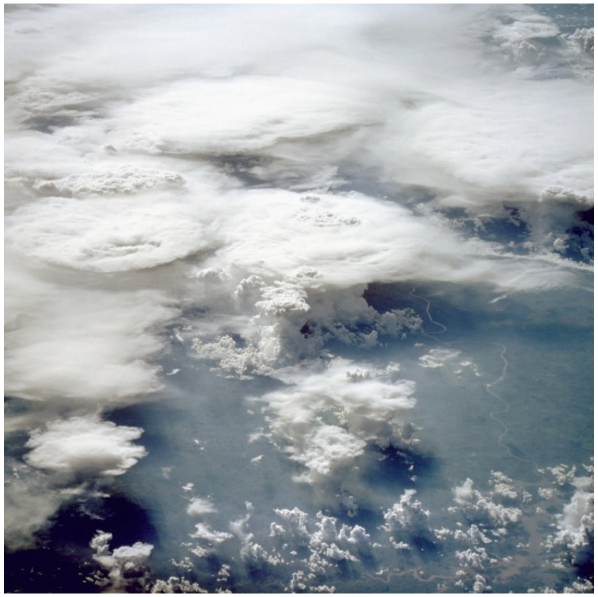


10,000 km
1000 km
100 km
10 km
1 km
100 m
10 m

Planetary waves
Extratropical Cyclones
Mesoscale Convective Systems
Cumulonimbus clouds
Cumulus clouds
Turbulence =>

Global Climate Model (GCM)
Cloud System Resolving Model (CSRM)
Large Eddy Simulation (LES) Model





The First CSRMs

気象研究所研究報告　第26巻　第3号　63−91頁　昭和50年9月
Papers in Meteorology and Geophysics Vol. 26, No. 3, pp, 63—91. September 1975

A Numerical Experiment of the Interaction between Cumulus Convection and Larger-scale Motion

by

Masanori Yamasaki

Meteorological Research Institute, Tokyo

(Received May 20, 1975)

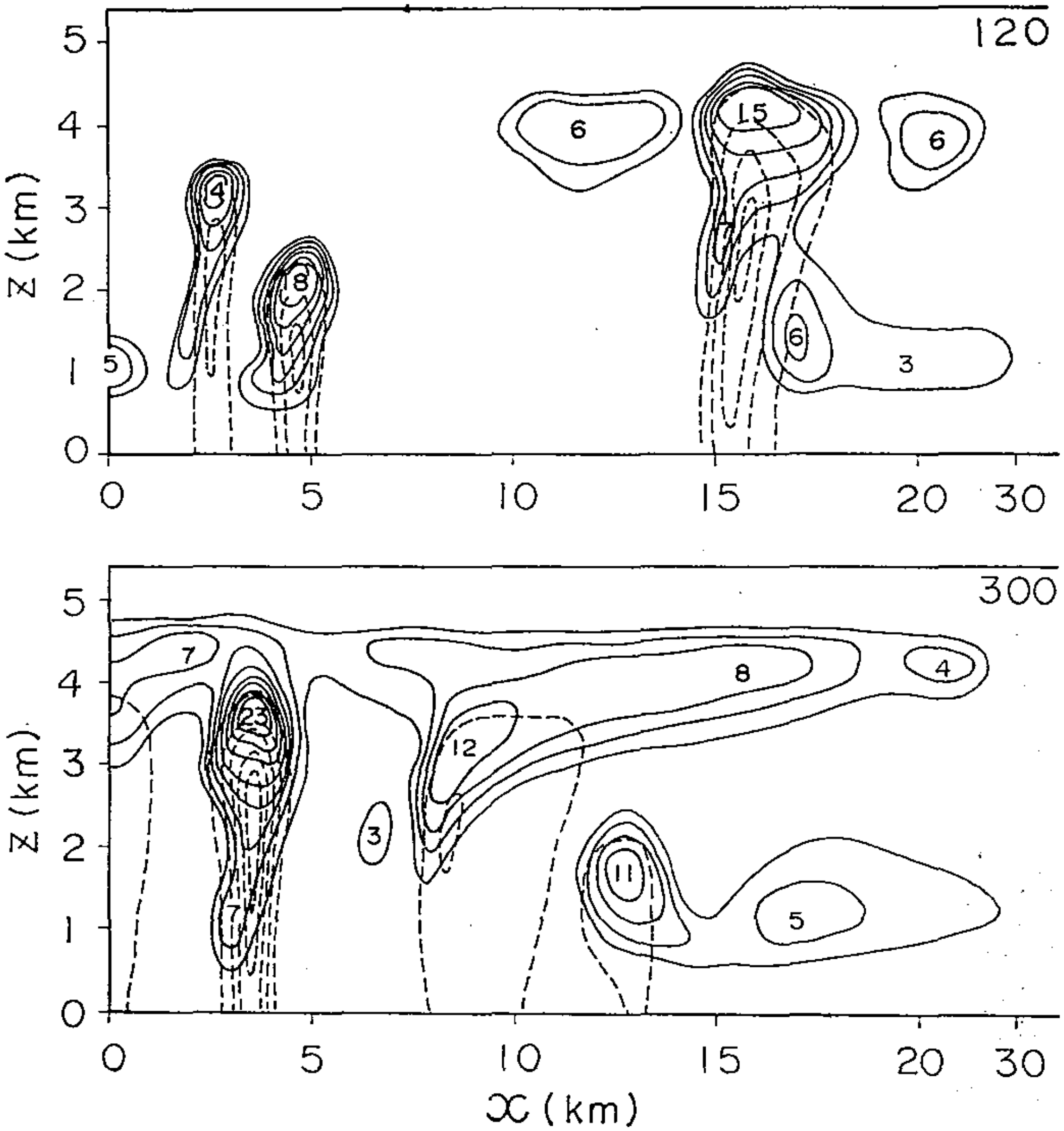
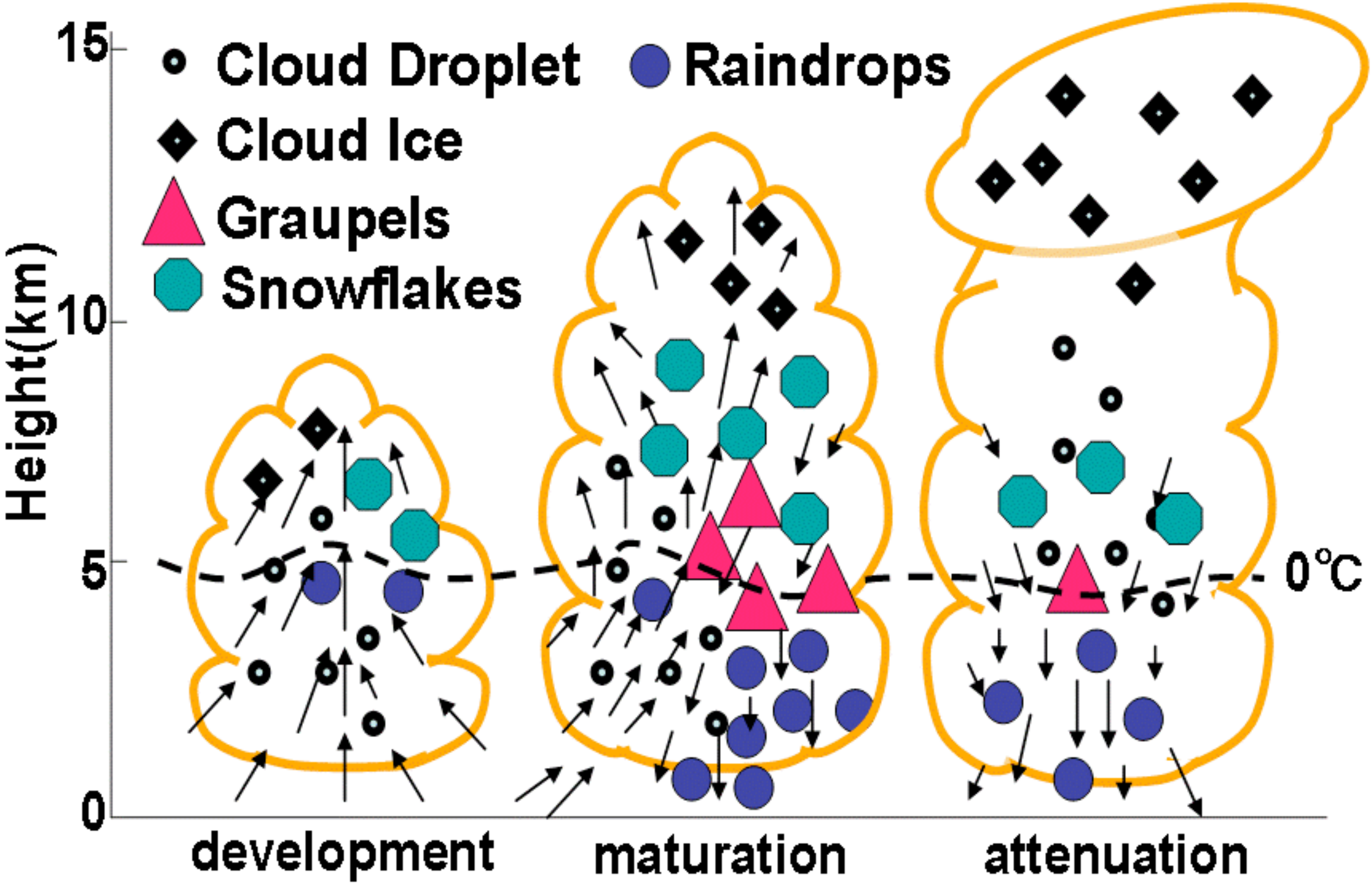


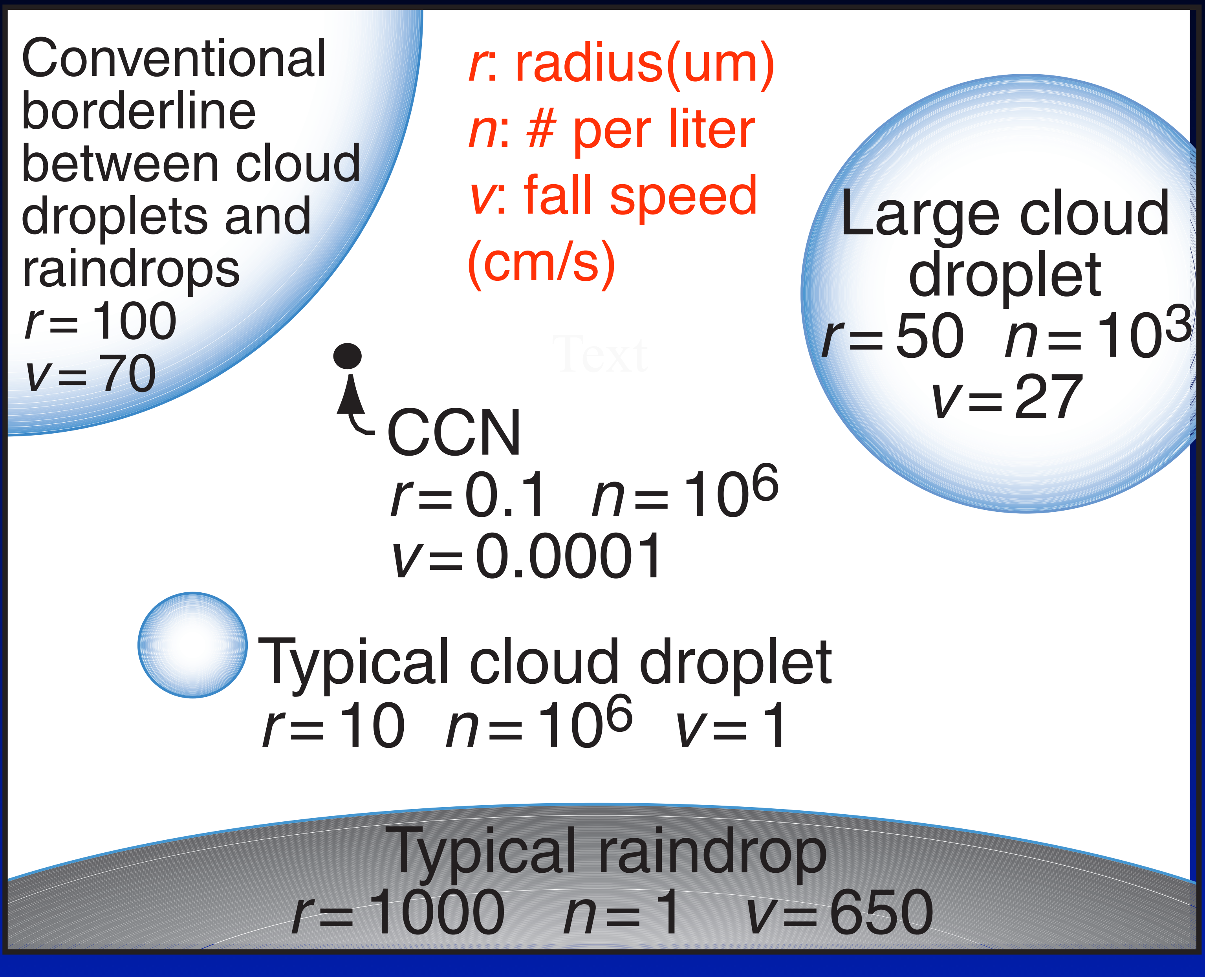
Fig. 4. Mixing ratio of rainwater (dashed lines) and mixing ratio of cloud water (solid lines) at 120 and 300 min. The dashed lines are drawn for 0.1, 0.5, 1.0, 2.0 and 3.0 g/kg.

giga LES

small scale structure and microphysics


Cloud Droplet
Raindrops
Cloud Ice
Graupels
Snowflakes
Height(km)
15
10
5
0
0°C
development
maturation
attenuation

Growth of Cloud Droplets in Warm Clouds



r: radius(um)
n: # per liter
v: fall speed (cm/s)

Conventional borderline between cloud droplets and raindrops
$r = 100$
$v = 70$

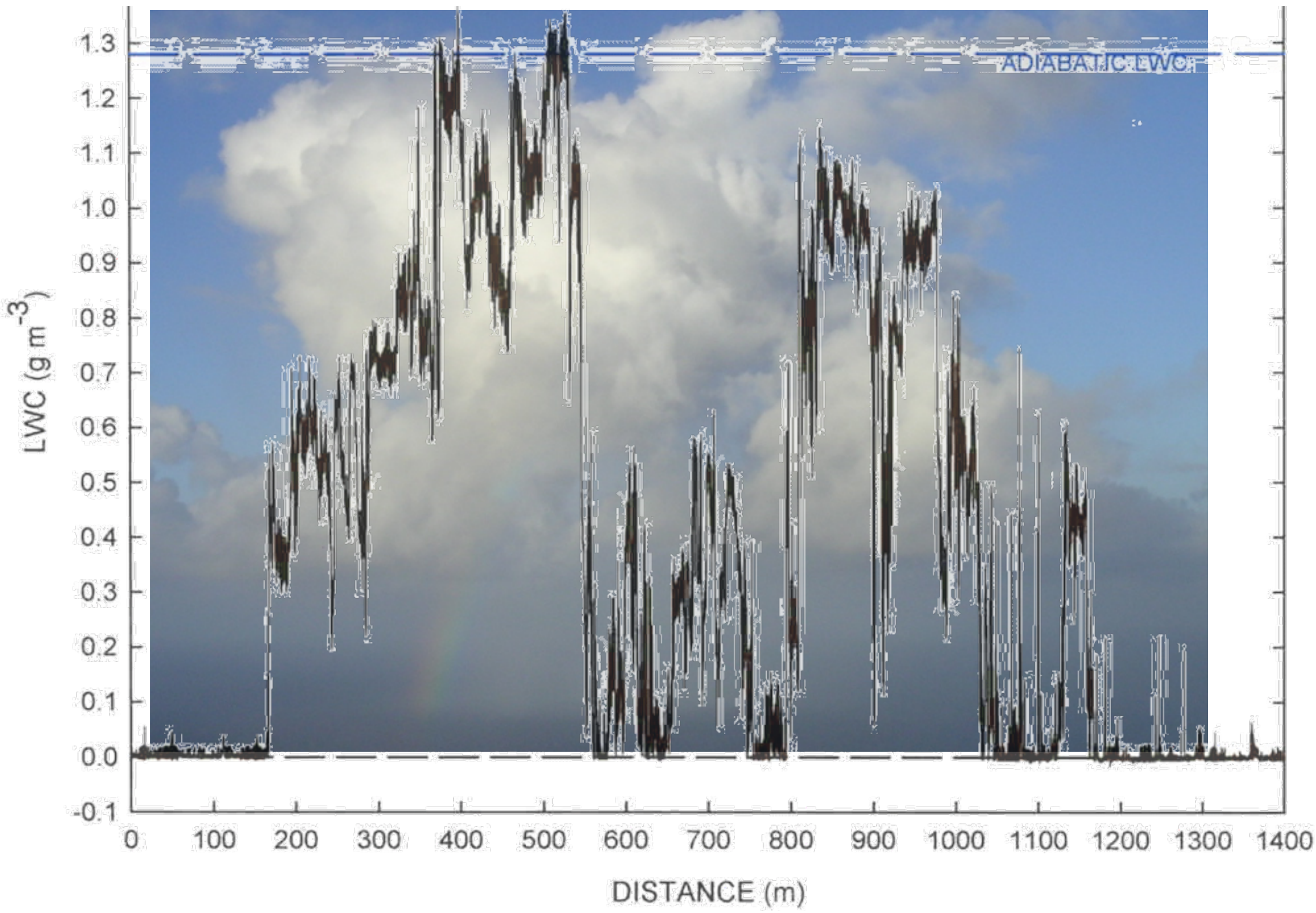
Large cloud droplet
$r = 50$ $n = 10^3$
$v = 27$

CCN
$r = 0.1$ $n = 10^6$
$v = 0.0001$

Typical cloud droplet
$r = 10$ $n = 10^6$ $v = 1$

Typical raindrop
$r = 1000$ $n = 1$ $v = 650$

Small-scale variability in Cumulus mediocris



overlay is for illustration only

Small-scale variability in Cumulus fractus

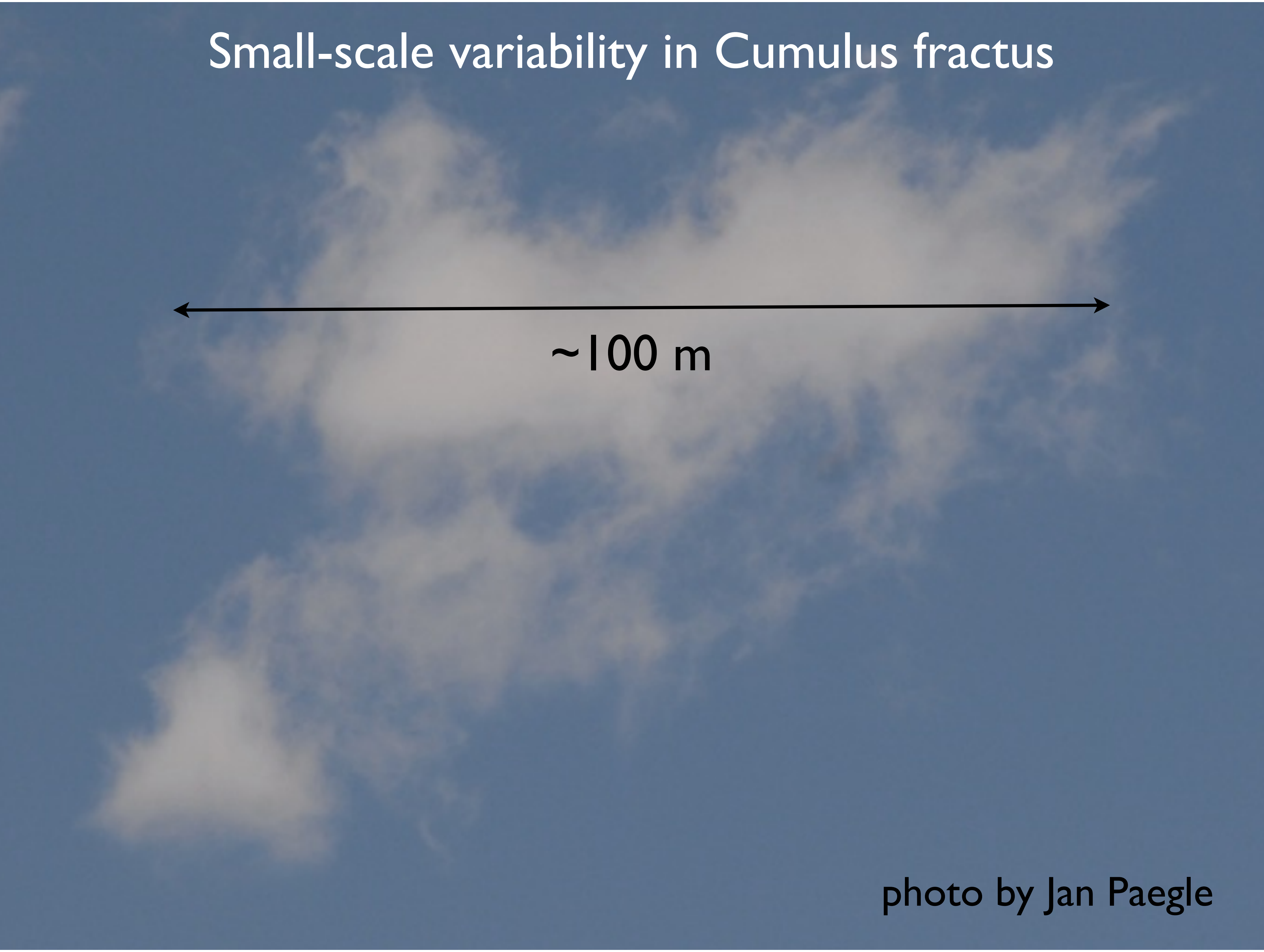
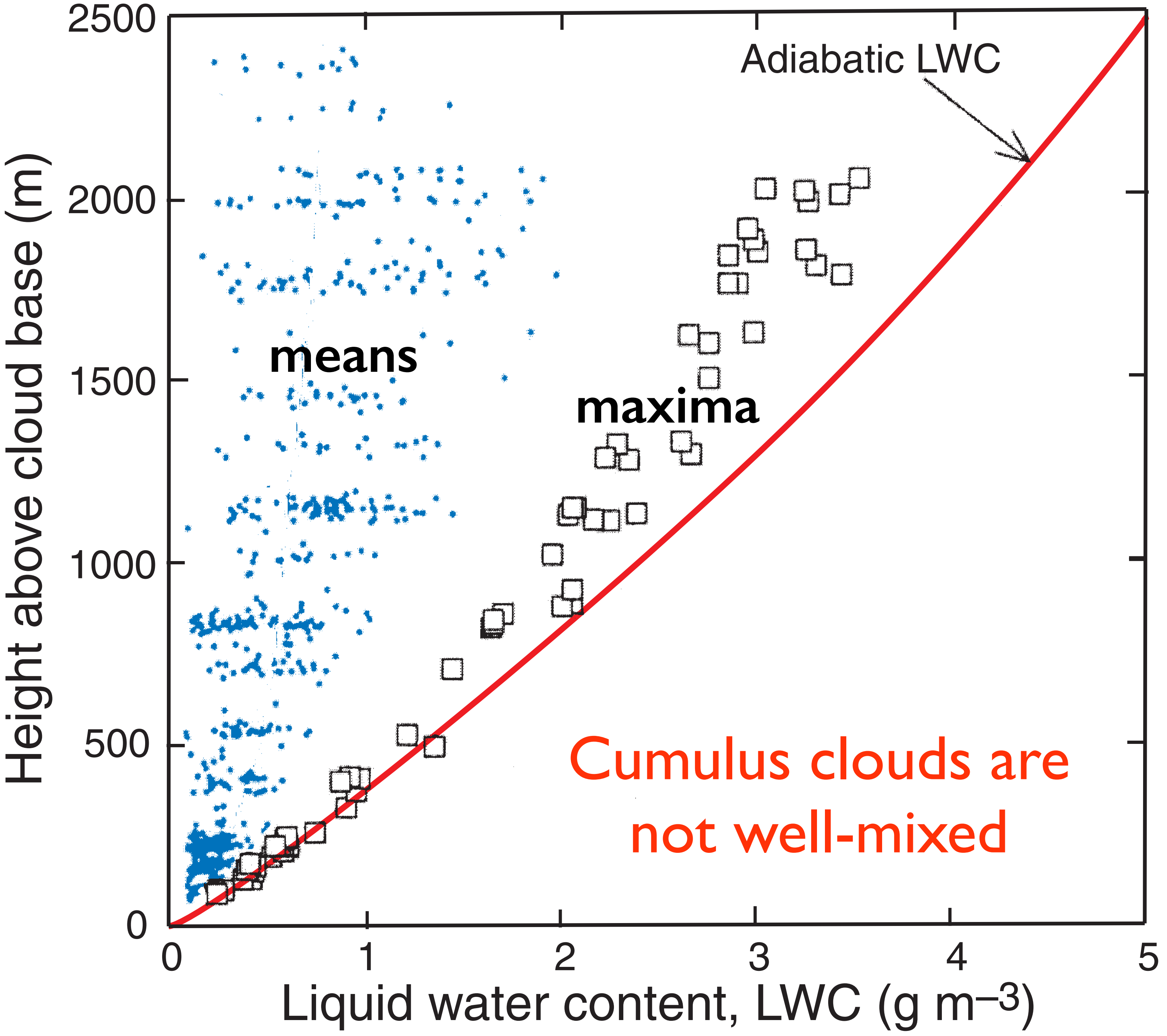


photo by Jan Paegle



Cumulus clouds are not well-mixed

LES Limitations

- The premise of LES is that only the large eddies need to be resolved.

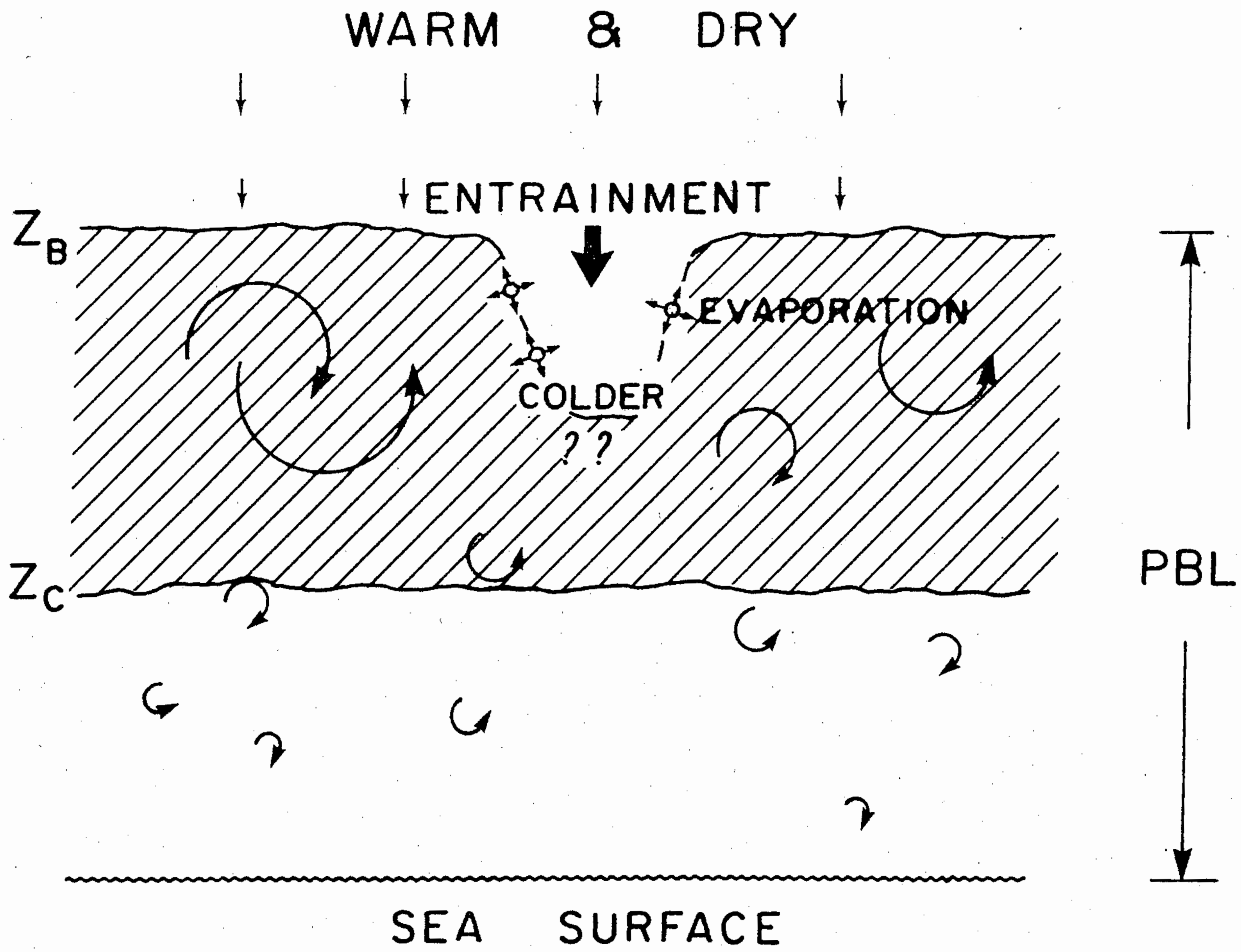
- LES is appropriate if the important small-scale processes can be parameterized.

- Many cloud processes are subgrid-scale, yet can't (yet) be adequately parameterized.

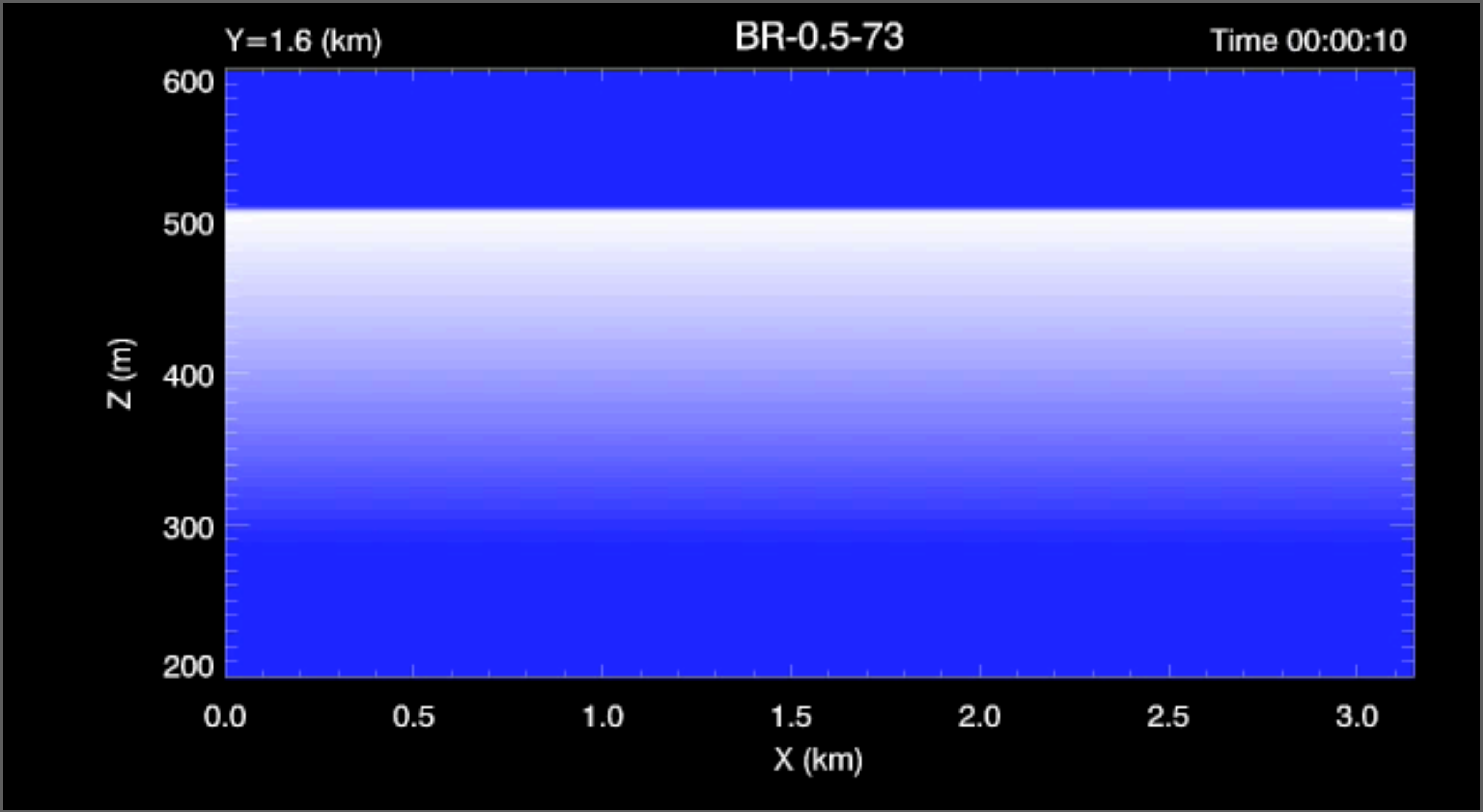
Subgrid-scale Cloud Processes

- Small-scale finite-rate **mixing** of clear and cloudy air determines evaporative cooling rate and affects buoyancy and cloud dynamics.
- Small-scale variability of water vapor due to entrainment and **mixing** broadens droplet size distribution (DSD) and increases droplet collision rates.
- Small-scale **turbulence** increases droplet collision rates.

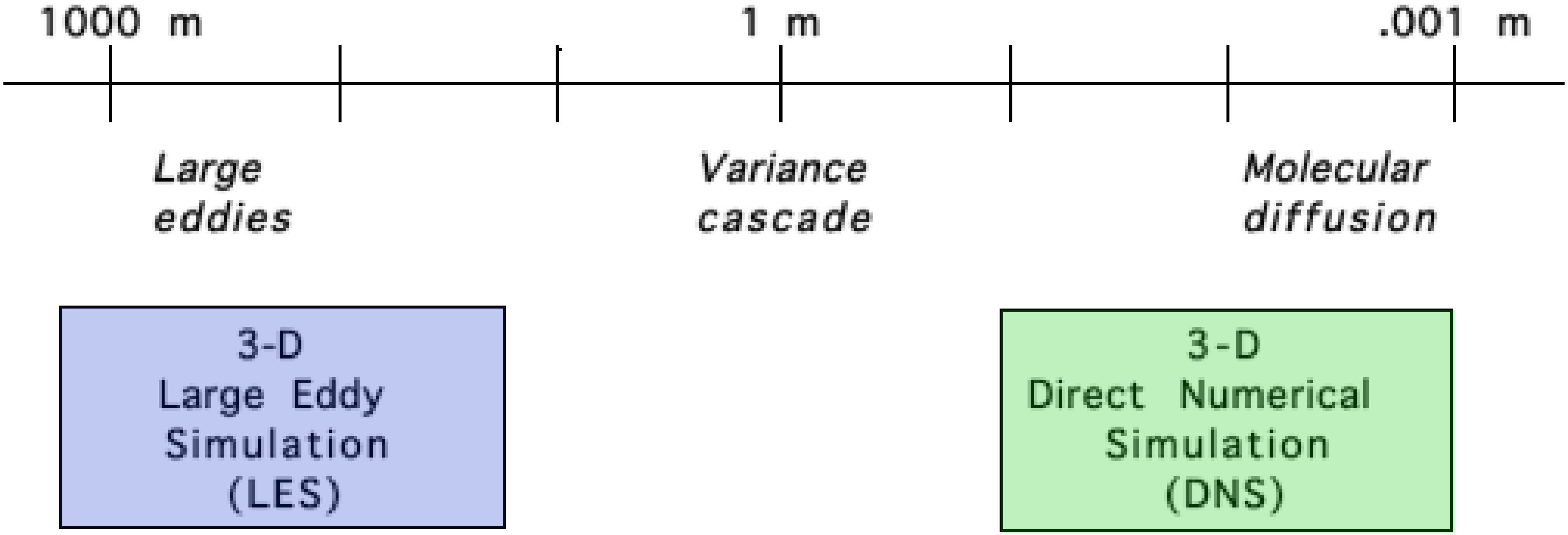
Cloud-top Entrainment Instability (CEI)



LES with 5 m isotropic grid



Scales of Atmospheric Turbulence



1000 m

1 m

.001 m

Large eddies

Variance cascade

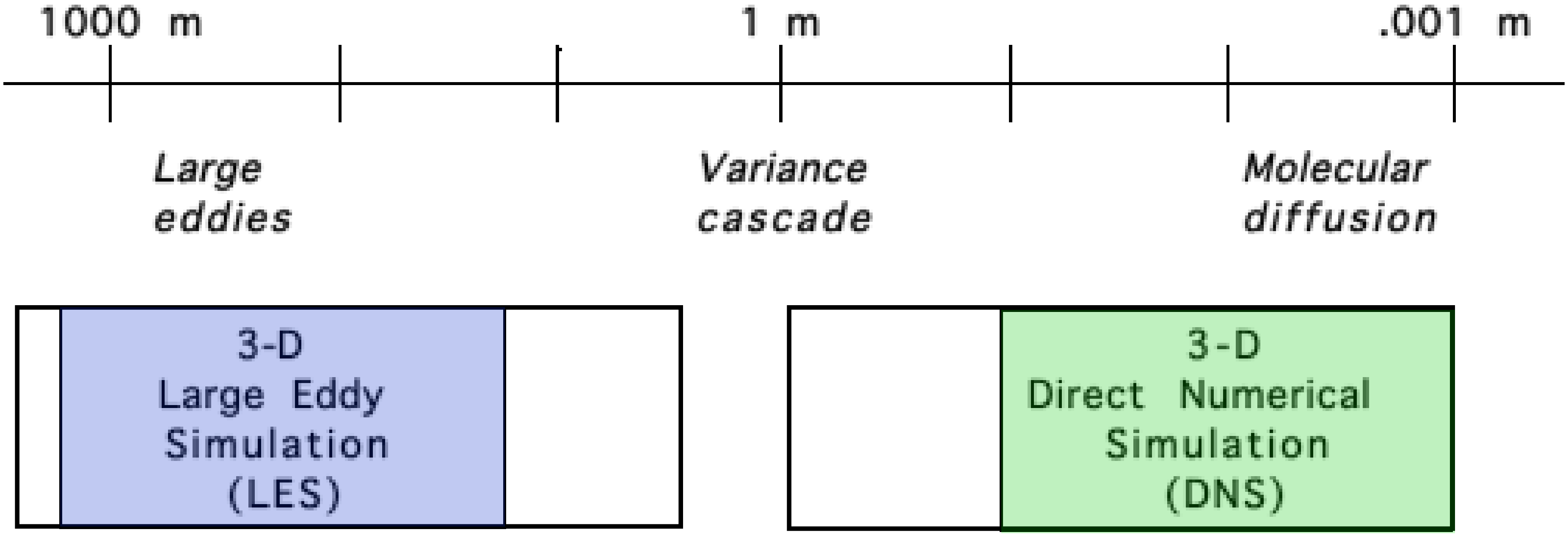
Molecular diffusion

3-D
Large Eddy
Simulation
(LES)

3-D
Direct Numerical
Simulation
(DNS)

1993

Scales of Atmospheric Turbulence



1000 m

1 m

.001 m

Large eddies

Variance cascade

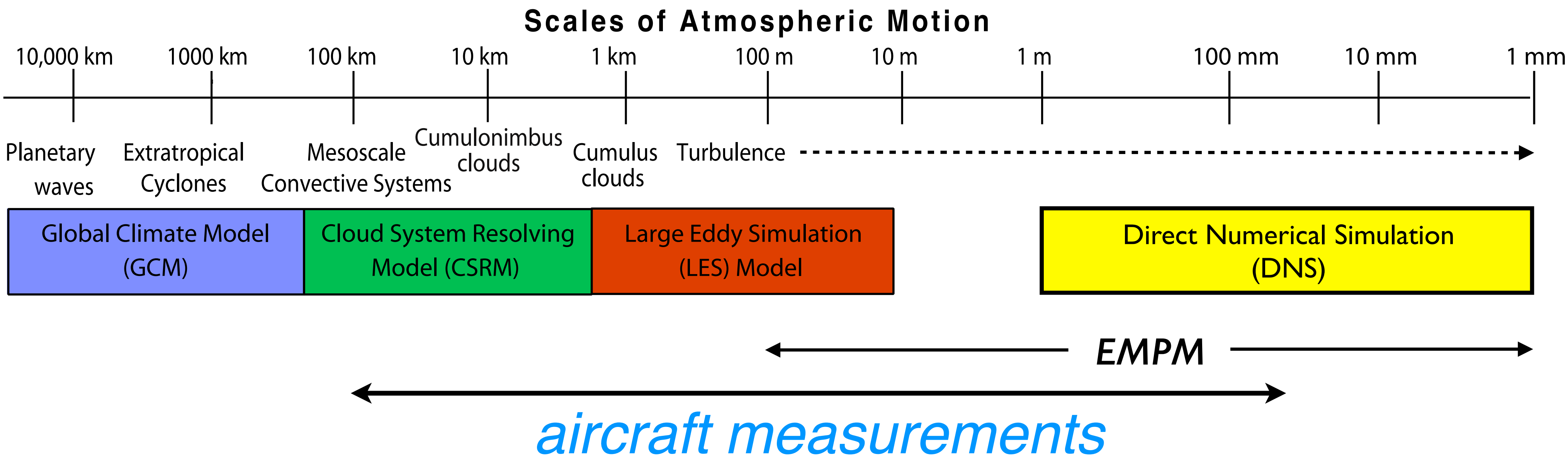
Molecular diffusion

3-D
Large Eddy
Simulation
(LES)

3-D
Direct Numerical
Simulation
(DNS)

2010

- **Bridging the LES-DNS gap**
  - Difficulty depends on process of interest.
  - Higher resolution or improved conventional parameterization may work for some processes.
  - For investigating how turbulence affects cloud droplet growth, multi-scale modeling (super-parameterization) is a promising solution.



Scales of Atmospheric Motion

10,000 km
1000 km
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100 mm
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Planetary waves
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Turbulence

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EMPM

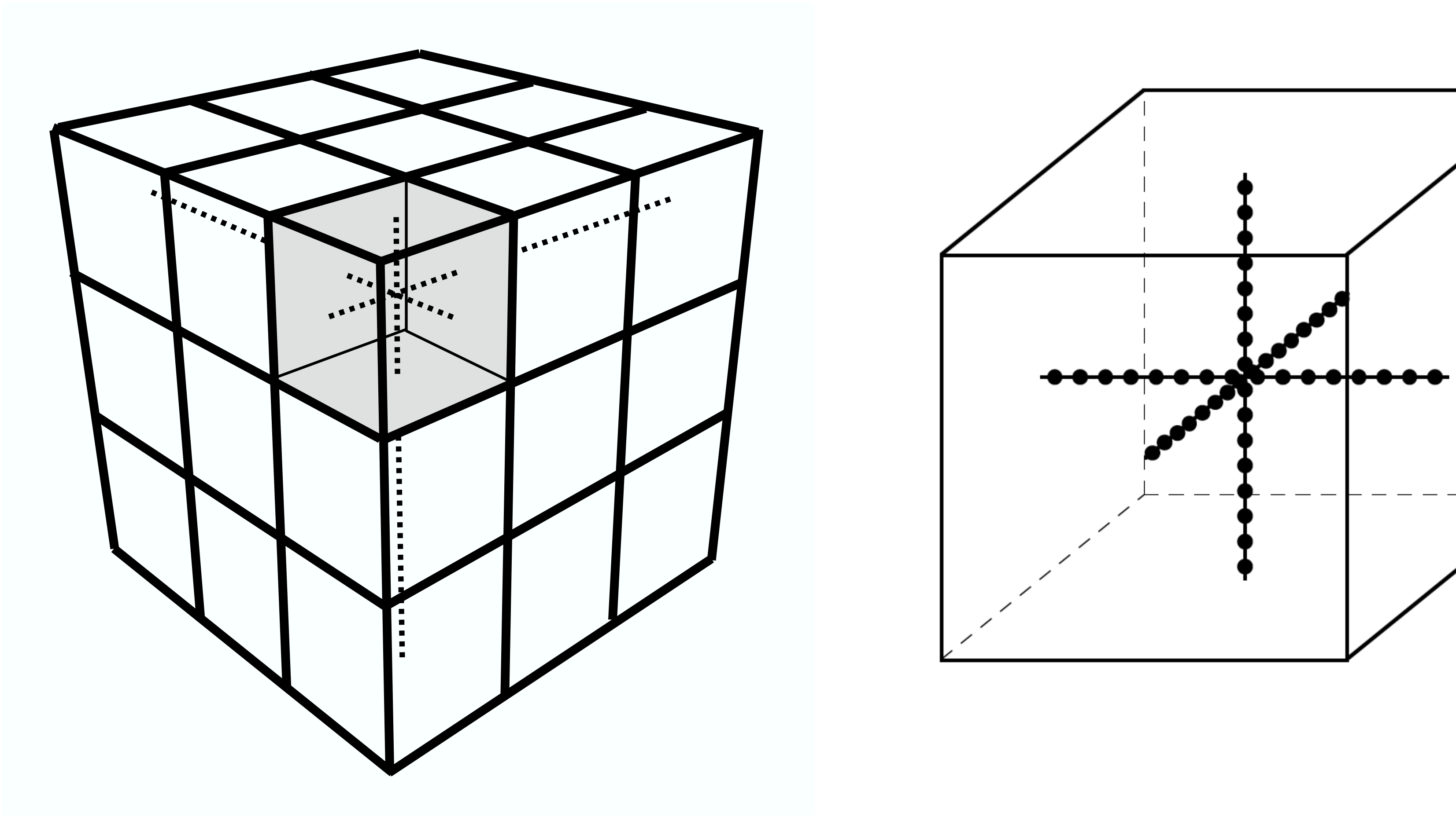
aircraft measurements

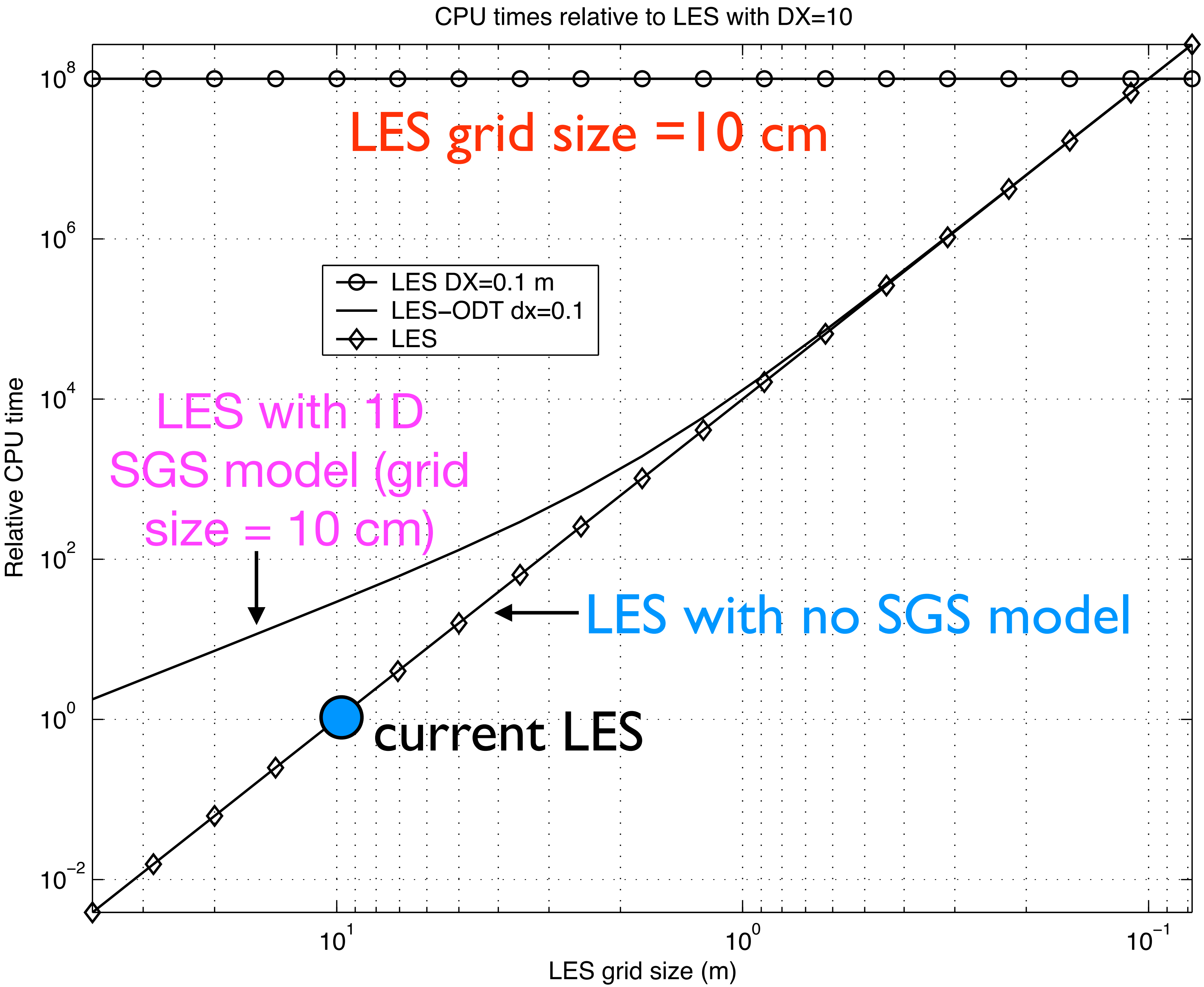
The smallest scale of turbulence is the Kolmogorov scale:

$$\eta \equiv (\nu^3/\epsilon)^{1/4}$$

For $\epsilon = 10^{-2}$ m^2 s^{-3} and $\nu = 1.5 \times 10^{-5}$ m^2 s^{-1}, $\eta = 0.7$ mm.

LES with 1D subgrid-scale model





LES grid size =10 cm

LES with 1D SGS model (grid size = 10 cm)

LES with no SGS model

current LES

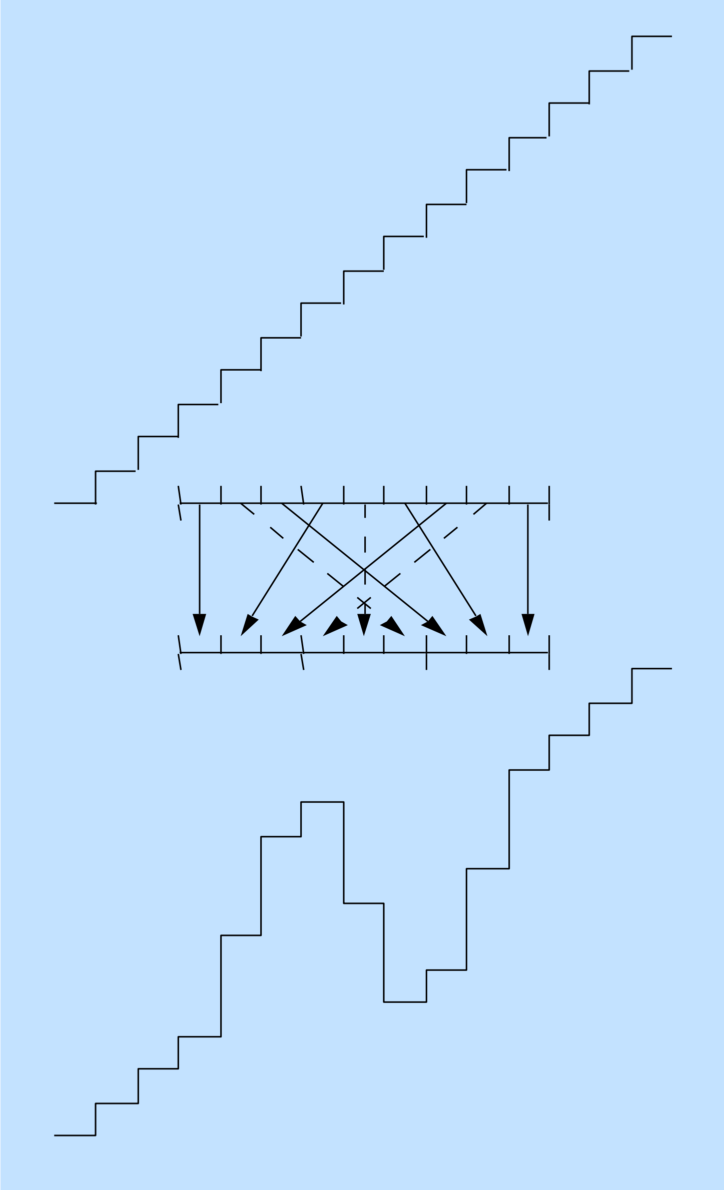
Summary

- Reducing the dimensionality is an established method.

- Removes or reduces the need for SGS parameterizations.

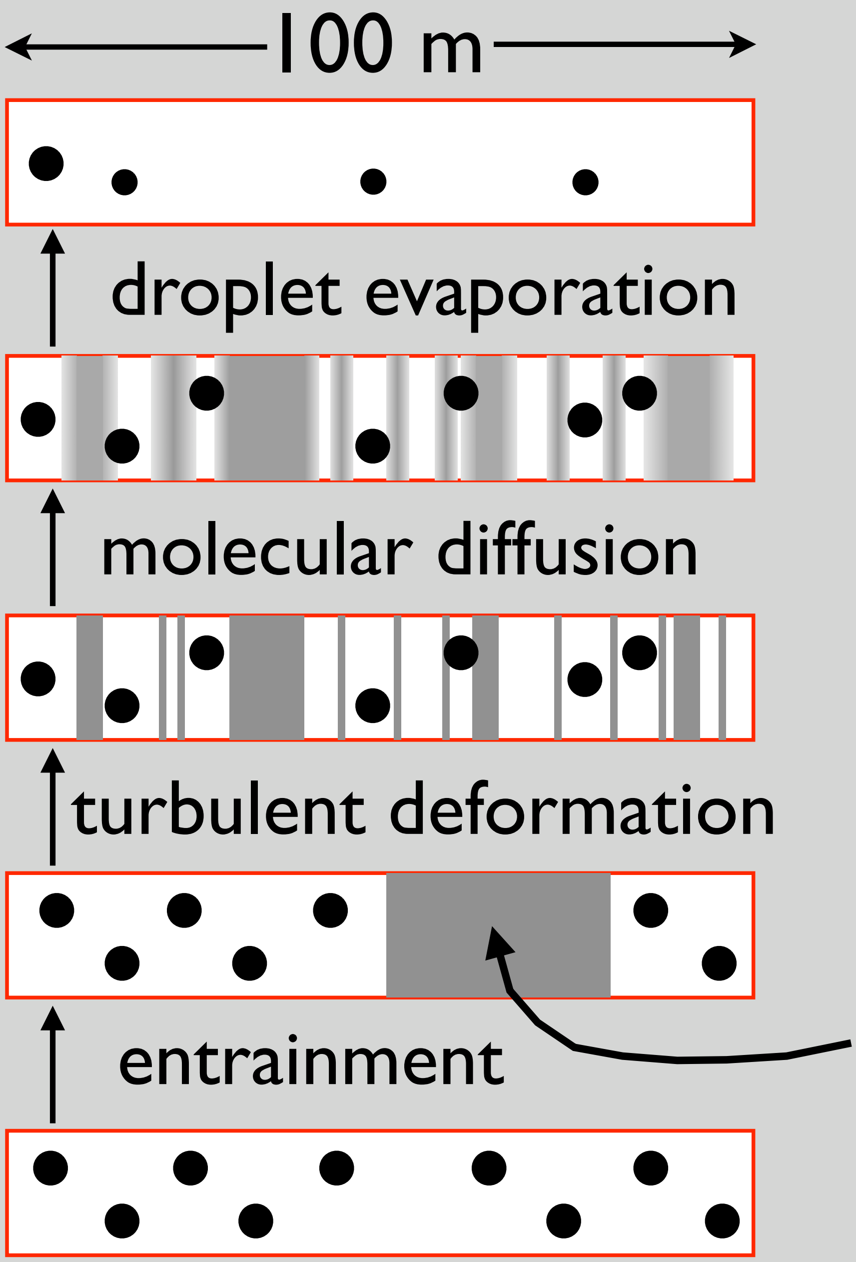
- It is very well suited for high-Reynolds number turbulent flows when small-scale mixing processes are important.

Advection is modeled as a sequence of *triplet maps* that preserve desired advection properties, even in 1D



The triplet map is implemented numerically as a permutation of fluid cells (or on an adaptive mesh)

EMPM with droplets and entrainment



100 m

droplet evaporation

molecular diffusion

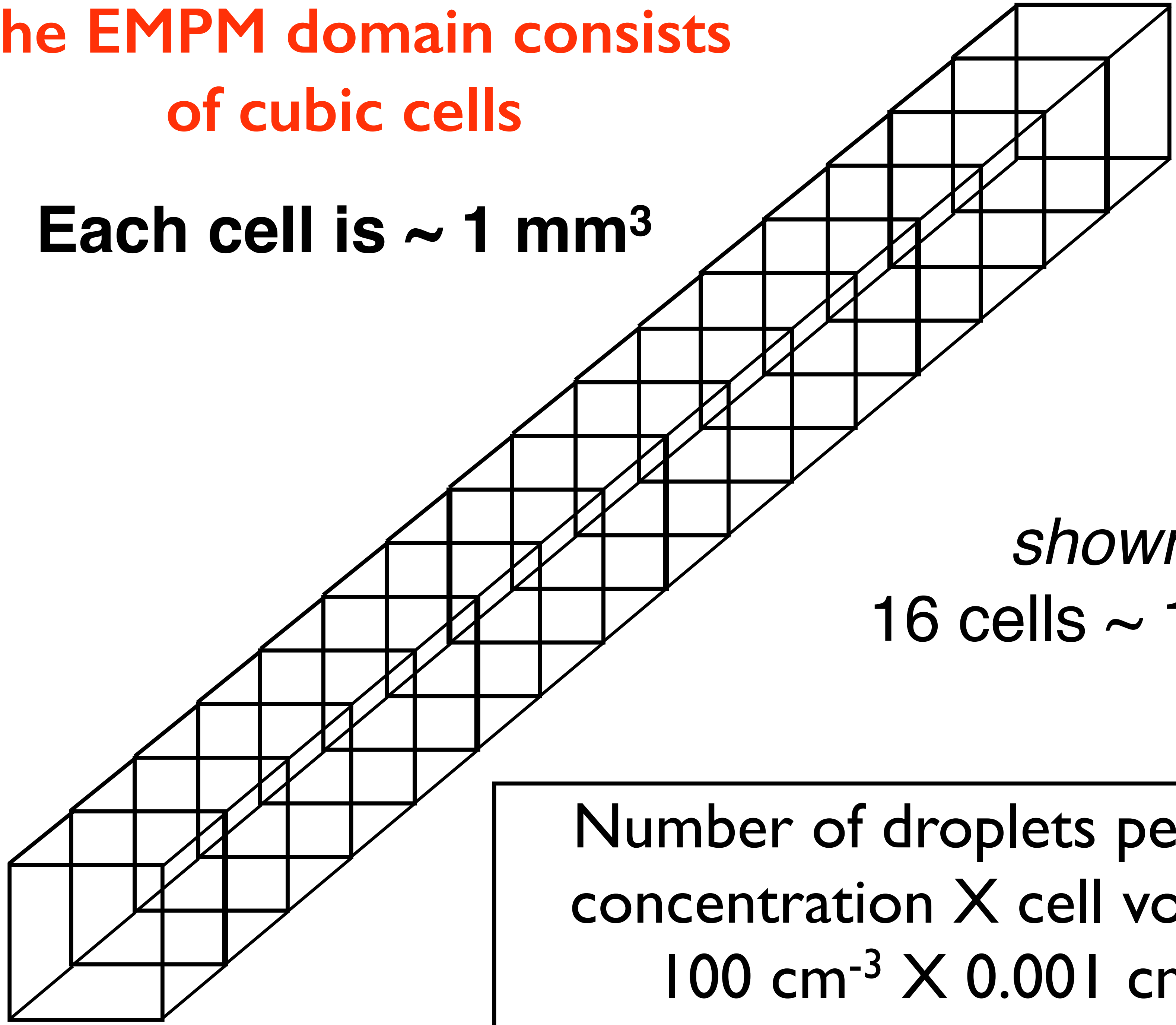
turbulent deformation

entrainment

saturated parcel

The EMPM domain consists of cubic cells

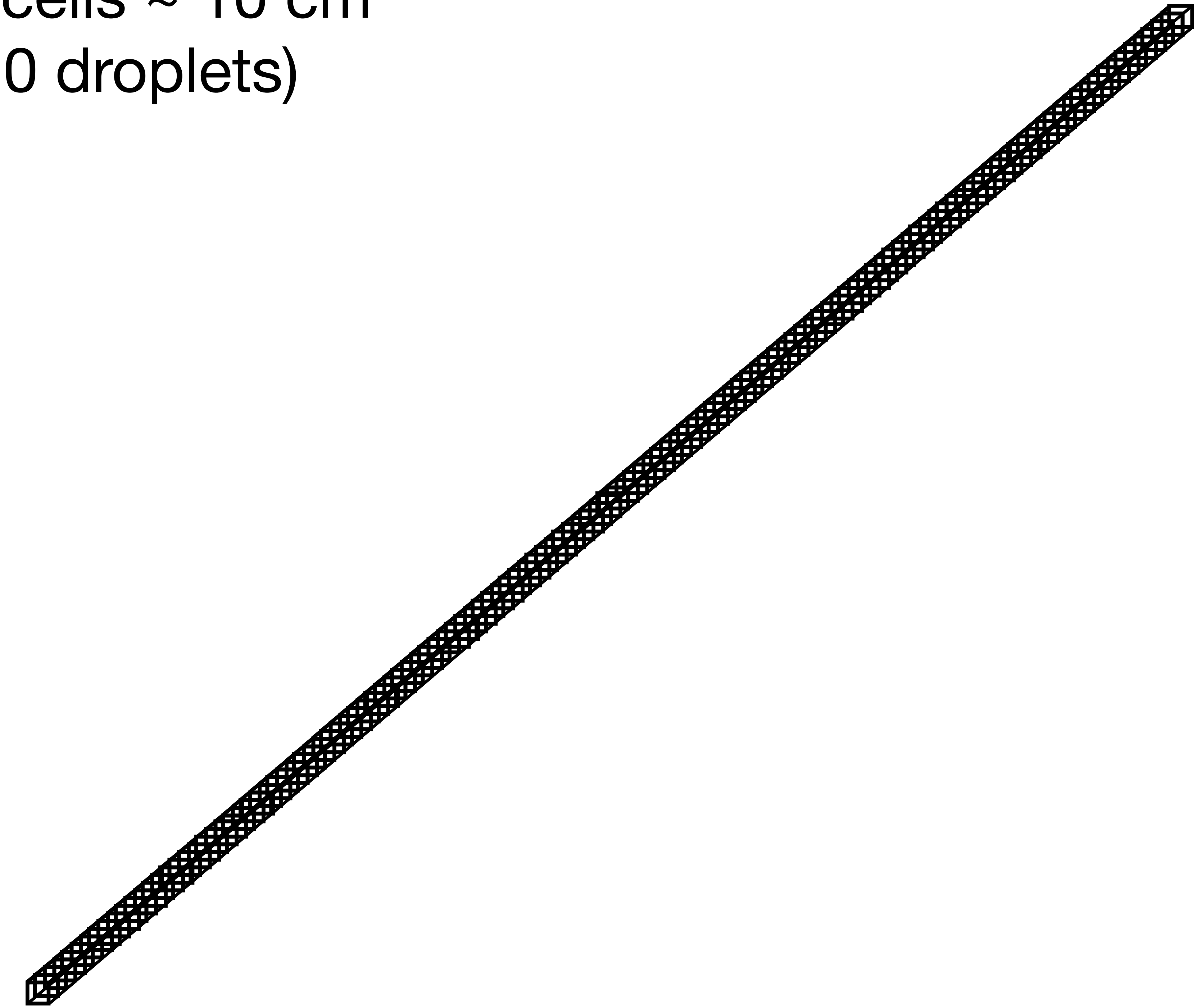
Each cell is ~ 1 mm^3



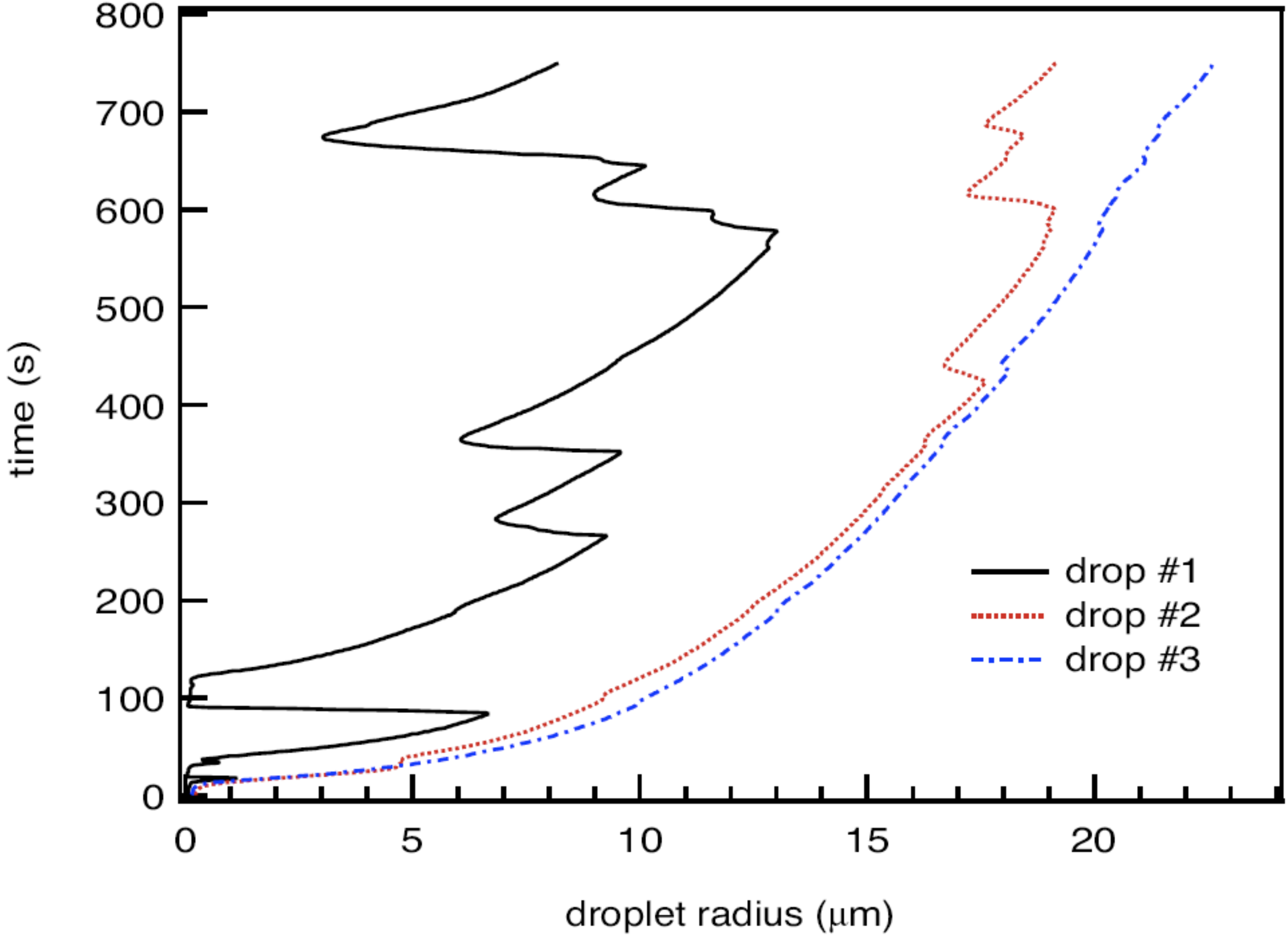
shown:
16 cells ~ 1.6 cm

Number of droplets per cell =
concentration X cell volume =
100 cm^{-3} X 0.001 cm^3 =
0.1 (1 droplet per cm)

128 cells ~ 10 cm
(10 droplets)



1024 cells ~ 1 m
(100 droplets)


800
700
600
500
400
300
200
100
0
time (s)
0
5
10
15
20
droplet radius (μm)
drop #1
drop #2
drop #3

What’s ahead...

- Resolving only the large turbulent eddies is not sufficient to realistically represent the interactions between microphysics and turbulence.
- Models that resolve the smaller (and sometimes the smallest) turbulent eddies are necessary.
- It is not yet possible to simulate all scales of cloud turbulence in 3D, so other approaches are currently being used and developed.