Modeling of Entrainment Processes at Various Scales: State of the Art

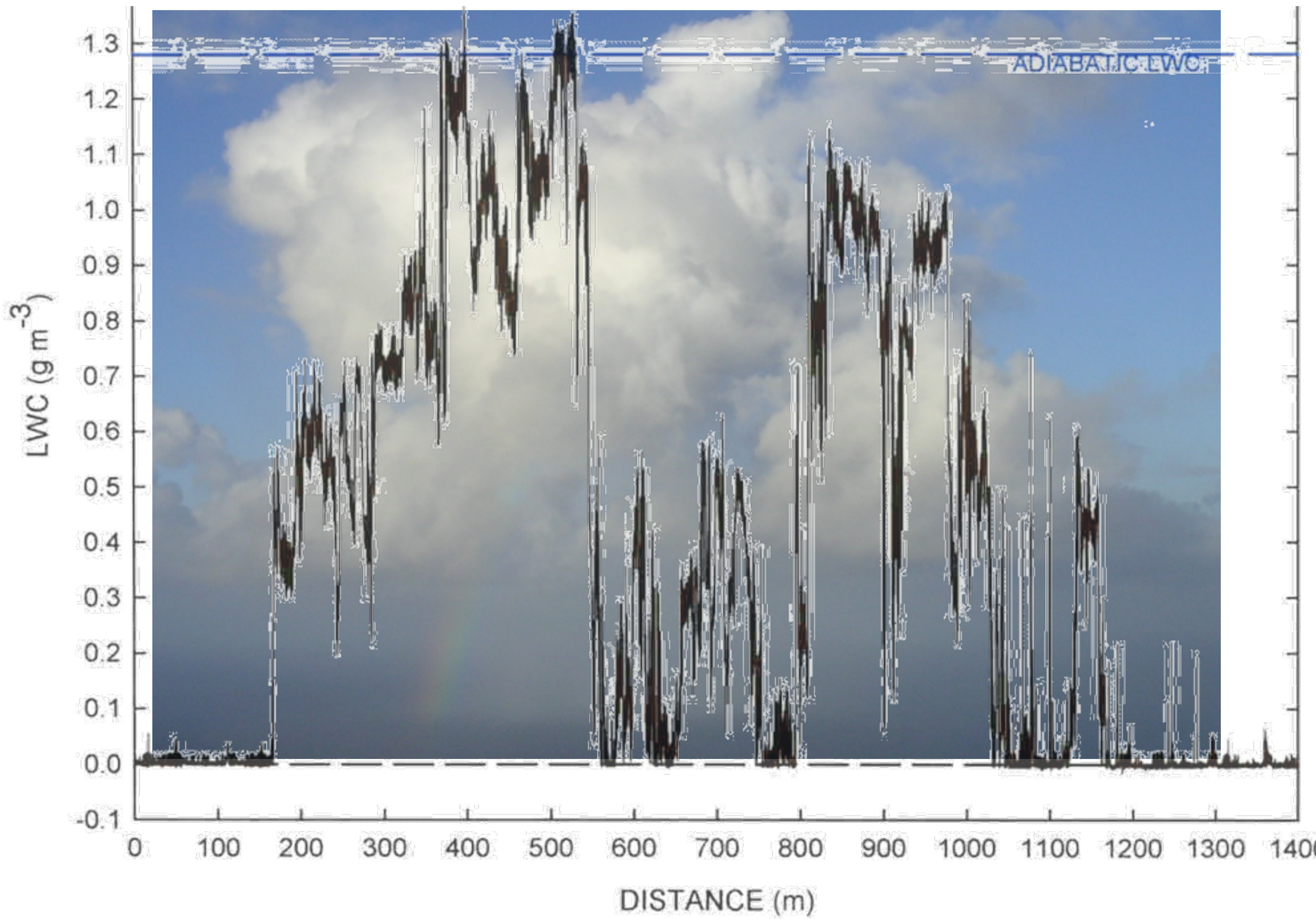
Steven K. Krueger
University of Utah, Salt Lake City, UT

Workshop on the Modeling and Observation of Entrainment

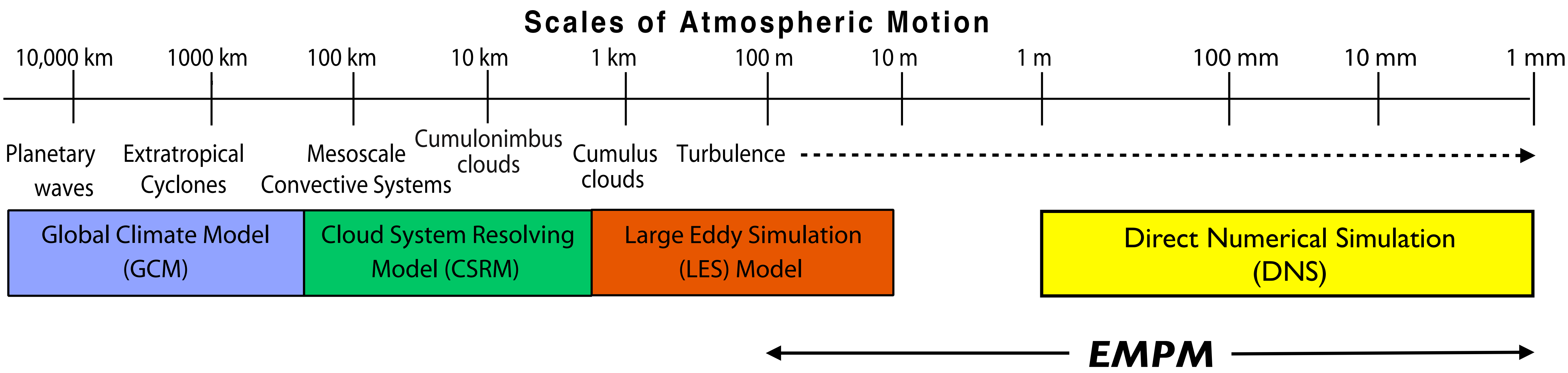
8 July 2011
Brookhaven National Laboratory , Upton, NY


Mt Lemmon
10:39:29 Fri Aug 16 2002

Small-scale variability in Cumulus mediocris



overlay is for illustration only

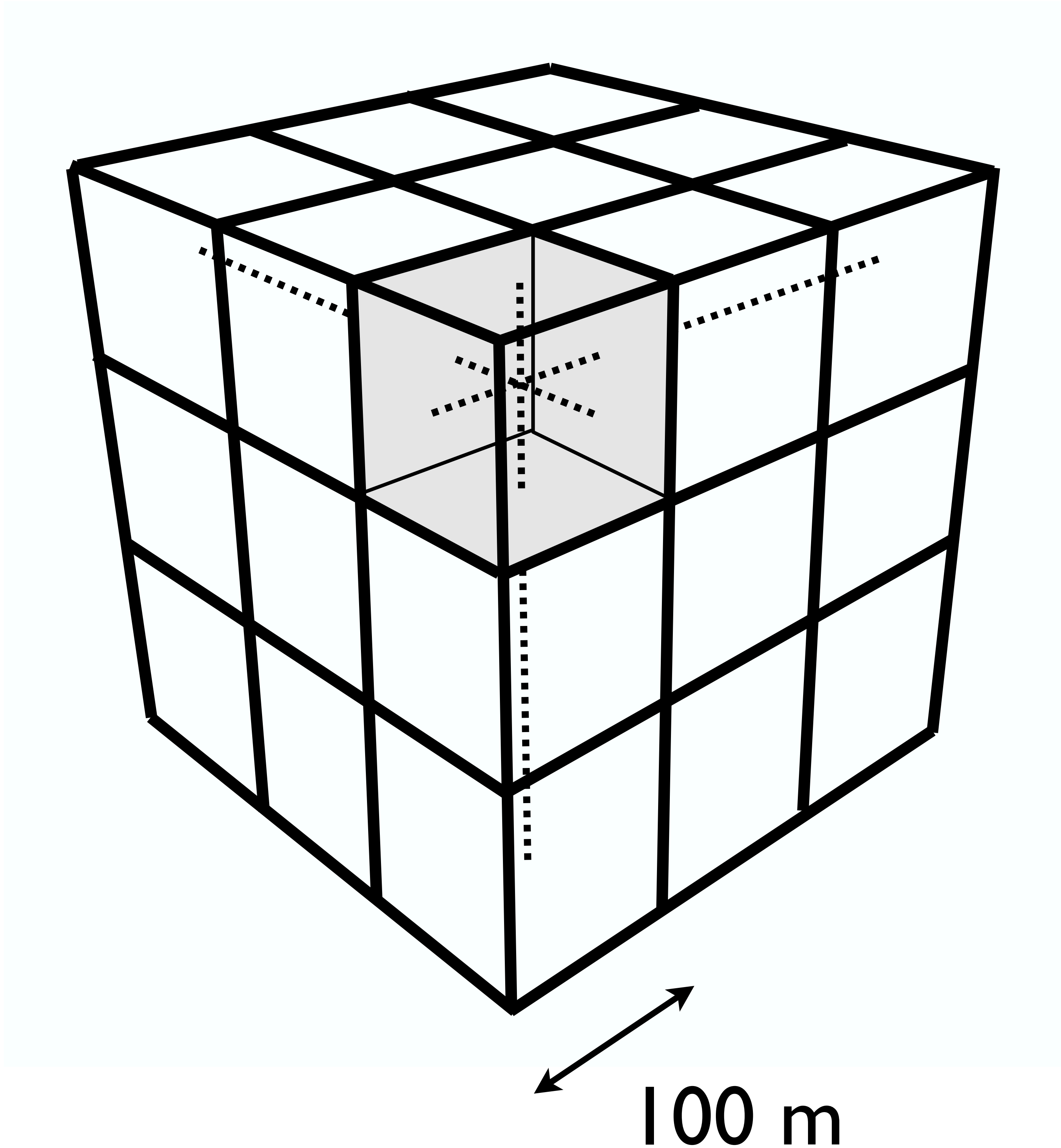


The smallest scale of turbulence is the Kolmogorov scale:

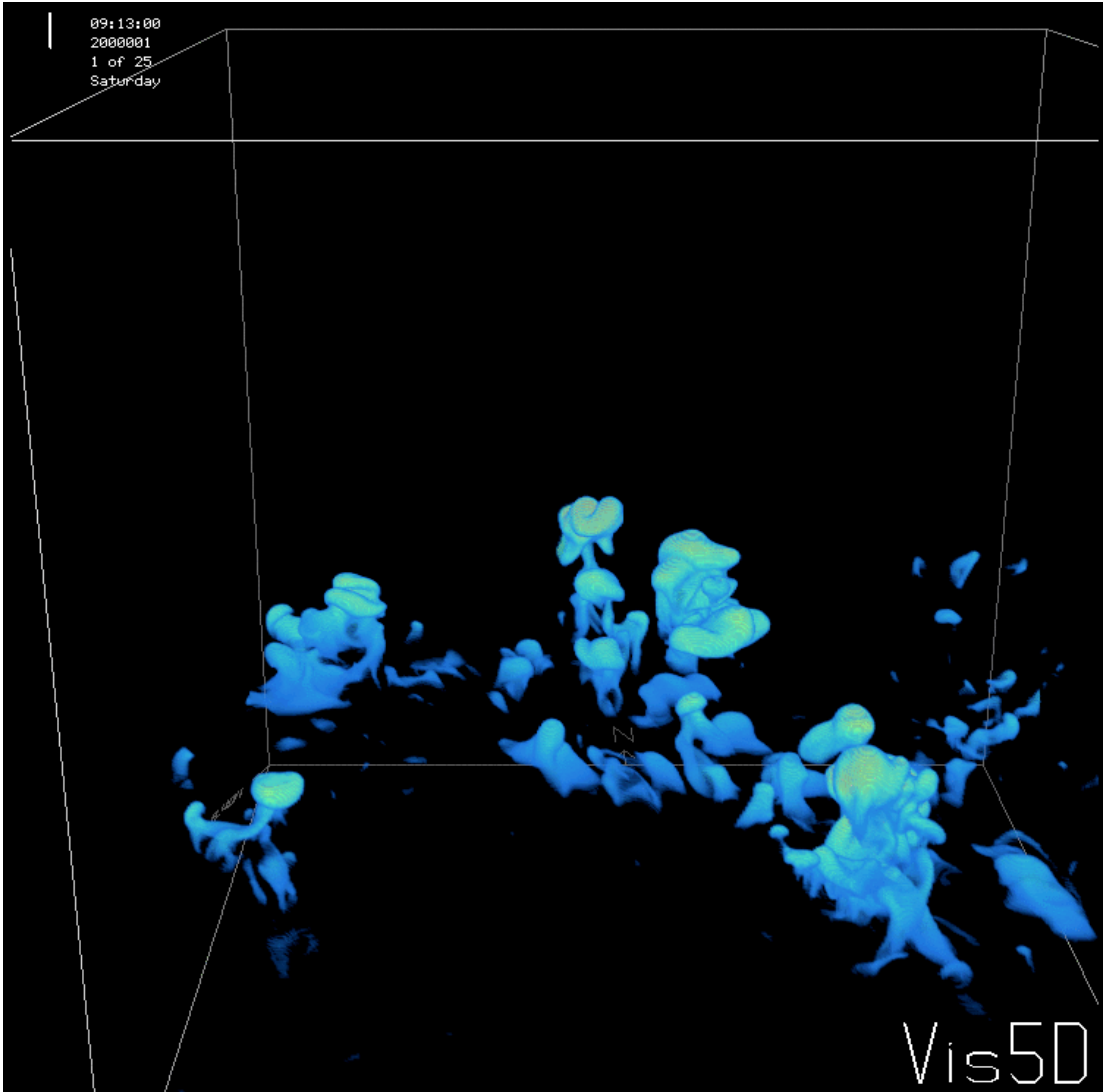
$$\eta \equiv (\nu^3/\epsilon)^{1/4}$$

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

Large-Eddy Simulation (LES) model



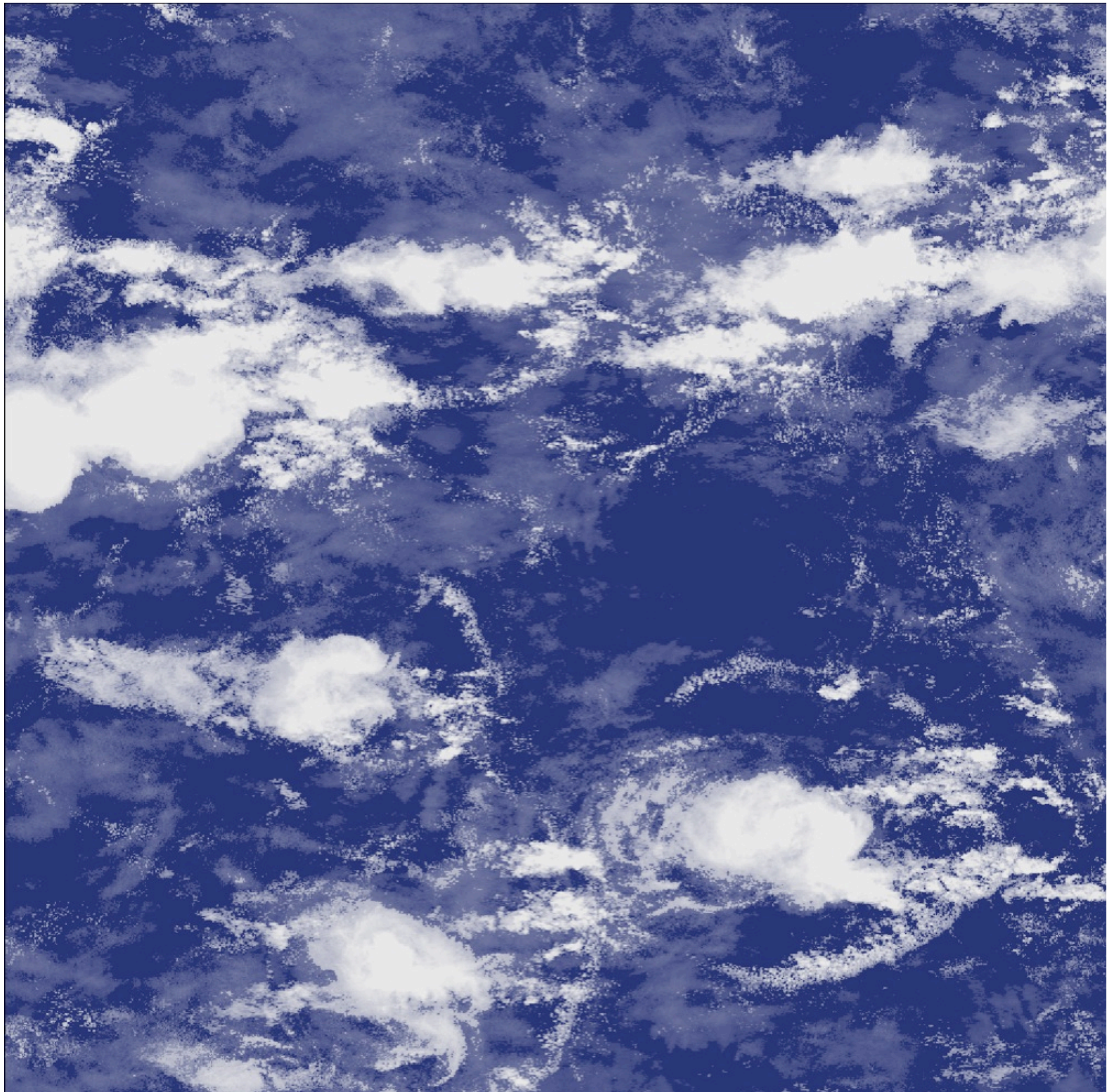
no subgrid-scale variability

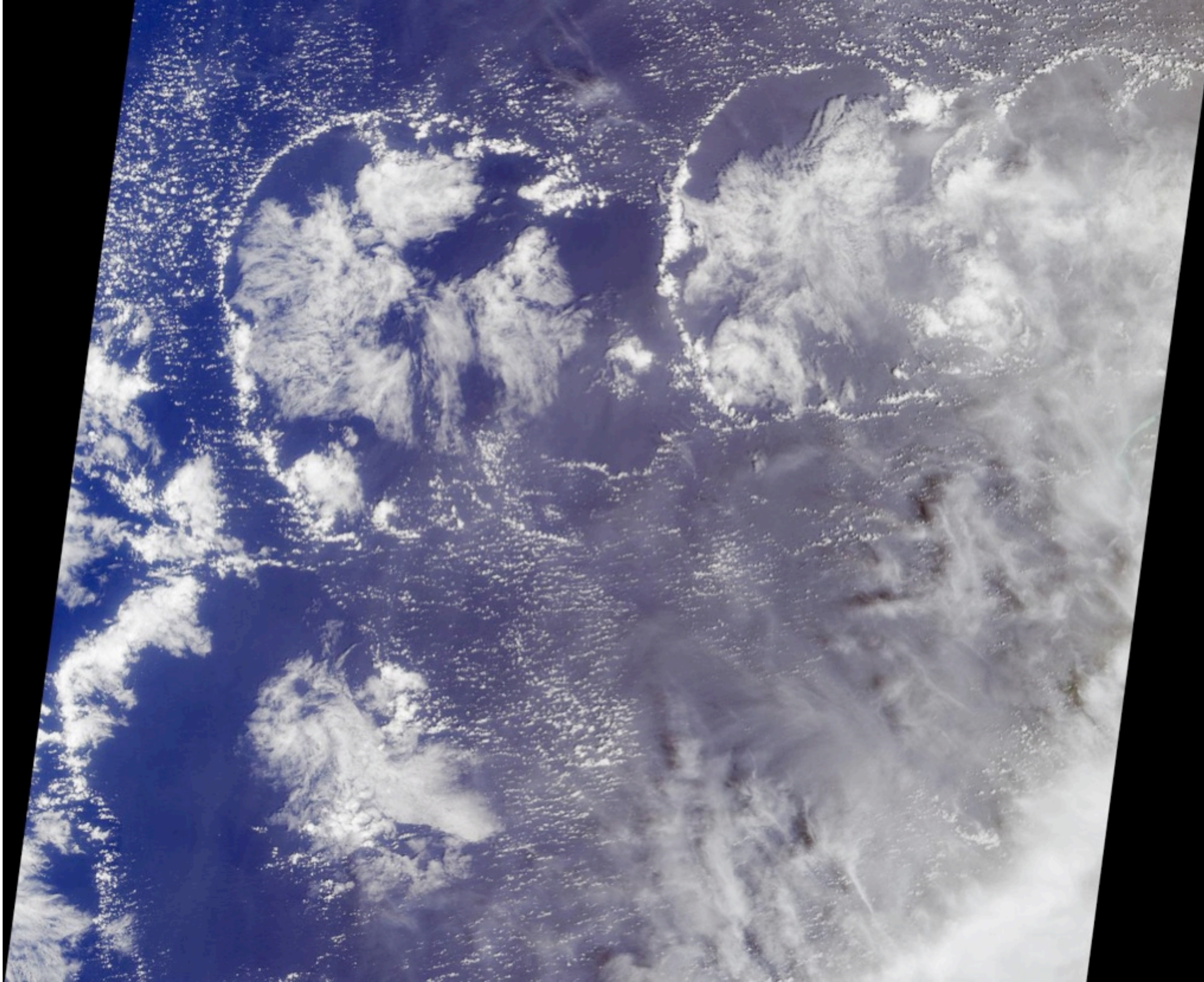

09:13:00
2000001
1 of 25
Saturday
Vis5D

Giga-LES of deep convection

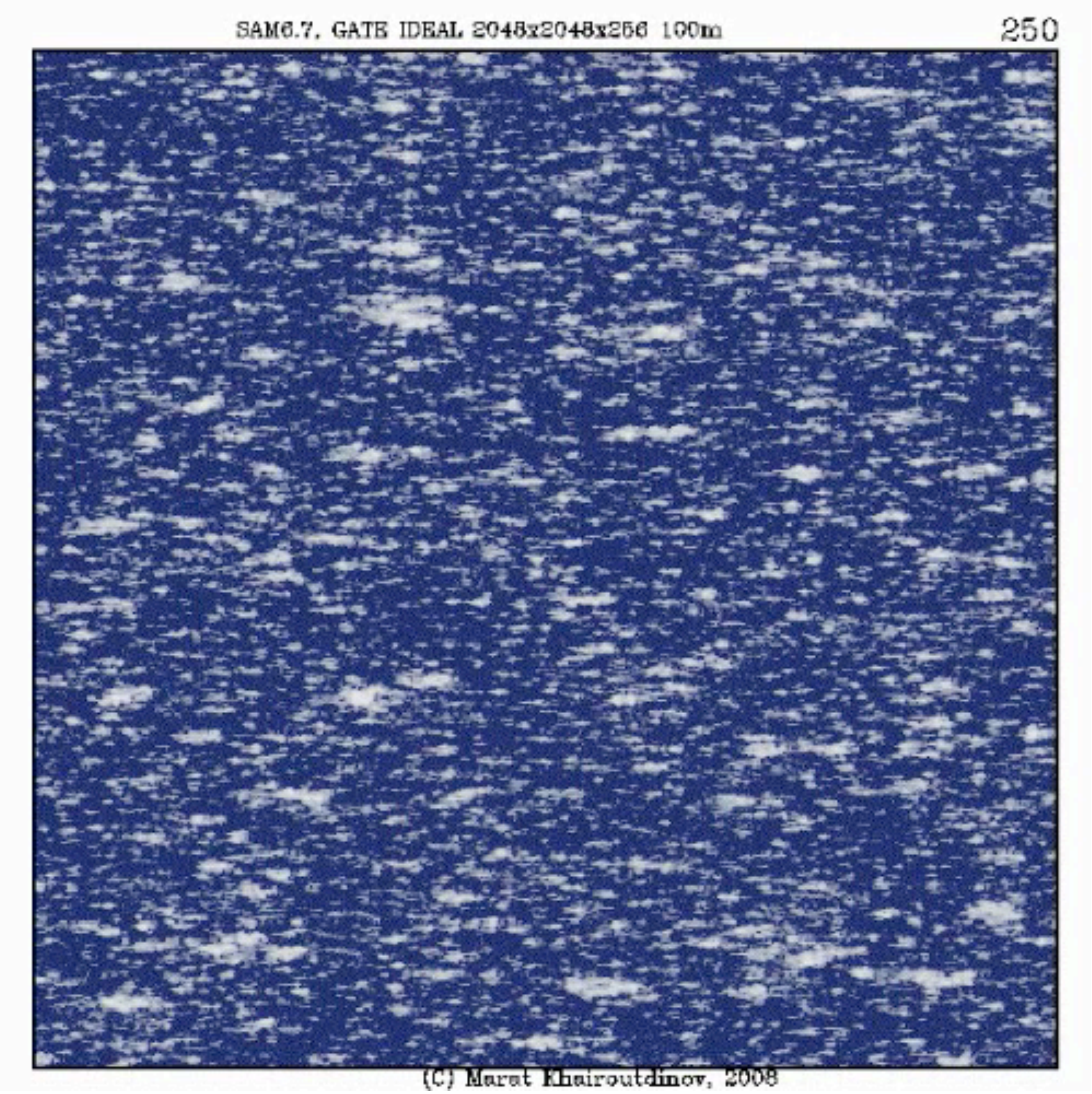
- Idealized GATE (tropical ocean) simulation with shear.
- Used a CRM (SAM) with 2048 x 2048 x 256 (10^9) grid points and 100-m grid size for a 24-h LES.

Giga-LES "visible image" 180 km x 180 km





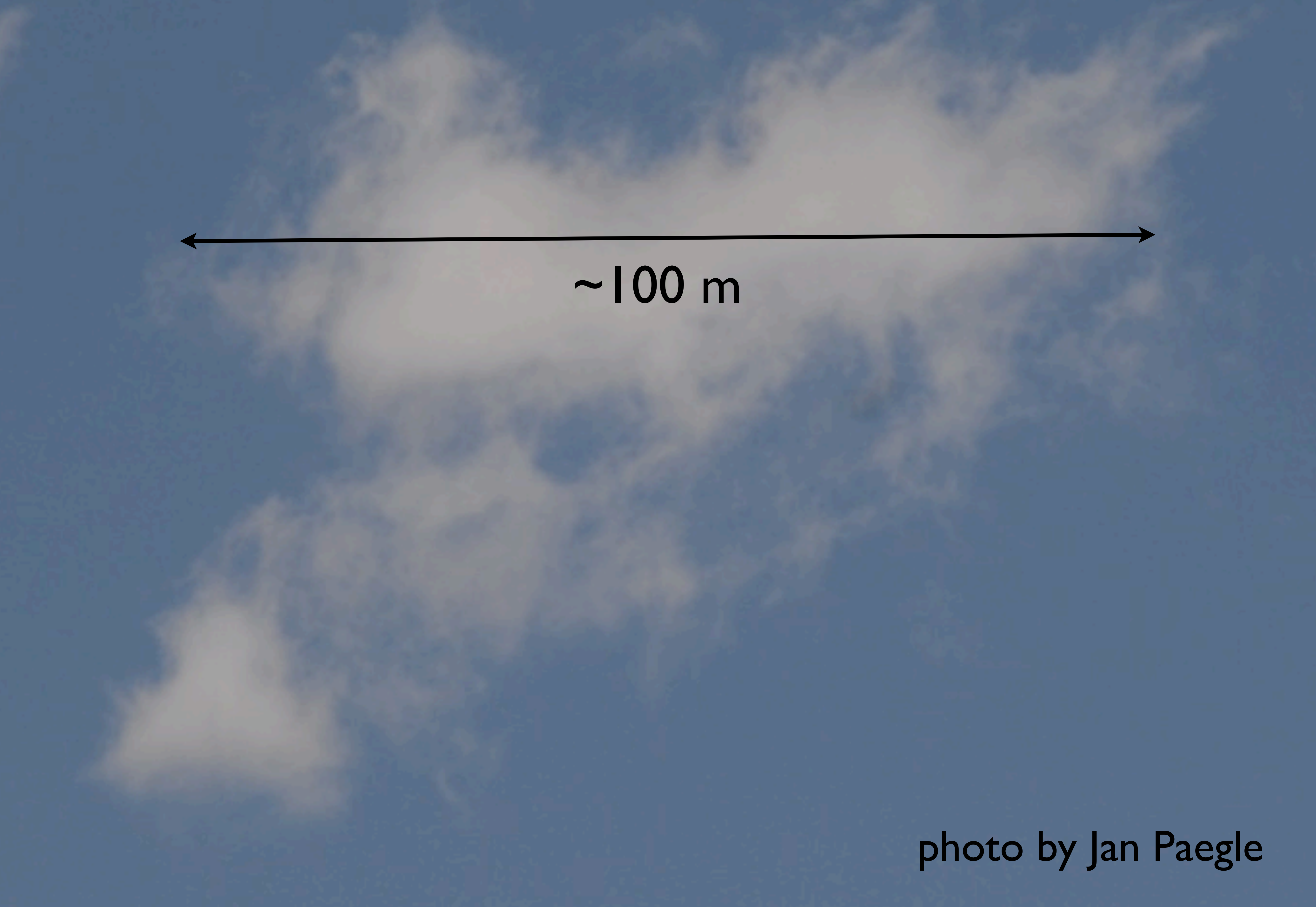
zoom into 50 km by 50 km



LES Limitations

- The premise of LES is that only the large eddies need to be resolved.
- Why resolve any finer scales? Why resolve the finest scales?
- 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.

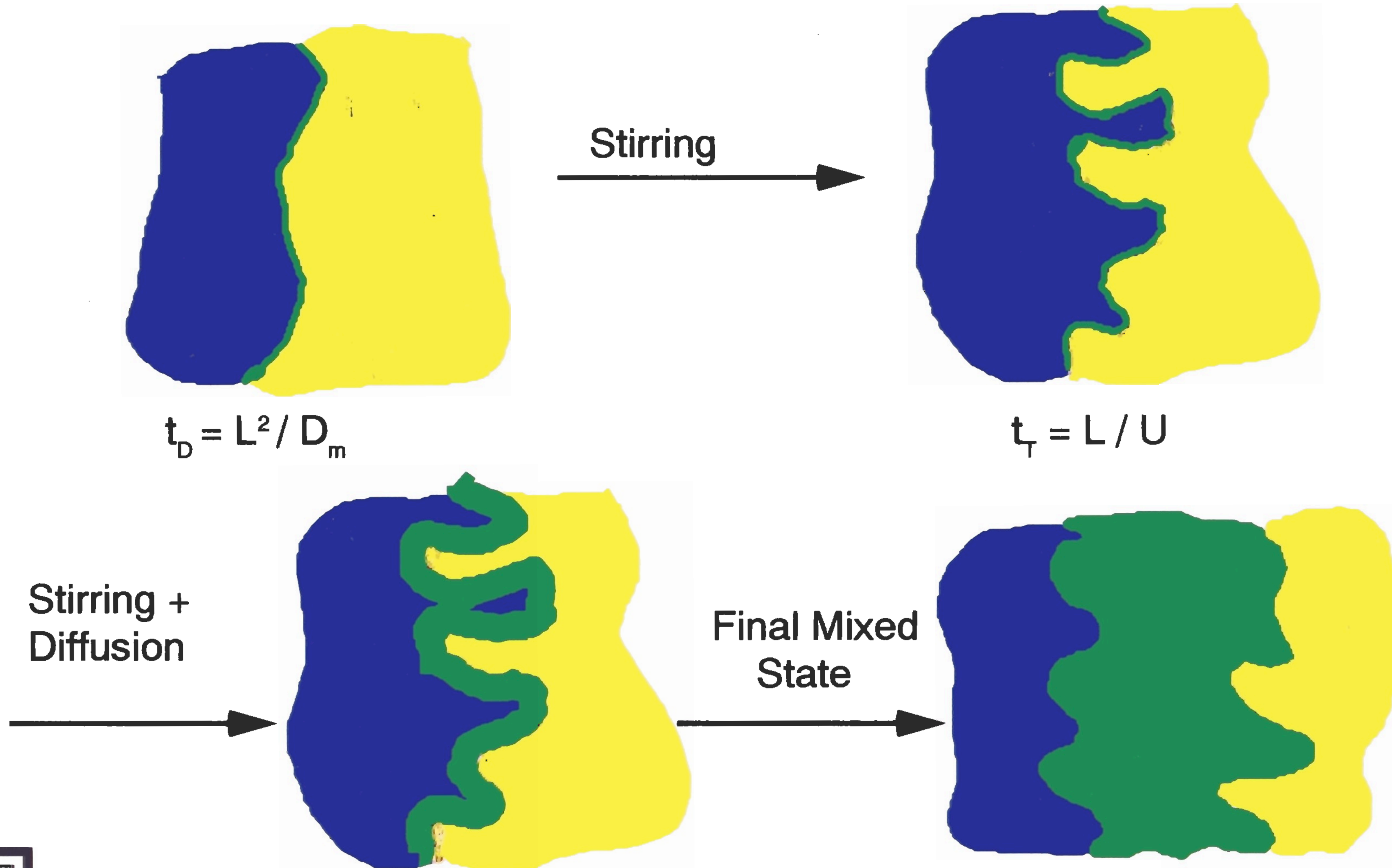
Small-scale variability in Cumulus fractus



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.

Turbulent Mixing: Process by which a fluid with two initially segregated scalar properties mix at the molecular level



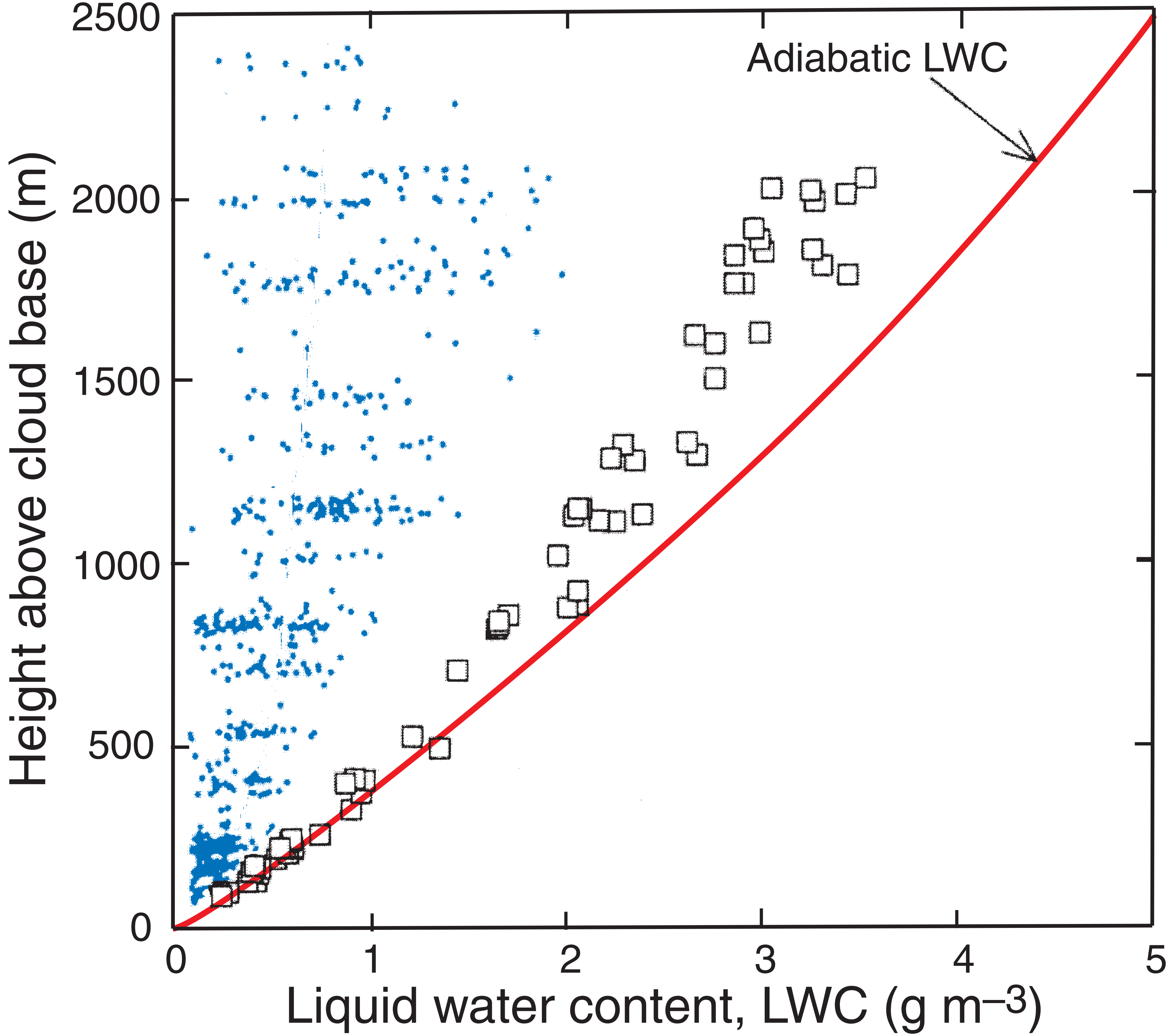
LES of passive scalar in a convective boundary layer (grid size = 20 m)

Mixing Time Scale

$$\tau = \left(\frac{d^2}{\epsilon}\right)^{1/3},$$

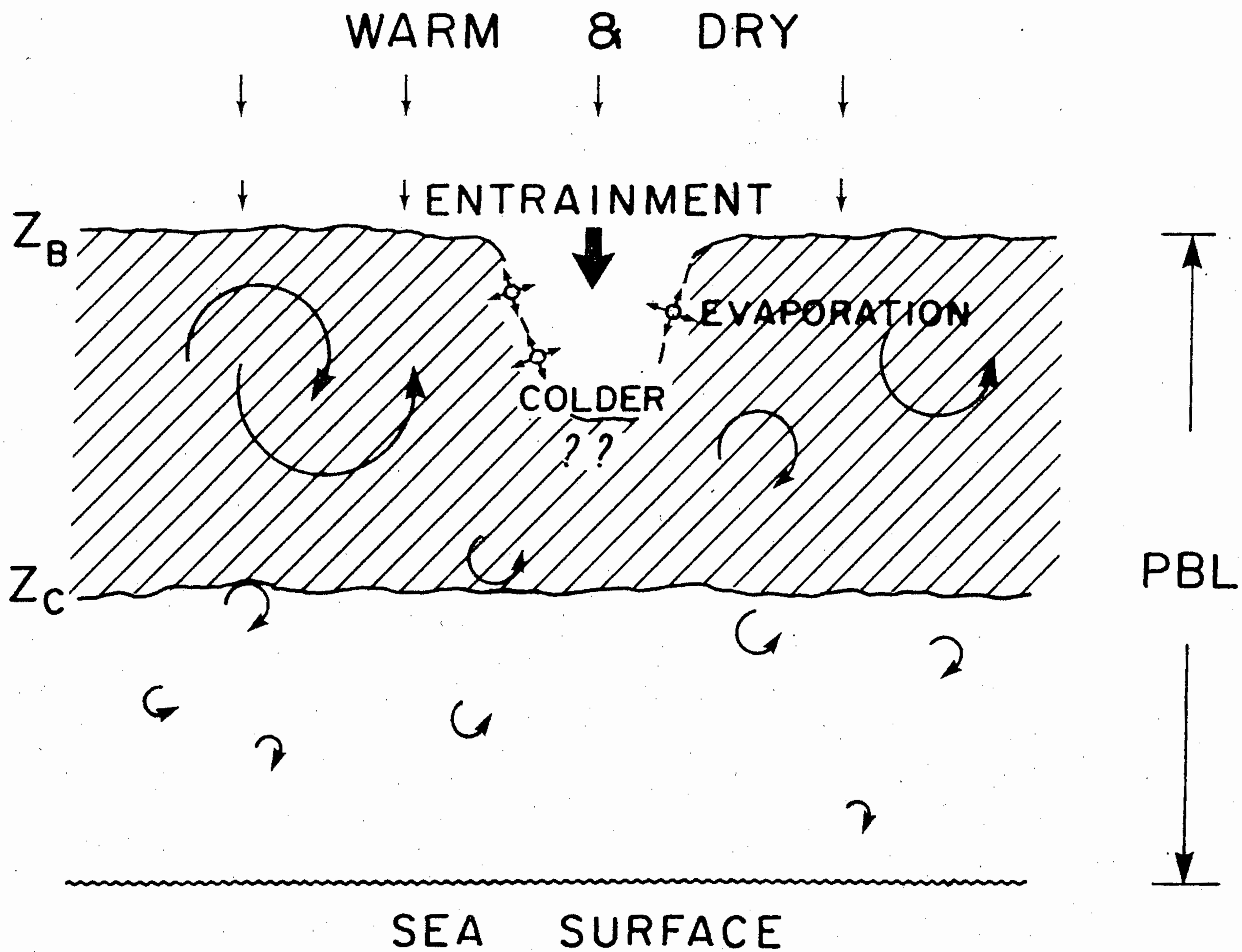
d is entrained blob size, ϵ is dissipation rate of turbulence kinetic energy.

For a **cumulus cloud,** $U \sim 2$ m/s, $L \sim 1000$ m, so $\epsilon \sim U^3/L = 10^{-2}$ m^2/s^3. For $d = 100$ m, $\tau \sim 100$ s.

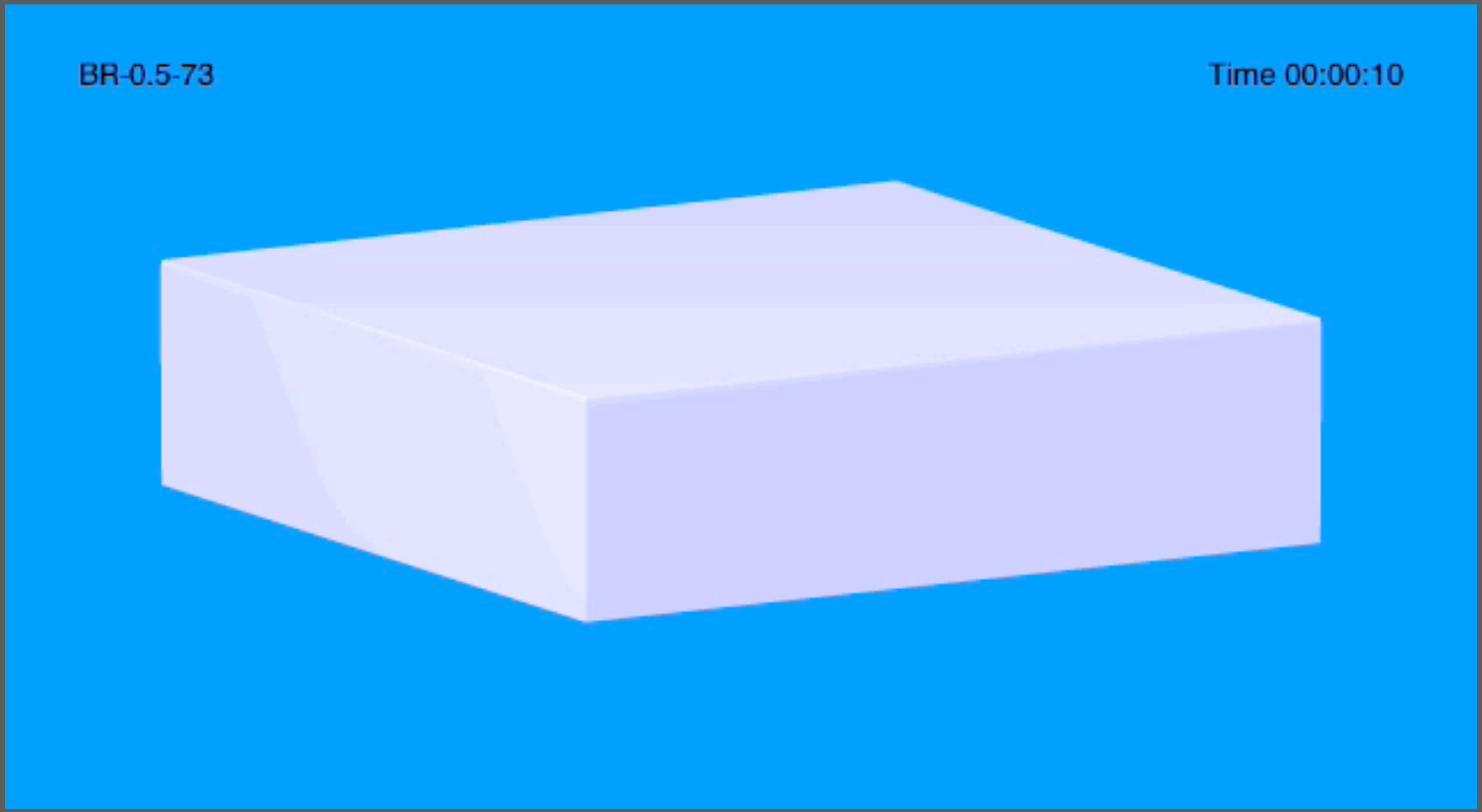


Adiabatic LWC
Height above cloud base (m)
0
500
1000
1500
2000
2500
0
1
2
3
4
5
Liquid water content, LWC (g m–3)

Cloud-top Entrainment Instability (CEI)

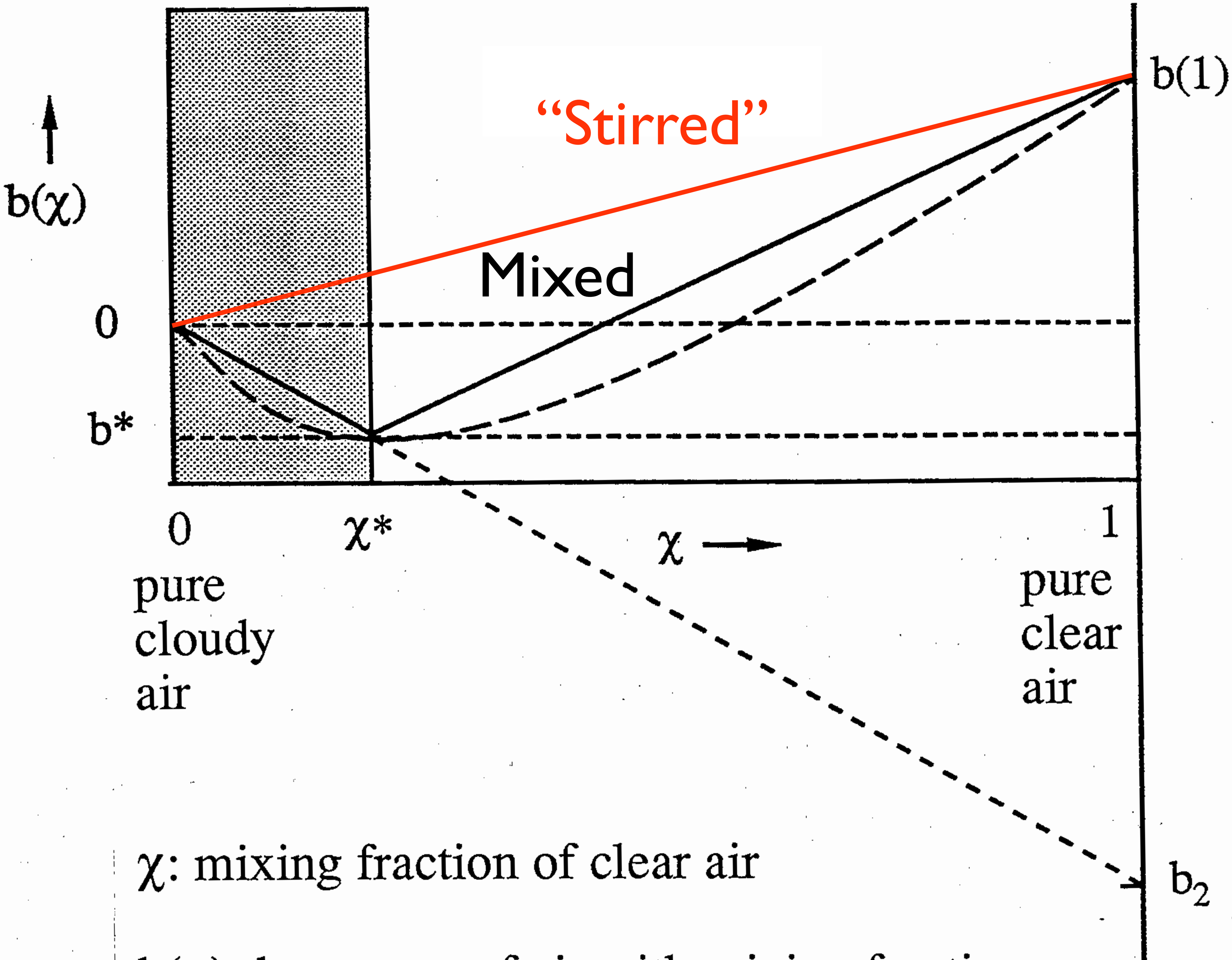


5 m isotropic grid



- Newly entrained thermals tend to follow the dry paths of earlier thermals.
- The dry paths become wider.

Buoyancy vs Mixture Fraction



χ: mixing fraction of clear air

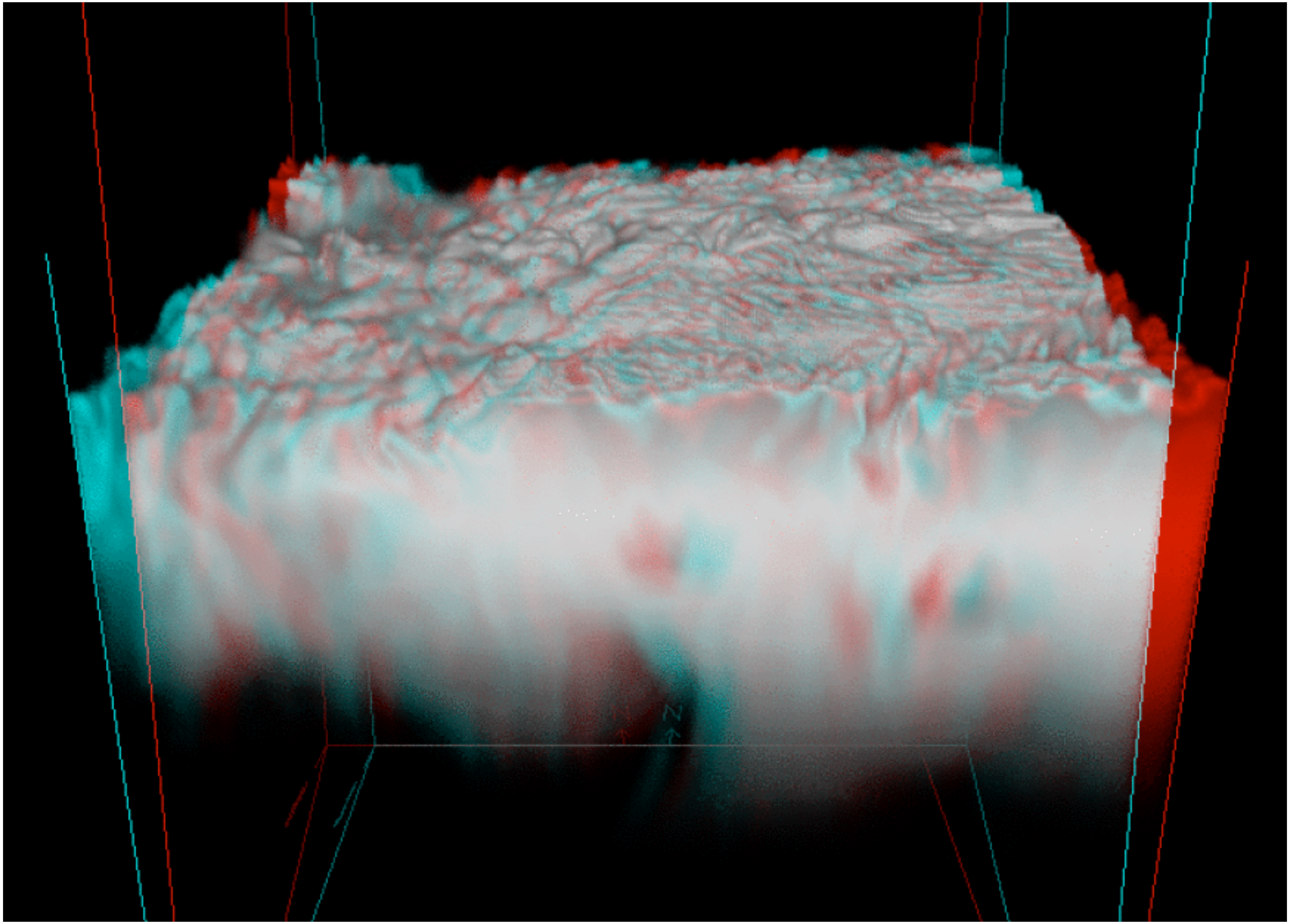
$b(\chi)$: buoyancy of air with mixing fraction χ

an example of high-resolution LES...

Stratocumulus-topped boundary layer

- horizontal grid size = 6.25 m
- vertical grid size = 5 m near cloud top

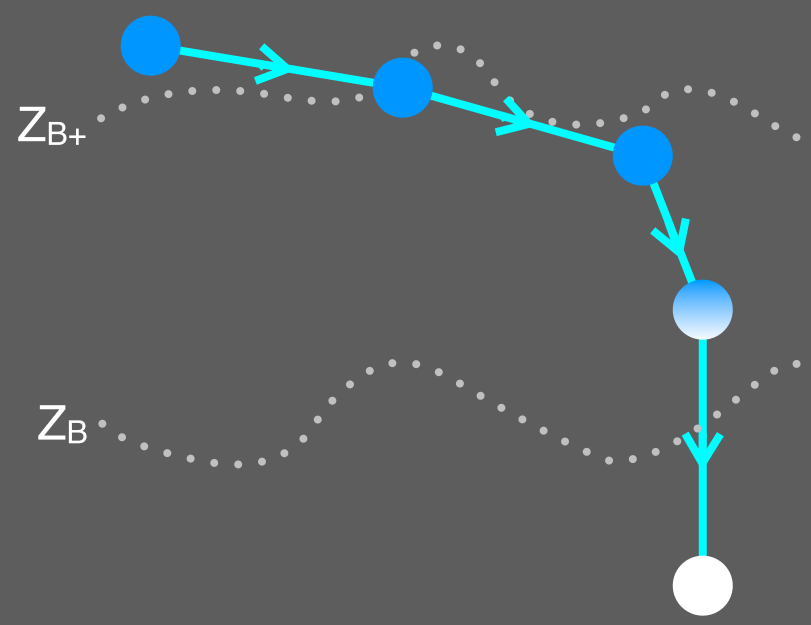
a quarter of the domain



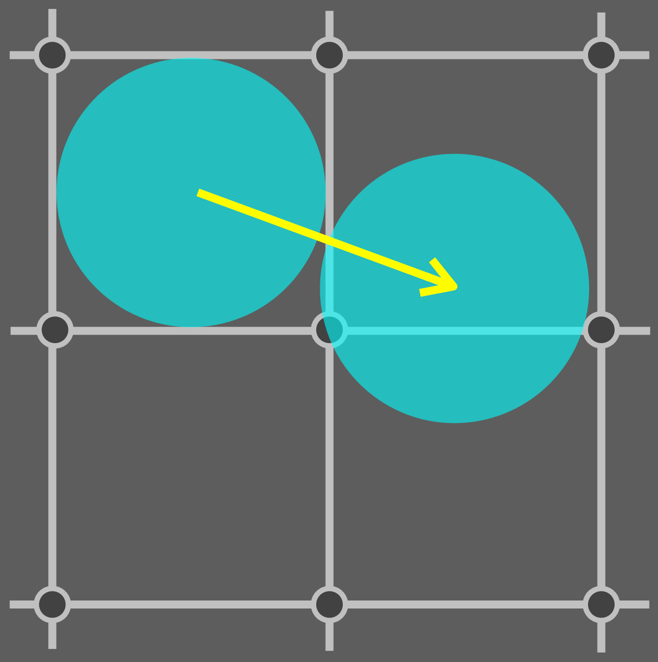
Tracking Parcels
That Are Entrained Across Cloud Tops

Takanobu Yamaguchi
Department of Atmospheric Science, Colorado State University
Fort Collins, Colorado, USA

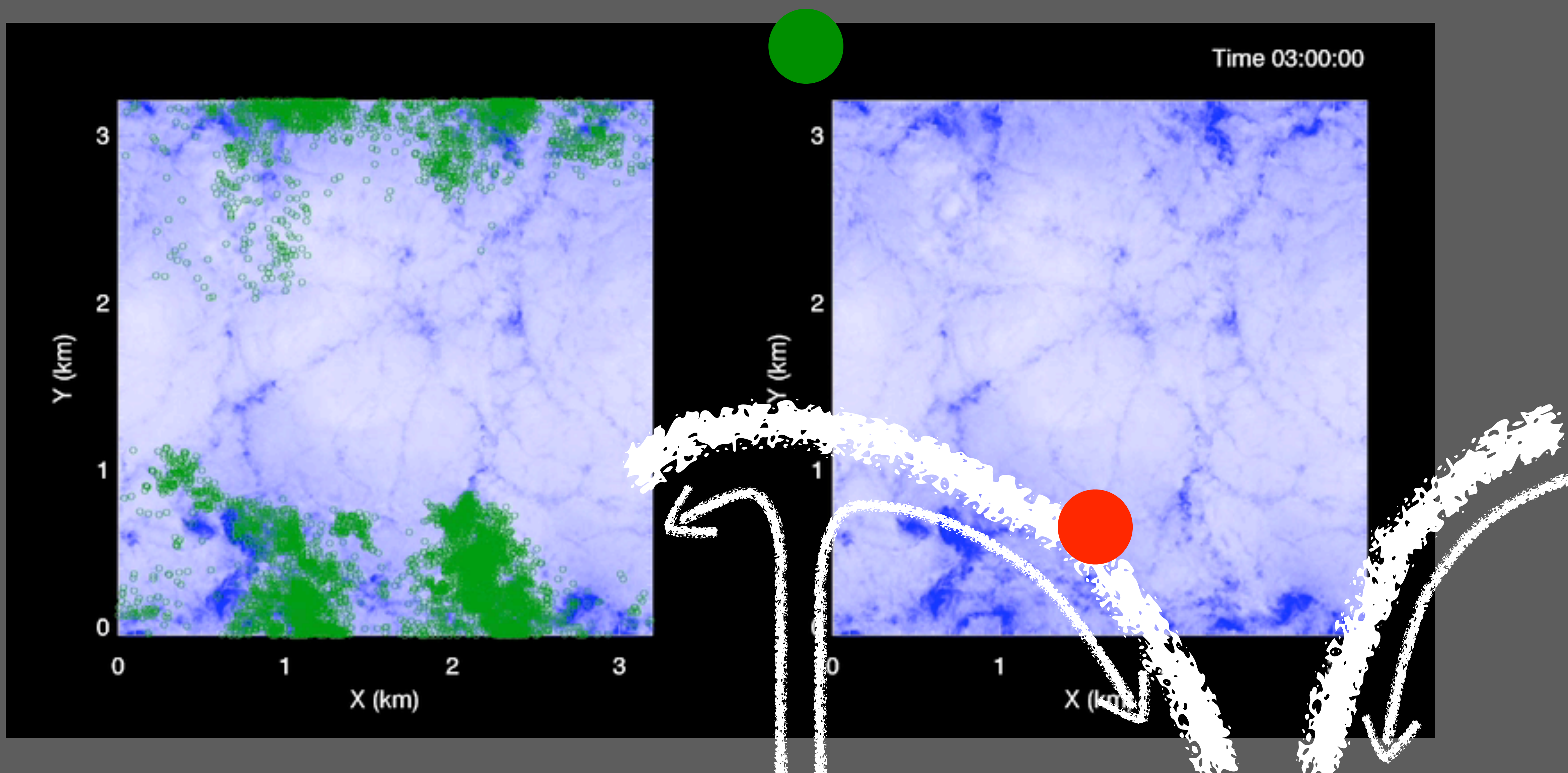
Strategy - Lagrangian tracking and LES



- Observation: Tracking individual entrained parcels is impossible.
- Lagrangian parcel tracking model (LPTM)
  - Parcel position is predicted with diagnosed parcel velocity from LES.
  - LPTM is implemented in our LES model, SAM.

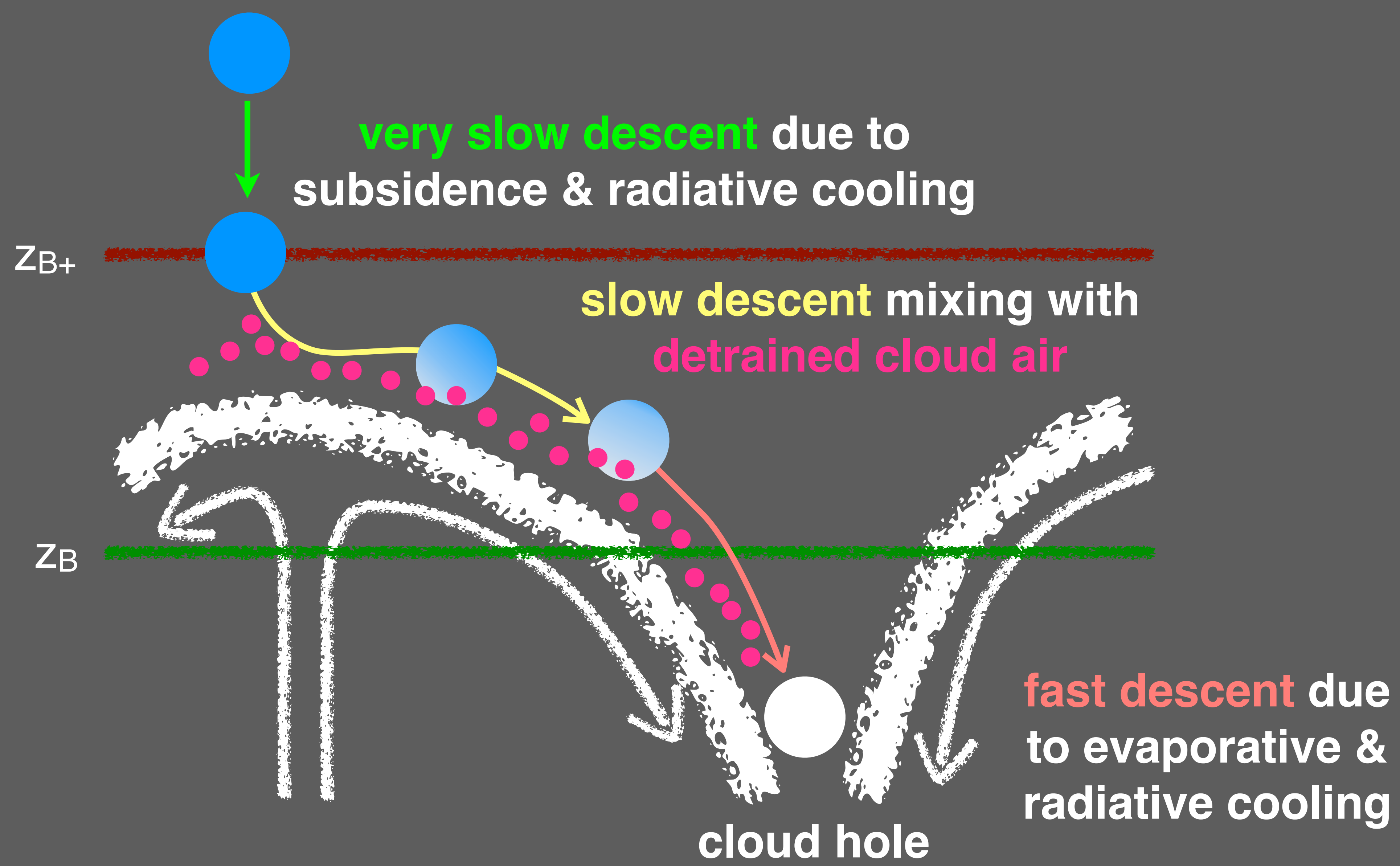


Locations of Parcels entrained at 03:45

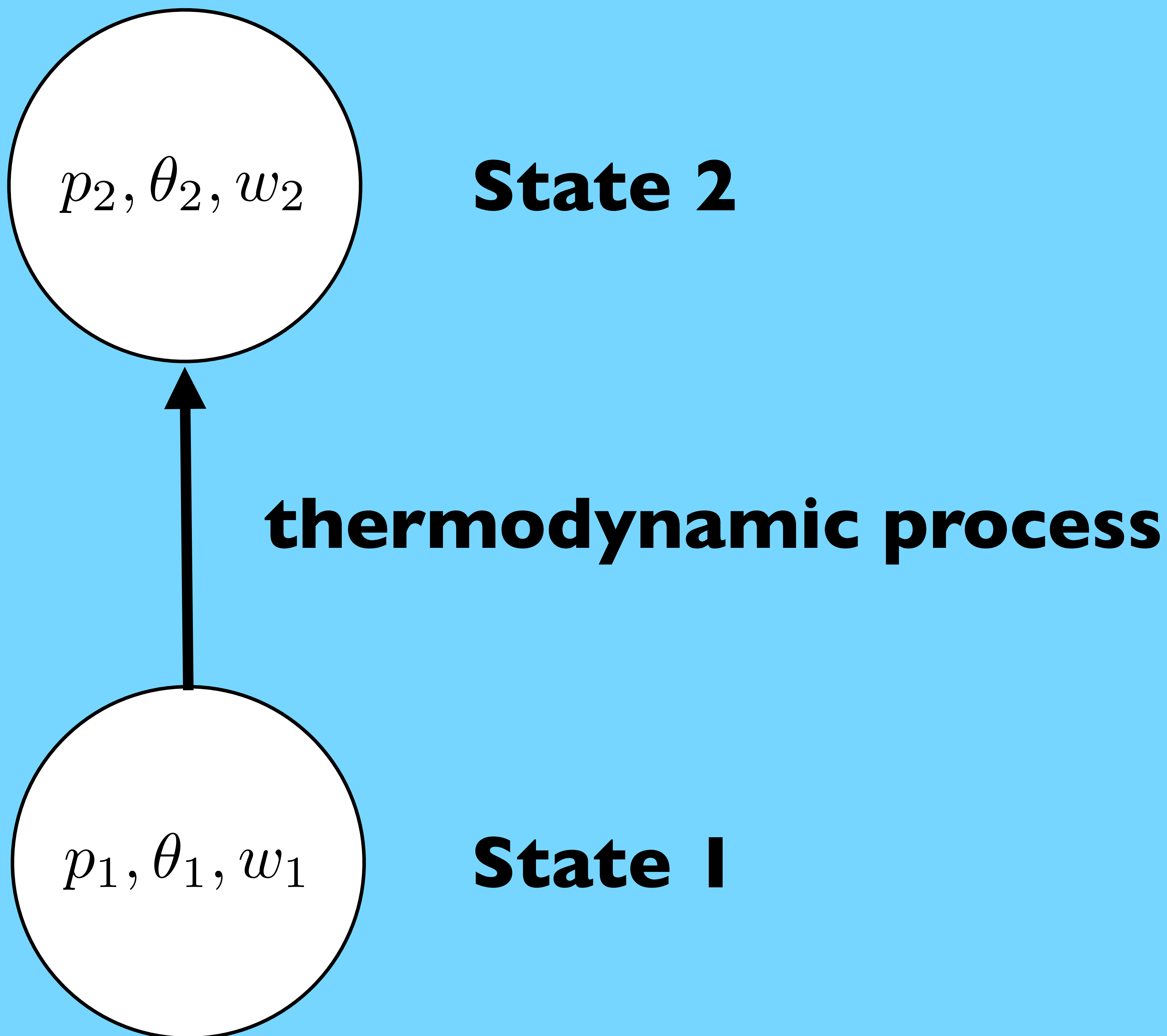


- Parcels entrained at 3:45 are shown.
- Green parcels are unsaturated.
- Red parcels contain cloud water.

Cloud-top entrainment



Parcel Model



- **Parcel model**
  - No internal structure or variability.
  - Entrained air is instantly mixed.
  - Simplest model for microphysics and turbulence interactions.
  - Lagrangian framework avoids numerical artifacts due to advection.

Mixing Time Scale

$$\tau = \left(\frac{d^2}{\epsilon}\right)^{1/3},$$

d is entrained blob size, ϵ is dissipation rate of turbulence kinetic energy.

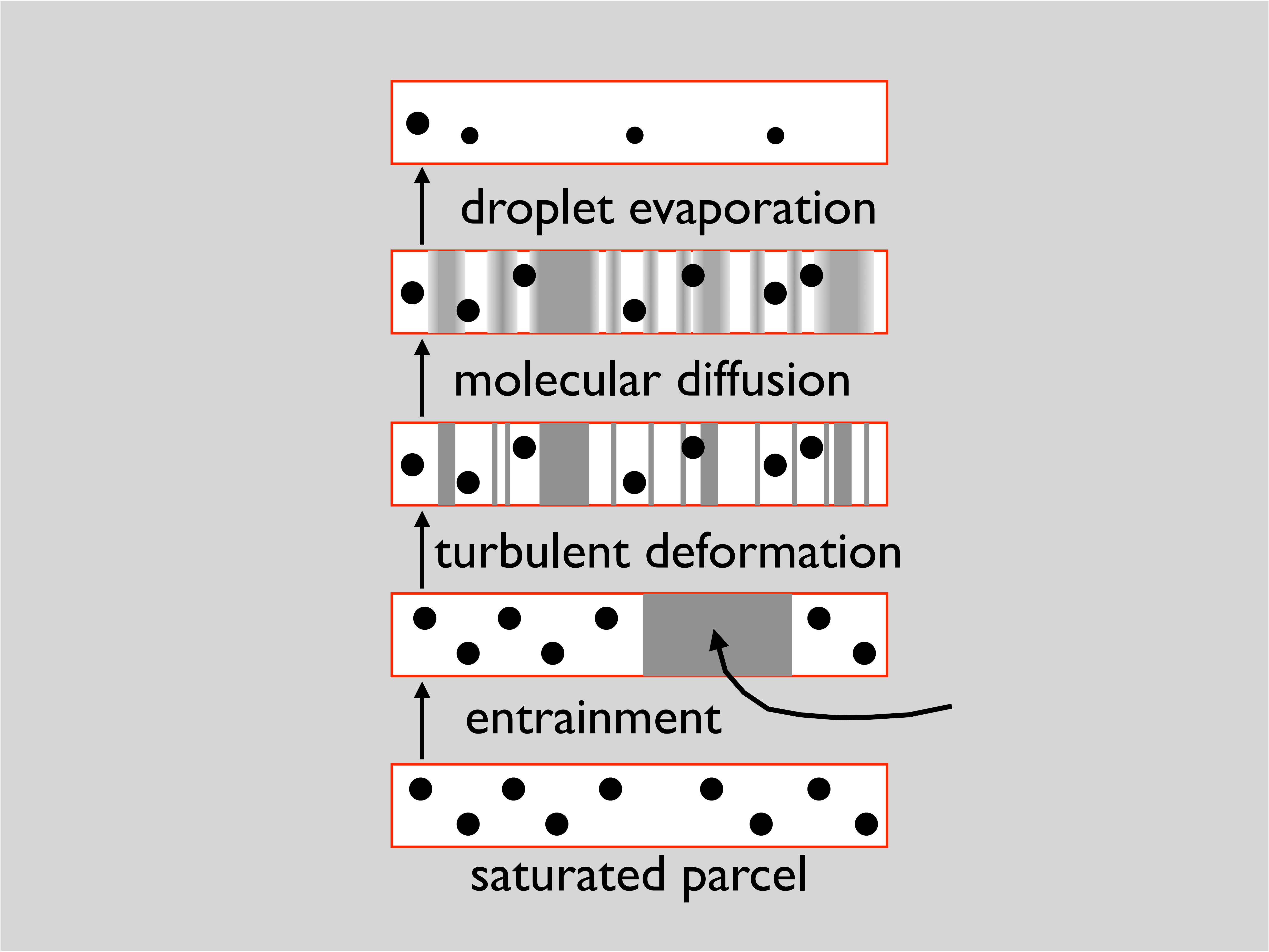
For a **cumulus cloud,** $U \sim 2$ m/s, $L \sim 1000$ m, so $\epsilon \sim U^3/L = 10^{-2}$ m^2/s^3. For $d = 100$ m, $\tau \sim 100$ s.

Classic (instant mixing) parcel model is recovered when

- Entrained blob size, $d \to 0$
- Turbulence intensity, $\epsilon \to \infty$

- **Explicit Mixing Parcel Model (EMPM)**
  - Combines a parcel model with:
    - A turbulent mixing model (Linear Eddy Model).
    - Stochastic entrainment events.
    - Bulk or droplet microphysics.
    - Specified ascent speed.
  - Cloud droplets can grow or evaporate according to their local environments.

EMPM with droplets and entrainment



- **Linear Eddy Model (LEM)**
  - Evolves **scalar** spatial variability on all relevant turbulence scales using one dimension.
  - Distinguishes turbulent deformation and molecular diffusion.
  - Turbulence properties are **specified**.

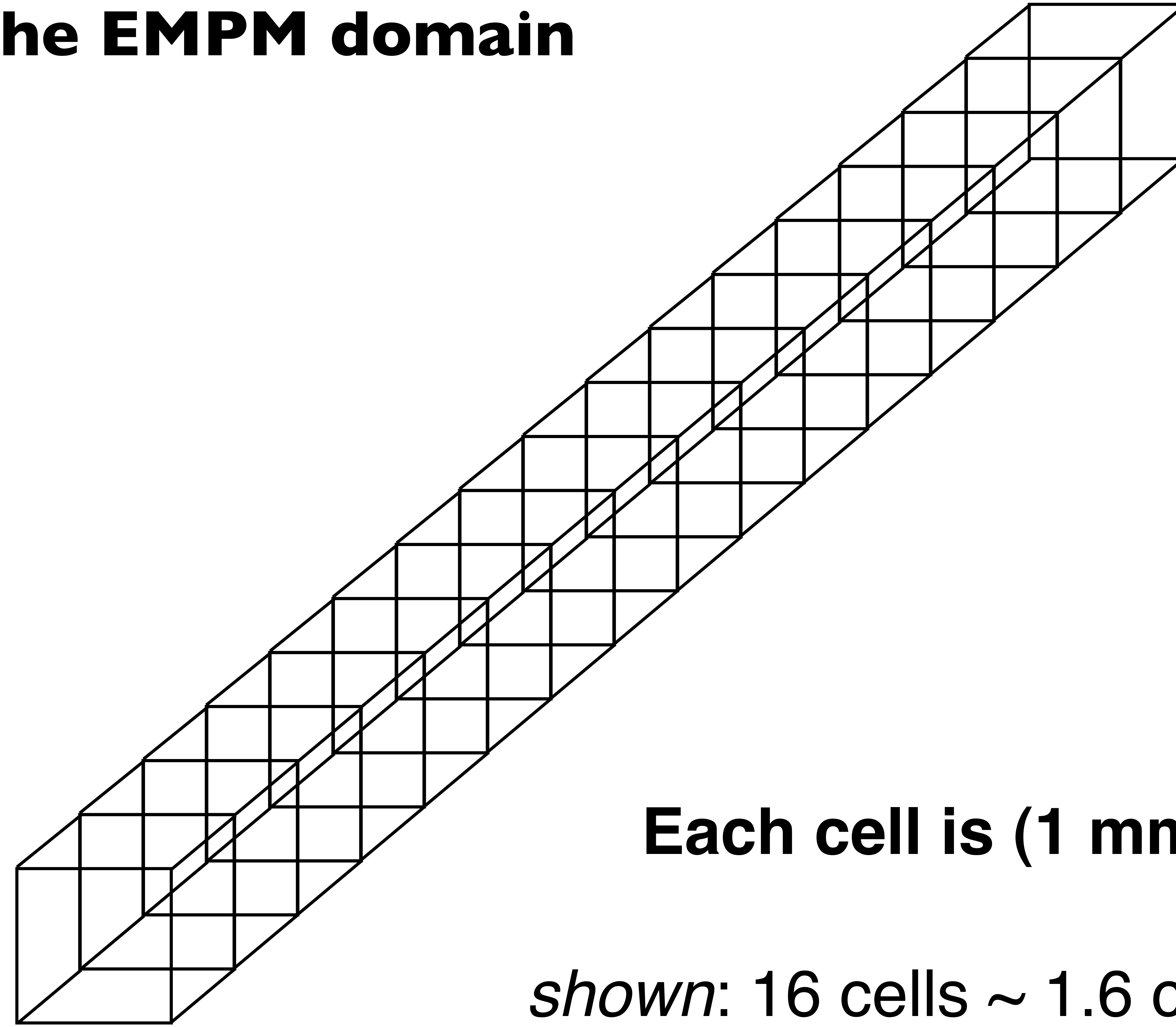
Dimensionality Reduction

- 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.

EMPM Fluid Variables

- Bulk microphysics:
  - Liquid water static energy
  - Total water mixing ratio
- Droplet microphysics:
  - Temperature
  - Water vapor mixing ratio

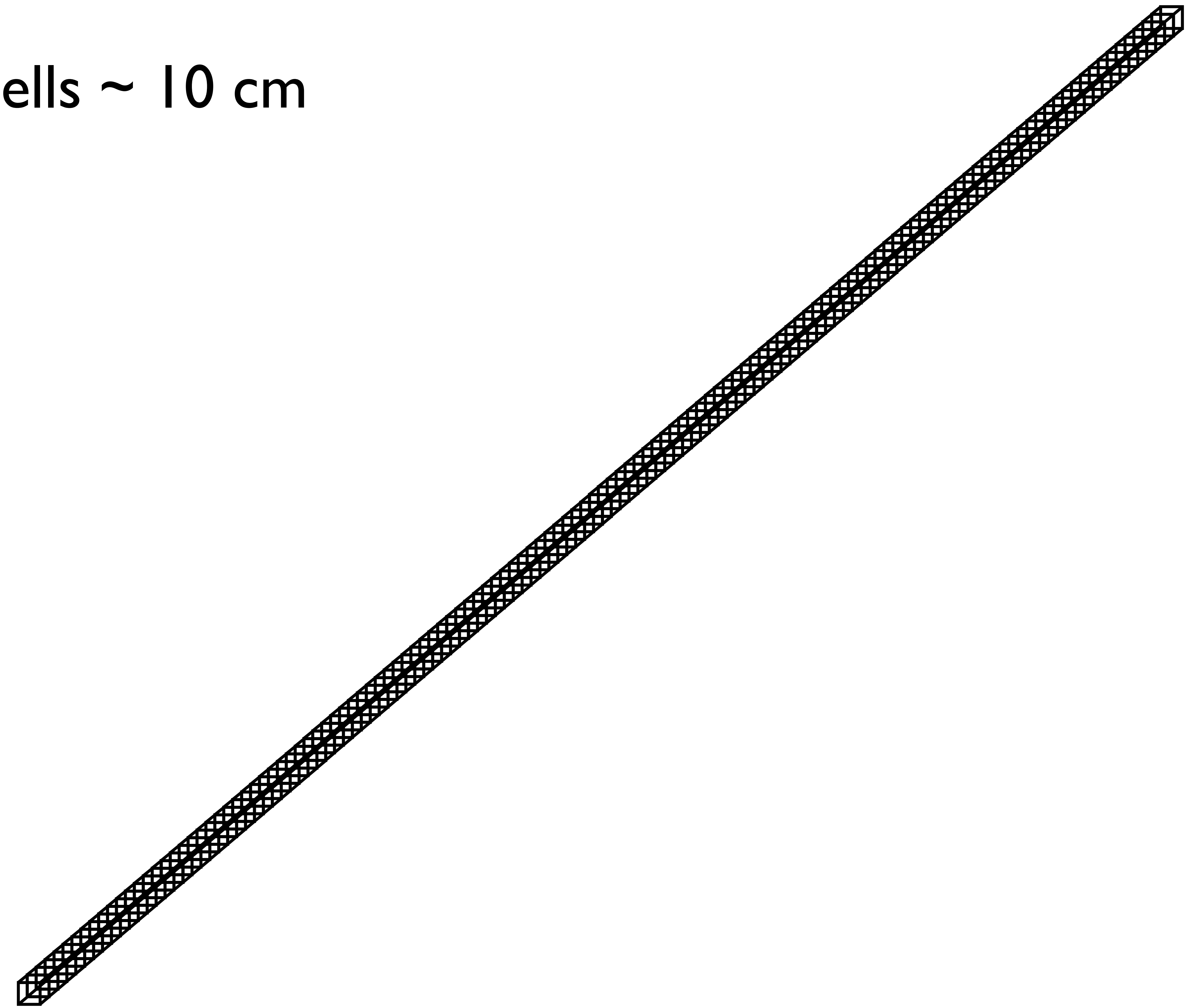
The EMPM domain



Each cell is $(1\ mm)^3$

shown: 16 cells ~ 1.6 cm

128 cells ~ 10 cm



1024 cells ~ 1 m

EMPM Required Inputs

- Required for a classical (instant mixing) parcel model calculation:

  Thermodynamic properties of cloud-base air

  Updraft speed

  Entrainment rate

  Thermodynamic properties of entrained air

  Aerosol properties

- In addition, the EMPM requires:

  Parcel size

  Entrained blob size, d

  Turbulence intensity (e.g., dissipation rate, ϵ)

Droplet growth by diffusion of water vapor

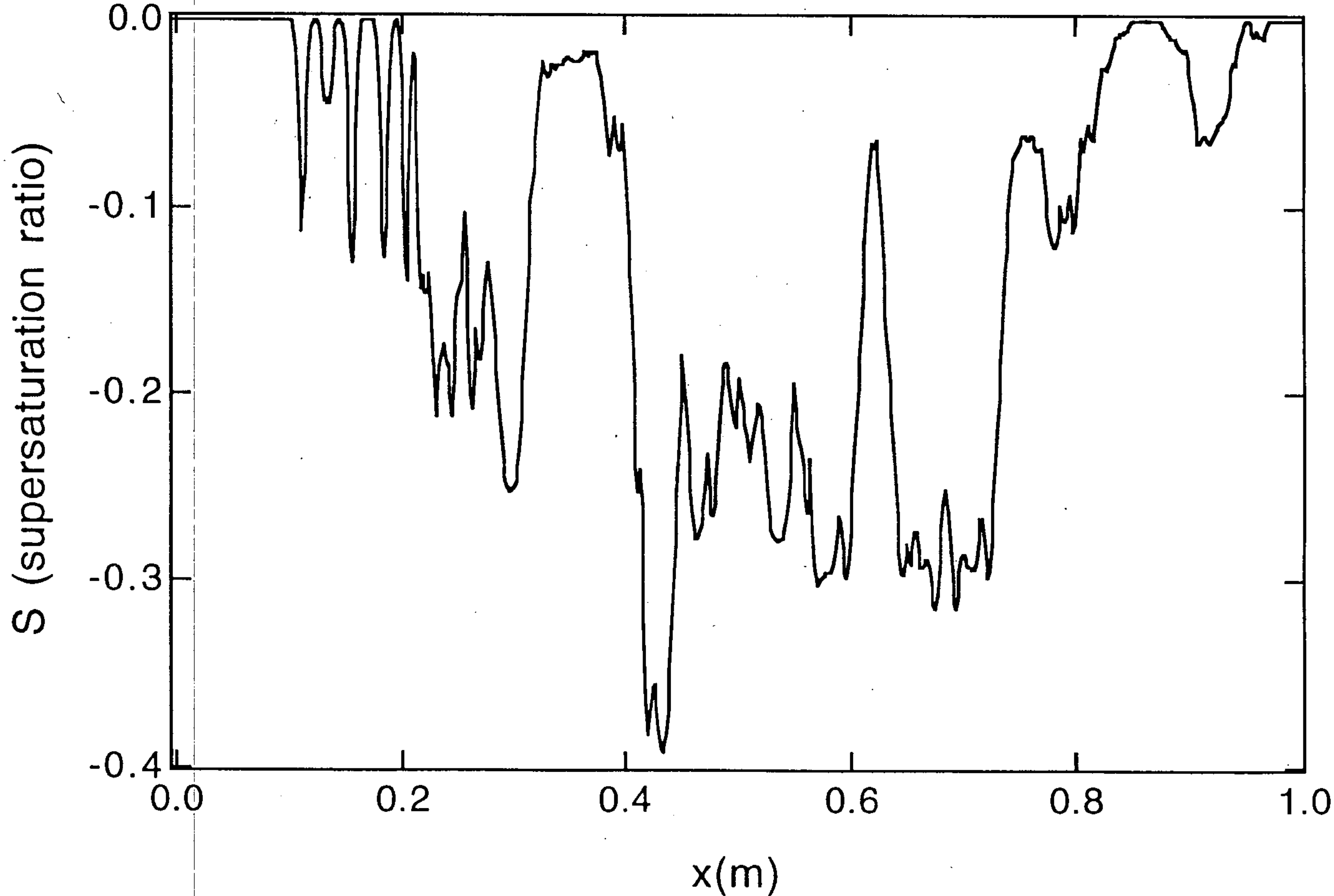
$$r_j \frac{dr_j}{dt} = \frac{S - A_1 + A_2}{A_3 + A_4}$$

r_j is the radius of the jth droplet, A_1 and A_2 are the correction factors for droplet curvature and solute effects, A_3 and A_4 are the heat conduction and vapor diffusion terms, and S is the supersaturation.

In the EMPM, droplets move relative to the fluid at their terminal velocities.

Snapshot of supersaturation ratio during mixing

(from the EMPM)



Droplet histories during mixing

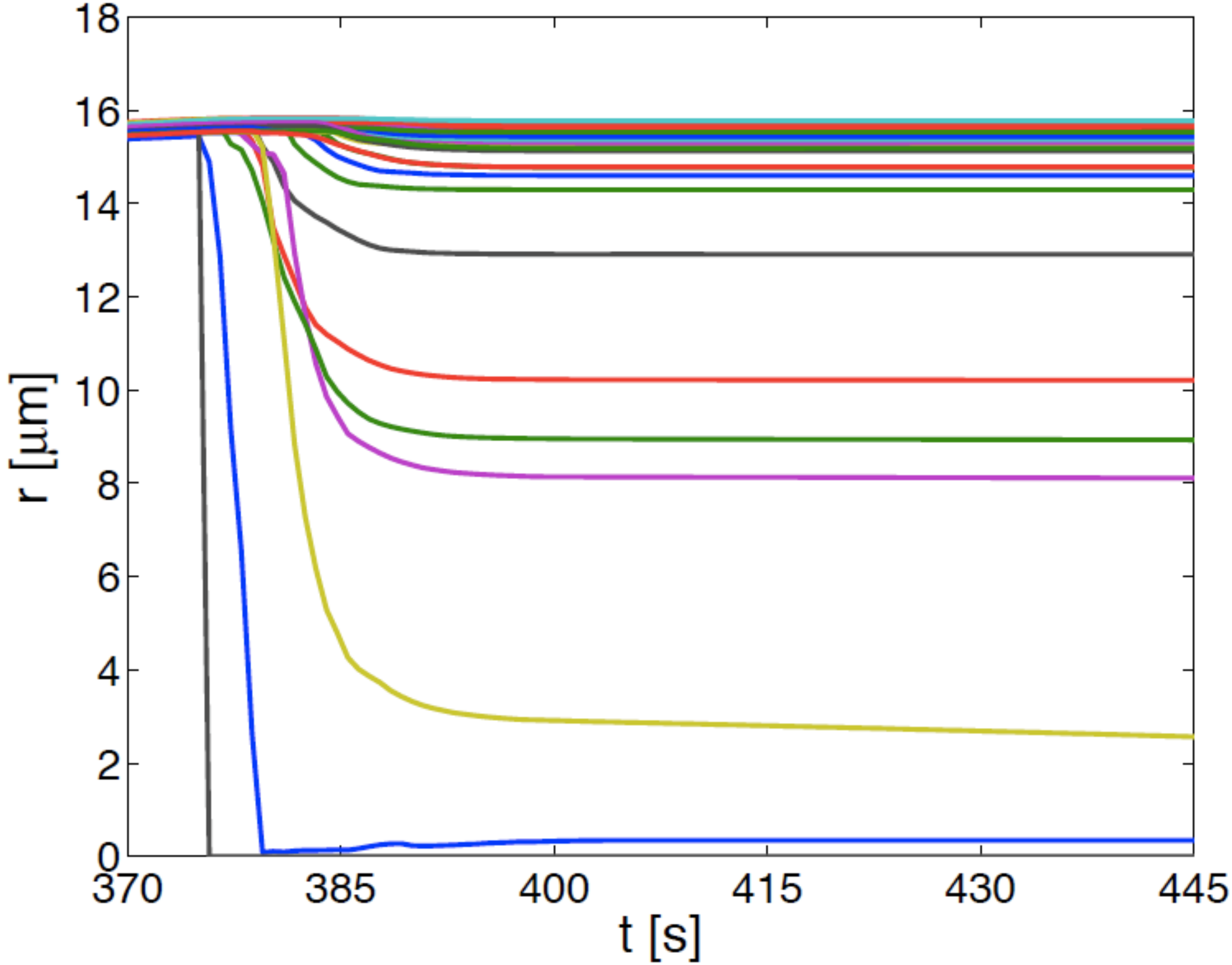
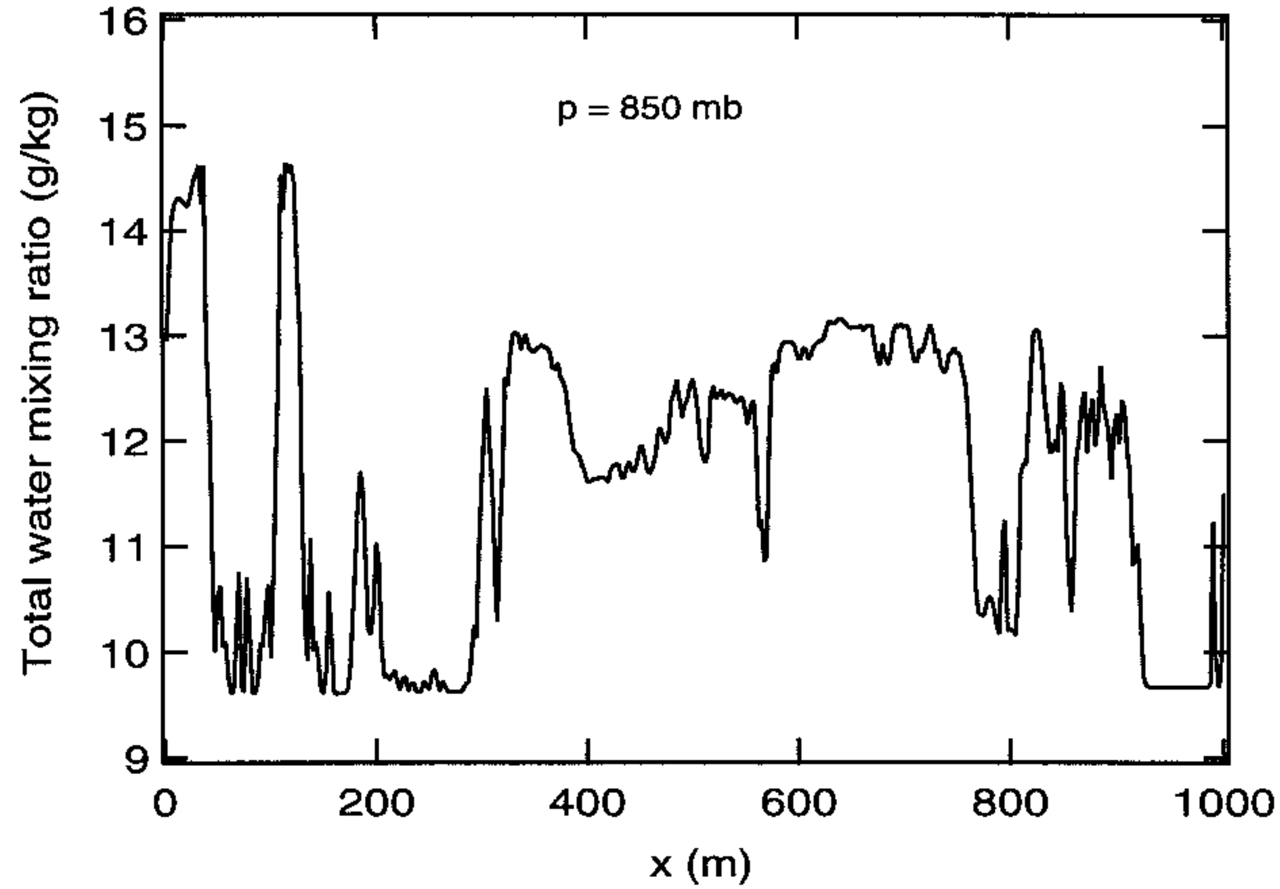
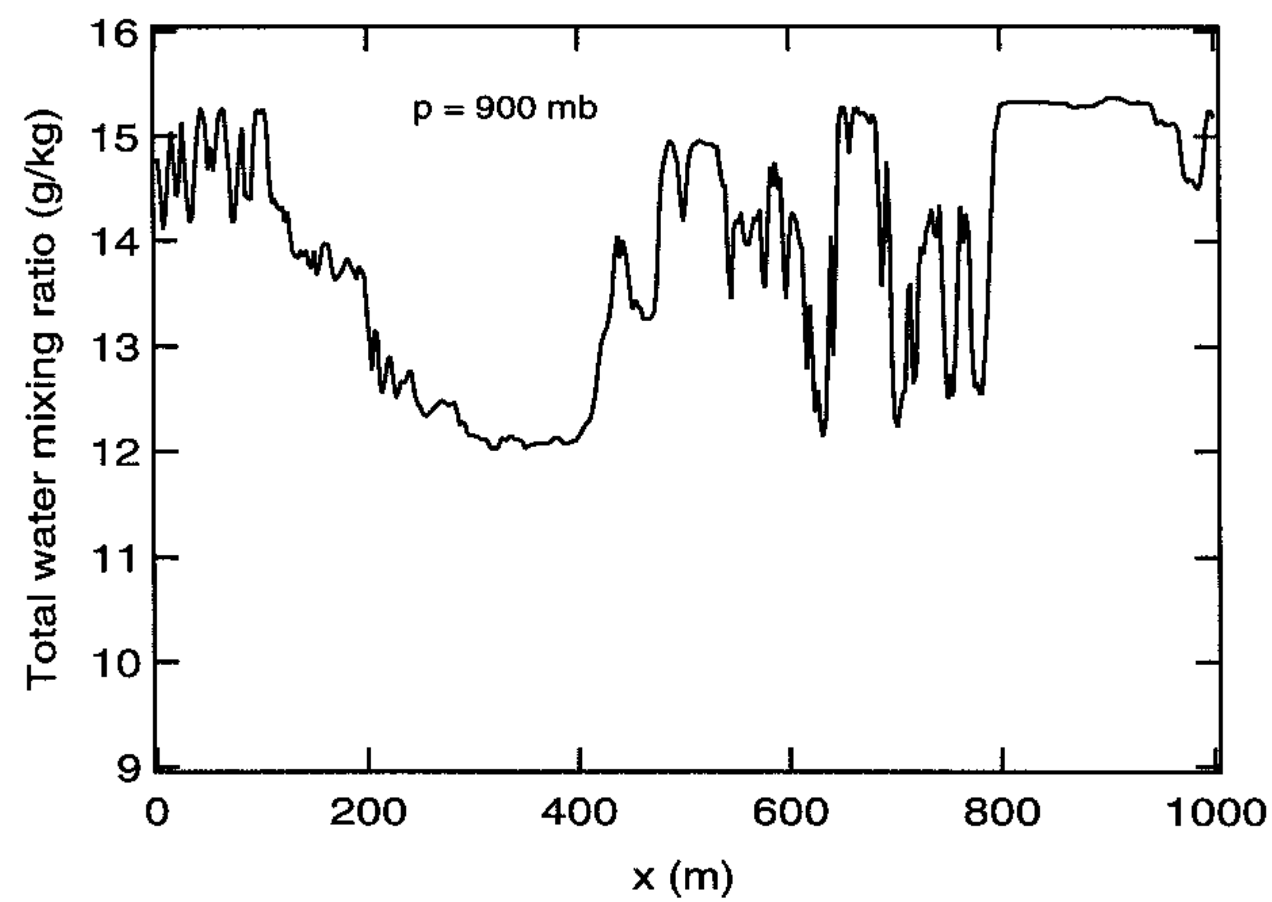


Figure 4.10: Radius histories of 30 droplets for $f = 0.1$ and $RH_e = 0.219$.

Comparison to Measurements

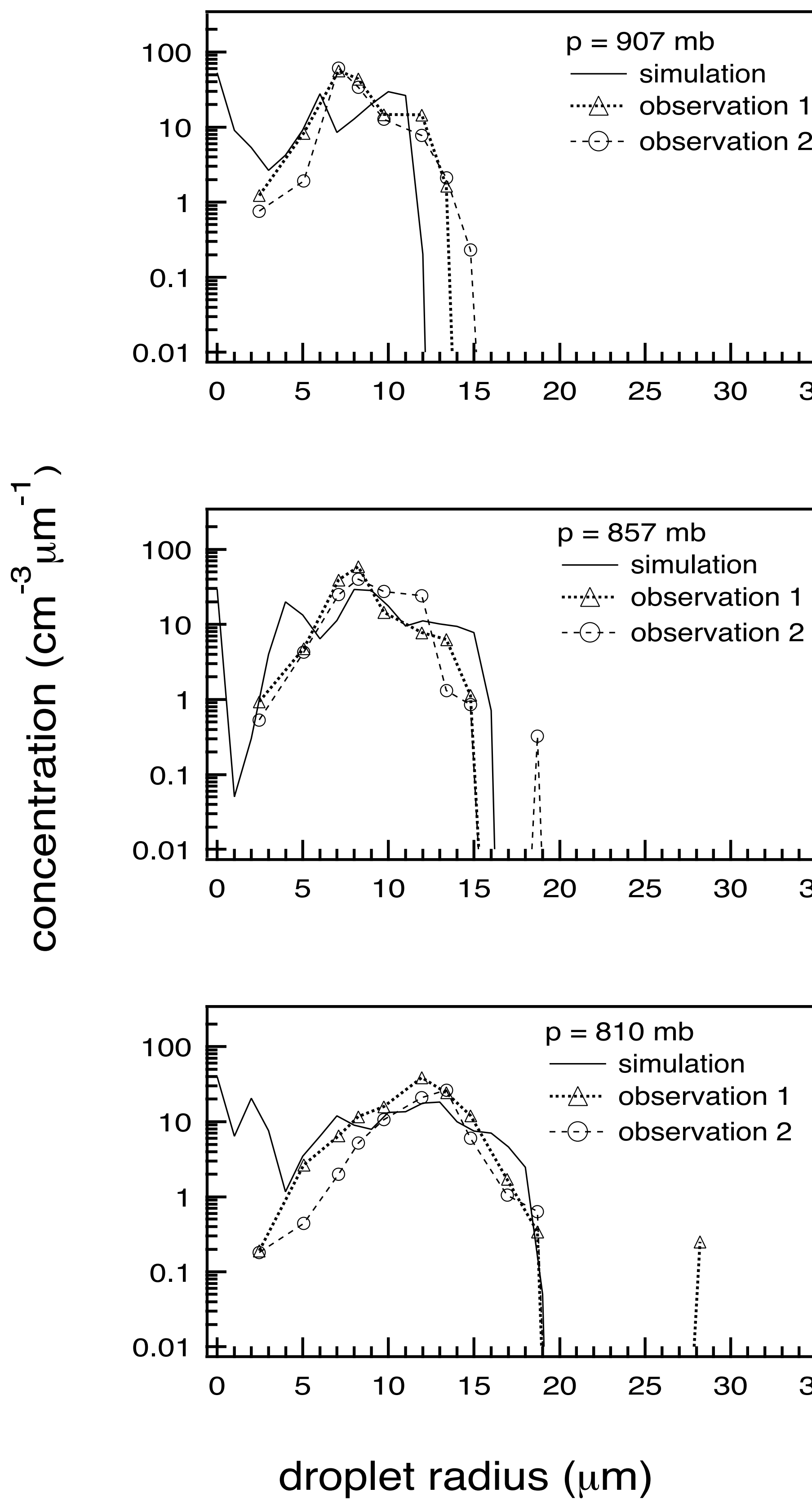
EMPM results can be directly compared to high-rate aircraft measurements of temperature, water vapor, liquid water content, and droplet size spectra.



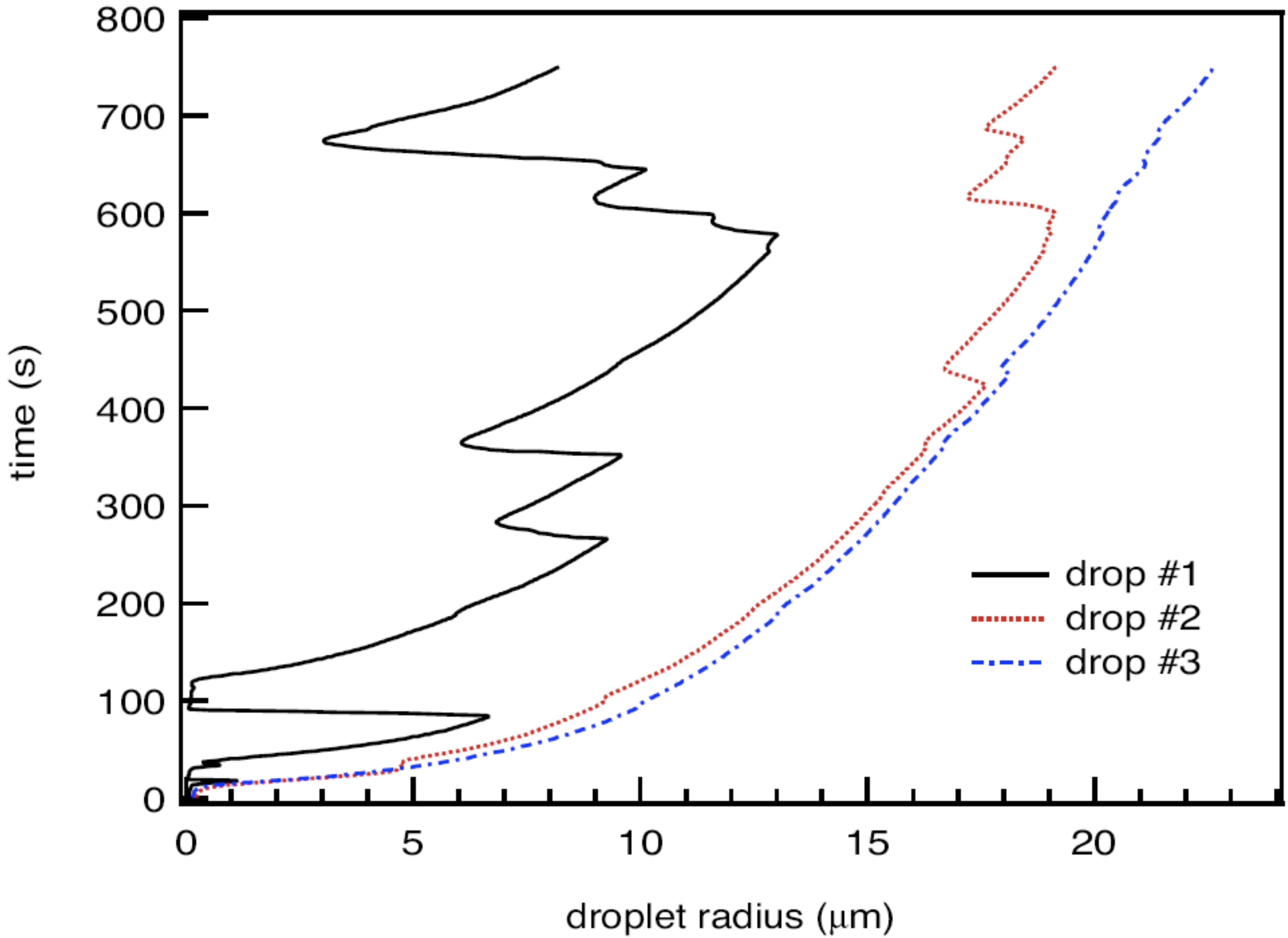


Applying the EMPM to Hawaiian Cumuli

The EMPM produced realistic, broad droplet size spectra that included super-adiabatic-sized droplets. The computed spectra agreed with those measured by aircraft.



Large Droplet Production due to Entrainment and Mixing



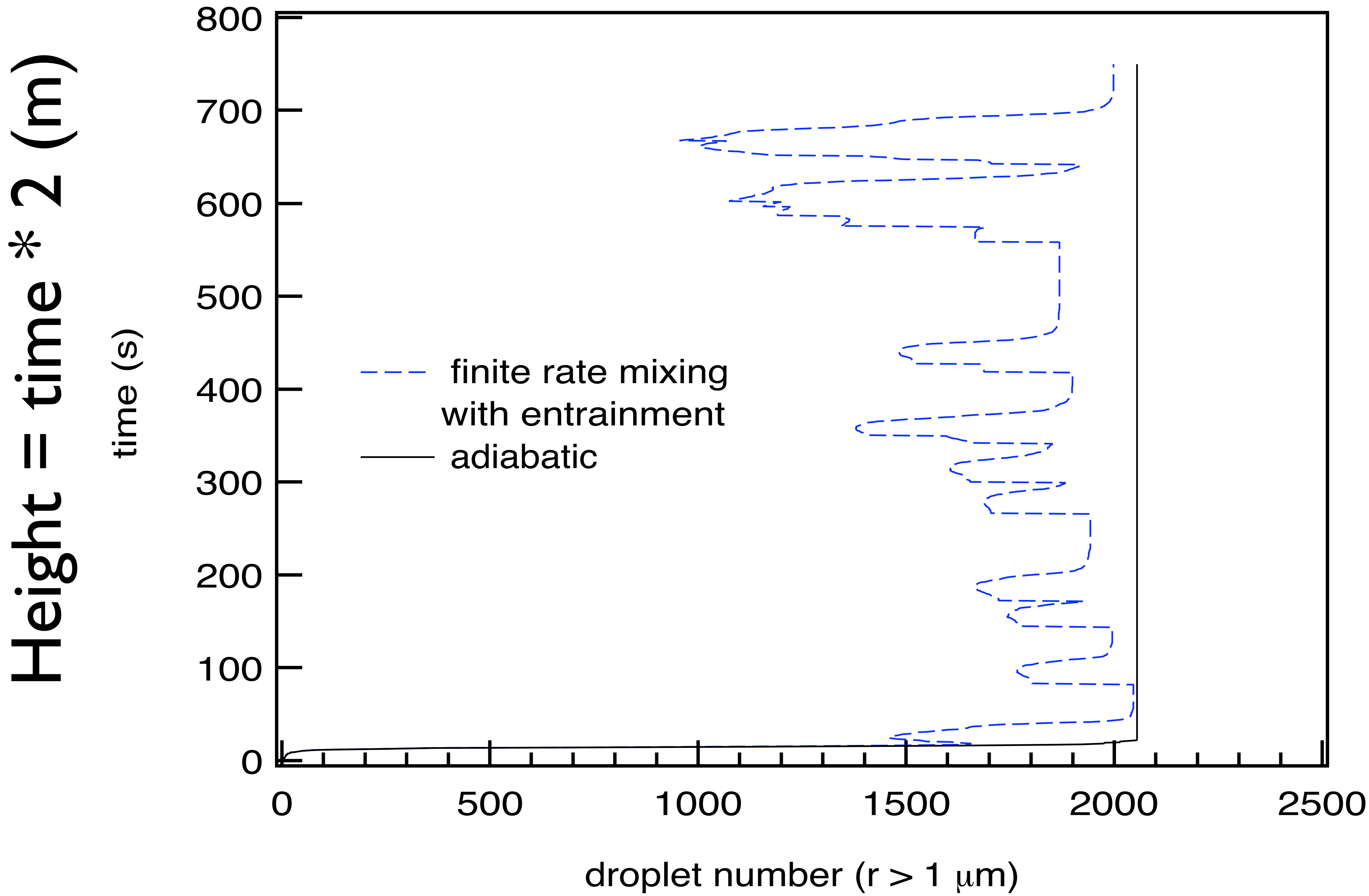
800
700
600
500
400
300
200
100
0
time (s)
0
5
10
15
20
droplet radius (μm)
drop #1
drop #2
drop #3

Some factors that affect large droplet production

- Turbulence intensity (dissipation rate)
- Entrained blob size
- Entrainment rate
- Relative humidity of entrained air

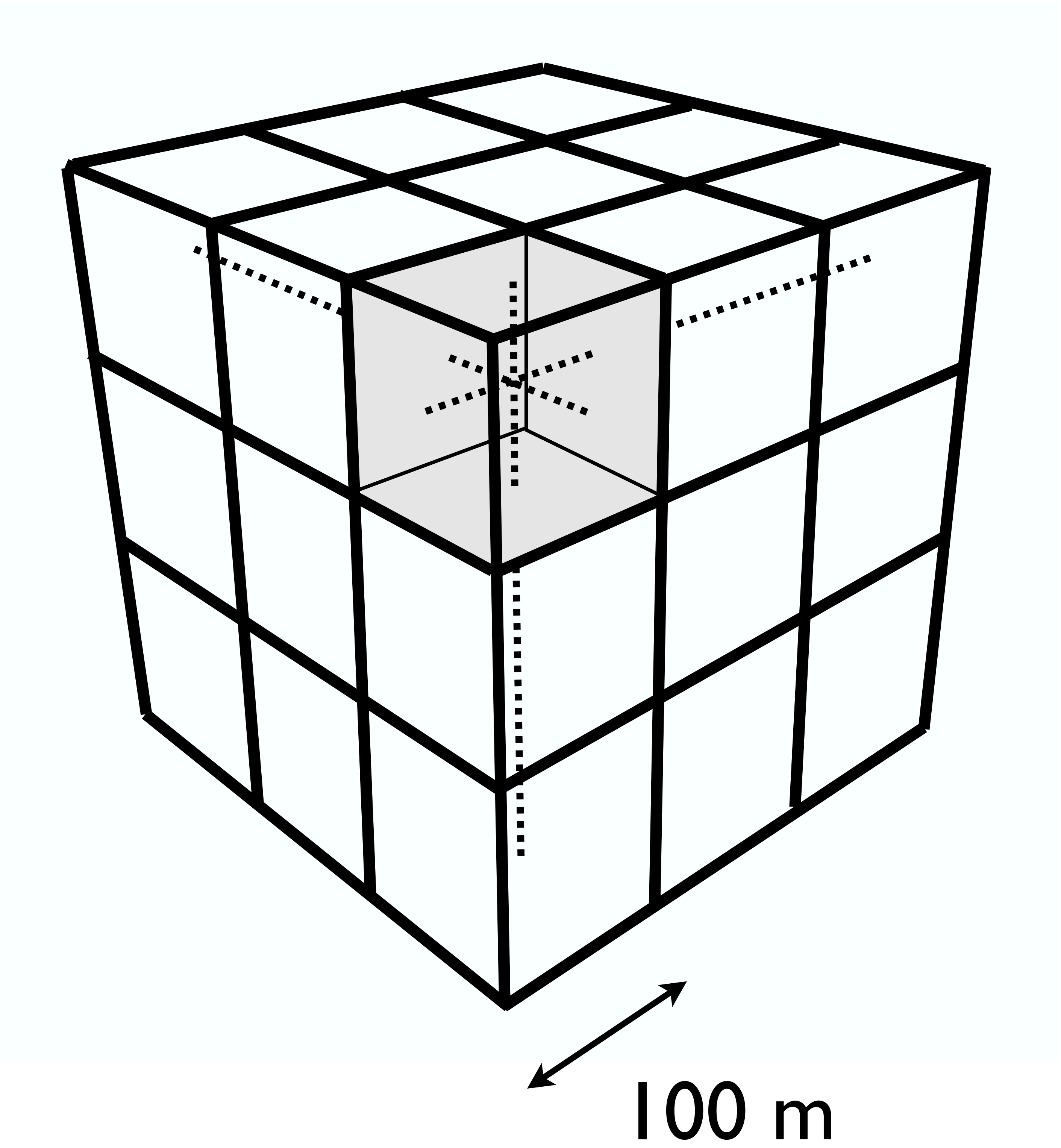
How entrainment and mixing scenarios affect droplet spectra in cumulus clouds

N(z) with entrained CCN



Su 1997

Large-Eddy Simulation (LES) model



Linear Eddy Model for SGS