Multi-Scale Modeling of Fine-Scale Structure in Cumulus Clouds

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Collaborators

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Motivation

- Our overall goal is to use the Explicit Mixing Parcel Model (EMPM) with droplet growth to study the relative importance of several physical mechanisms that have been proposed to explain droplet spectral broadening and rain initiation in warm cumulus clouds.

- The mechanisms that we are investigating are

  entrainment and mixing,

  droplet clustering due to turbulence, and

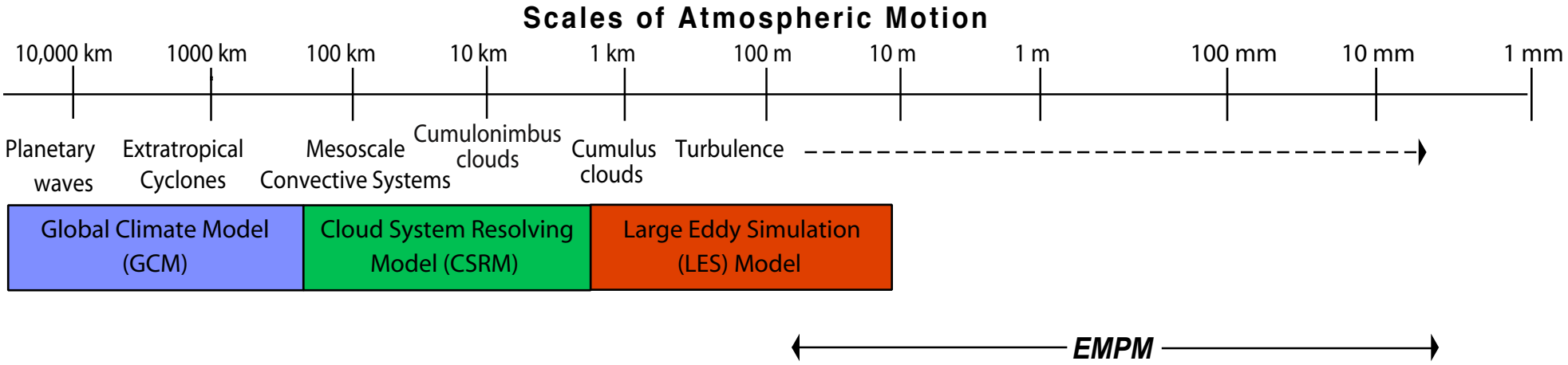
  ultragiant cloud condensation nuclei.

Explicit Mixing Parcel Model (EMPM)

- The EMPM predicts the evolving in-cloud variability due to entrainment and finite-rate turbulent mixing using a 1D representation of a rising cloudy parcel.

- The 1D formulation allows the model to resolve fine-scale variability down to the smallest turbulent scales ($\sim$ 1 mm).

- The EMPM can calculate the growth of several thousand individual cloud droplets based on each droplet s local environment.


Scales of Atmospheric Motion
10,000 km
1000 km
100 km
10 km
1 km
100 m
10 m
1 m
100 mm
10 mm
1 mm
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
EMPM

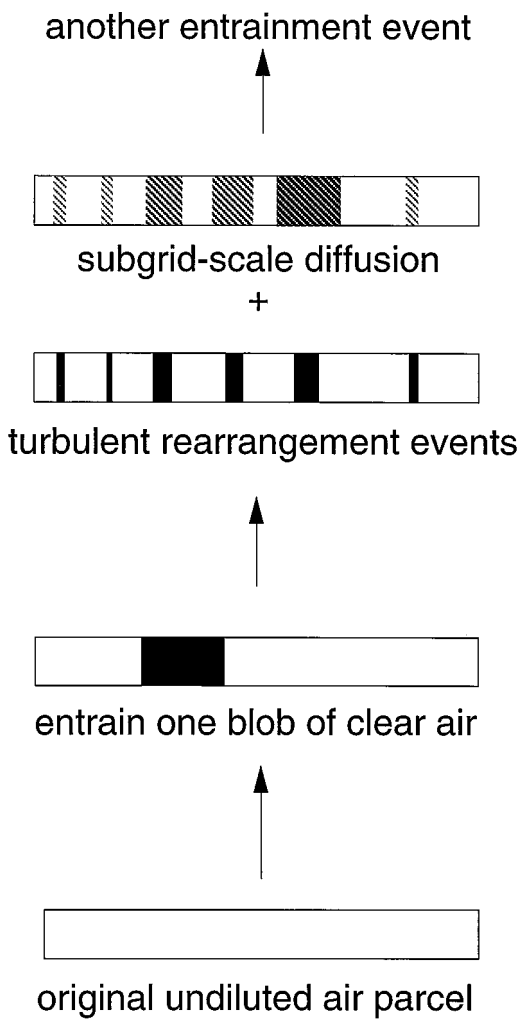


FIG. 3. A parcel is represented by a 1D domain in the EMPM. The parcel's internal structure evolves due to discrete entrainment events and turbulent mixing (rearrangement events and subgrid-scale diffusion).

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)

Mixing Time Scale

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

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

$$\epsilon \sim \frac{U^3}{L} = \frac{u(l)^3}{l} = \frac{u(d)^3}{d},$$

U is velocity scale for largest eddies (of size L); $u(l)$ is same for size l eddies. Therefore,

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

which is the eddy turnover time for an eddy of size d.

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

Classic (instant mixing) parcel model is recovered when

- Mixing time scale $\rightarrow 0$

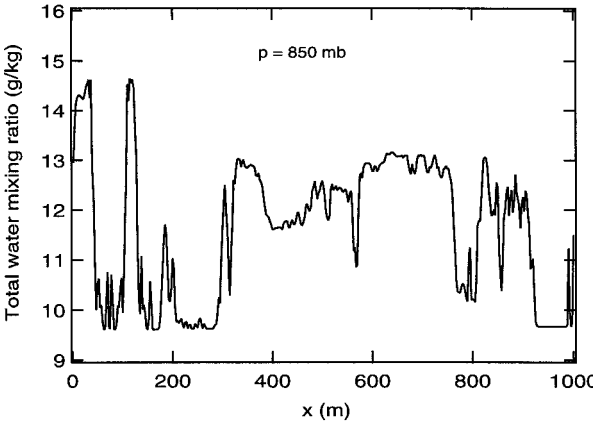
- This occurs when

  Entrained blob size $\rightarrow 0$, or

  Turbulence intensity $\rightarrow \infty$

Comparison to Measurements

EMPM results can be directly compared to high-rate [1 Hz (100 m) to 1000 Hz (10 cm)] aircraft measurements of temperature, water vapor, liquid water content, and droplet size spectra.



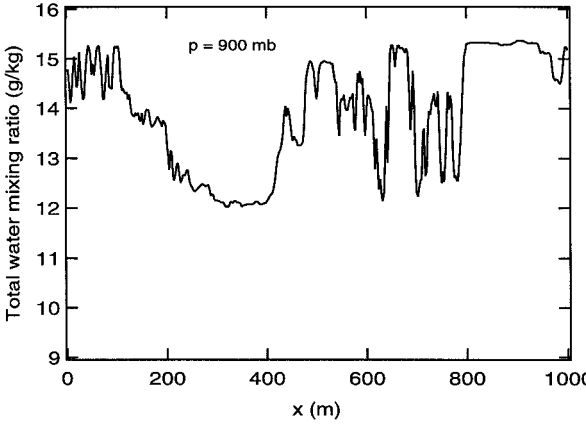
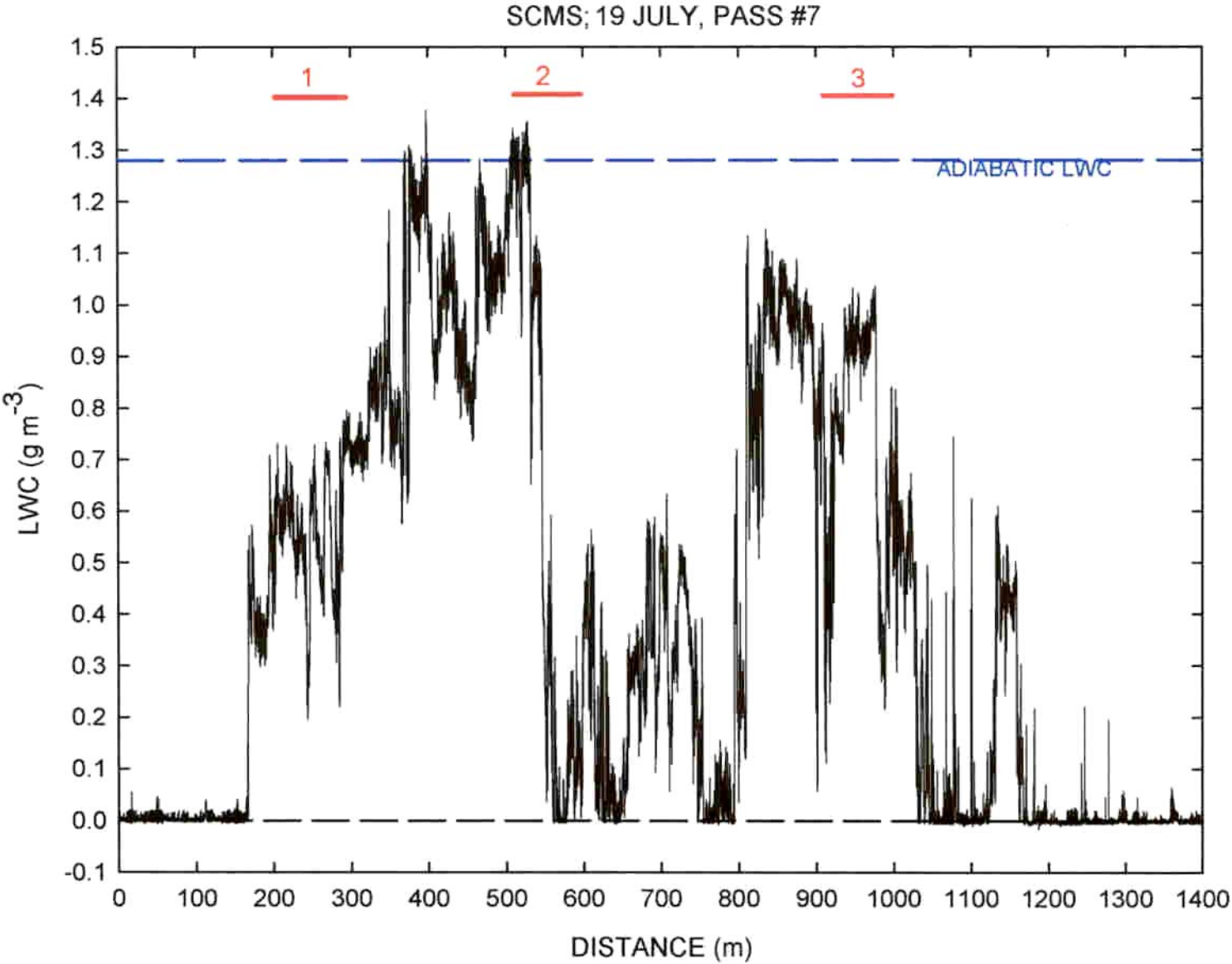
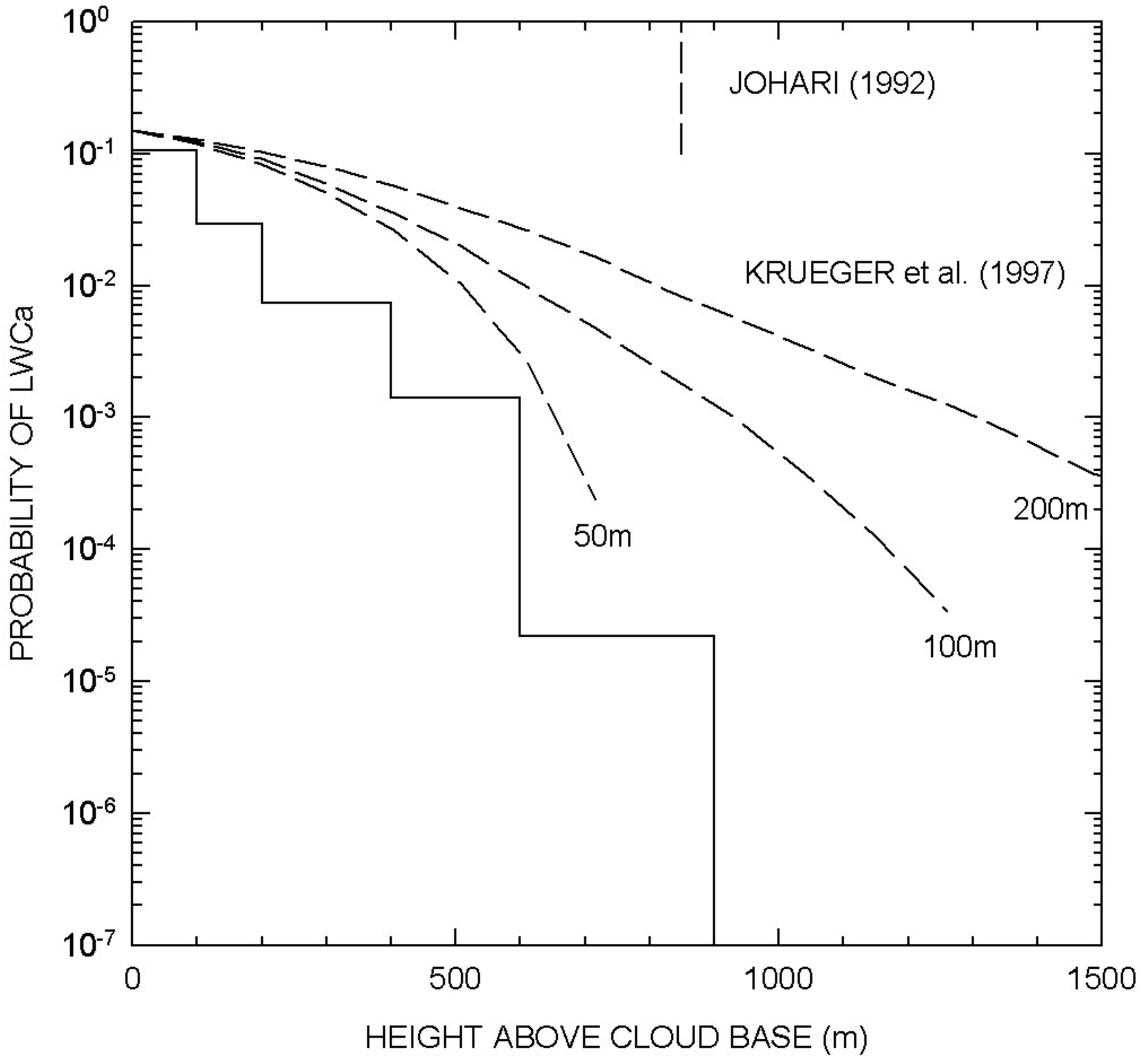


FIG. 4. ''Snapshots'' from the EMPM of q_w (x) at $p = 900$ mb (top) and $p = 850$ mb (bottom) during one realization.


SCMS; 19 JULY, PASS #7
1
2
3
ADIABATIC LWC
LWC (g m-3)
DISTANCE (m)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400


JOHARI (1992)
KRUEGER et al. (1997)
50m
100m
200m
PROBABILITY OF LWCa
HEIGHT ABOVE CLOUD BASE (m)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
500
1000
1500

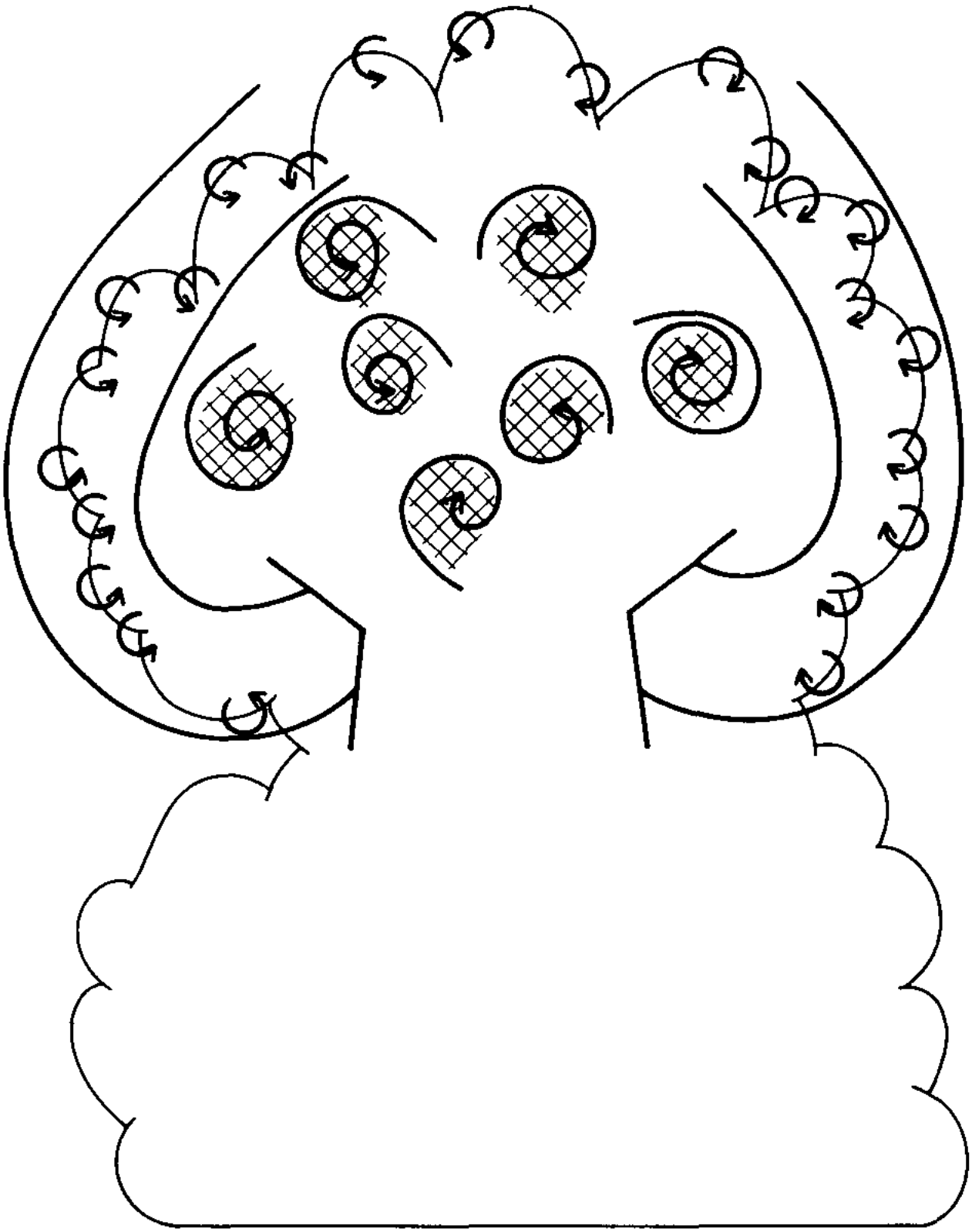


FIG. 13. Illustration of entrainment and mixing in small cumulus clouds. Key characteristics: initial entrainment and mixing near edges, simultaneous but discrete large-scale entrainment events due to cloud-scale eddies, subsequent homogenization of regions 10–100 m in length.

Applying the EMPM to Hawaiian Cumuli

Results

- Based on composited measurements of active cloud turrets (Raga et al. 1990)
- **Macrophysics:** in-cloud profiles (data: G. Raga)
- **Microphysics:** droplet spectra (data: C. Pontikis)
- **Large-droplet production**

Applying the EMPM to Hawaiian Cumuli

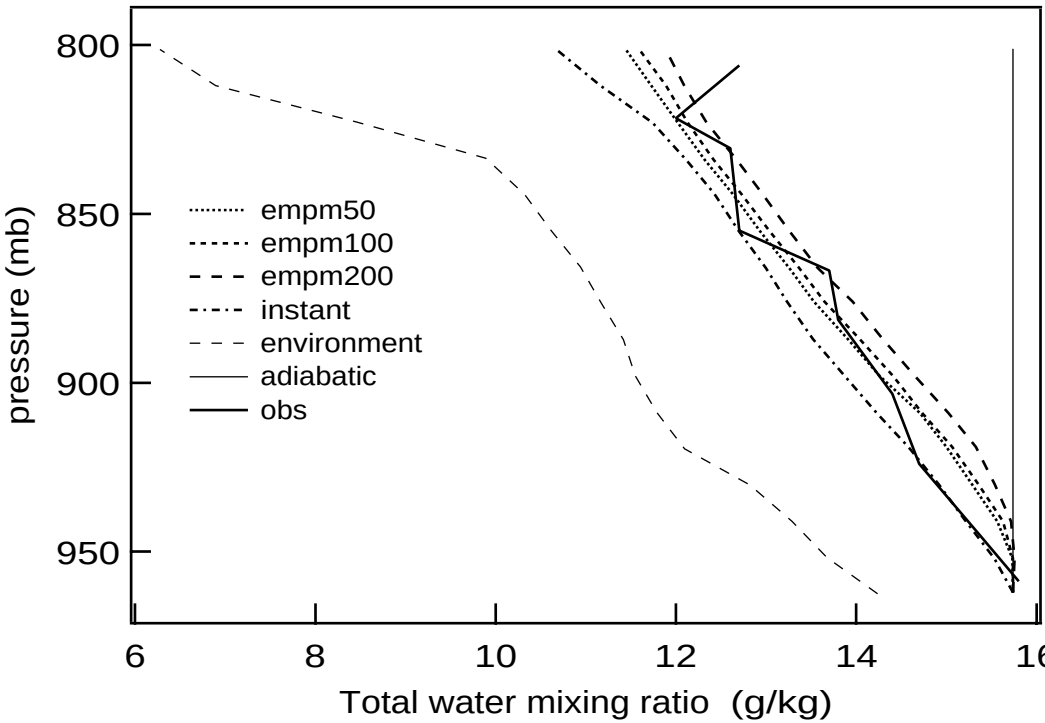
References

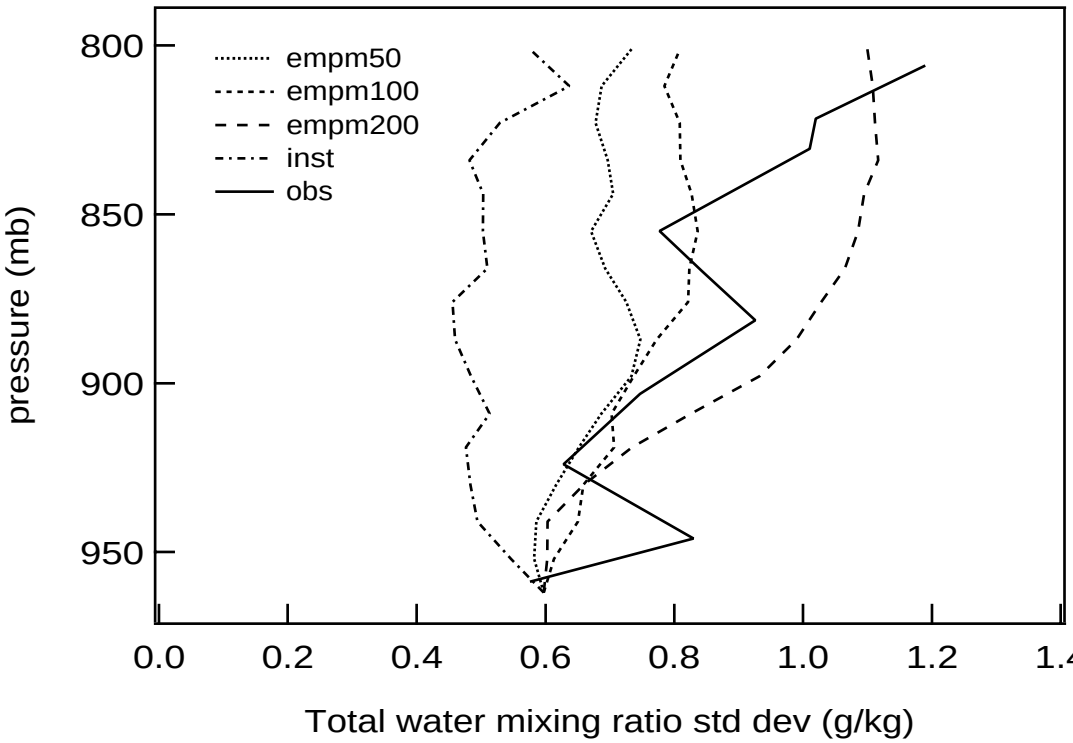
Krueger, S. K., C.-W. Su, and P. A. McMurtry, 1997: Modeling entrainment and fine-scale mixing in cumulus clouds. *J. Atmos. Sci.,* **54,** 2697--2712.

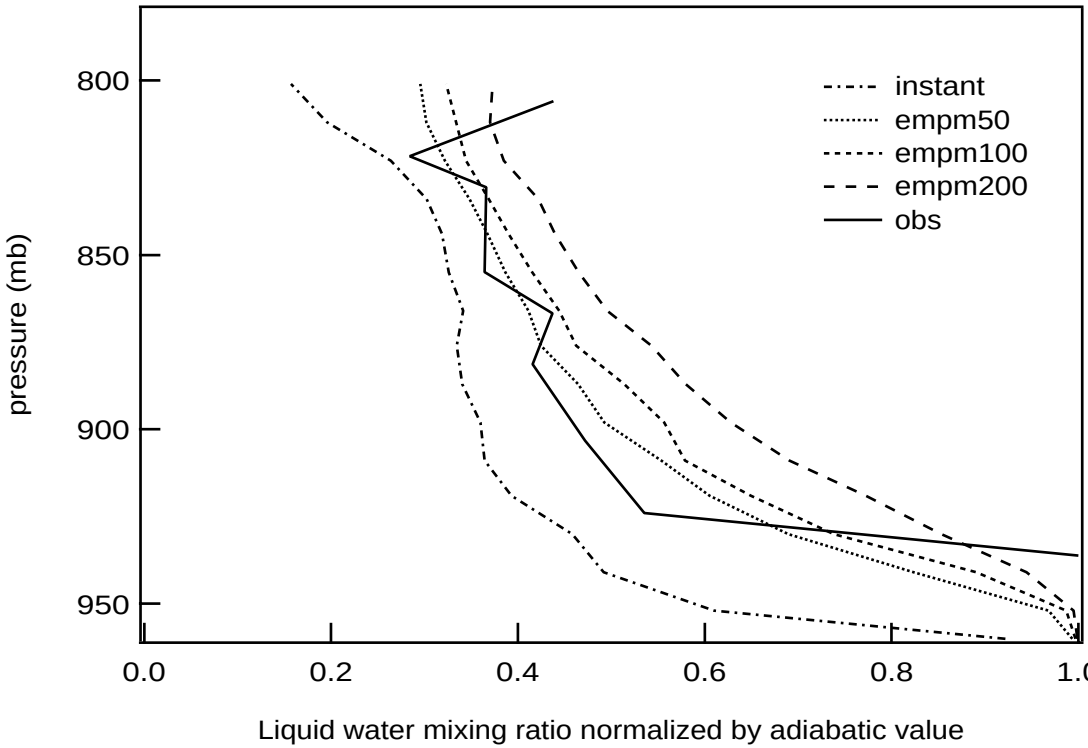
Su, C.-W., S. K. Krueger, P. A. McMurtry, and P. H. Austin, 1998: Linear eddy modeling of droplet spectral evolution during entrainment and mixing in cumulus clouds. *Atmos. Res.,* **47--48,** 41--58.
<http://www.met.utah.edu/skrueger/publications/su-1998.pdf>

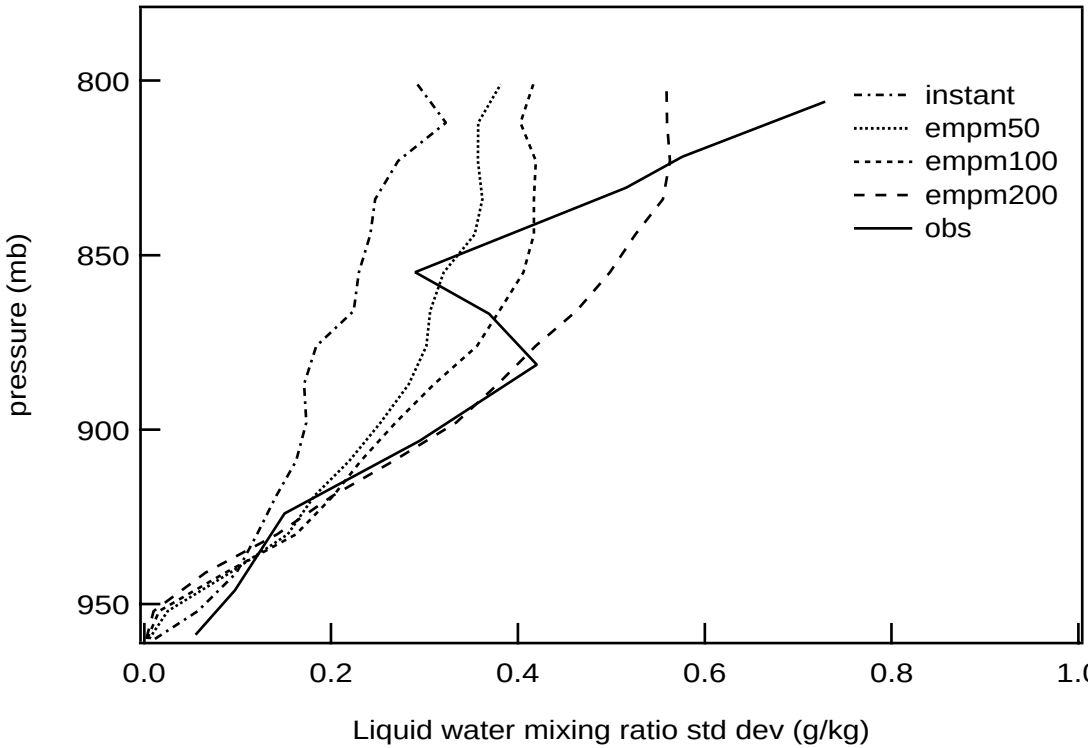
Su, Chwen-Wei, 1997: Linear Eddy Modeling of Entrainment and Mixing in Cumulus Clouds, Ph.D. dissertation, Univ. of Utah, 106 pp.
<http://www.met.utah.edu/skrueger/publications/su-dissertation.pdf>

Macrophysics: in-cloud profiles

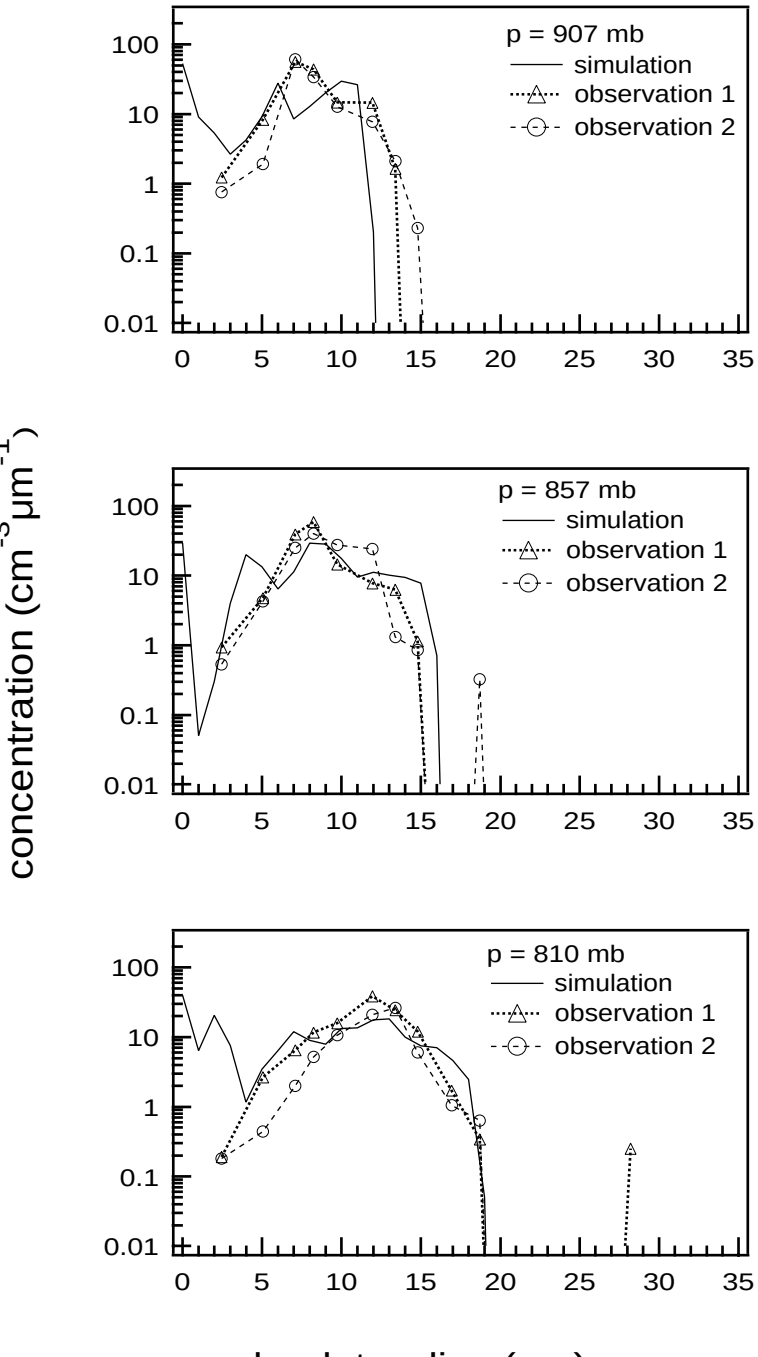

800
850
900
950
pressure (mb)
empm50
empm100
empm200
instant
environment
adiabatic
obs
6
8
10
12
14
16
Total water mixing ratio (g/kg)

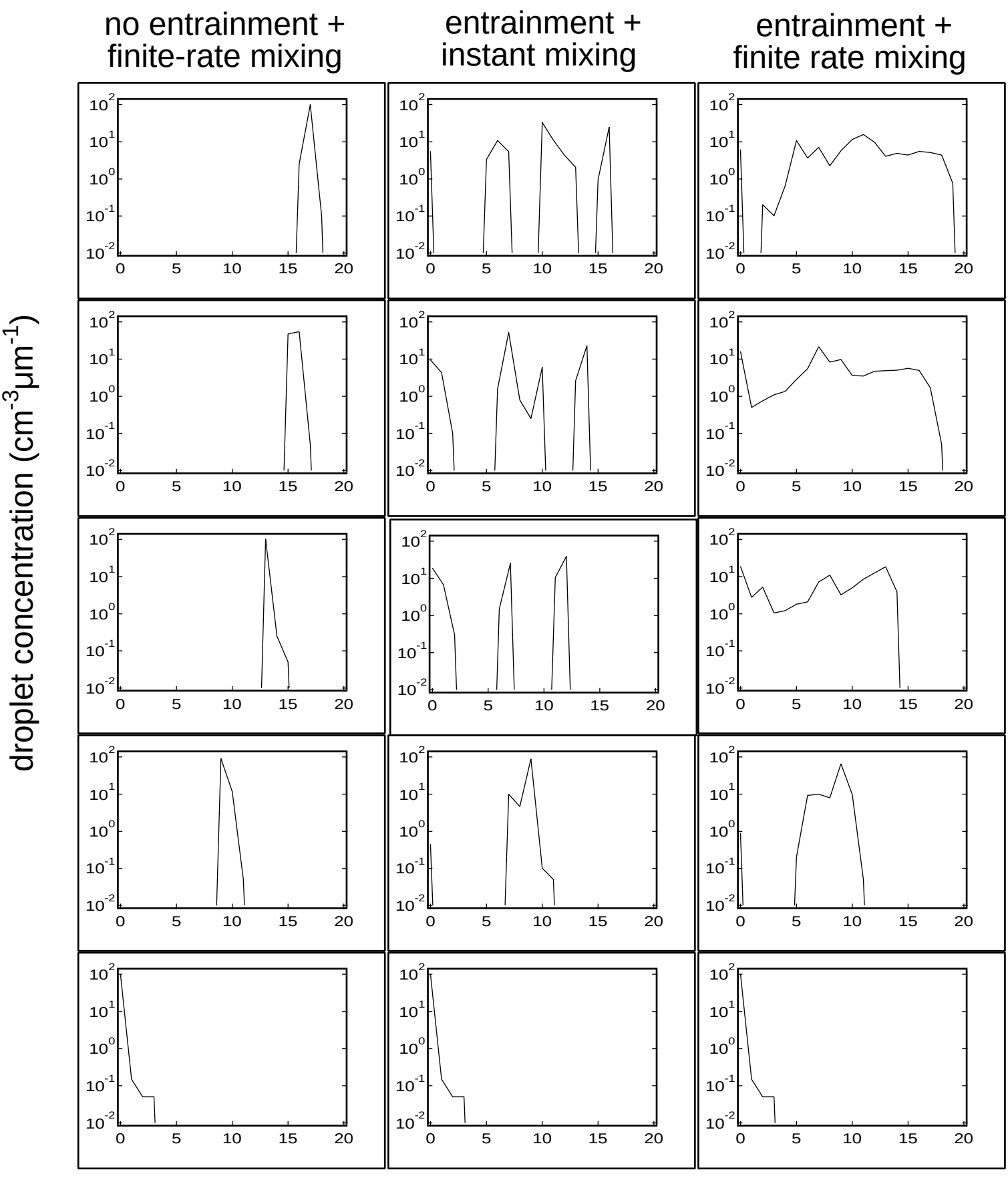

800
850
900
950
pressure (mb)
empm50
empm100
empm200
inst
obs
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Total water mixing ratio std dev (g/kg)

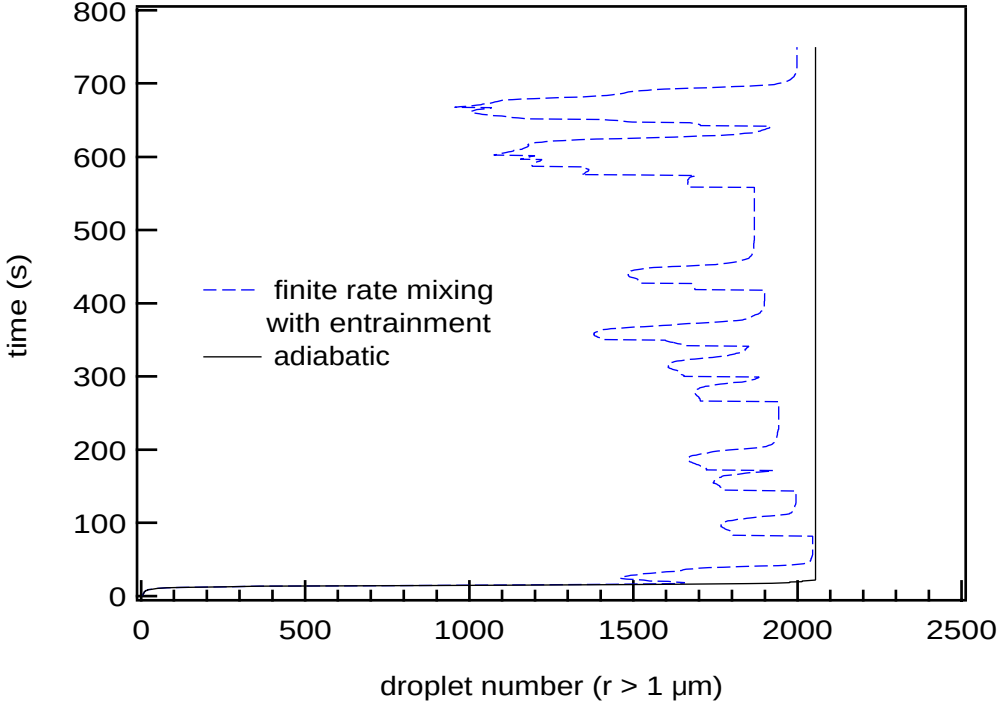

pressure (mb)
800
850
900
950
0.0
0.2
0.4
0.6
0.8
1.0
instant
empm50
empm100
empm200
obs
Liquid water mixing ratio normalized by adiabatic value


pressure (mb)
800
850
900
950
0.0
0.2
0.4
0.6
0.8
1.0
instant
empm50
empm100
empm200
obs
Liquid water mixing ratio std dev (g/kg)

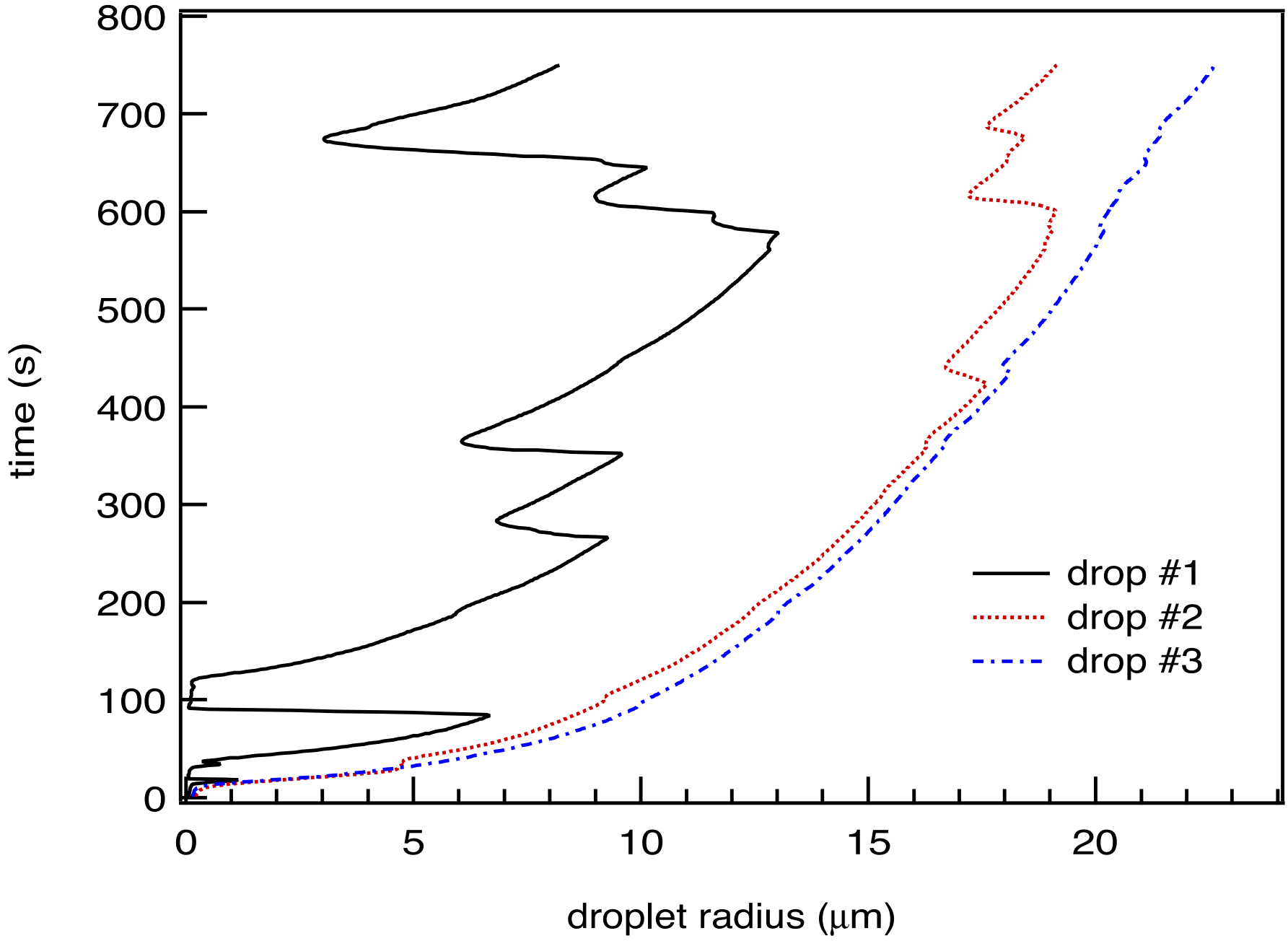
Microphysics: droplet spectra

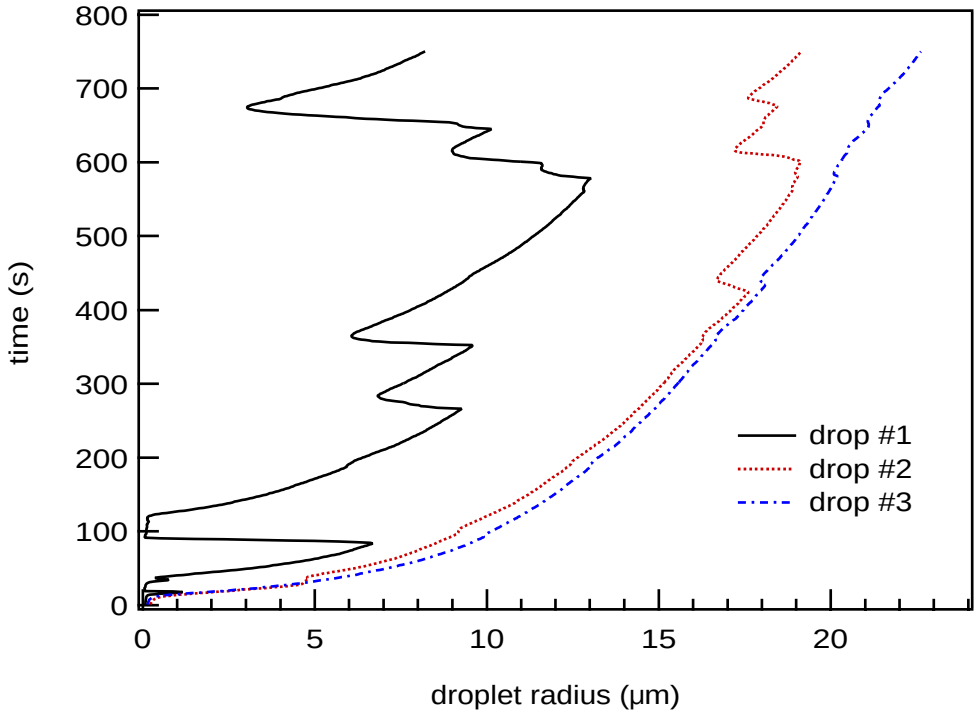

p = 907 mb
simulation
observation 1
observation 2
p = 857 mb
simulation
observation 1
observation 2
p = 810 mb
simulation
observation 1
observation 2
100
10
1
0.1
0.01
0
5
10
15
20
25
30
35
concentration (cm-3 µm-1)
droplet radius (µm)

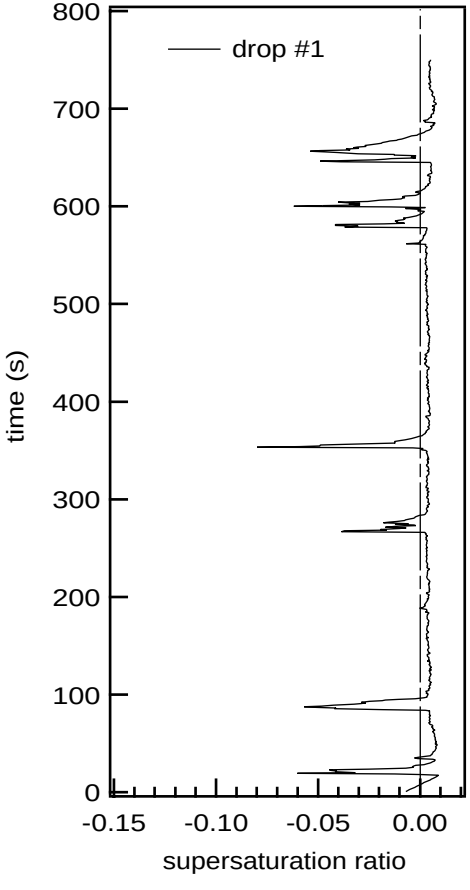

no entrainment + finite-rate mixing
entrainment + instant mixing
entrainment + finite rate mixing
droplet concentration (cm-3µm-1)
droplet radius (µm)

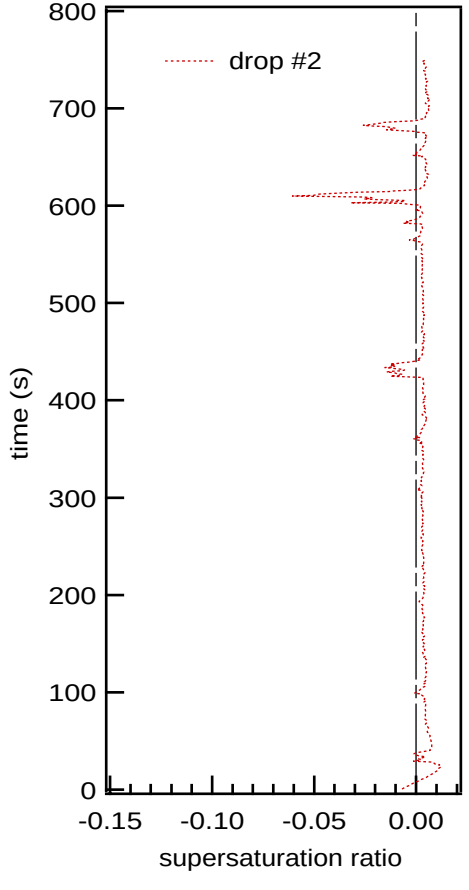

800
700
600
500
400
300
200
100
0
time (s)
finite rate mixing
with entrainment
adiabatic
0
500
1000
1500
2000
2500
droplet number (r > 1 μm)

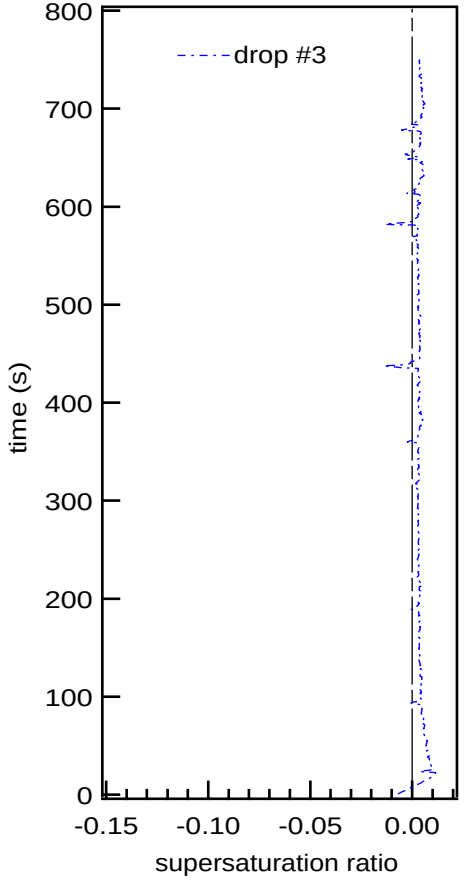
Large-droplet production

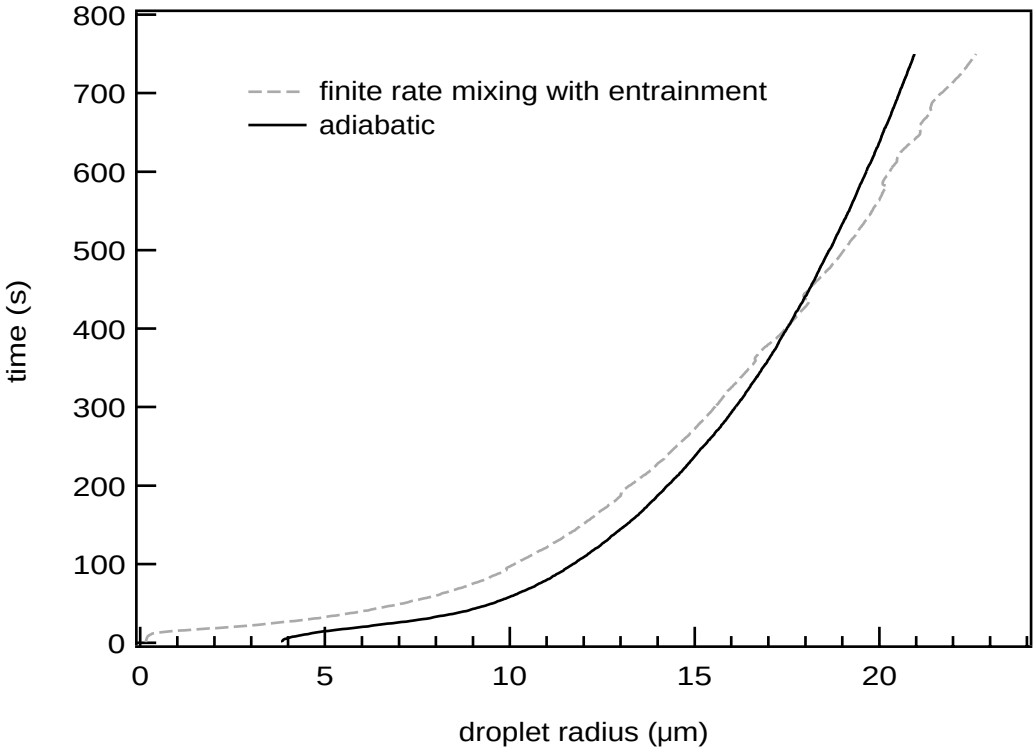

800
700
600
500
400
300
200
100
0
time (s)
0
5
10
15
20
droplet radius (μm)
drop #1
drop #2
drop #3

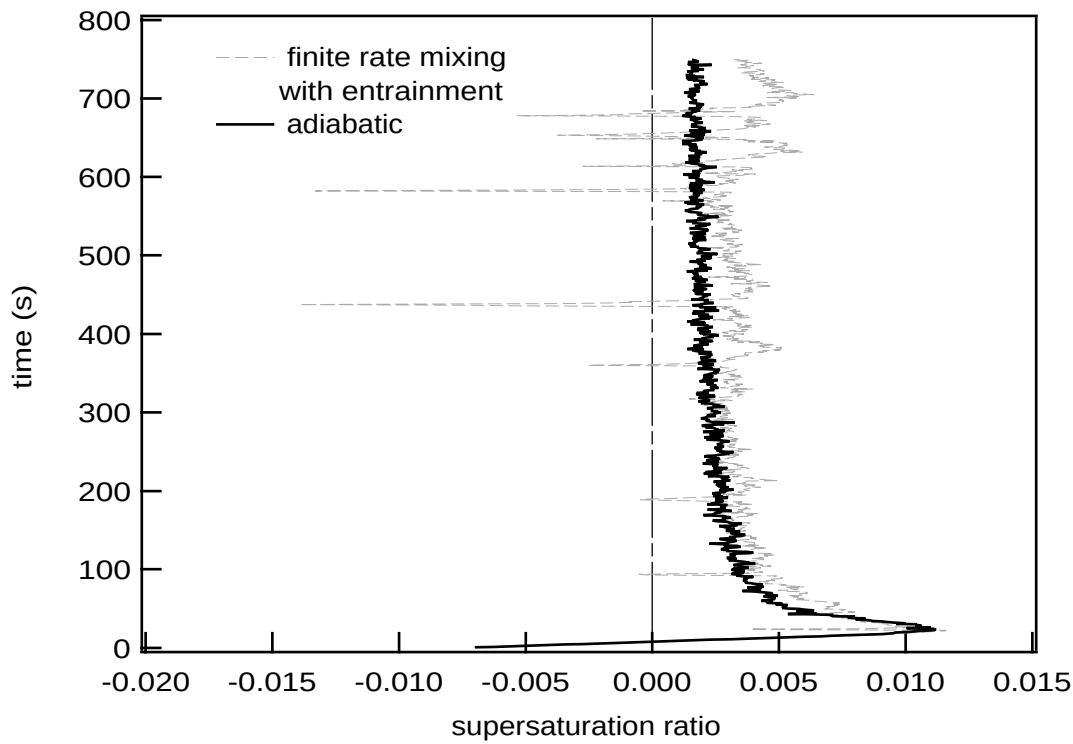

time (s)
droplet radius (μm)
drop #1
drop #2
drop #3


drop #1
time (s)
supersaturation ratio


drop #2
time (s)
supersaturation ratio

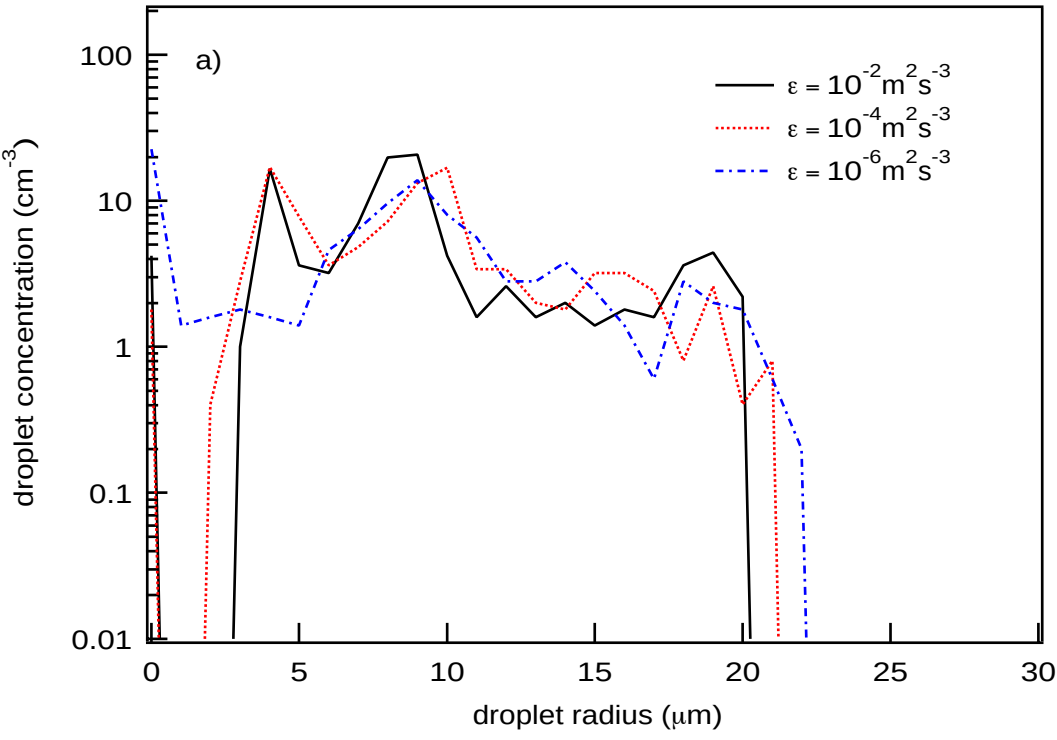

drop #3
time (s)
supersaturation ratio

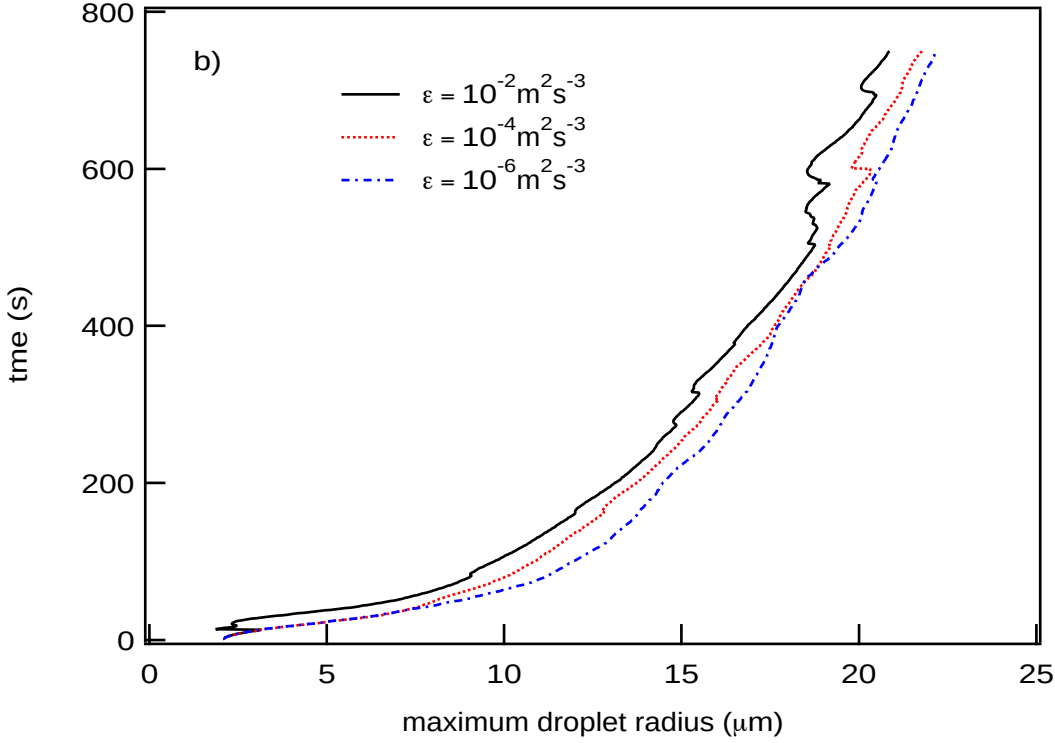

finite rate mixing with entrainment
adiabatic
time (s)
droplet radius (μm)
0
100
200
300
400
500
600
700
800
0
5
10
15
20

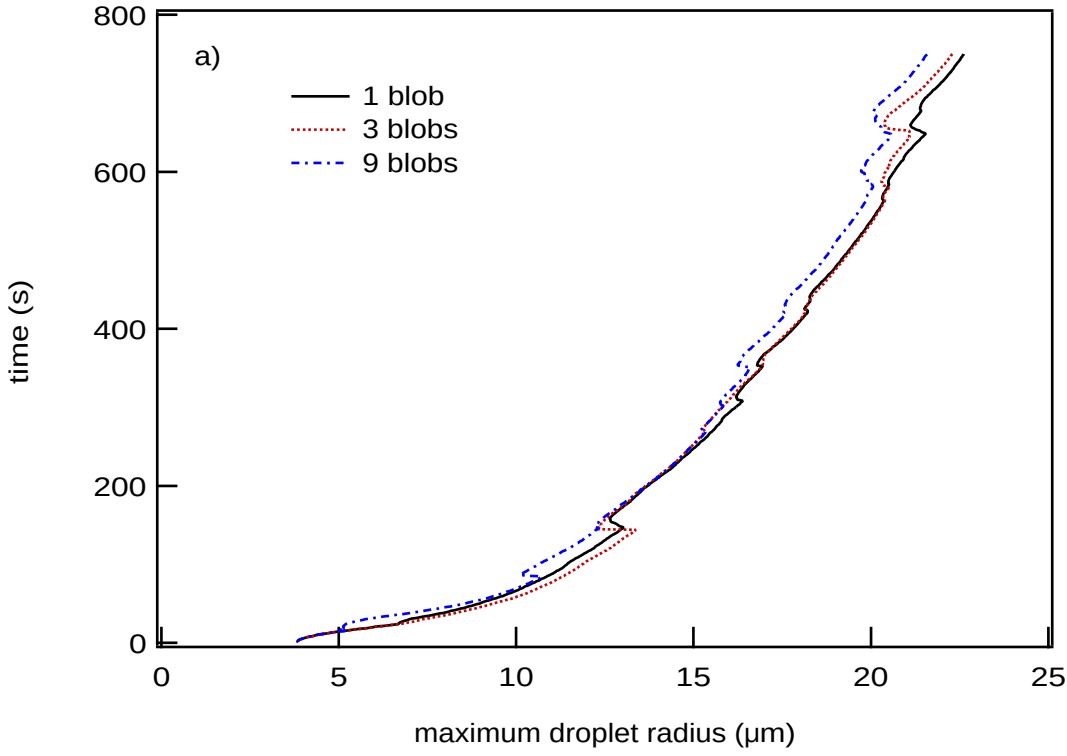

finite rate mixing
with entrainment
adiabatic
time (s)
supersaturation ratio
0
100
200
300
400
500
600
700
800
-0.020
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015

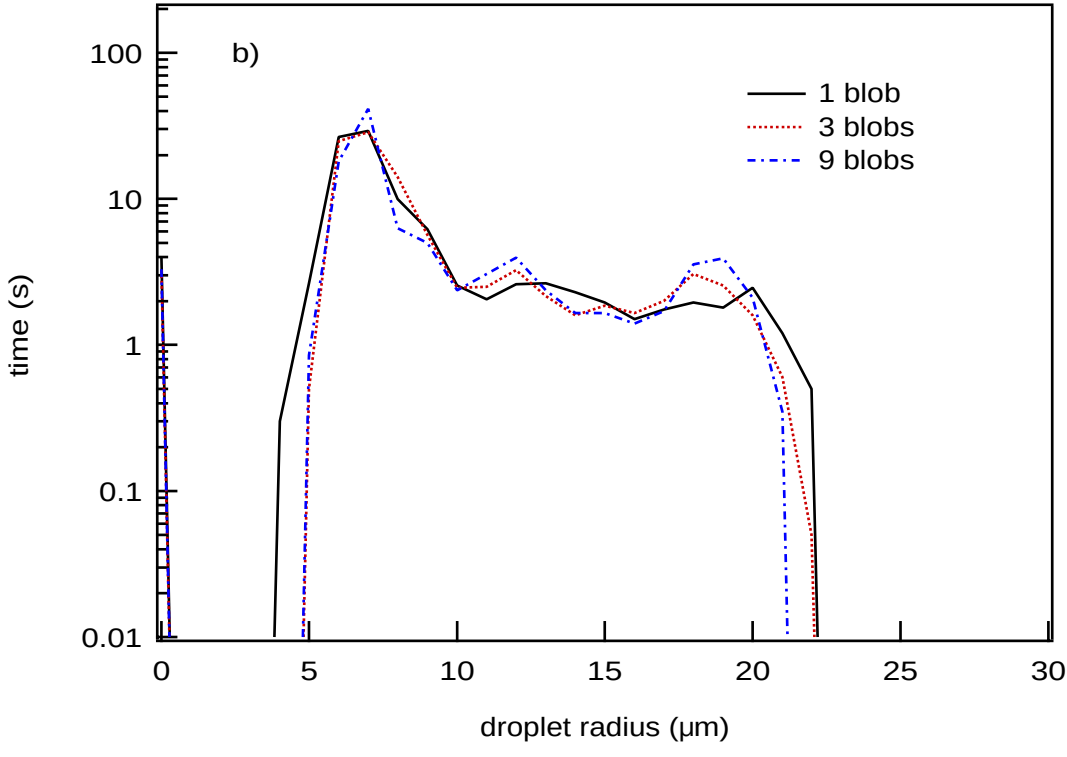
Some factors that affect large droplet production

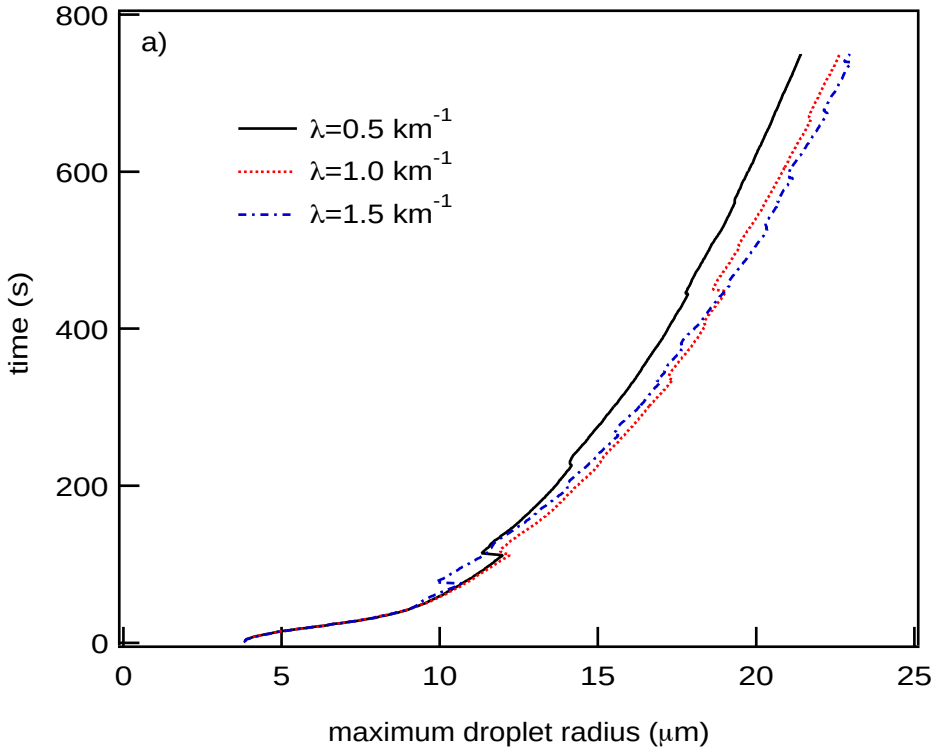
- Turbulence intensity (dissipation rate)
- Entrained blob size
- Entrainment rate
- Relative humidity of entrained air

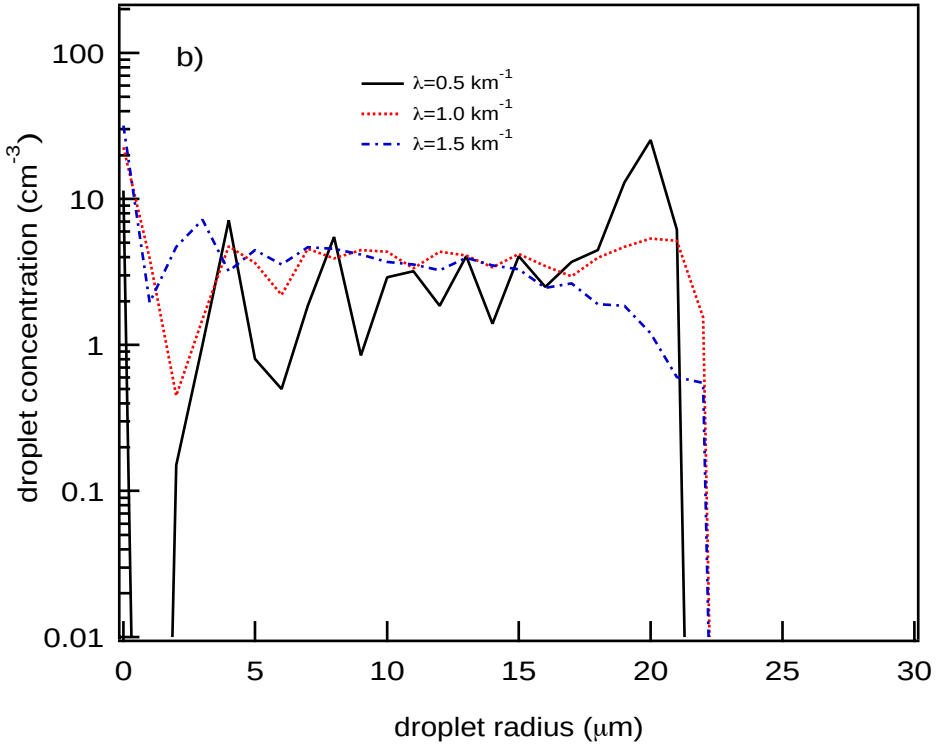

a)
ε = 10-2m2s-3
ε = 10-4m2s-3
ε = 10-6m2s-3
droplet concentration (cm-3)
100
10
1
0.1
0.01
0
5
10
15
20
25
30
droplet radius (μm)

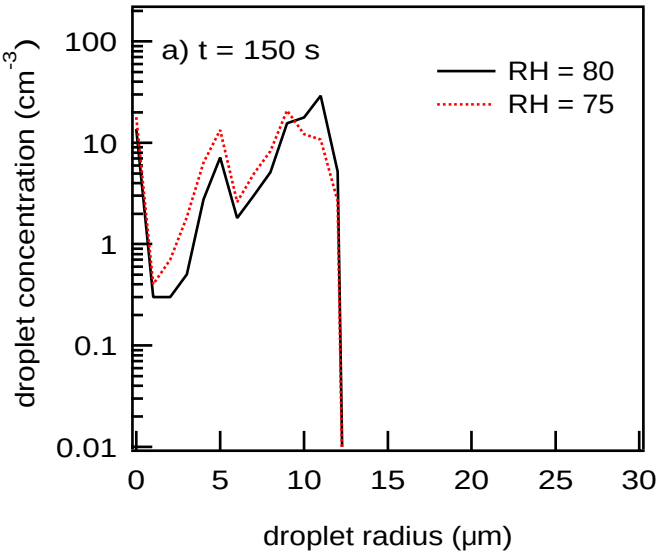

b)
ε = 10-2m2s-3
ε = 10-4m2s-3
ε = 10-6m2s-3
tme (s)
800
600
400
200
0
0
5
10
15
20
25
maximum droplet radius (μm)

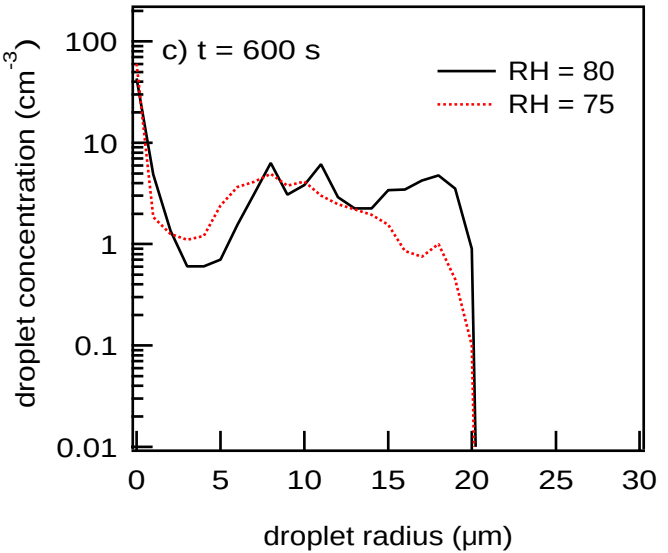

a)
1 blob
3 blobs
9 blobs
time (s)
maximum droplet radius (μm)
0
200
400
600
800
0
5
10
15
20
25

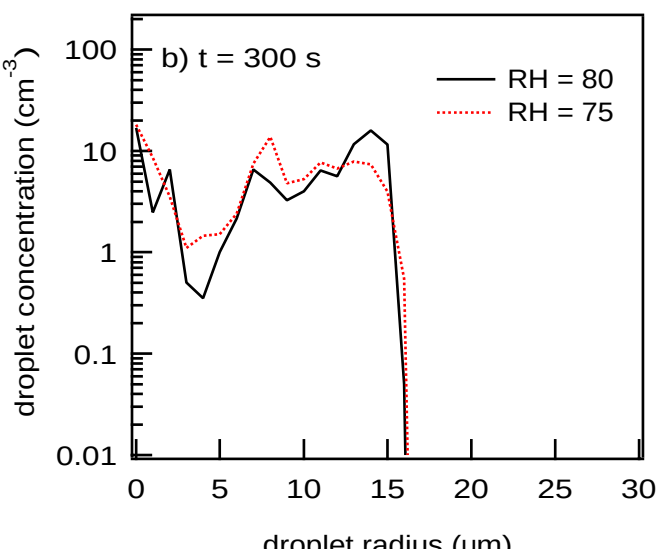

b)
1 blob
3 blobs
9 blobs
time (s)
droplet radius (μm)
0.01
0.1
1
10
100
0
5
10
15
20
25
30

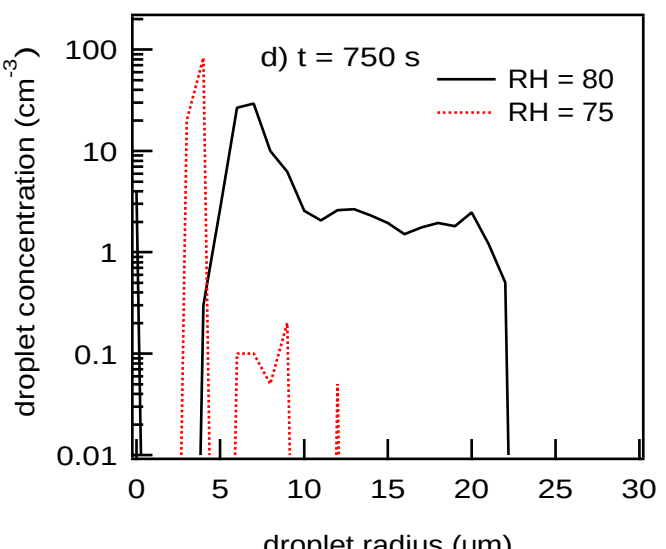

a)
λ=0.5 km-1
λ=1.0 km-1
λ=1.5 km-1
time (s)
maximum droplet radius (μm)
0
200
400
600
800
0
5
10
15
20
25

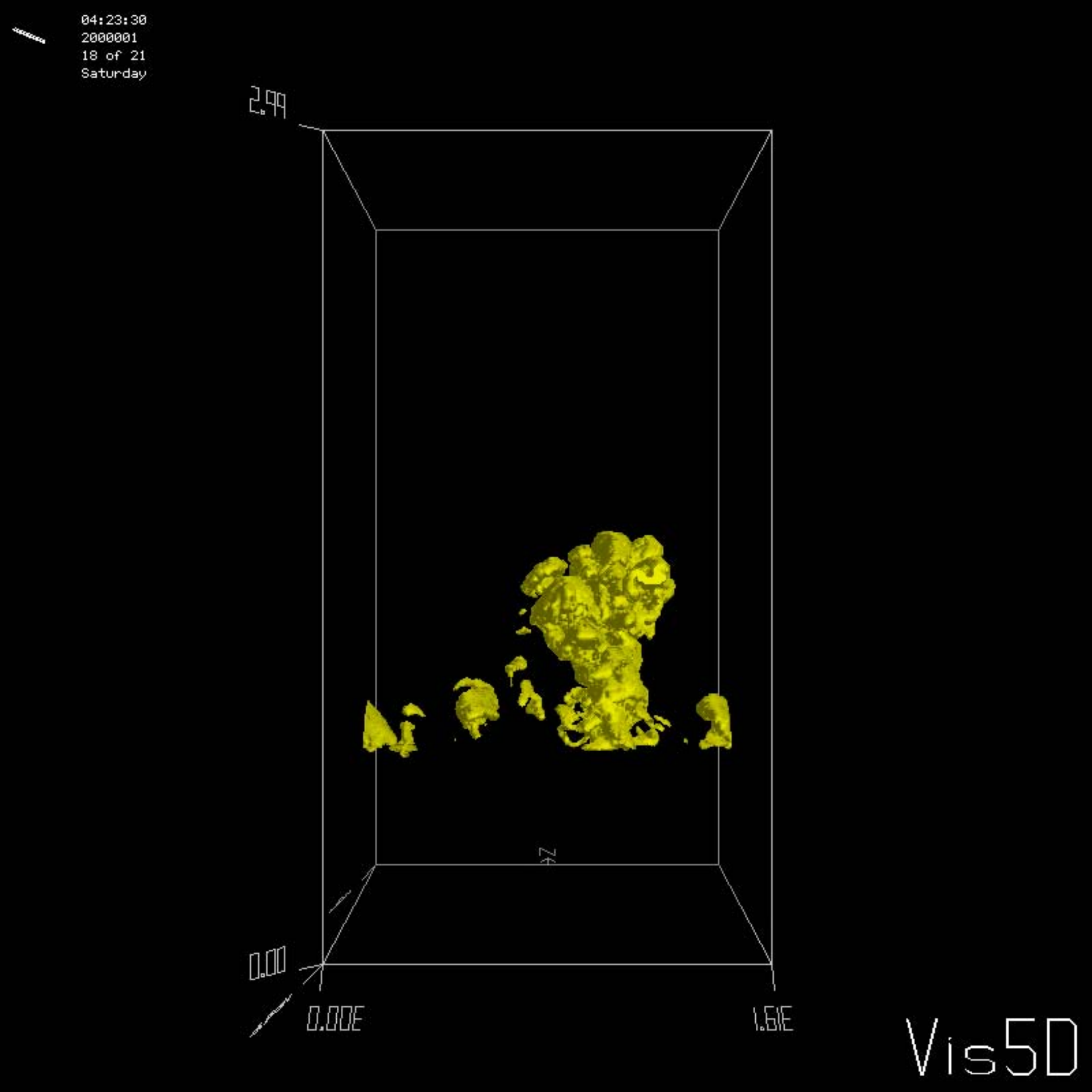

b)
λ=0.5 km-1
λ=1.0 km-1
λ=1.5 km-1
droplet concentration (cm-3)
droplet radius (μm)
100
10
1
0.1
0.01
0
5
10
15
20
25
30


a) t = 150 s
RH = 80
RH = 75
droplet concentration (cm-3)
droplet radius (μm)
100
10
1
0.1
0.01
0
5
10
15
20
25
30


c) t = 600 s
RH = 80
RH = 75
droplet concentration (cm-3)
droplet radius (μm)
100
10
1
0.1
0.01
0
5
10
15
20
25
30


b) t = 300 s
RH = 80
RH = 75
droplet concentration (cm-3)
droplet radius (μm)
100
10
1
0.1
0.01
0
5
10
15
20
25
30


d) t = 750 s
RH = 80
RH = 75
droplet concentration (cm-3)
droplet radius (μm)
100
10
1
0.1
0.01
0
5
10
15
20
25
30


04:23:30
2000001
18 of 21
Saturday
2.99
N
0.00
0.00E
1.61E
Vis5D

Coupling EMPM and 3D large-eddy simulations (LES)

- We will better resolve the SGS structure in 3D LES by implementing a 1D subgrid-scale (SGS) mixing model with a grid size of about 10 cm---a scale of variability that is measurable by aircraft.

- The CPU time required for a LES with a grid size of 0.1 m is 10^8 more than one with a grid size of 10 m.

Coupling EMPM and 3D LES

CPU times for ODT grid size = 0.1 m with different $(\Delta x)_{LES}$:

$(\Delta x)_{LES}$	Relative CPU time	CPU hours	GAUs
10 (no ODT)	1	800	200
5	9	7200	1800
40 (with ODT)	2	1600	400
20	7	5600	1400
10	28	22,400	5600

Multiscale Modeling Framework

Stand-alone **Averaged**	Stand-alone **Reduced dimensionality**	Coupled **MMF**
1D Cu par 0D parcel model	2D CRM 1D EMPM	3D GCM + 2D CRM 3D LES + 1D ODT

Conclusions

- Stand-alone and coupled ODT-based models are promising for studying fundamental physics of cloud-turbulence-microphysics-radiation interactions.

- MMF approacch is viable for cloud-turbulence scale interactions as well as for synoptic-meso-cloud scale interactions.

- Cross-fertilization of ideas & techniques should be beneficial to further development of both approaches.

- Perhaps coupling GCM, CRM, and ODT will be useful for certain problems, such as aerosol-microphysics-climate interactions. . .

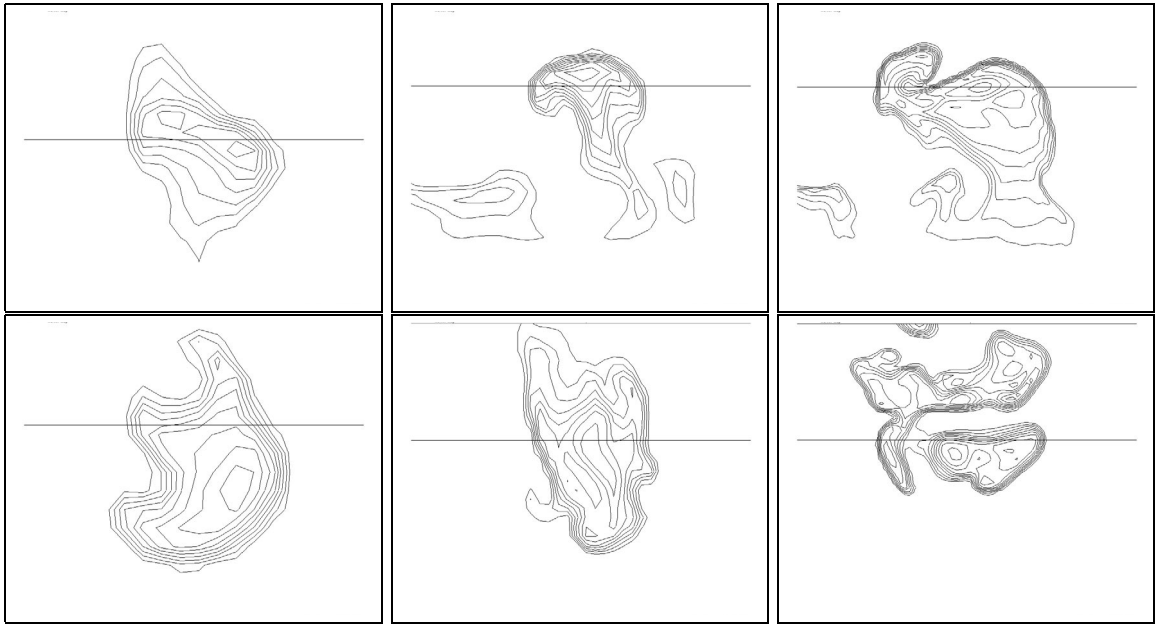
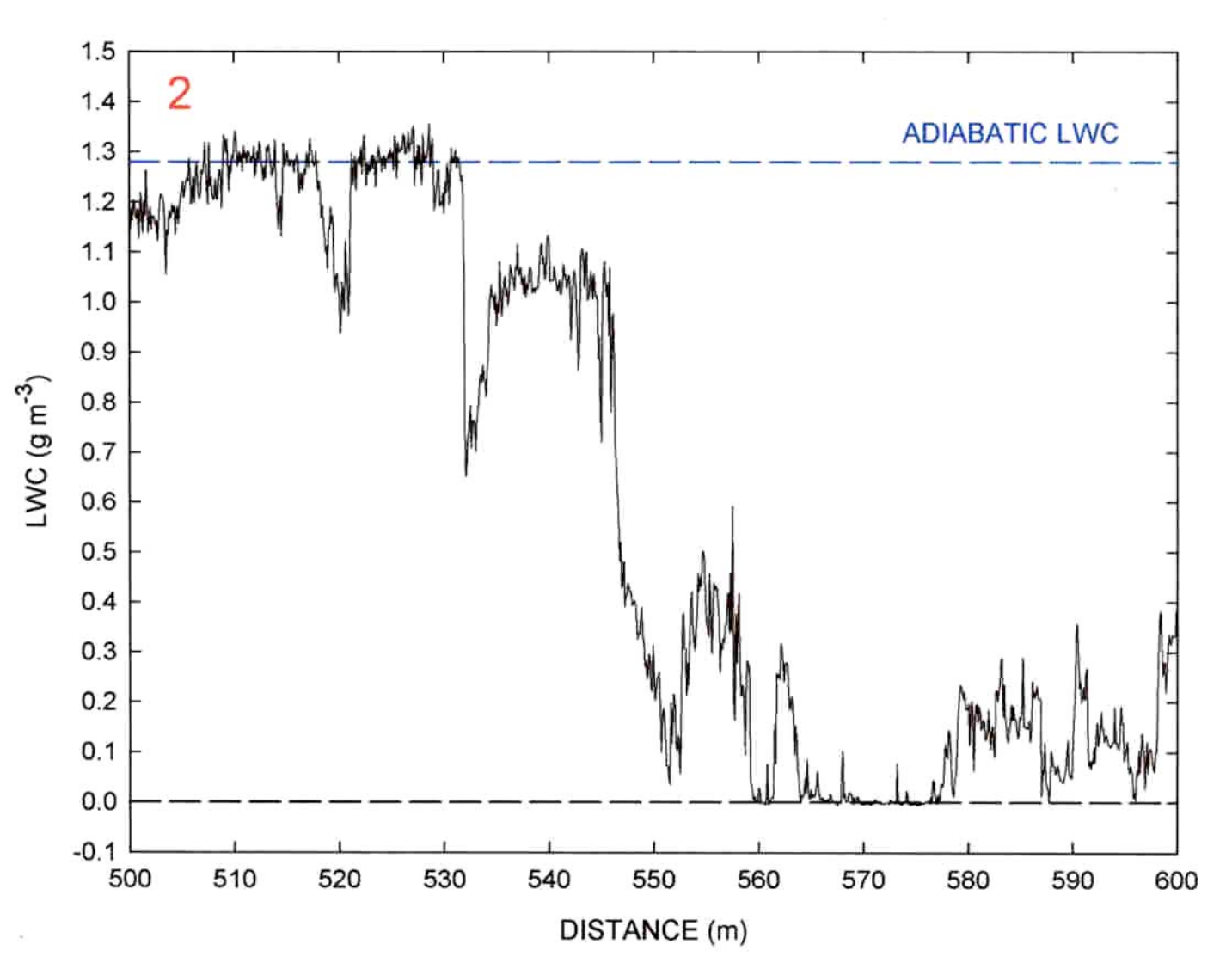
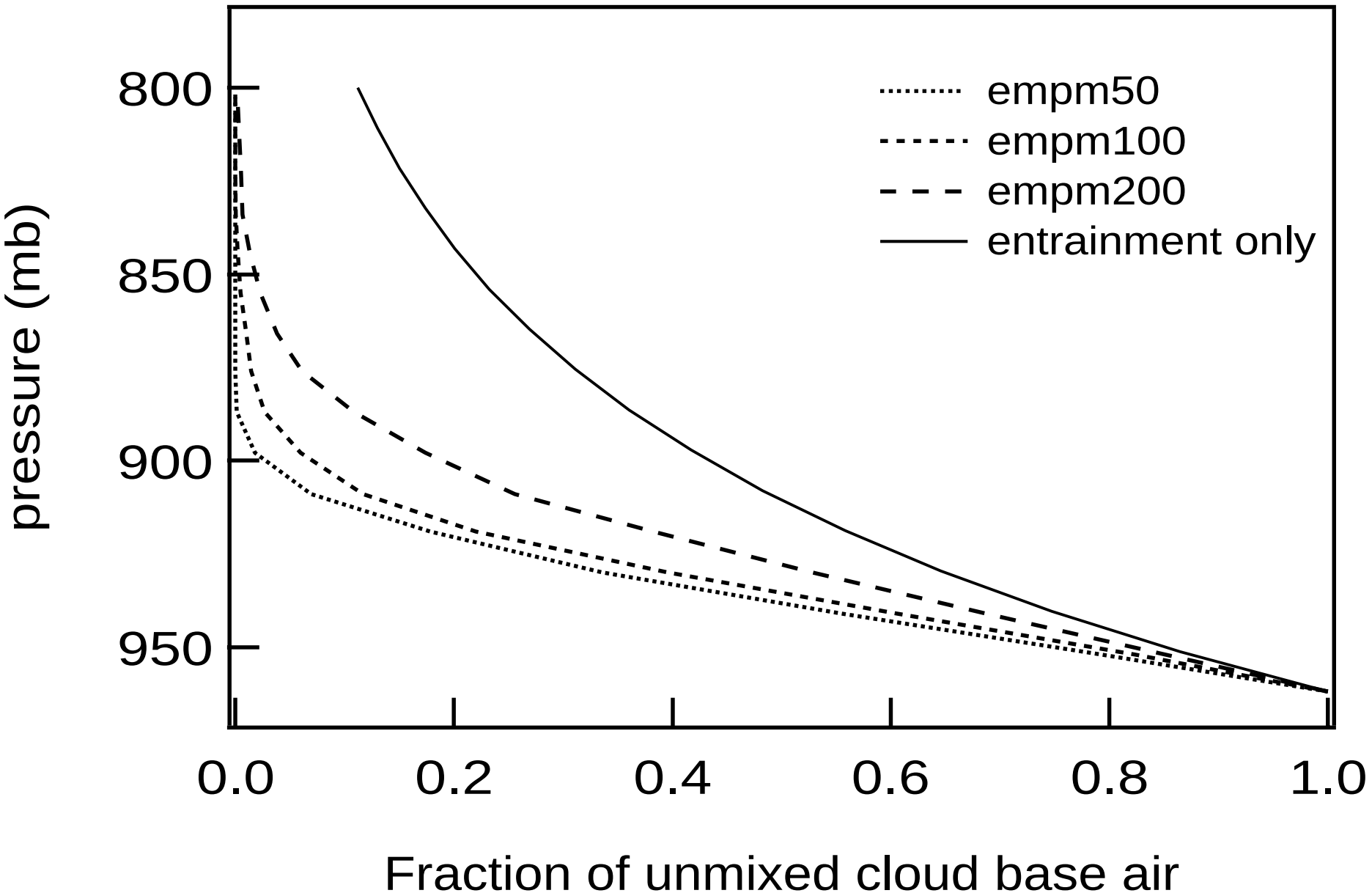


Figure 5: Vertical (top) and horizontal (bottom) cross-sections of liquid water mixing ratio for BOMEX trade cumulus simulations with resolutions of 40 m (left), 20 m (center), and 10 m (right). The horizontal cross sections are located at $z = 1000$ m. The contour interval is 0.1 g kg^{-1}. The line through each cross-section indicates its intersection with the accompanying perpendicular cross-section. Each cross section displays an area 590 m by 725 m.


2
ADIABATIC LWC
LWC (g m-3)
DISTANCE (m)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
500
510
520
530
540
550
560
570
580
590
600


800
850
900
950
pressure (mb)
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of unmixed cloud base air
empm50
empm100
empm200
entrainment only

Planned EMPM Improvements

- Additional physics:

  Collision and coalesence growth of cloud droplets

  Turbulence effects on droplet clustering

- Better representation of entrainment:

  Use realistic trajectories obtained from a 3D Large-Eddy Simulation Model (LESM).

  Analyze entrainment in the LESM.

  Compare relevant EMPM and aircraft statistics.