Multi-Scale Modeling of Fine-Scale Structure and Droplet Spectral Evolution in Cumulus Clouds

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February 25, 2004

Project Summary

- The 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 propose to investigate are (1) entrainment and mixing, (2) droplet inertial effects, and (3) ultragiant 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 1000 individual cloud droplets based on each droplet s local environment.

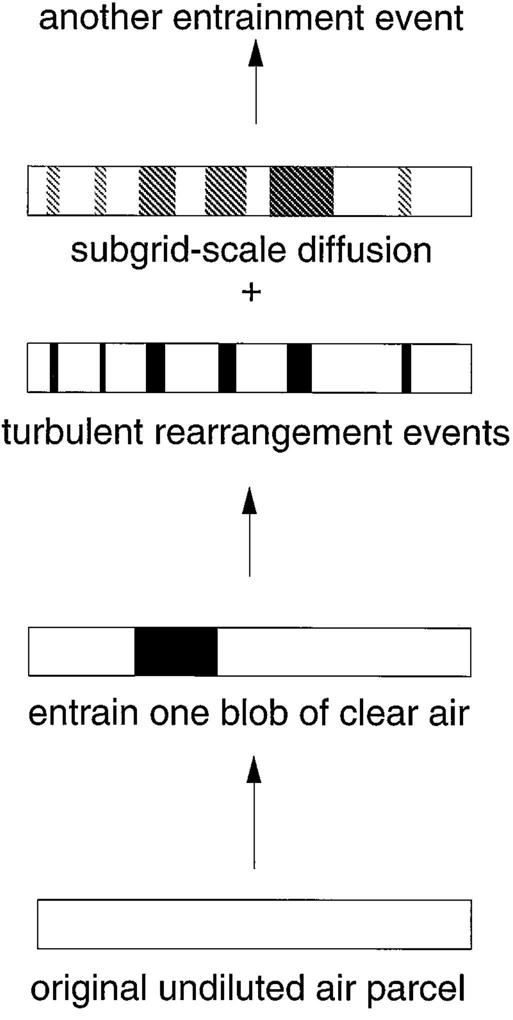


FIG. 3. A parcel is represented by a 1D domain in the EMPM. The parcel's internal structure evolves due to discrete entrainment events and turbulent mixing (rearrangement events and subgrid-scale diffusion).

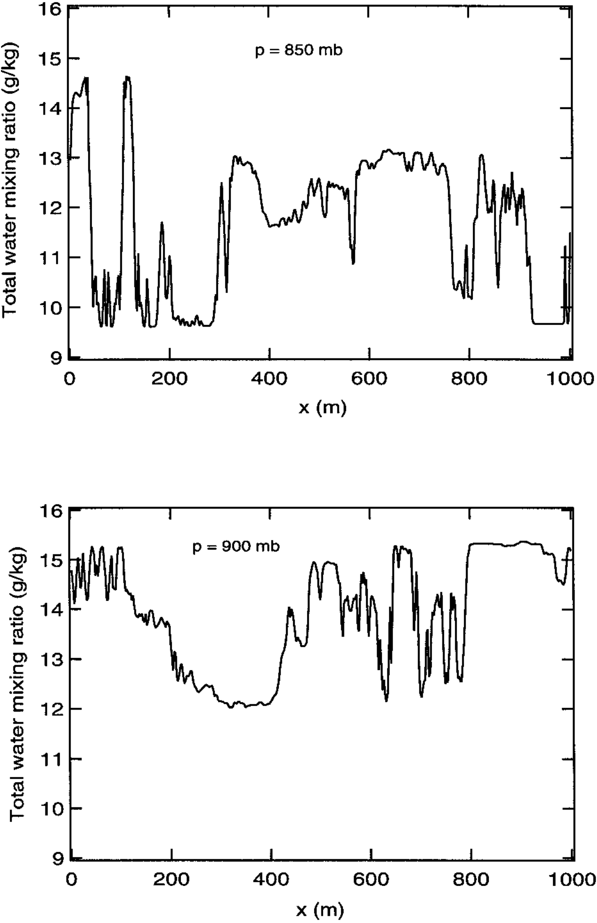
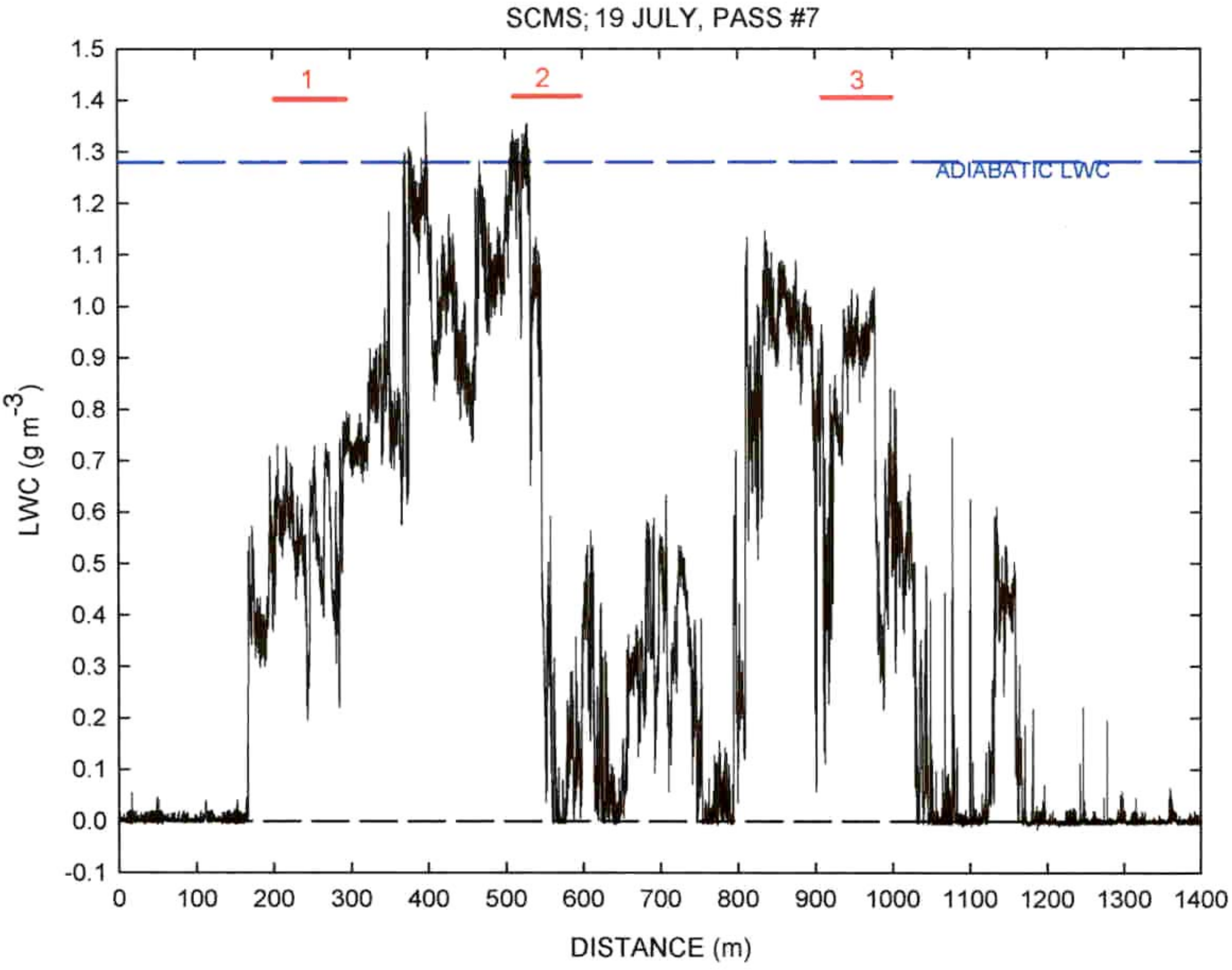
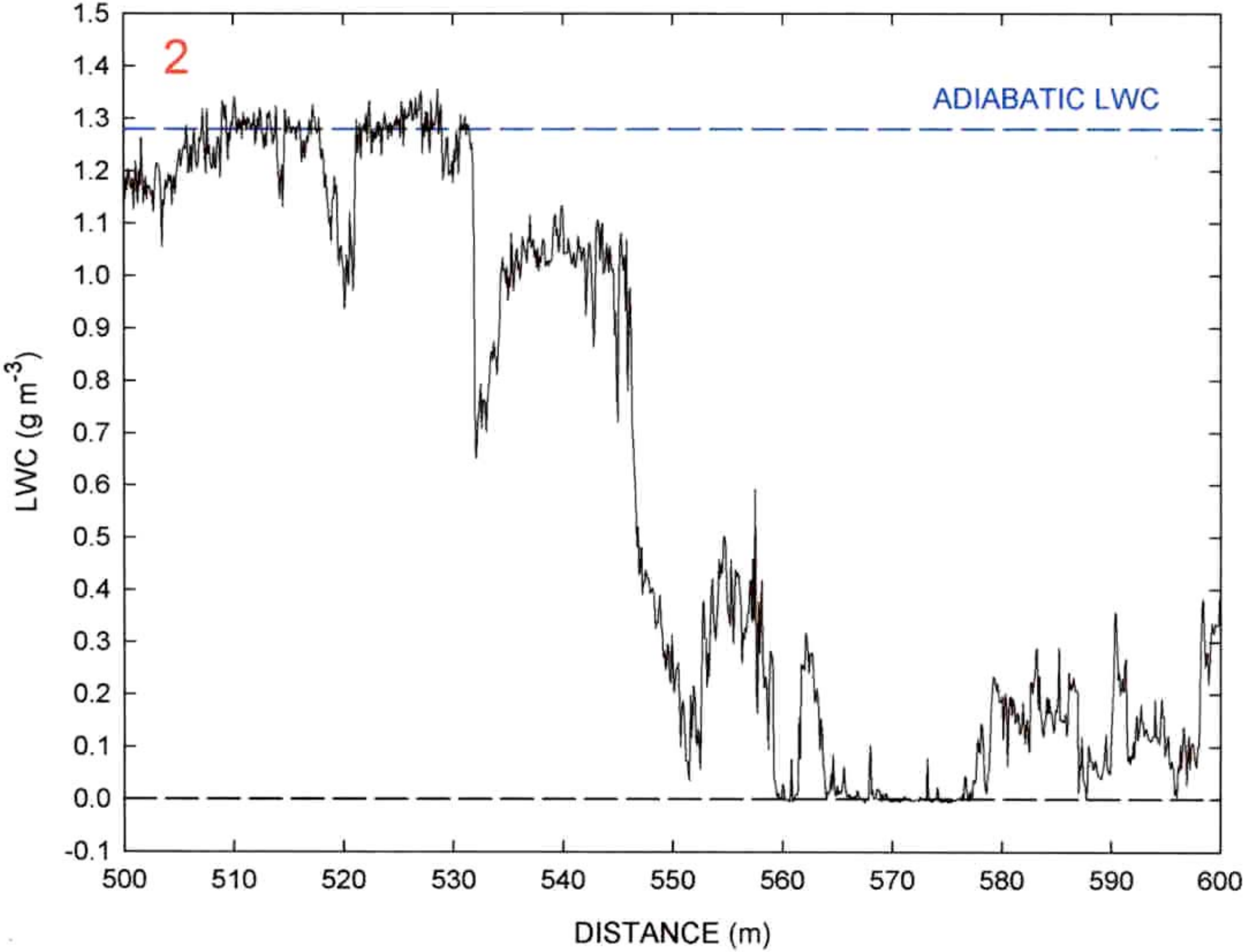


FIG. 4. ''Snapshots'' from the EMPM of q_w (x) at p = 900 mb (top) and p = 850 mb (bottom) during one realization.


SCMS; 19 JULY, PASS #7
1
2
3
ADIABATIC LWC
LWC (g m^{-3})
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
DISTANCE (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

We propose to extend and improve the physics of the EMPM by adding new physics:

- Stochastic collection growth of cloud droplets
- Droplet inertial effects

and by further evaluating and improving the EMPM S representation of entrainment:

- Using realistic trajectories obtained from a 3D Large-Eddy Simulation Model (LESM),
- Performing detailed analyses of entrainment in the LESM
- Implementing the linear eddy mixing model as a subgrid-scale mixing model in the LESM.

Modeling and Measurements

- In addition to the measurements required to perform a classical (instant mixing) parcel model calculation, the EMPM requires the parcel size, the size (distribution) of the entrained blobs, and the turbulence intensity.

- Initially, we will use the EMPM to explore the effects of entrainment and mixing, droplet inertial effects, and ultragiant nuclei on droplet spectral broadening for realistic ranges of cloud and environment properties.

- To perform and analyze EMPM simulations based on observed cloud and environment properties, we require aircraft measurements of temperature, water vapor, vertical velocity, size-resolved aerosol properties, droplet size spectra, and liquid water content.

We will also perform high-resolution 3D large-eddy simulations (LES) of cumulus clouds in order to:

- evaluate the LES approach by comparing LES fine-scale structure to RICO measurements,
- study the (simulated) entrainment/detrainment process,
- evaluate the EMPM s entrainment parameterization,
- collect realistic trajectories for driving the EMPM.
- We eventually plan to better resolve the SGS structure in a 3D LESM 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.

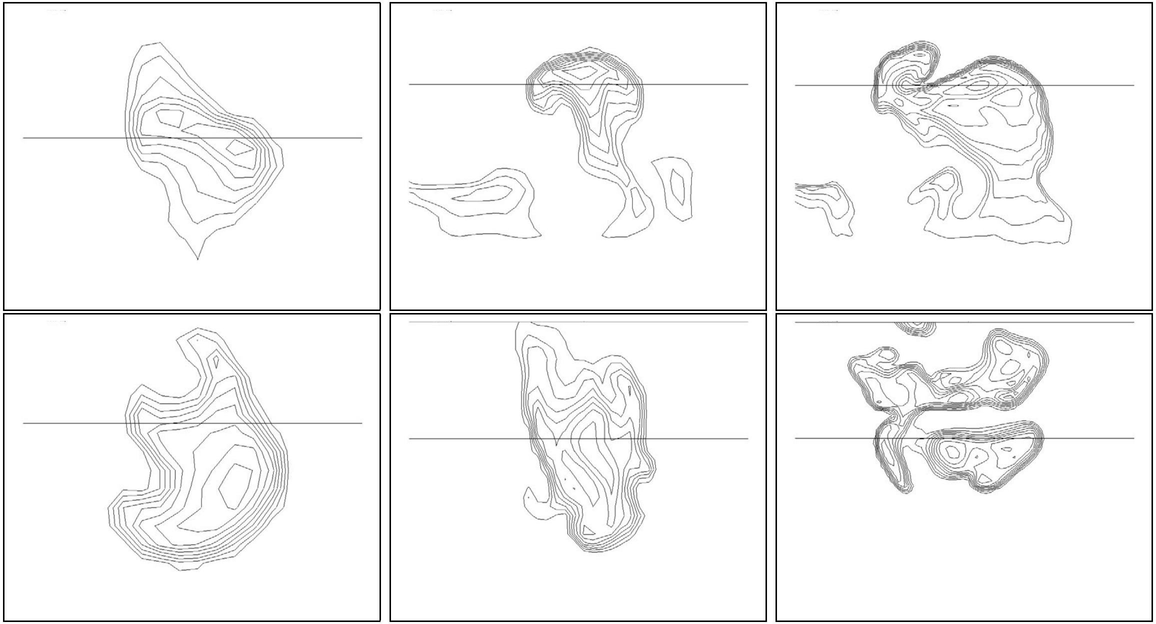


Figure 5: Vertical (top) and horizontal (bottom) cross-sections of liquid water mixing ratio for BOMEX trade cumulus simulations with resolutions of 40 m (left), 20 m (center), and 10 m (right). The horizontal cross sections are located at $z = 1000$ m. The contour interval is 0.1 g kg^{-1}. The line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

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>`

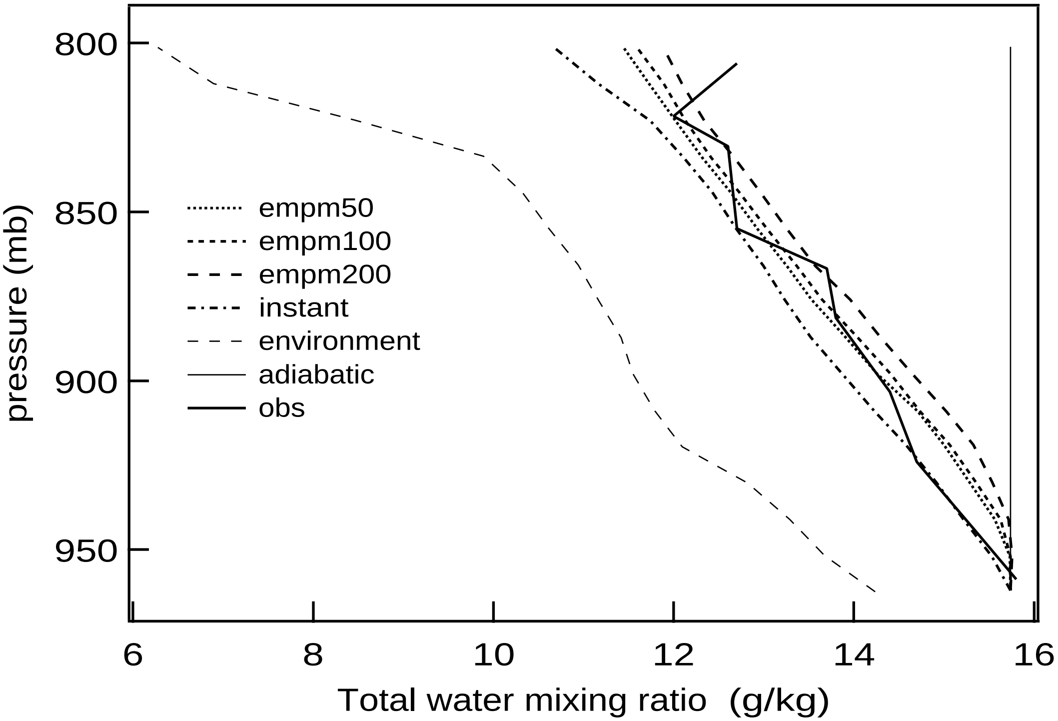
Su, Chwen-Wei, 1997: Linear Eddy Modeling of Entrainment and Mixing in Cumulus Clouds, Ph.D. dissertation, Univ. of Utah, 106 pp. `<http://www.met.utah.edu/skrueger/publications/su-dissertation.pdf>`

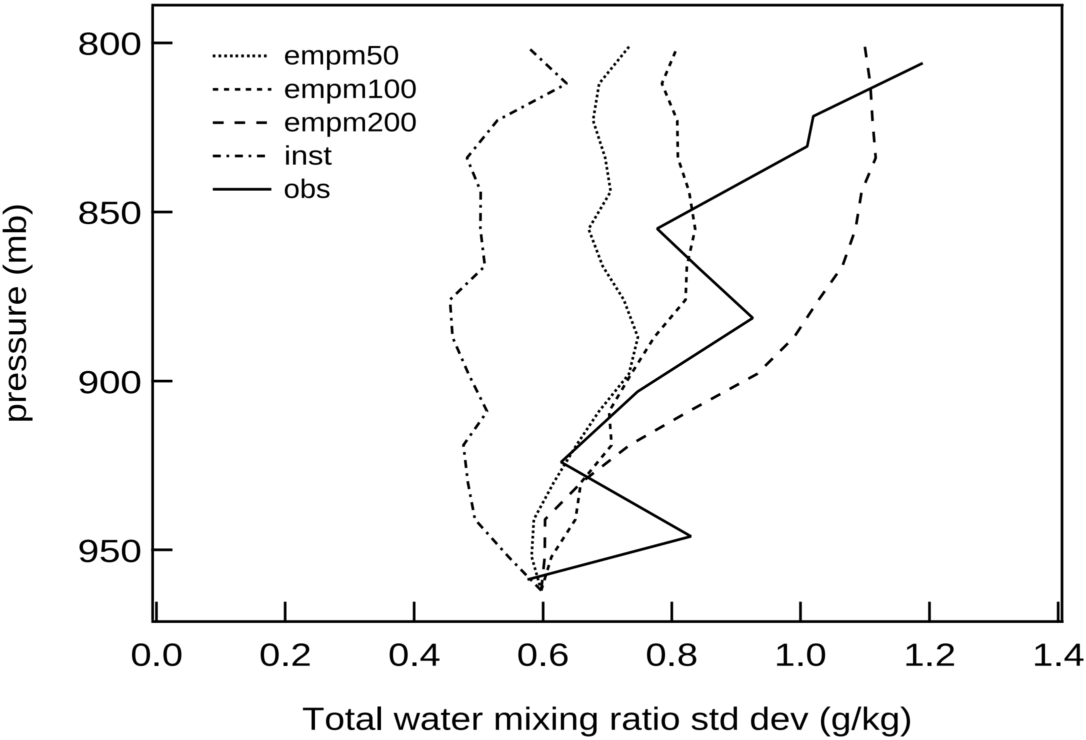
Applying the EMPM to Hawaiian Cumuli

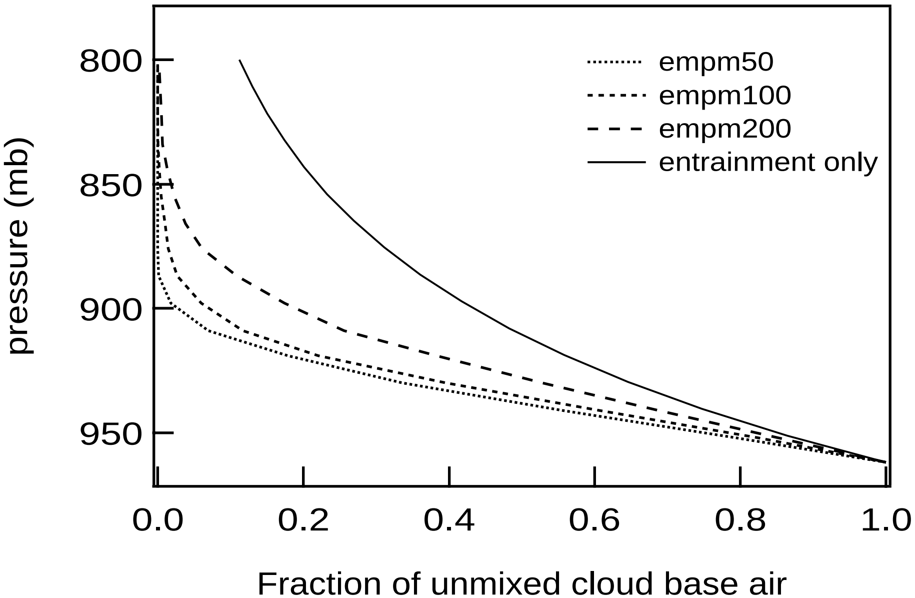
Results

- **Macrophysics:** in-cloud profiles (data: G. Raga)
- **Microphysics:** droplet spectra (data: C. Pontikis)
- **Large-droplet production**

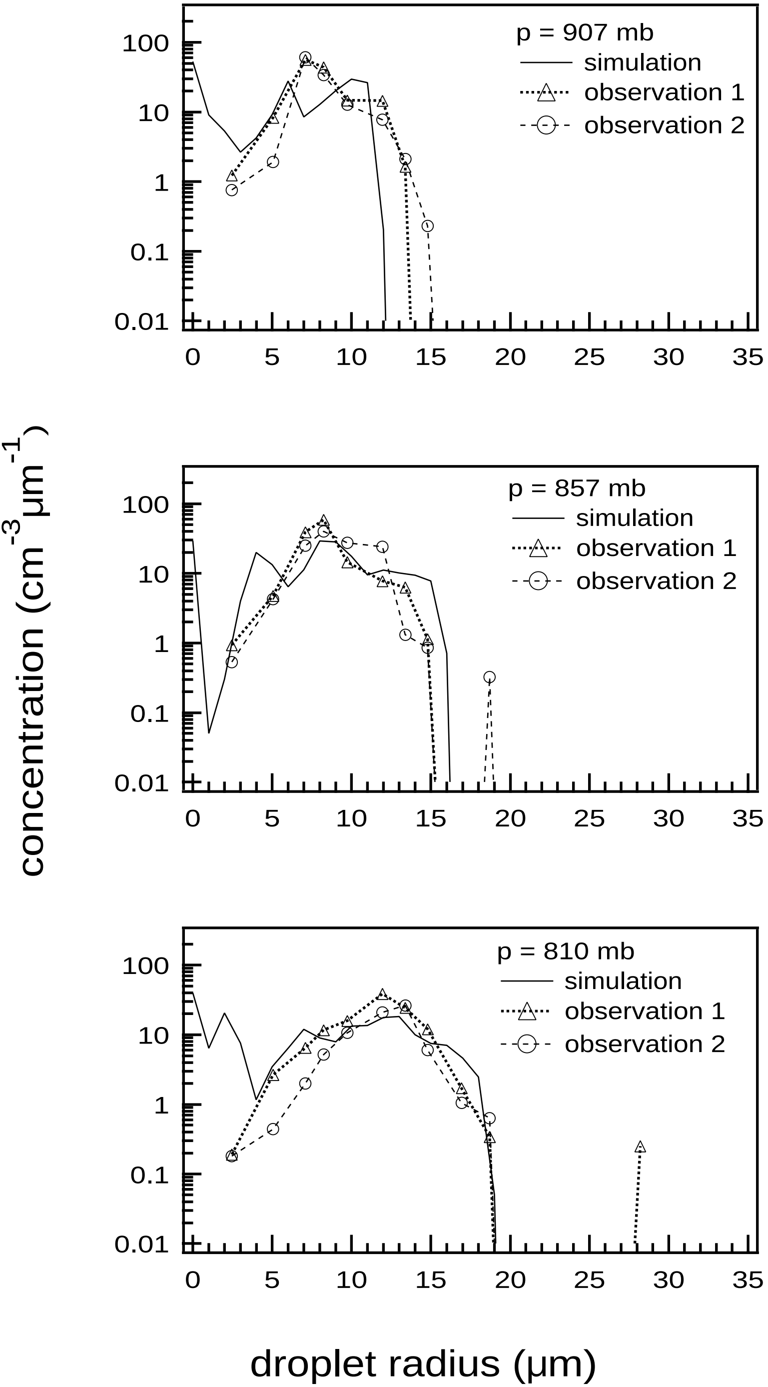
Macrophysics: in-cloud profiles


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)

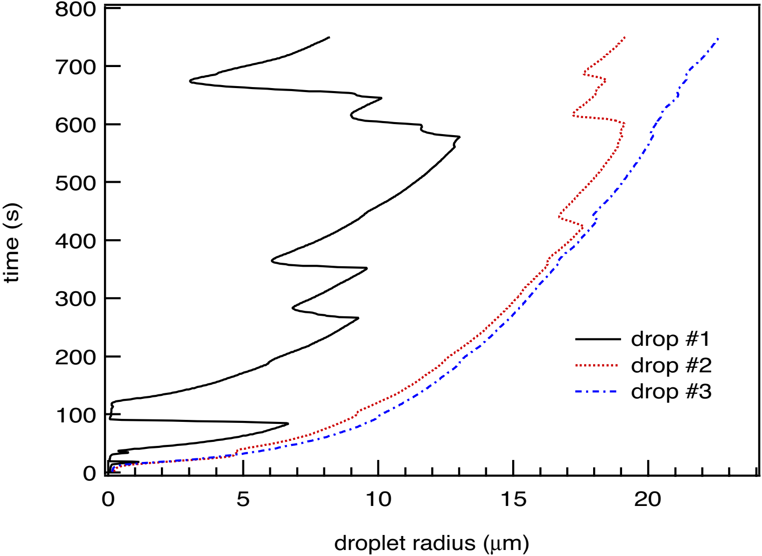

800
850
900
950
pressure (mb)
empm50
empm100
empm200
inst
obs
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Total water mixing ratio std dev (g/kg)

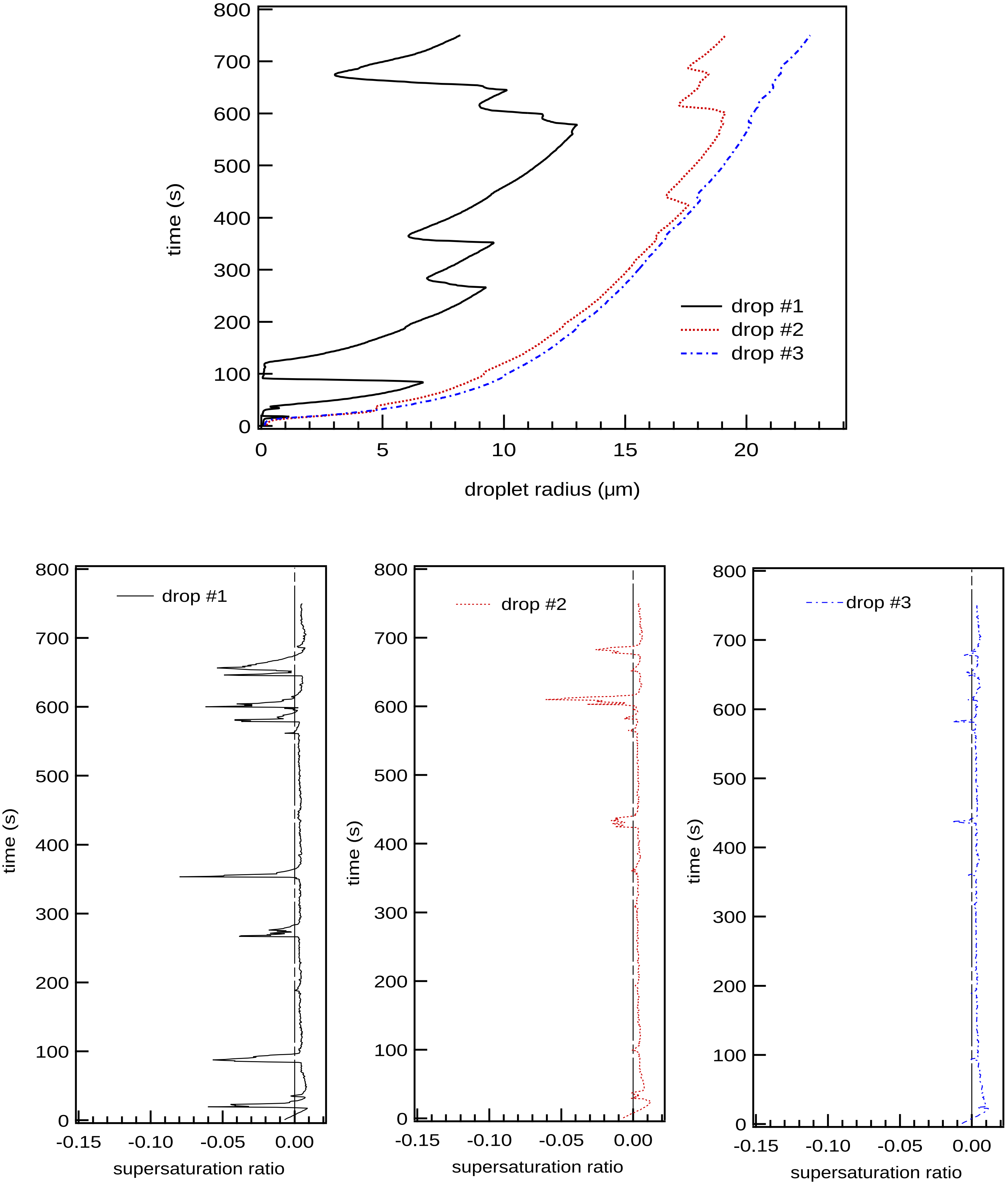

800
850
900
950
pressure (mb)
0.0
0.2
0.4
0.6
0.8
1.0
Fraction of unmixed cloud base air
empm50
empm100
empm200
entrainment only

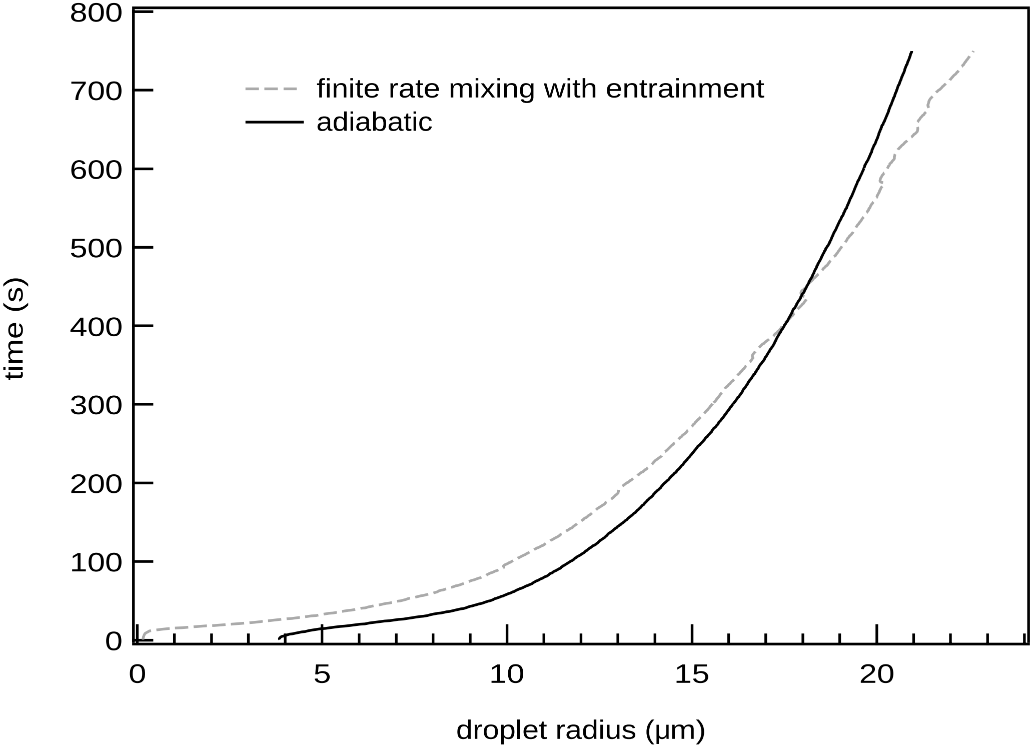
Microphysics: droplet spectra

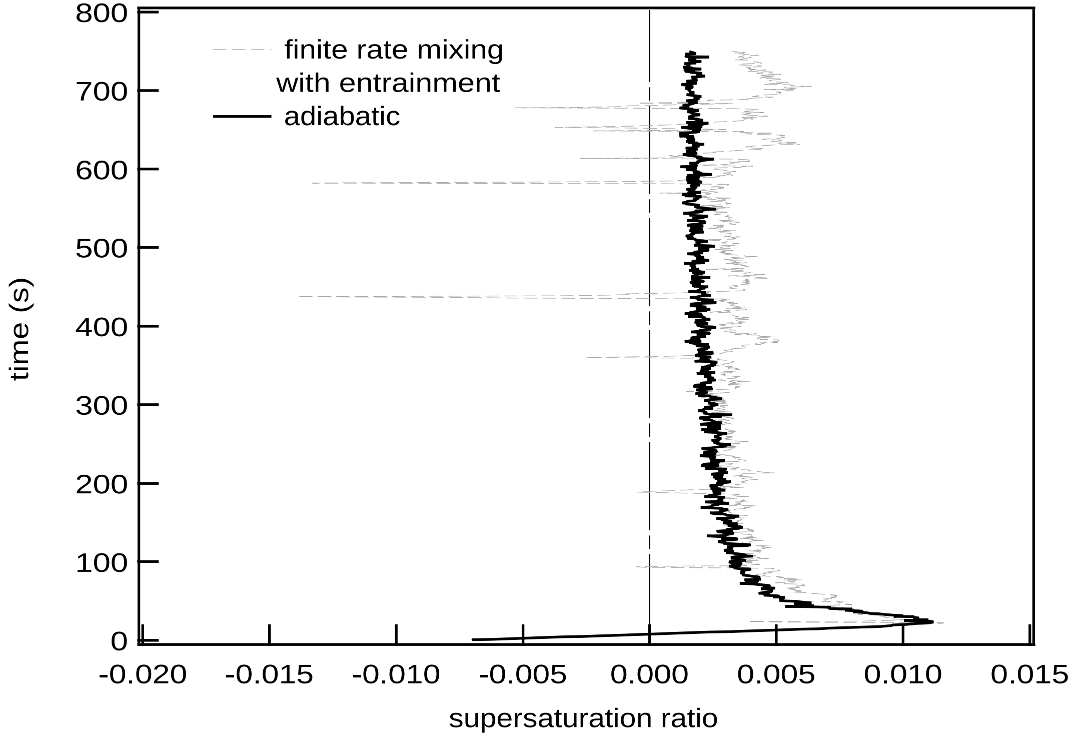

p = 907 mb
simulation
observation 1
observation 2
p = 857 mb
simulation
observation 1
observation 2
p = 810 mb
simulation
observation 1
observation 2
100
10
1
0.1
0.01
0
5
10
15
20
25
30
35
concentration (cm^{-3} µm^{-1})
droplet radius (µm)

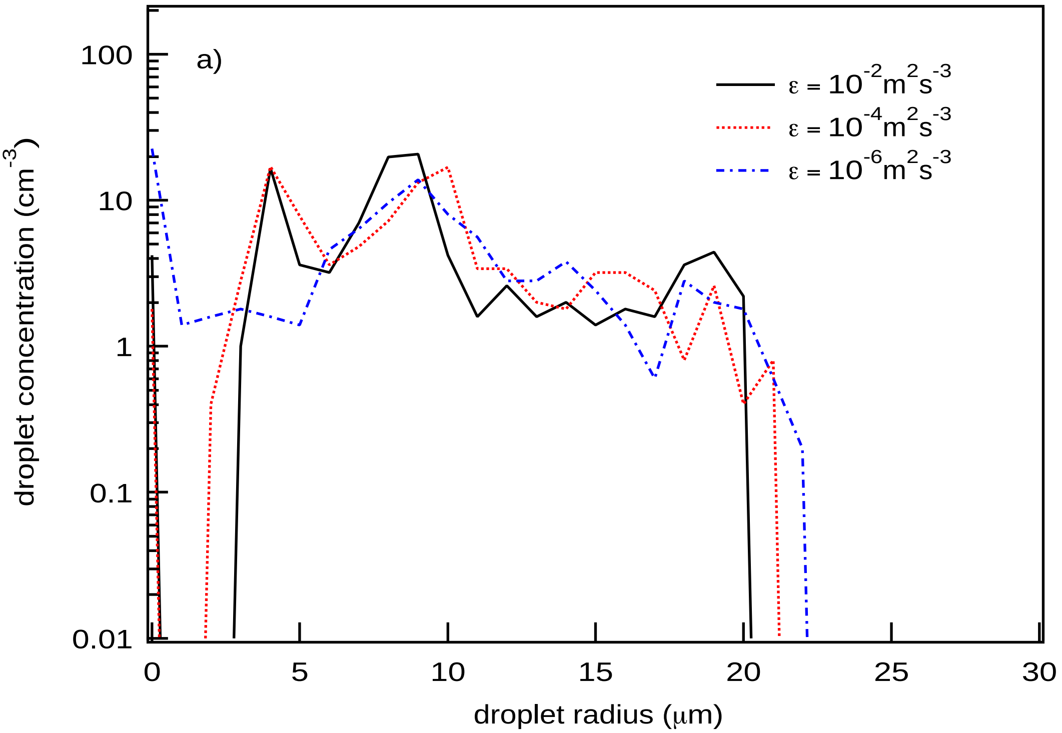
Large-droplet production

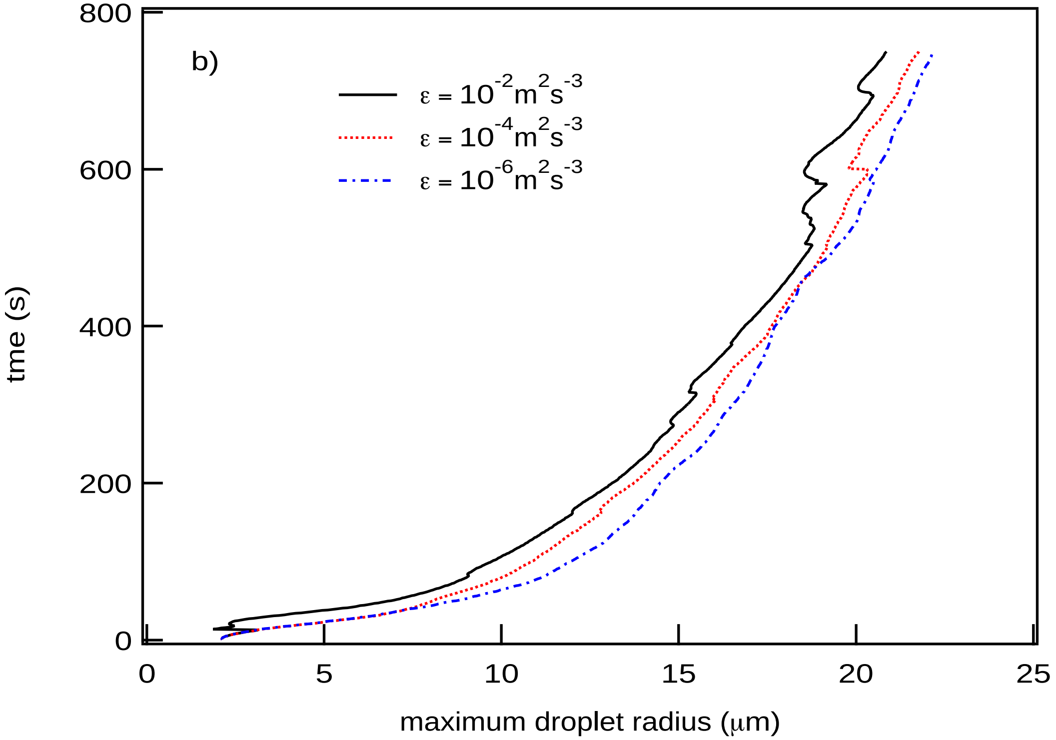

time (s)
0
100
200
300
400
500
600
700
800
droplet radius (μm)
0
5
10
15
20
drop #1
drop #2
drop #3

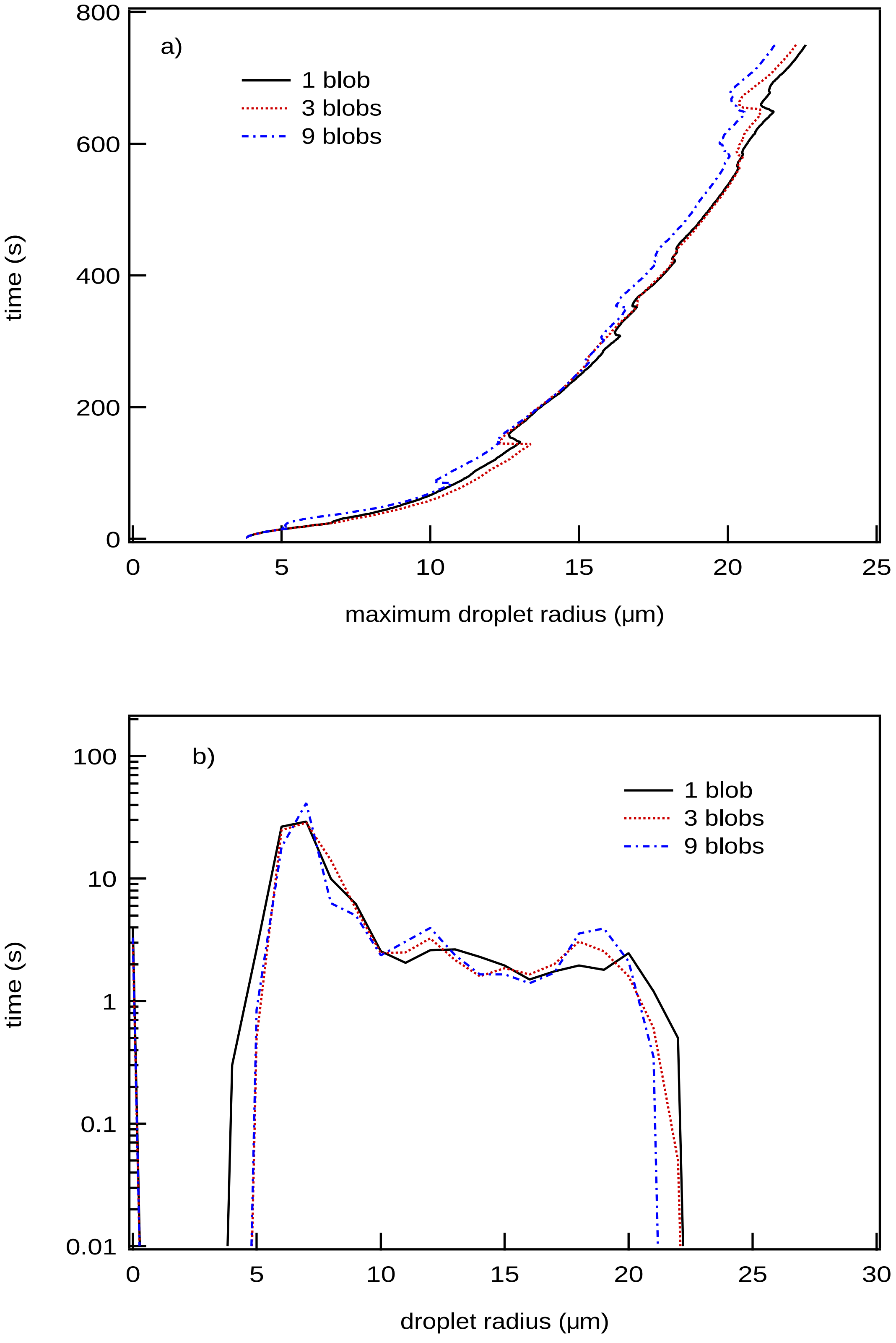

time (s)
0
100
200
300
400
500
600
700
800
0
5
10
15
20
droplet radius (μm)
drop #1
drop #2
drop #3
time (s)
-0.15
-0.10
-0.05
0.00
supersaturation ratio
drop #1
drop #2
drop #3

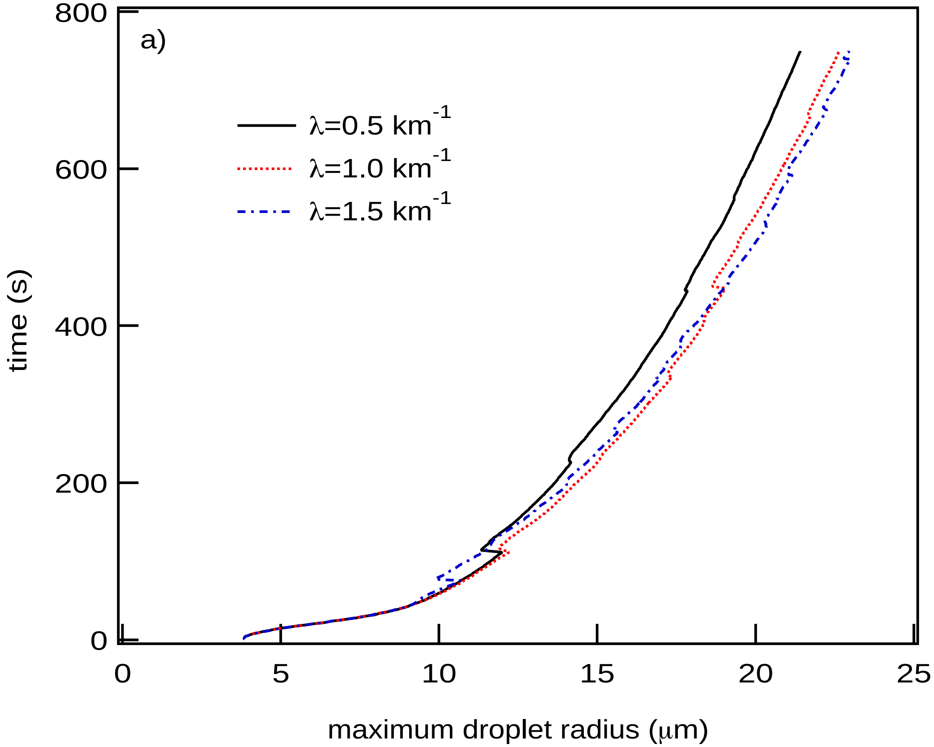

finite rate mixing with entrainment
adiabatic
time (s)
0
100
200
300
400
500
600
700
800
0
5
10
15
20
droplet radius (μm)

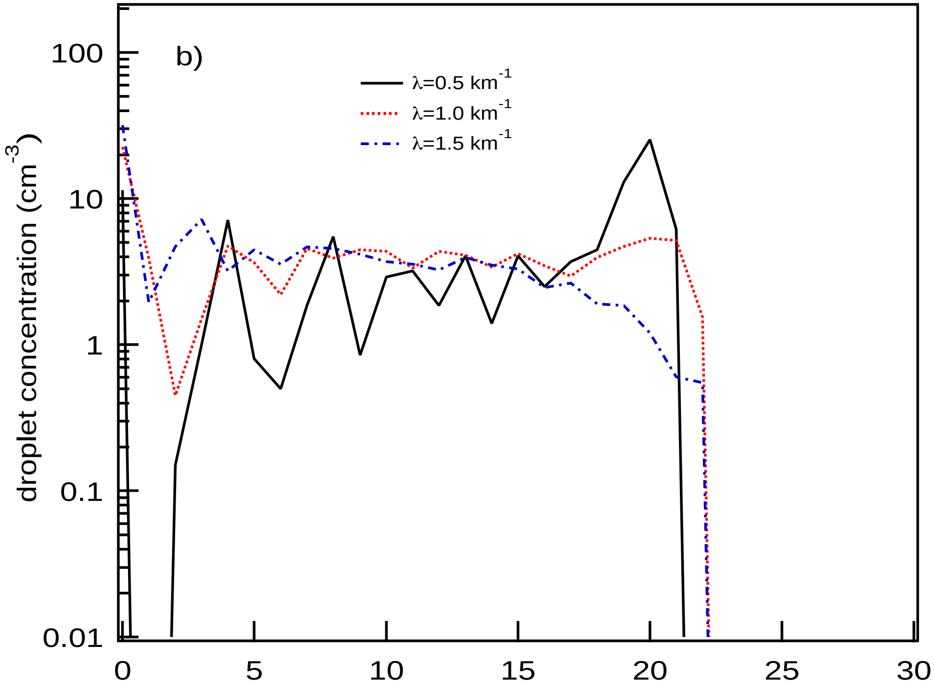

finite rate mixing
with entrainment
adiabatic
time (s)
0
100
200
300
400
500
600
700
800
-0.020
-0.015
-0.010
-0.005
0.000
0.005
0.010
0.015
supersaturation ratio

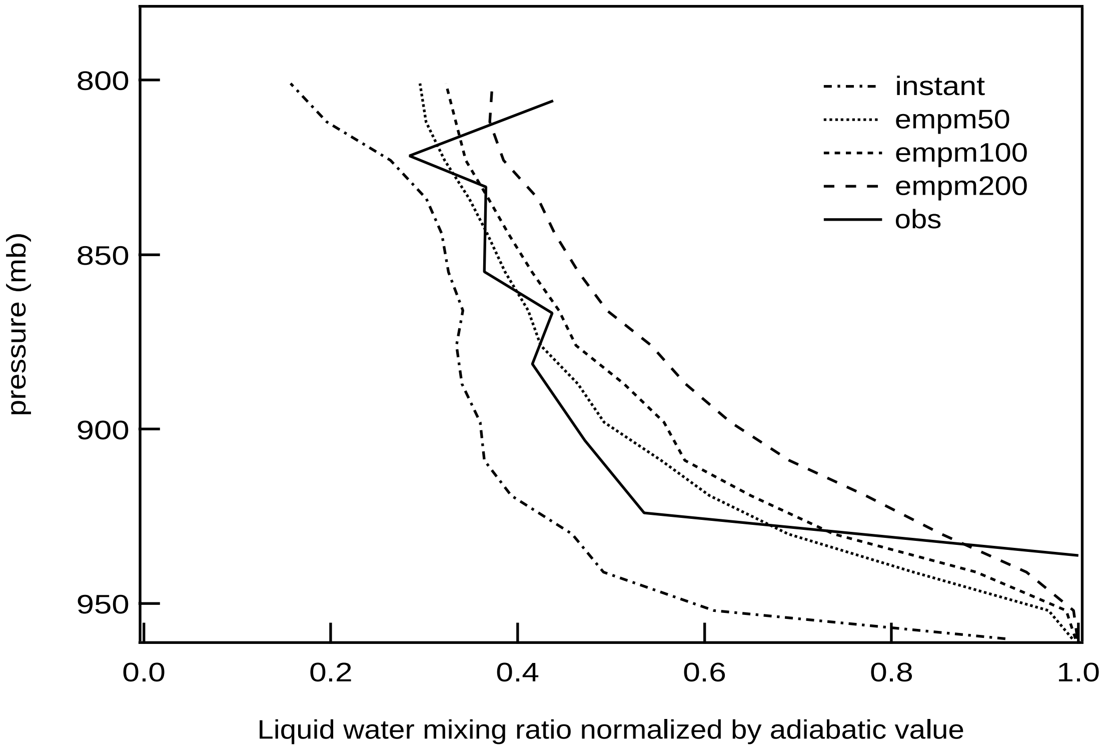

a)
ε = 10^-2 m^2 s^-3
ε = 10^-4 m^2 s^-3
ε = 10^-6 m^2 s^-3
droplet concentration (cm^-3)
0.01
0.1
1
10
100
0
5
10
15
20
25
30
droplet radius (μm)

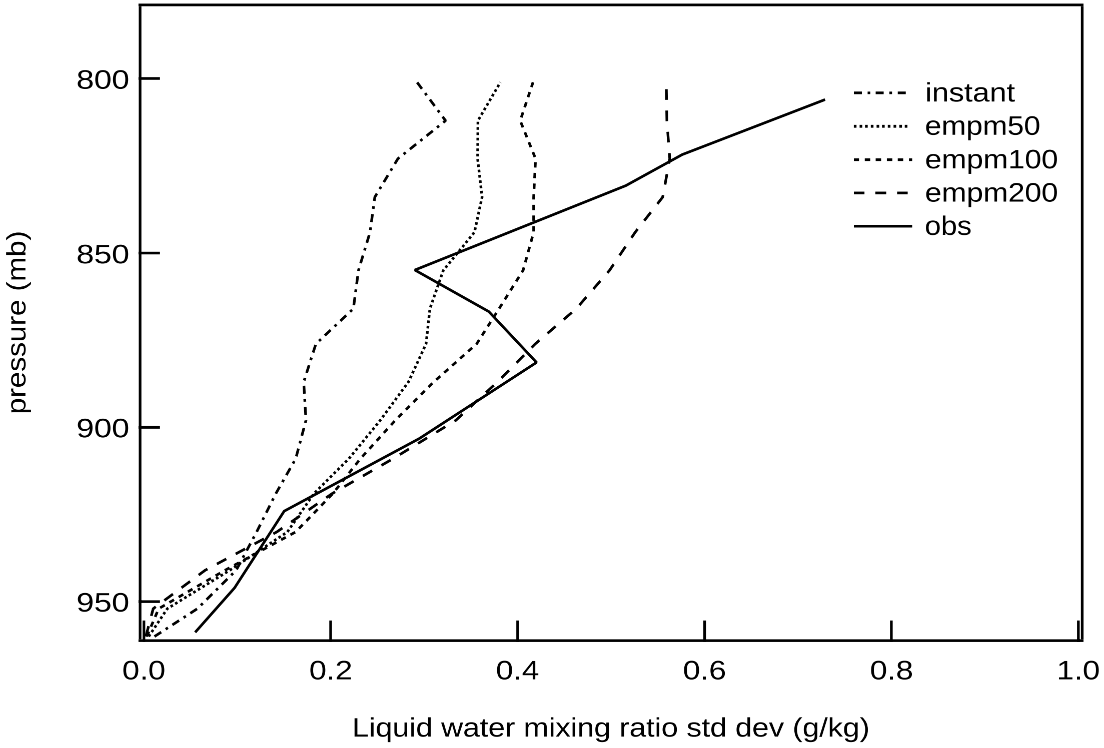

b)
ε = 10^-2 m^2 s^-3
ε = 10^-4 m^2 s^-3
ε = 10^-6 m^2 s^-3
tme (s)
0
200
400
600
800
0
5
10
15
20
25
maximum droplet radius (μm)

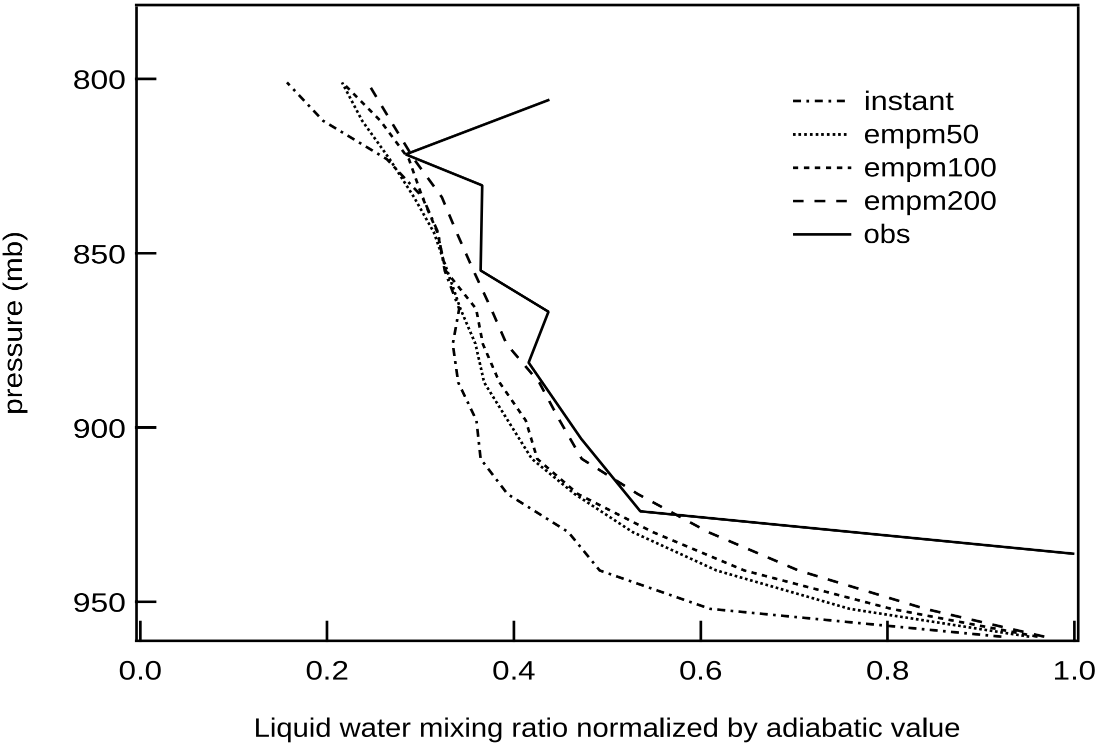

a)
1 blob
3 blobs
9 blobs
time (s)
0
200
400
600
800
0
5
10
15
20
25
maximum droplet radius (µm)
b)
1 blob
3 blobs
9 blobs
time (s)
0.01
0.1
1
10
100
0
5
10
15
20
25
30
droplet radius (µm)

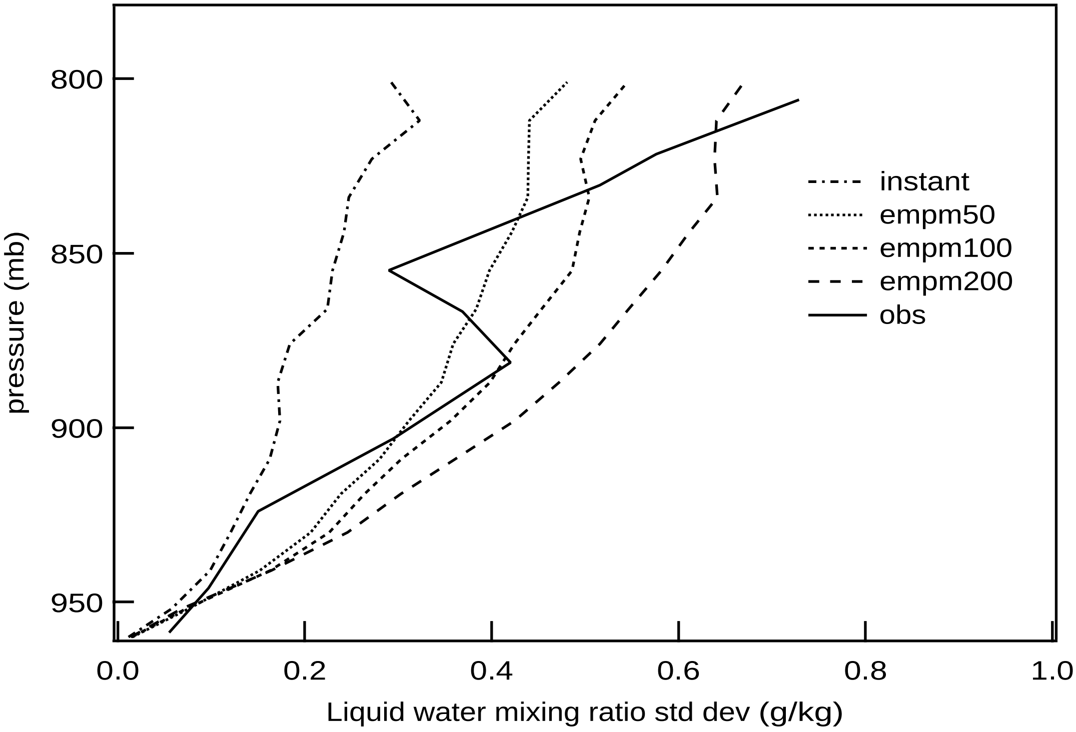

a)
λ=0.5 km^{-1}
λ=1.0 km^{-1}
λ=1.5 km^{-1}
time (s)
0
200
400
600
800
0
5
10
15
20
25
maximum droplet radius (μm)

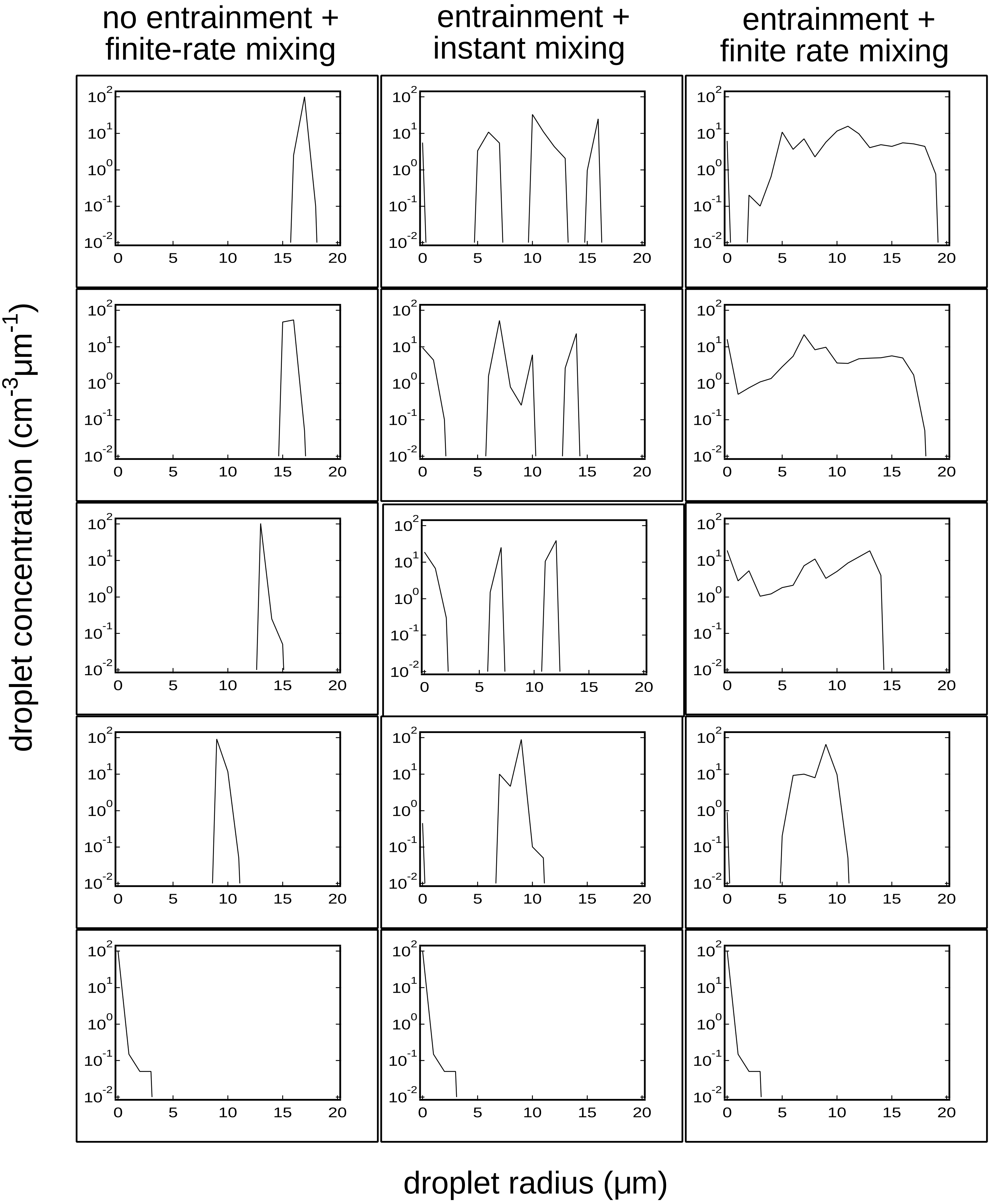

b)
λ=0.5 km^{-1}
λ=1.0 km^{-1}
λ=1.5 km^{-1}
droplet concentration (cm^{-3})
0.01
0.1
1
10
100
0
5
10
15
20
25
30
droplet radius (μm)

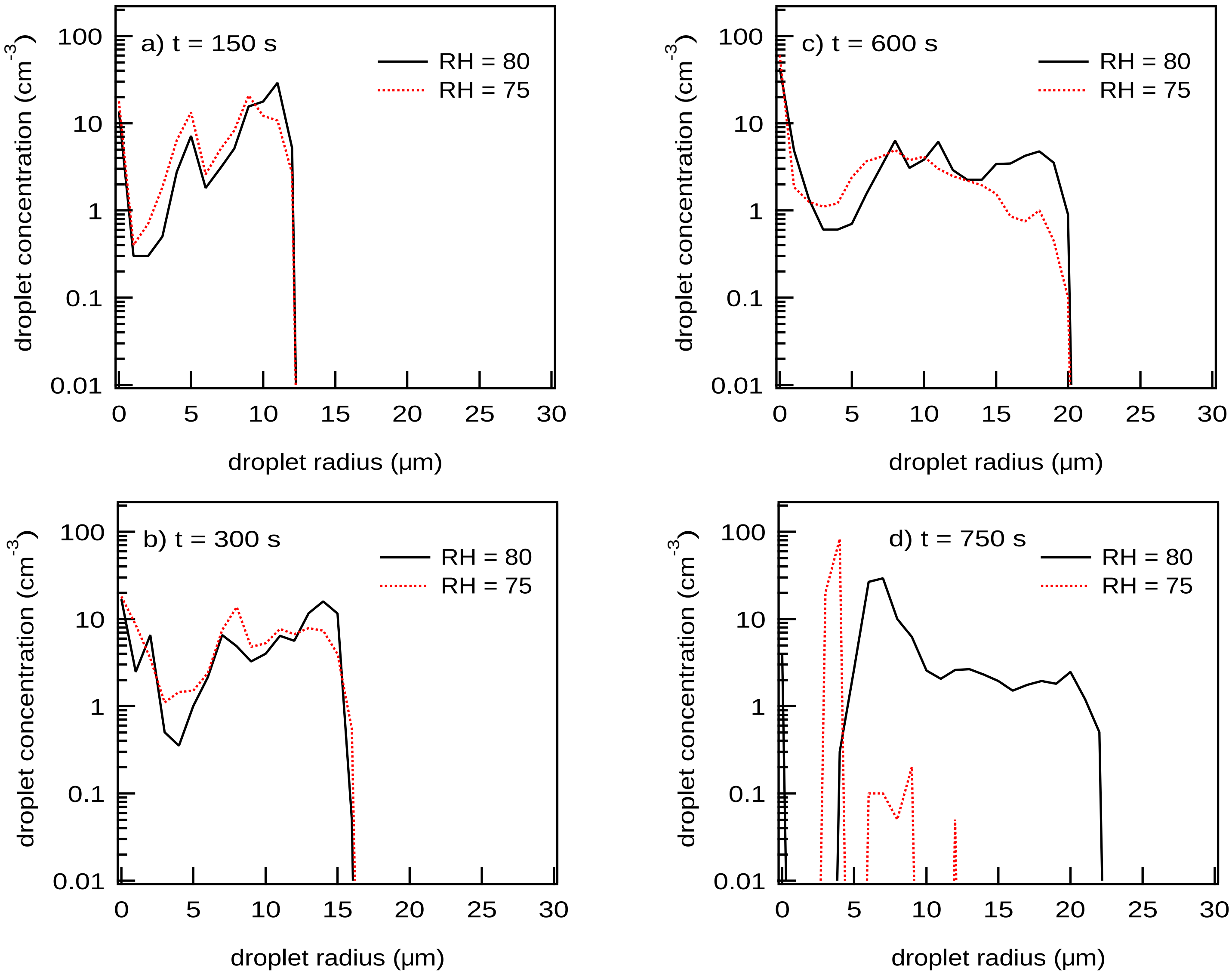

800
850
900
950
pressure (mb)
0.0
0.2
0.4
0.6
0.8
1.0
Liquid water mixing ratio normalized by adiabatic value
instant
empm50
empm100
empm200
obs

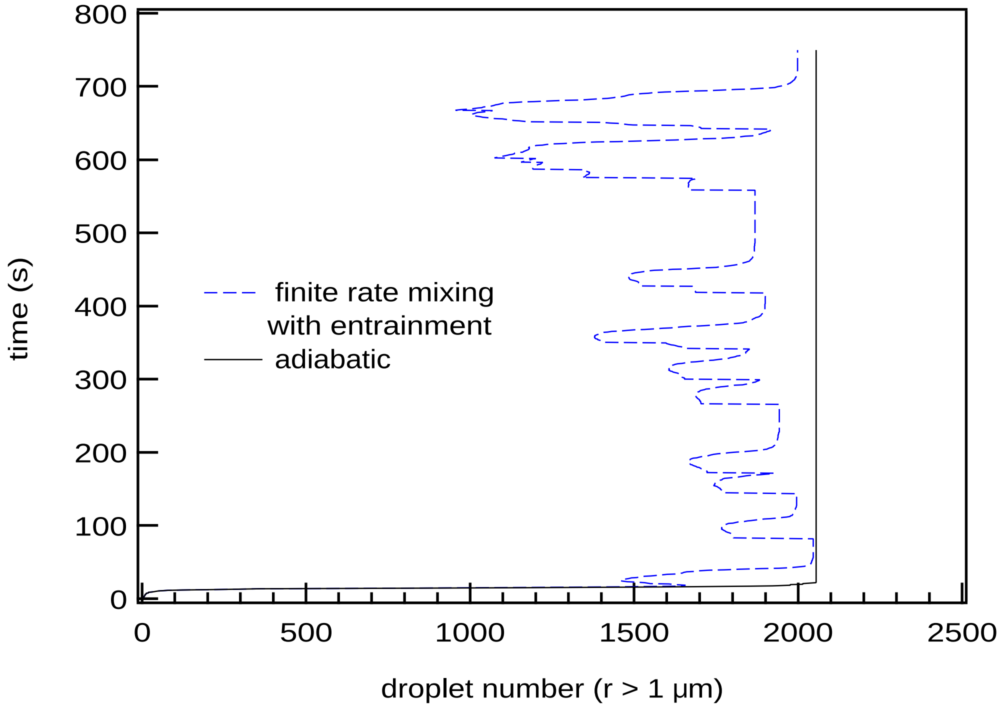

800
850
900
950
pressure (mb)
0.0
0.2
0.4
0.6
0.8
1.0
Liquid water mixing ratio std dev (g/kg)
instant
empm50
empm100
empm200
obs


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


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


no entrainment + finite-rate mixing
entrainment + instant mixing
entrainment + finite rate mixing
droplet concentration (cm^{-3}μm^{-1})
droplet radius (μm)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
5
10
15
20


a) t = 150 s
b) t = 300 s
c) t = 600 s
d) t = 750 s
RH = 80
RH = 75
droplet concentration (cm^{-3})
droplet radius (µm)
0.01
0.1
1
10
100
0
5
10
15
20
25
30


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)