Clouds in a Box Versus Clouds in the Sky: Studying Cloud Processes with a Laboratory Convection Cloud Chamber

Steve Krueger, University of Utah

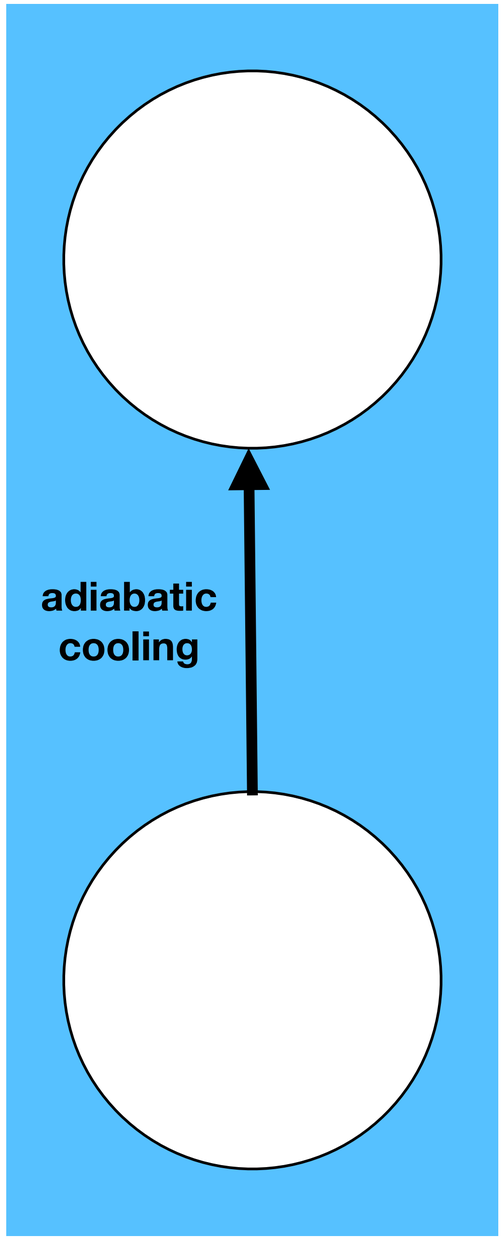
Raymond Shaw, Michigan Technological University

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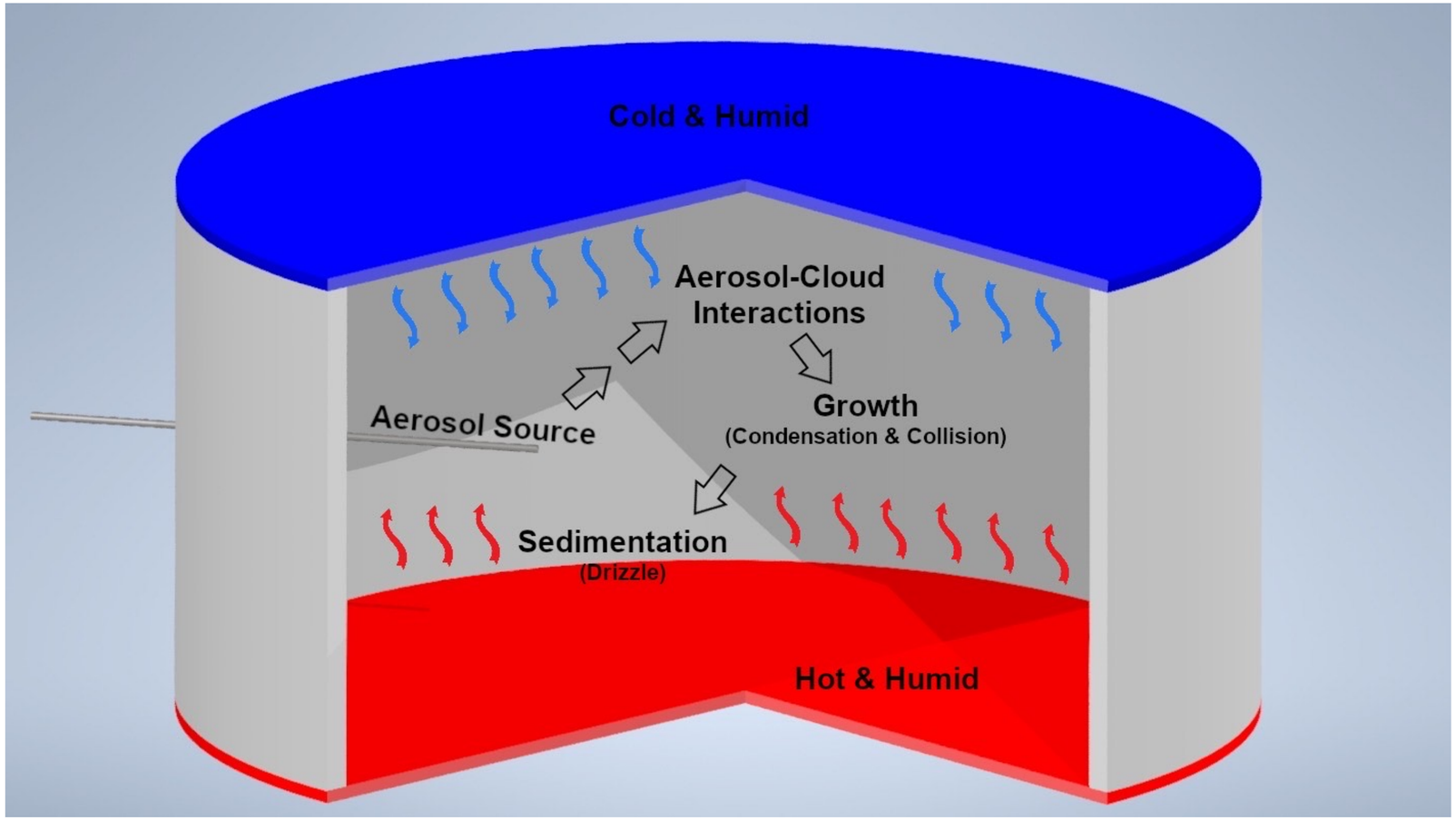


Artwork by Michele De Matthaeis

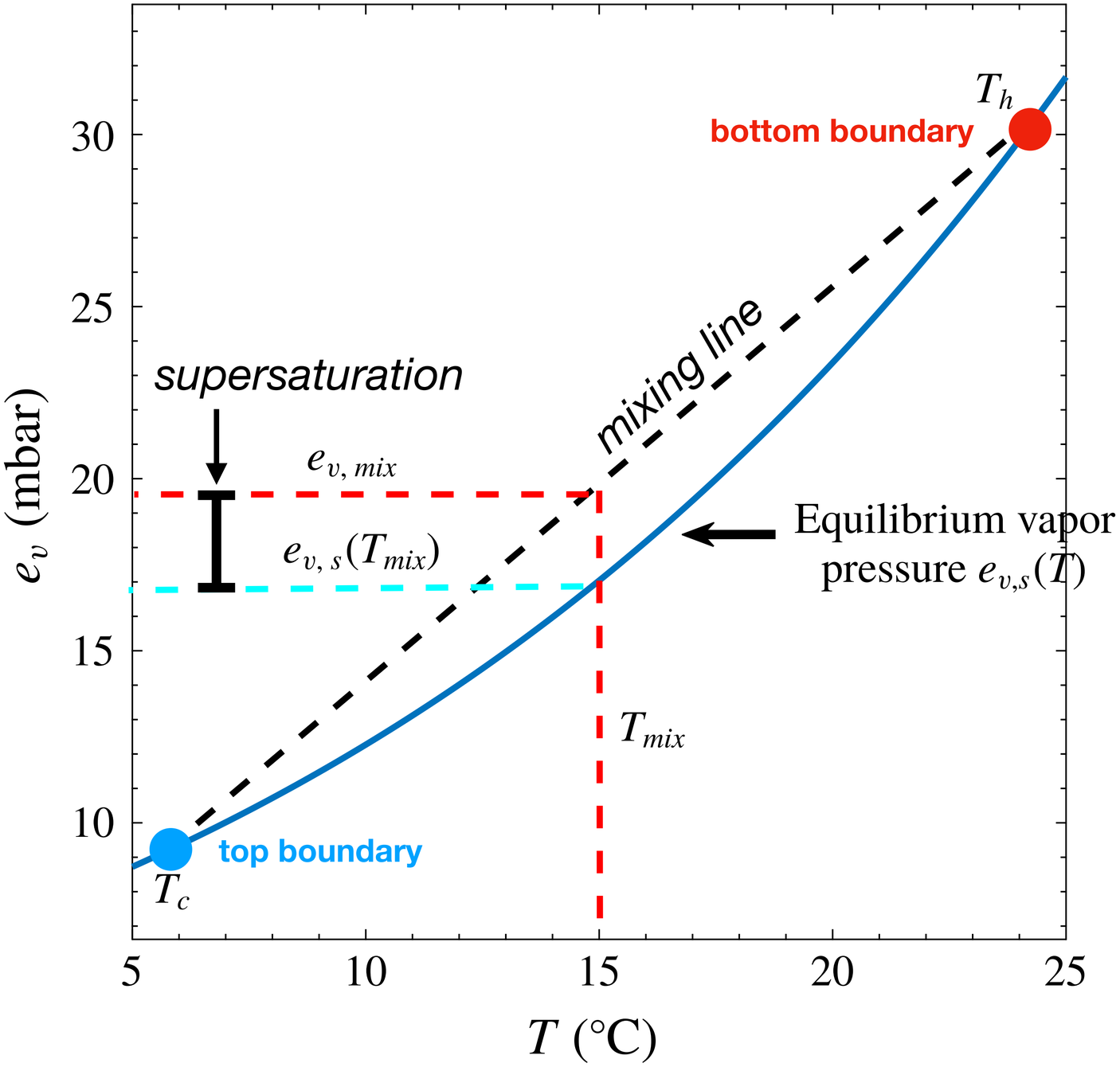
ascending parcel



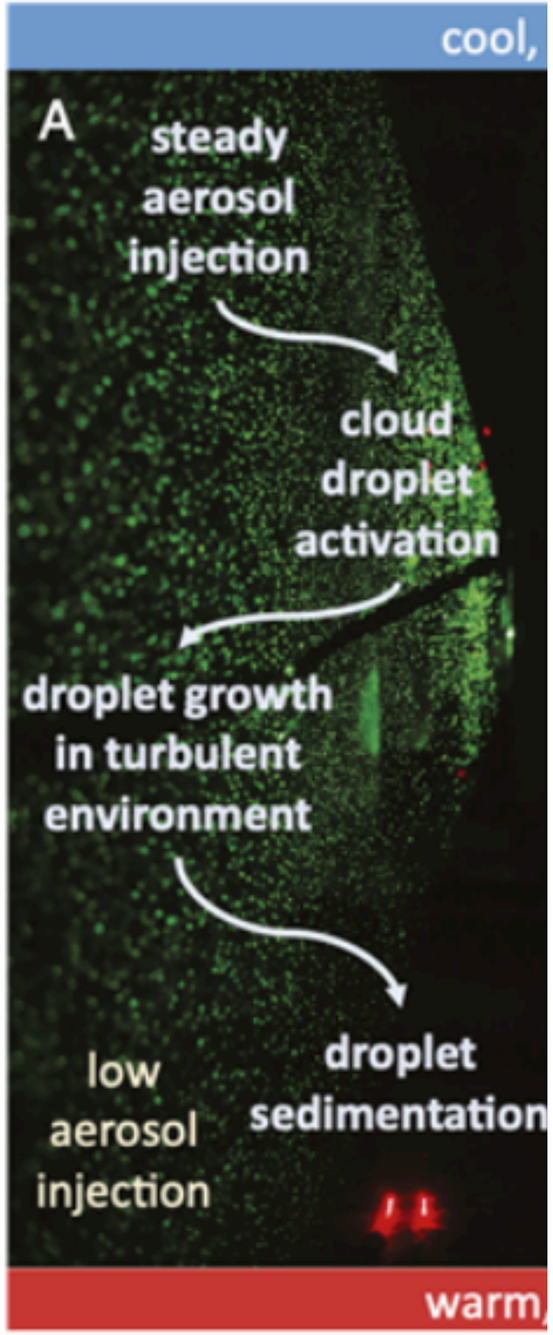
Pi Convection–Cloud Chamber



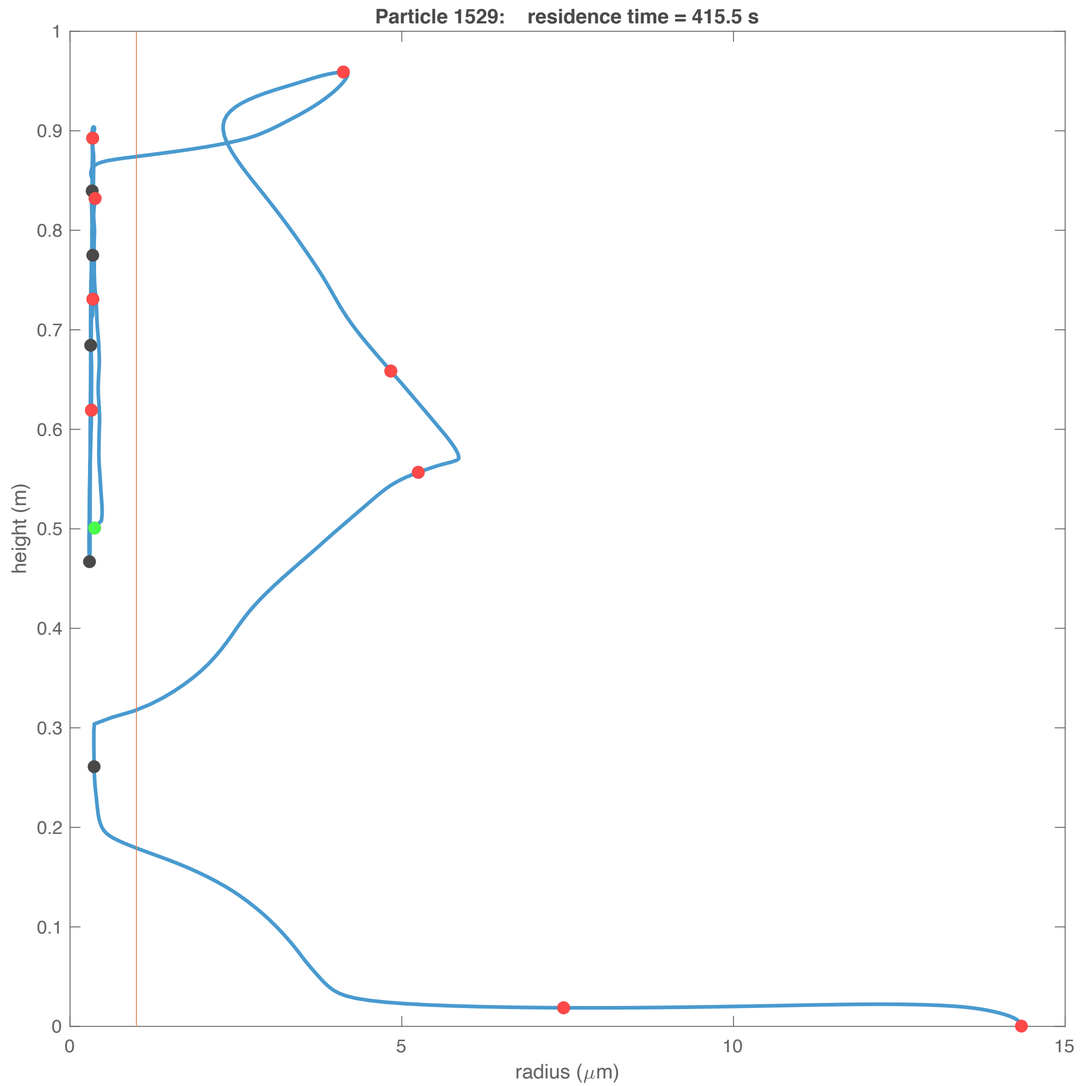
Supersaturation due to mixing

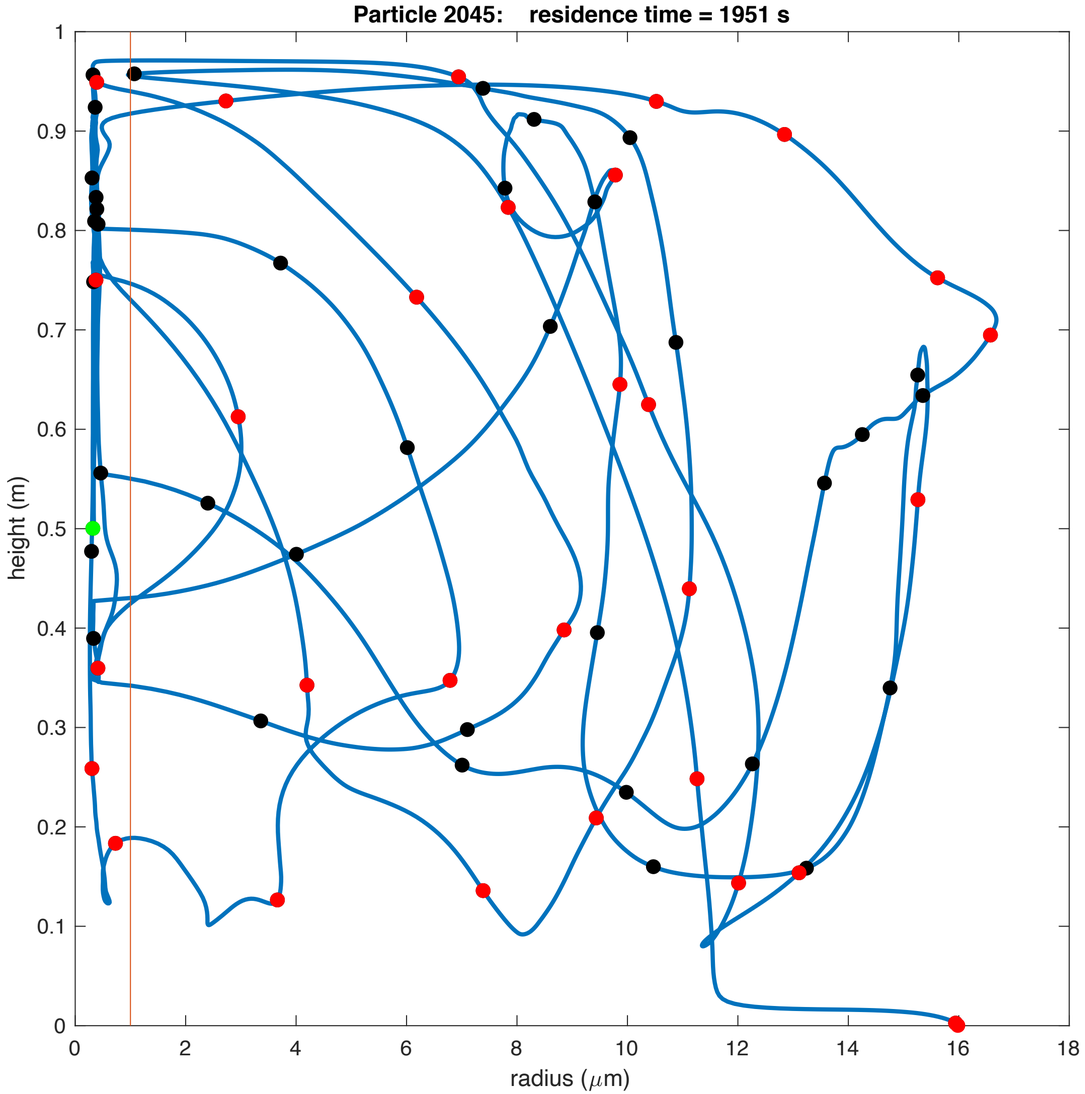


Droplet histories in a convection-cloud chamber



Cloud-convection chamber particle trajectories (from DNS)





DNS data from Theodore MacMillan and David Richter

Droplet Growth in an Adiabatic Ascending Parcel

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- $r^3(z) \sim z/N$ so LWC $\sim Nr^3 \sim z$.

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- Mean supersaturation, $\bar{s}$, and droplet growth time, τ, combine to produce the radius, $r(\tau)$, of an individual droplet.
- In a convection cloud chamber:
  - $h\bar{s} \sim (\Delta T^2/N)^{4/5}$ (Shaw et al. 2023), where ΔT is the temperature difference across the chamber height h.
  - $\bar{\tau} = \dfrac{h}{k_1 \overline{r^2}} \rightarrow \dfrac{\bar{\tau}}{h} = \dfrac{1}{k_1 \overline{r^2}}$ (Krueger 2020).
  - $\overline{r^2} \sim \bar{s}\,\bar{\tau} \sim \dfrac{(\Delta T^2/N)^{4/5}}{\overline{r^2}}$. Solution is $\overline{r^2} \sim \dfrac{\Delta T^{4/5}}{N^{2/5}}$.
  - $LWC \sim N\overline{r^3} \sim (\Delta T)^{6/5} N^{2/5}$.

Supersaturation Equation

ascending
adiabatic parcel

$$\frac{ds}{dt} = aw - \frac{s}{\tau_c}$$

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ascending adiabatic parcel

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convection-cloud chamber

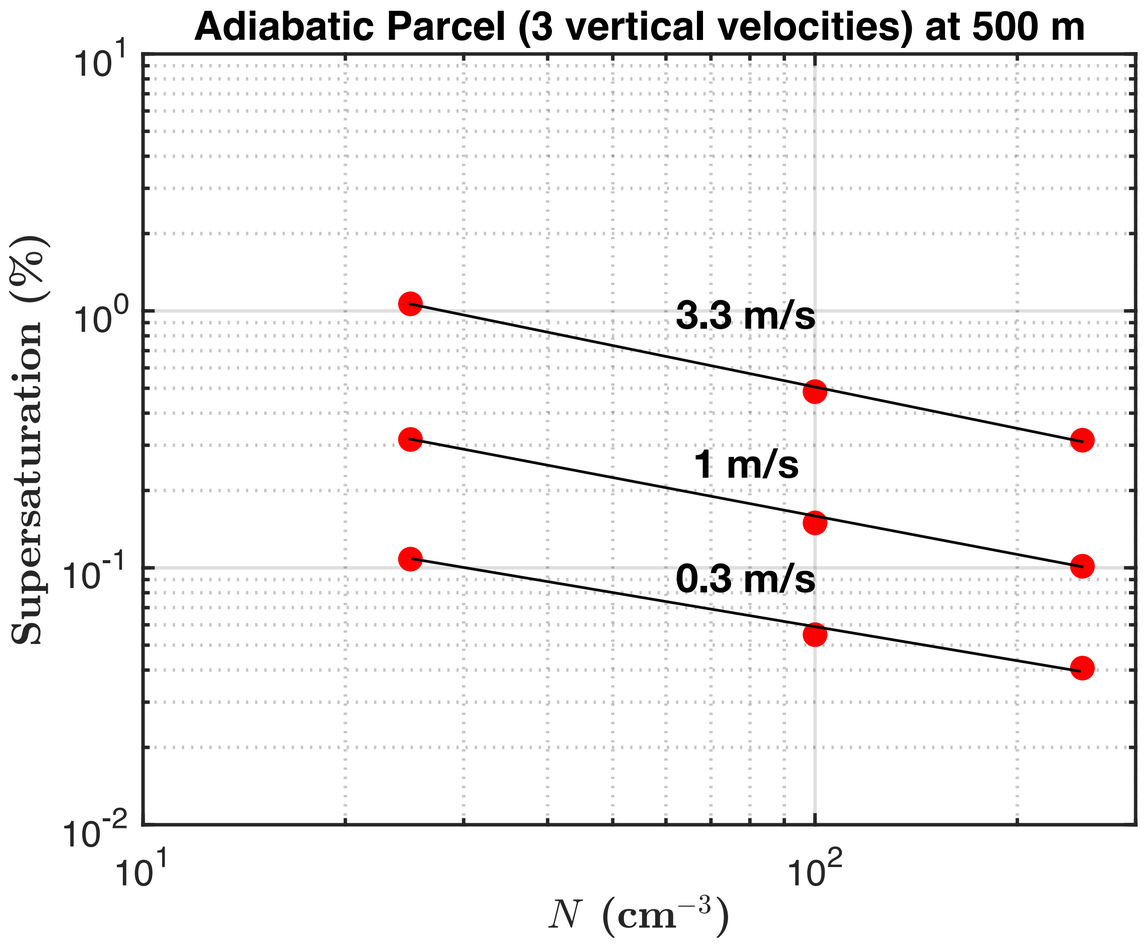
$$\frac{ds}{dt} = \frac{1}{\tau_t}(s_0 - s) - \frac{s}{\tau_c},$$

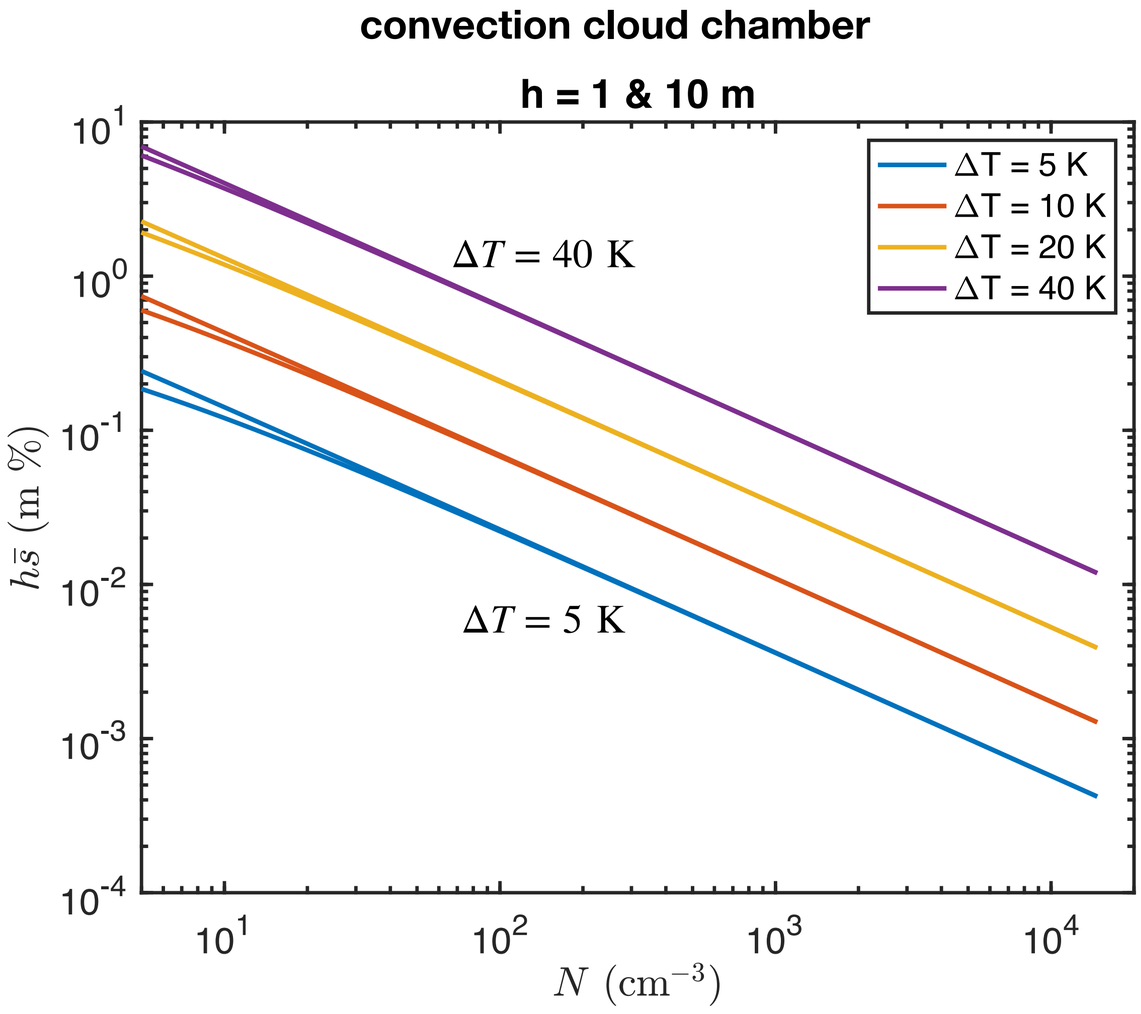
where τ_c is the phase relaxation time. It is given by

$$\tau_c = (4\pi D' n r)^{-1},$$

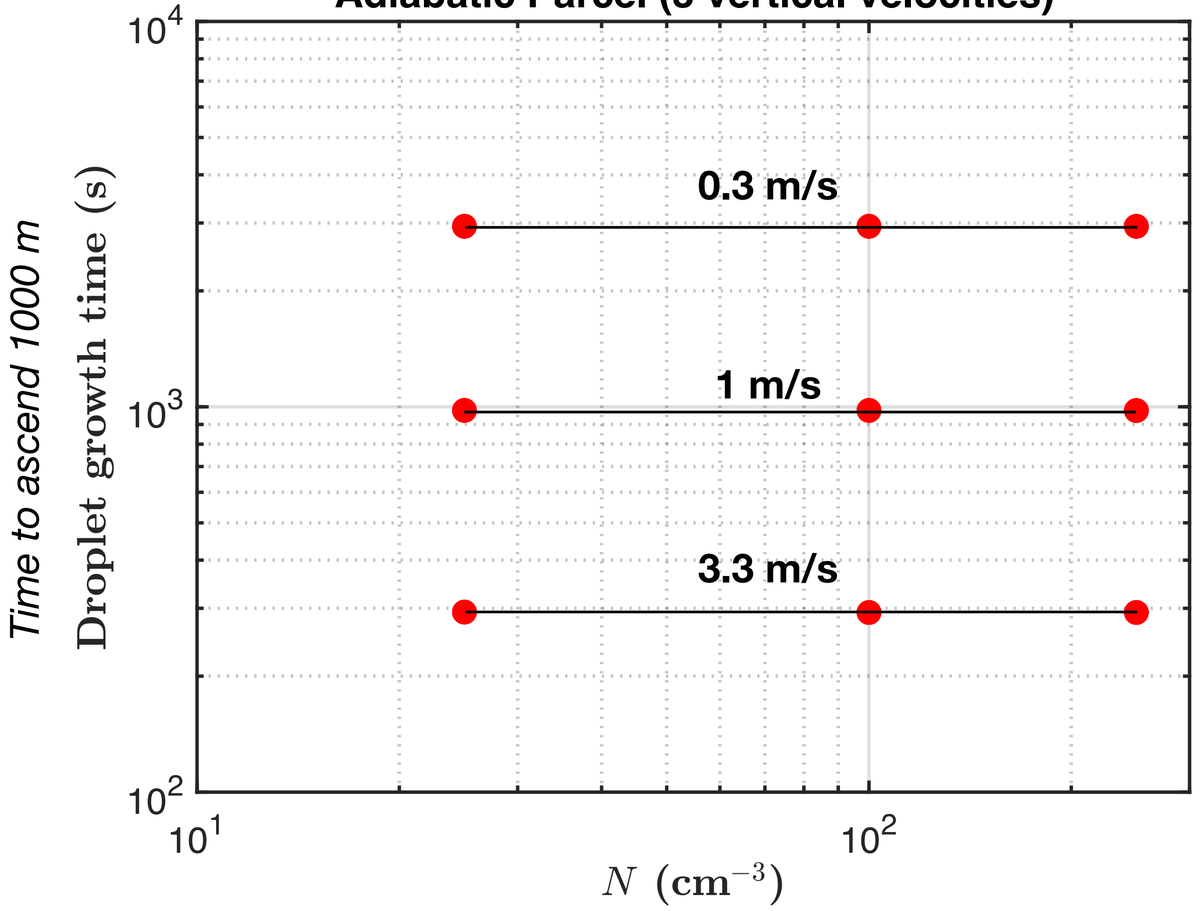
$$s_0 = \frac{1}{2}\left(\frac{L\Delta T}{2R_v T_0^2}\right)^2,$$

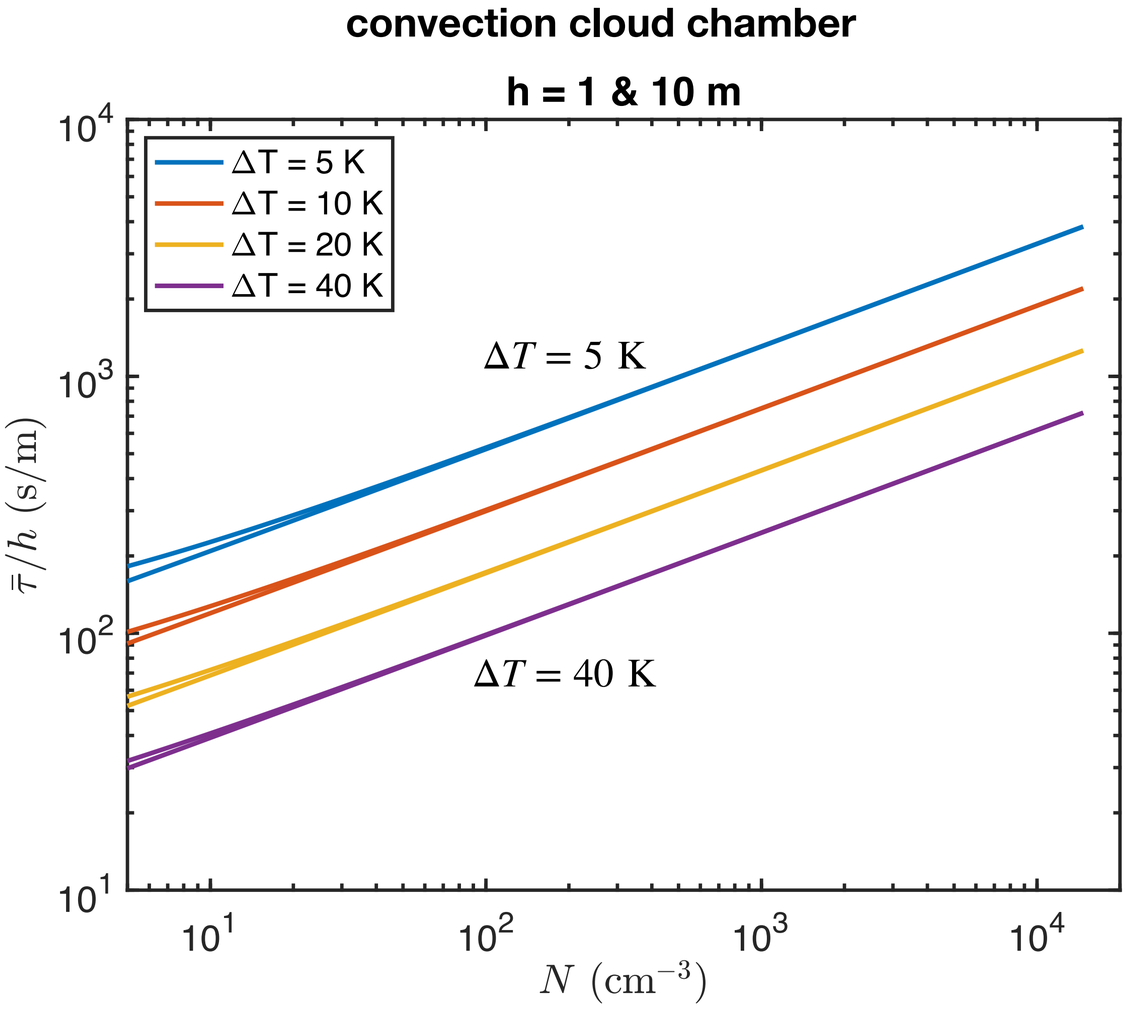
(Quasi-static) Supersaturation



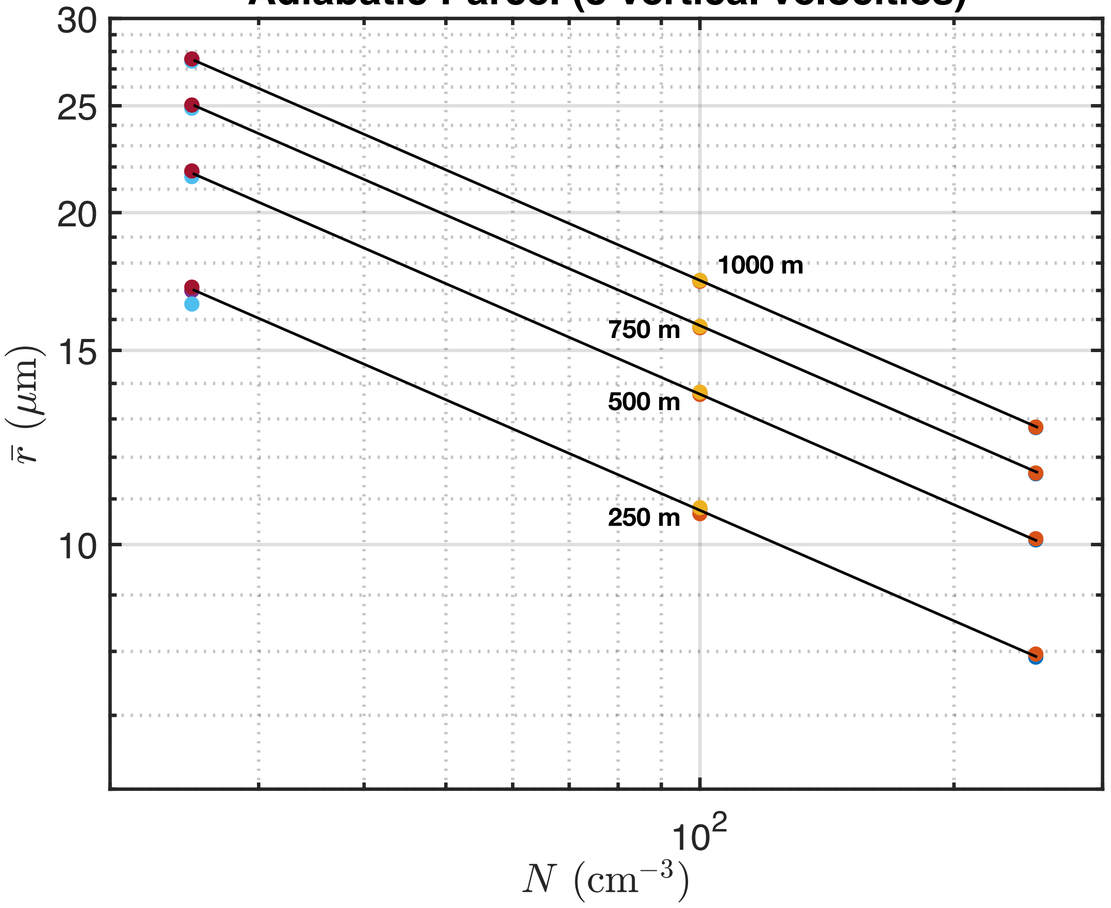


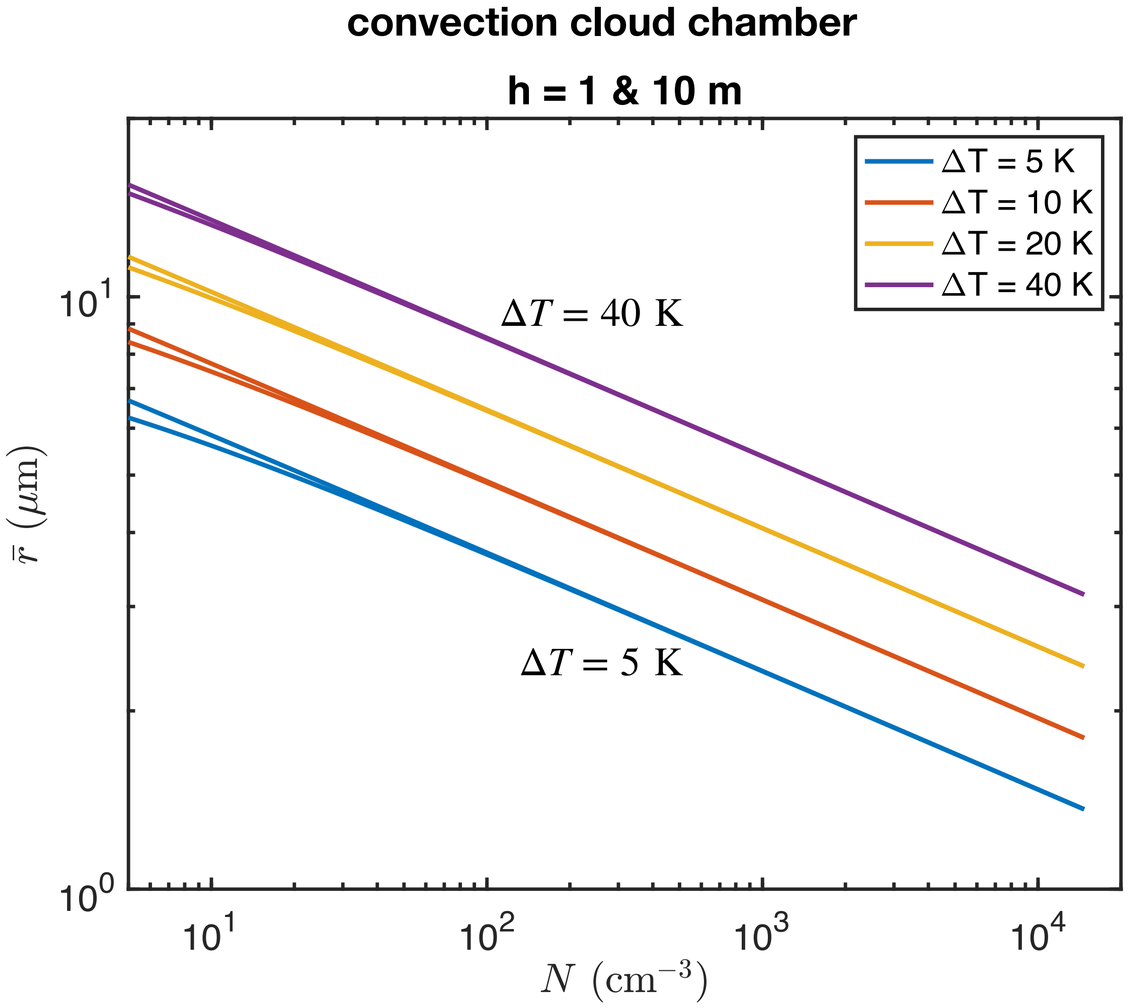
Growth Time


Adiabatic Parcel (3 vertical velocities)
Time to ascend 1000 m
Droplet growth time (s)
0.3 m/s
1 m/s
3.3 m/s
10^4
10^3
10^2
10^1
10^2
N (cm^{-3})

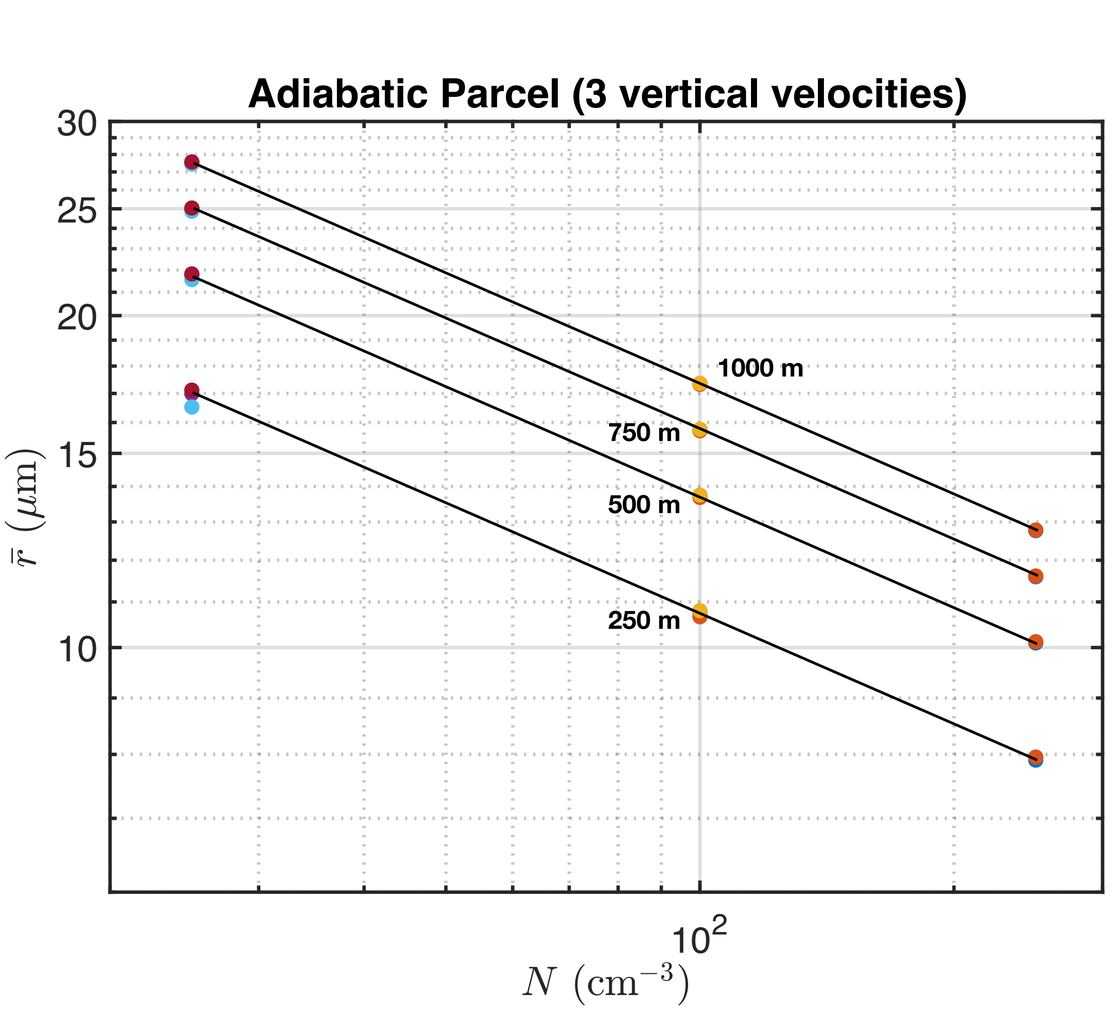

convection cloud chamber
h = 1 & 10 m
ΔT = 5 K
ΔT = 10 K
ΔT = 20 K
ΔT = 40 K
$\Delta T = 5$ K
$\Delta T = 40$ K
$\bar{\tau}/h$ (s/m)
10^4
10^3
10^2
10^1
10^1
10^2
10^3
10^4
N (cm^{-3})

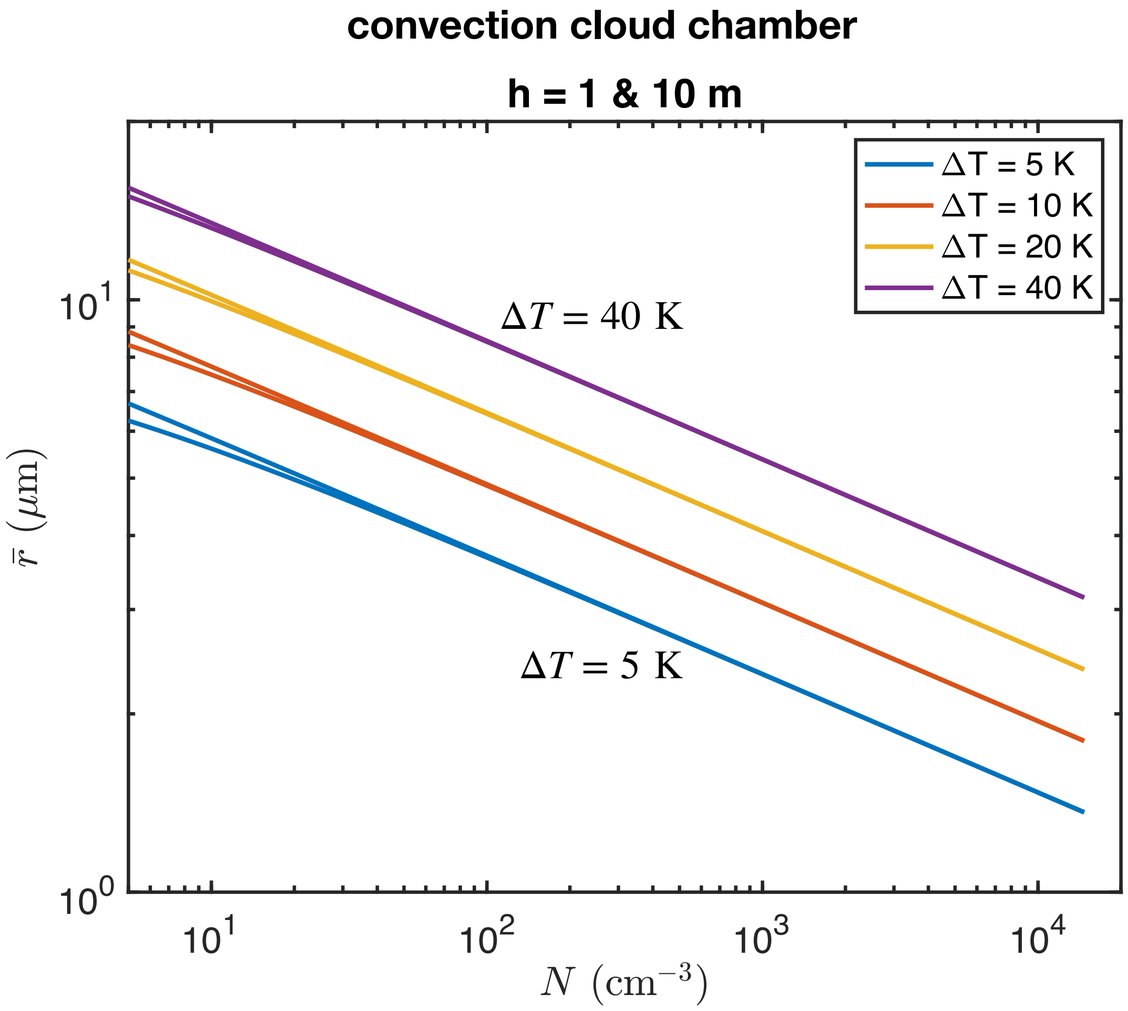
Mean Radius


Adiabatic Parcel (3 vertical velocities)
30
25
20
15
10
$\bar{r}$ (μm)
1000 m
750 m
500 m
250 m
10^2
N (cm^{-3})


convection cloud chamber
h = 1 & 10 m
ΔT = 5 K
ΔT = 10 K
ΔT = 20 K
ΔT = 40 K
$\Delta T = 40$ K
$\Delta T = 5$ K
10^1
10^0
$\bar{r}$ (μm)
10^1
10^2
10^3
10^4
N (cm^{-3})

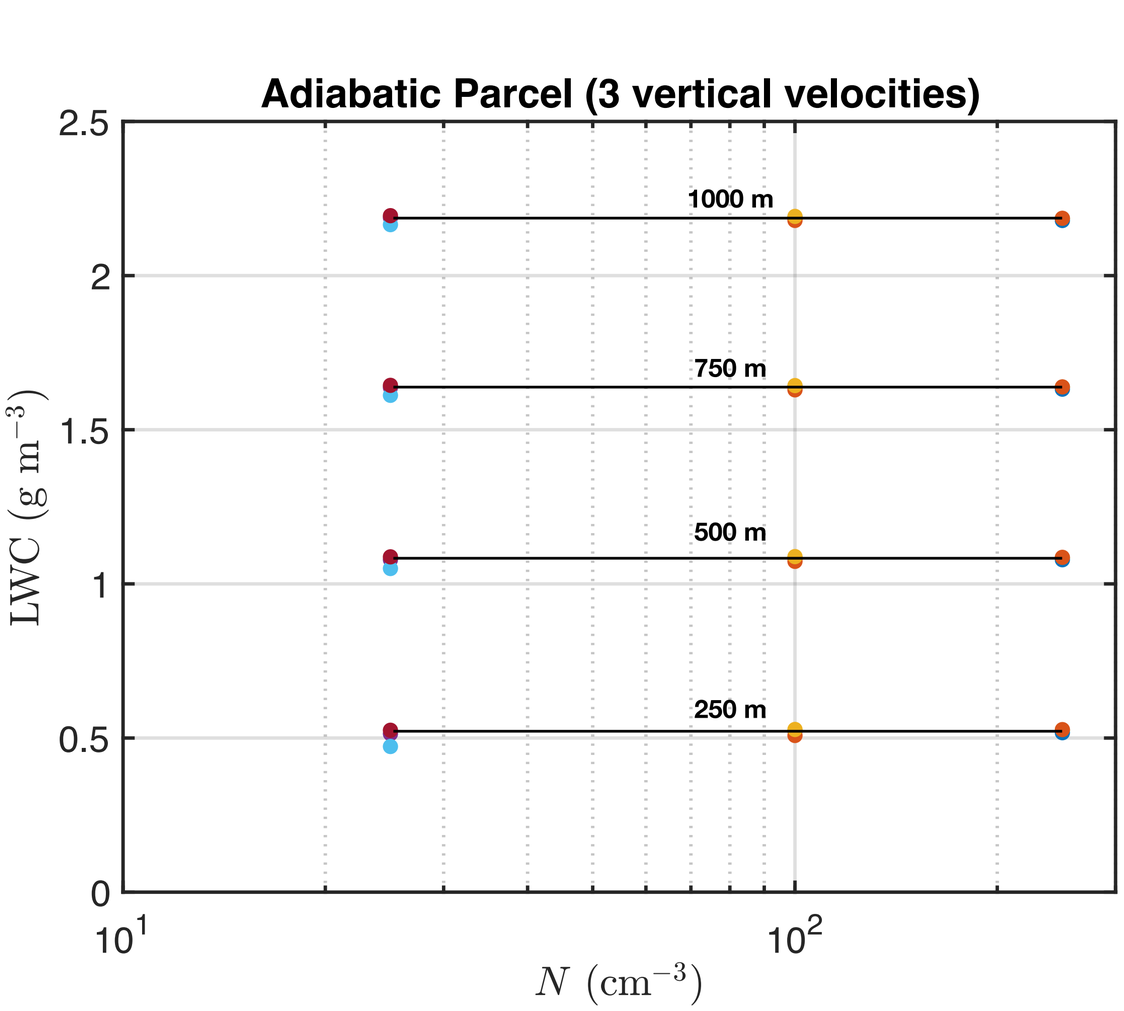
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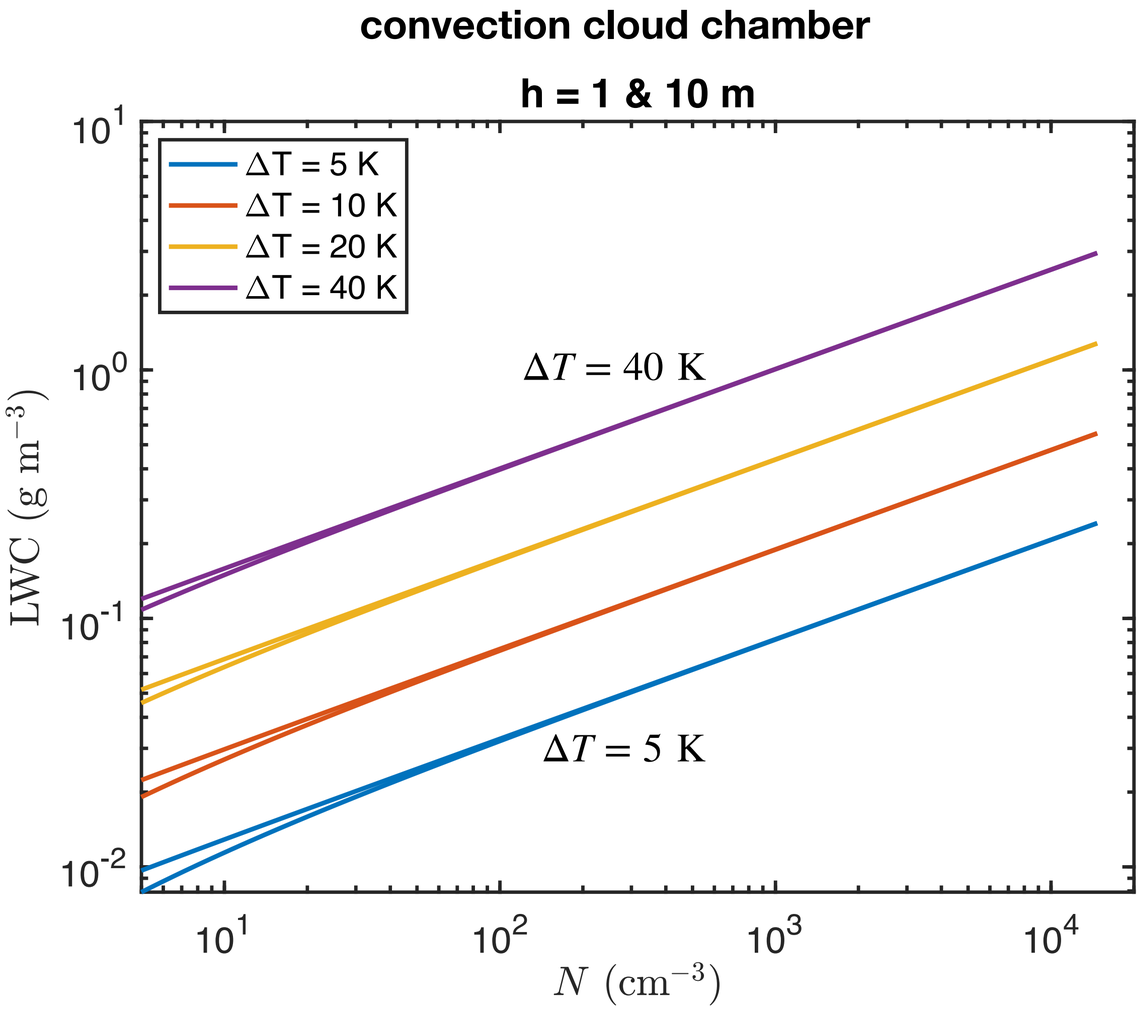




Properties measured at a fixed height above cloud base in an ascending parcel correspond to properties measured at a specific ΔT in a convection-cloud chamber.

Liquid Water Content





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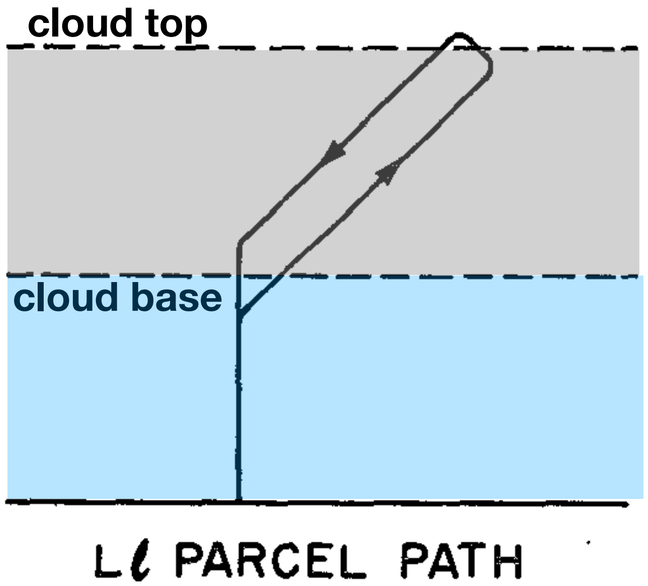
Ascending parcel versus convection-cloud chamber

- ***Supersaturation forcing*:** Vertical velocity (w) corresponds to ΔT.
- ***Droplet growth time:*** Decrease with increasing w corresponds to decrease with increasing ΔT.
- ***Mean radius:*** Height above cloud base (Δz) corresponds to ΔT.
- ***Liquid water content:*** Δz corresponds to ΔT.

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Cloud-topped
boundary layer



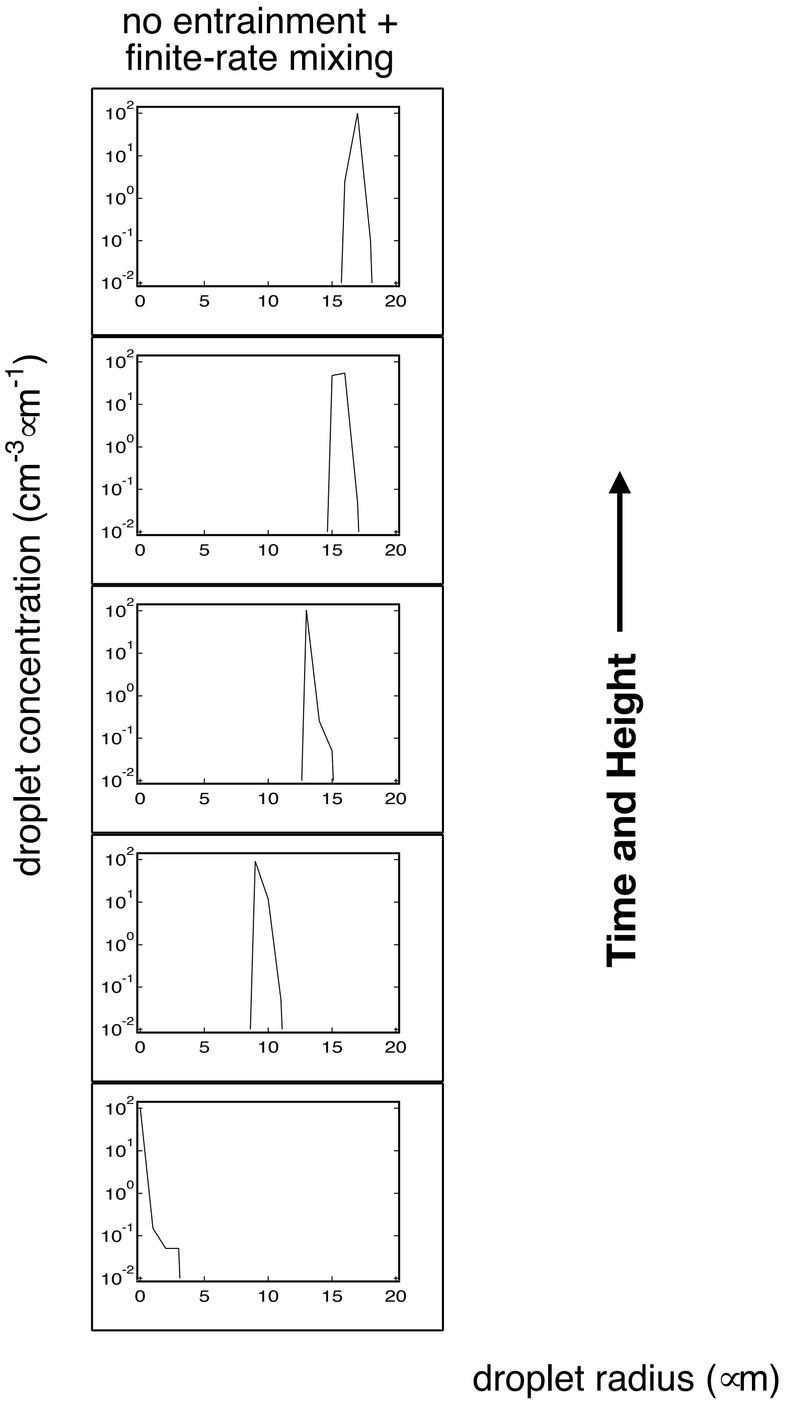
Schubert et al. 1979

Dependencies on droplet number concentration

- ***Supersaturation forcing*:** Both decrease.
- ***Droplet growth time:*** None for parcel; increases with N in chamber.
- ***Mean radius:*** Both decrease.
- ***Liquid water content:*** None for parcel; increases with N in chamber.

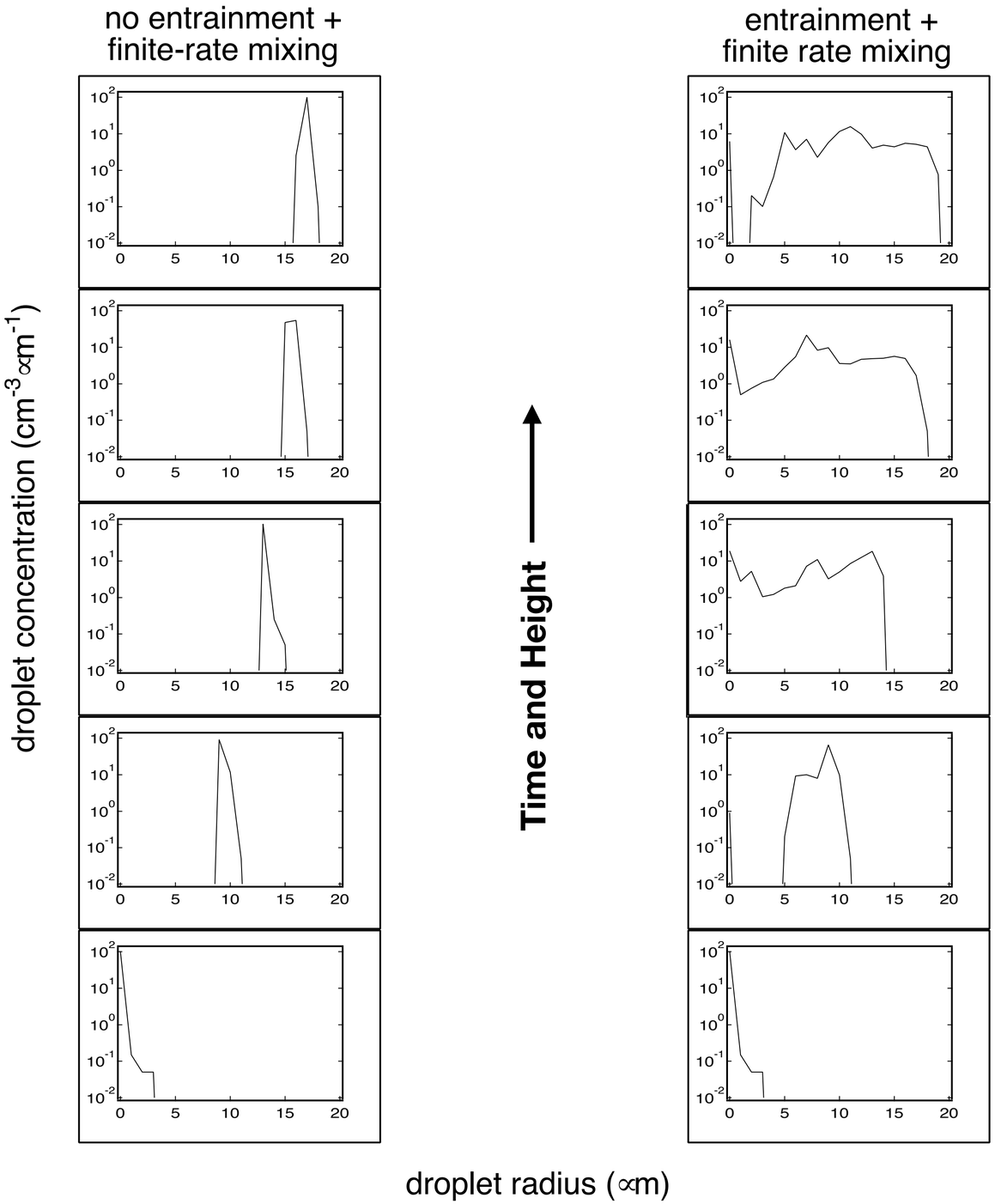
DSDs in ascending parcels

- **Without entrainment:** All droplet supersaturation histories are nearly the same, so the DSD is narrow.

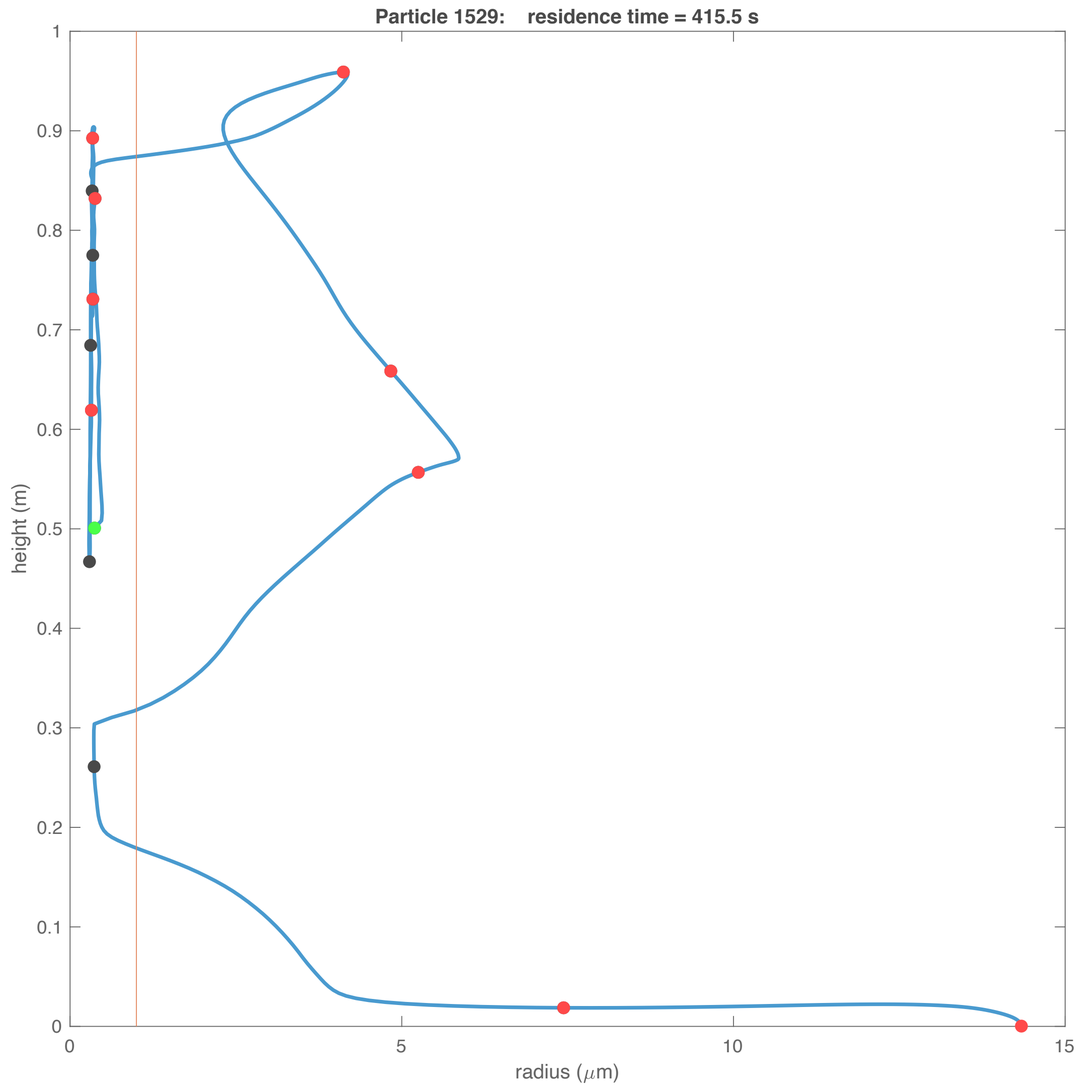


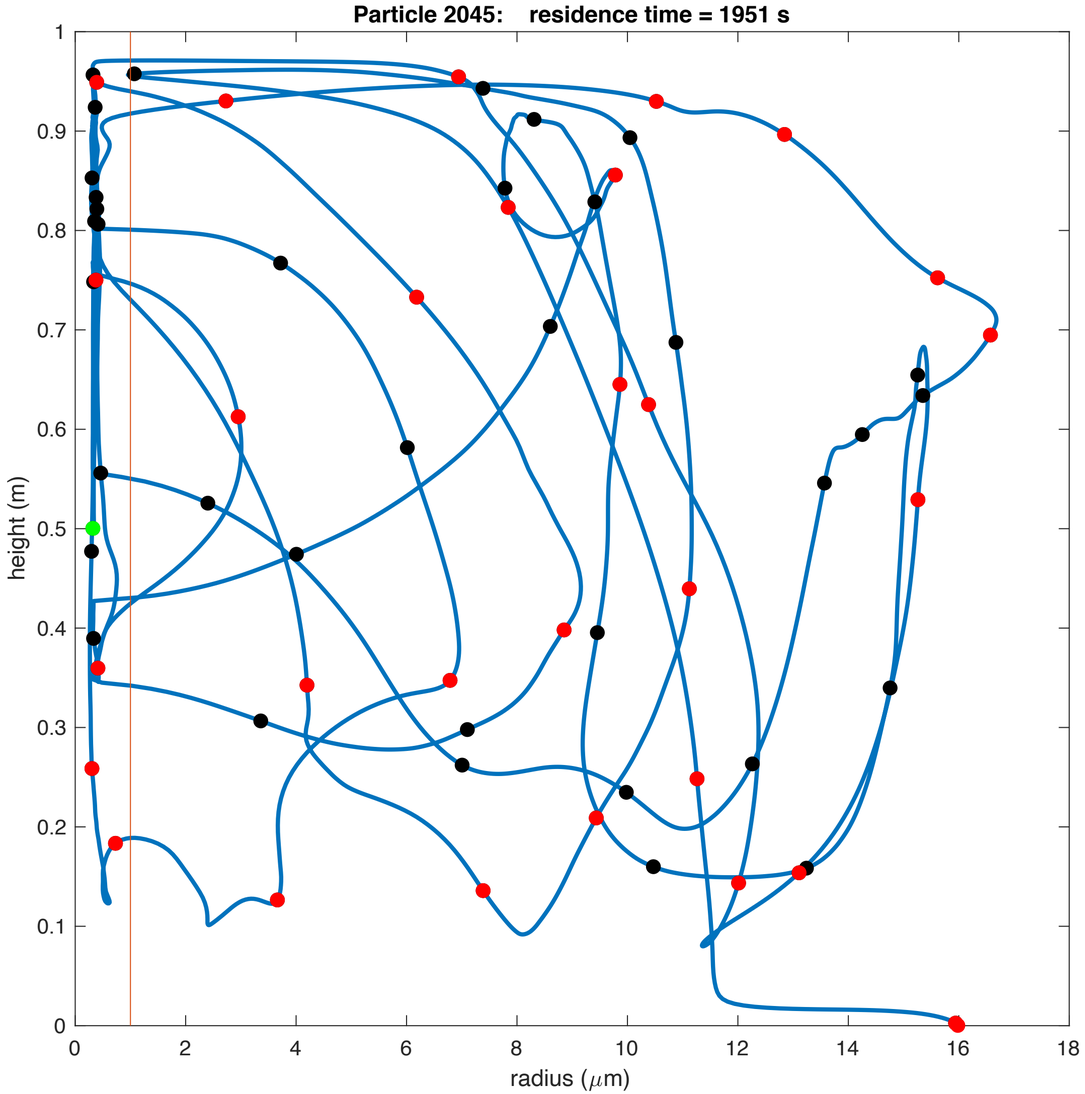
DSDs in ascending parcels

- **Without entrainment:** All droplet supersaturation histories are nearly the same, so the DSD is narrow.
- **With entrainment:**
  - *Supersaturation varies among droplets* due to entrainment and mixing, so DSD is broad.
  - Entrained CCN may be activated.



Cloud-convection chamber particle trajectories (from DNS)

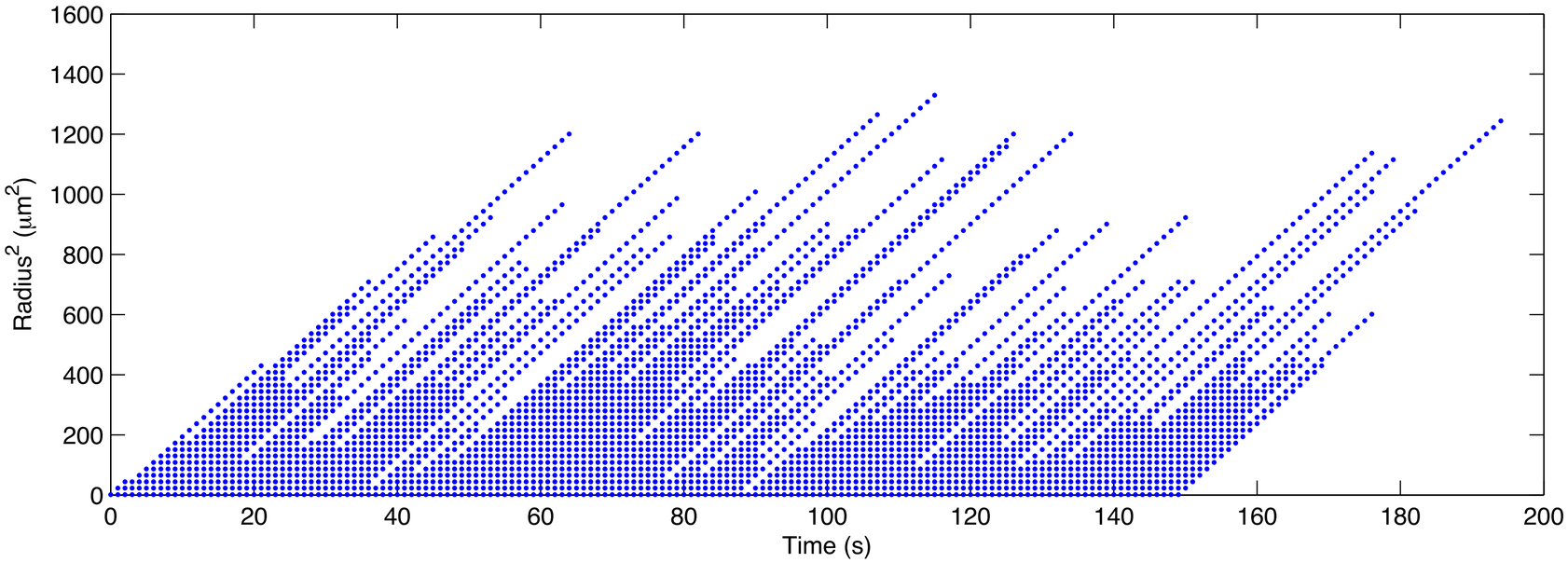


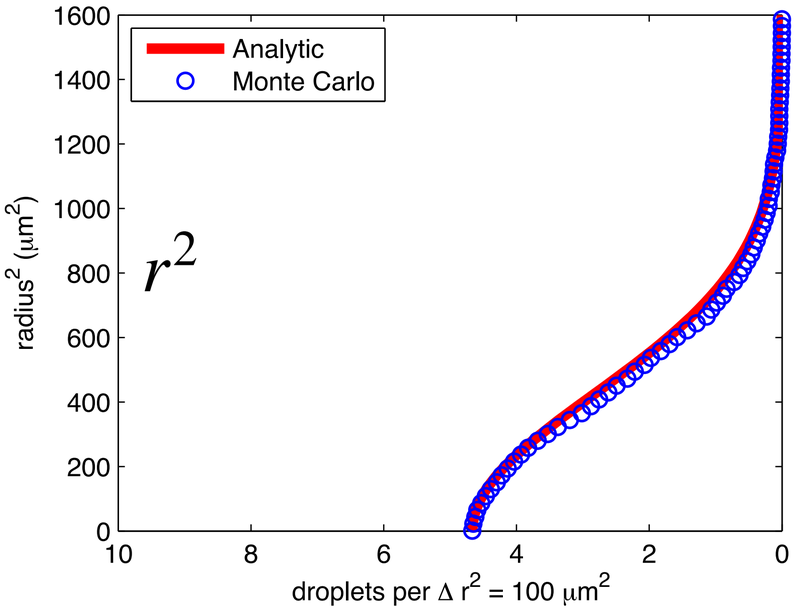


DNS data from Theodore MacMillan and David Richter

Droplet life cycles in *uniform* supersaturation: A Monte Carlo model

1. **Droplets are injected at a constant rate.**
2. **Droplets grow due to *uniform* supersaturation:** $dr^2/dt = As$
3. **Due to turbulence, droplet locations are random, so fall out is stochastic.**





Broad DSDs occur in *entraining* ascending parcels and in convection-cloud chambers

- Both have wide DSDs due to variable droplet saturation histories.
- The droplet saturation histories in both exhibit variability in supersaturation itself and in droplet growth times.

Overall summary

- **Adiabatic parcels** and **convection-cloud chambers** have similar scalings:
  - *Supersaturation forcing*: Vertical velocity (w) corresponds to ΔT.
  - *Mean radius:* Height above cloud base (Δz) corresponds to ΔT.
  - *Supersaturation and radius* both decrease as N increases in both.
  - *LWC* depends only on Δz in a parcel, but on ΔT and N in chambers.
- **Entraining parcels** and **convection-cloud chambers** both have wide DSDs due to variable droplet saturation histories.
- **Wide DSDs** are more favorable for collision-coalescence growth.