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

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Artwork by Michele De Matthaeis

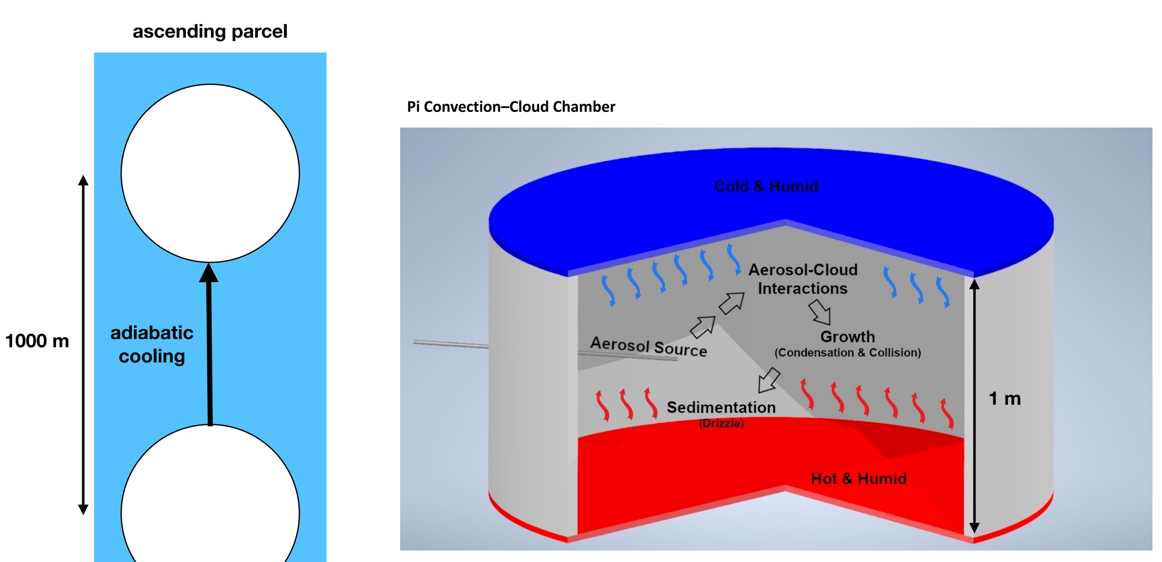
Abstract

It is natural to inquire how clouds in a laboratory convection cloud chamber (“clouds in a box”) are related to clouds in the atmosphere (“clouds in the sky”). In what follows, we describe the basic scalings that govern how cloud droplets grow in an adiabatic ascending parcel and in a convection cloud chamber.

Clouds in the atmosphere are most often a result of adiabatic cooling of ascending air. A convection-cloud chamber produces a cloud by mixing warm saturated air with cool saturated air. Mixing is due to convection and turbulence.

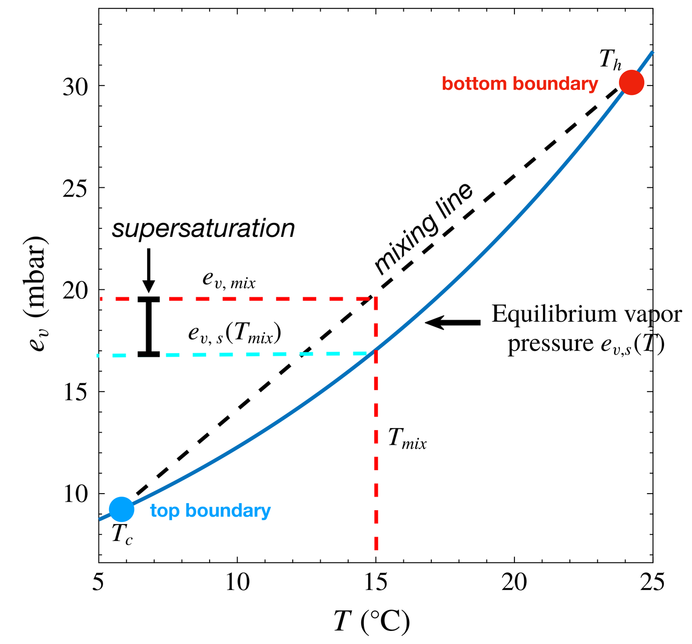
In a convection-cloud chamber, such as the Pi Chamber at MTU, aerosols are continuously injected. The aerosols grow into cloud droplets which eventually fall out by sedimentation. Because the droplet fall speeds are small compared to the turbulent flow speeds, the droplets mostly “go with the flow”. As a droplet grows its fall speed increases with the square of the droplet radius (Stokes' drag law). Consequently, the droplet is increasingly likely to fall out as it grows.

The rate of aerosol injection is eventually balanced by the rate of droplet fallout. In addition, the loss of liquid water by fallout is balanced by condensation, and the condensation is balanced by evaporation from the walls. The result is a thermodynamic state and droplet size distribution in equilibrium.

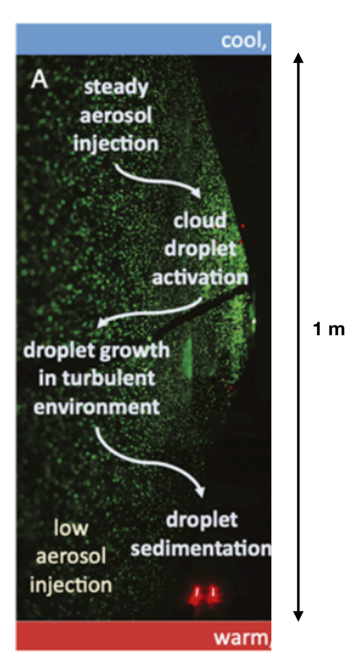


Cloudy Rayleigh-Benard convection produces a mixed layer.

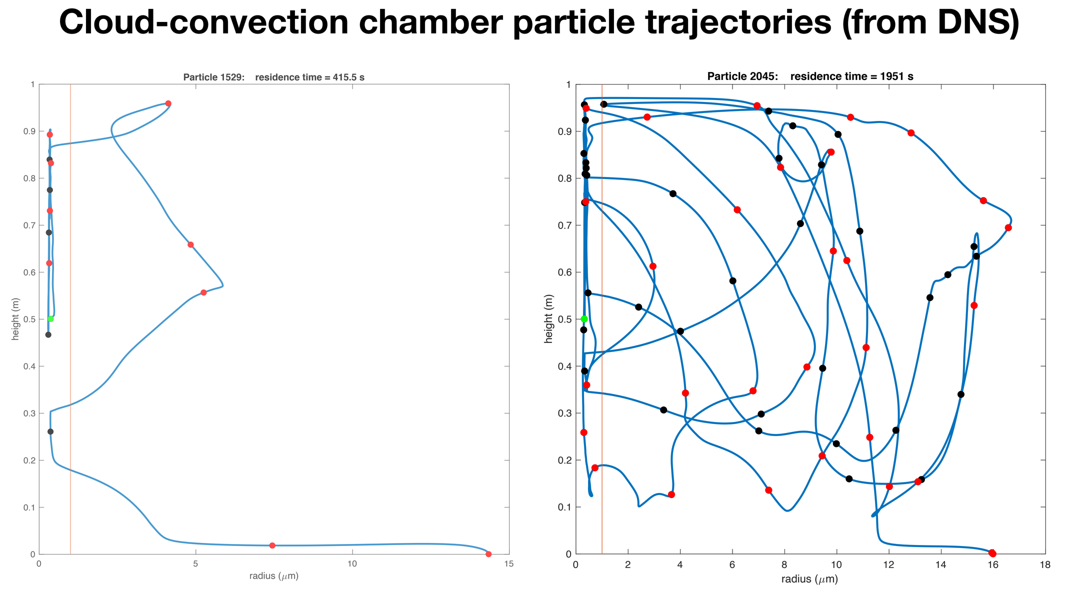
Supersaturation due to mixing



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

- Mean supersaturation, $\bar{s}$, and droplet growth time, τ, combine to produce the radius, $r(\tau)$, of an individual droplet:

$$\frac{dr^2}{dt} = 2\xi_1 s \quad \text{(integrate over time)} \longrightarrow$$

$$r^2(\tau) = r^2(0) + 2\xi_1 \int_0^\tau s\, dt$$

- In an ascending parcel, $\bar{s} \sim w/(N\bar{r})$, where N is droplet number concentration (Korelev & Mazin 2003).
- At height z above cloud base, $\tau = z/w$, so
- $r^2(z) \sim \bar{s}\,\tau \sim z/(N\bar{r})$,
- $r^3(z) \sim z/N$ so LWC $\sim Nr^3 \sim z$.

Droplet Growth in a Convection Cloud Chamber

- 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.
  - $\overline{\tau} = \dfrac{h}{k_1\overline{r^2}} \to \dfrac{\overline{\tau}}{h} = \dfrac{1}{k_1\overline{r^2}}$ (Krueger 2020).
  - $\overline{r^2} \sim \bar{s}\,\overline{\tau} \sim \dfrac{(\Delta T^2/N)^{4/5}}{\overline{r^2}}$. 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

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

convection-cloud chamber

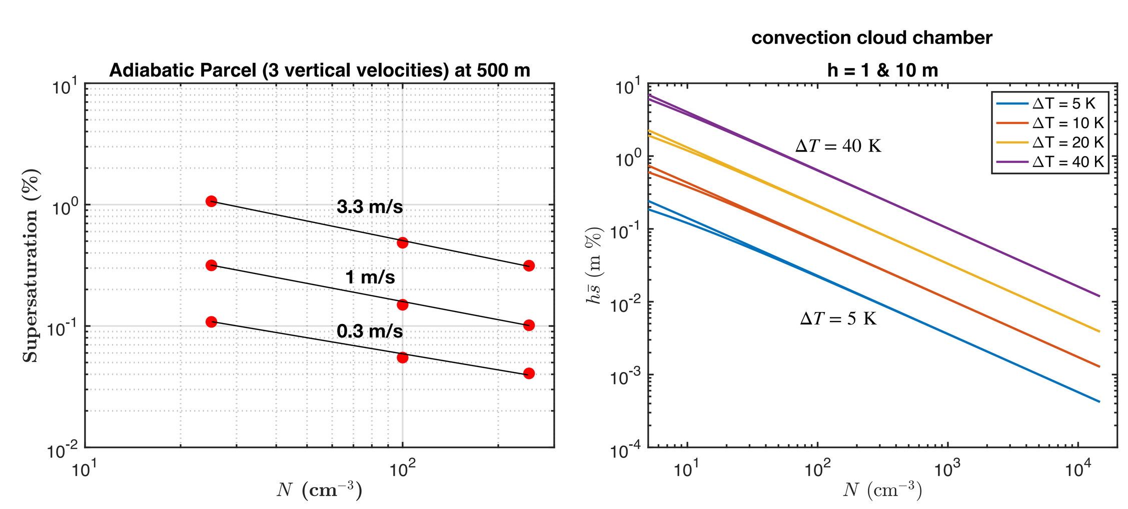
$$\frac{ds}{dt} = \frac{1}{\tau_t}(s_0 - s) - \frac{s}{\tau_c},$$

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

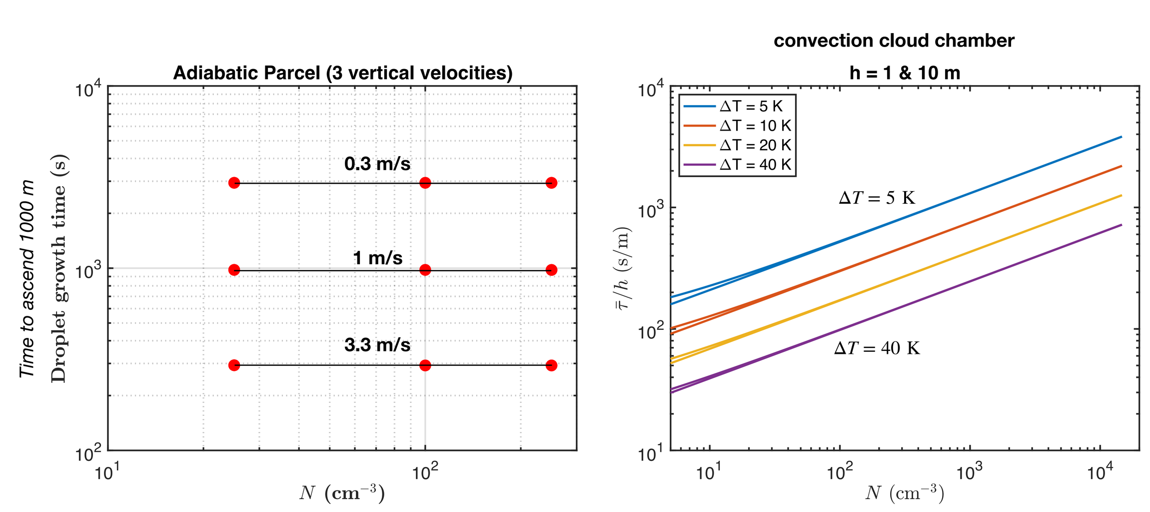
$$\tau_c = (4\pi D' n r)^{-1},$$

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

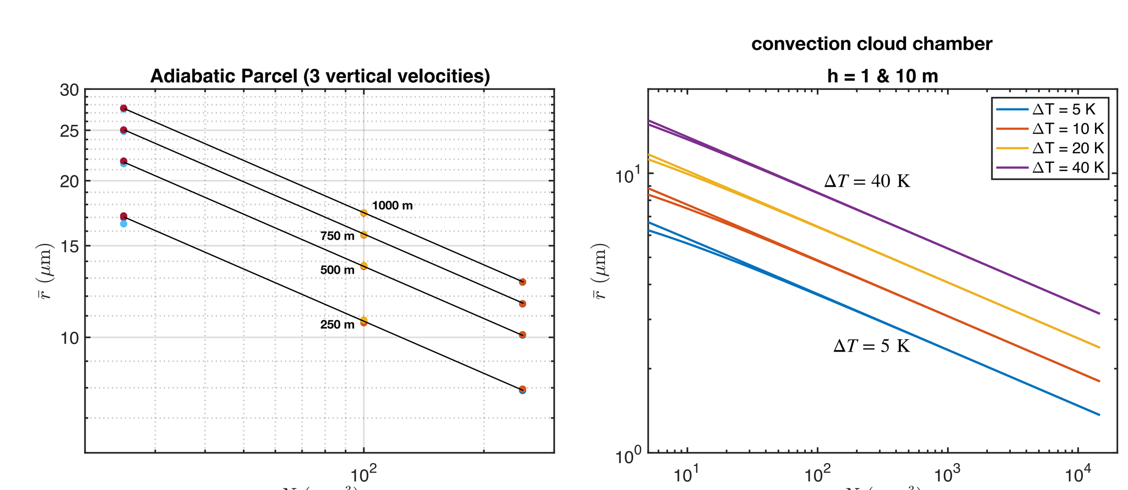
(Quasi-static) Supersaturation



Growth Time

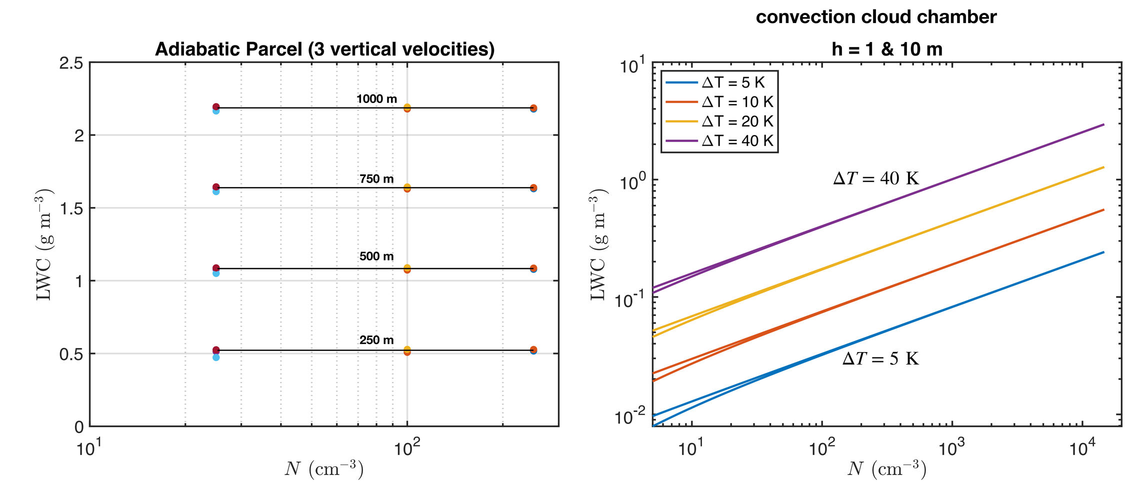


Mean Radius



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.

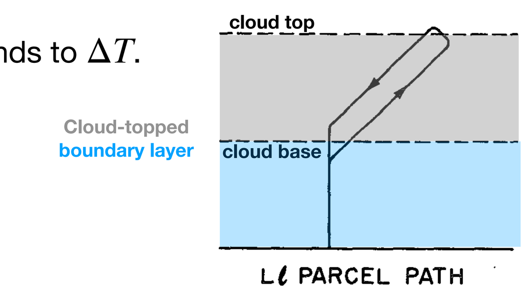
Liquid Water Content



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.

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.



Schubert et al. 1979

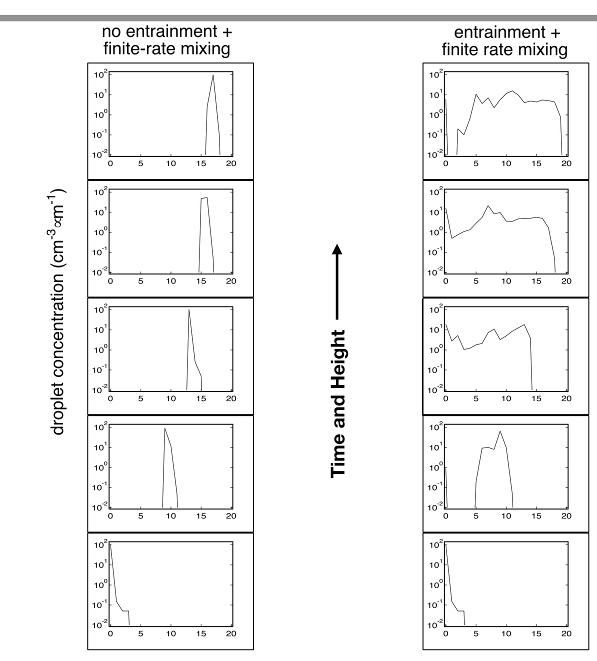
Dependencies on droplet number concentration

- ***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.
- **With entrainment:**
  - Supersaturation varies among droplets due to entrainment and mixing, so DSD is broad.
  - Entrained CCN may be activated.

(Su et al 1998)



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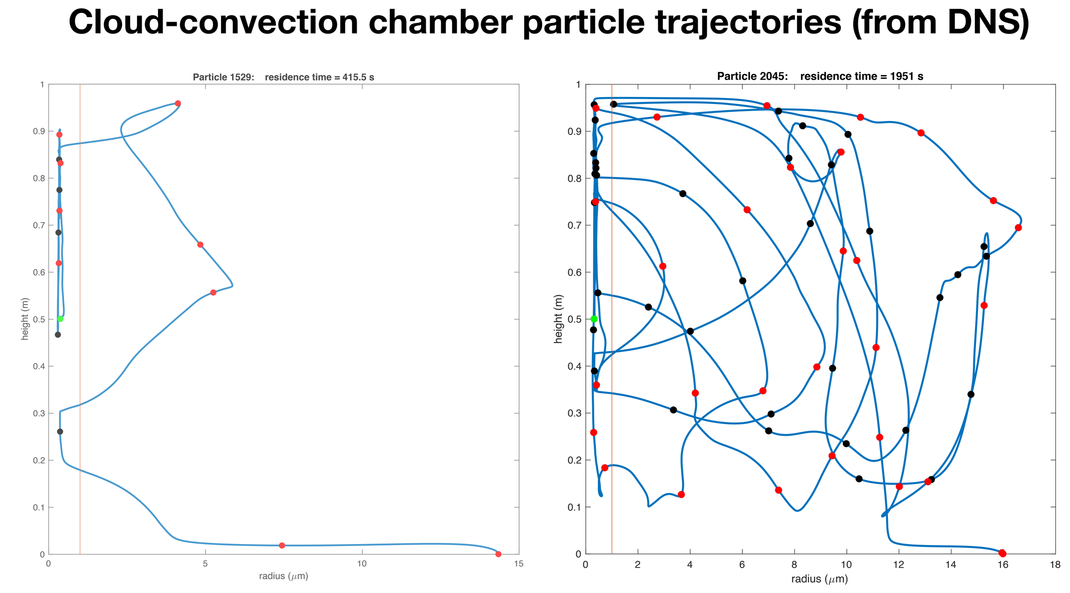
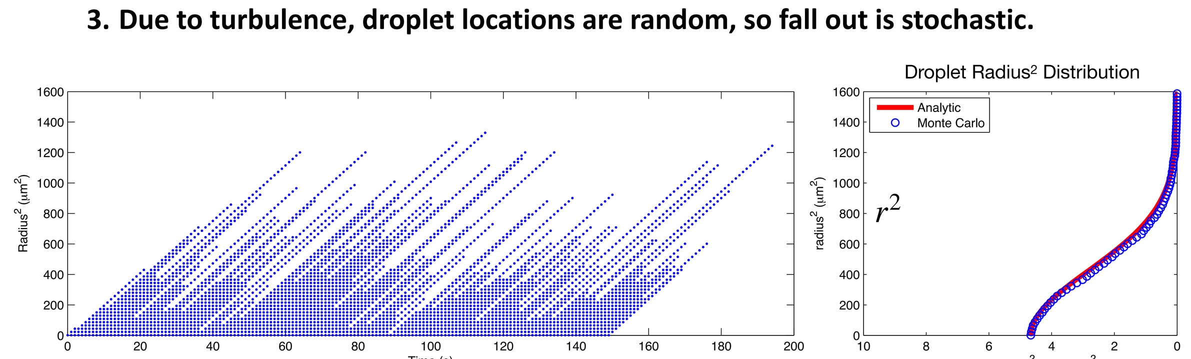


DNS data from Theodore MacMillan and David Richter

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.**

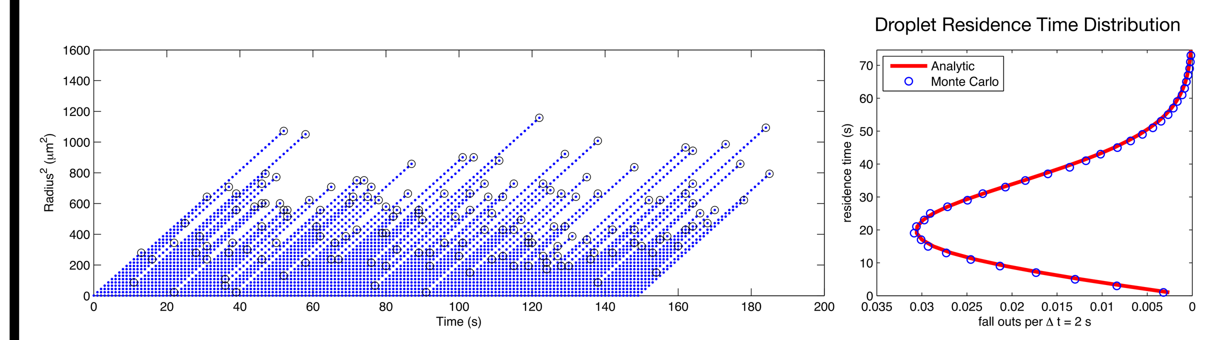


(Krueger 2020)

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

4. **Fallout is stochastic because droplets are well-mixed due to turbulence.**

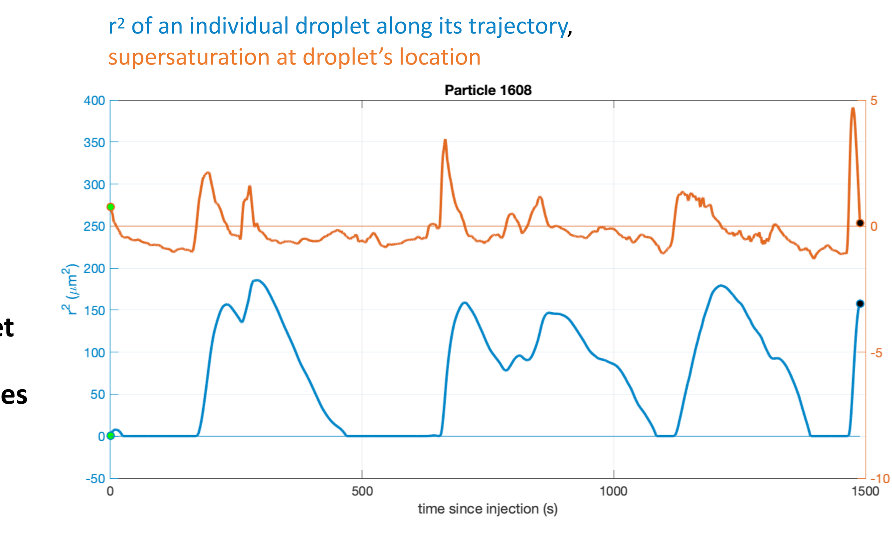
Larger droplets have a greater probability of fallout per unit time due to their greater fall speeds.



(Krueger 2020)

Droplet history from a direct numerical simulation*

When the supersaturation is *fluctuating*, a droplet may grow and evaporate many times before falling out.

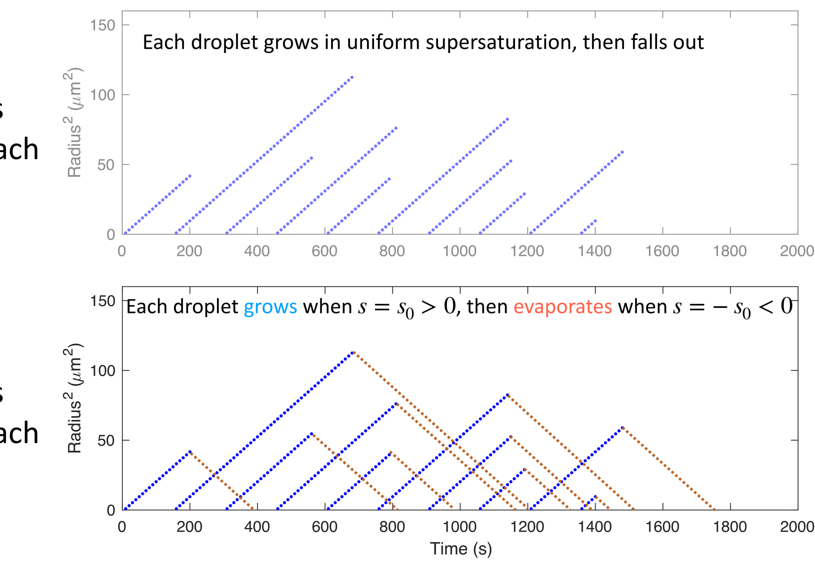


* Theodore MacMillan/ David Richter (University of Notre Dame)

Similar droplet radius PDFs can be achieved by uniform or fluctuating supersaturation

A **positive** mean supersaturation is experienced by each droplet.

A **zero** mean supersaturation is experienced by each droplet.



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.

References

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Acknowledgements

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