How do the vertical distributions of aerosol sizes and concentrations affect the cloud life-cycle?

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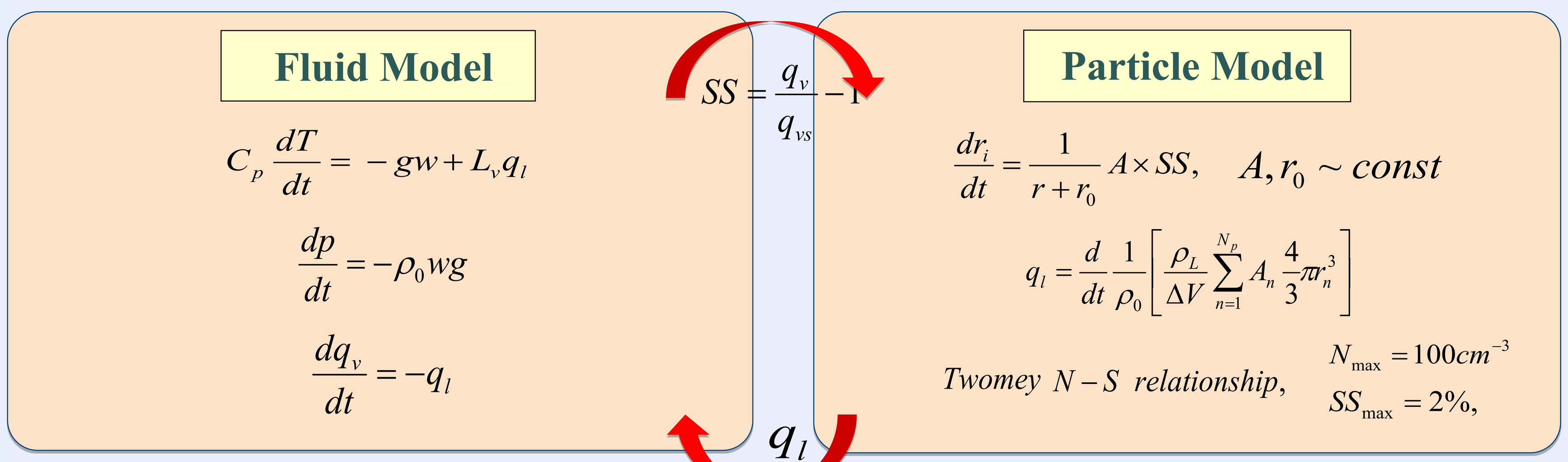
1. Introduction

- The motivation is to use the Lagrangian methodology from the most straightforward framework called Adiabatic Parcel (AP) to Large Eddy Simulations (LES) to investigate the effects of aerosol particles on the cloud life-cycle.
- We apply various size distributions and vertical concentrations of aerosol, which play a significant role in cloud evolution.
- Also, both models include the Eddy hopping mechanism. The idea is each droplet within a turbulent flow has a different history that results in the broadening of spectra.

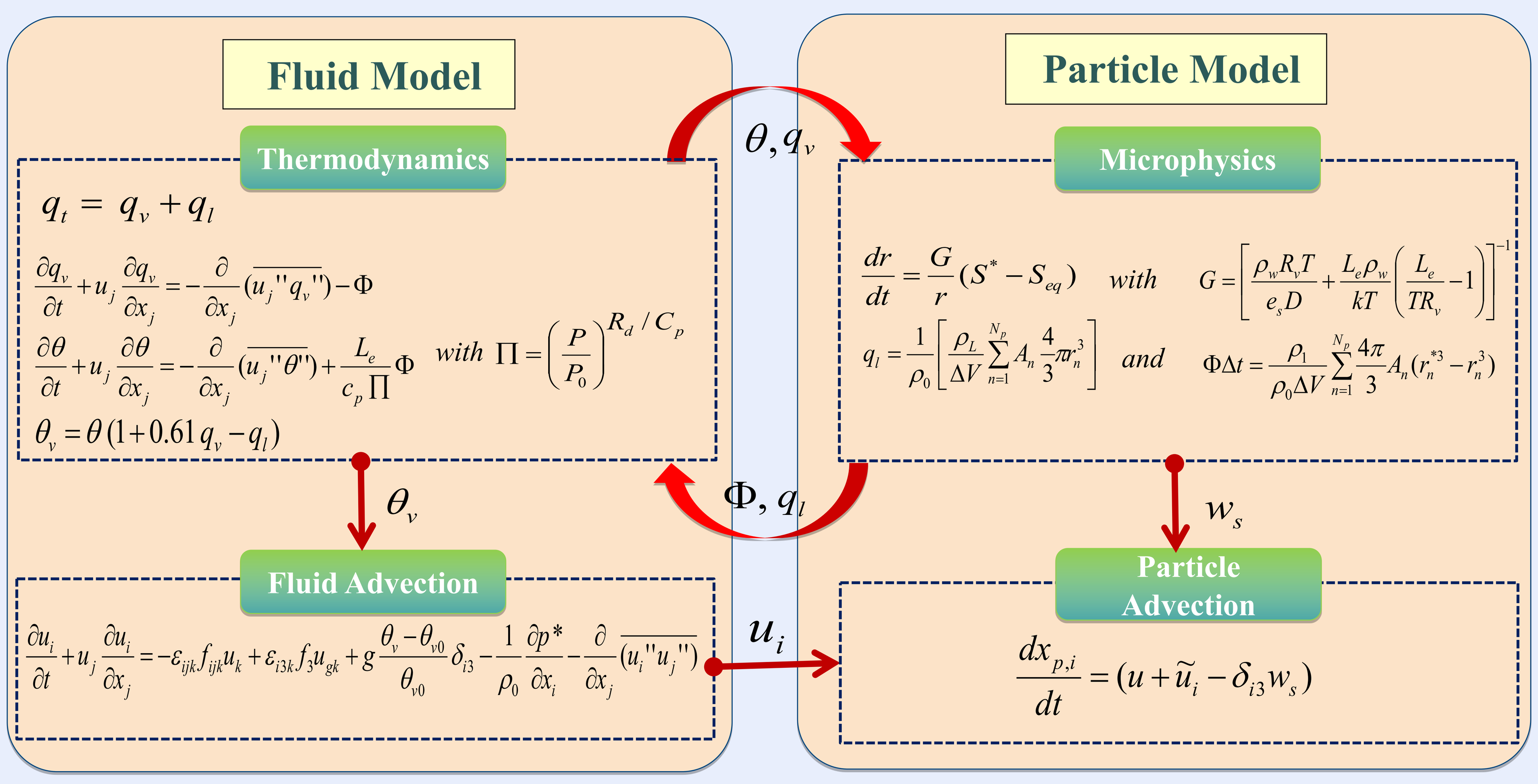
2. Lagrangian methodology

2.1 Adiabatic Parcel model (AP)



See more in detail in Grabowski and Abade (2017)

2.2 Coupled with Large Eddy Simulation (LCM-LES)



See more in detail in Hoffmann et al. (2017)

Fig. 1: A mathematical representation of the AP model (upper) and the LCM-LES (lower). Both use a two-way coupling of the fluid model to the Lagrangian particle model.

2.3 Eddy hopping mechanism (EH)

$$\frac{dSS_i'}{dt} = c_1 w_i' - \frac{SS_i'}{\tau_{relax}},$$

$$\tau_{relax} = (c_2 \sum_i^N r_i N_i)^{-1}, \quad c1, c2 \sim const$$

$$w_i'(t) = w_i'(t-\Delta t)e^{-\Delta t/\tau} + \sqrt{\frac{2}{3}(1-e^{-2\Delta t/\tau})}E\varphi$$

AP model

$\tau \sim f(L, TKE^{1/2})$ $\quad TKE \sim f(L^{2/3}, \varepsilon^{2/3})$

LCM-LES

$\tau \sim k_m / TKE$ $\quad w_i$: Stochastic velocity obtained from Monte Carlo process

3. Model setup

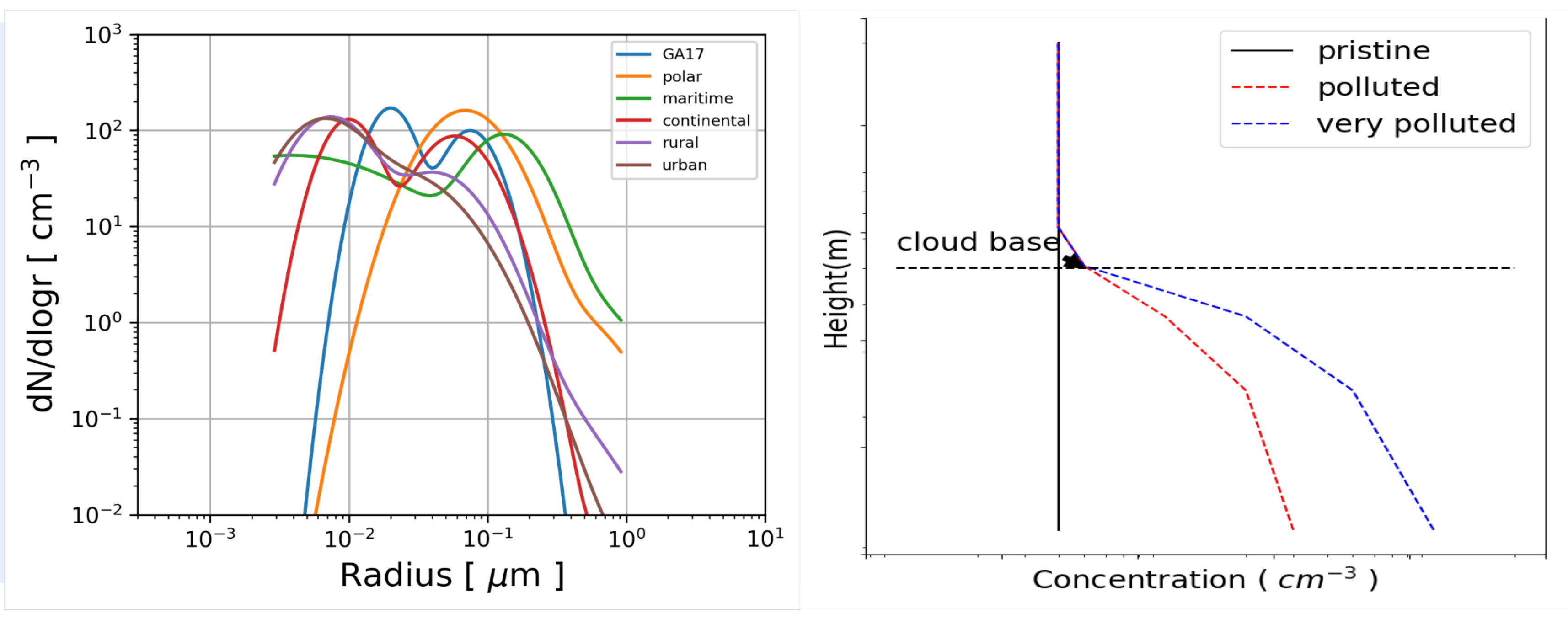


Fig. 2: Characteristics of the size distribution (Left) over various regions, and different scenarios of the vertical profiles of aerosol concentration with height (Right).

4. Results

The AP results

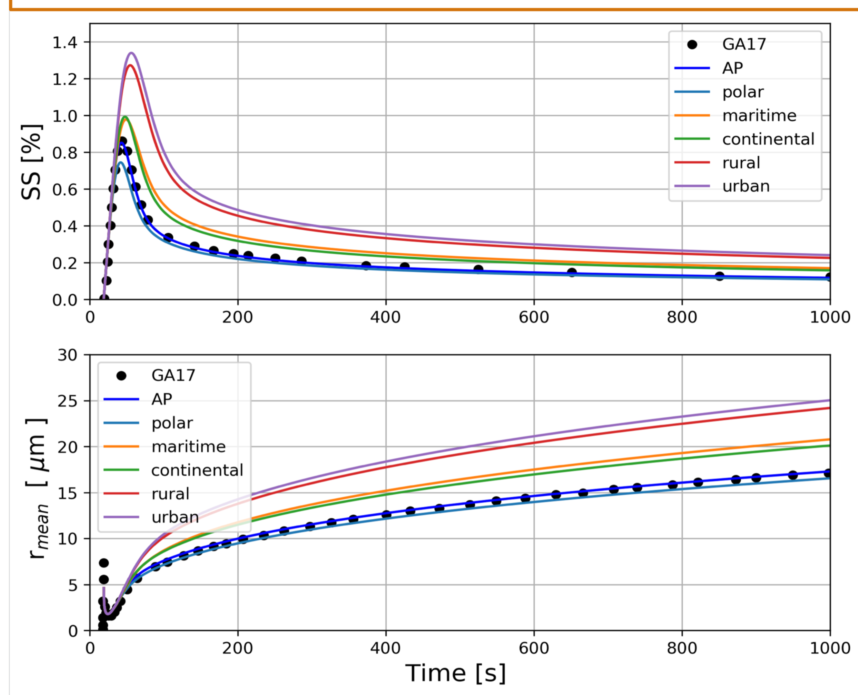


Fig. 3: Evolutions of averaged supersaturation (SS) and mean radius of activated droplets(r_{mean})

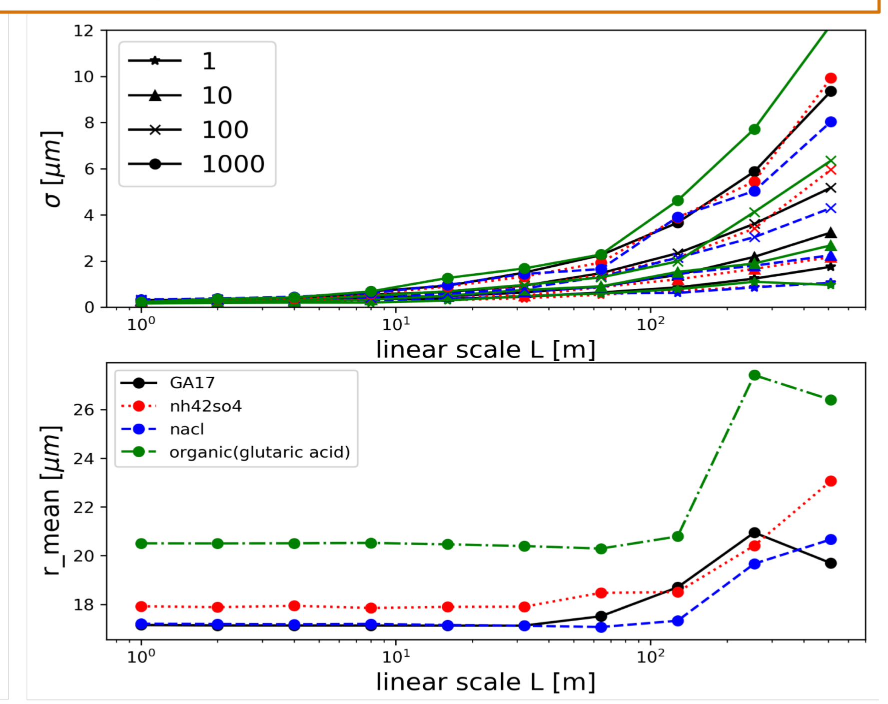


Fig. 4: Standard deviation (σ) of activated droplets as a function of parcel length scale L at the end of the simulation (t=1000s). The symbols represent different dissipation rates (cm^2s^{-3}), and chemical compositions are shown with different colors.

- **Left:** In the AP model, the aerosol distribution affects the mean radius (r_{mean}) and supersaturation (SS) of activated droplets, but it does not effect the widths of the spectra.
- **Right:** Eddy hopping mechanism is applied to the AP. The increase of TKE dissipation rate leads to the larger spectral width of the activated cloud droplets.

The LCM-LES results with Eddy hopping (EH)

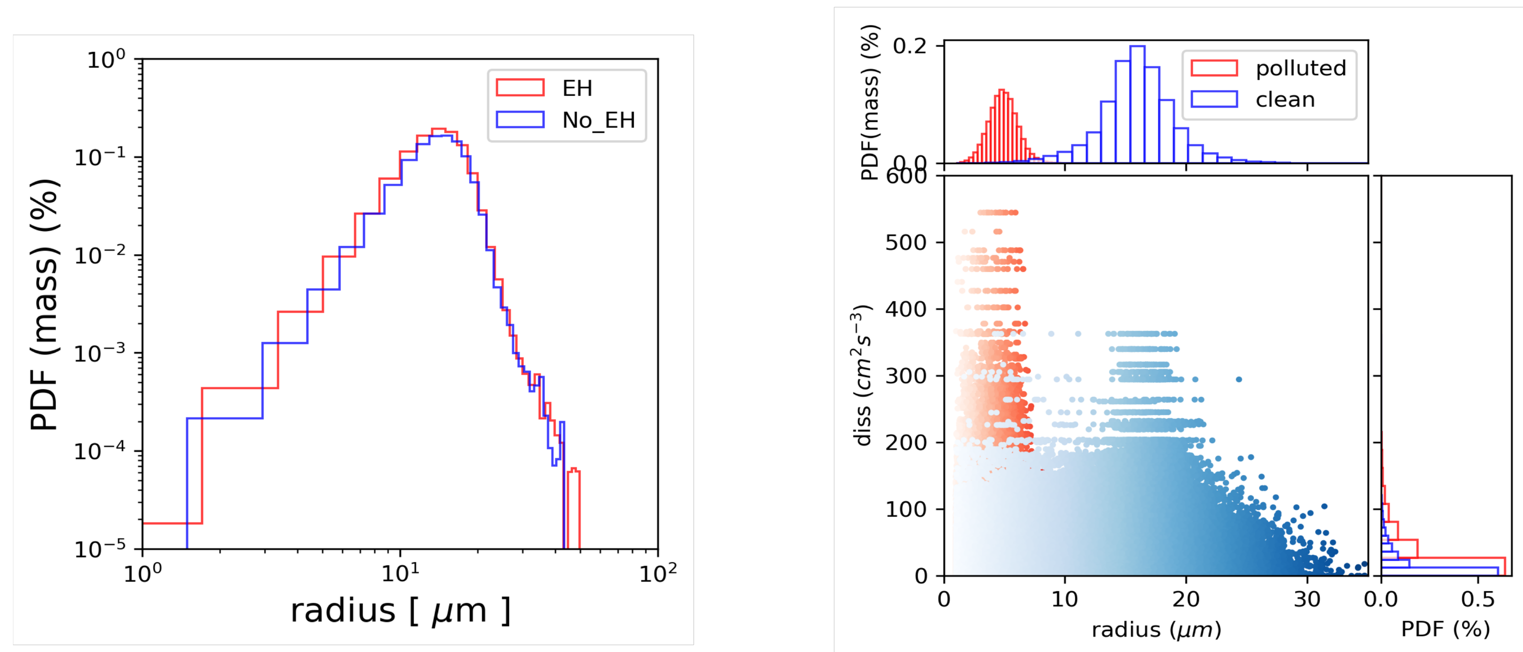


Fig. 5: PDFs of radius with/without Eddy hopping (Left) and scatter plot of dissipation rate as a function of radius(Right) at time = 20min after releasing a bubble.

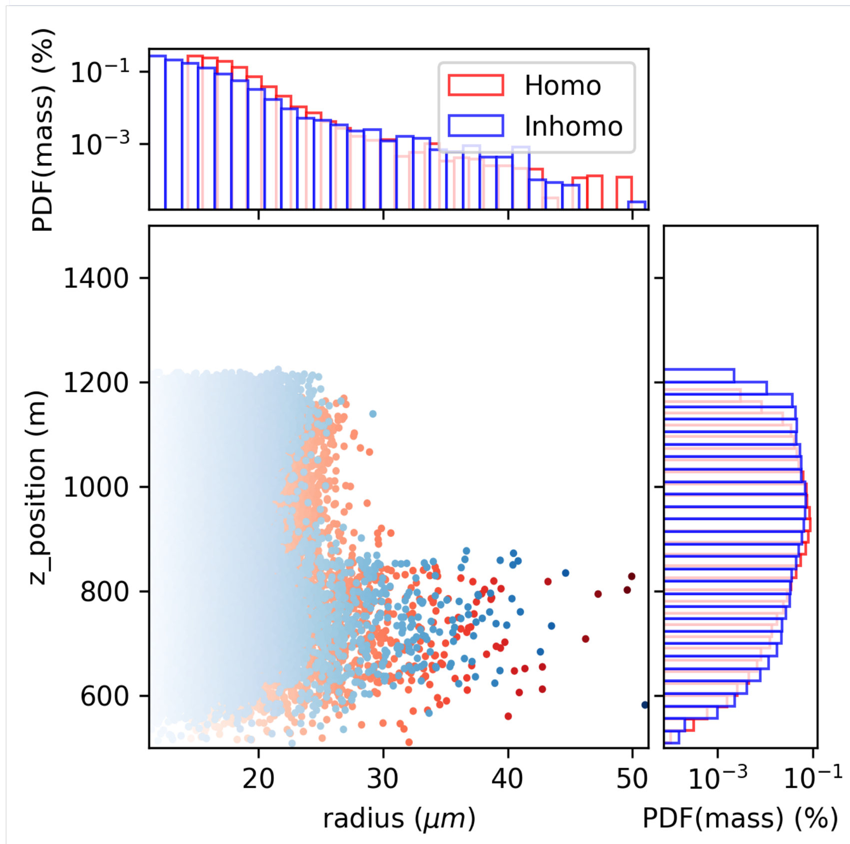


Fig. 5: Spectral broadening happens at the cloud edges with the help of the EH mechanism, although broadening is not significant in a shallow cloud. Also, the case of homogeneously distributed aerosols shows high number concentration delays the development of cloud life-cycle so that it inhibits precipitation embryos in shallow clouds.

Fig. 6: When anthropogenic aerosol particles are released from the surface as a source of polluted emission, they enrich the layer below the cloud base that results in more activated droplets of smaller radii at the cloud base while the largest droplet still grows. By doing so, giant CCN can collect increase the change of collision. Insoluble aerosols also are included and affect broadening spectra significantly.

Fig. 6: Superdroplets distribution with height and PDFs of droplet mass for a homogeneous (red) and inhomogeneous (blue) distribution case. Collected droplets represent the top 20th percentile in size.

5. Conclusions

1. Different CCN characteristics such as size distributions, number concentration, and chemical compositions lead to a different mean radius, but they do not affect the spectral width of activated droplets.
2. With the help of an Eddy hopping mechanism, a spectral broadening of cloud droplets is shown as TKE dissipation rate increases.
3. The broadening of droplet spectra plays an initial role in the effective collision-coalescence process.
4. The Eddy hopping mechanism was also incorporated in the LCM-LES framework and tested in shallow cloud cases.
5. In the case of homogeneously distributed aerosols at the beginning, high number concentrations which delay the development at the early stage of the cloud life-cycle.
6. The change of vertical profiles leads to a more significant number of smaller radii at the cloud base. Giant CCNs as the collector can increase the chance of collision. It may play a different role in cloud life-cycle between the deep and shallow cloud case.

6. References

Grabowski, W. W., & Abade, G. C. (2017). Broadening of Cloud Droplet Spectra through Eddy Hopping: Turbulent Adiabatic Parcel Simulations. *Journal of the Atmospheric Sciences*, 74(5), 1485–1493.

Hoffmann, F., Noh, Y., & Raasch, S. (2017). The Route to Raindrop Formation in a Shallow Cumulus Cloud Simulated by a Lagrangian Cloud Model. *Journal of the Atmospheric Sciences*, JAS-D-16-0220.1.