The Route to Raindrop Formation in a Shallow Cumulus Cloud Simulated by a Lagrangian Cloud Model

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(Hoffmann, Noh & Raasch, *JAS* 2017)

Cloud microphysics is characterized by a particle-laden flow.

However, its simulation is still dominated by Eulerian models such as the spectral bin model, unlike in fluid dynamics community.

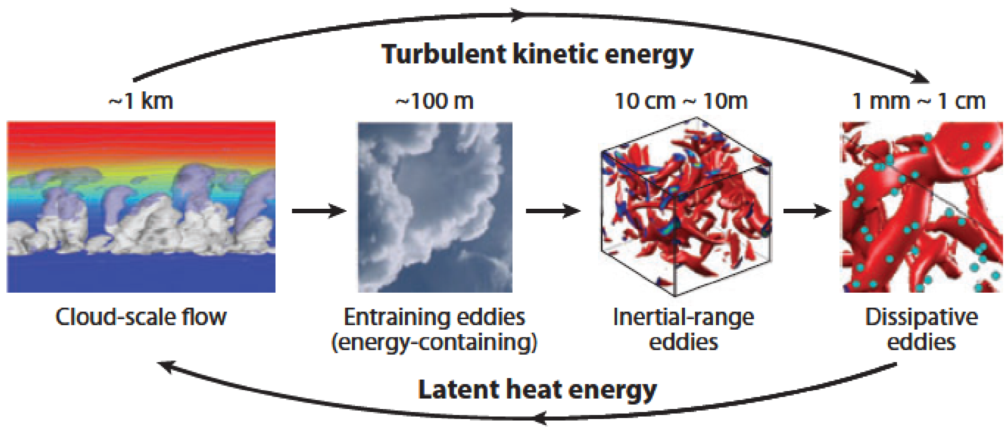


Figure 1

Multiscale interactions in atmospheric clouds. The turbulent kinetic energy flows from cloud-scale motion to dissipative eddies. Latent heat energy flows from individual droplets to cloud-scale motion.

If the Lagrangian motion of cloud droplets is calculated directly,

- Diffusion and settling of droplets can be calculated directly.
- Activation and condensational growth are calculated naturally following droplets.
- Conversion from cloud water to rain ('autoconversion') and sweeping of cloud water by rain water ('accretion') are realized naturally.
- Time history of each droplet can be obtained.
- Direct interaction between droplets and turbulence

However, the Lagrangian LES cloud model must resolve the following problems.

1. How to deal with an extremely large number of droplets ?

- LWC must to be calculated by Largrangian droplets.

2. How to deal with droplet collision?

- LES cannot simulate droplet collision directly unlike DNS.

How to deal with an extremely large number of droplets ?

$$M_n = A_n \cdot \frac{4}{3}\pi\rho_1 r_n^3$$

$$q_l = \frac{1}{\rho_0 \Delta V}\sum_{n=1}^{N_P} M_n$$

A_n = weighting factor

$$= \frac{\text{mass of real droplets per unit volume}}{\text{mass of simulated droplet per unit volume}}$$

- A weighting factor (An) differs for each super-droplet, and change with time as a result of collision/coalescence

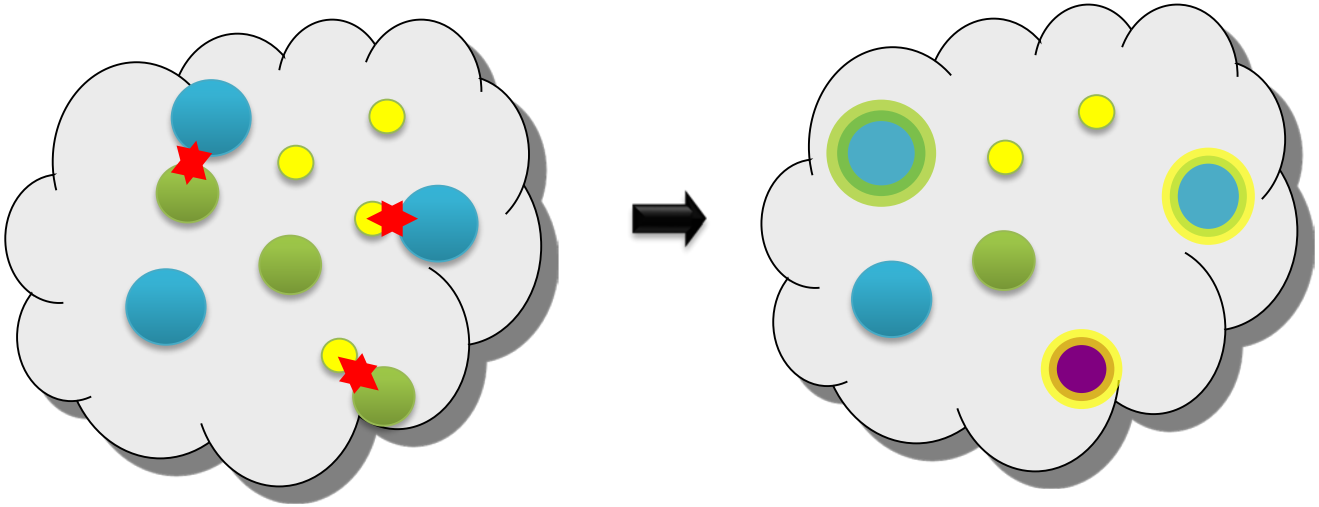
Collision/Coalescence Process

Basic Concepts

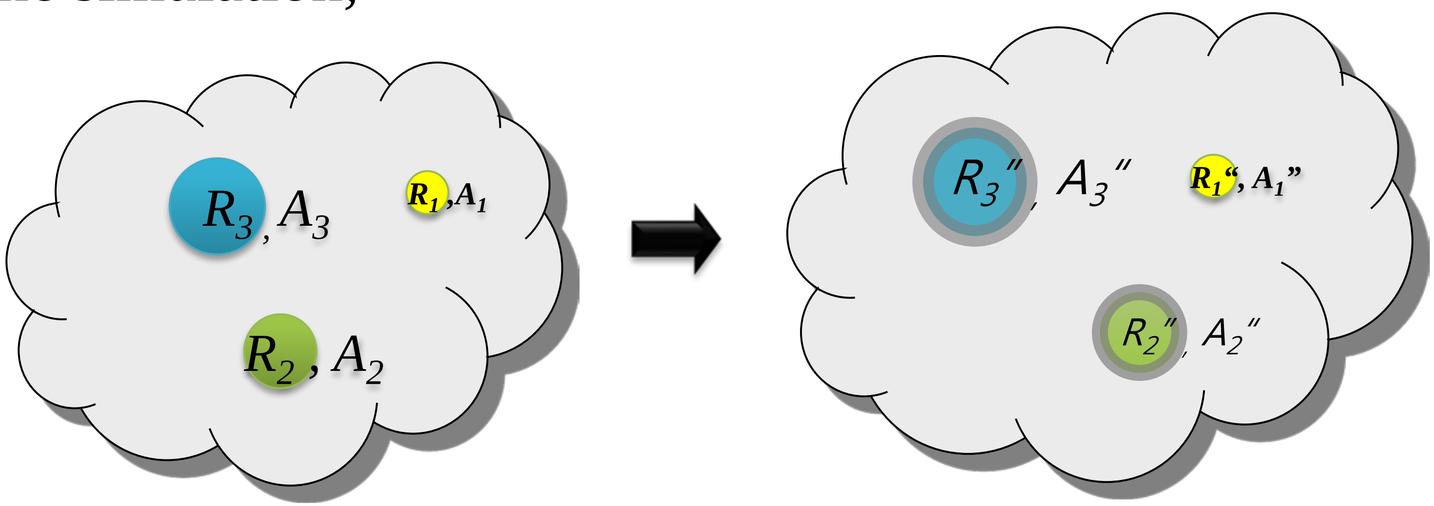
- A statistical approach is taken in which the growth of a super-droplet is calculated based on the background droplet spectrum using the collection kernel, similar to the spectral bin model.

- Collision causes the change of the weighting factor (A_n) and the total mass of each droplet (M_n) , which results in the change of the droplet radius (r_n).

In the real cloud,



In the simulation,



- Particle collision is parameterized in terms of the modification of r_i and A_i.

If two super-droplets collide with $A_m < A_n$, $\rightarrow A_m$, M_m (r_m) - increase
A_n - decrease, r_n - invariant

$$\frac{dA_n}{dt}\delta t = -\frac{1}{2}(A_n - 1)P[K(r_n, r_n)A_n\delta t / \Delta V] - \sum_{m=n+1}^{N_P} A_m P[K(r_m, r_n)A_n\delta t / \Delta V]$$

self-collection

loss of droplets to super-droplets with smaller A_m

$$\frac{dM_n}{dt}\delta t = -\sum_{m=1}^{n-1} A_m \frac{M_n}{A_n} P\left[\frac{K(r_n, r_m)A_n\delta t}{\Delta V}\right] + \sum_{m=n+1}^{N_P} A_n \frac{M_m}{A_m} P\left[\frac{K(r_m, r_n)A_m\delta t}{\Delta V}\right]$$

loss of mass to super-droplets with larger A_m

gain of mass from super-droplets with smaller A_m

P[φ] = the probability that a collection takes place
(If φ > ξ, a collection takes place (P = 1), where ξ is a random number between 0 and 1)
→ **It realizes the stochastic collisional growth.**

cf. stochastic collection equation

$$\left.\frac{\partial n(r)}{\partial t}\right|_{Col} = \frac{1}{2}\int_0^r K(p,q)n(q)n(p)dpdq - n(r)\int_0^\infty K(R,r)n(R)dR$$

ref. Hoffmann et al. (*JAS* 2017)

Structure of Langrangian Cloud Model

(Riechelmann et al., *NJP* 2012, Lee et al., *MAP* 2014, Hoffmann et al. *AR* 2015, *JAS* 2016)

Fluid Motion

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \quad \cdots \quad + g \frac{\theta_v - \theta_{v0}}{\theta_{v0}} \delta_{i3}$$

$$\theta_v = \theta (1 + 0.61 q_v - q_l)$$

SGS Turbulence

$$\frac{\partial e}{\partial t} + u_j \frac{\partial e}{\partial x_j} = \quad \cdots \quad - \varepsilon$$

$$\varepsilon = (0.19 + 0.74 l / \Delta s) e^{3/2} / l$$

Thermodynamics

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = -\frac{\partial}{\partial x_j} (\overline{u_j'' \theta''}) + \frac{L_e}{c_p \prod} \Phi$$

$$\frac{\partial q_v}{\partial t} + u_j \frac{\partial q_v}{\partial x_j} = -\frac{\partial}{\partial x_j} (\overline{u_j'' q_v''}) - \Phi$$

Microphysics

$$q_l = \frac{1}{\rho_0} \left[\frac{\rho_L}{\Delta V} \sum_{n=1}^{N_p} A_n \frac{4}{3} \pi r_n^3 \right]$$

$$\Phi \Delta t = \frac{\rho_1}{\rho_0 \Delta V} \sum_{n=1}^{N_p} \frac{4\pi}{3} A_n (r_n^{*3} - r_n^3)$$

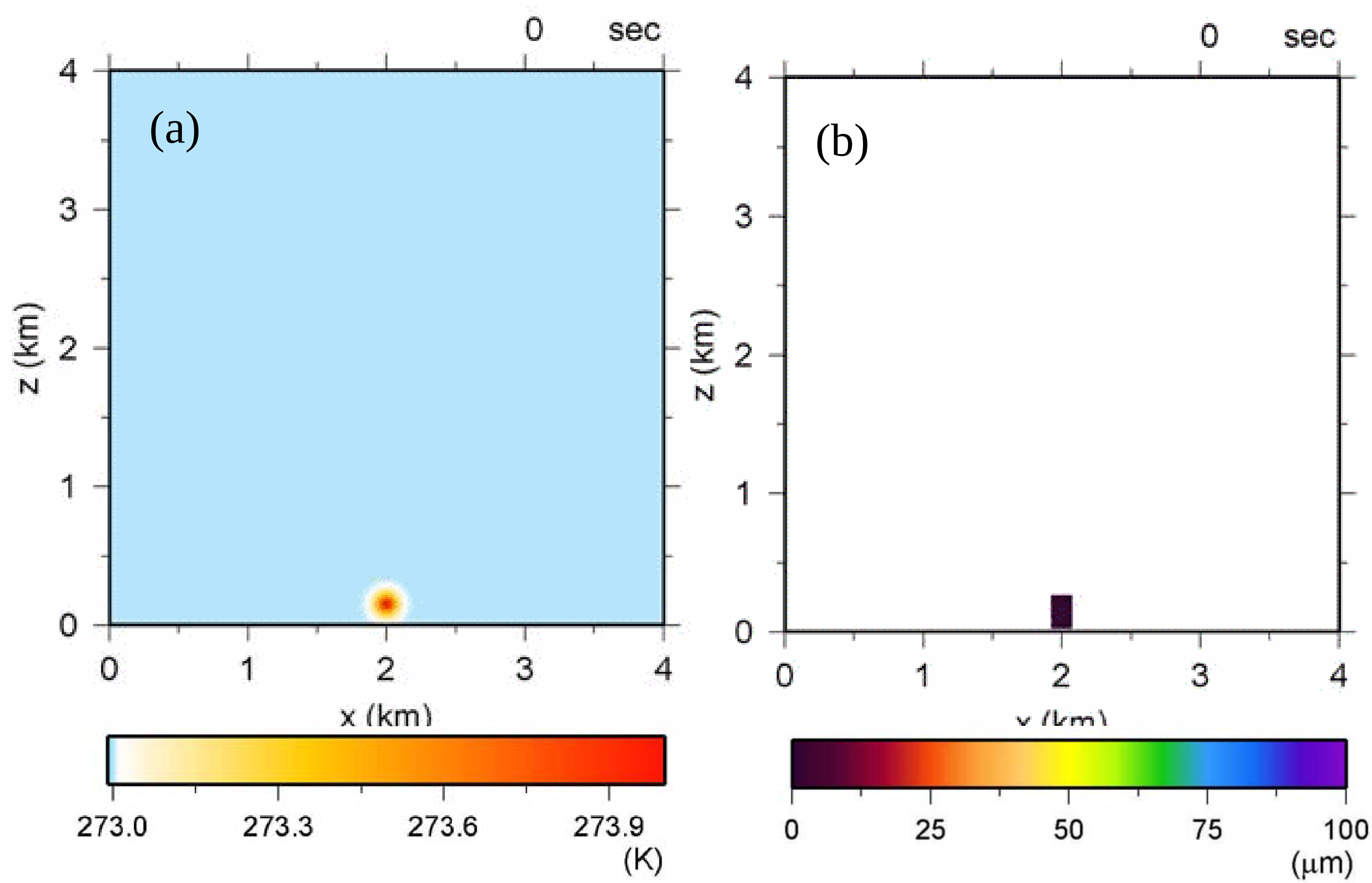
$$r \frac{dr}{dt} = \frac{S - 1}{F_k + F_d}$$

$$\frac{dR}{dt} = f[n(r), \varepsilon] \qquad \frac{dA_r}{dt} = f[n(r), \varepsilon]$$

Particle Motion

$$\frac{dV_i}{dt} = \frac{1}{\tau_p} [u_i (X_i) - V_i - \delta_{i3} w_s]$$

Simulation of an Idealized Single Cloud



Evolutions of (a) potential temperature and (b) droplets position with radius

Questions to Raindrop Formation

It is difficult to explain the rapid growth of cloud droplets in the size range 15 - 40 μm, for which neither the diffusional growth and nor the collisional growth is effective.

$$\rightarrow \quad K(R,r) = \pi (R+r)^2 \left| v(R) - v(r) \right| E(R,r)$$

- Entrainment and mixing broaden the droplet size distribution (DSD) (Baker et al. 1980, Cooper 1989, Lasher-Trapp et al. 2005)

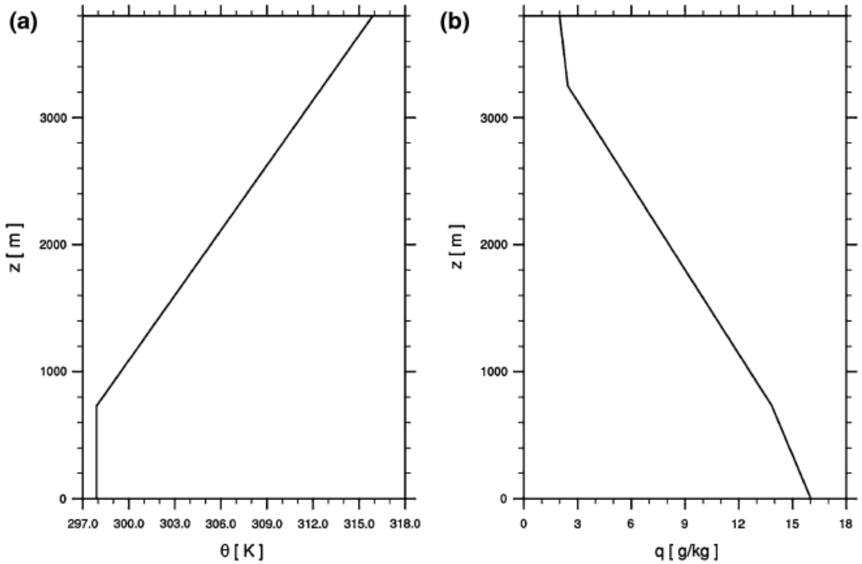
- Enhancement of the collection kernel by turbulence (Pinsky and Khain 2002, Wang and Grabowski 2009)

- Effects of giant aerosol particles (Ochs 1978, Johnson 1982)

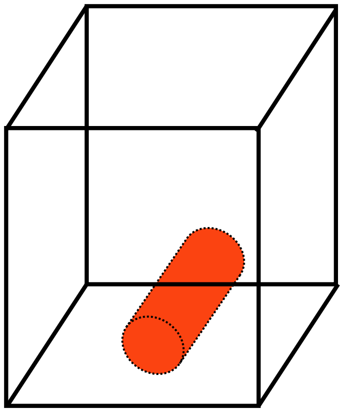
⇨ ***The best way to investigate raindrop formation is how and under which condition cloud droplets grow to raindrops by tracking Lagrangian droplets in LCM!***

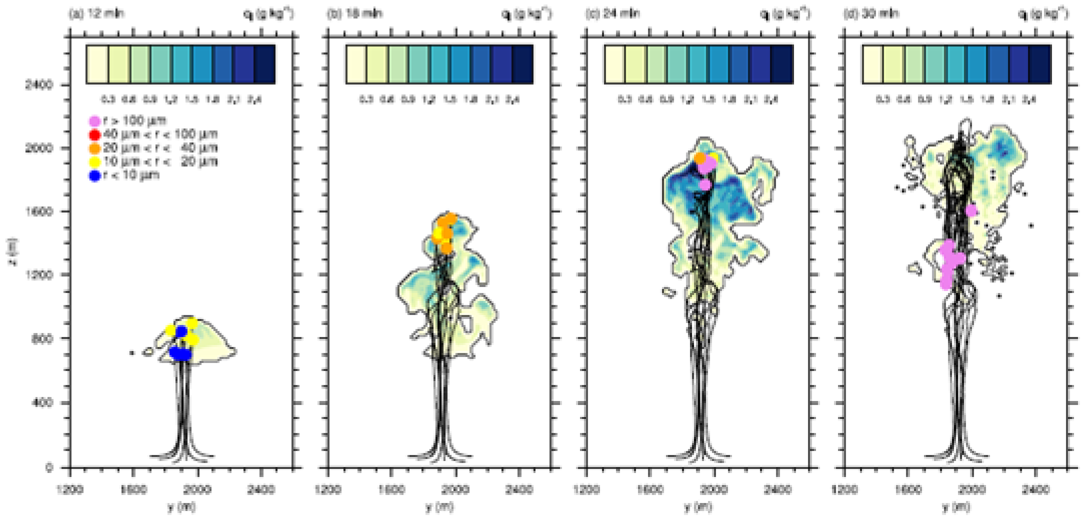
An Idealized Single Cloud Experiment (RICO)

- **MODEL : LES (PALM)**
  - ✓ Domain size : 1.28 km x 3.84 km x 3.84 km
  - ✓ Time step: 0.1 s
  - ✓ Resolution: 20 m
  - ✓ Collision kernel: Hall kernel (GRAV)
    AW kernel (TURB)

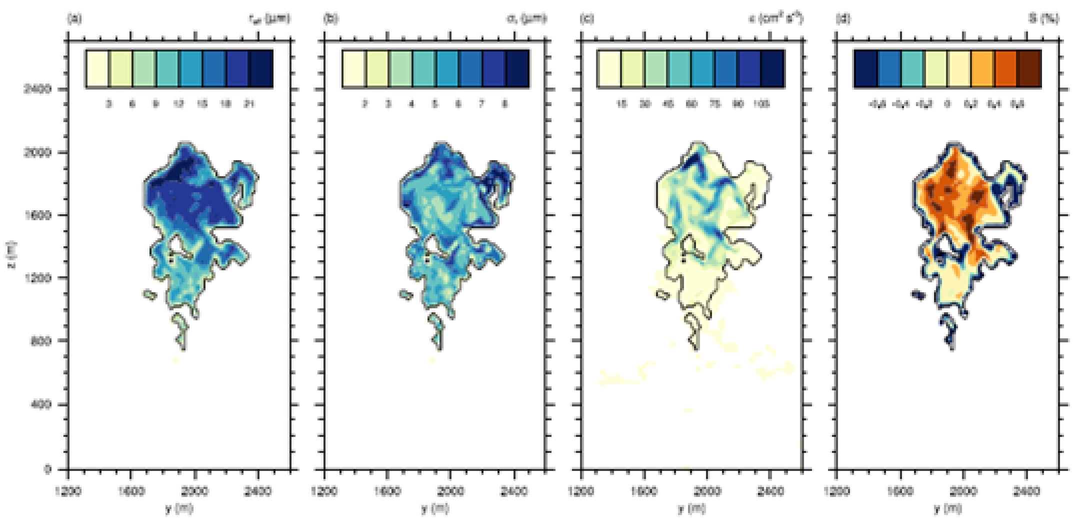


- **Particles information**
  - ✓ Initial particles size: 0.1 µm
  - ✓ Initial weighting factor: $9 \cdot 10^9$
  - ✓ Total number of particles: ~ 3.4×10^8 (~ 200 per grid box)
  - ✓ Particle concentration: 100 cm^{-3}
  - ✓ Bubble size : 1280 m x 150 m x 200 m, $\Delta T = 0.4$ K
  - ✓ Initial CCN concentration: 20, 70, 150 cm^{-3}

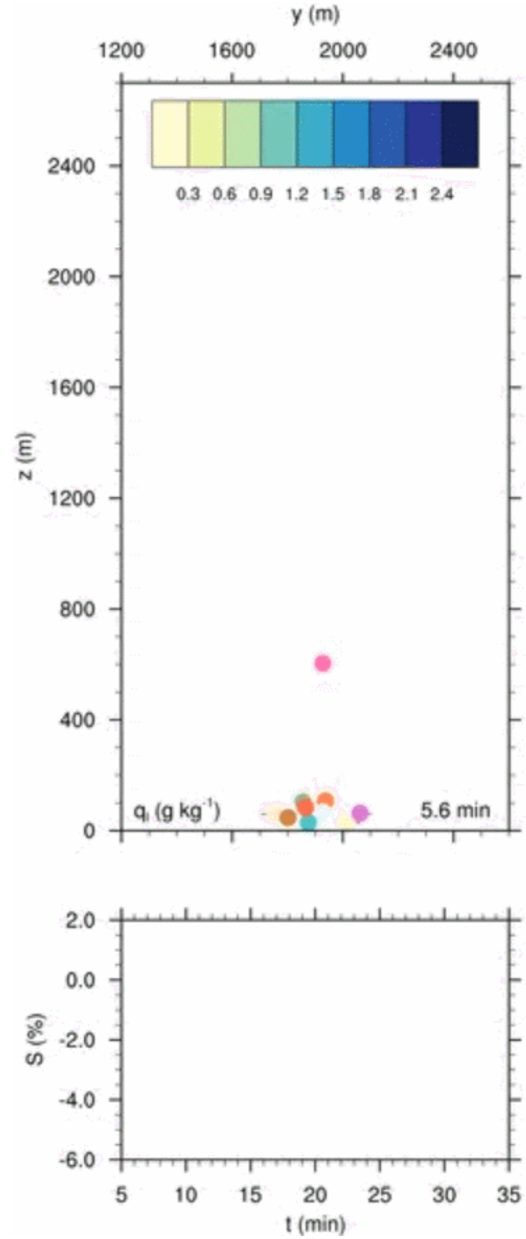




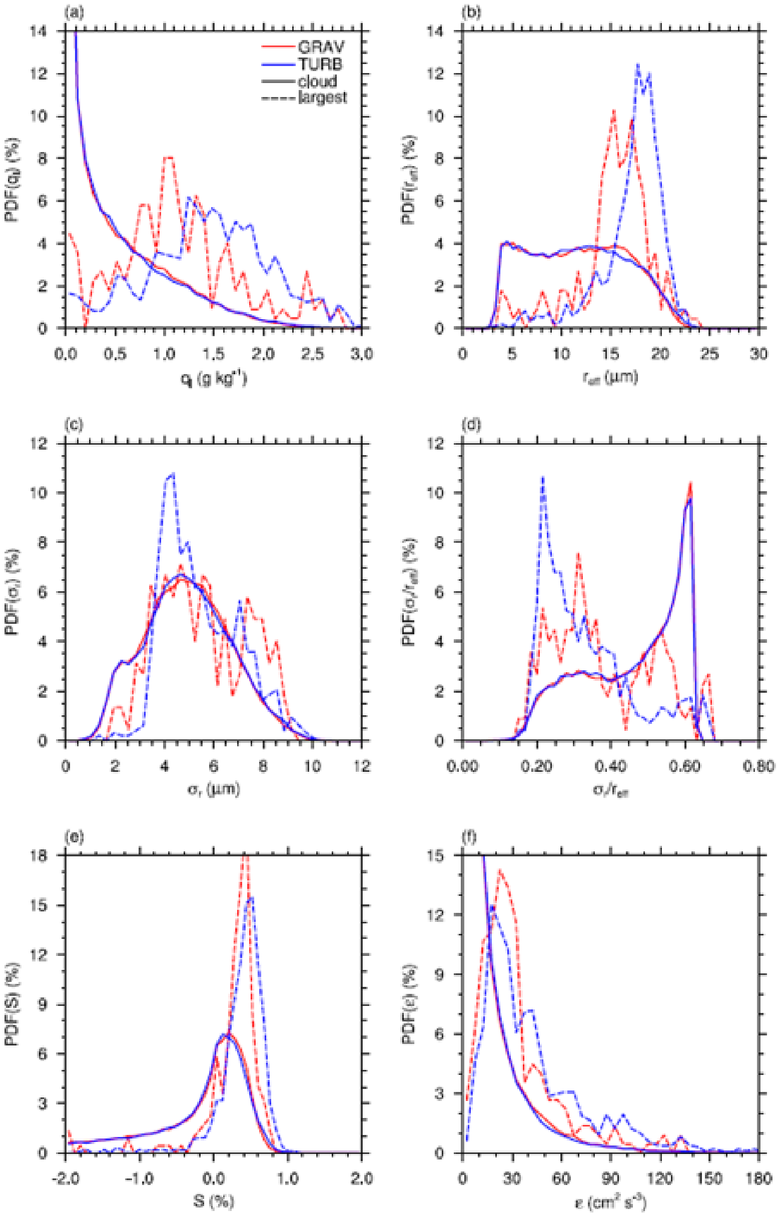
Evolution of q_l with largest droplets



Distributions of r_{eff}, σ_r, ε, and S



Raindrop formation is triggered when droplets with a radius of 20 mm appear in the region near the cloud top, characterized by a large q_l, ε, r_{eff}, σ_r, and S.



Pdf of variables

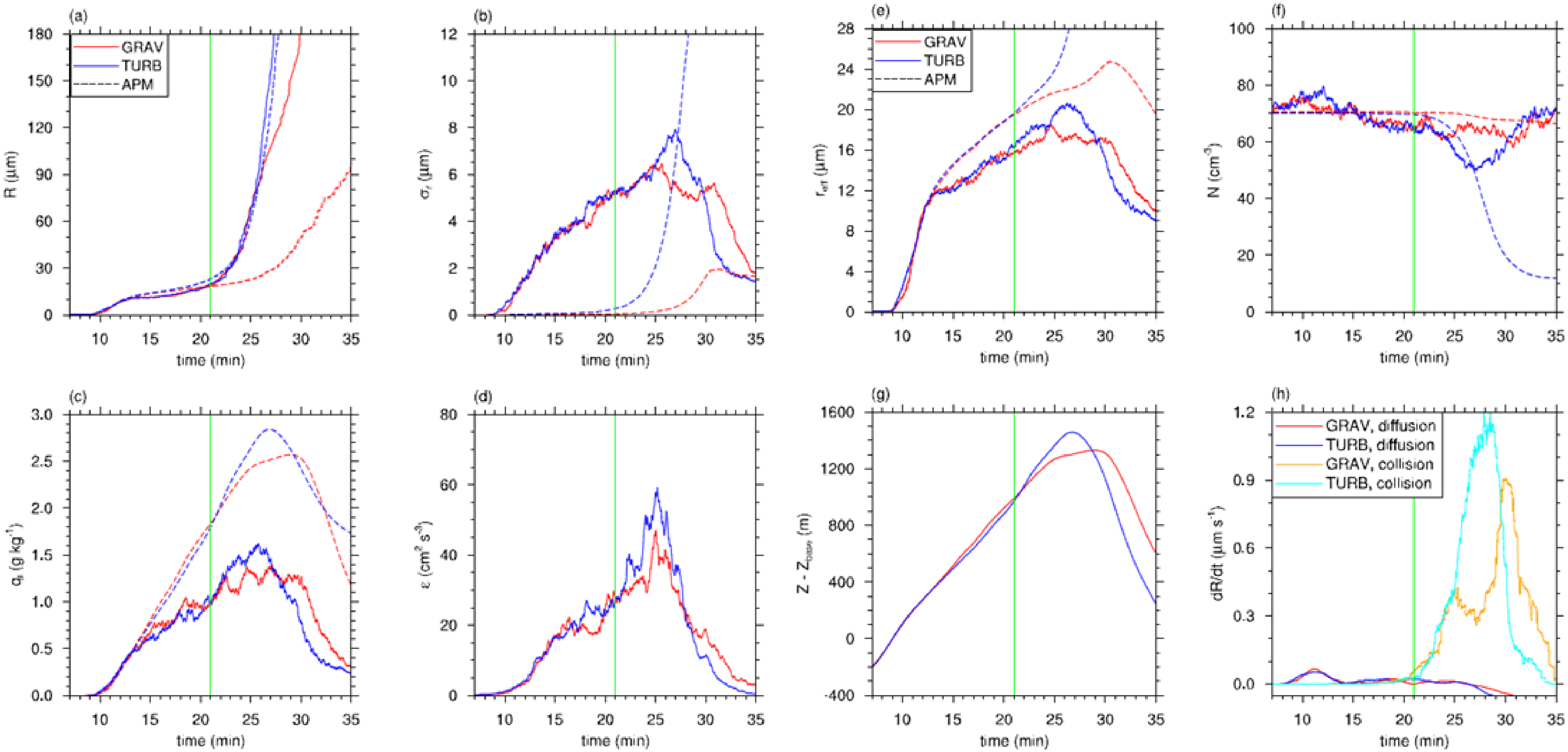
--- : potential raindrops

— : whole cloud

red: GRAV

blue: TURB

- Raindrop is formed in the region of high q_l , r_{eff} , ε, σ_r and S
- TURB – higher q_l , r_{eff} , ε, and S
- GRAV – higher σ_r



Time series following potential raindrops
(--- : adiabatic parcel model (no DSD broadening), — : LCM; red: GRAV, blue: TURB)

- Raindrop formation is triggered, when largest droplets grow to r = 20 μm.
- TURB - Raindrop formation is triggered in time, regardless of DSD broadening
- GRAV – Raindrop formation is severely delayed without DSD broadening
- TURB does not accelerate the timing of raindrop formation, but it enhances the collisional growth rate substantially, leading to stronger precipitation.

Time to reach raindrops (τ_R) from the collision box model

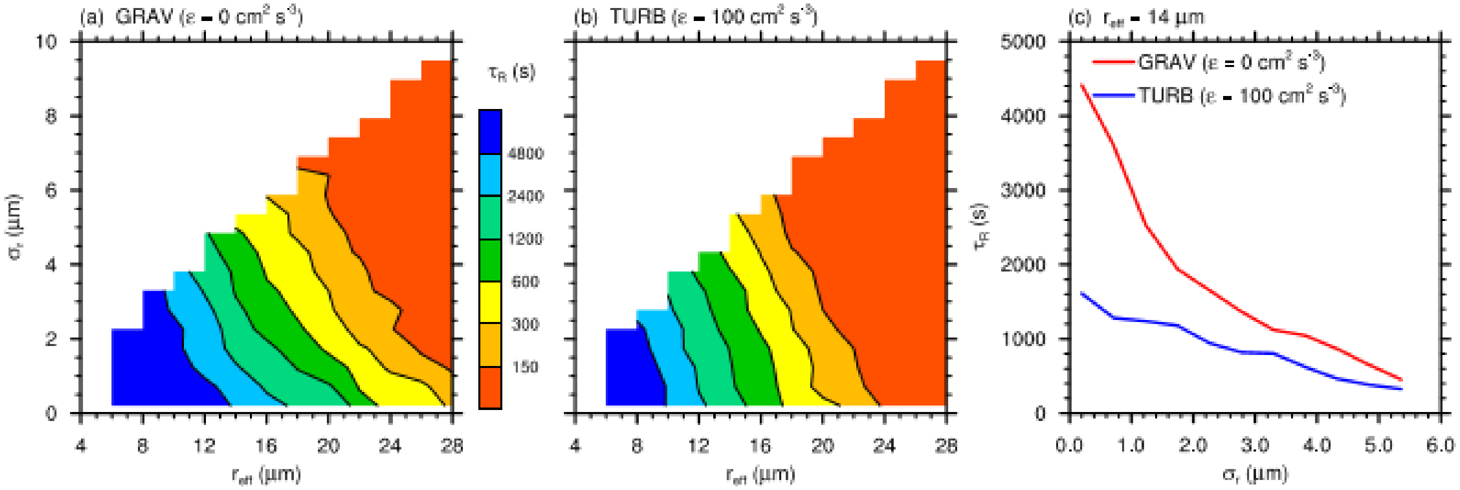
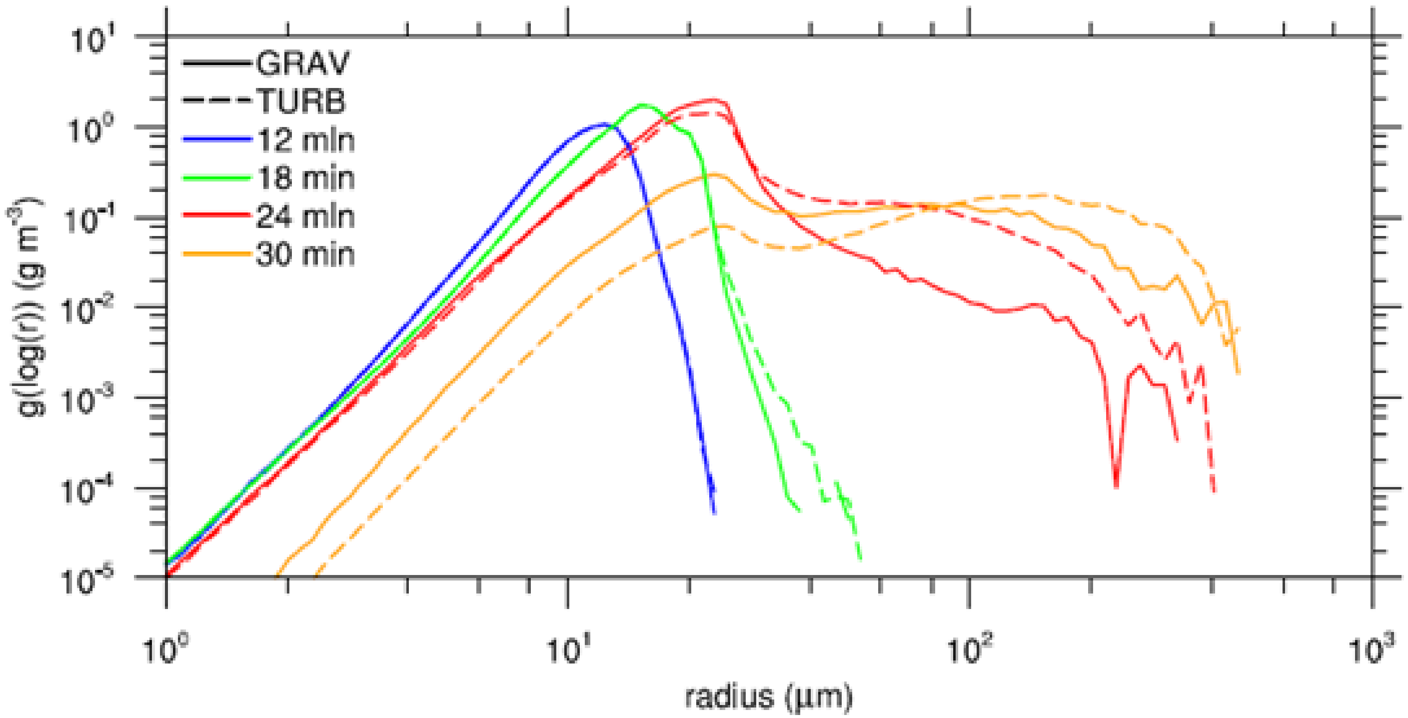


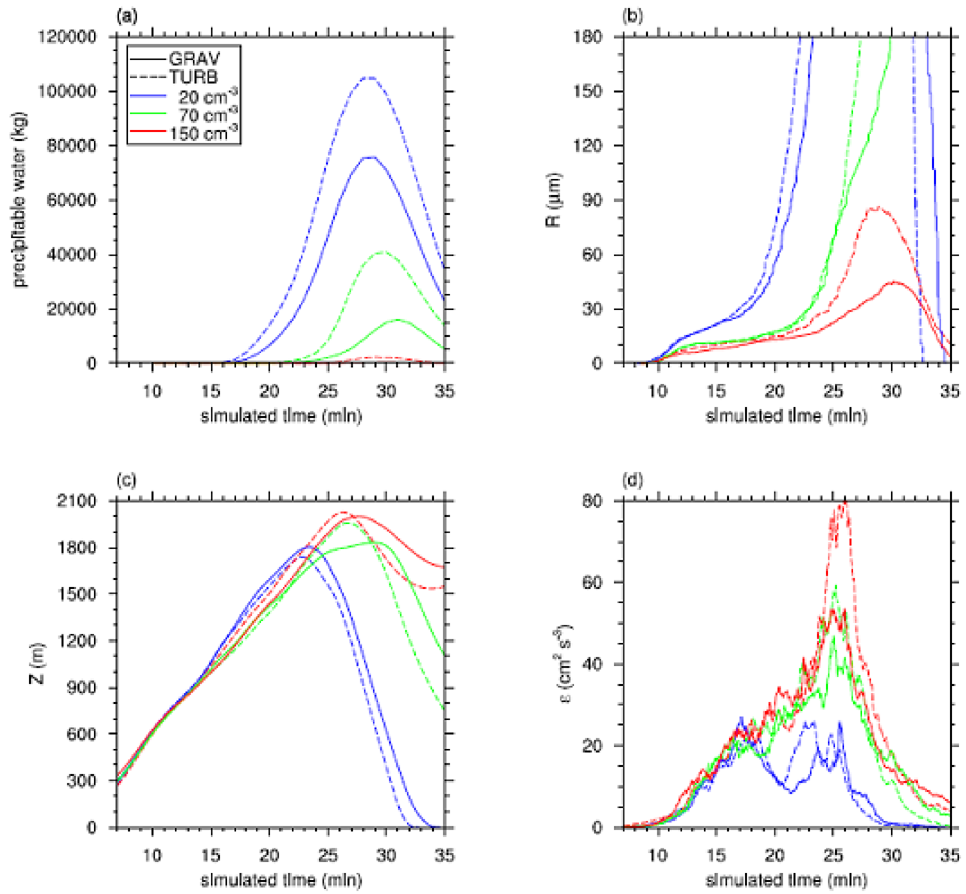
FIG. 9. The variation of the time to reach raindrops τ_R from box simulations of the collisional growth process starting from different log-normally shaped drop size distributions with different σ_r and r_{eff}: (a) GRAV ($\varepsilon = 0\,\mathrm{cm^2\,s^{-3}}$), (b) TURB ($\varepsilon = 100\,\mathrm{cm^2\,s^{-3}}$), and (c) the variation of τ_R with σ_r for $r_{eff} = 14\,\mu\mathrm{m}$.

- small $\varepsilon \rightarrow \tau_R$ becomes very large for small σ.
- large $\varepsilon \rightarrow \tau_R$ does not vary much with σ.



Evolution of droplet spectrum

- ql (r > 40 μm) appears at the same time, but larger at TURB
- ql (r < 40 μm) decreases at 30 min by the collection to settling raindrops (accretion)



Times series of variables from different initial droplet concentrations (Nc): (a) ql (r > 40 µm), (b) R, (c) Z, and (d) ε (solid: GRAV, dotted: TURB) (blue: 20 cm^{-3}, green: 70 cm^{-3}, red: 150 cm^{-3}).

- Delayed raindrop formation for larger Nc.
- stronger effect of TICE for larger Nc.

Conclusion

- Raindrop formation is triggered
  - when droplets with a radius of 20 μm appear in the region near the cloud top

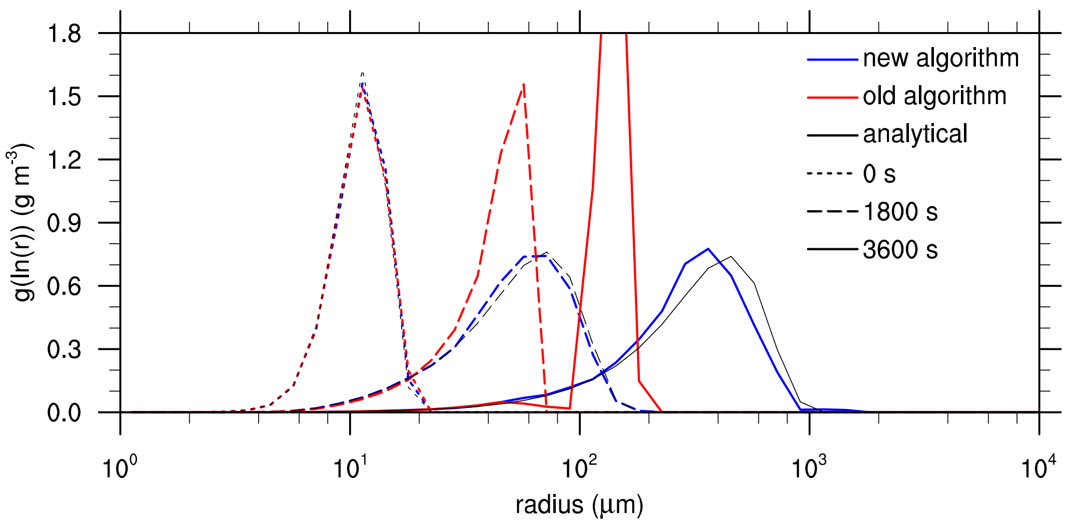
- Raindrop is formed in the region of high q_l , r_{eff} , ε, σ_r and S.
  - q_l , r_{eff} , ε, and S are higher in TURB
  - σ_r is higher in GRAV.

- TURB - Raindrop formation is triggered in time, regardless of DSD broadening.
  GRAV – Raindrop formation is severely delayed without DSD broadening.

- TURB does not accelerate the timing of raindrop formation, but it enhances the collisional growth rate substantially, leading to stronger precipitation.

- As aerosol concentration (N) increases,
  - faster and stronger precipitation
  - stronger effect of turbulence

old algorithm (continuous growth)	**new algorithm** (stochastic growth)
The super-droplet with the larger radius collected droplets from the super-droplet with the smaller radius.	The super-droplet with the smaller weighting factor collects droplets from the super-droplet with the larger weighting factor.
The collected mass is distributed among a much larger number of droplets represented by the collecting super-droplet	The collection is treated as a zero-one process, in which either all droplets of the collecting super-droplet coalesce with the same number of droplets from the collected super-droplet or not.



Evolution of droplet spectrum by collision
(Unterstrasser et al., *GMD* 2016)