The influence of cloud turbulence on droplet growth and precipitation

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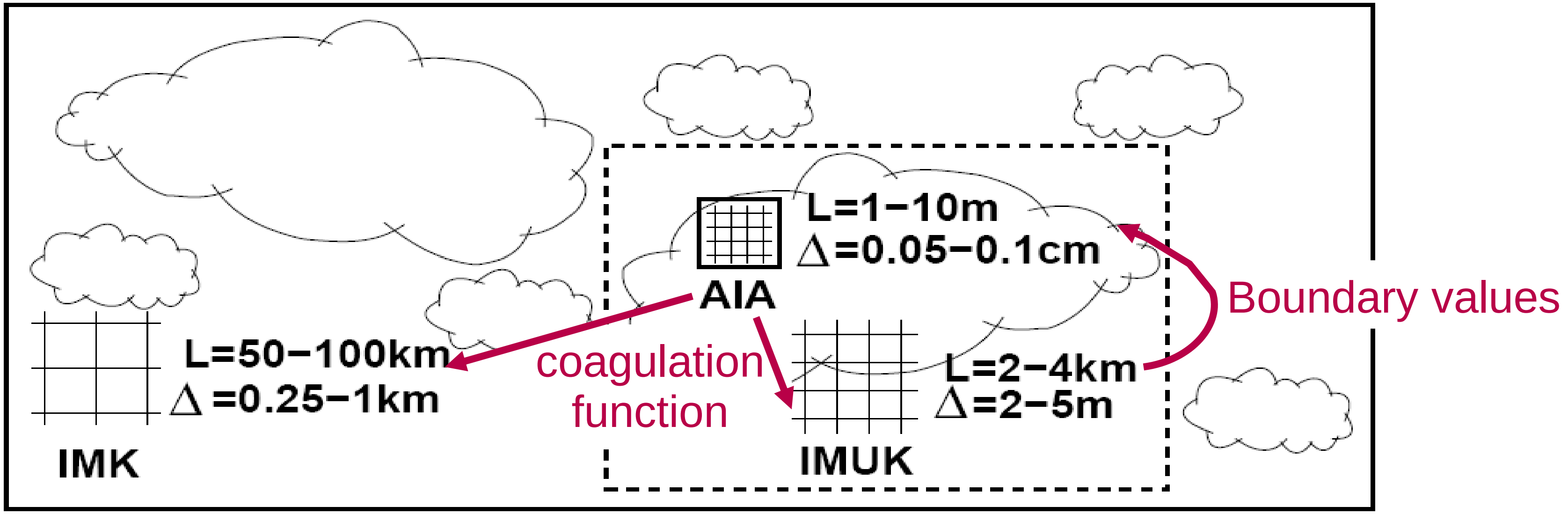
Questions to be answered:

- Which influence has the local cloud turbulence on the collision efficiency of small cloud droplets and thus on the coagulation function?
- What is the impact of turbulence on cloud micro physics compared to the traditional approach disregarding this effect?

Mechanisms and processes involved cover a large range of scales

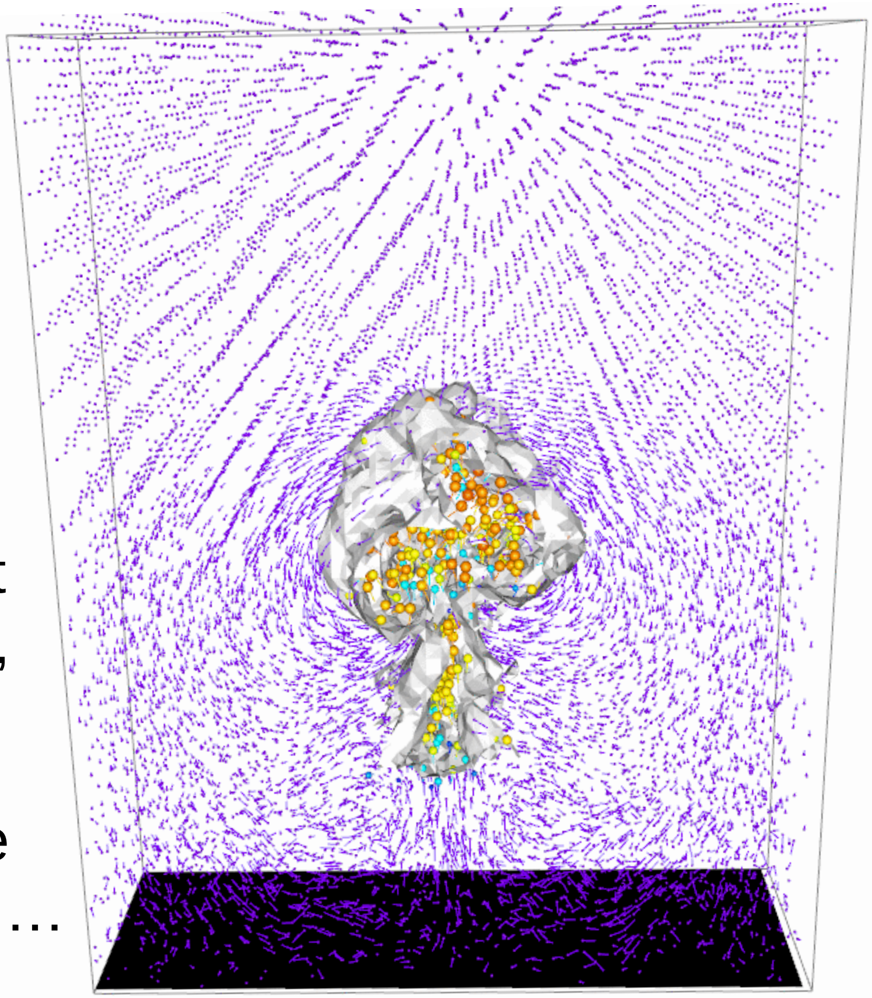
• Collision of small droplets	➢ centimeter scale	➢ **DNS**
• Local turbulent structures	➢ meter scale	➢ **LES**
• Distribution of precipitation	➢ kilometer scale	➢ **RANS**

→ Different simulation models



LES of cumulus clouds with explicit simulation of cloud droplets

- Simulate clouds by simulating a large number of water droplets explicitly
  - Combination of LES model PALM and Lagrangian particle model



- Advantages:
  - Enables e.g. analysis of droplet spectra, droplet concentrations, droplet paths
  - Useful to investigate turbulence effects, entrainment processes …

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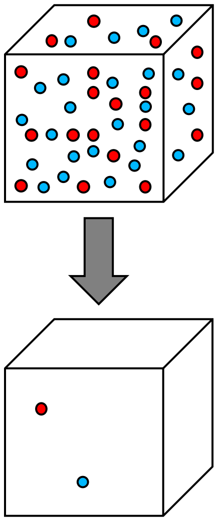
Method (I)

- Simulation of enormous particle numbers like in real clouds is impossible
  - ➢ Ensembles of water droplets are simulated
  - ➢ Concept of weighting factor is used:

$$A_i = \frac{real\ volume\ of\ droplets}{simulated\ volume\ of\ droplets}$$



  - ➢ Every simulated droplet stands for a very high number of real droplets
- Equation of motion including friction and gravity is solved for each simulated droplet
- Droplets can change size by evaporation/condensation and collision
- Liquid water is only/completely transferred within cloud droplets

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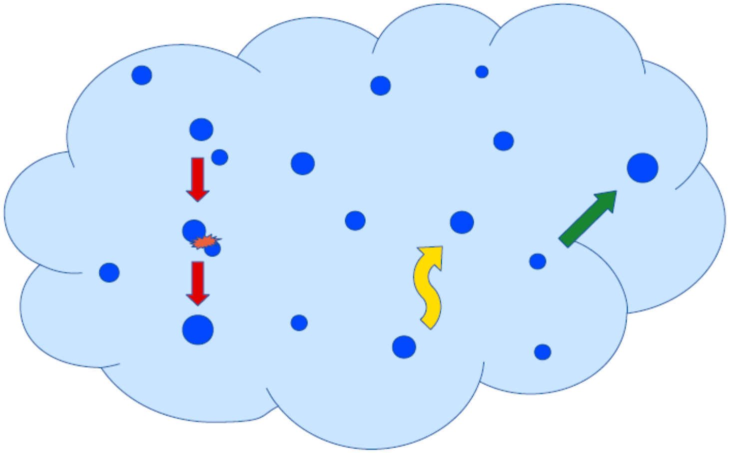
Method (II)



During every time step:

Advection

- Using non-linear drag law (Clift,1978)

Condensation

- Calculated from diffusion equation (Mason, 1971)

Collision

- Using continuous growth model (e.g. Rogers, 1976)

$$\frac{dR}{dt} = \frac{1}{3R^2} \int_0^R r^3 \cdot K(R,r) \cdot n(r)\, dr$$ where K(R,r) is the collision kernel

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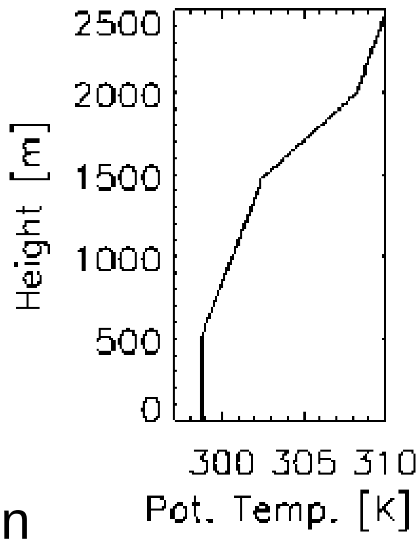
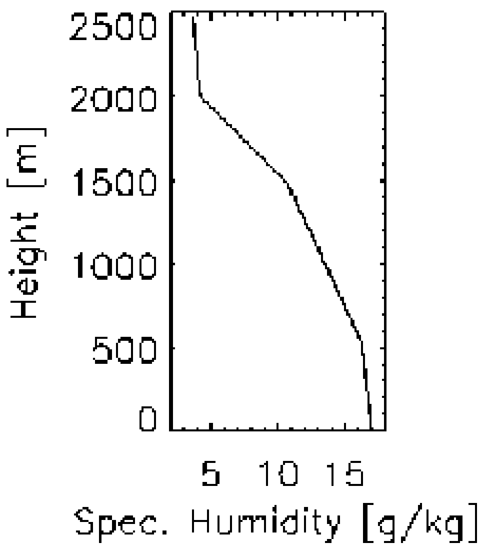
Simulation setup of idealized case

- Cloud is initialized by a warm air bubble (1200m x 150m x 150m) near the bottom, ΔT = 0.2 K
- Domain size: 1.2 km x 4 km x 4 km
  Resolution: 20 m
- Particles are released every 4.5 m in whole model domain
- Initial particles size: 1 µm
  Initial weighting factor: $9 \cdot 10^9$
- Total number of particles: ~ 150 Million
  Particle concentration: 100 cm^{-3}





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Influence of turbulence (I)

- **Collision kernel without turbulence effects**

$$\mathrm{K}(\mathrm{R},\mathrm{r}) = \pi\,(R+r)^2 \cdot E^g \cdot [|u(R)-u(r)|]$$

- **Collision kernel with turbulence effects from Ayala et al., 2008 and Wang et al., 2008**

$$K(R,r) = \pi(R+r)^2 \cdot \eta_E\, E^g \cdot 2\langle|w_{Rr}|\rangle \cdot g_{Rr}$$

E^g = collision efficiency
η_E = turbulent enhancement factor for collision efficiency
w_{Rr} = radial relative velocity
g_{Rr} = radial distribution function

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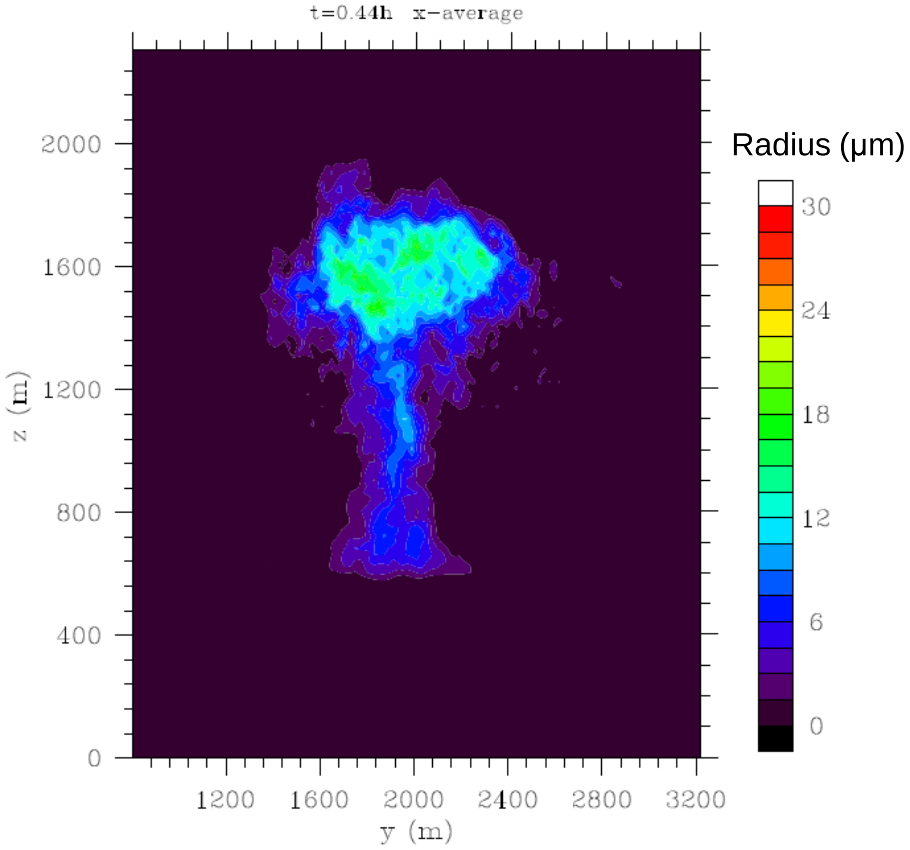
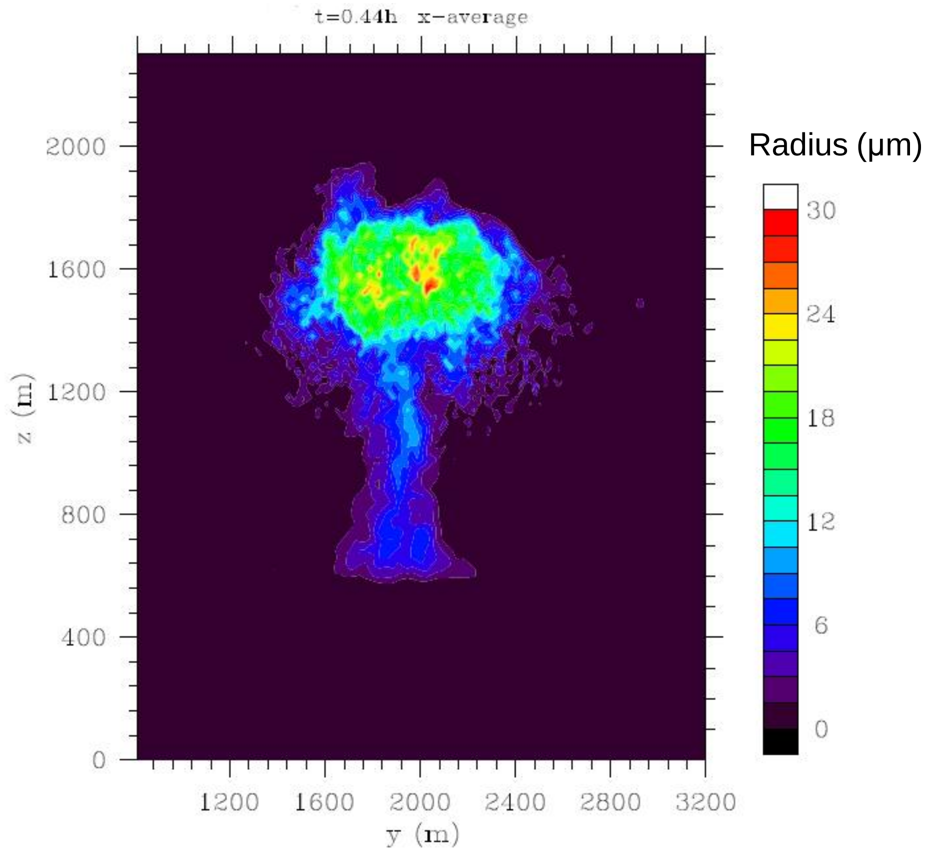
Influence of turbulence (II)

Kernel without turbulence effects



Kernel with turbulence effects



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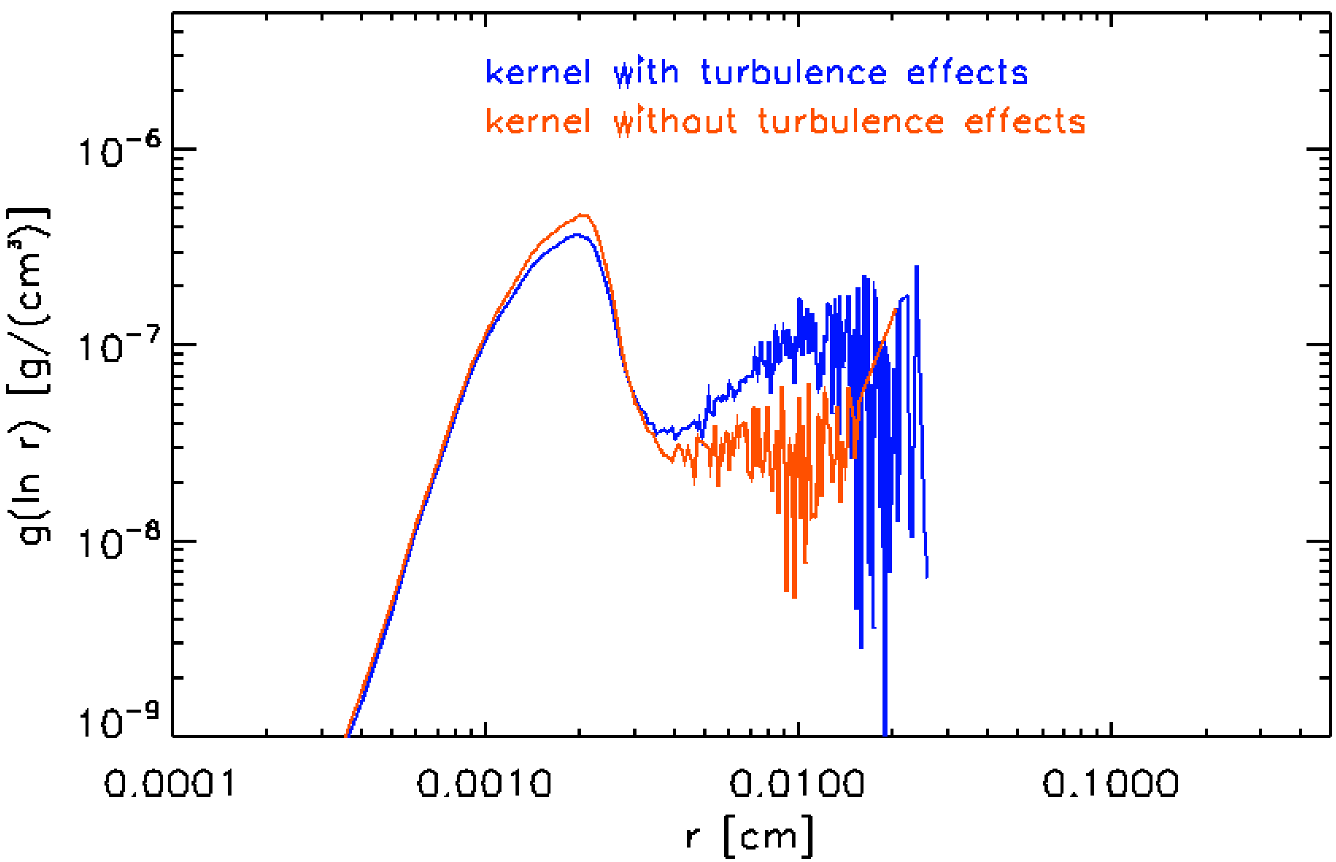
Influence of turbulence (II)

Mass distribution function after 1600 s



→ Turbulence enhances the droplet growth

DNS with Lagrangian particles and collision detection

Equation of motion for small, heavy particles ($\rho_p >> \rho_f$ and $a << \eta$)

$$\frac{d\mathbf{v}}{dt} = \frac{f_D}{\tau_p}(\mathbf{u} - \mathbf{v}) + \mathbf{g}$$

Particle response time

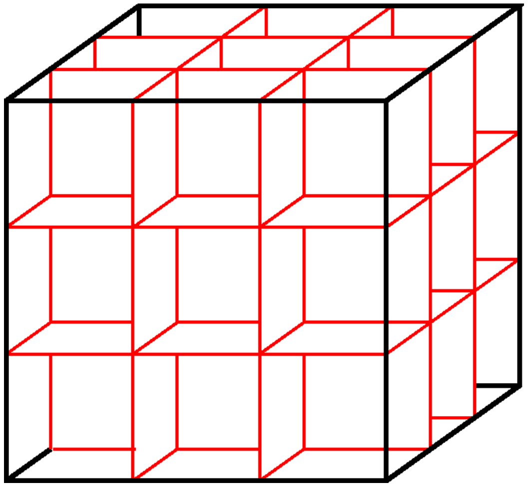
$$\tau_p = \frac{\rho_p}{\rho_f}\frac{2a^2}{9\nu}$$

Nonlinear drag correction

$$f_D = 1 + 0.15Re^{0.687}$$

Divide particles into subdomains; collision check only within subdomain (cell-index method)

“Ghost particles” assumed, i.e. collisions detected without interaction

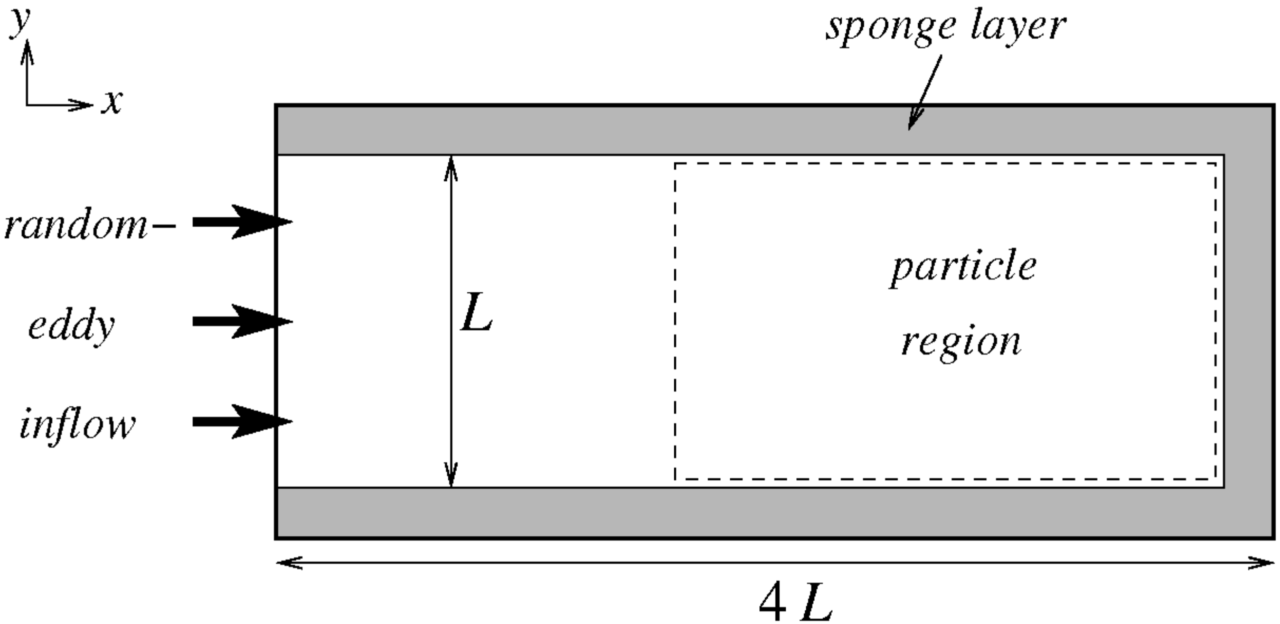


Flow domain

Domain of characteristic size L = 0.1 m

Turbulence generated at inlet, swept across domain by prescribed mean flow U = 1 m/s

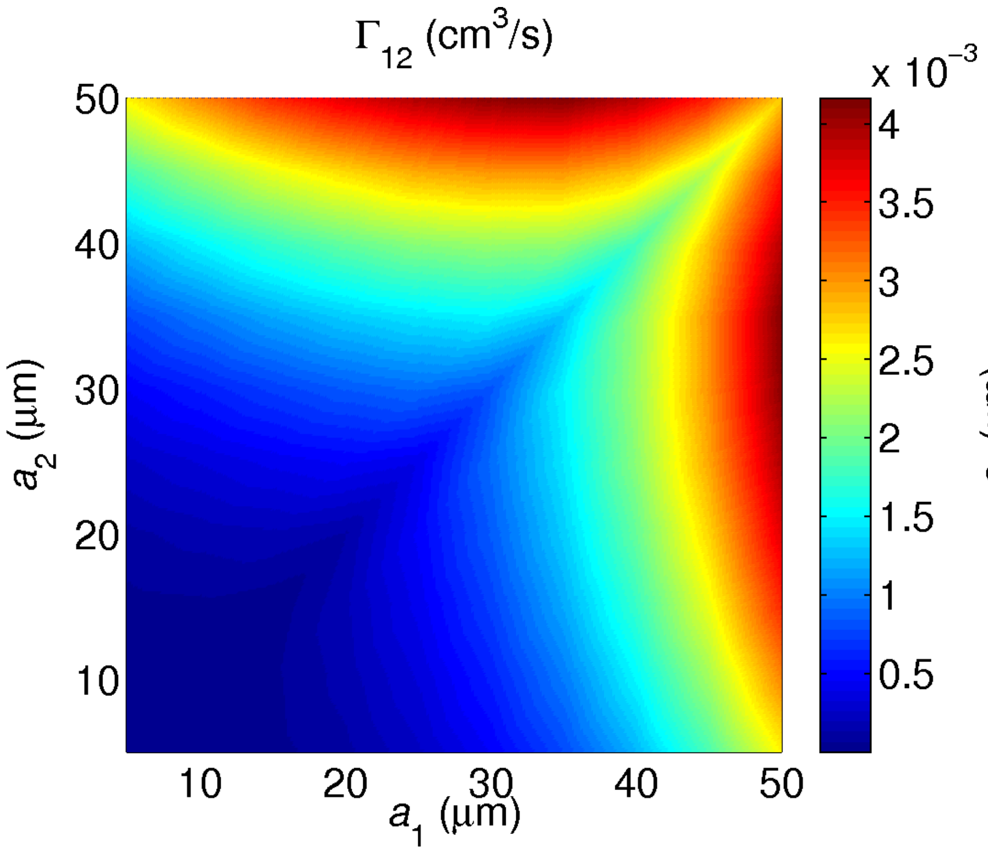
1.88 million particles of radius 5, 10, …, 50 μm



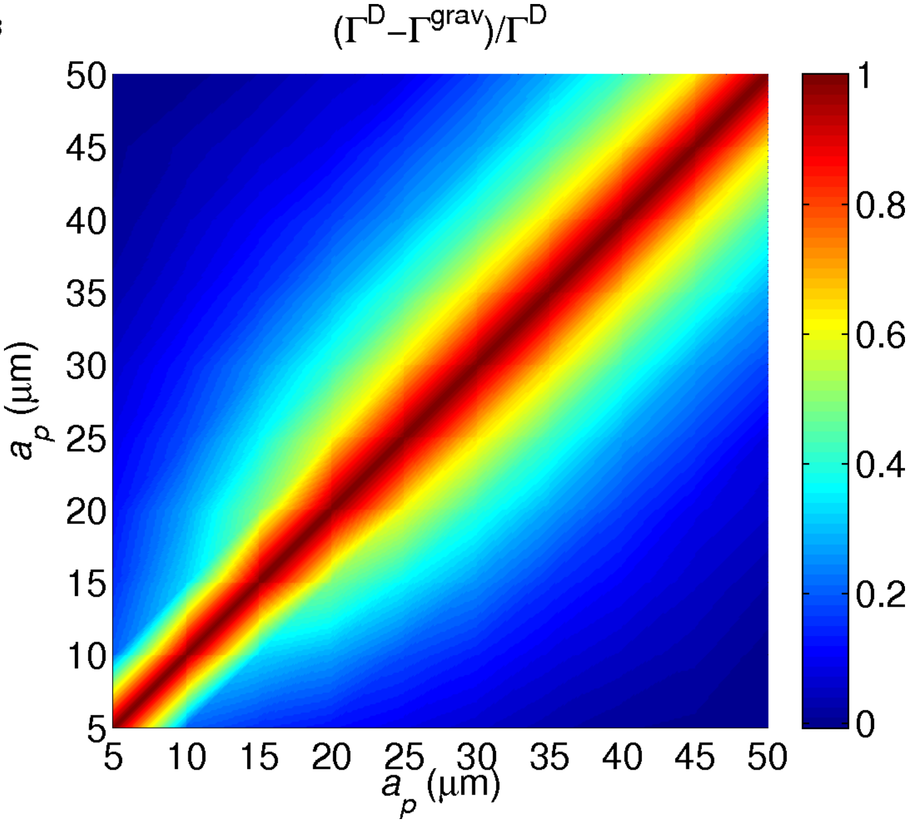
A turbulent kernel

R_λ = 78.6, ε = 267 cm^2/s^3

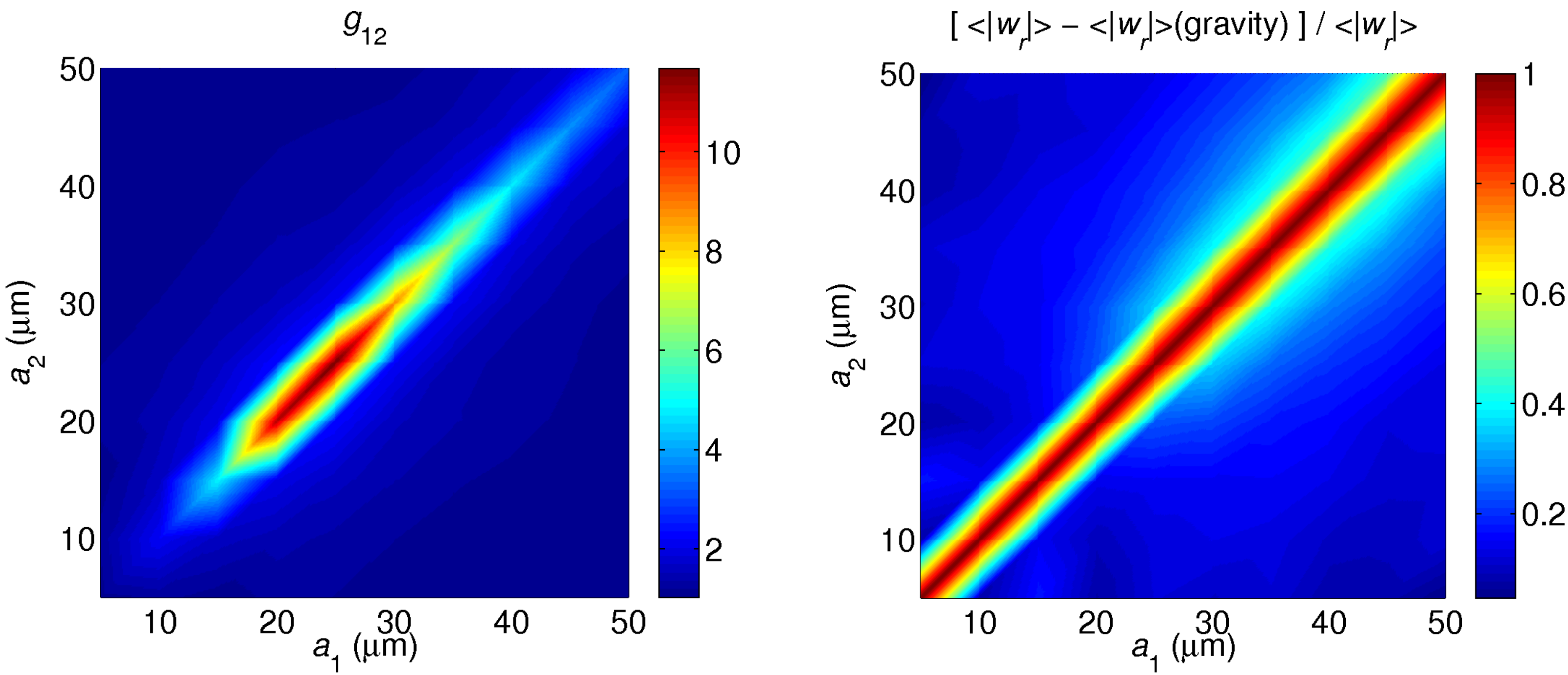
absolute



relative turbulent contribution



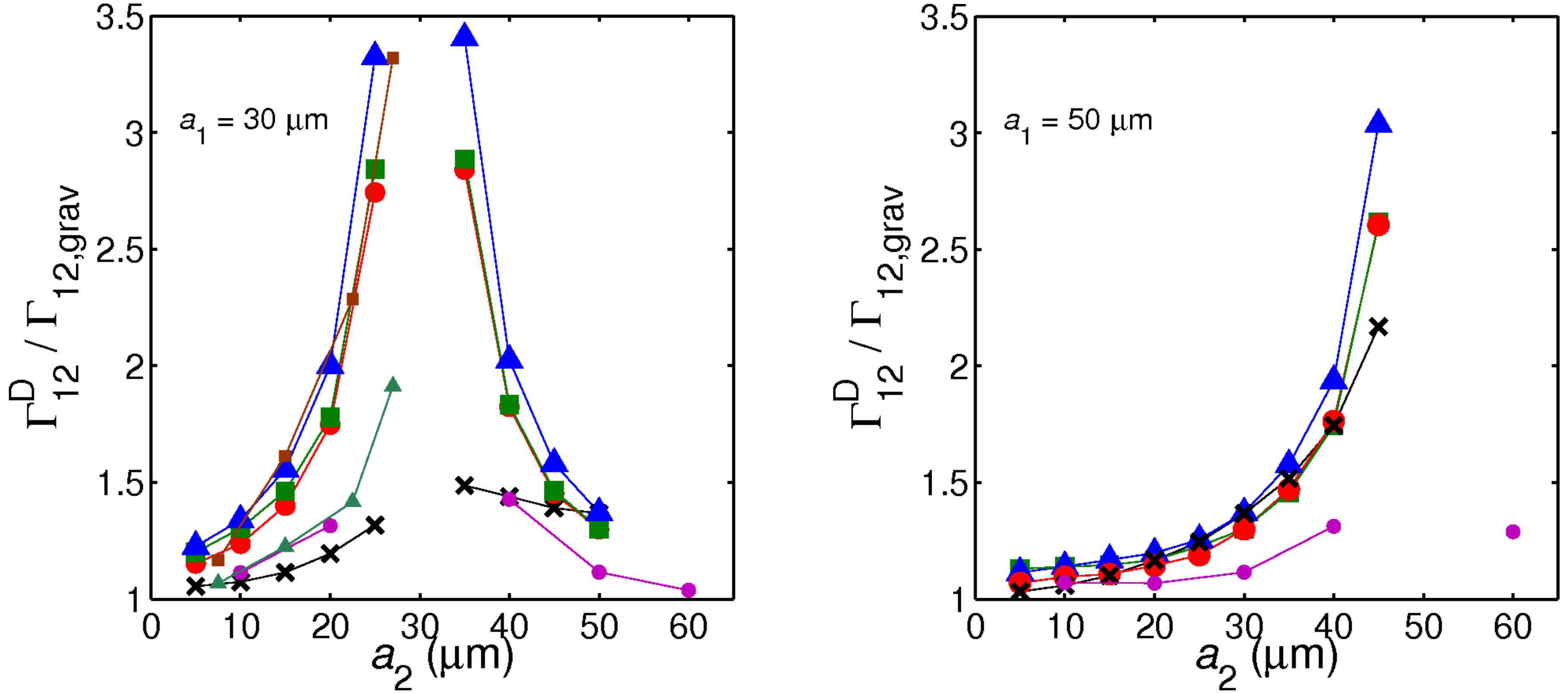
R_λ = 78.6, ε = 267 cm²/s³



g_{12} peaks at a = 25 μm
Preferential concentration

<|w_r|> ≠ 0 also for equal-size particles
Effect largest for 45-50-μm combination:
45% of <|w_r|> due to turbulence

Different flow conditions

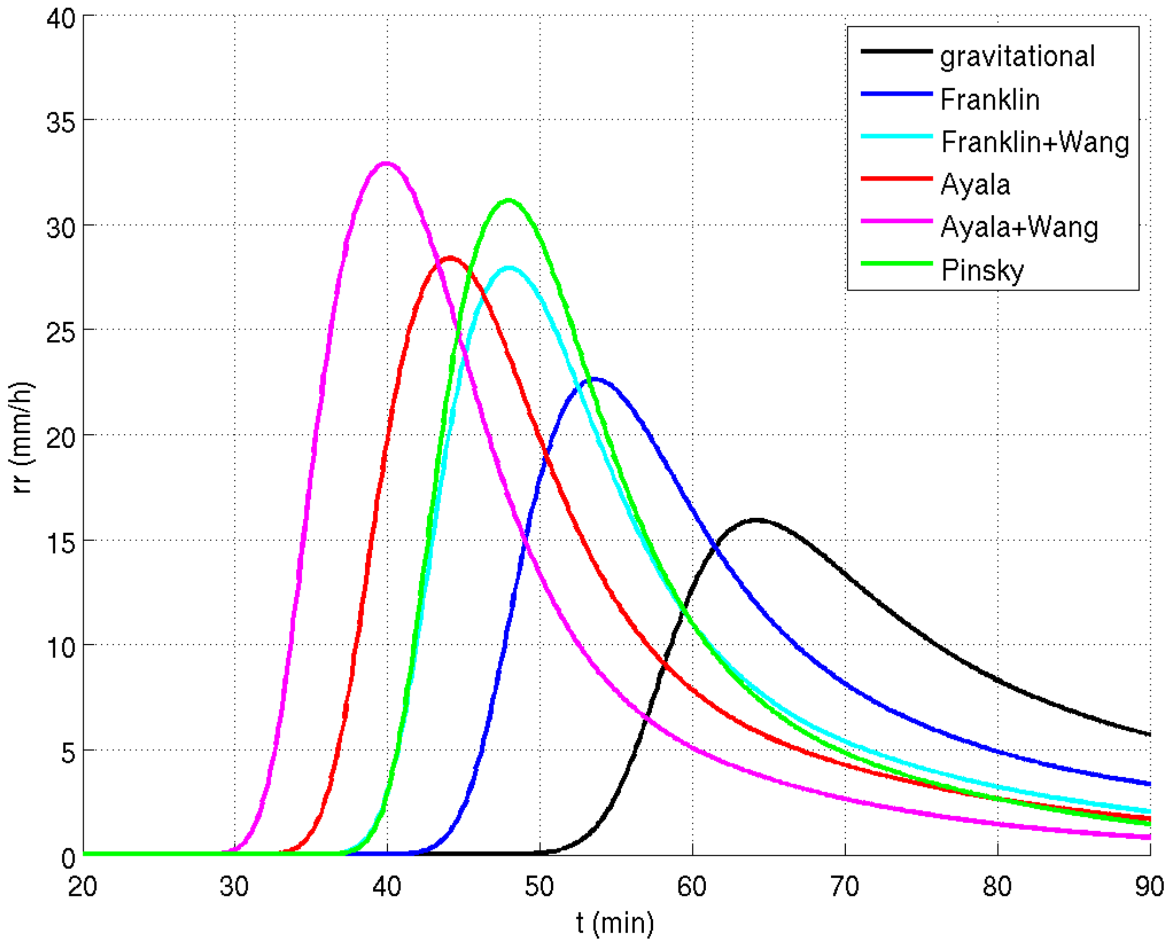


R_λ = 11.6, ε = 99 cm^2/s^3
R_λ = 63.7, ε = 213 cm^2/s^3
R_λ = 78.6, ε = 267 cm^2/s^3
R_λ = 49.9, ε = 678 cm^2/s^3

R_λ = 72.4, ε = 400 cm^2/s^3 Ayala et al. (2008)

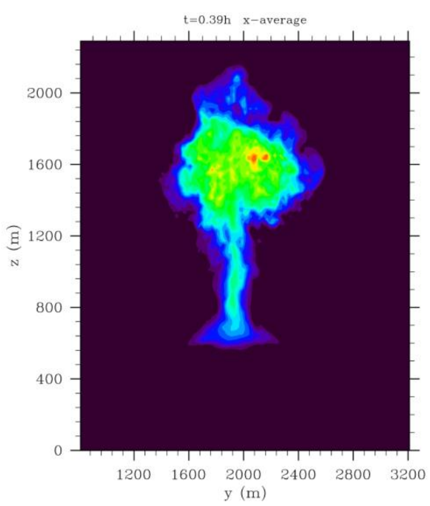
R_λ = 40, ε = 280 cm^2/s^3
R_λ = 48, ε = 656 cm^2/s^3 Franklin et al. (2007)

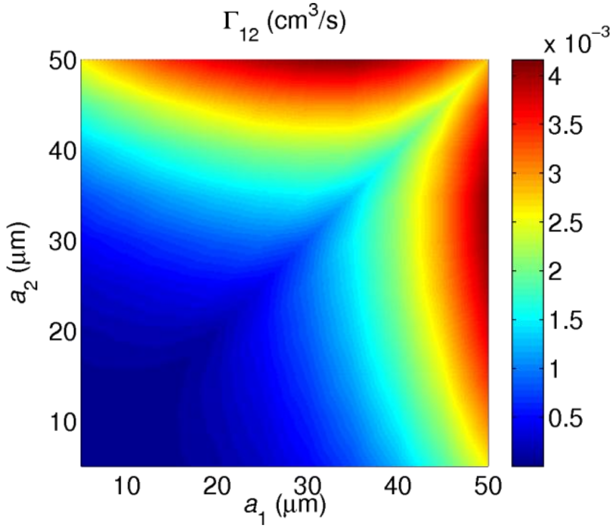
Rain rate at surface in mm/h vs simulation time from results of 1D rainshaft model with continental initial spectrum for gravitational and several turbulent kernels at $\varepsilon = 400$ cm^2/s^3

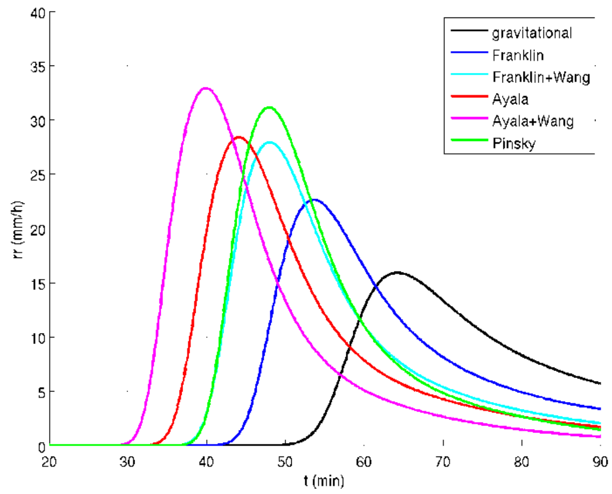


Conclusions & Outlook

- Effects of turbulence on droplet growth investigated with multi-scale approach
- Collision kernel evaluated; its parameterization is next step
- Application of parameterized collision kernel in LES of a cloud as well as in larger-scale weather/climate simulation







Thank you for listening!