Modeling of cloud microphysics: Can we do better?

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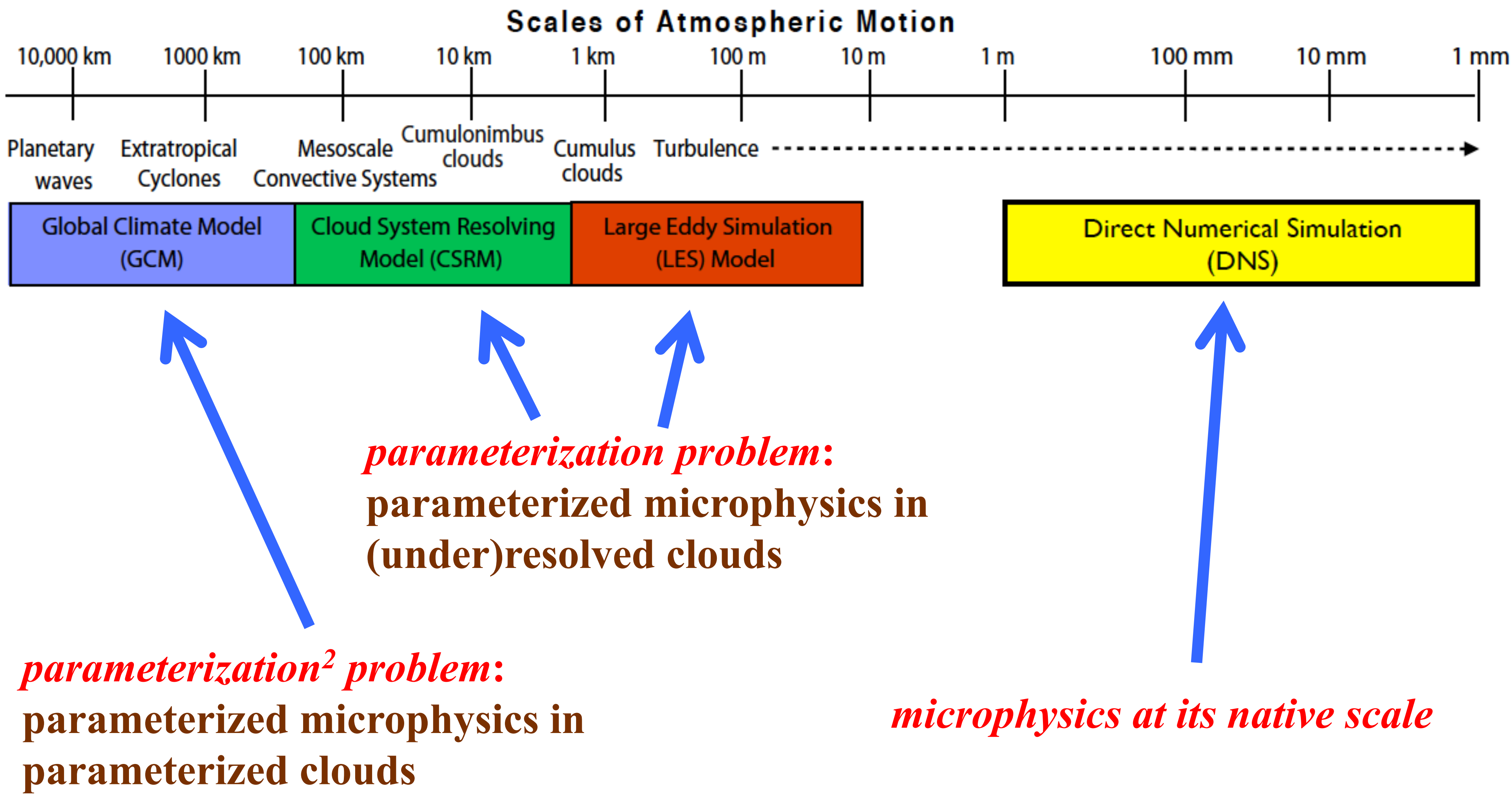


Cloud microphysics across scales

Traditional modeling approaches are based on continuous medium approach, that is, applying density of various condensed water species (e.g., mass of particles per unit volume).

In practice, mixing ratios are used (i.e., mass per unit mass of dry air) as these are conserved along fluid trajectories when particle growth and sedimentation are excluded.

Such an approach has been a workhorse for cloud modeling for decades…

Microphysical schemes:

Bulk schemes: single-moment (mass only, really no μphysics)
double-moment (mass and number)
triple-moment (mass, number, spectral shape).

Bin schemes: representing the spectrum of particles
(single moment, double moment).

Multidimensional bin schemes: representing the spectrum plus
additional particle properties (e.g., aerosol).

Is bin microphysics the ultimate scheme?

Such a scheme is often used as a benchmark for bulk schemes (e.g., deriving formulas for bulk schemes)…

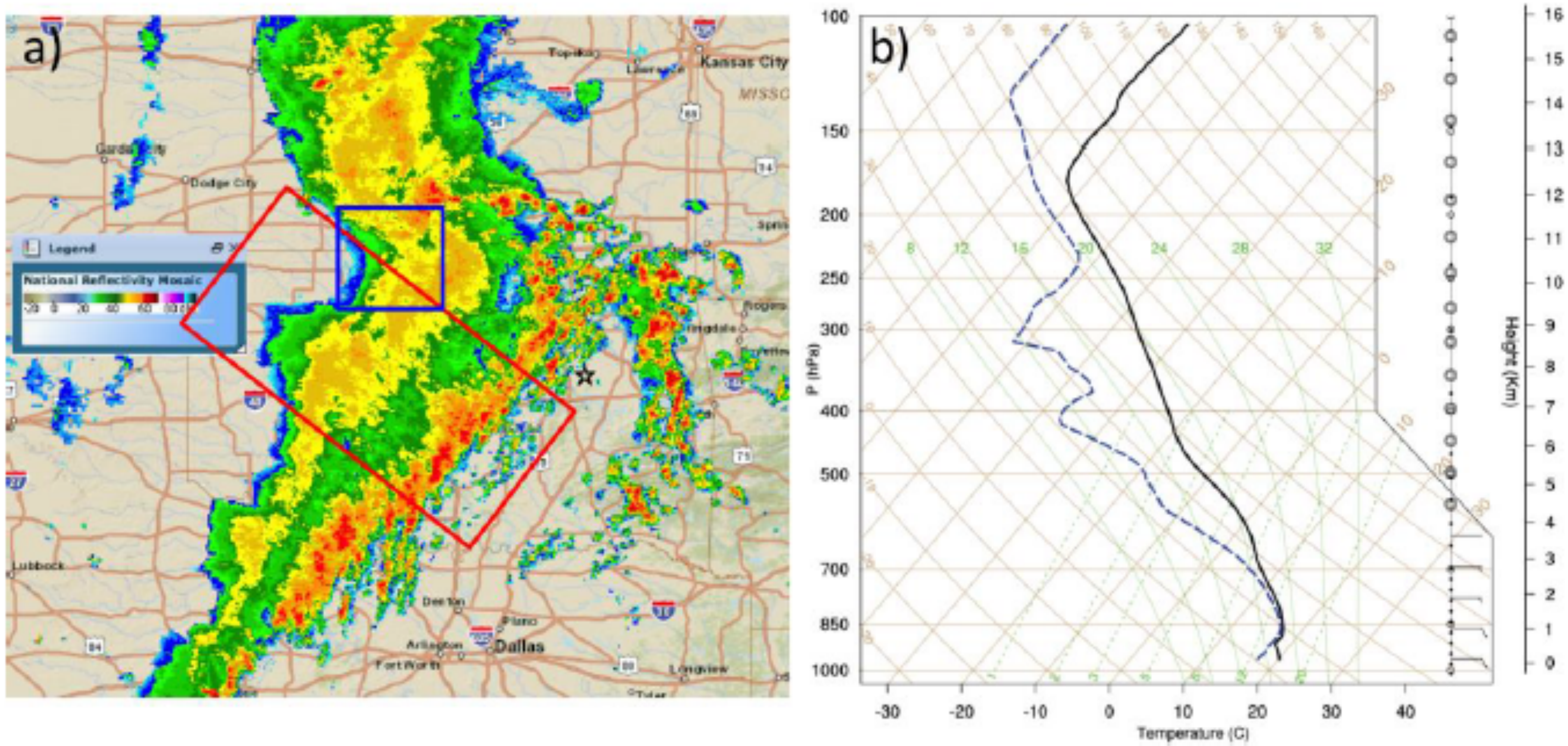
But, there are issues:

- physical complexity, especially for ice...
- numerical implementation...

Idealized simulations of a squall line from the MC3E field campaign applying three bin microphysics schemes.

Mon. Wea. Rev. 2017

Lulin Xue[1], Jiwen Fan[2], Zachary J. Lebo[3], Wei Wu[4,1], Hugh Morrison[1], Wojciech W. Grabowski[1], Xia Chu[3], Istvan Geresdi[5], Kirk North[6], Ronald Stenz[7], Yang Gao[2], Xiaofeng Lou[8], Aaron Bansemer[1], Andrew J. Heymsfield[1], Greg M. McFarquhar[4,1], Roy M. Rasmussen[1]*



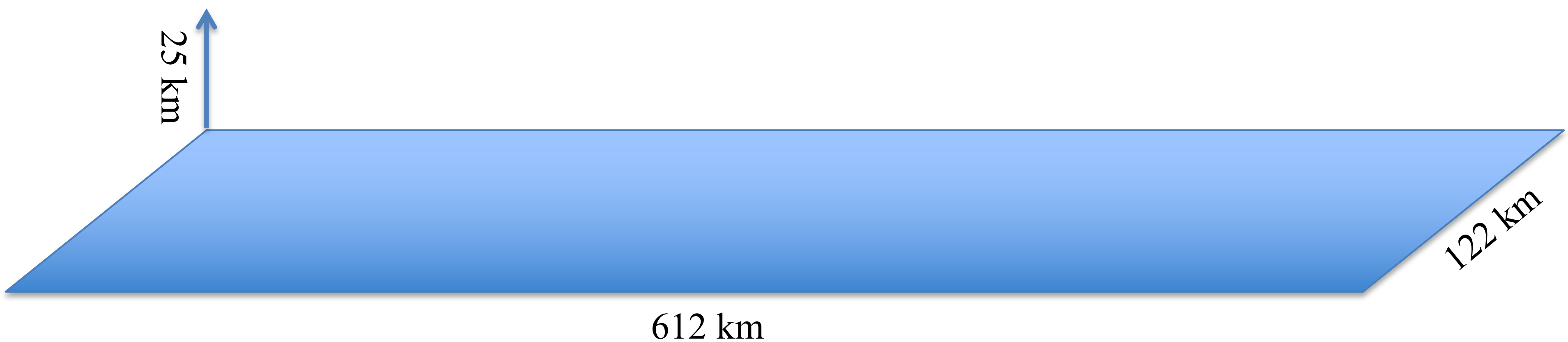
Setup of simulations:

bowling alley horizontal domain; open at the ends, periodic across

1 km/0.25 km horizontal/vertical grid length, 3 sec time step

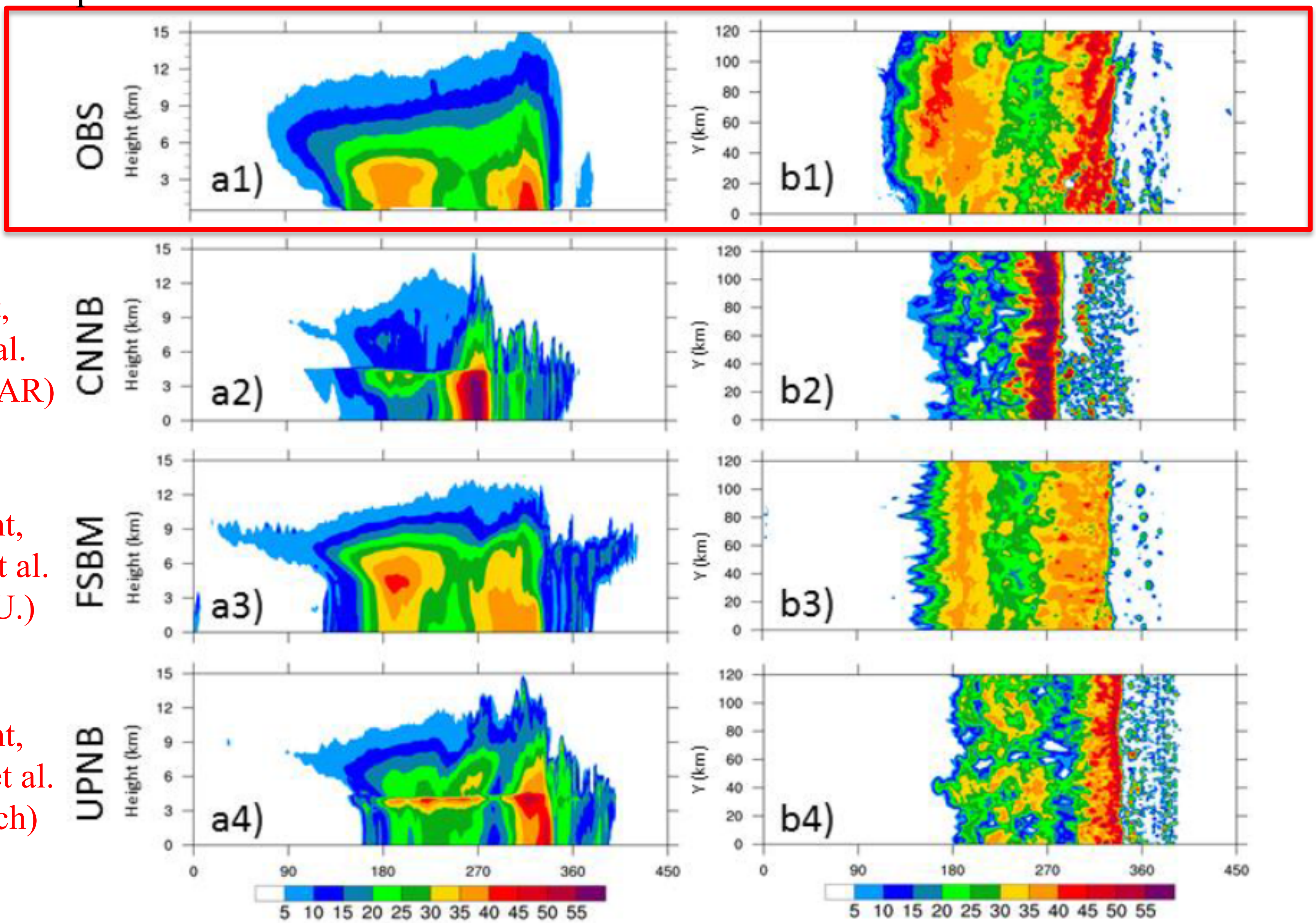
single sounding (from observed environment ahead of the squall line) initialization, low-level convergence applied to initiate convection

model run for 6 hours, two initial hours considered as spinup



Radar reflectivity

composite of observations



2-moment,
Z. Lebo et al.
(Caltech, NCAR)

1-moment,
A. Khain et al.
(Hebrew U.)

1-moment,
I. Geresdi et al.
(U. of Petch)

line average

horizontal cross section at 2 km

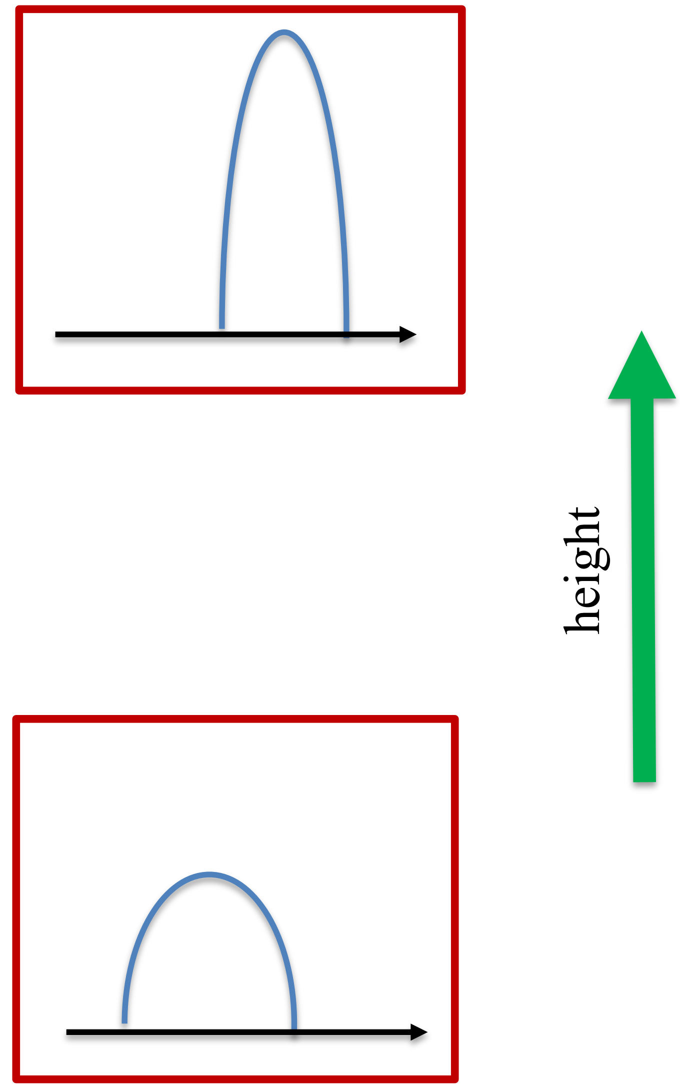
To what extent numerical aspects affect bin scheme solutions?

RISING PARCEL MODEL
(diffusional growth only)

the only issue is the
diffusion in the radius space

$$\frac{\partial f(r,t)}{\partial t} + \frac{\partial}{\partial r}\left[\frac{dr}{dt}\; f(r,t)\right] = 0$$

evolution of the spectral density function…



RISING PARCEL MODEL

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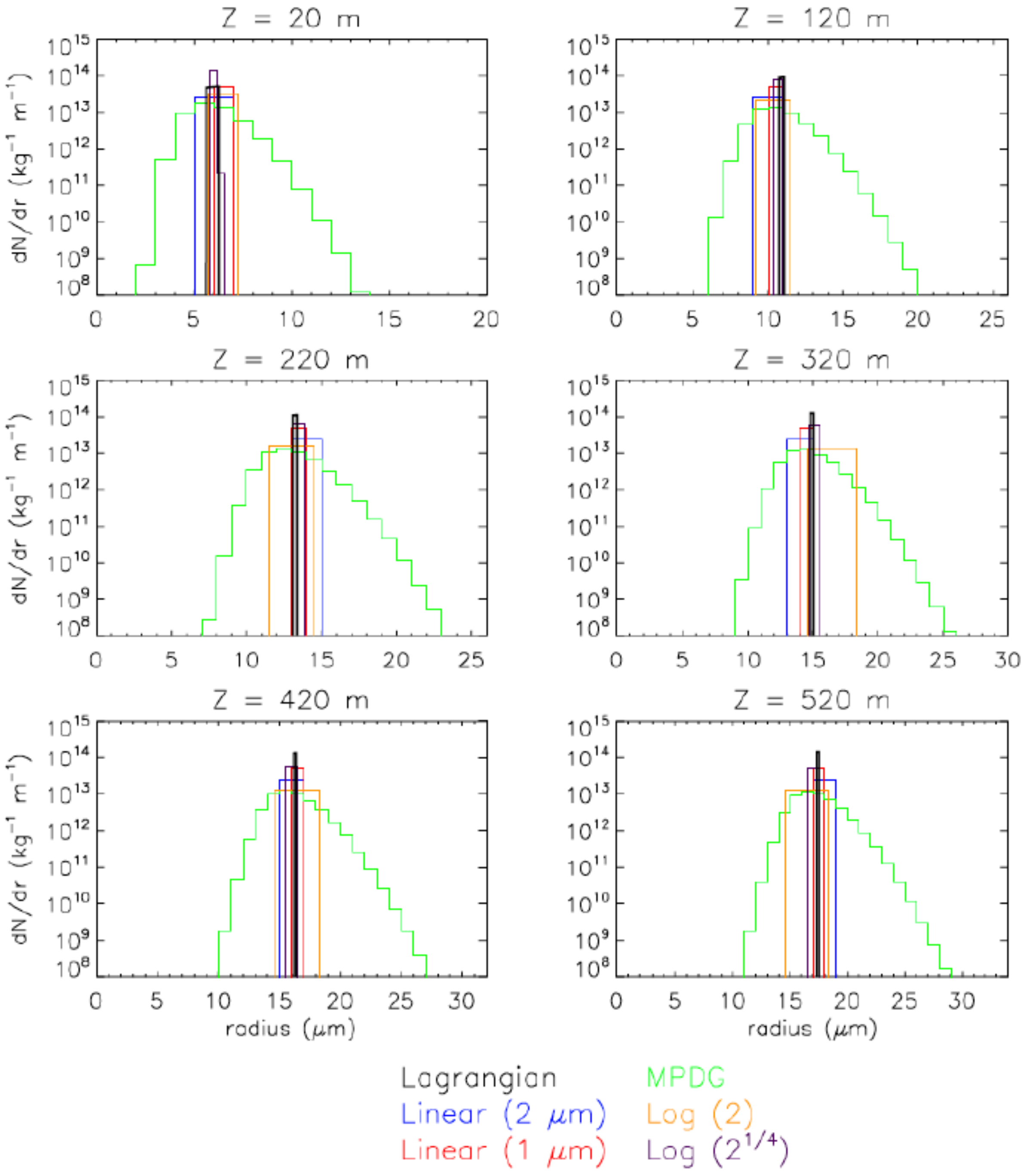
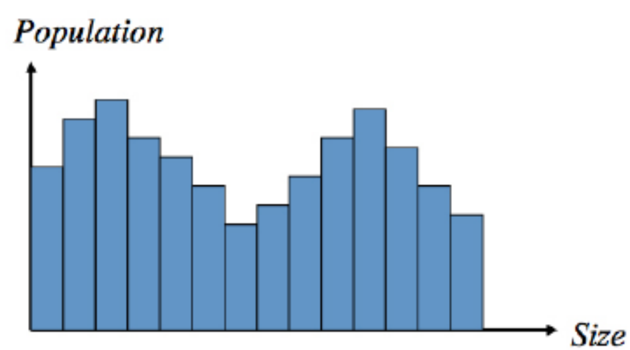


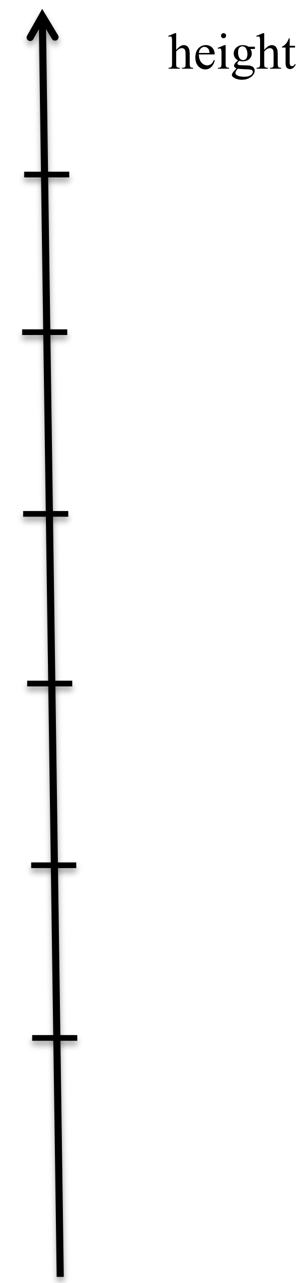
Morrison et al. *JAS* (submitted)

1D UPDRAFT MODEL
(diffusional growth only)

combination of 1D advection in the physical space and droplet growth…

$$\frac{\partial f(r,z,t)}{\partial t} + \frac{\partial}{\partial z}\left[w\ f(r,z,t)\right] + \frac{\partial}{\partial r}\left[\frac{d\,r}{d\,t}\ f(r,z,t)\right] = 0$$





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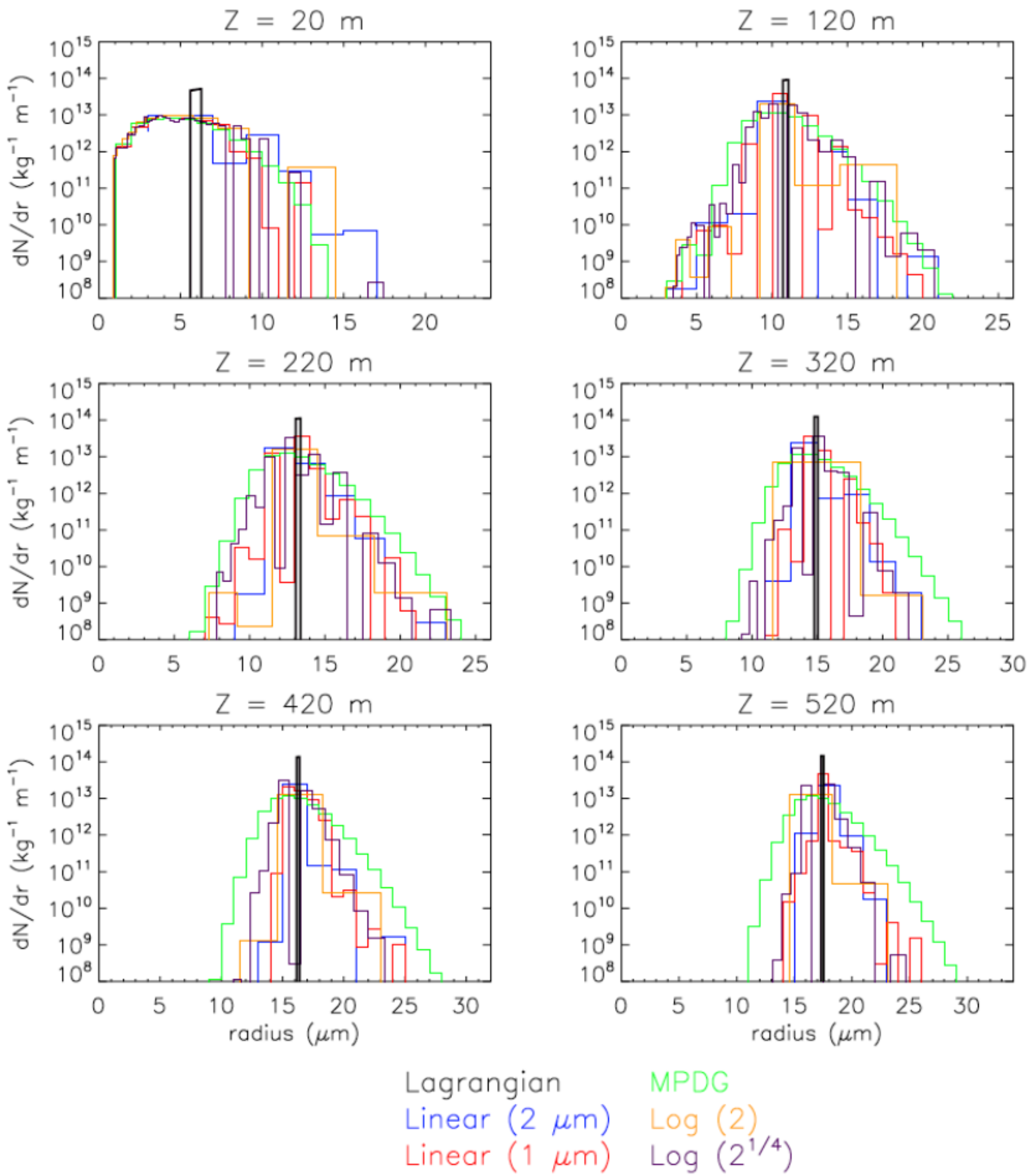
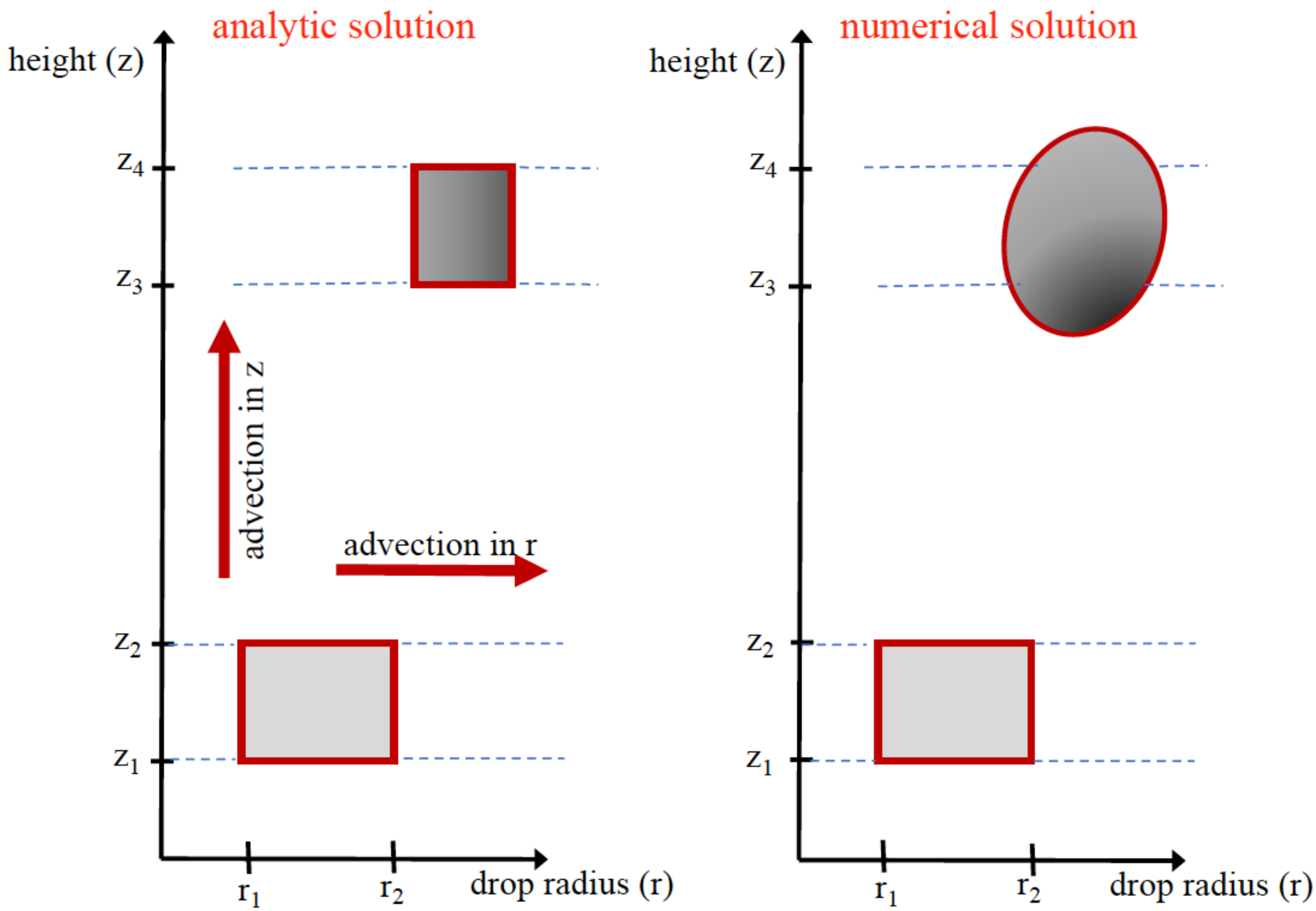
combination of 1D advection in the physical space and droplet growth…

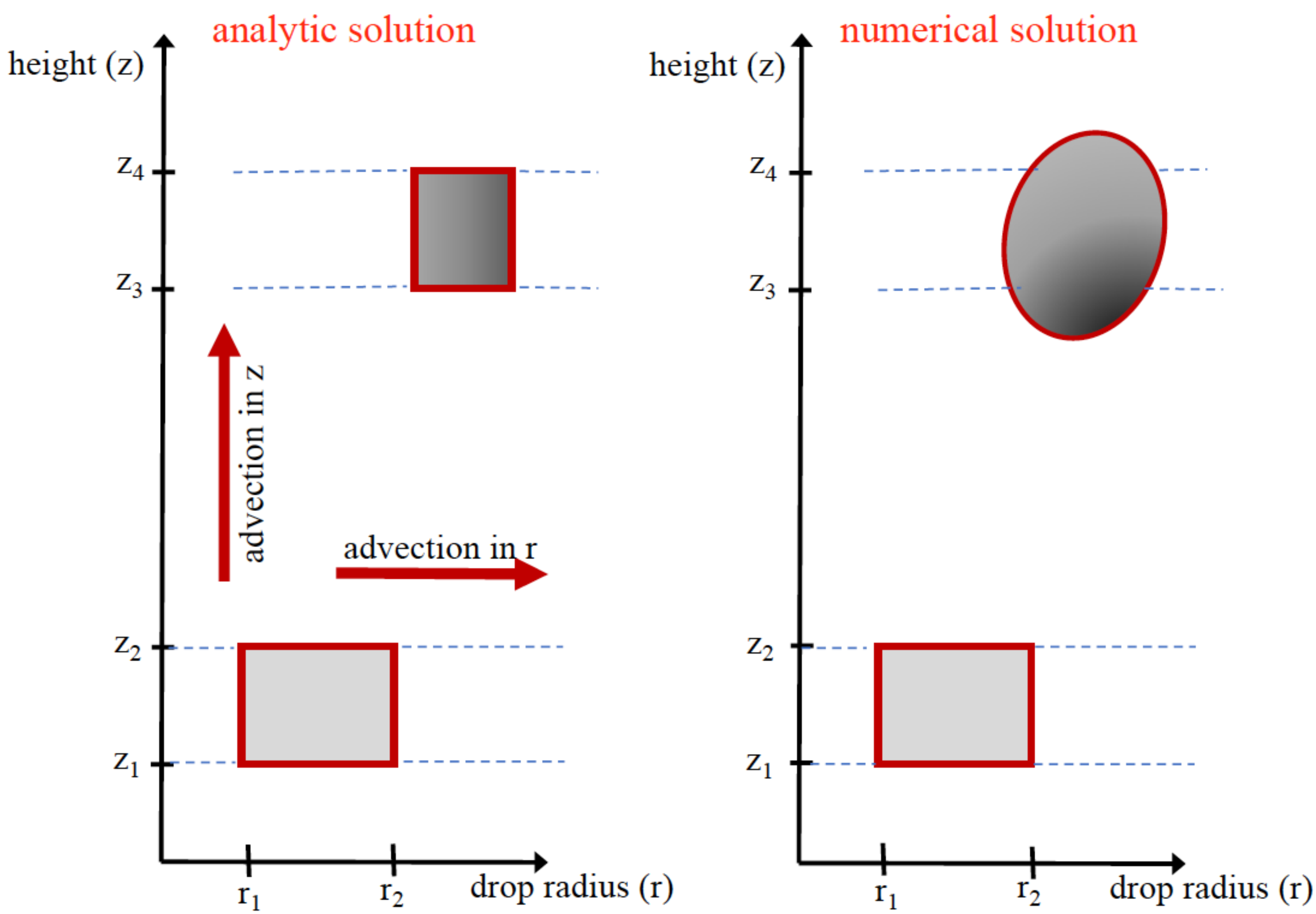


Morrison et al. *JAS* (submitted)

Eulerian bin microphysics



Eulerian bin microphysics



NB: For the multidimensional advection in a cloud model, these problems increase…

Can we do better?

Lagrangian treatment of the condensed phase: "Lagrangian Cloud Model", "Super-droplet method":

The super-droplet method for the numerical simulation of clouds and precipitation: A particle-based and probabilistic microphysics model coupled with a non-hydrostatic model

S. Shima,[a*] K. Kusano,[c] A. Kawano,[a] T. Sugiyama[a] and S. Kawahara[b]

Cloud-aerosol interactions for boundary layer stratocumulus in the Lagrangian Cloud Model

M. Andrejczuk,[1] W. W. Grabowski,[2] J. Reisner,[3] and A. Gadian[1]

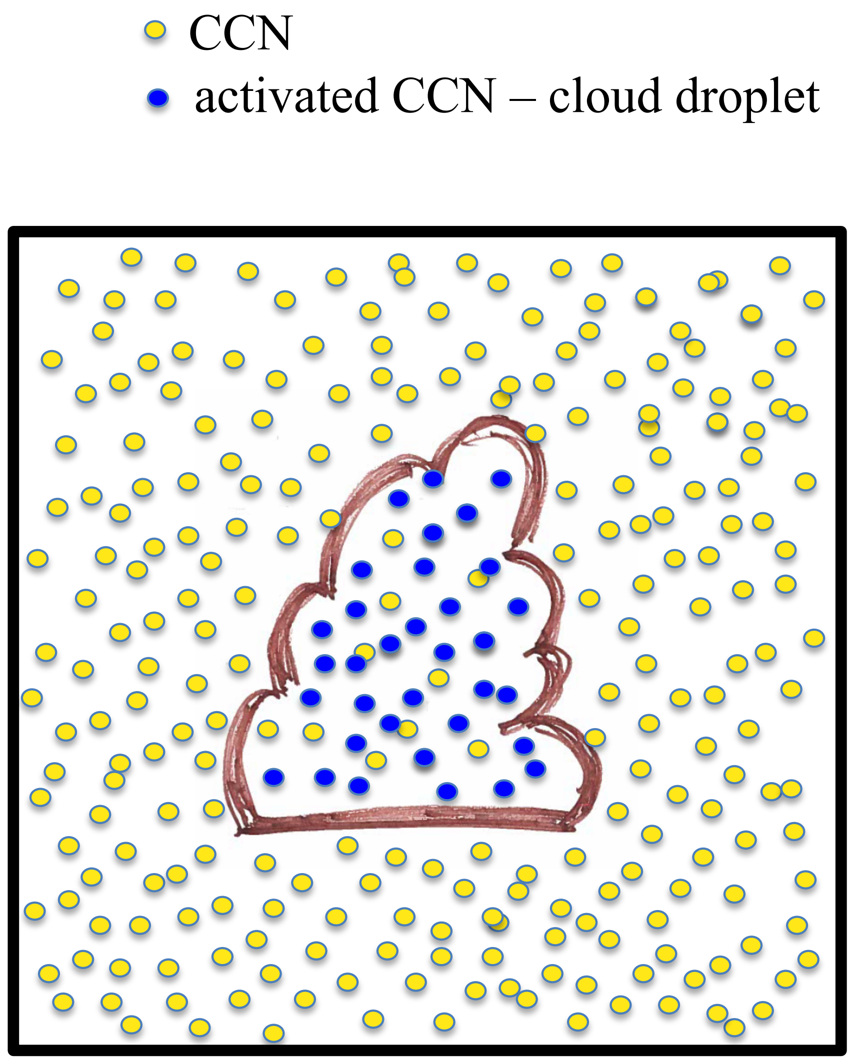
libcloudph++ 1.0: a single-moment bulk, double-moment bulk, and particle-based warm-rain microphysics library in C++

S. Arabas[1], A. Jaruga[1], H. Pawlowska[1], and W. W. Grabowski[2]

[1]Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[2]National Center for Atmospheric Research (NCAR), Boulder, CO, USA

A new method for large-eddy simulations of clouds with Lagrangian droplets including the effects of turbulent collision

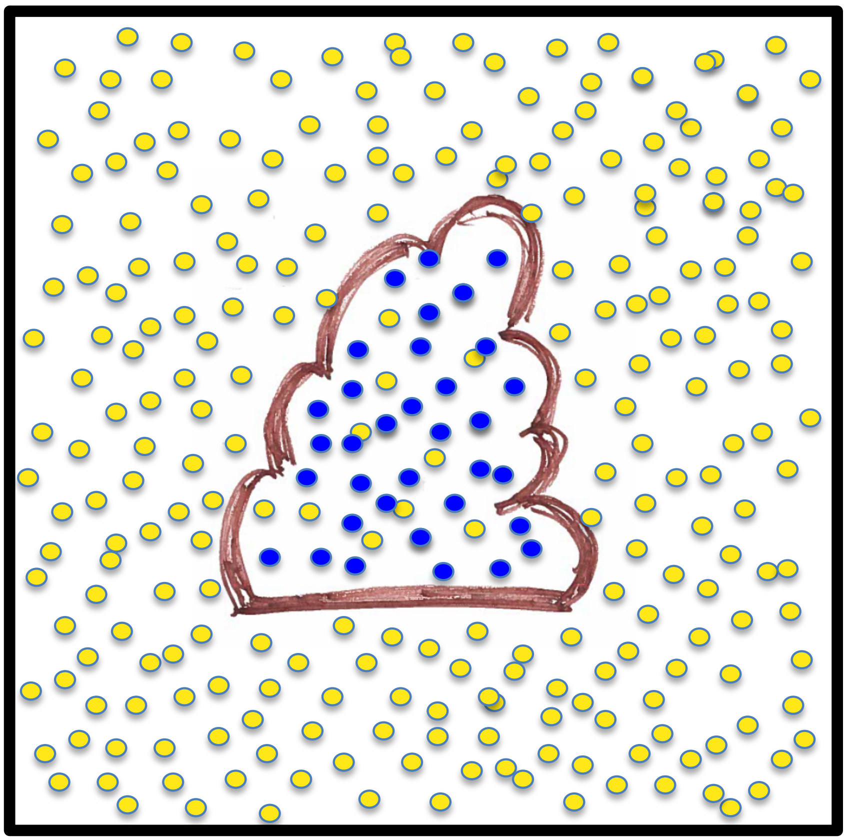
T Riechelmann[1,3], Y Noh[2] and S Raasch[1]



traditional Lagrangian warm-rain microphysics
(e.g., Andrejczuk et al., Shima et al., Arabas et al. and others)

CCN

activated CCN – cloud droplet

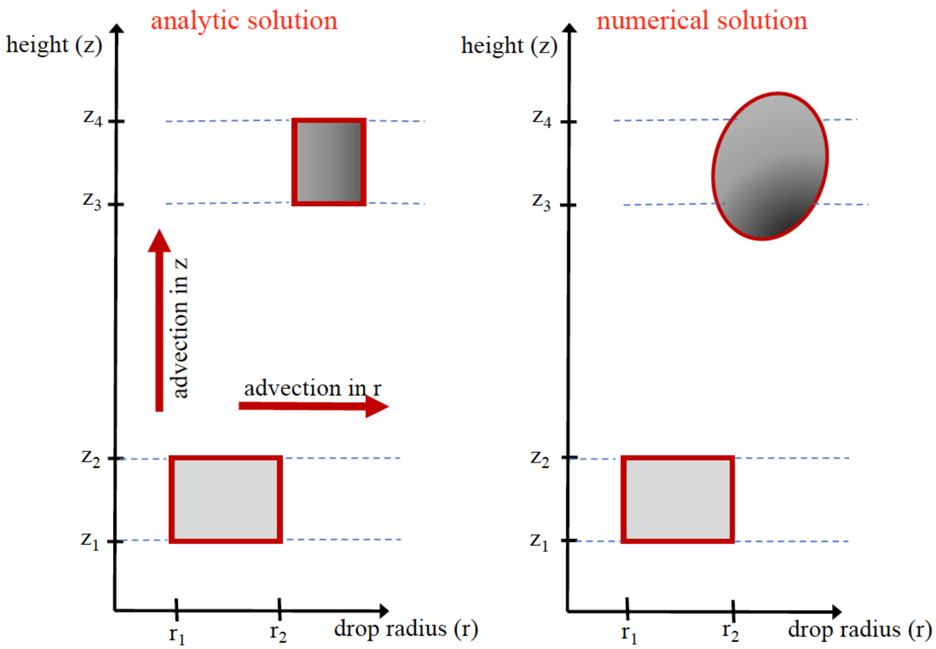


traditional Lagrangian warm-rain microphysics
(e.g., Andrejczuk et al., Shima et al., Arabas et al.)

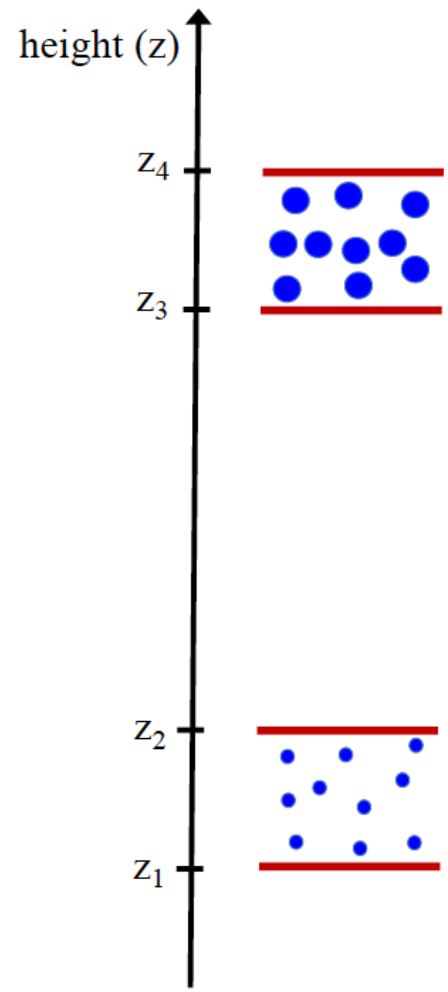
Advantages:

- PDEs replaced by ODEs (simpler!)
- no numerical diffusion due to advection
- particle growth from first principles
- aerosol processing represented
- allows subgrid-scale modeling
- more?

Eulerian bin microphysics



particle-based Lagrangian microphysics



Q. J. R. Meteorol. Soc. (2005), **131**, pp. 195–220 doi: 10.1256/qj.03.199

Broadening of droplet size distributions from entrainment and mixing in a cumulus cloud

By SONIA G. LASHER-TRAPP†[1], WILLIAM A. COOPER[2] and ALAN M. BLYTH[3]
[1]*New Mexico Institute of Mining and Technology, Socorro, USA*
[2]*National Center for Atmospheric Research, Boulder, USA*
[3]*University of Leeds, Leeds, UK*

First, run a traditional Eulerian fluid dynamics cloud model…

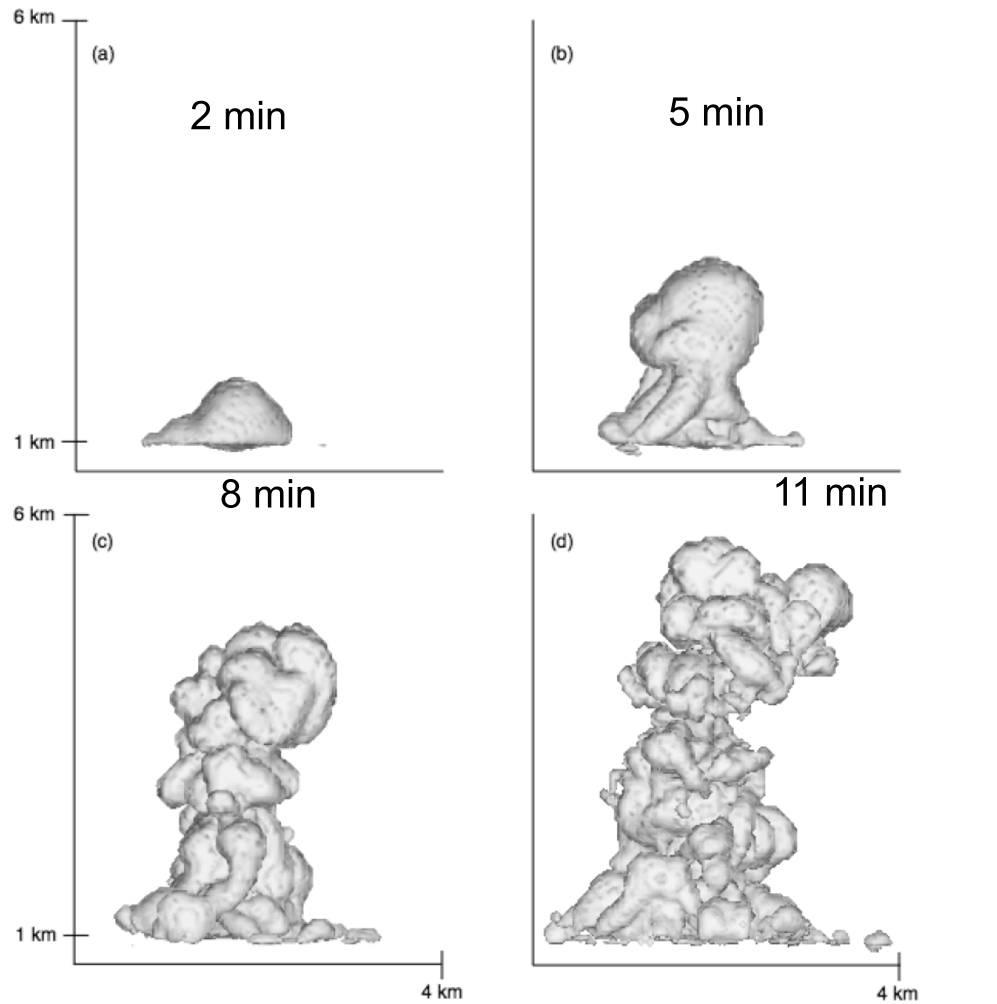
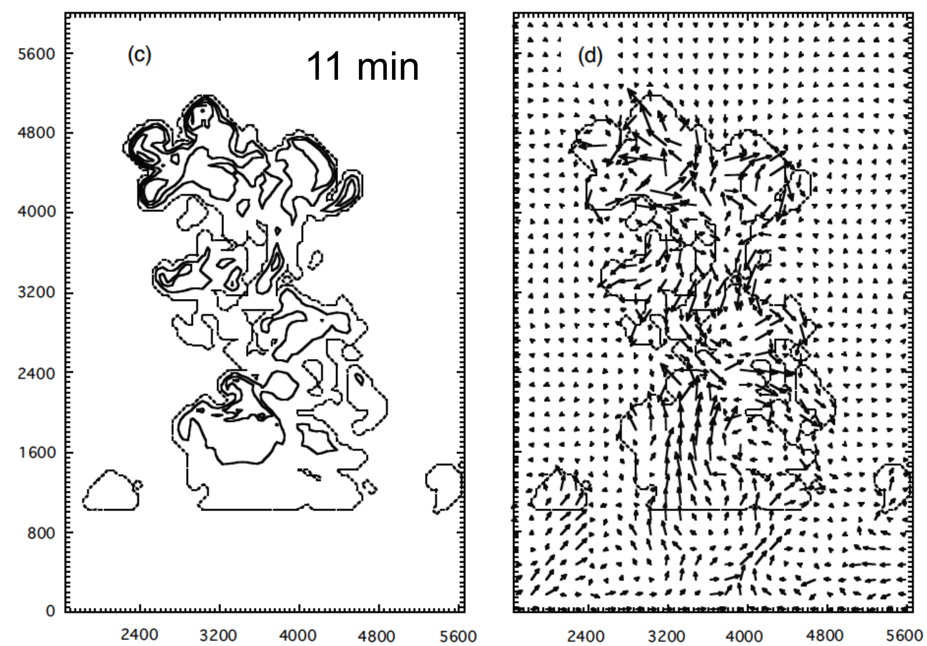


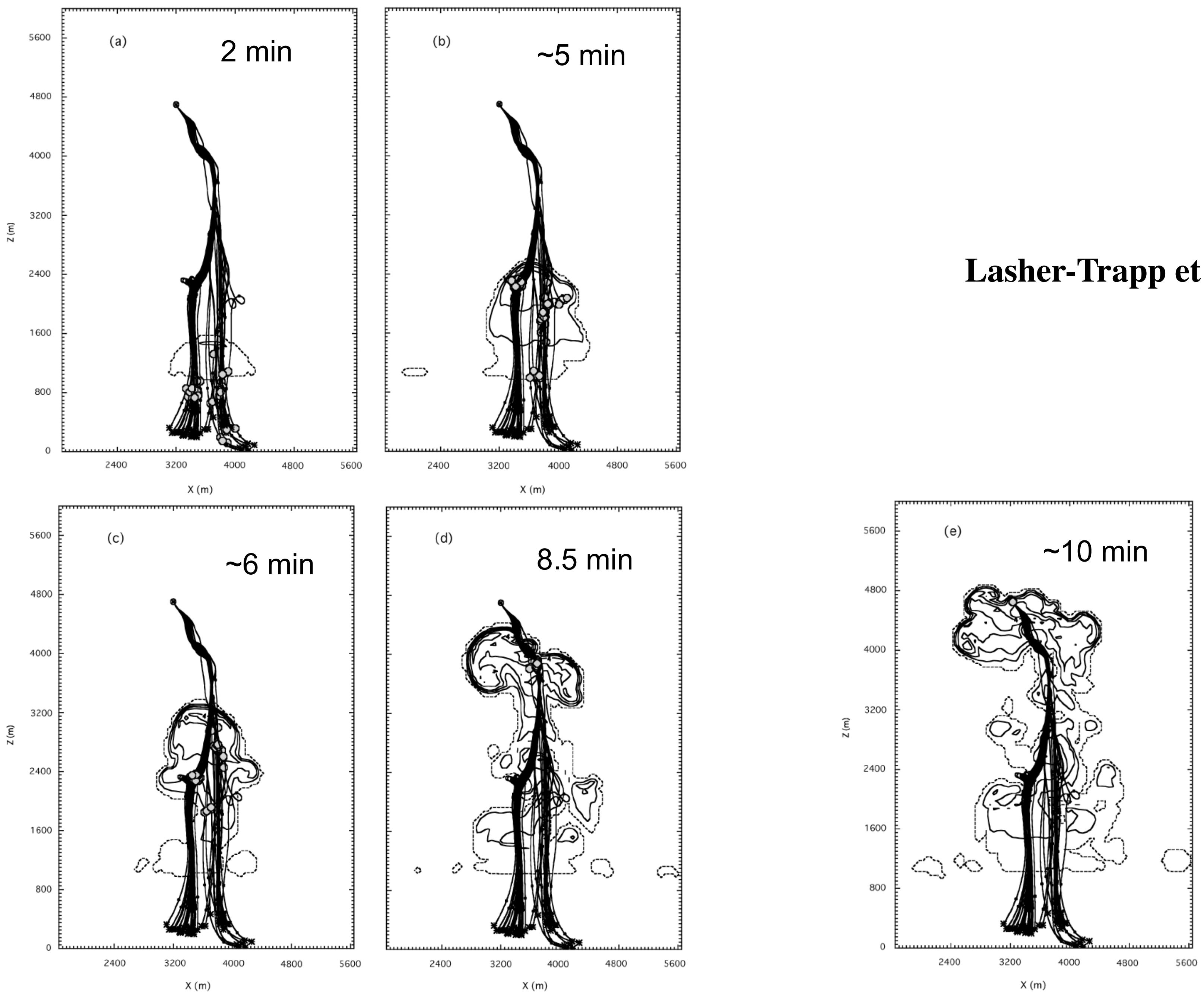
Figure 2. The simulated cloud used in this study. Shown is an isosurface of 0.005 g kg^{-1} of cloud-water mixing ratio at: (a) 2, (b) 5, (c) 8 and (d) 11 minutes after the first appearance of cloud.

$\Delta = 50$ m



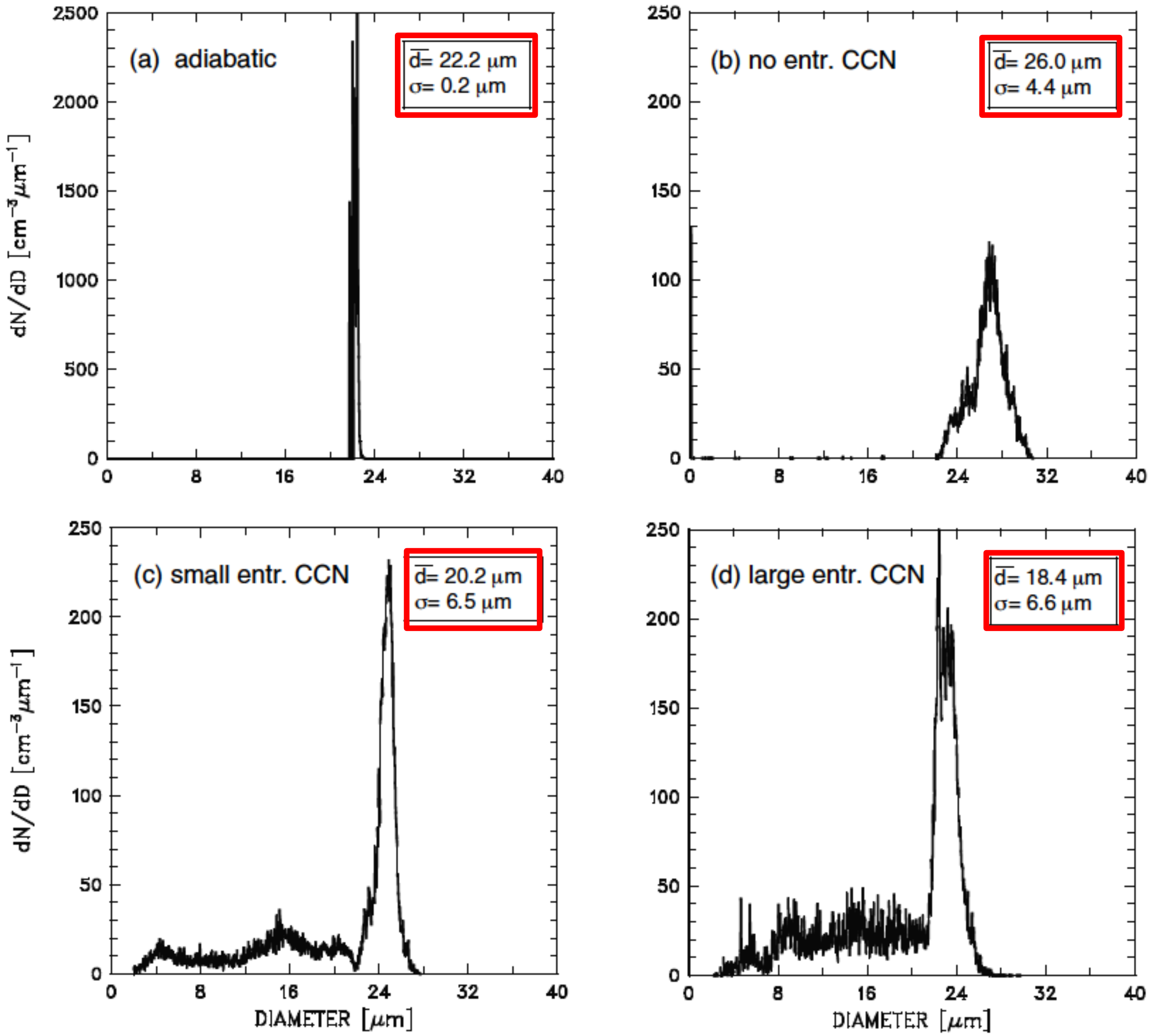
Lasher-Trapp et al. QJRMS 2005

…second, run backward ensemble of trajectories from a selected point…



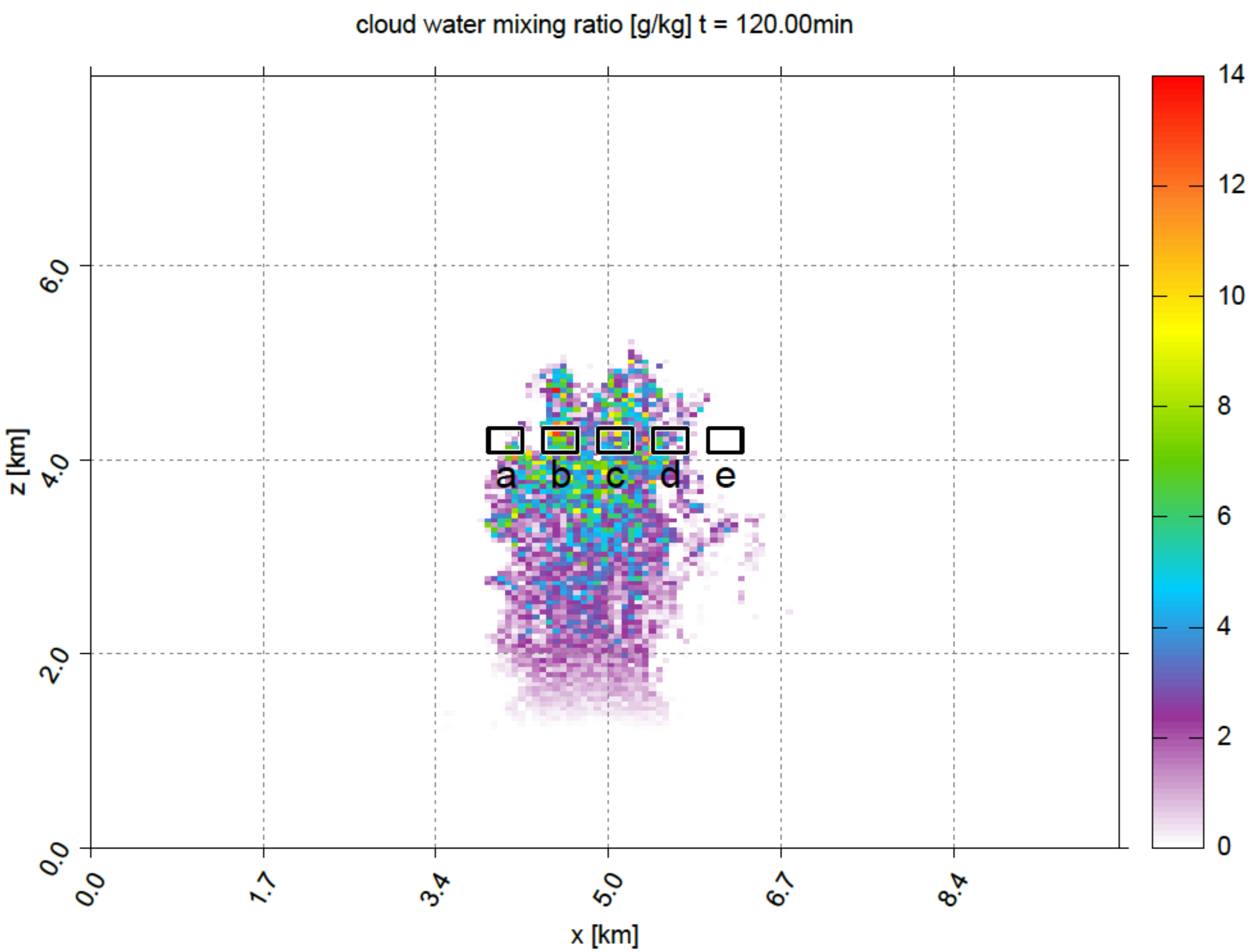
Lasher-Trapp et al. QJRMS 2005

...third, calculate activation and growth of cloud droplets along trajectories.

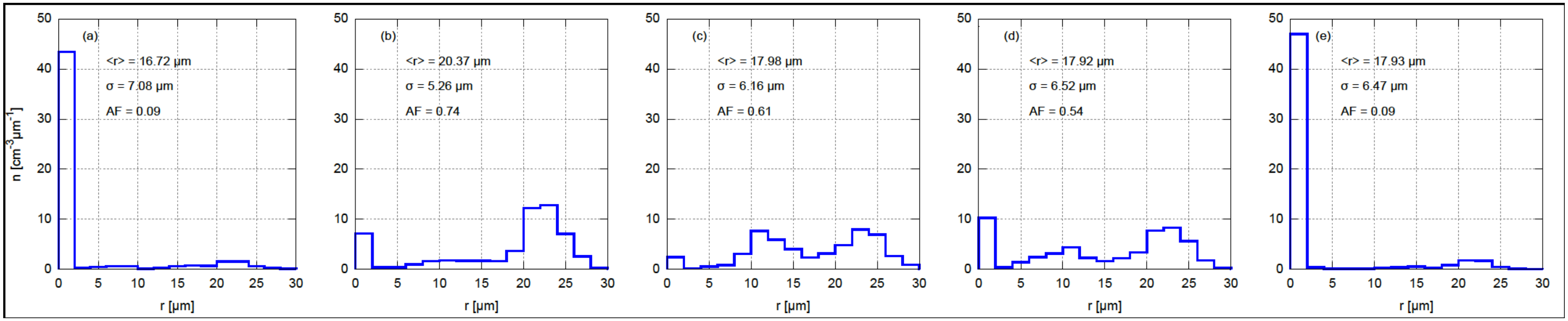


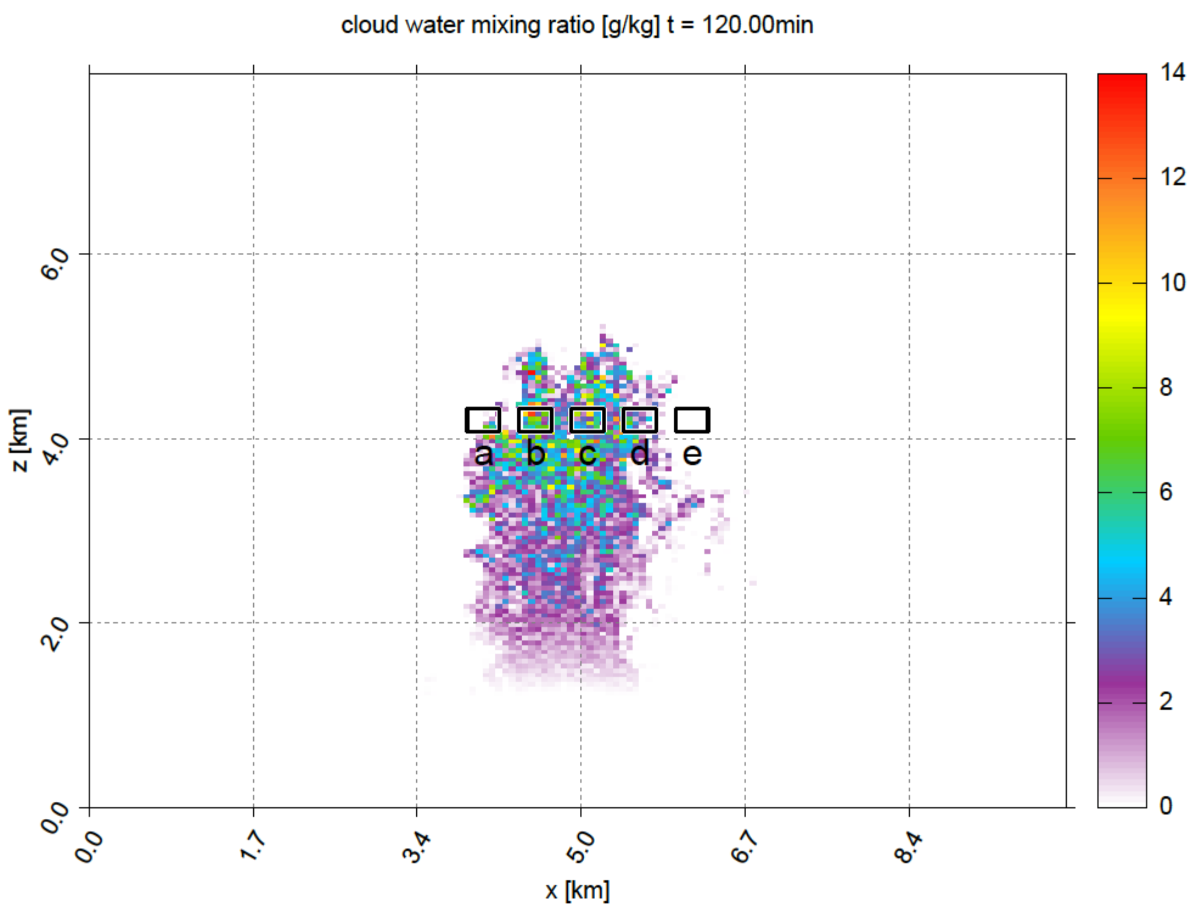
Lasher-Trapp et al. QJRMS 2005

This is really a nice result, but the methodology is cumbersome. Lagrangian microphysics can produce similar result on the fly!...



Courtesy of Dr. Piotr Dziekan, Institute of Geophysics, University of Warsaw





Courtesy of Dr. Piotr Dziekan, Institute of Geophysics, University of Warsaw

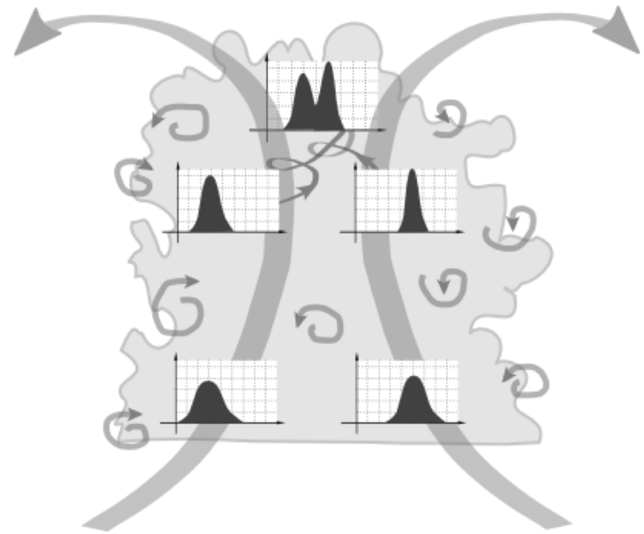
Lagrangian approach allows straightforward incorporation of a subgrid-scale that can better represent the multi-scale nature of turbulent clouds…

Nauman and Seifert (JAMES 2015, 2016)– raindrop recirculation study

Grabowski and Abade (JAS 2017), Abade et al. (JAS 2018)– "eddy hopping"…

Eddy-hopping mechanism

(Cooper 1989; Grabowski and Wang ARFM 2013)



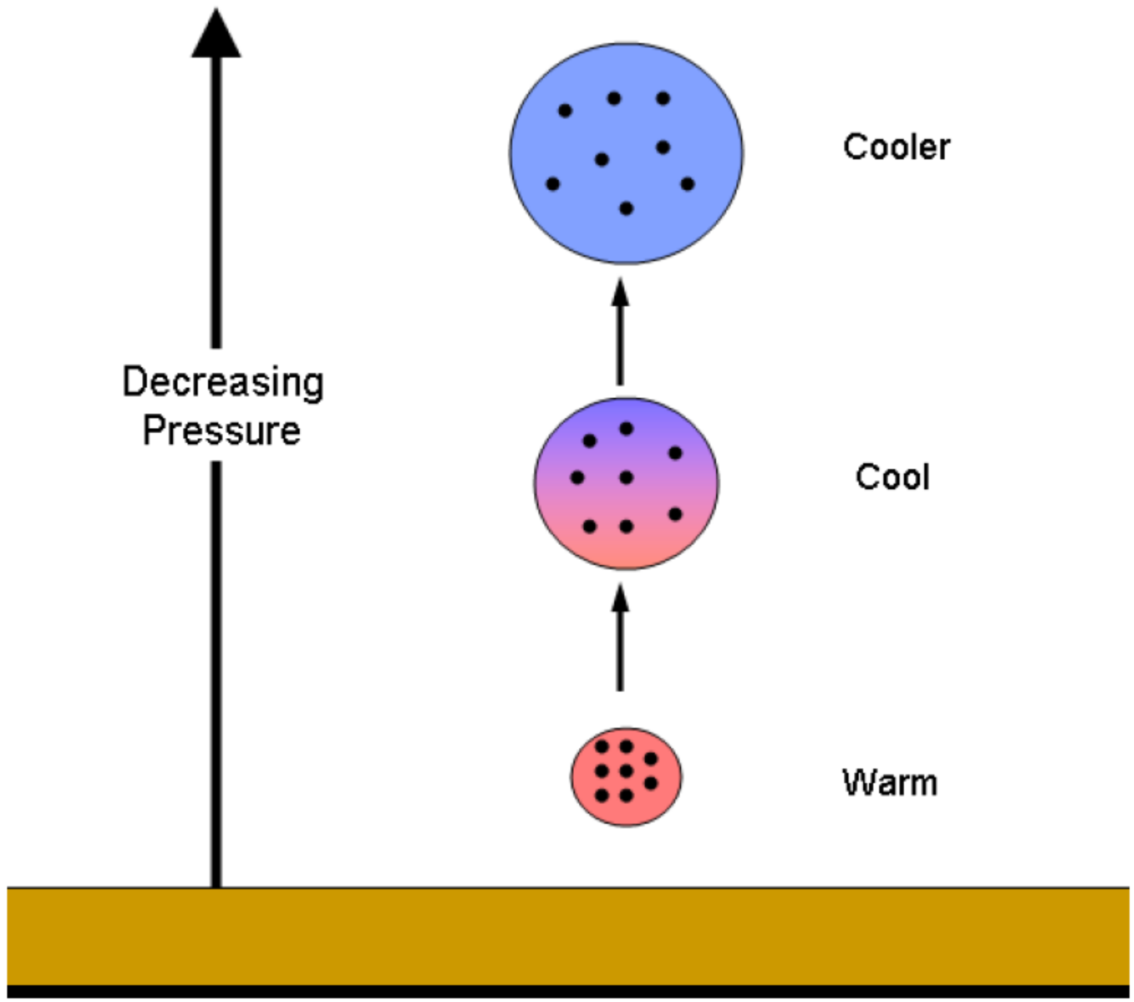
Droplets observed in a single location within a turbulent cloud arrive along variety of air trajectories:

- *large scales are needed to provide different droplet activation/growth histories;*

- *small scales needed to allow hopping from one large eddy to another.*

[see also Sidin et al. (*Phys. Fluids* 2009) for idealized 2D synthetic turbulence simulations]

The simplest model of cloud processes: the adiabatic parcel

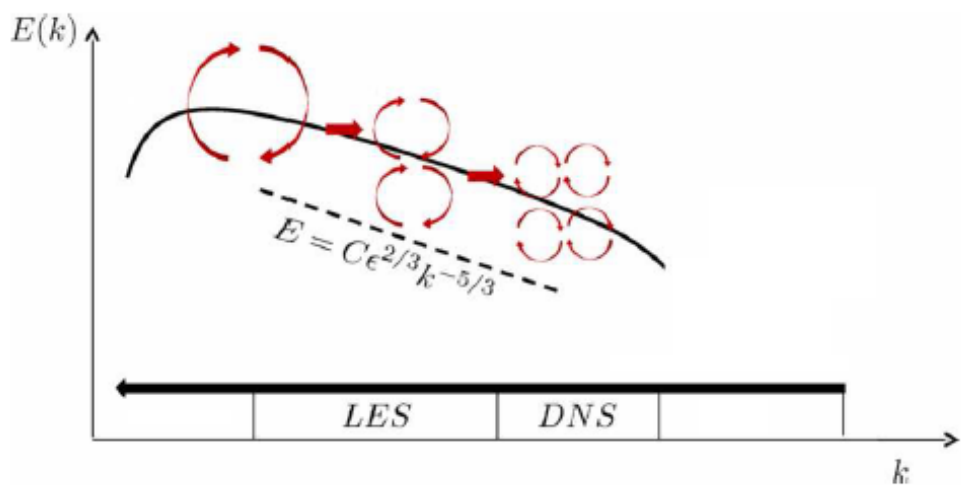


Grabowski and Abade, 2017: Broadening of cloud droplet spectra through eddy hopping: Turbulent adiabatic parcel simulations. *J. Atmos. Sci.* **74**, 1485-1493.

Turbulent adiabatic parcel model: adiabatic parcel assumed to be filled with homogeneous isotropic turbulence.

Two parameters determining the turbulence:

1) dissipation rate of TKE, ε
2) scale (extent) of the parcel, L



turbulent kinetic energy, E

$$E = \left(\frac{L\varepsilon}{C_E} \right)^{2/3}$$

integral time scale, τ

$$\tau = \frac{L}{(2\pi)^{1/3}} \left(\frac{C_\tau}{E} \right)^{1/2}$$

$C_E = 0.845$

$C_\tau = 1.5$

Grabowski and Abade *JAS* 2017

Supersaturation fluctuation *S'* (on top of the mean *S*) experienced by each superdroplet:

$$\frac{dS_i'}{dt} = a_1 w' - \frac{S_i'}{\tau_{\mathrm{relax}}}$$

$$\tau_{\mathrm{relax}} = \left(a_2 \sum r_i N_i\right)^{-1}$$

$$a_2 = 2.8 \times 10^{-4}\ \mathrm{m^2\,s^{-1}}$$

$$a_1 = 3 \times 10^{-4}\ \mathrm{m^{-1}}$$

Important note: phase relaxation time is the same for all droplets.

Hence, additional factors that may increase the impact (e.g., droplet concentration heterogeneities) are excluded…

Grabowski and Abade *JAS* 2017

Vertical velocity perturbation w' is assumed to be a random stationary processes and it is evolved in time as:

$$w'(t+\delta t) = w'(t)e^{-\delta t/\tau} + \sqrt{1-e^{-2\delta t/\tau}}\,\sigma_{w'}\psi$$

$$\sigma_{w'}^2 = \frac{2}{3}E$$

E - turbulent kinetic energy

τ – turbulence integral time scale

ψ Gaussian random number drawn every time step

δt model time step

Grabowski and Abade *JAS* 2017

no turbulence

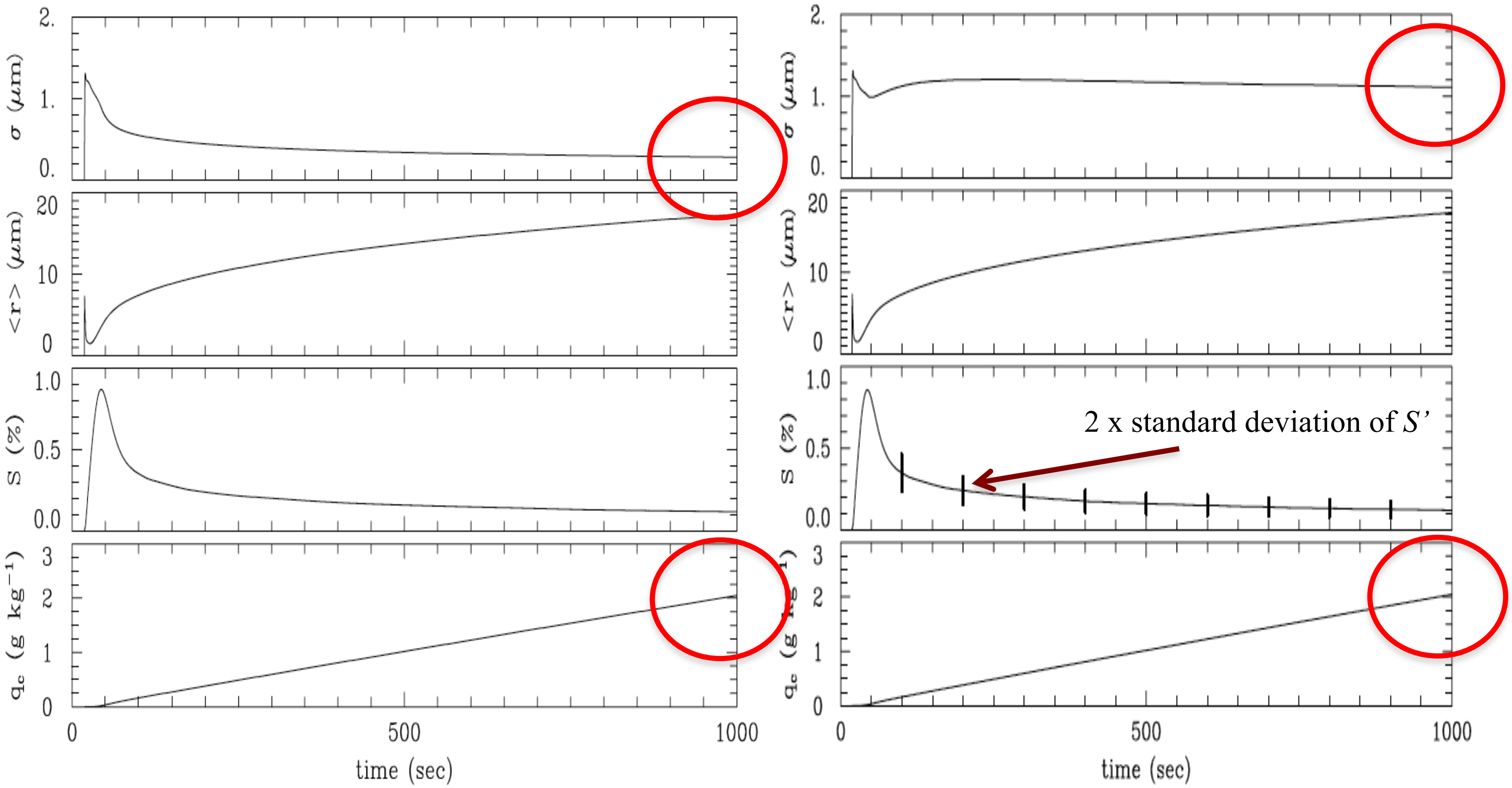
$L = 50$ m, $\varepsilon = 50$ cm^2 s^{-3}

spectral width

mean radius

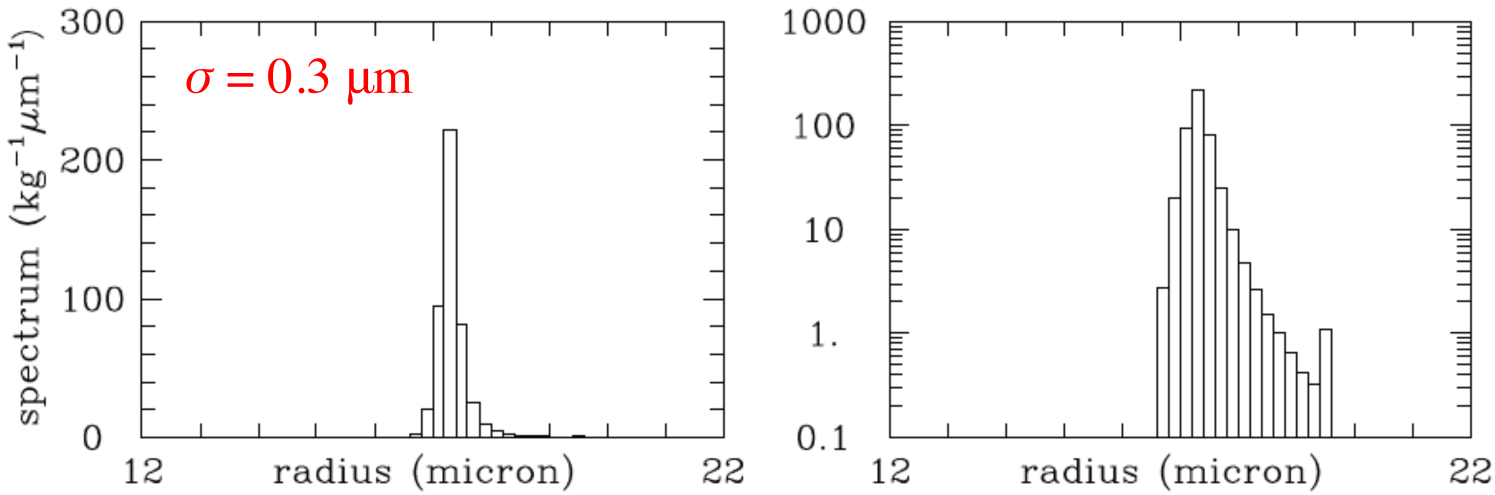
supersaturation

$$\sum_i \frac{4}{3}\pi r_i^3 N_i \frac{\rho_w}{\rho_0}$$

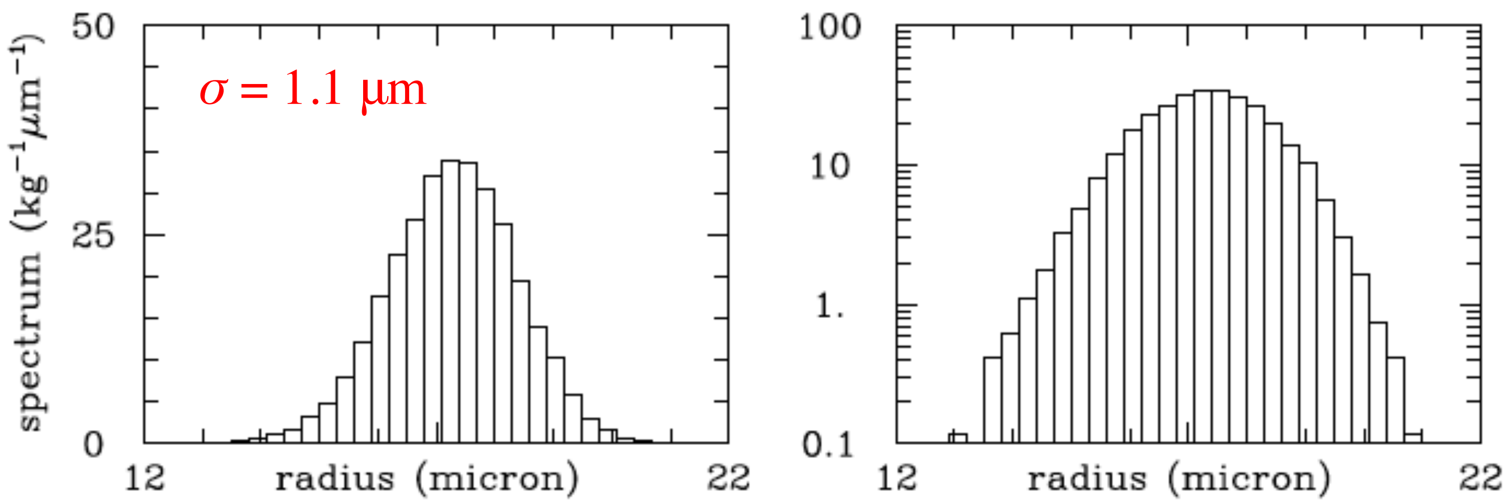


Grabowski and Abade *JAS* 2017

No turbulence



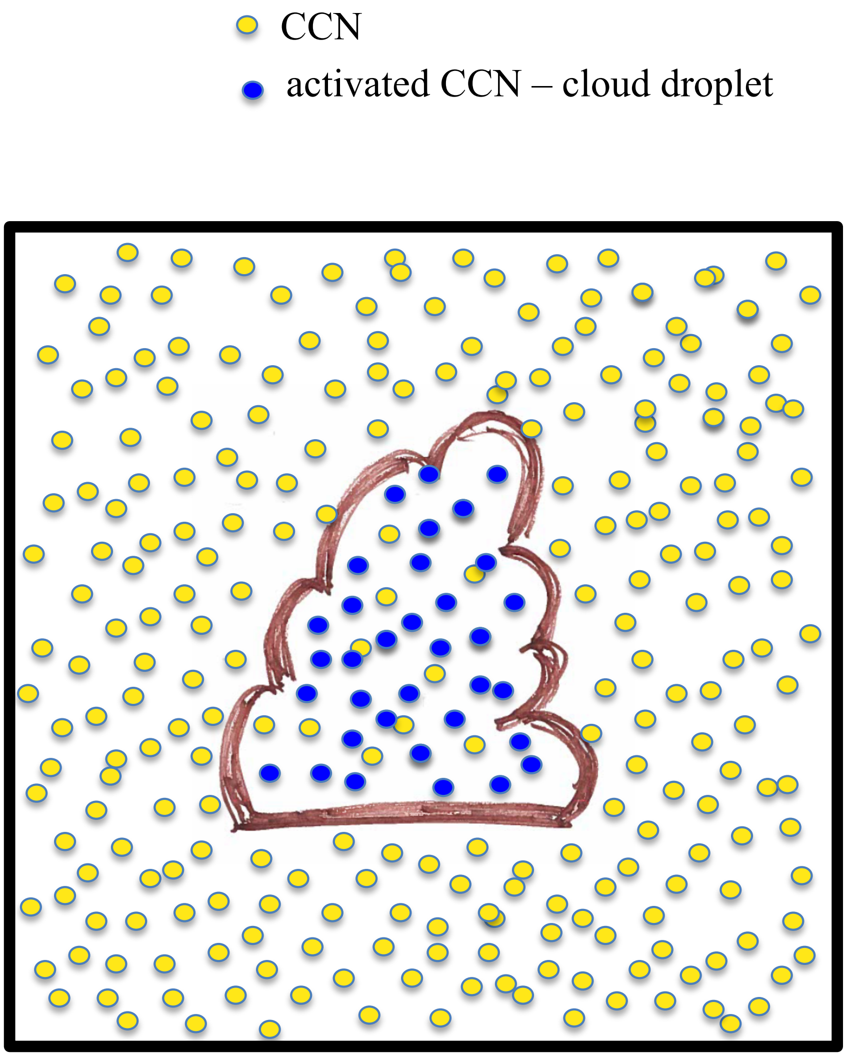
$L = 50$ m, $\varepsilon = 50$ cm^2 s^{-3}



Grabowski and Abade *JAS* 2017

This approach is relatively straightforward to include in LES model.

This work is in progress at U. of Warsaw (Gustavo Abade, Piotr Dziekan, Hanna Pawlowska)…



traditional Lagrangian warm-rain microphysics
(e.g., Andrejczuk et al., Shima et al., Arabas et al.)

Disadvantages:

- large number of particles needed
- whole domain filled with particles
- small time step for deliquescence
- maybe more?

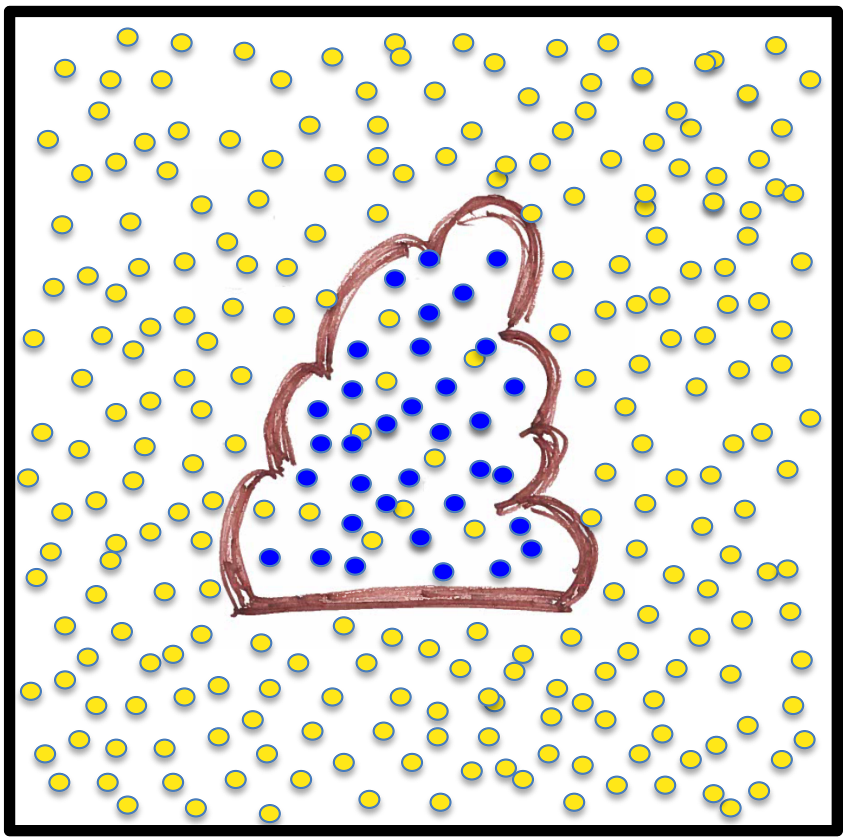
Can we modify the original Lagrangian Cloud Model proposal to keep as many advantages as possible, but make it more efficient?

Use Twomey activation!

Create super-droplets when activation is required, remove them when complete evaporation takes place, i.e., as in the bin scheme!

CCN

activated CCN – cloud droplet



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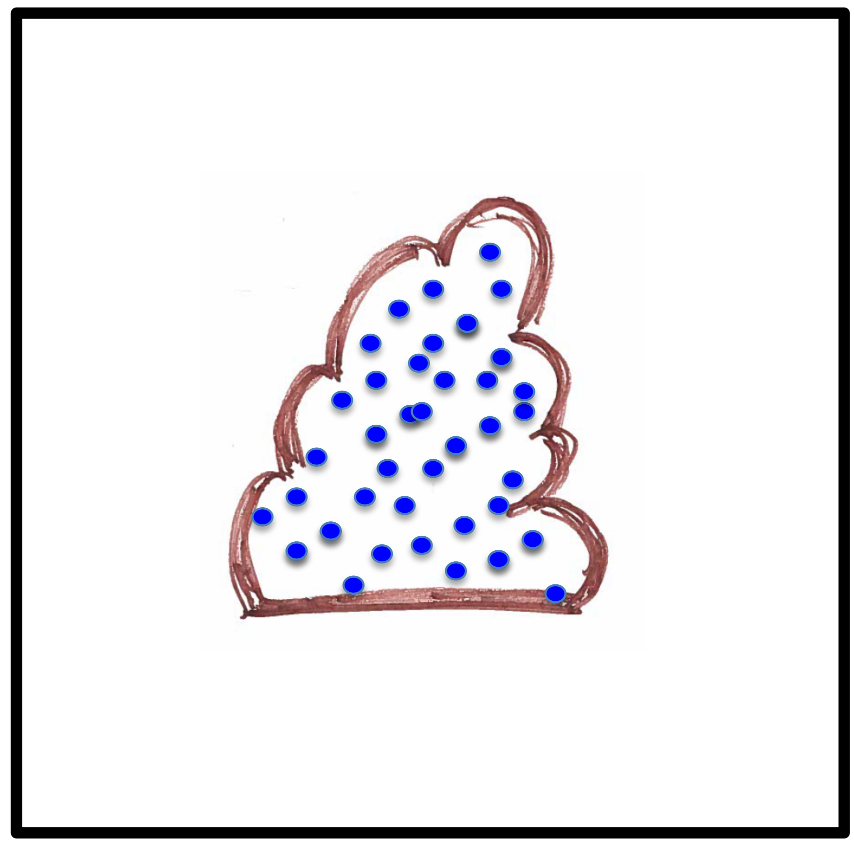
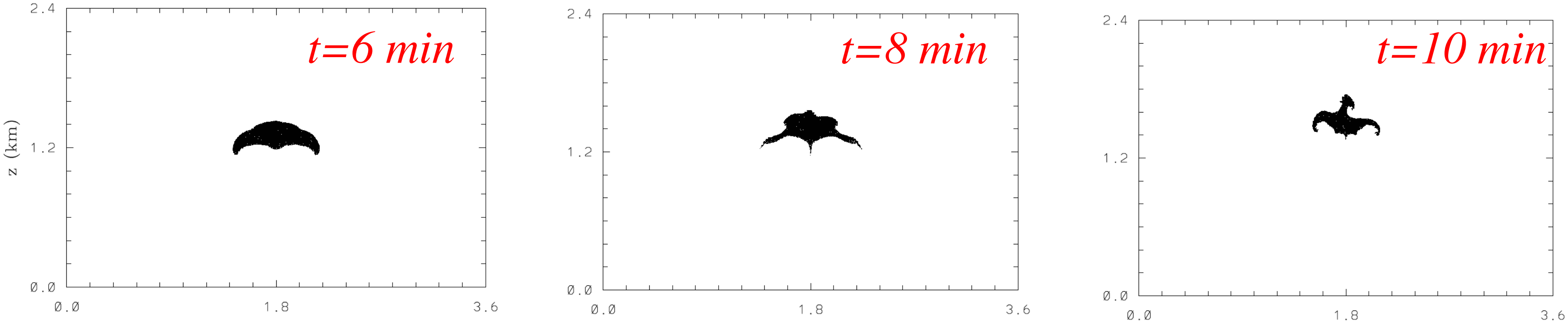
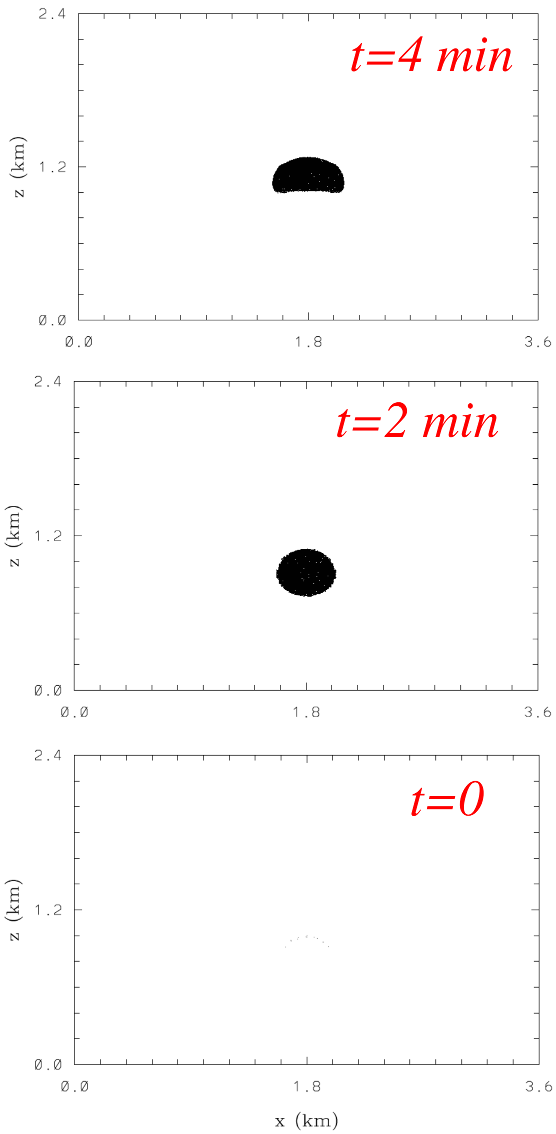


Lagrangian warm-rain microphysics with Twomey activation (Grabowski et al. *GMD* 2018)





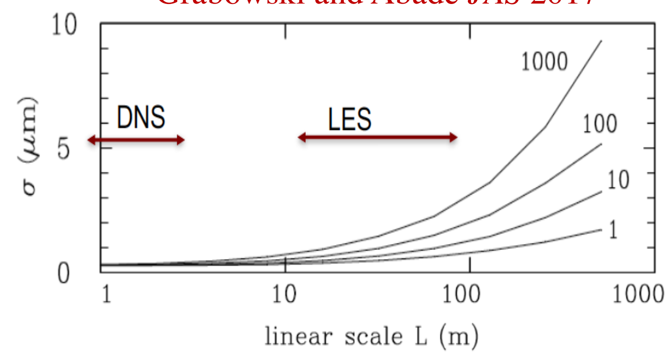
Super-droplets with Twomey CCN activation: super-droplets exist only inside a cloud. This is what makes the method computationally efficient. However, aerosol processing cannot be simulated. See Grabowski et al. *GMD* 2018 for more details and comparison with the traditional super-droplet simulations…

Summary and outlook:

Lagrangian approach to model cloud processes provides a straightforward methodology when compared to existing Eulerian bin microphysics schemes. Applying Twomey activation (e.g., $N=aS^b$) reduces computational cost as Lagrangian super-droplets exist only inside clouds. Excluding modeling of CCN deliquescence allows more savings. Application of other CCN activation parameterization makes it feasible to use the Lagrangian approach in lower resolution models (e.g., targeting deep convection).

Since typical grid lengths in LES cloud simulations are a few 10s of meters, the impact of eddy hoping on the droplet spectrum needs to be included. This is straightforward when the Lagrangian approach is used, but difficult (impossible?) for traditional Eulerian LES cloud models.

Grabowski and Abade *JAS* 2017



Extension of the Lagrangian approach to include ice processes seems straightforward and is pursued by several groups (Japan, Germany, Poland). Application to deep convection simulation should become a reality soon…