Particle-based cloud microphysics: rationale, state of the art and challenges

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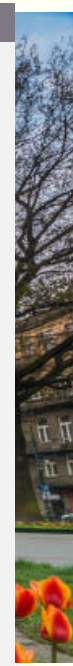

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- 1917 Smoluchowski elected as Rector (professor since 1913)

Maurycy Pius Rudzki (1862–1916)

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Maurycy Pius Rudzki (b. 1862, d. 1916) was the first person to call himself a professor of geophysics. He held the Chair of Geophysics at the Jagiellonian University in Kraków, and established the Institute of Geophysics there in 1895. His research specialty was elastic anisotropy, as applied to wave propagation in the earth, and he established many of the fundamental results in that arena. [1]

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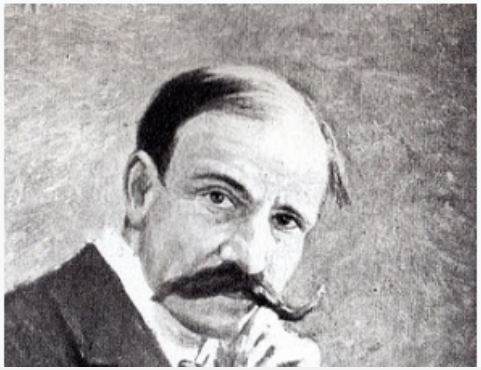

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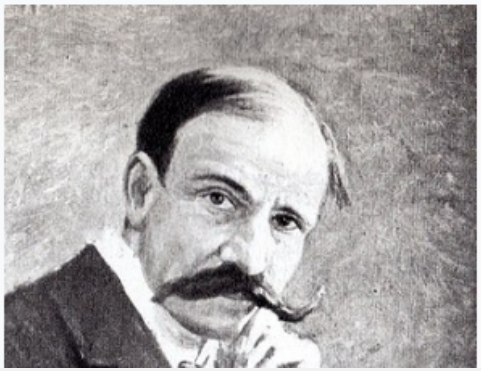
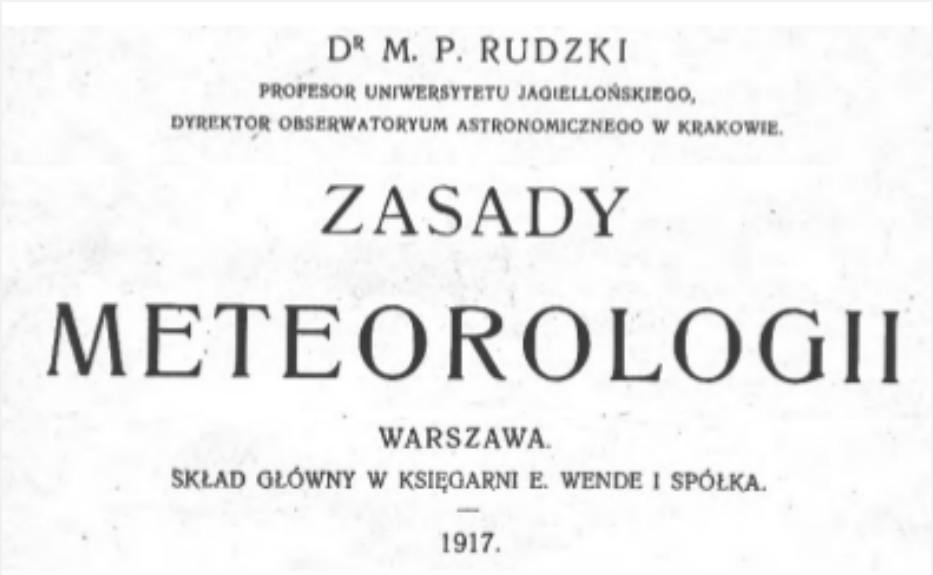


"Principles of Meteorology" book (1917)



Dr M. P. RUDZKI

PROFESOR UNIWERSYTETU JAGIELLOŃSKIEGO,
DYREKTOR OBSERWATORYUM ASTRONOMICZNEGO W KRAKOWIE.

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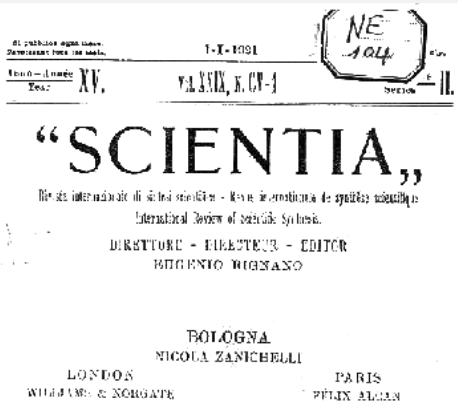

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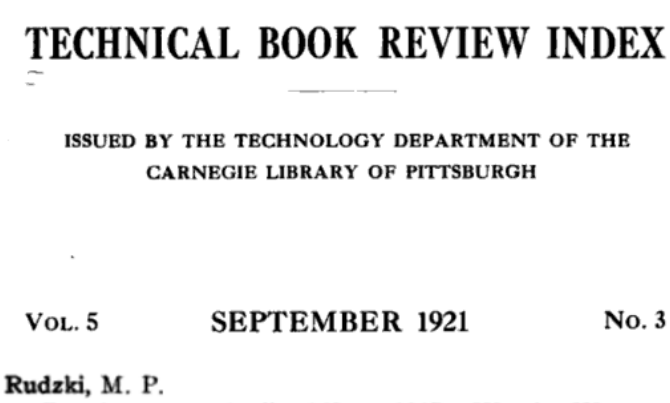

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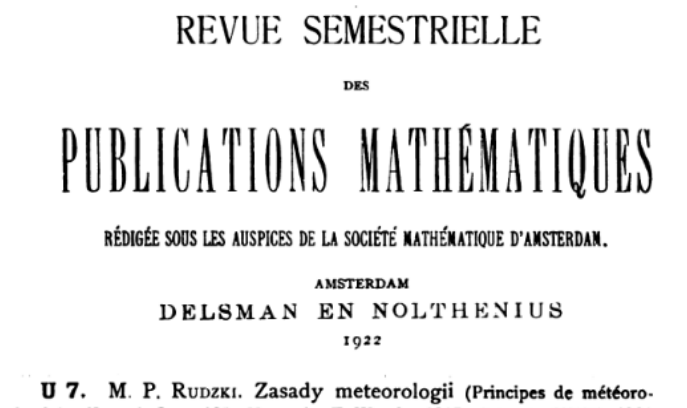

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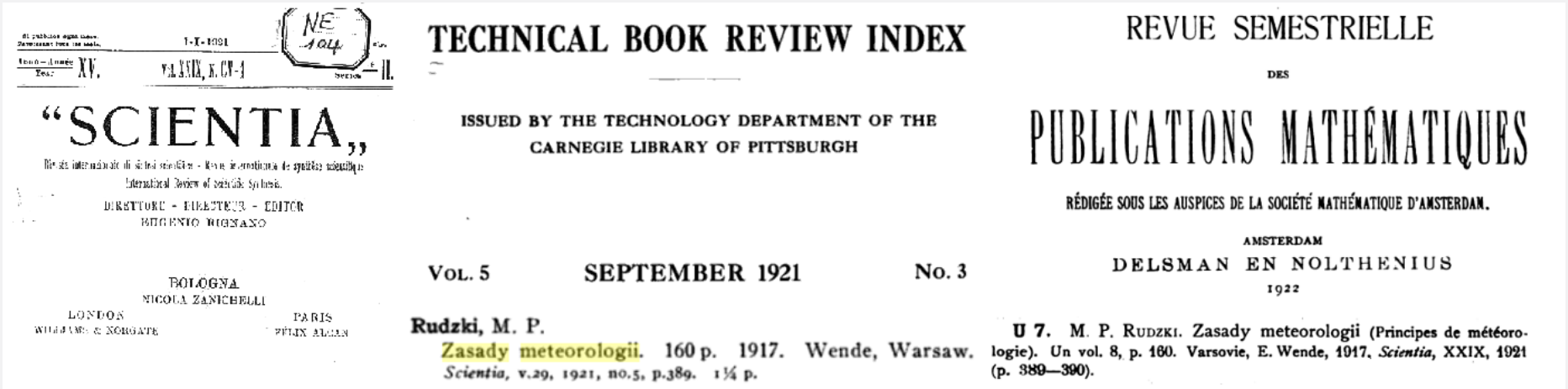

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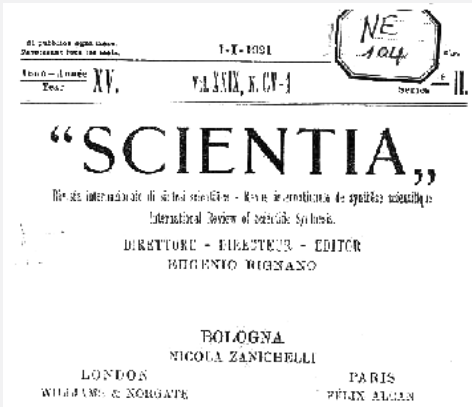

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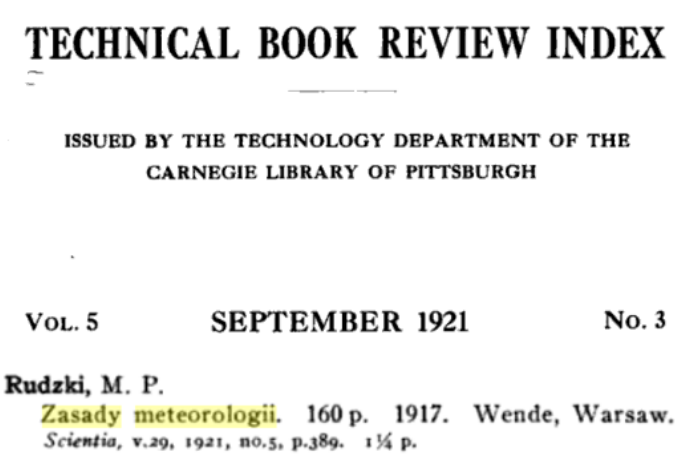

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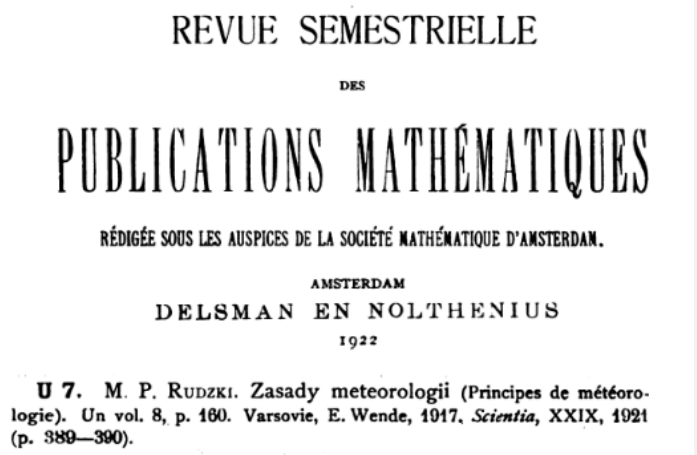

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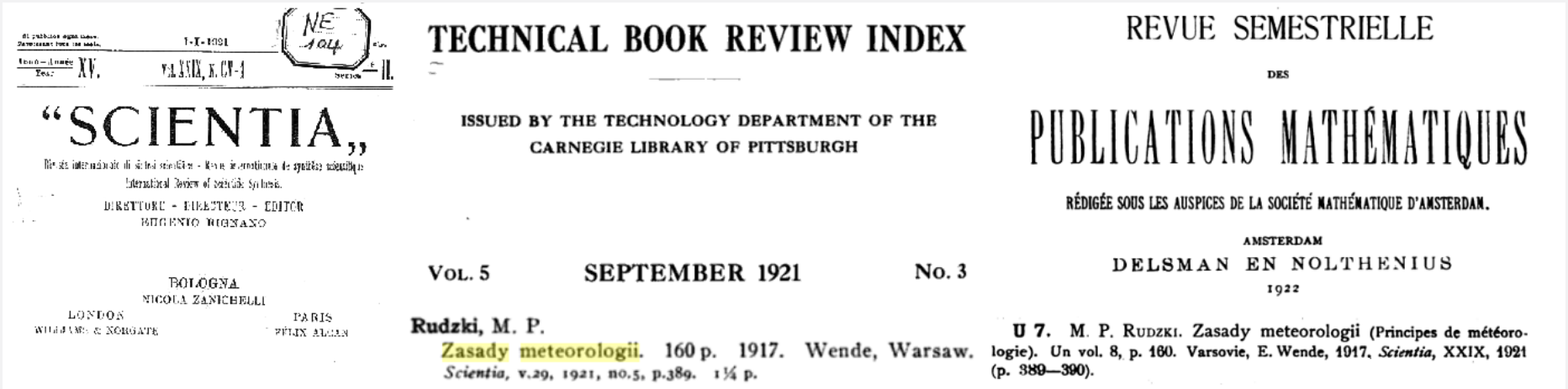

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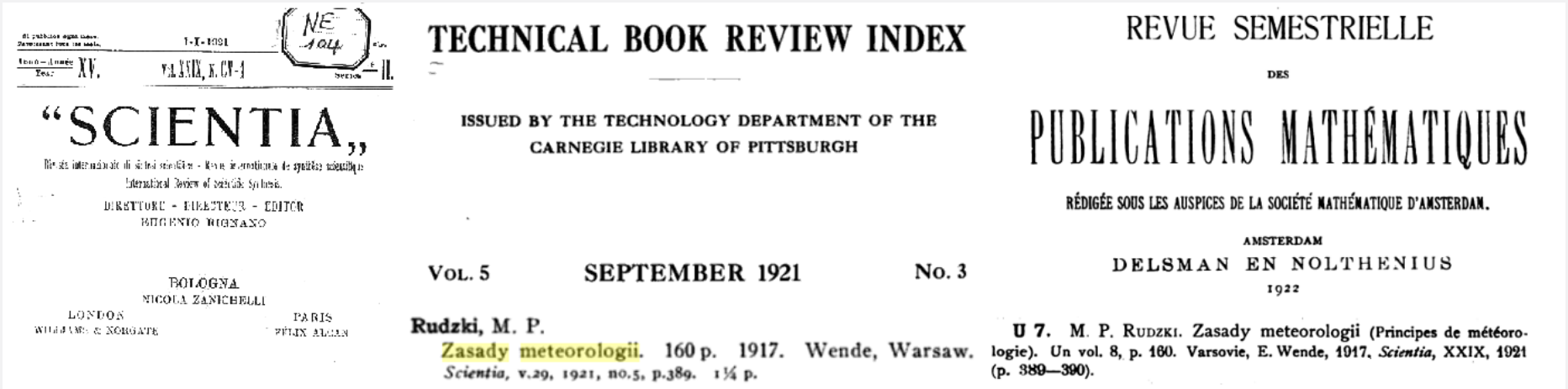

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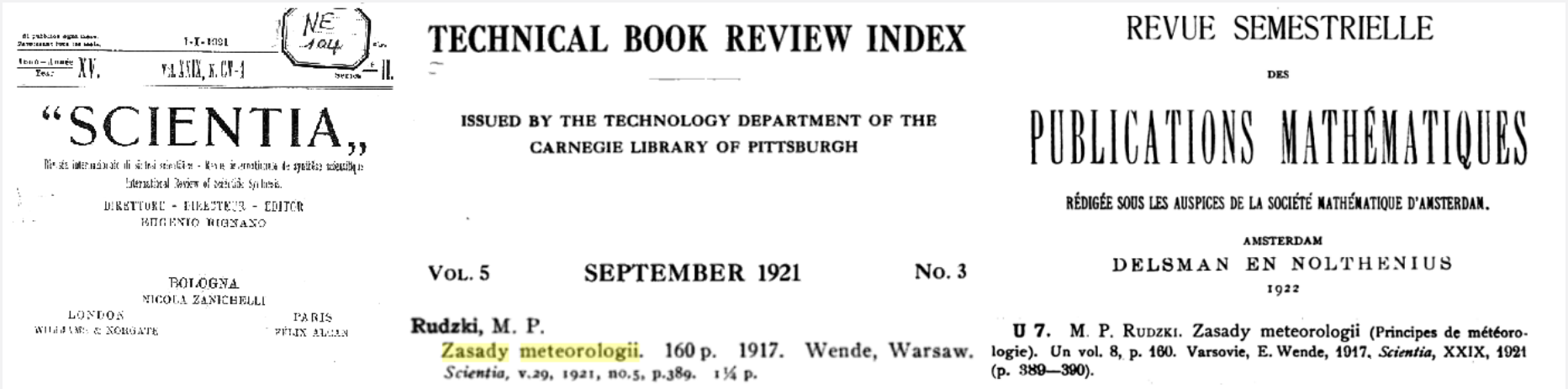

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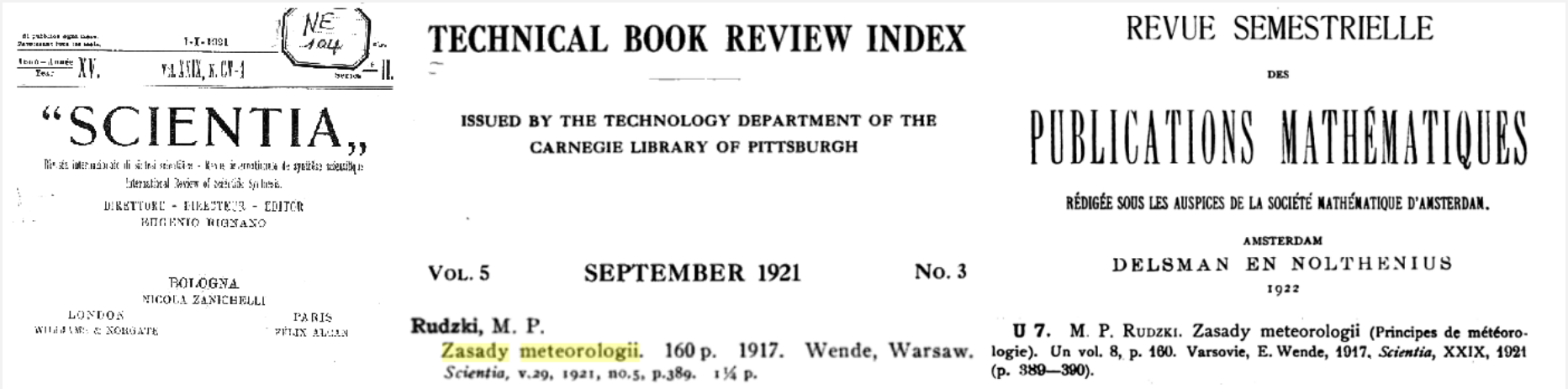

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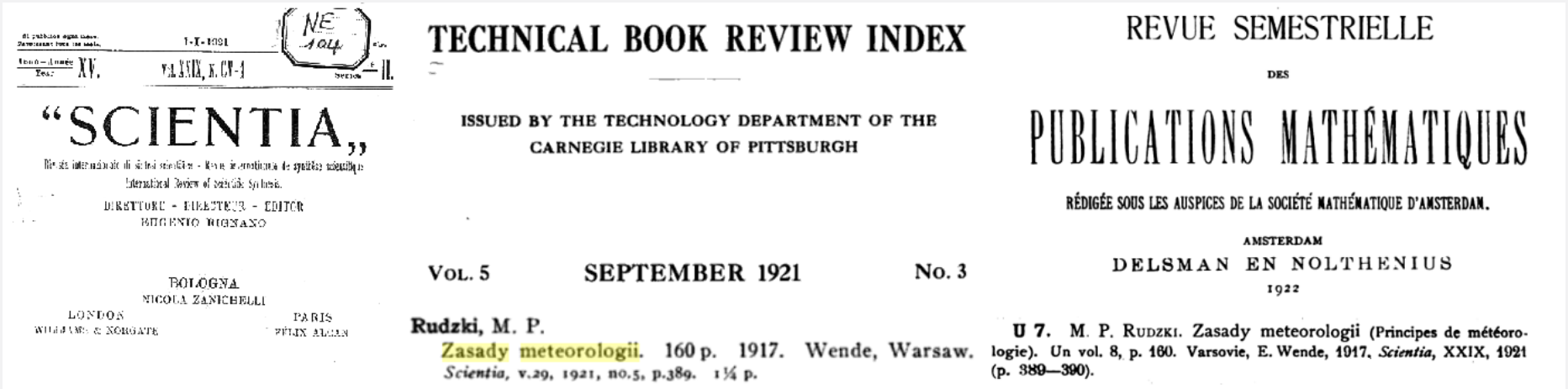

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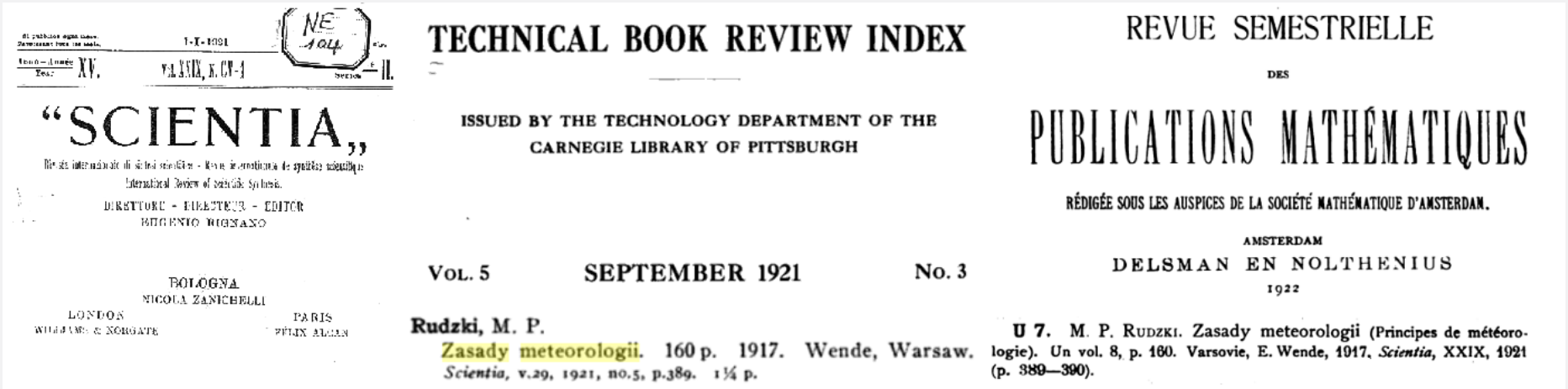

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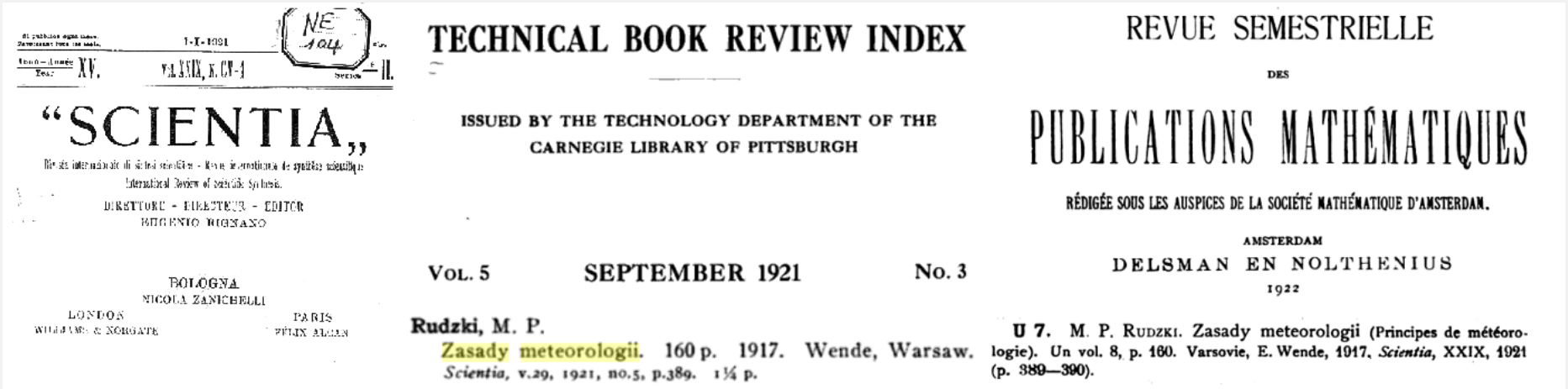

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aerosol-cloud interactions: conceptual picture

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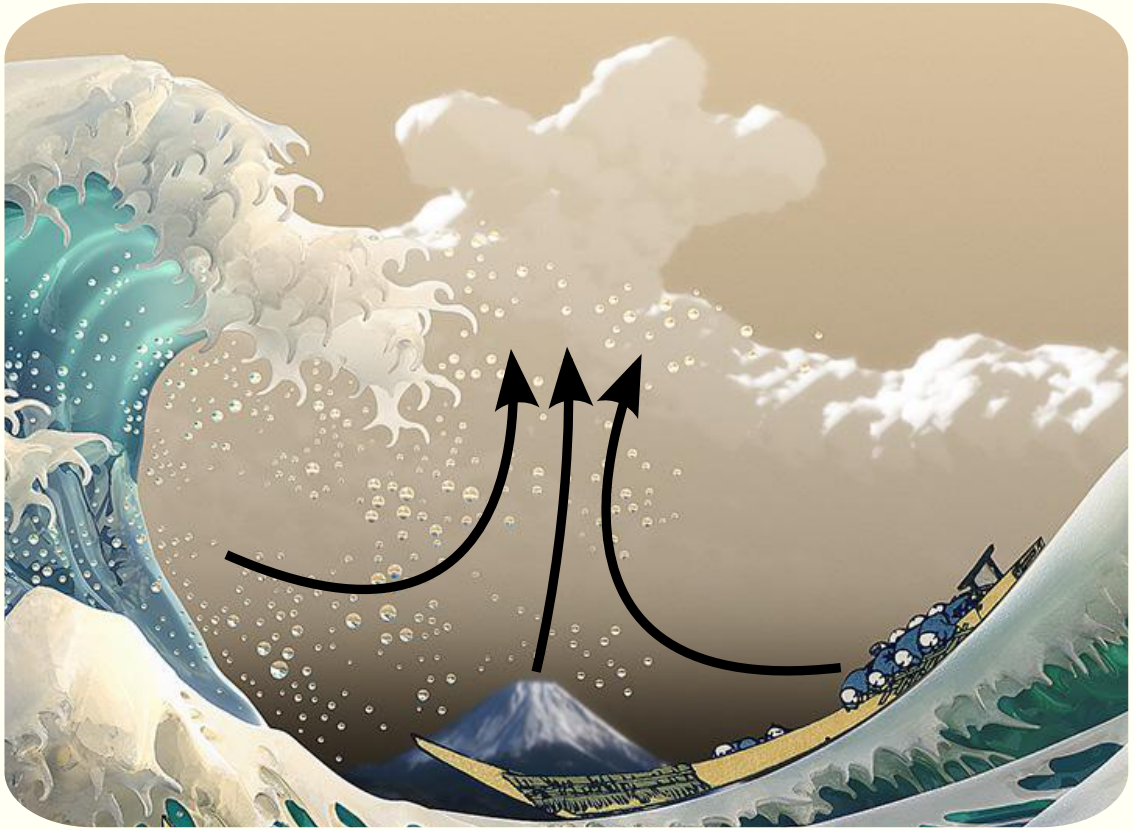

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aerosol-cloud interactions: conceptual picture

- aerosol particles of natural and anthropogenic origin act as condensation nuclei
- cloud droplets grow by water vapour condensation

background image: vitsly.ru / Hokusai

aerosol-cloud interactions: conceptual picture

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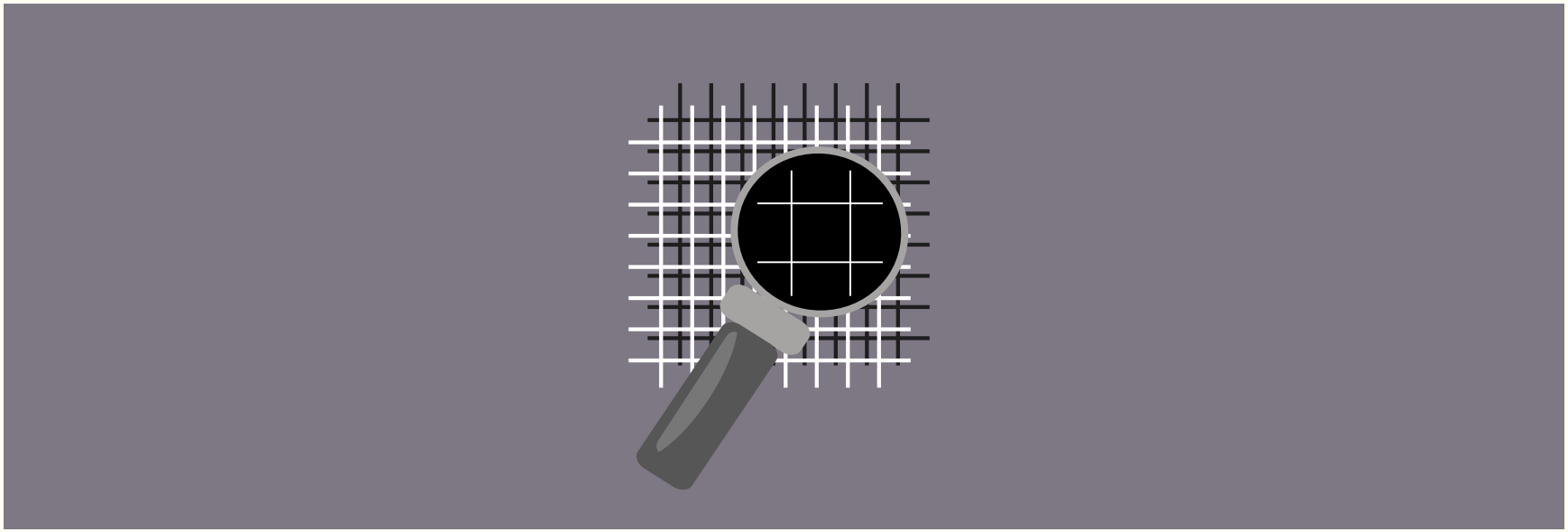
- rain drops precipitate washing out aerosol
- rain drops evaporate into aerosol particles of potentially altered size and/or composition (collisions, chemistry)

background image: vitsly.ru / Hokusai

rationale: modelling aerosol-cloud interactions



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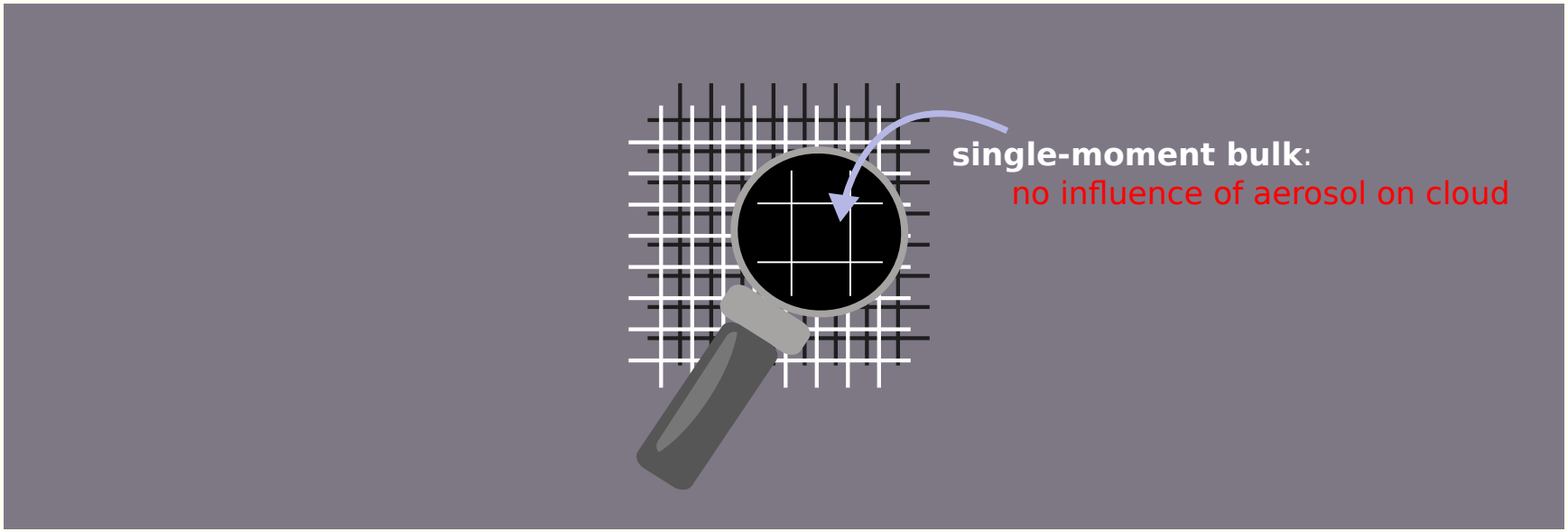

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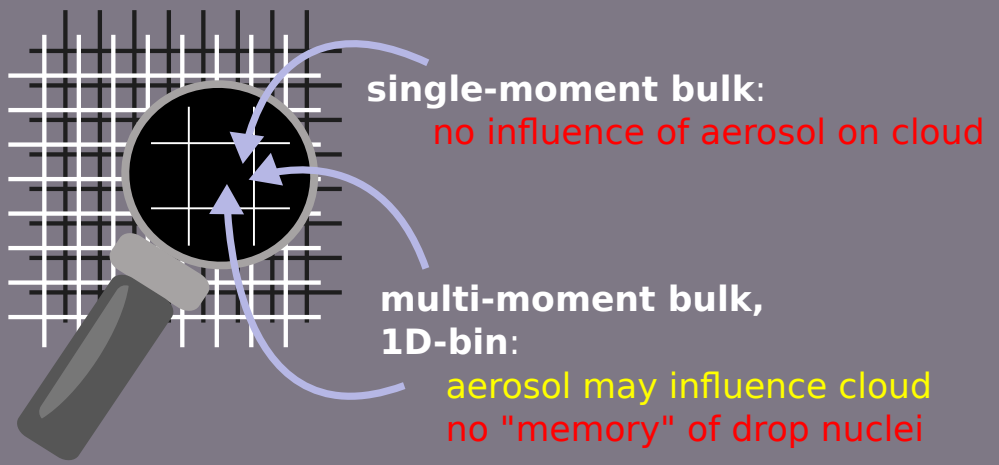

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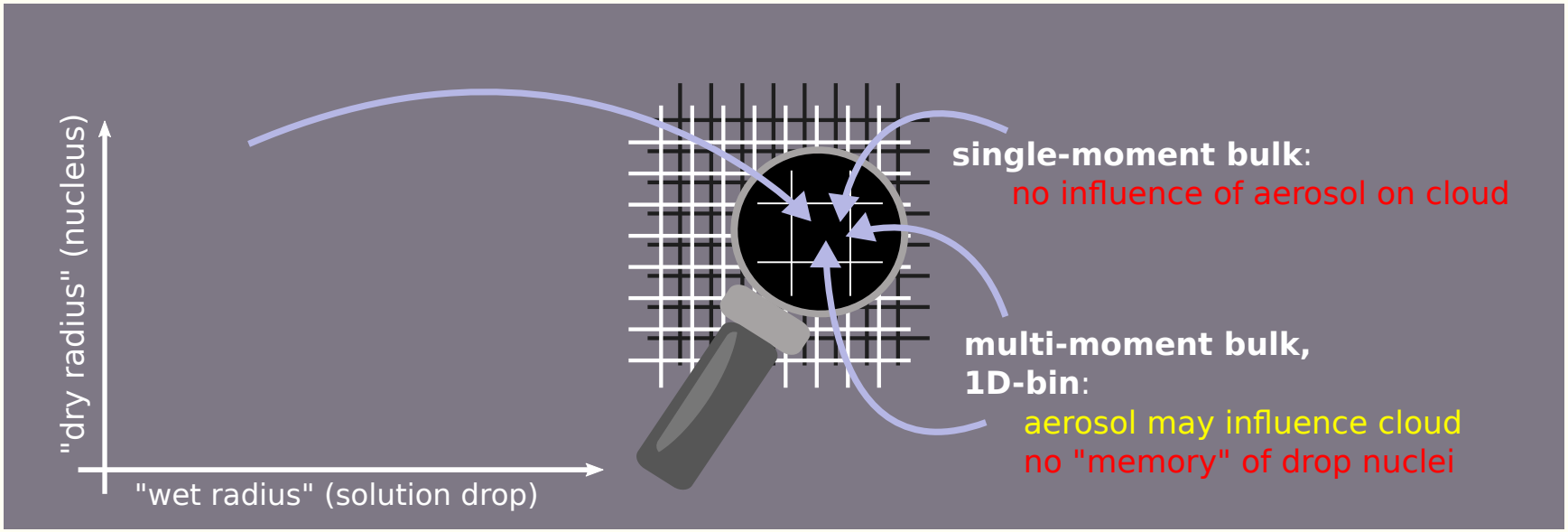

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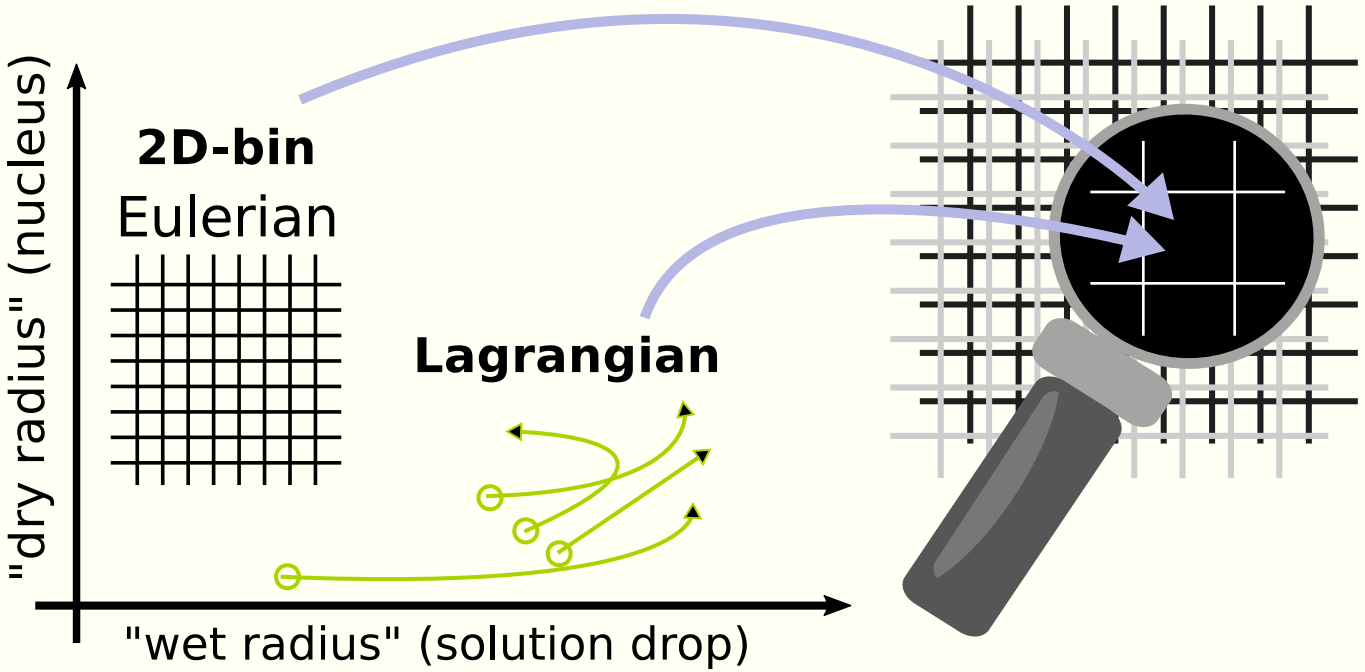

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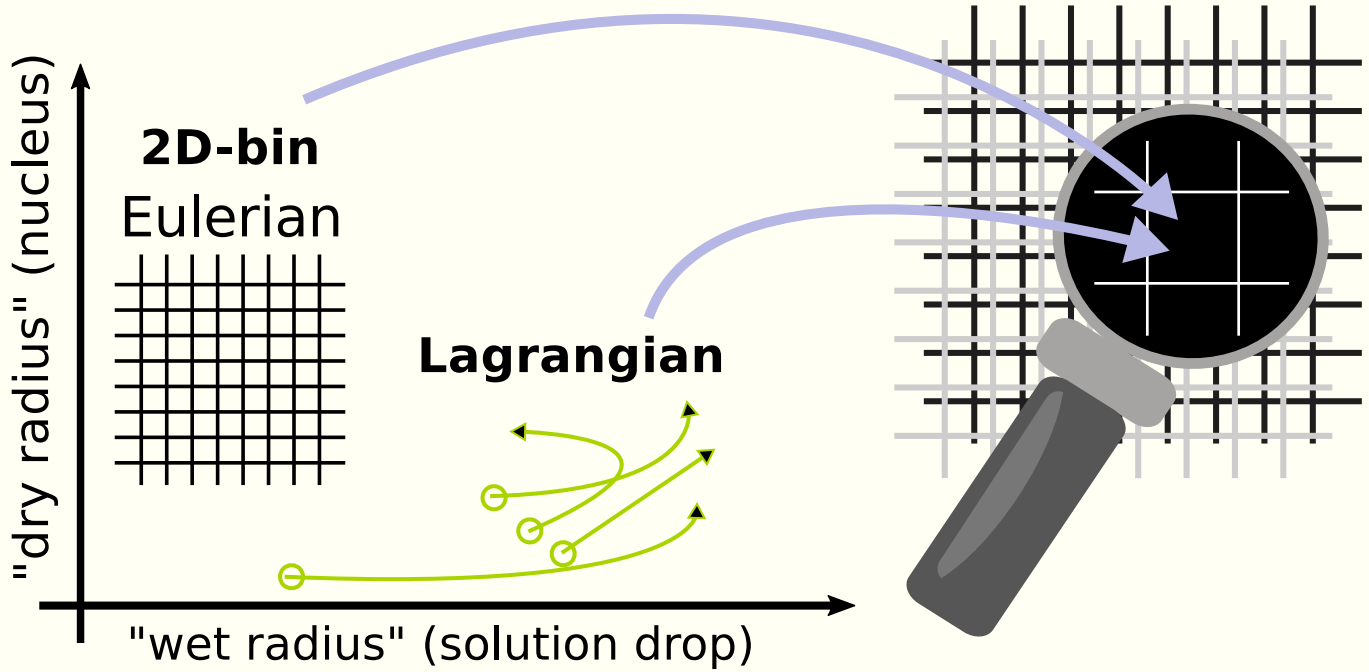

Pioneering warm-rain aerosol-cloud-interaction models:

Andrejczuk et al. 2010	
condensation:	Lagrangian
collisions:	Eulerian

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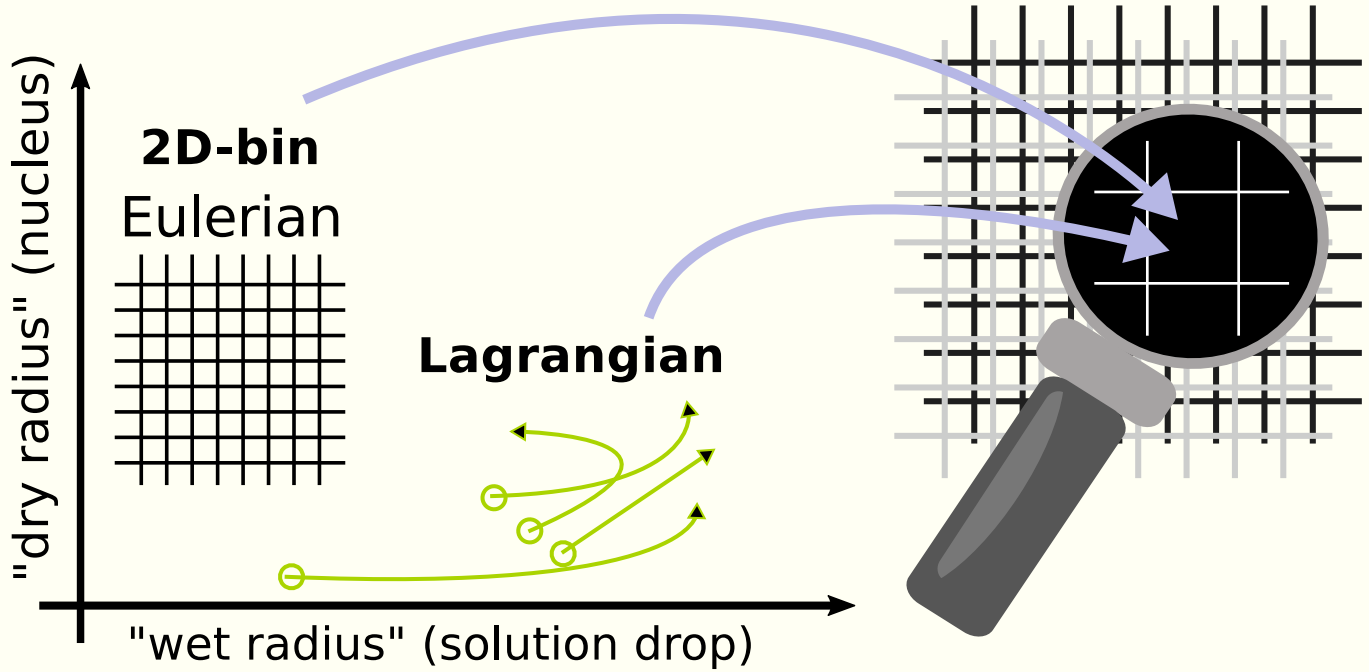

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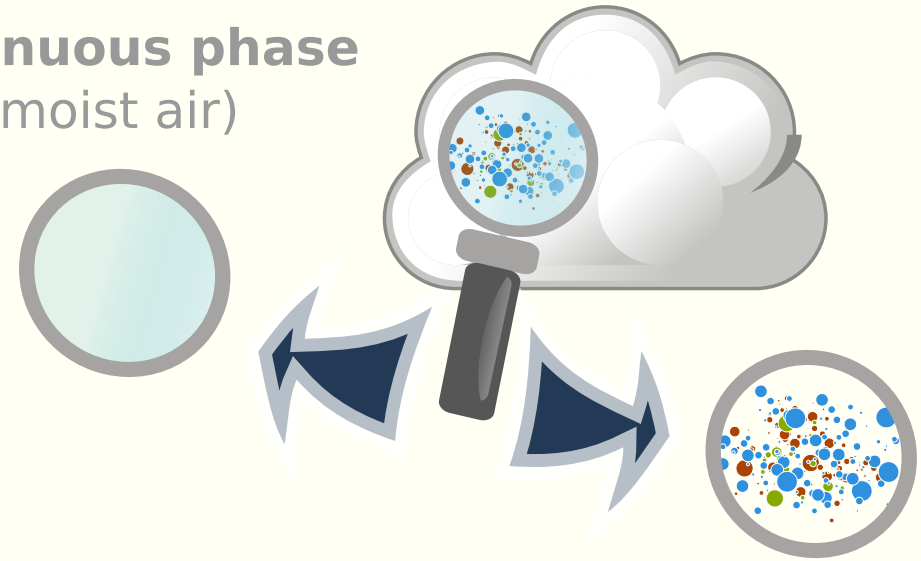
Shima et al.: stochastic coalescence and random phase-space sampling

Lagrangian μ-physics

Lagrangian μ-physics

continuous phase
(moist air)



dispersed phase
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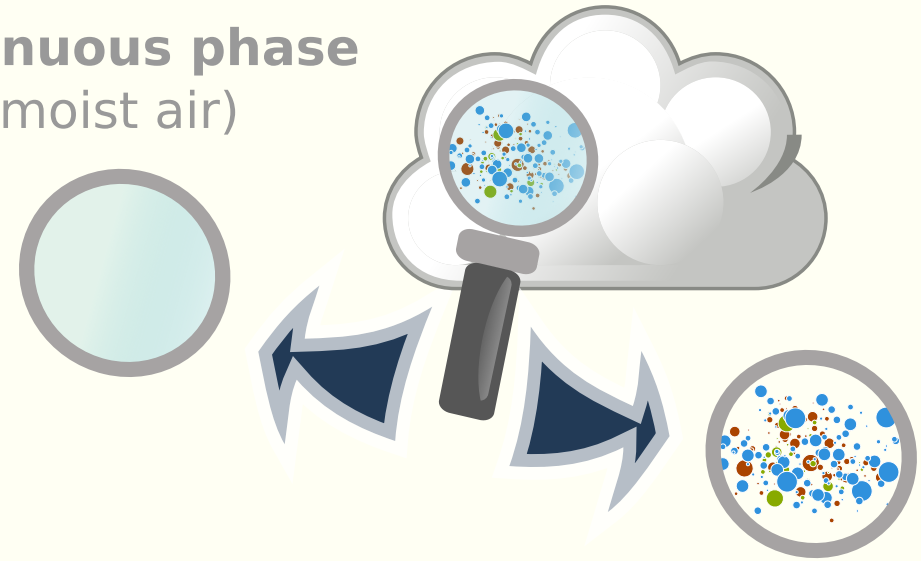

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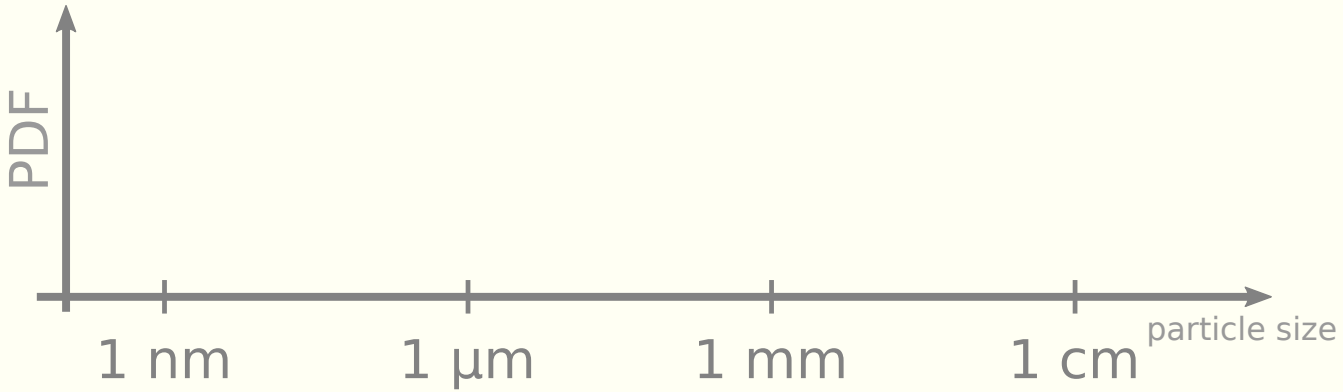

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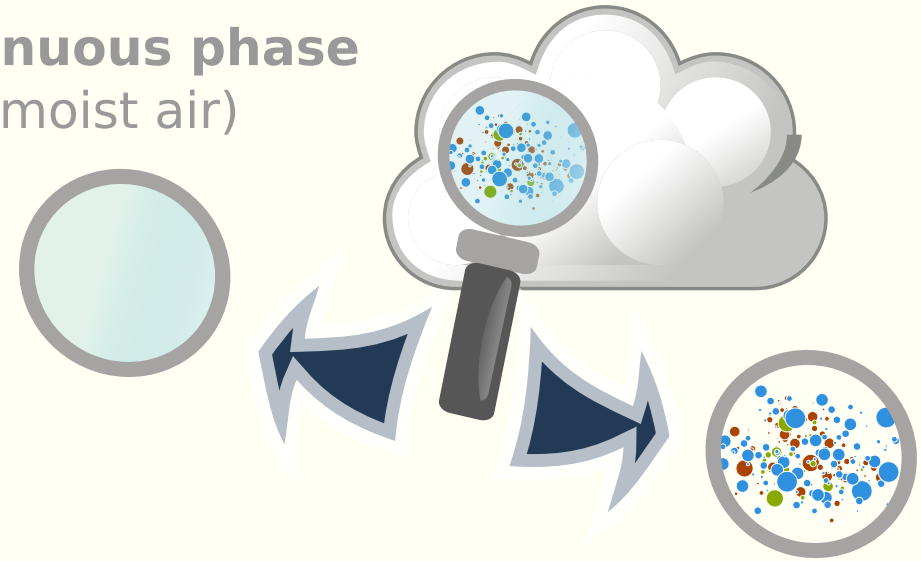

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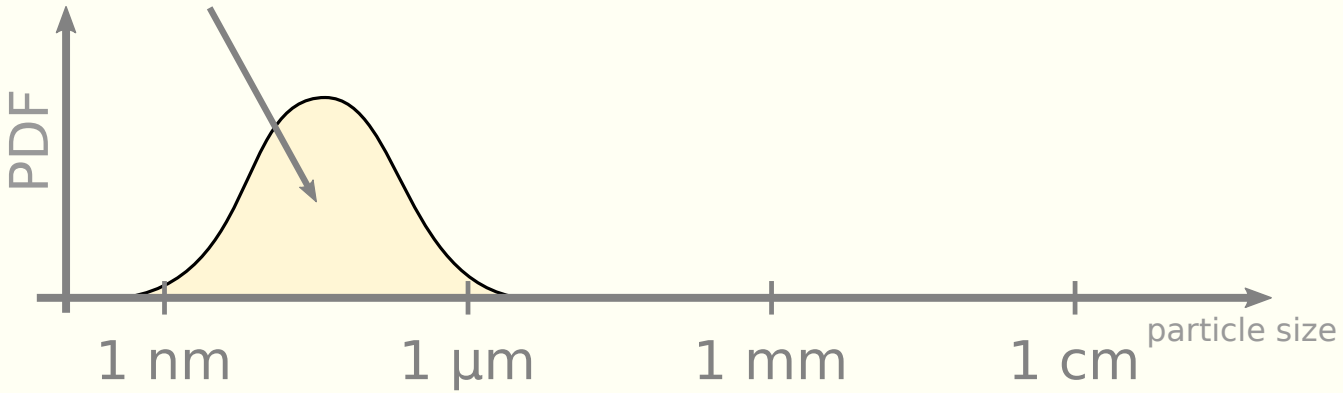

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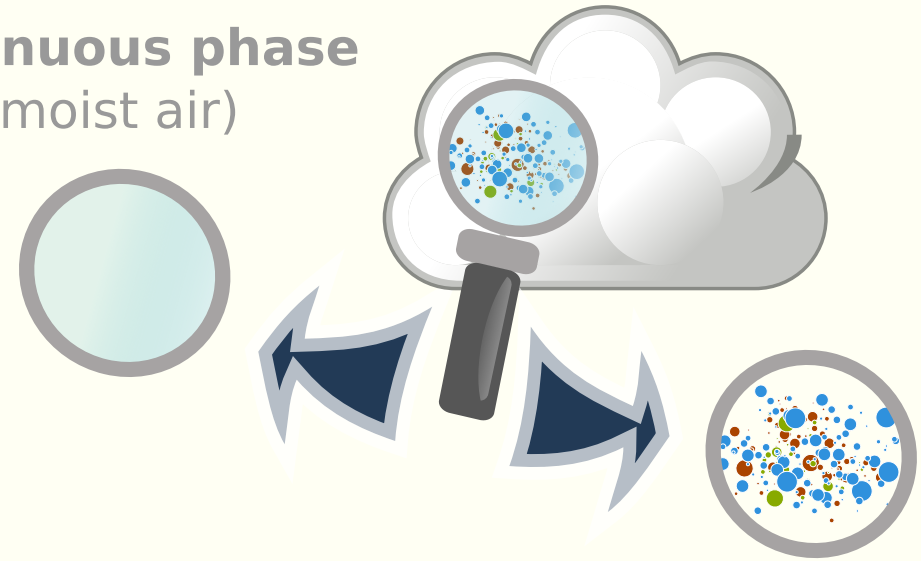

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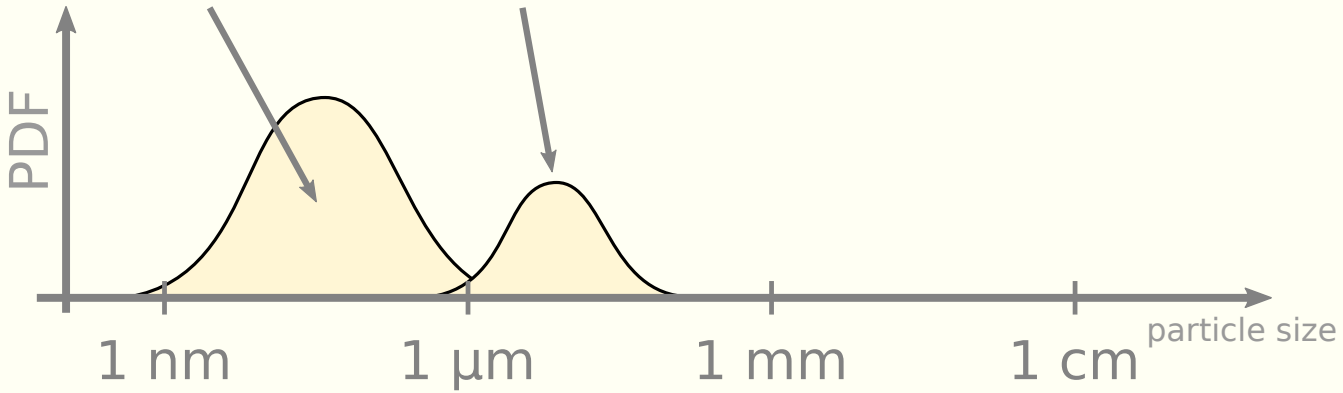

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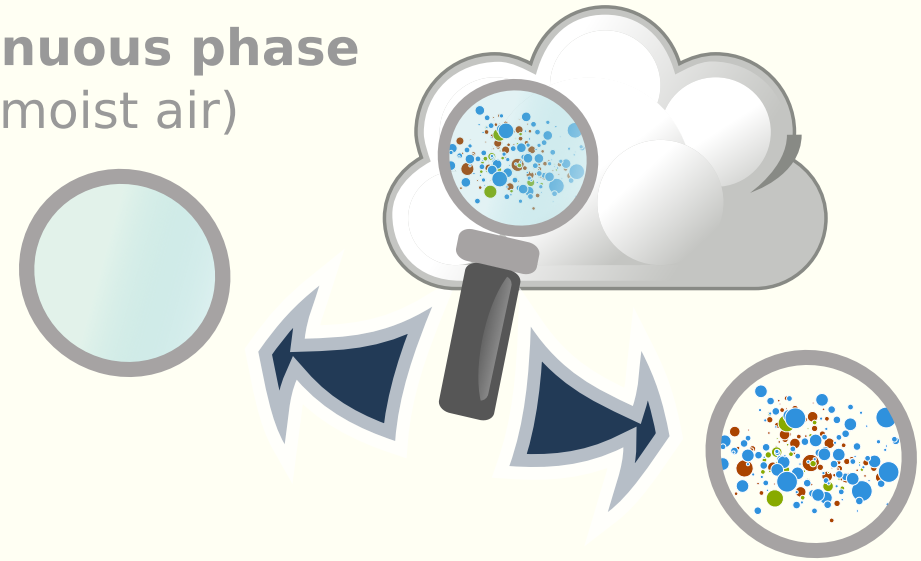

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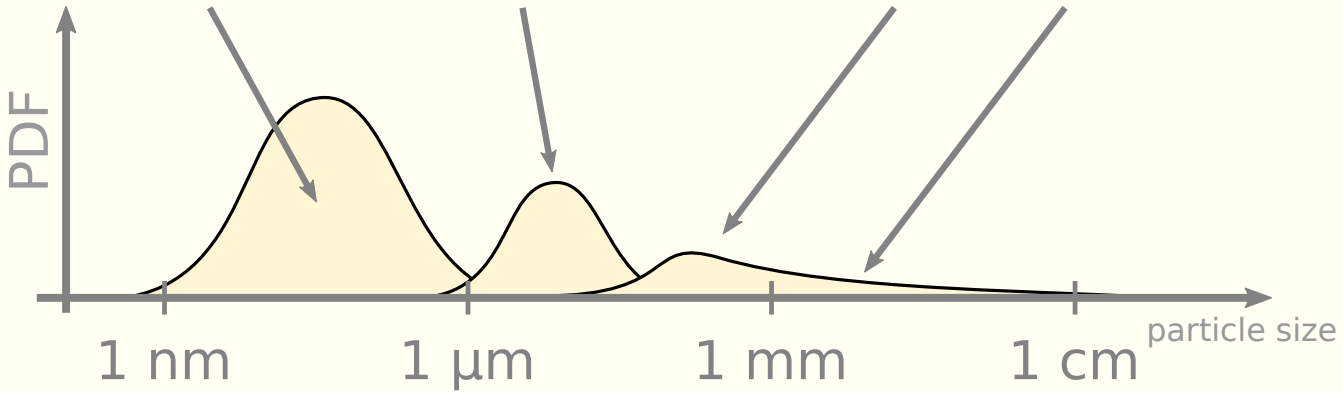

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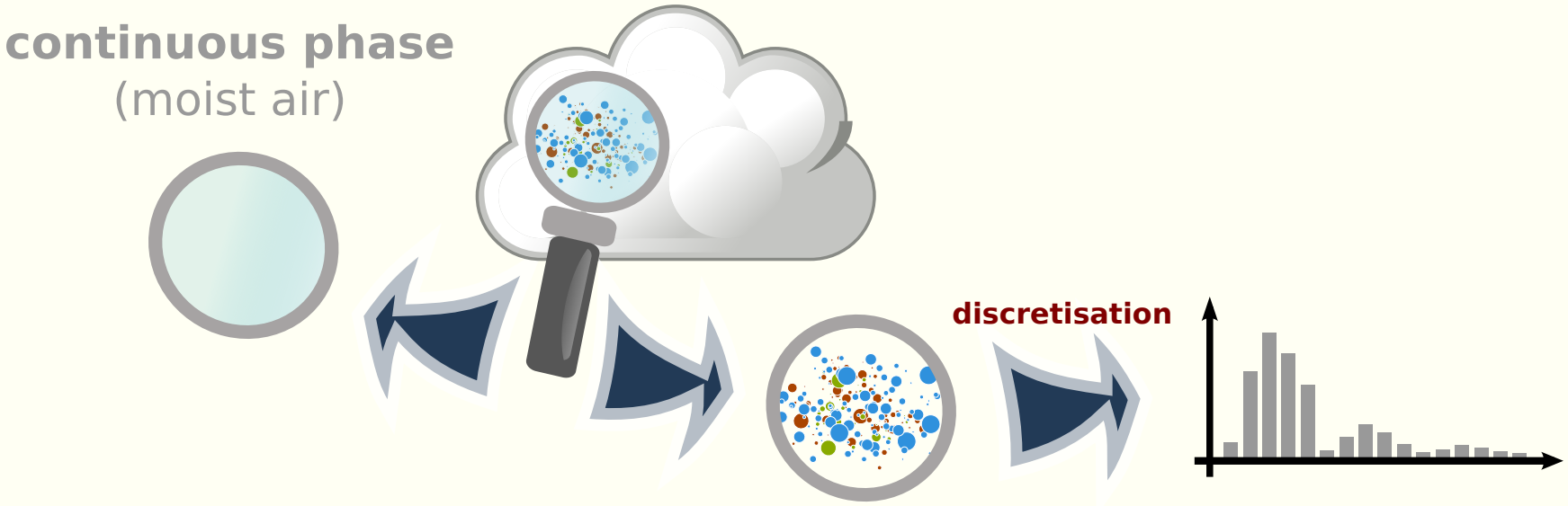

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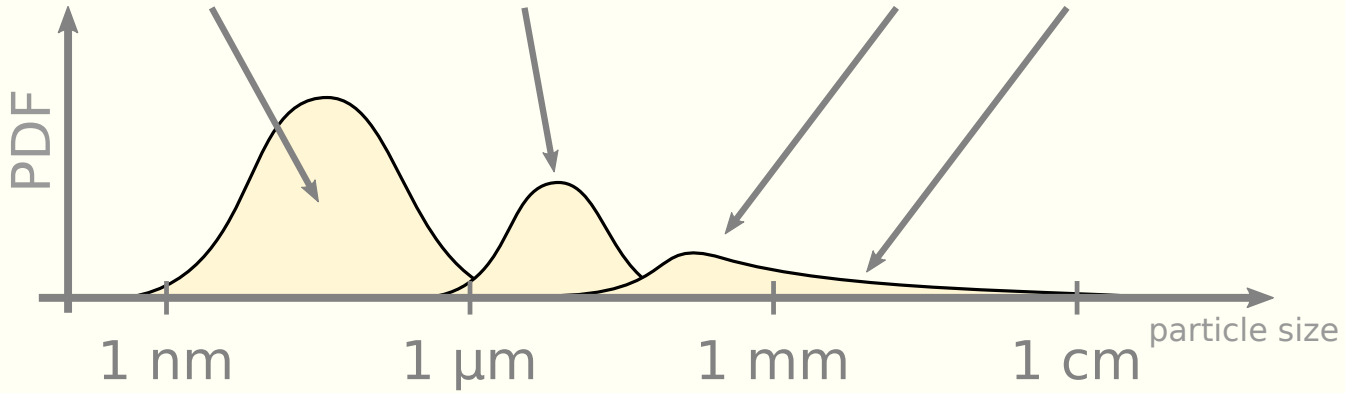

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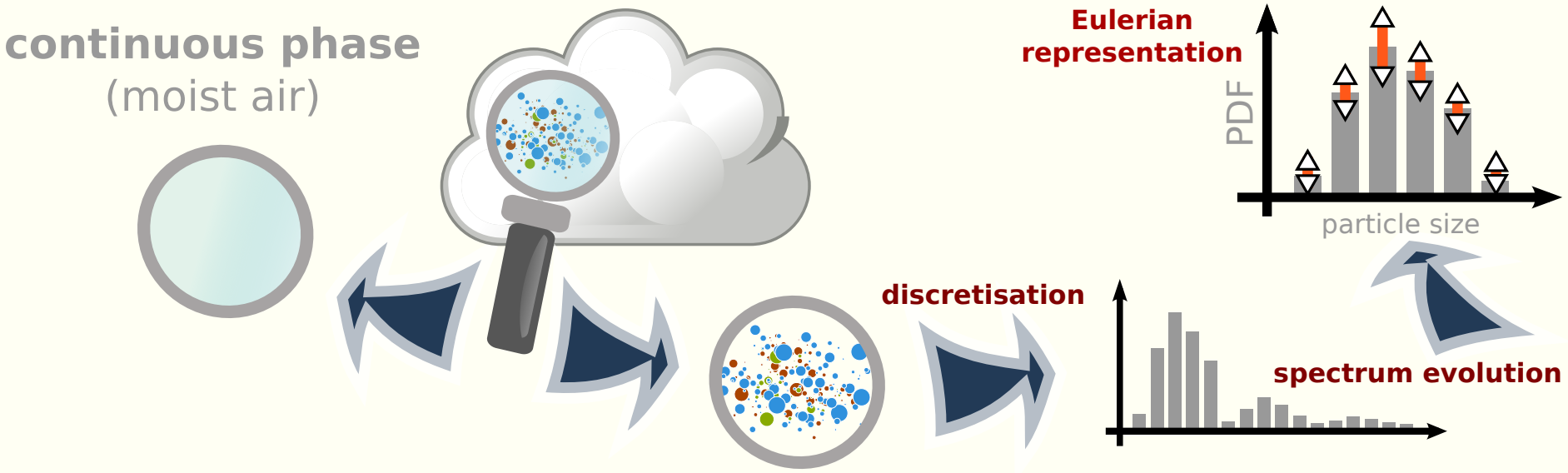

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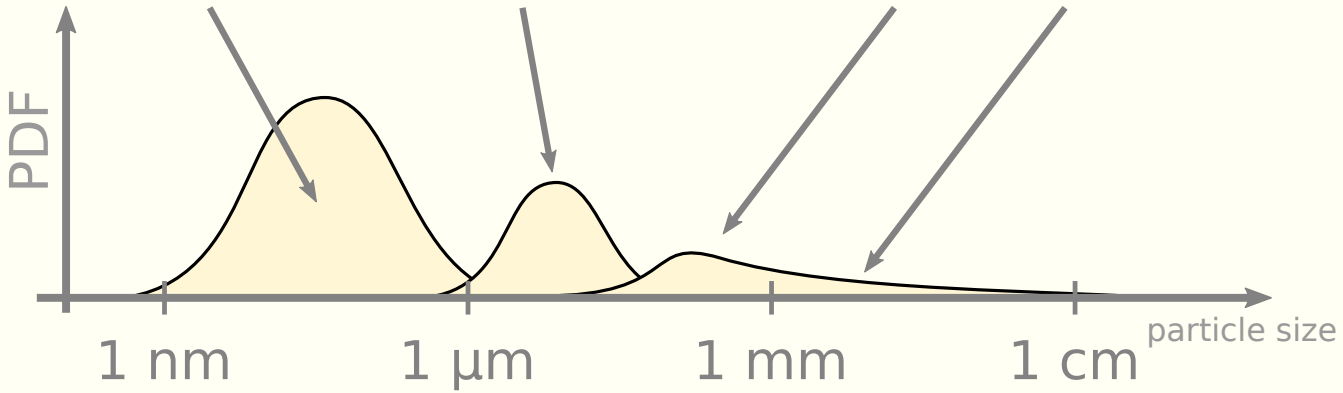

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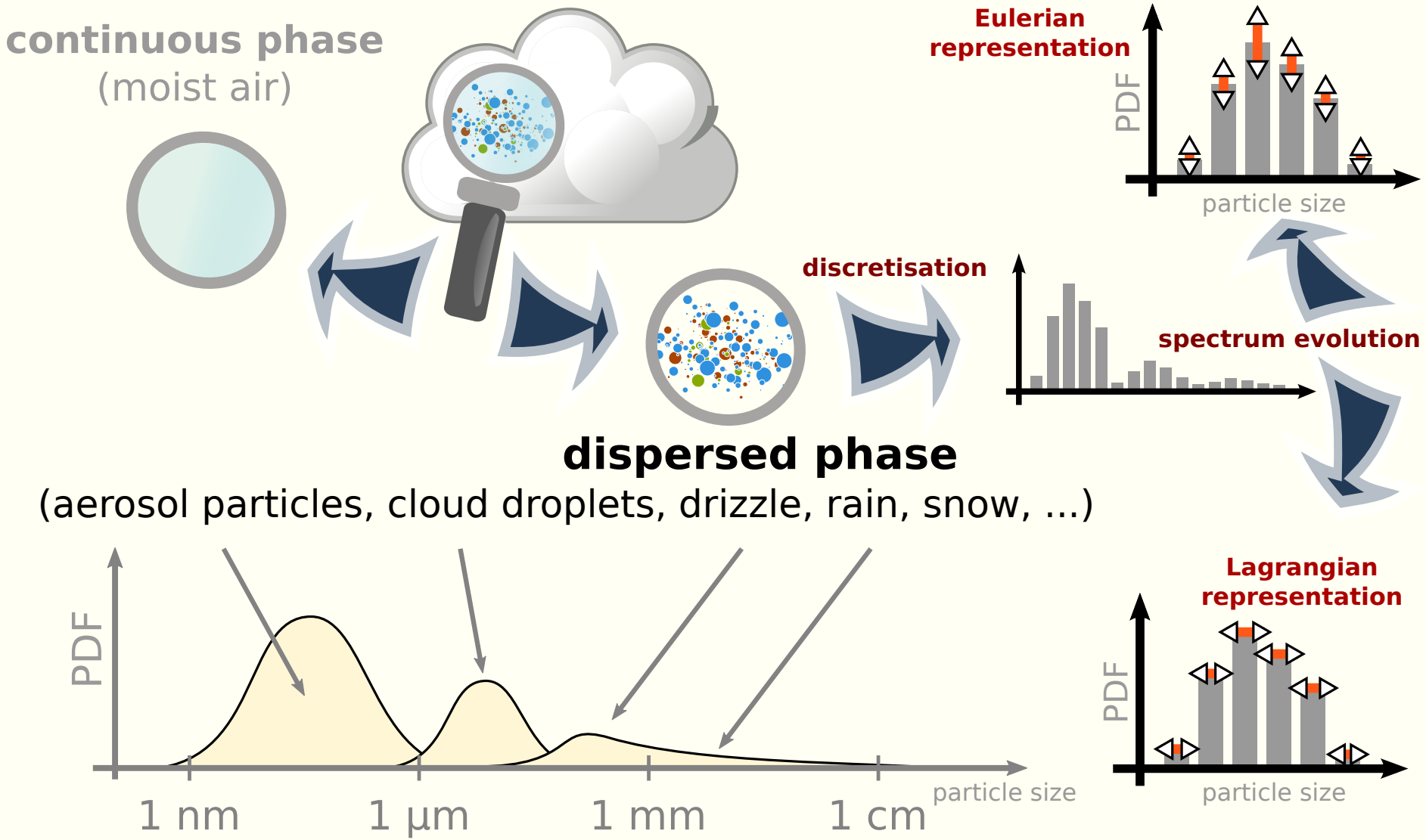
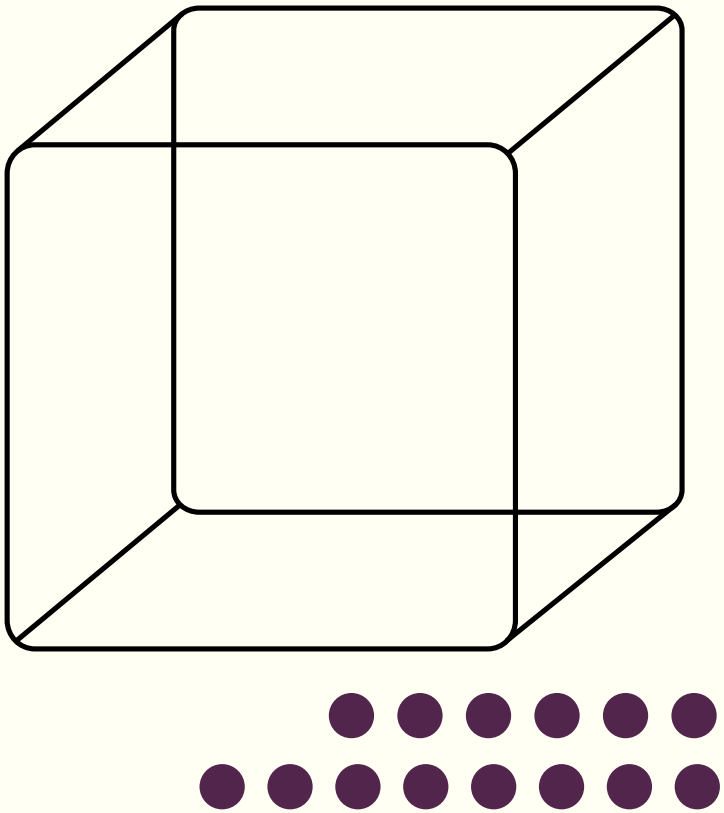


particle-based μ-physics: key concepts



Domain randomly populated with
"μ-physics information carriers"
(super particles / super droplets)

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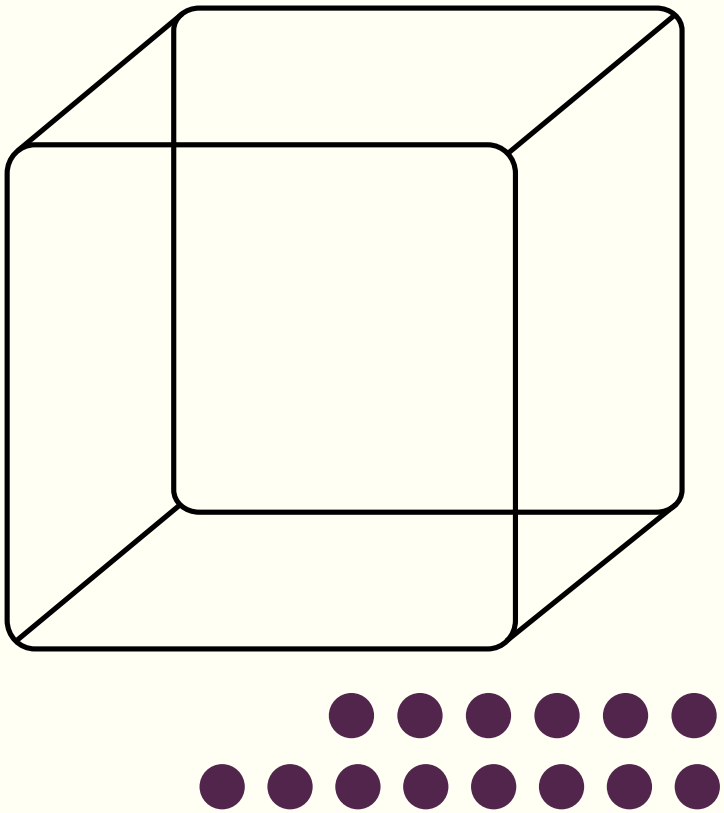

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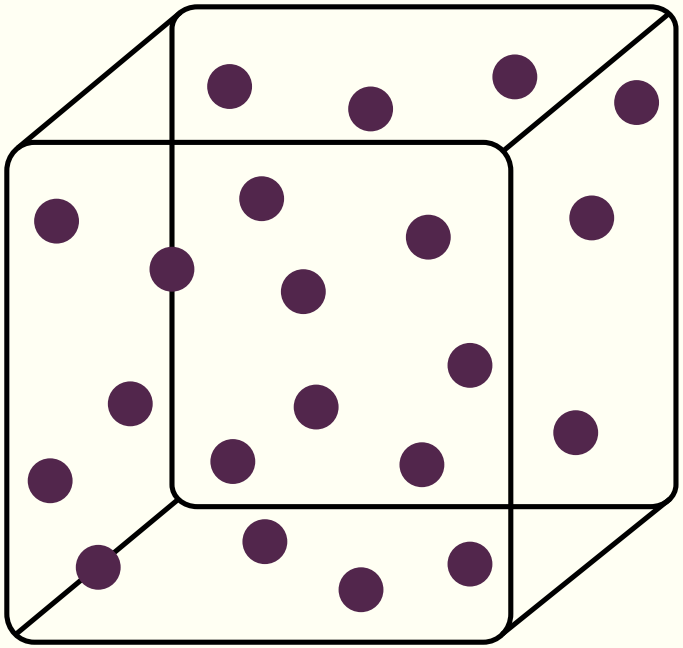

Domain randomly populated with "μ-physics information carriers" (super particles / super droplets)

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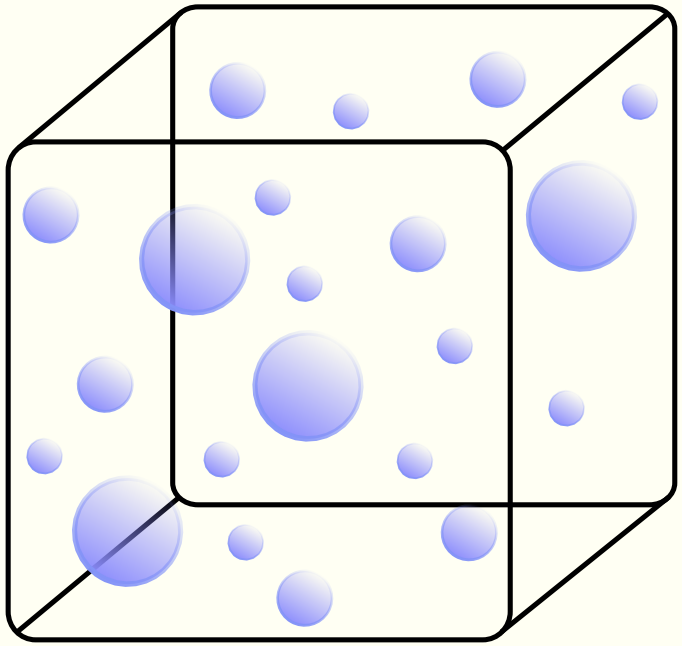

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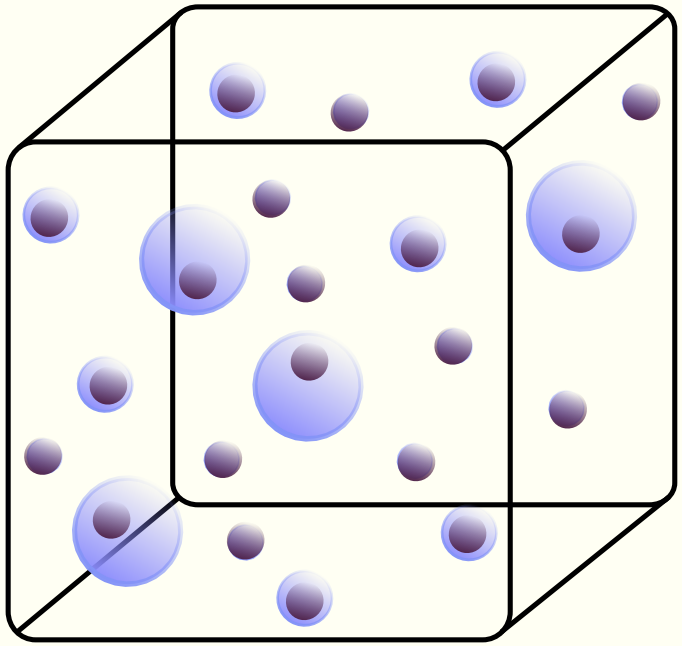

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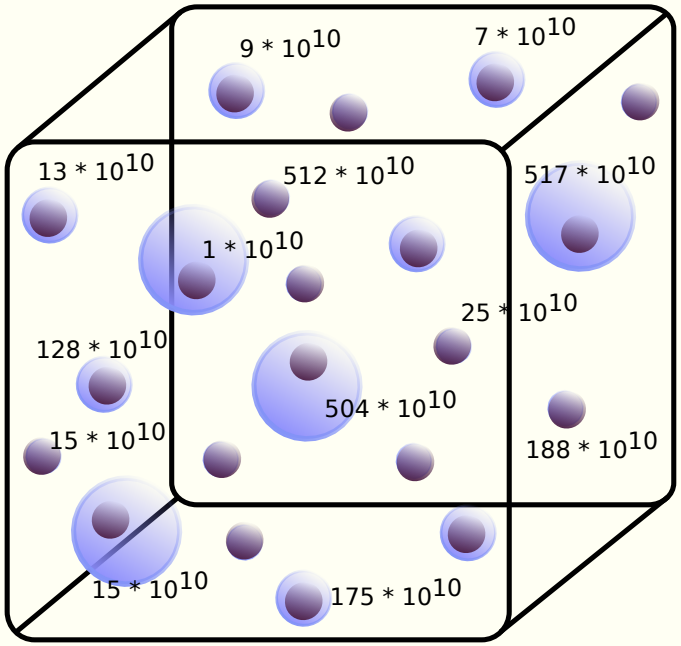

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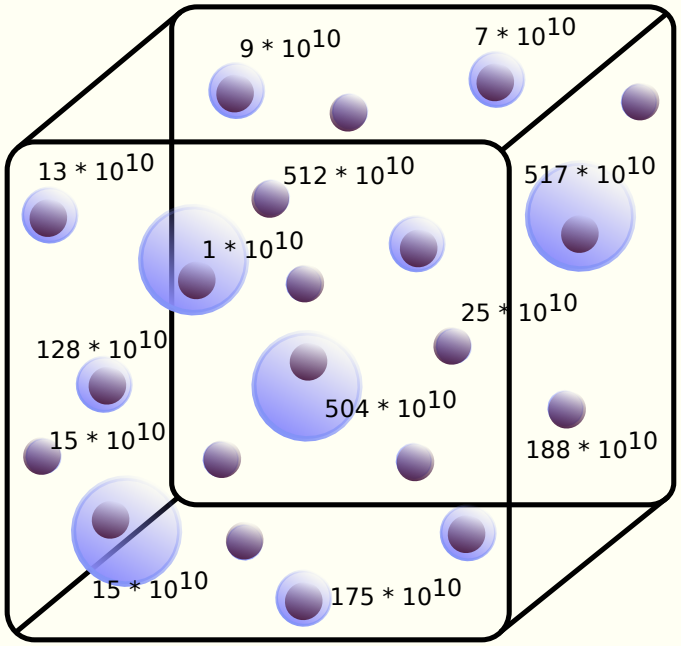

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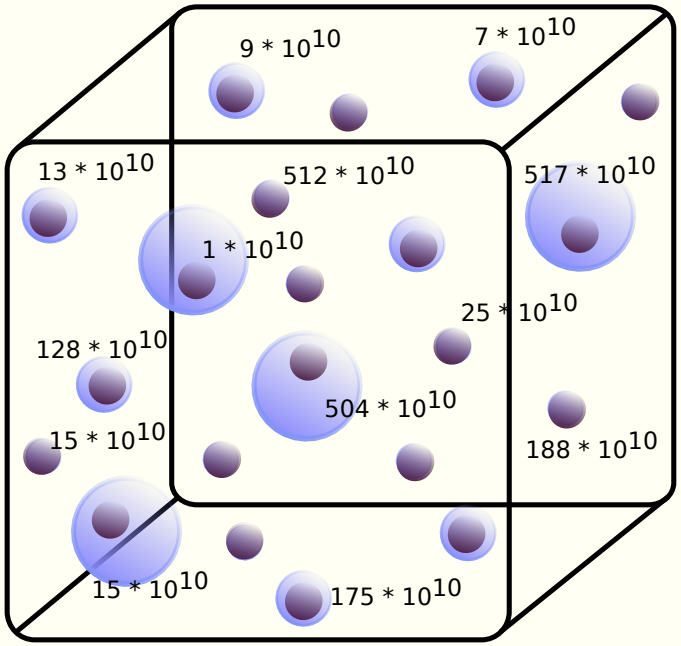

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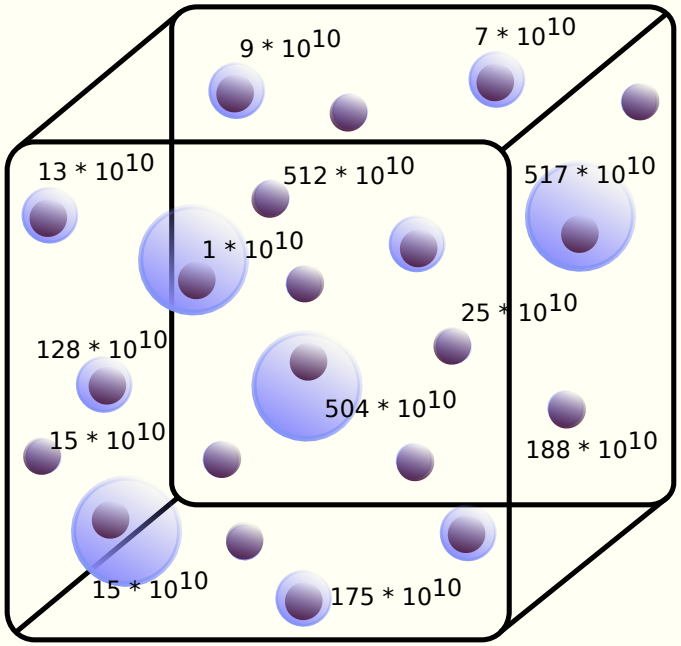

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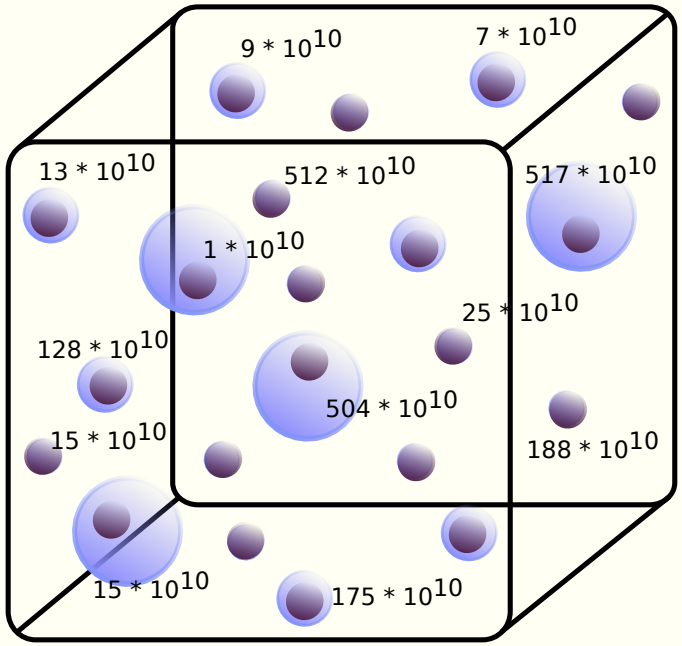

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particle-based μ-physics: coupling with the host model

Eulerian / PDE	Lagrangian / ODE

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	sedimentation
$\partial_t(\rho_d r) + \nabla \cdot (\vec{v}\rho_d r) = \rho_d \dot{r}$	$\dot{r} = \sum_{\text{particles} \in \Delta V} \ldots$
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challenges:

- scalability (cost vs. number of particles),
- super-particles "conservation" (coalescence!)

Monte Carlo coalescence scheme (Shima et al.)

- for all n super-droplets in a grid box of volume ΔV in timestep Δt

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- coalescence takes place following the latter of the two (consistent) scenarios:
  - a part of ξ real particles (defined by P_{ij}) coalesce every timestep
  - all min(ξ_i,ξ_j) drops coalesce once in a number of t-steps (defined by P_{ij})
    $\rightsquigarrow$ there's always a "bin" of the right size to store the collided particles

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- collisions triggered by comparing a uniform random number with P_{ij}
- [n/2] random non-overlapping (i,j) pairs examined instead of all (i,j) pairs
  cost: $O(n^2) \rightsquigarrow O(n)$, probability upscaled by $\frac{n \cdot (n-1)}{2} \Big/ \left[\frac{n}{2}\right]$

example simulation (2D, prescribed flow)

Geosci. Model Dev., 8, 1677-1707, 2015
https://doi.org/10.5194/gmd-8-1677-2015

Model description paper | 09 Jun 2015

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]

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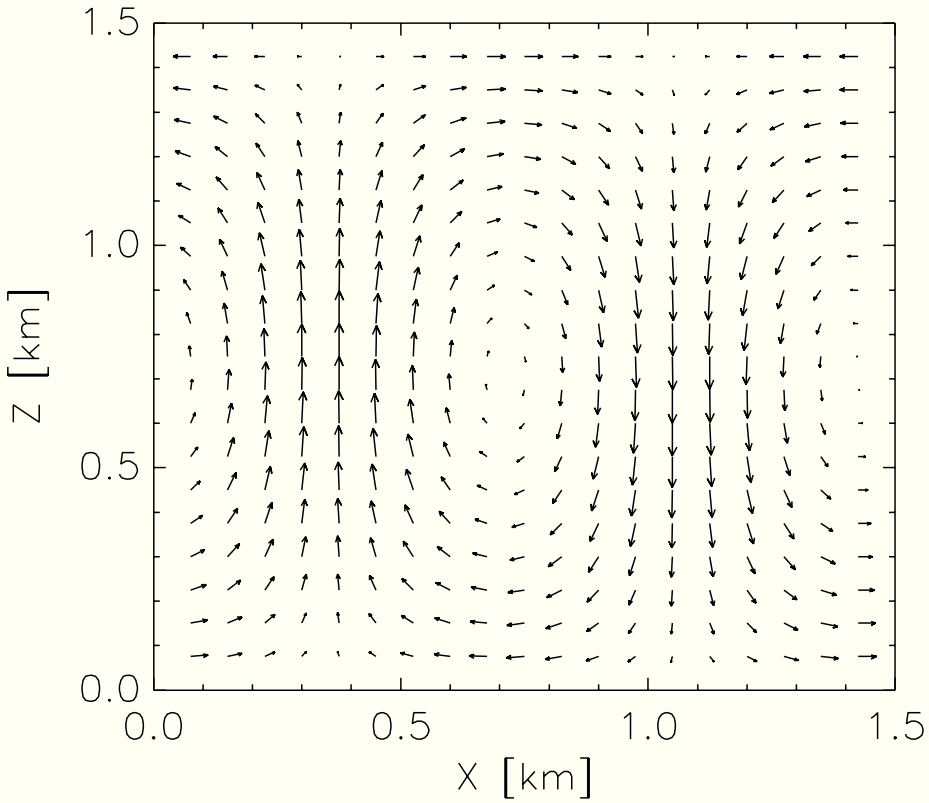
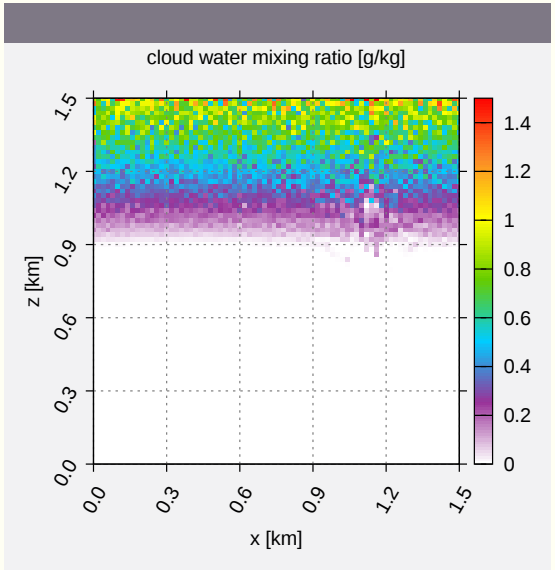
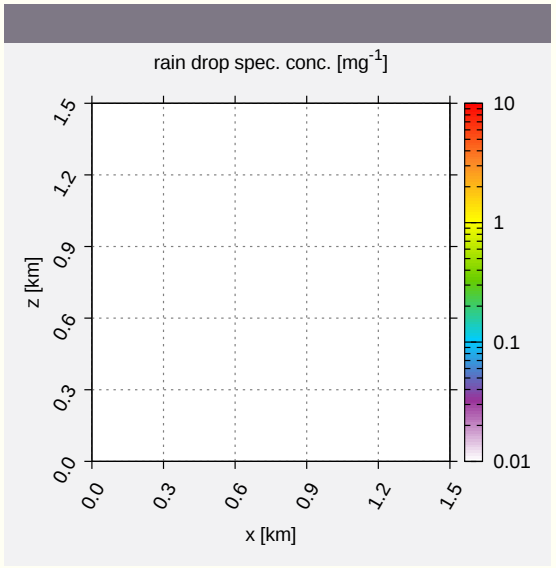
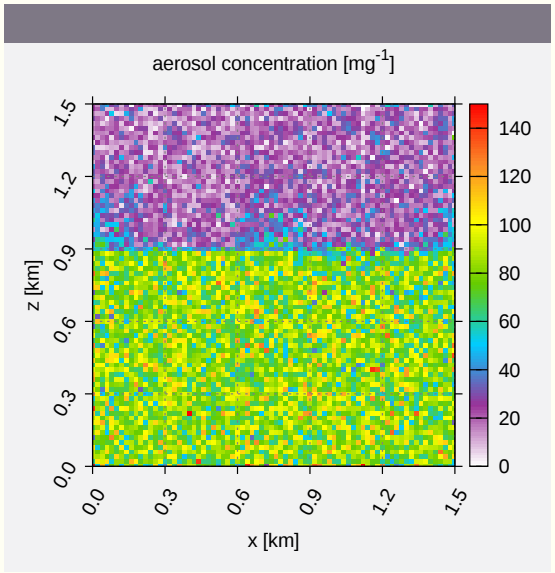
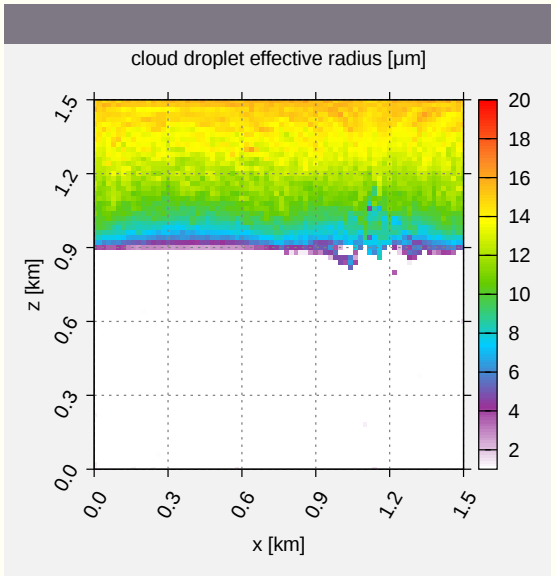


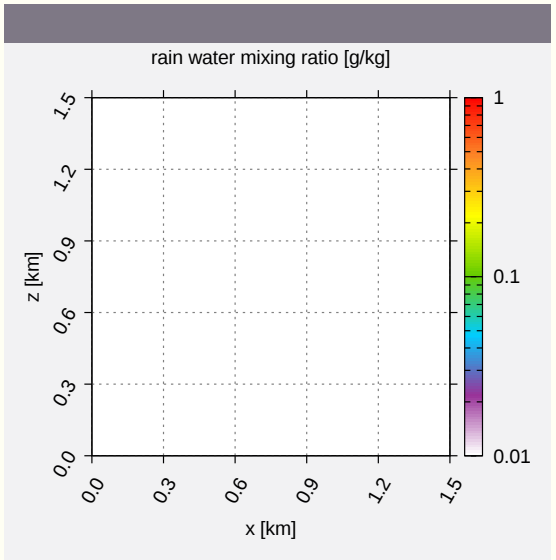
example simulation (Arabas et al. 2015, GMD)



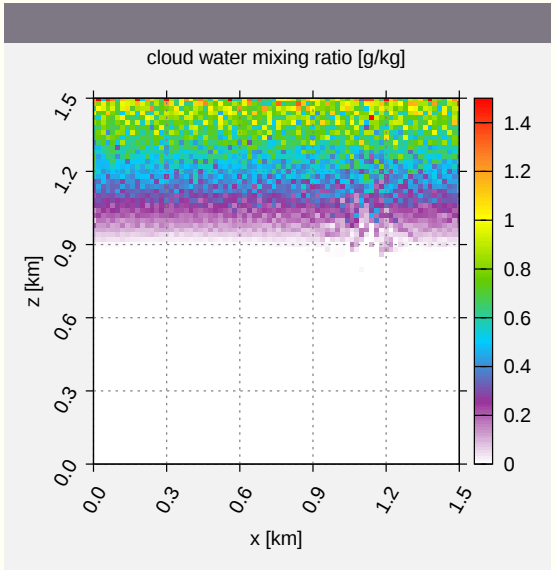


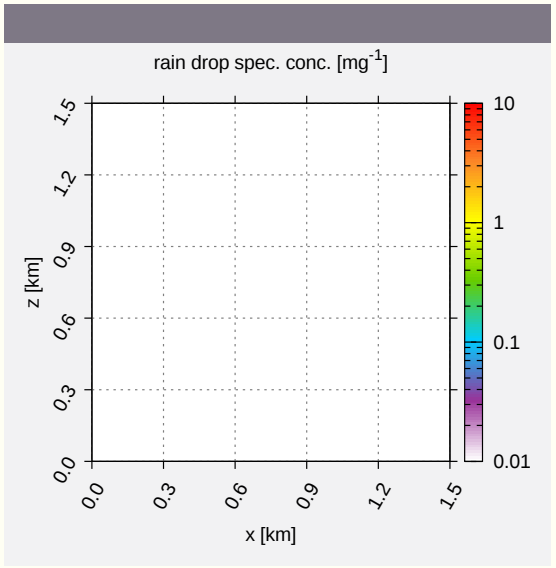


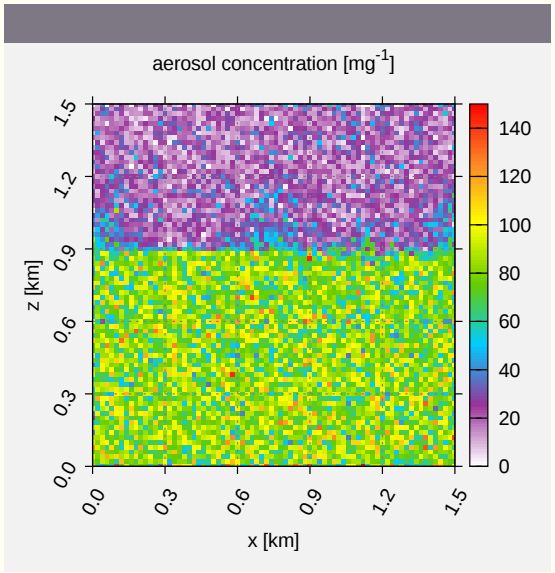


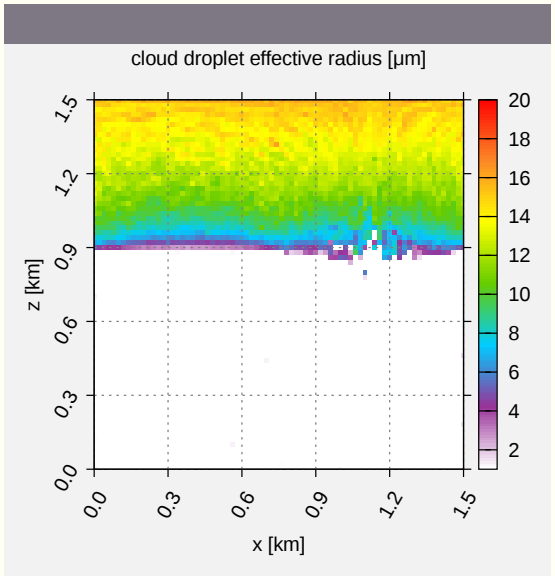


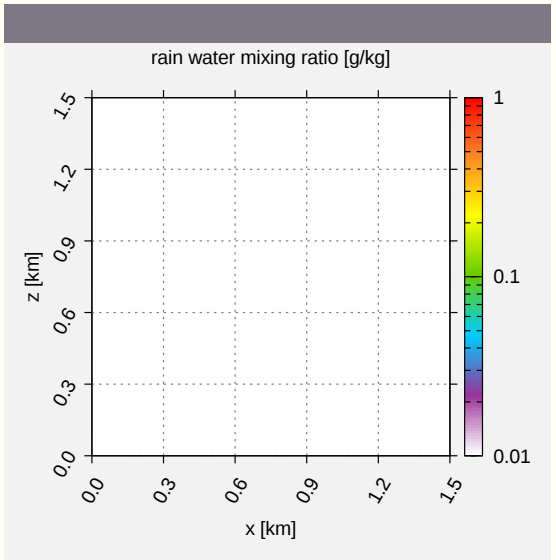
example simulation (Arabas et al. 2015, GMD)



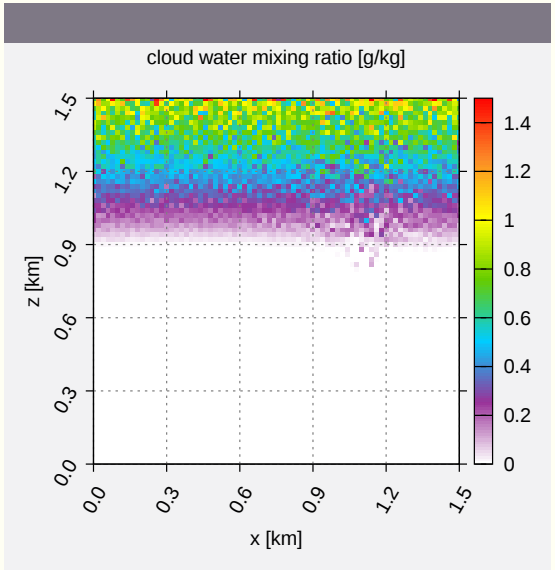


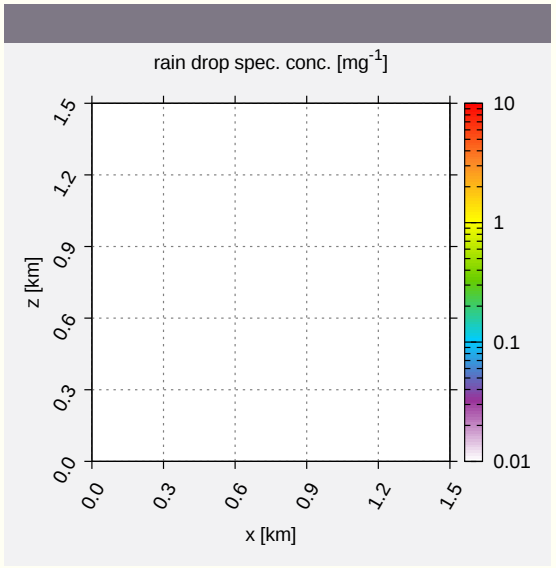


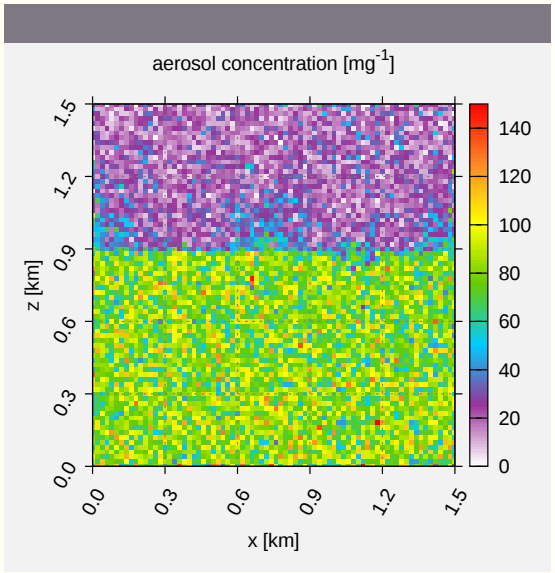


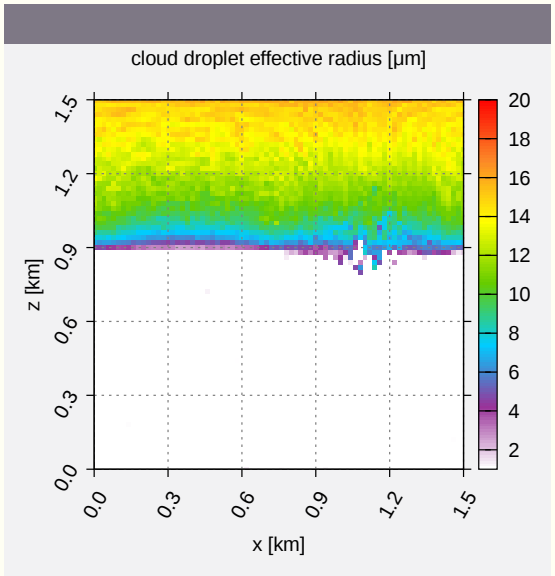


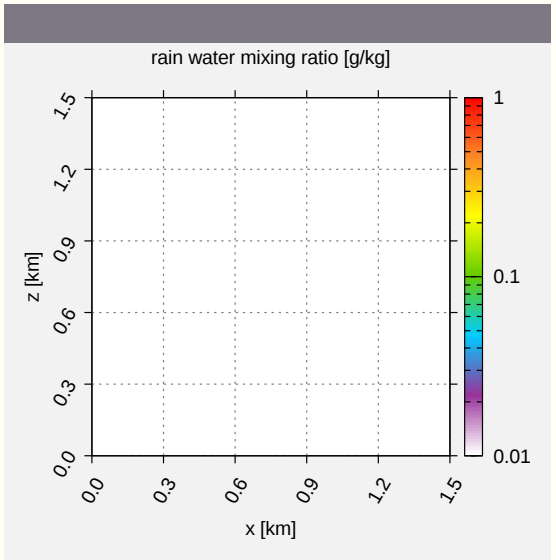
example simulation (Arabas et al. 2015, GMD)











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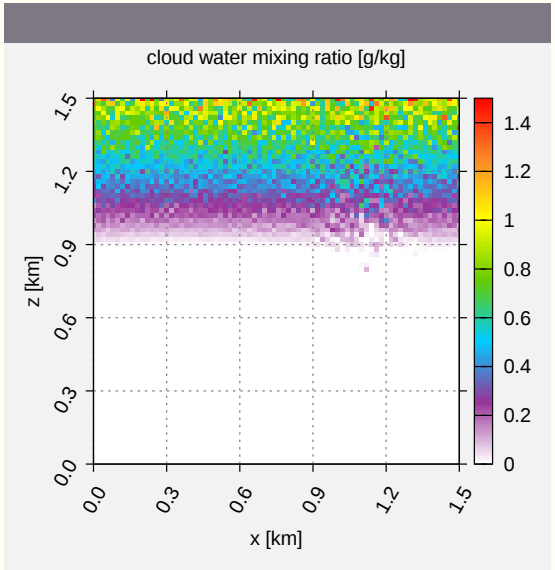
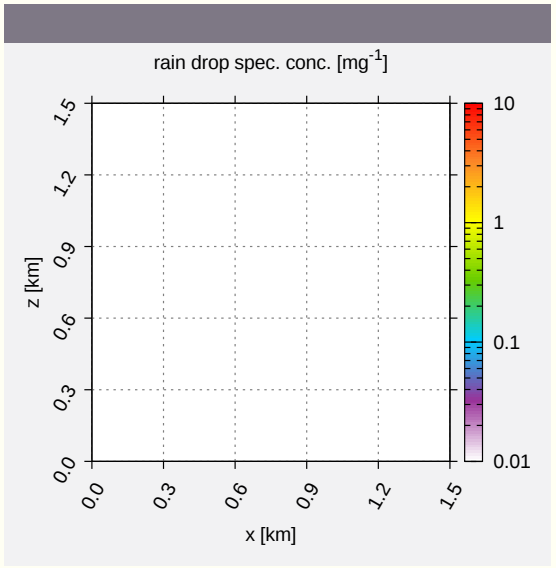
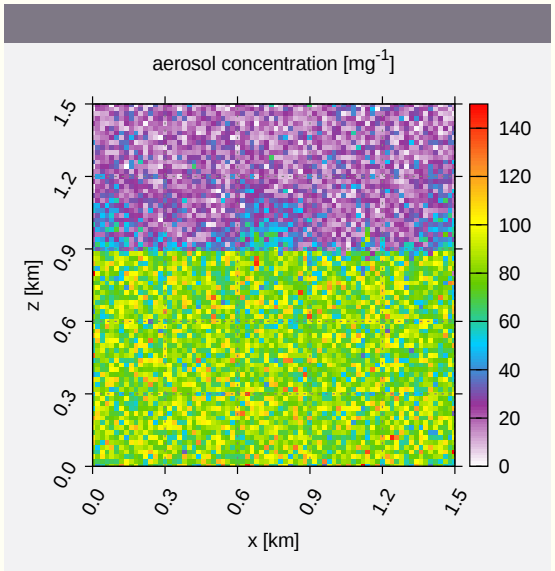
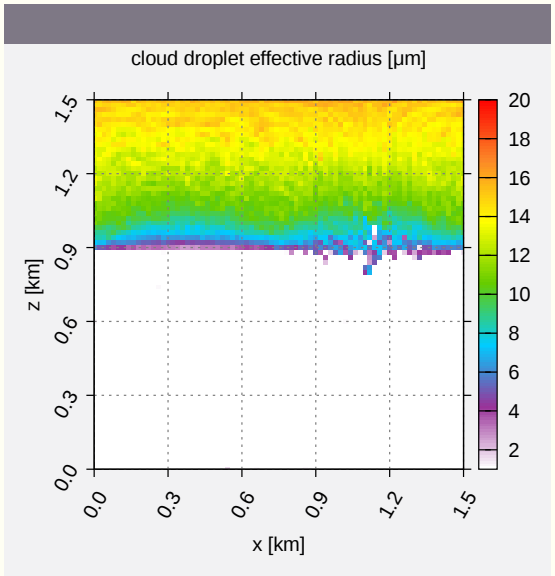
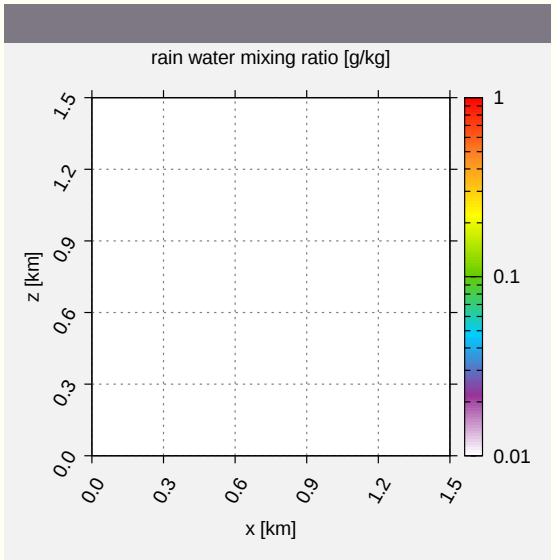


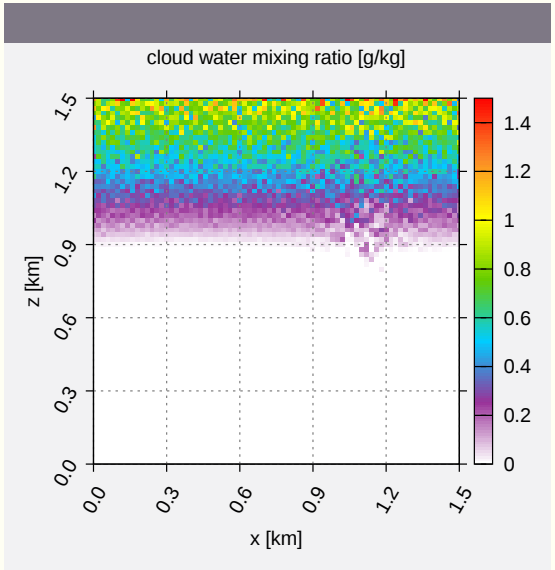


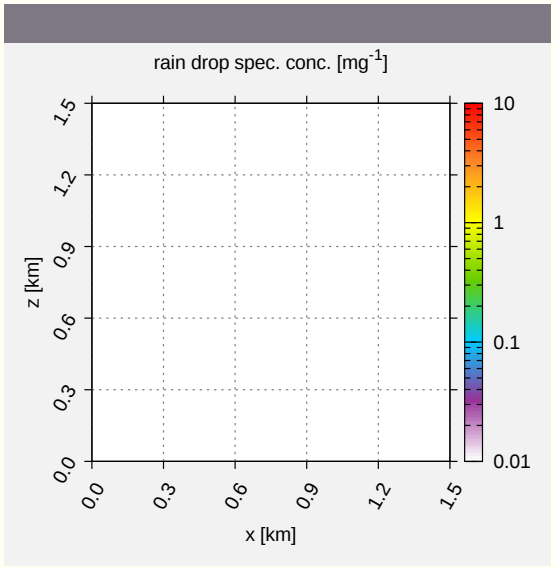


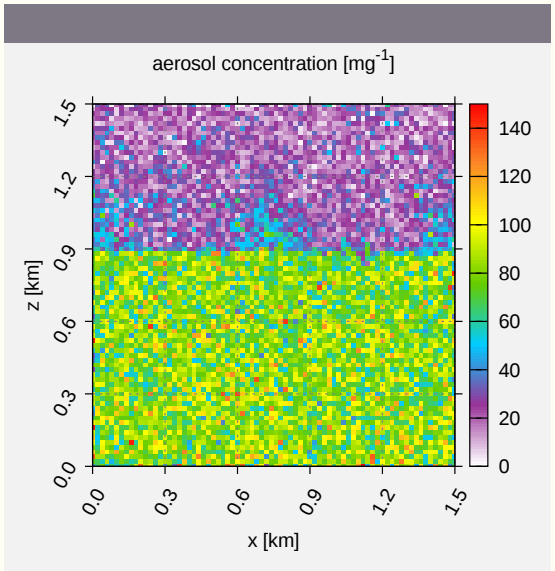


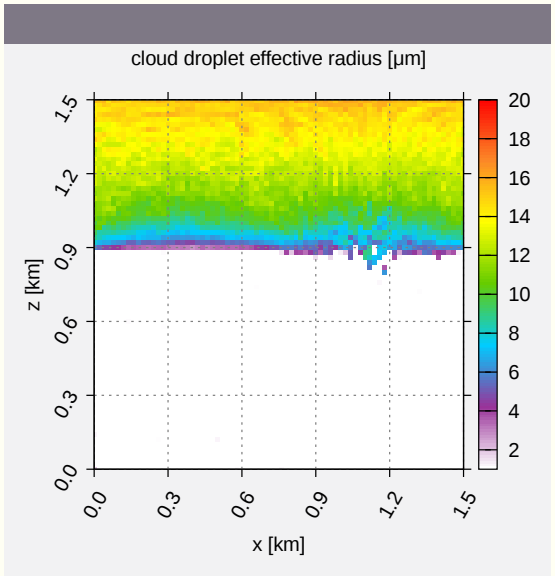


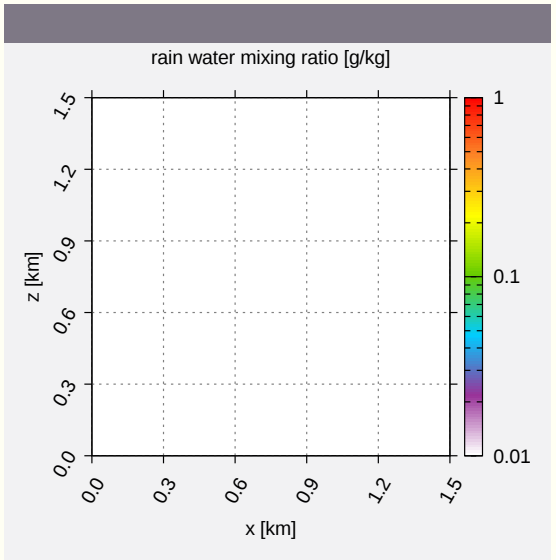
example simulation (Arabas et al. 2015, GMD)



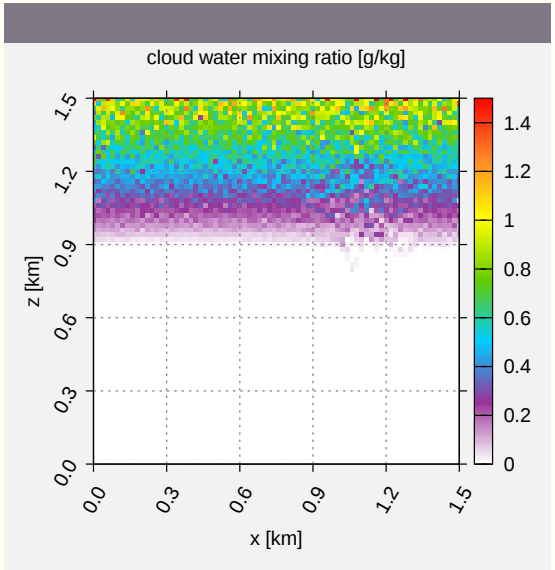


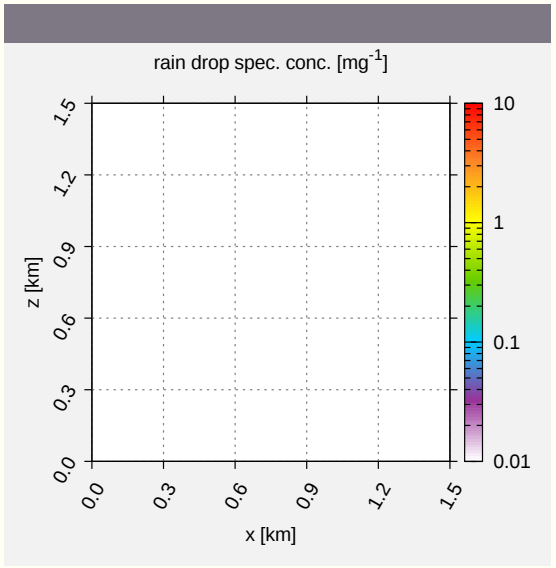


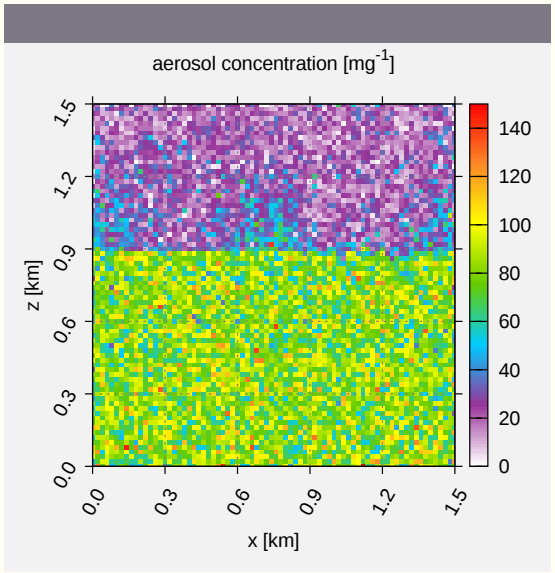


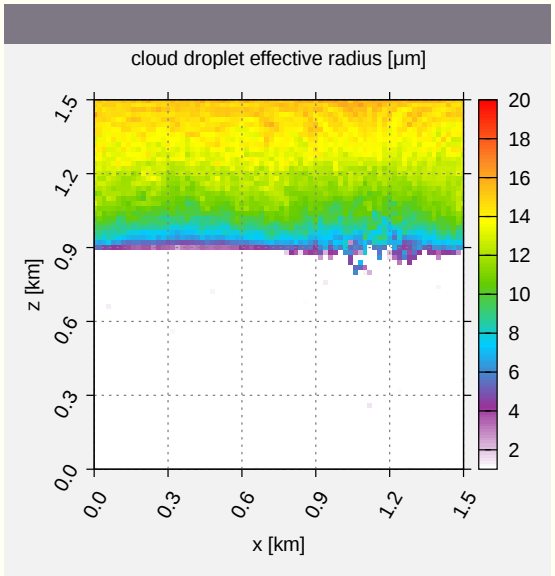


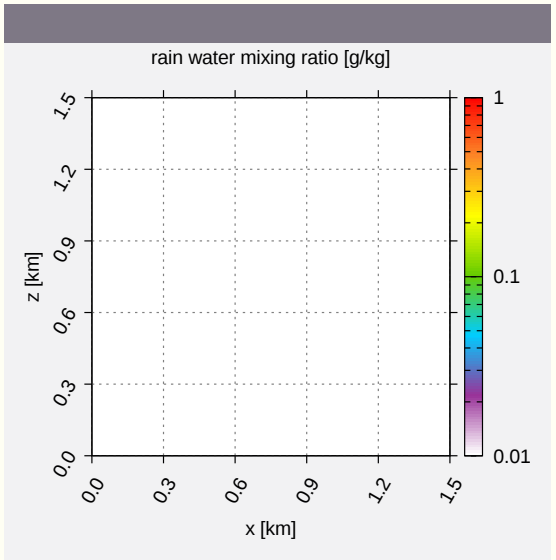
example simulation (Arabas et al. 2015, GMD)











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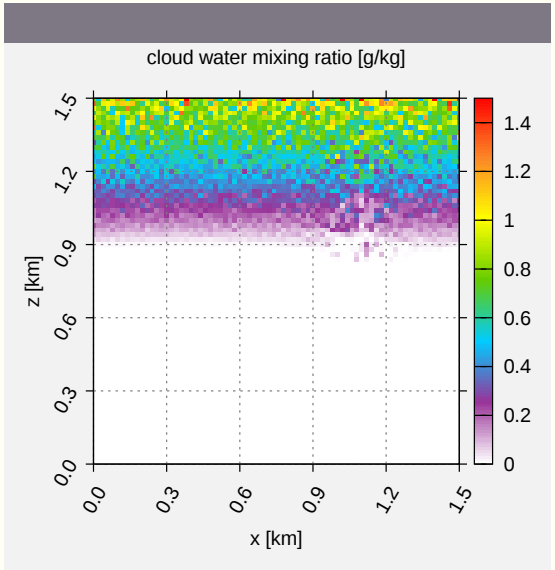

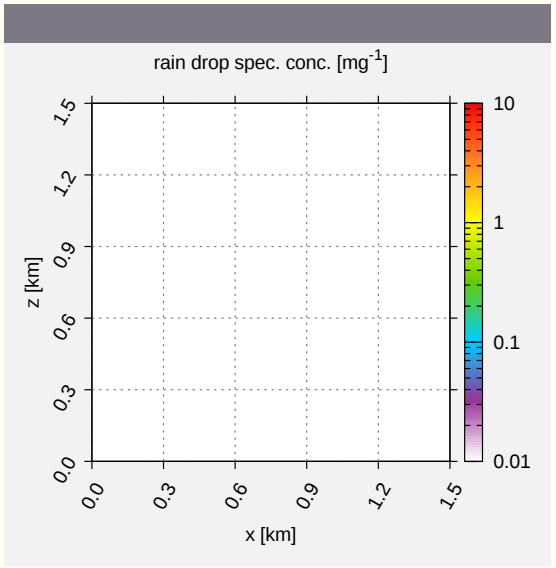

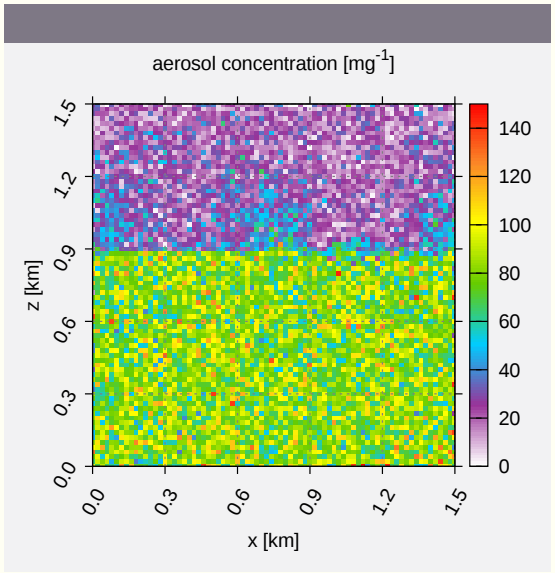

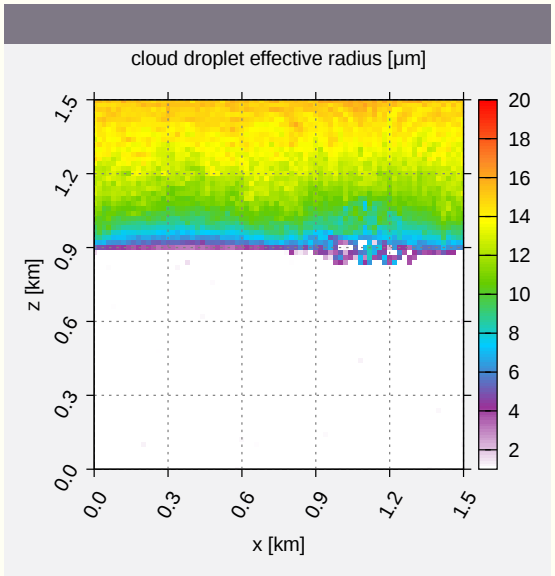

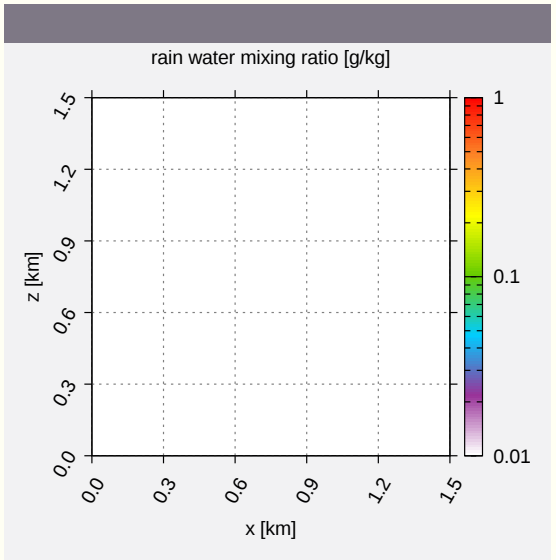

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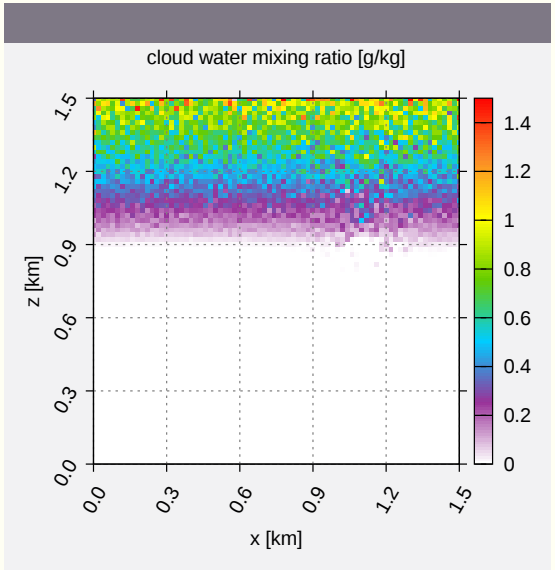

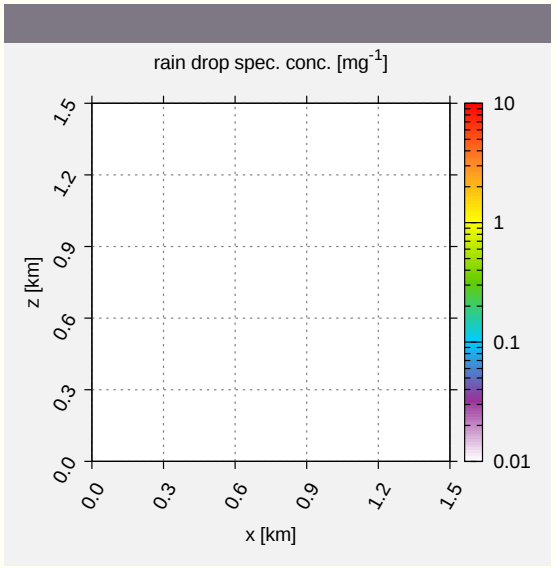

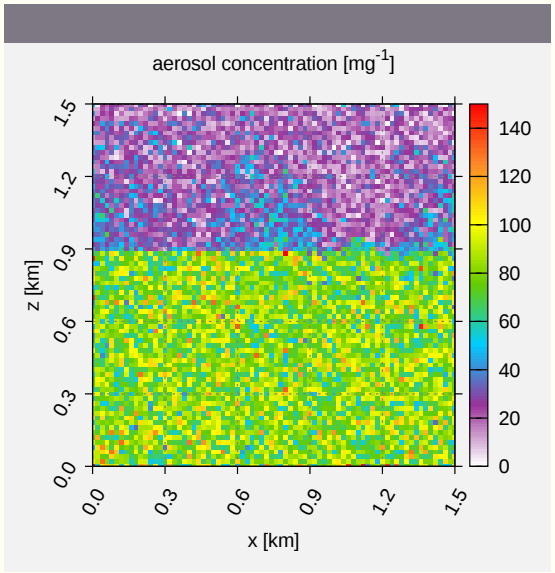

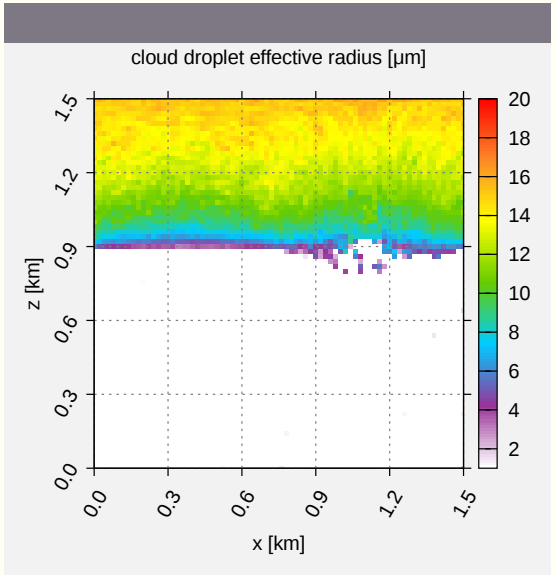

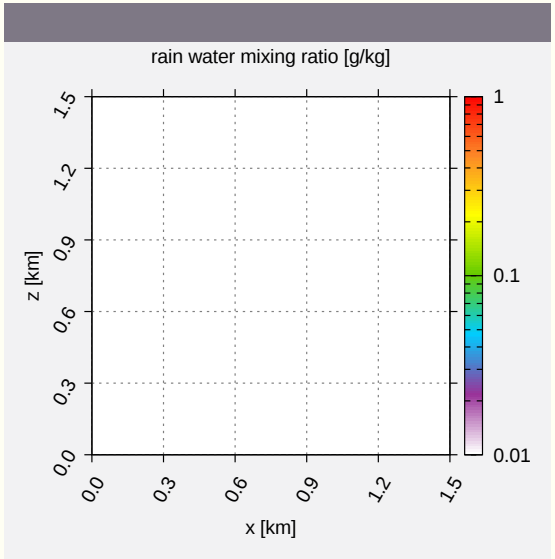

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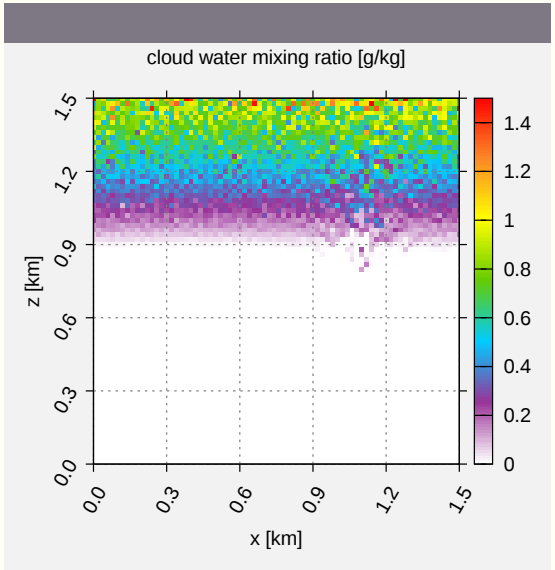

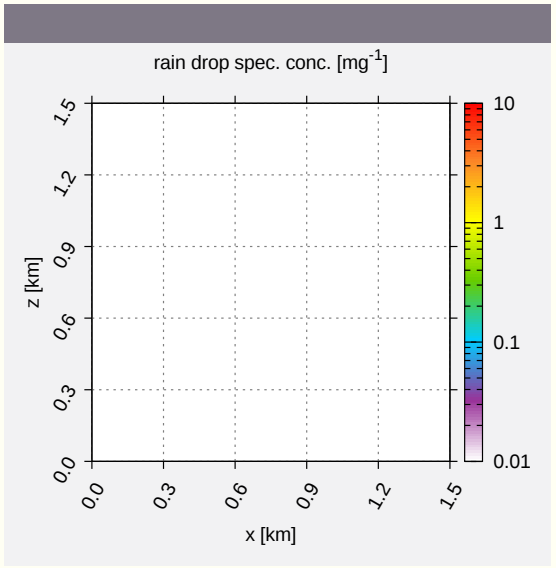

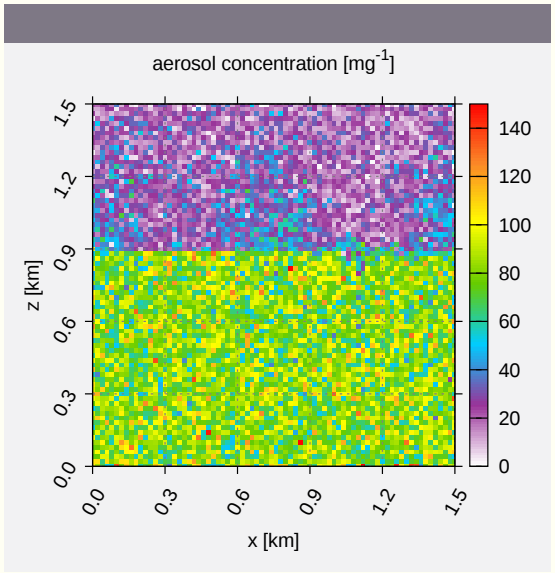

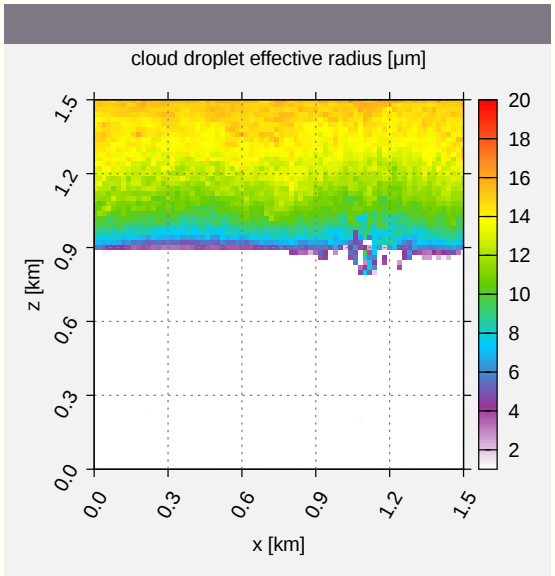

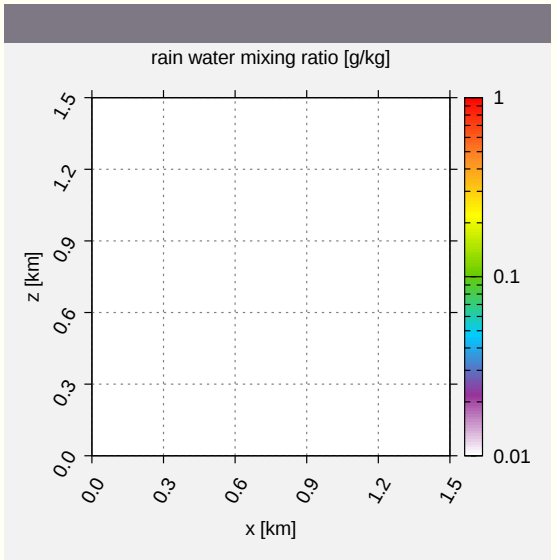

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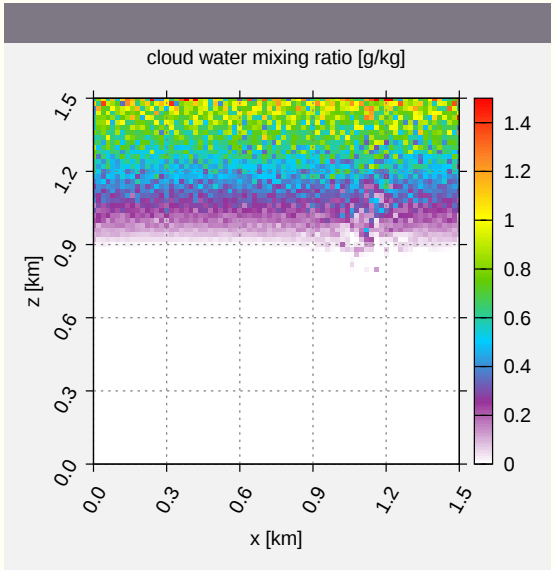

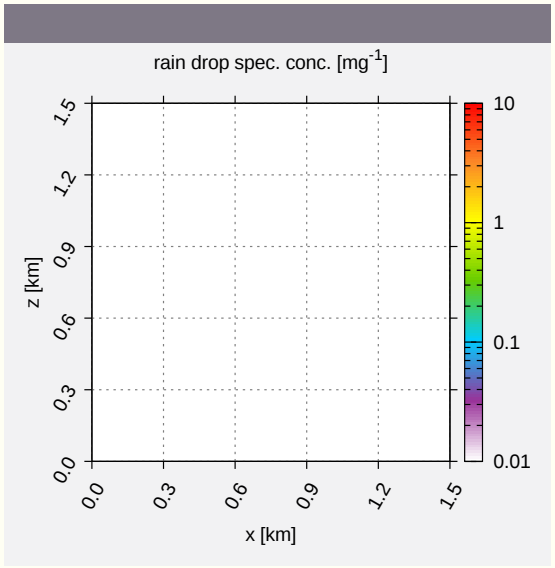

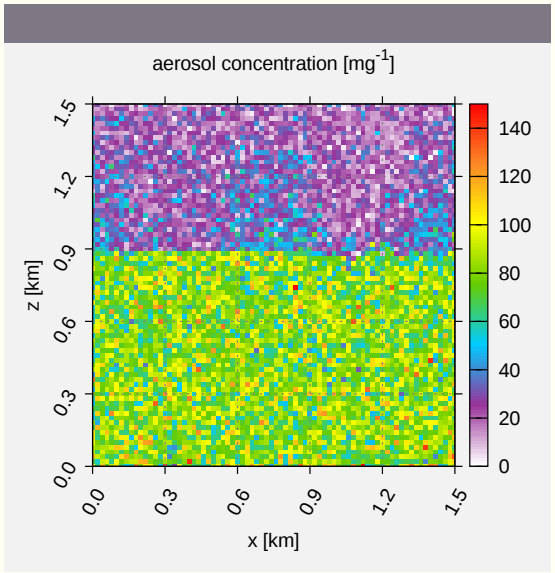

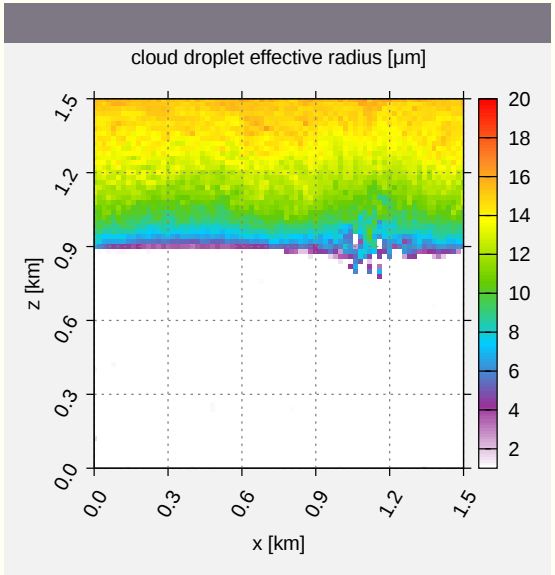

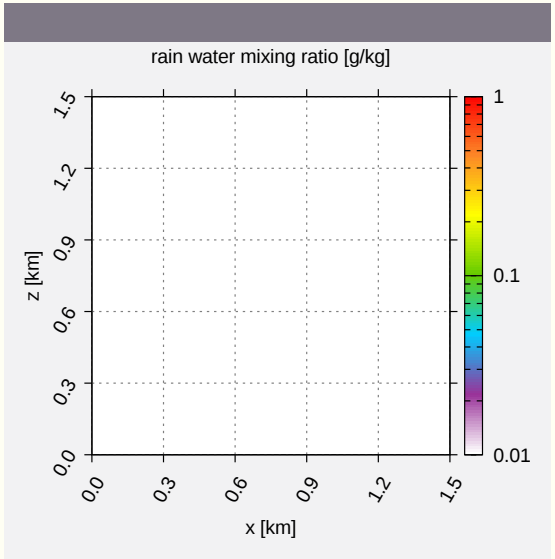

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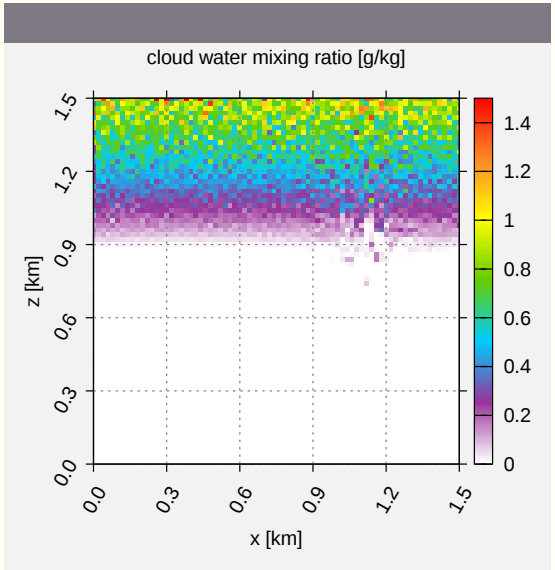

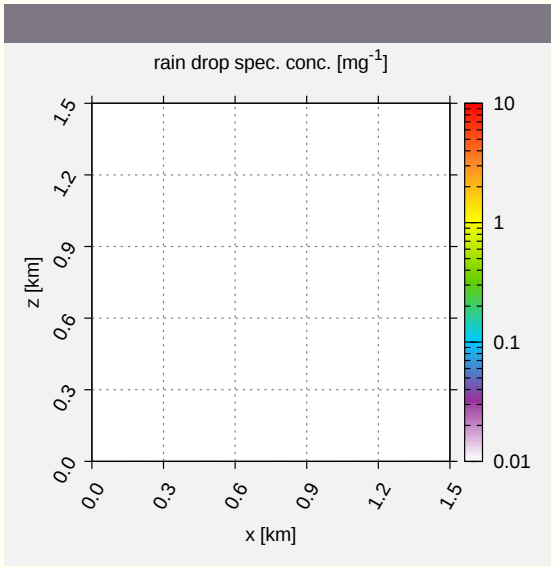

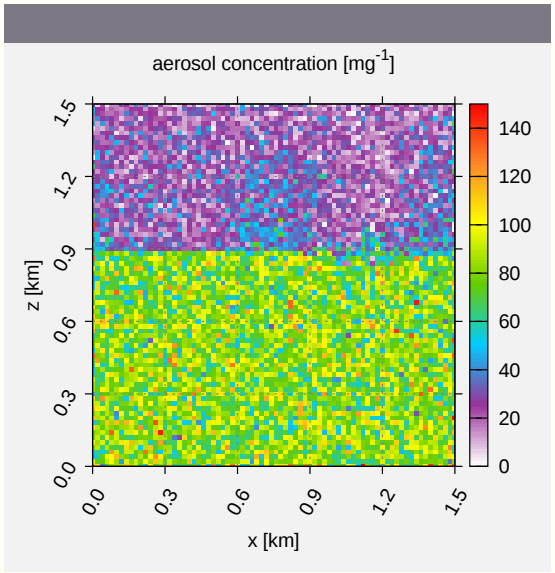

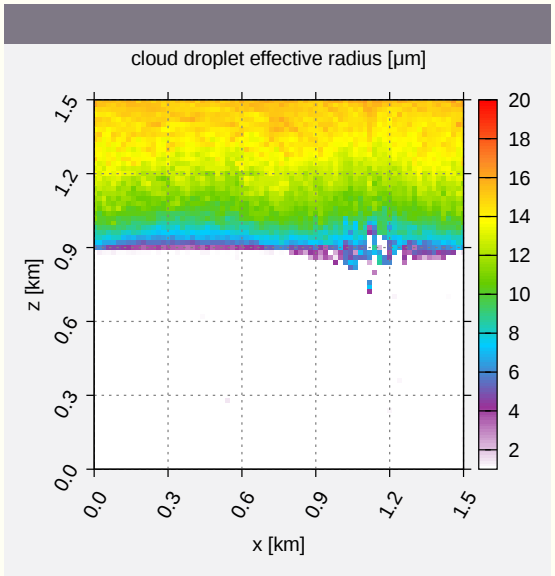

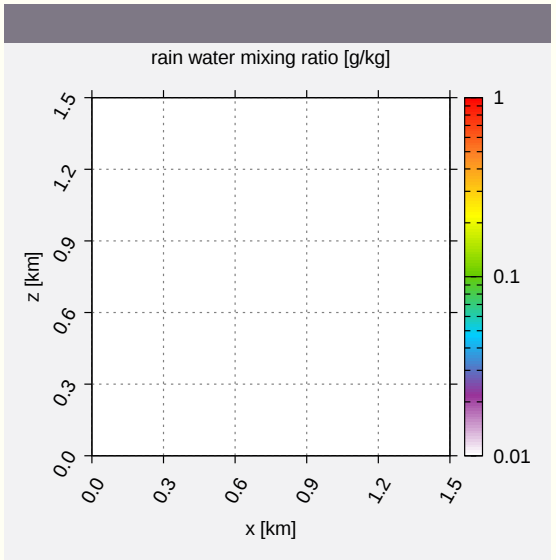

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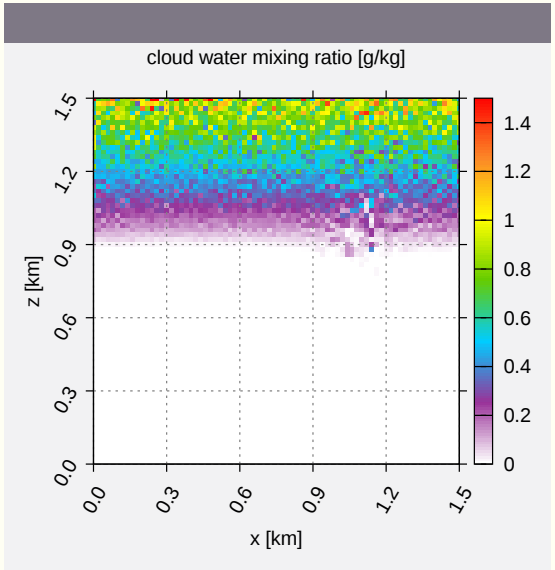

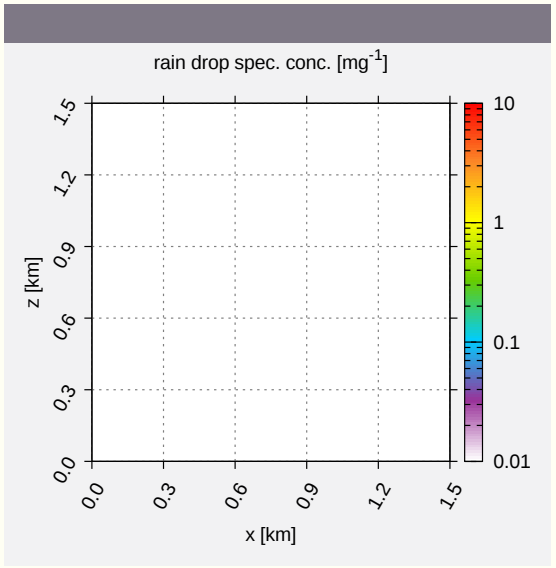

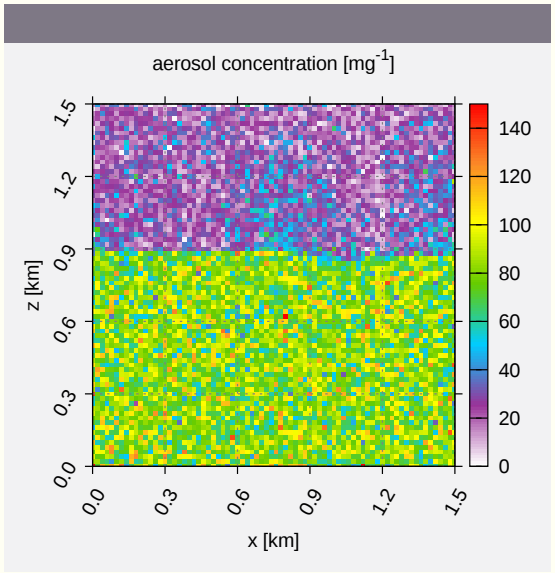

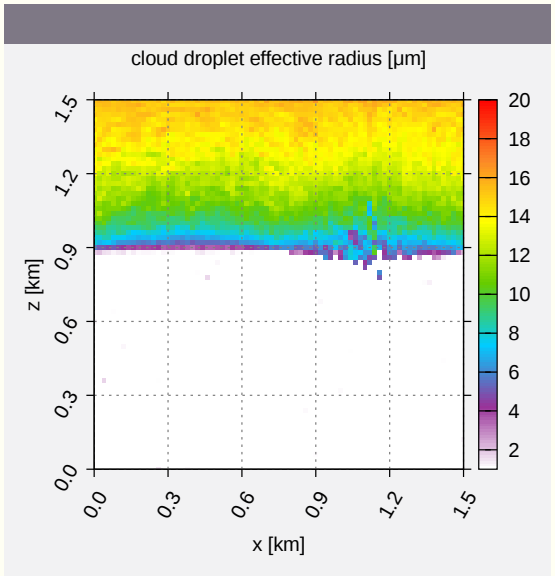

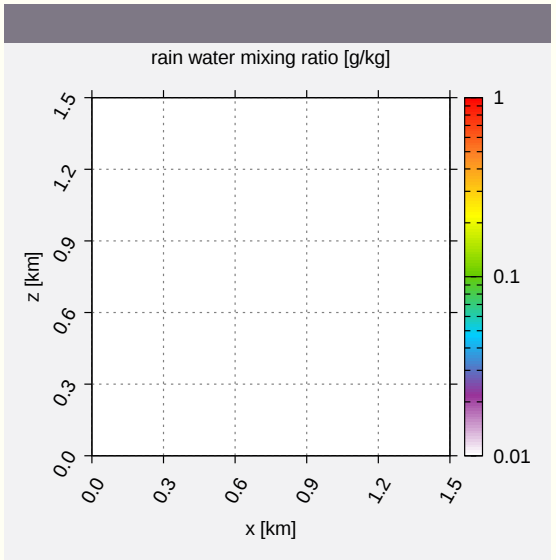

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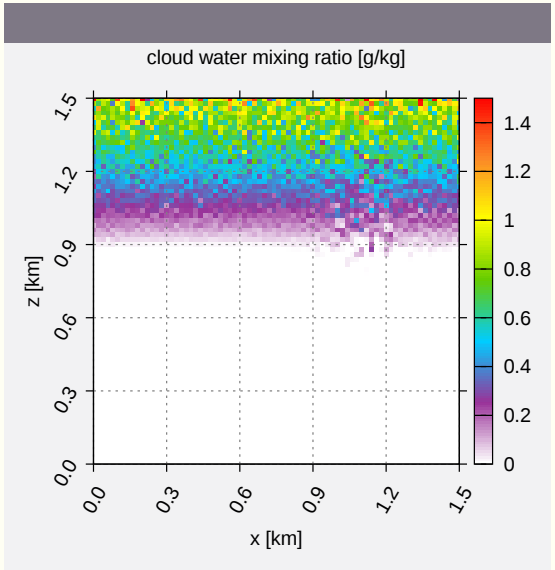

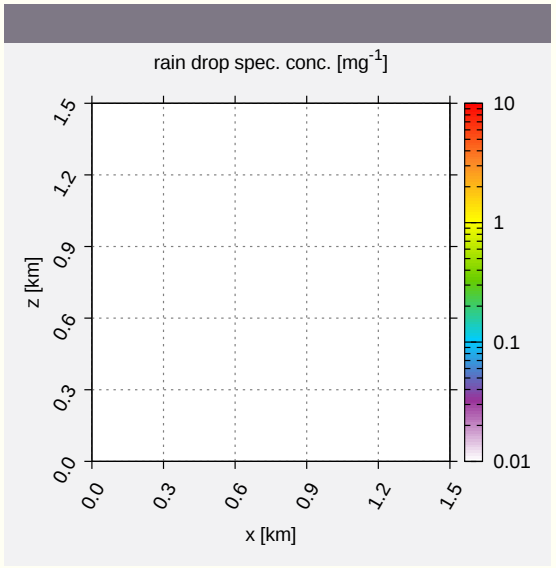

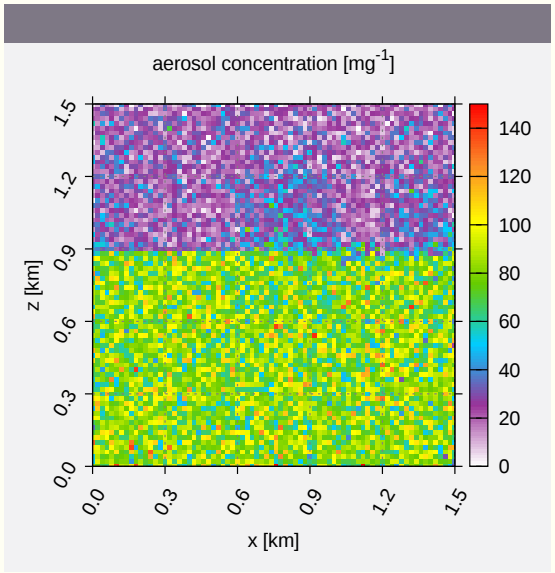

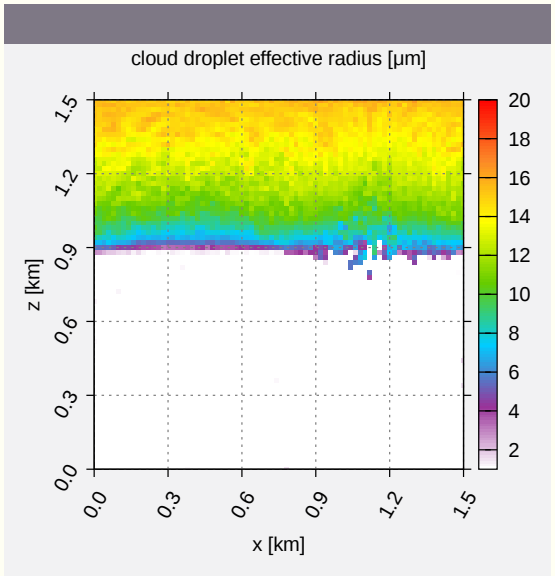

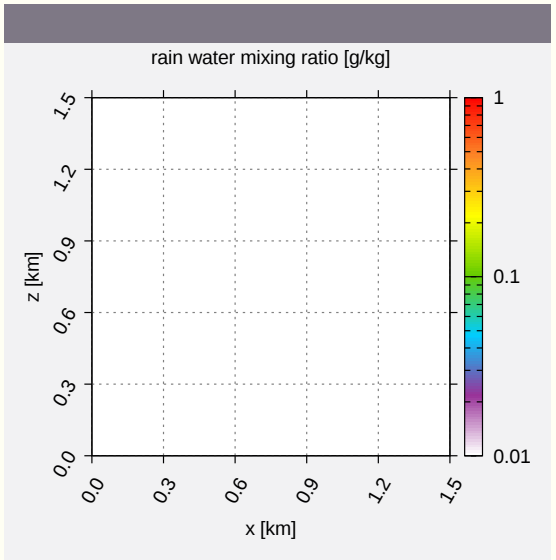

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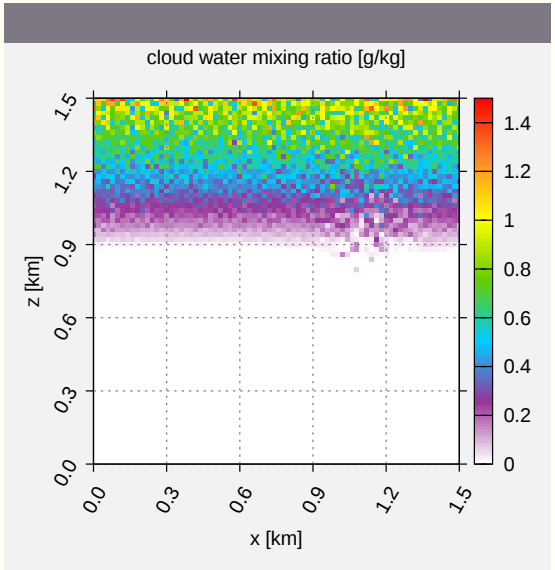

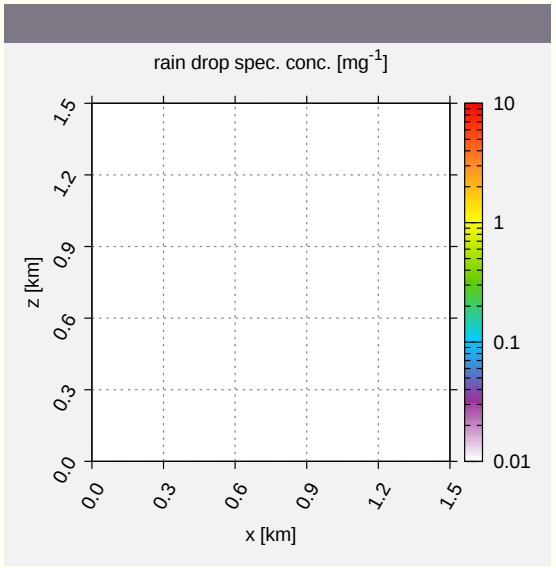

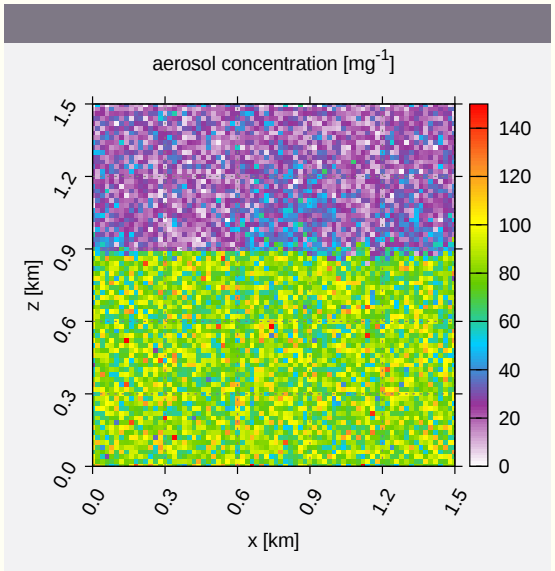

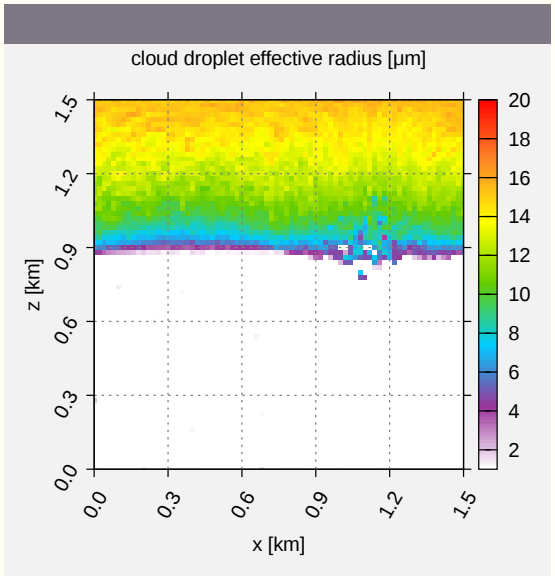

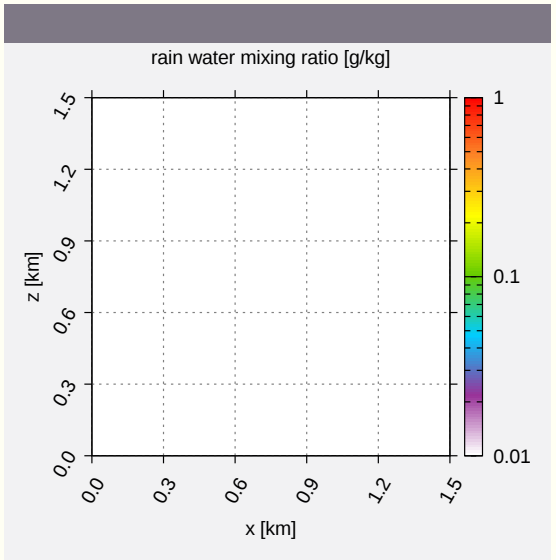

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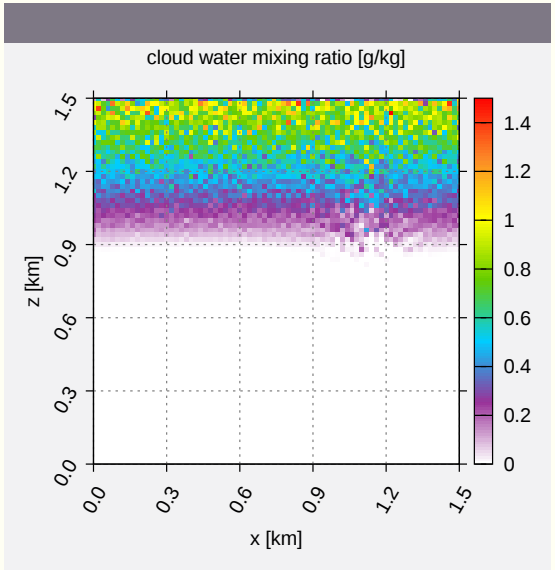

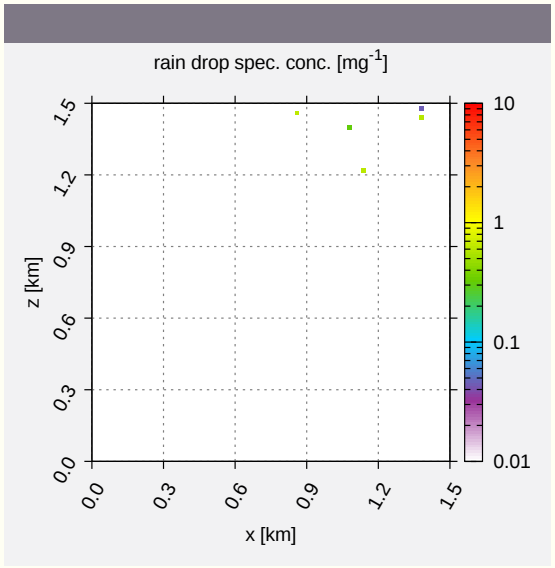

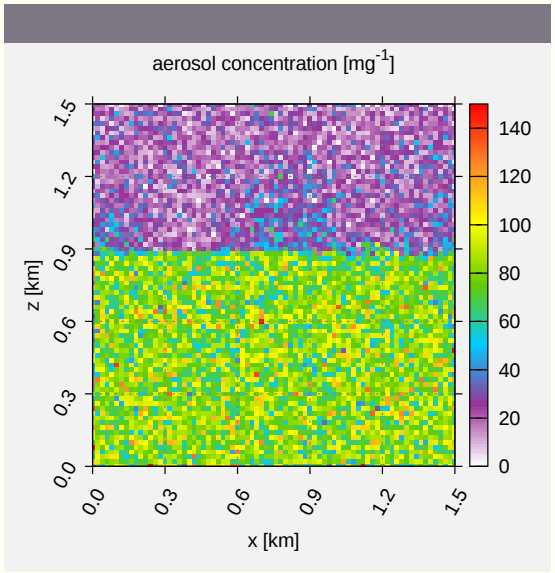

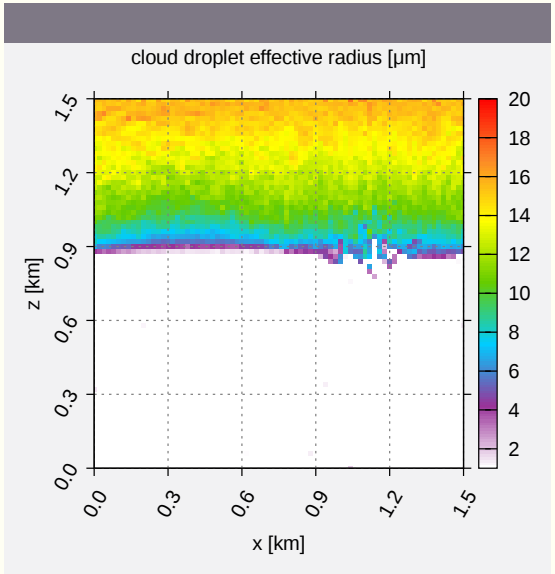

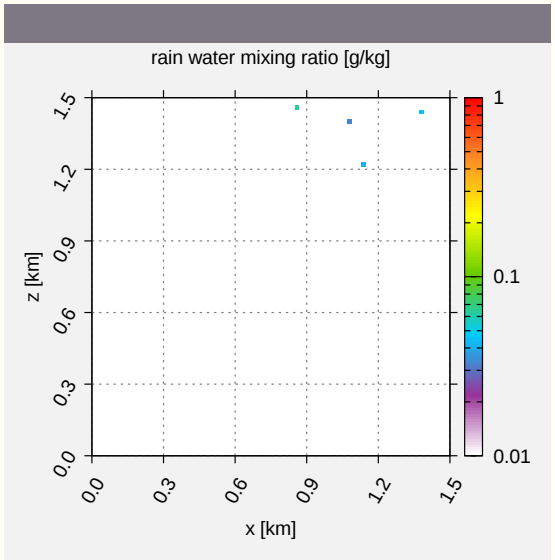

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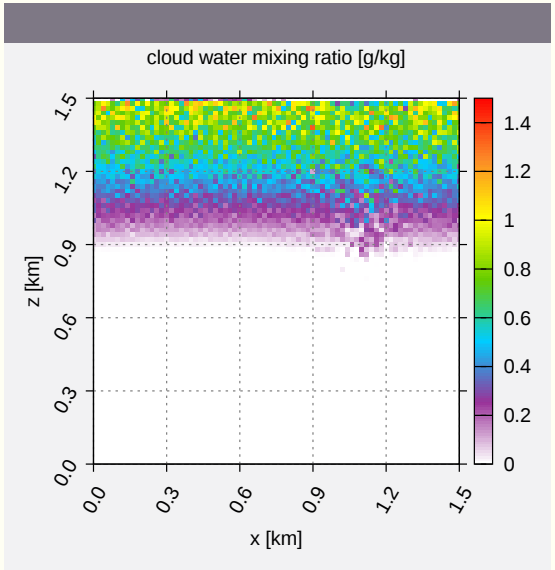

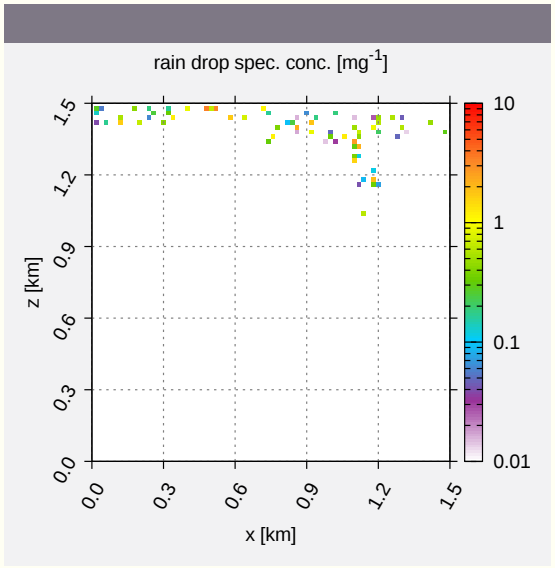

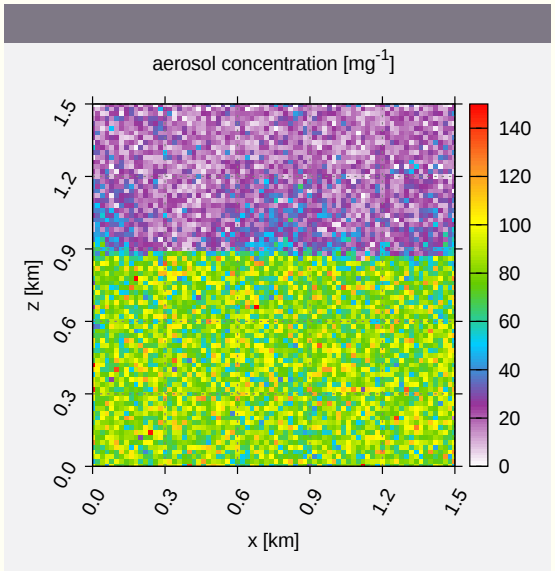

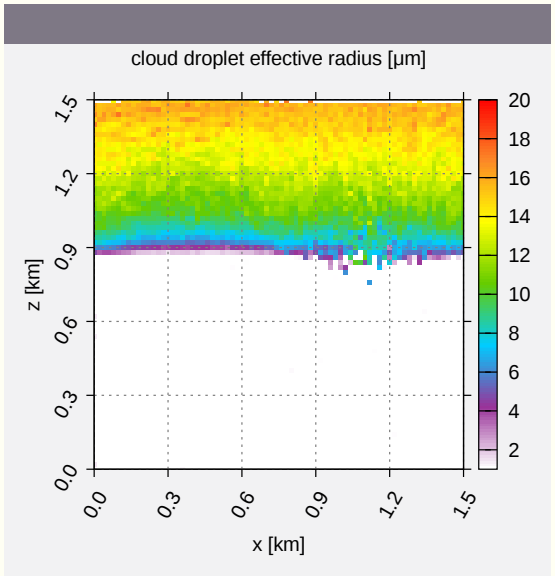

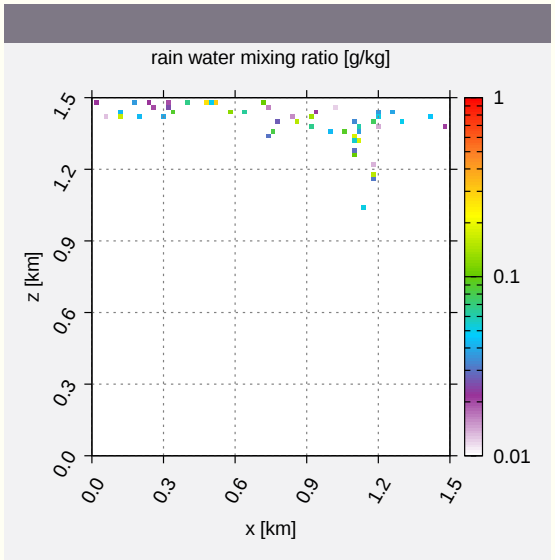

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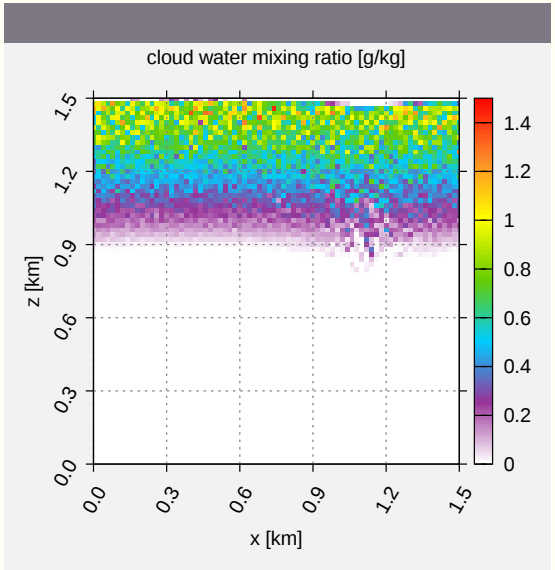

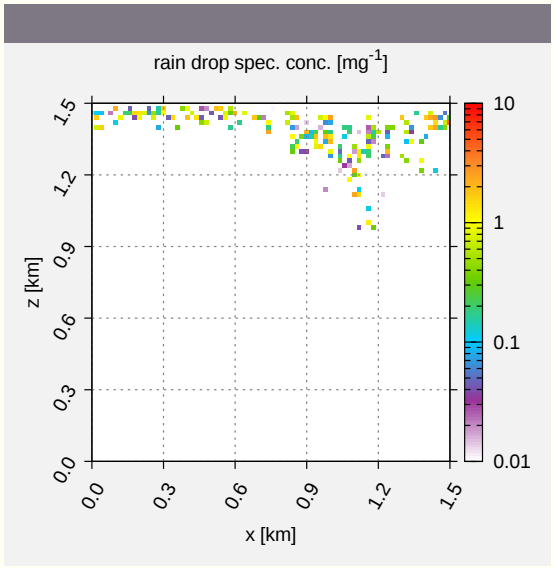

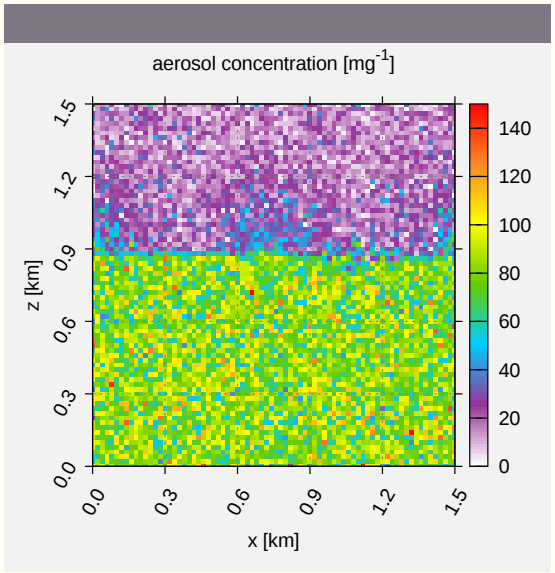

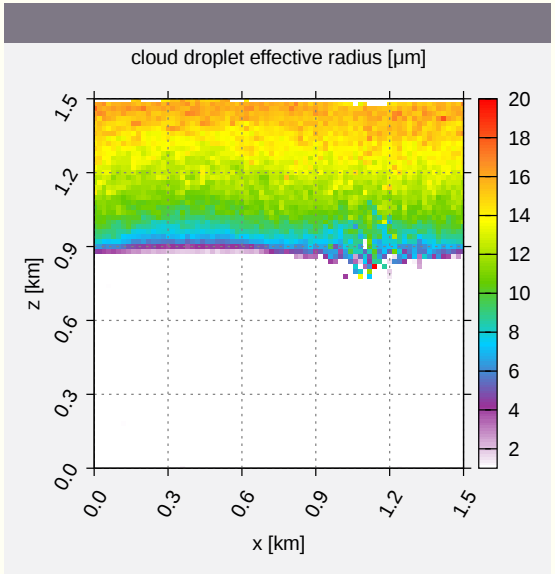

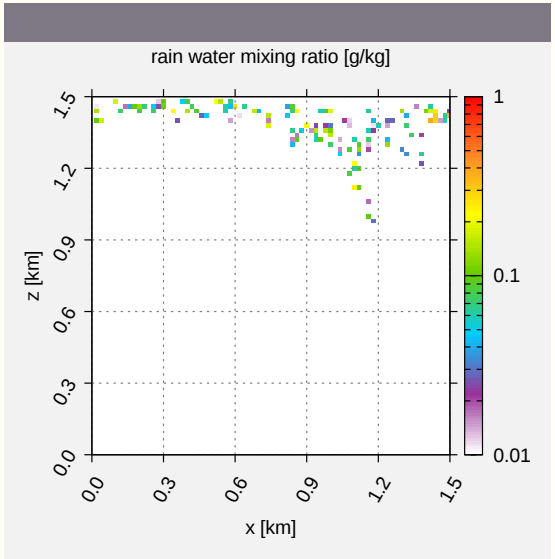

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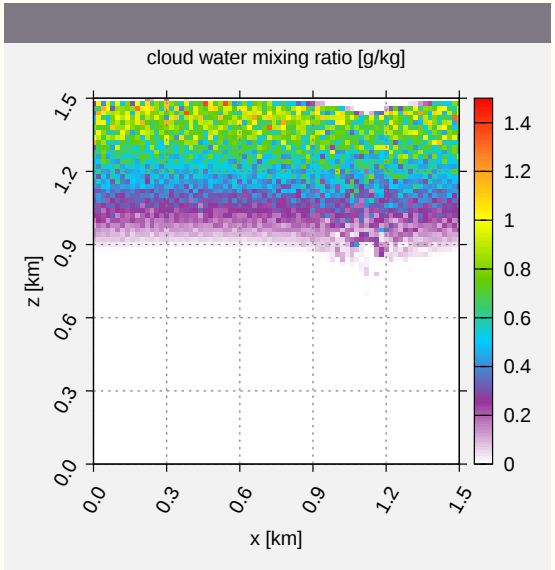

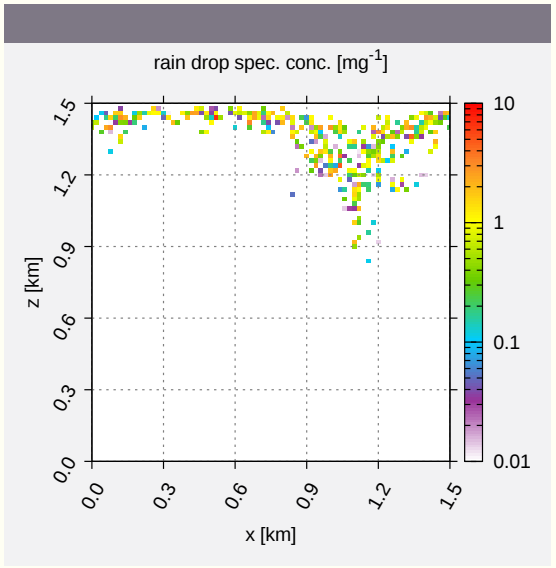

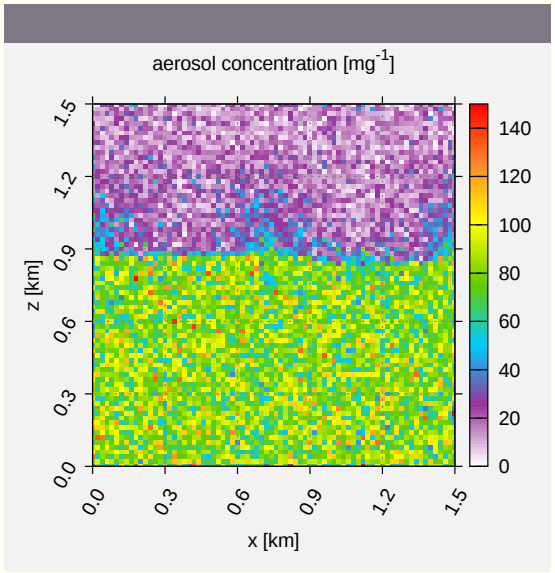

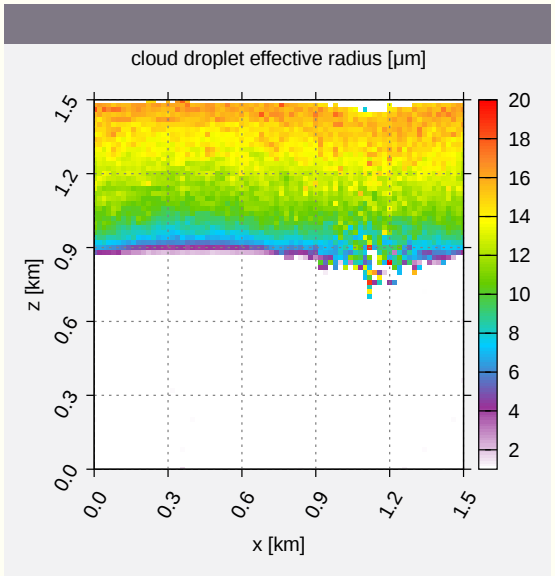

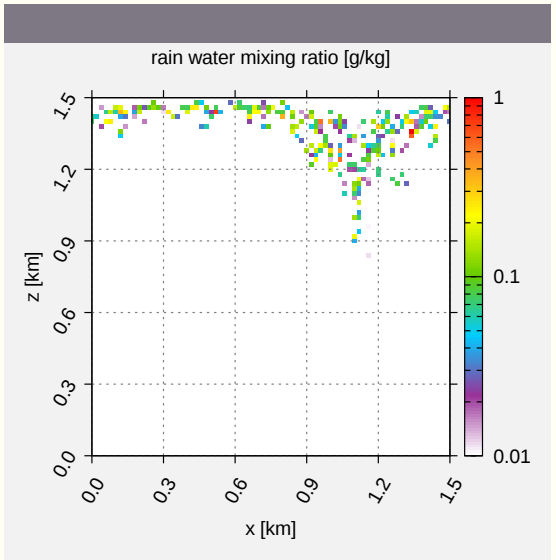

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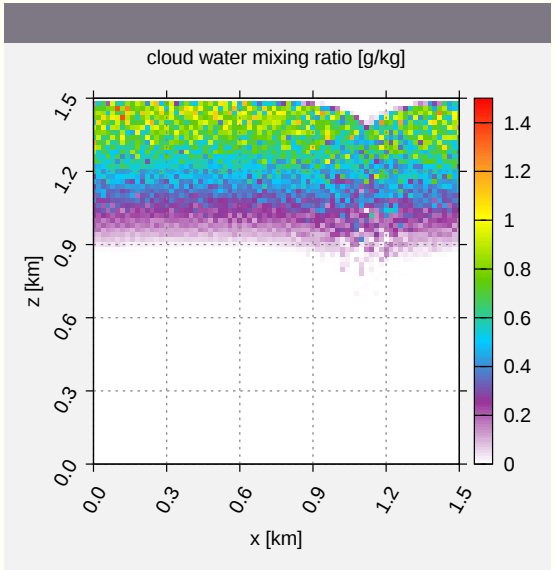

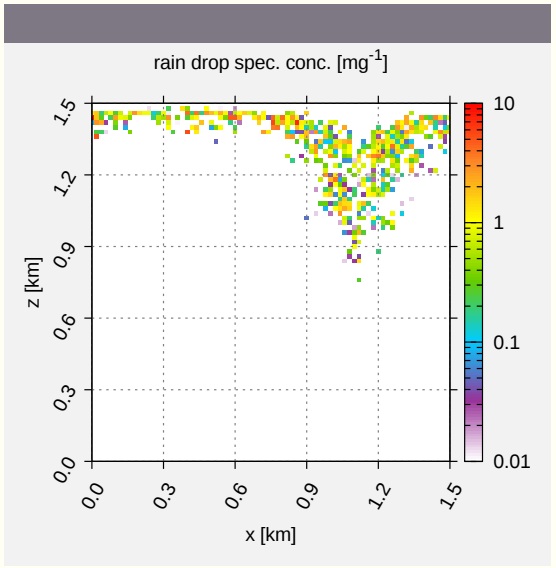

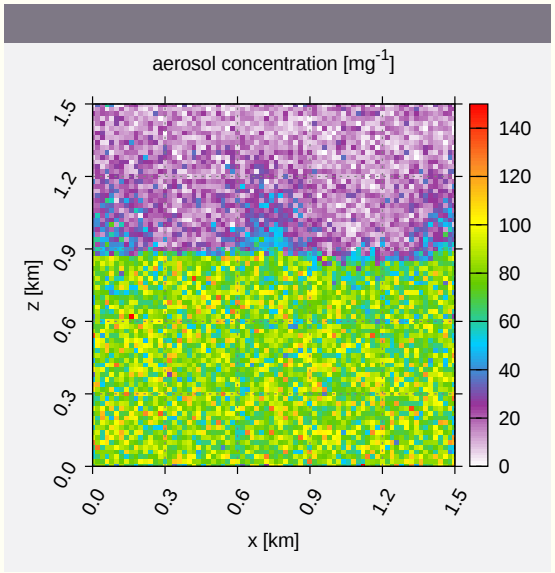

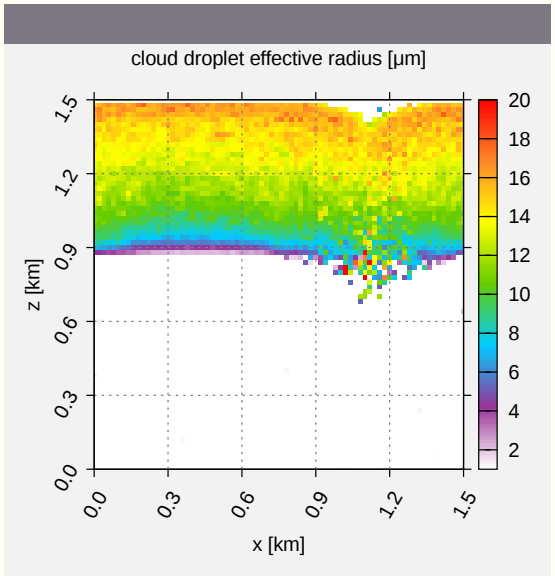

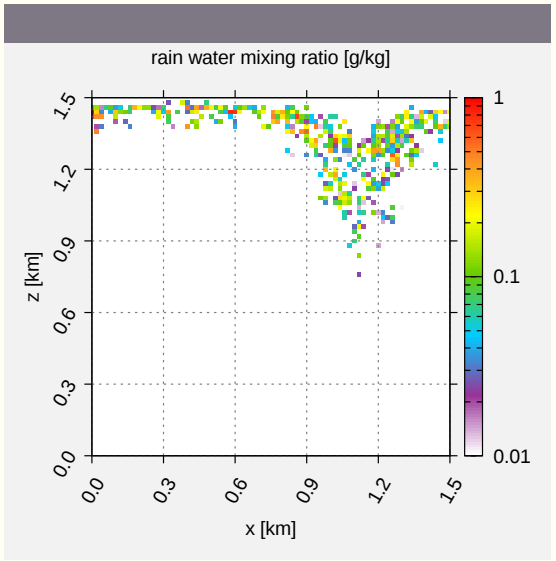

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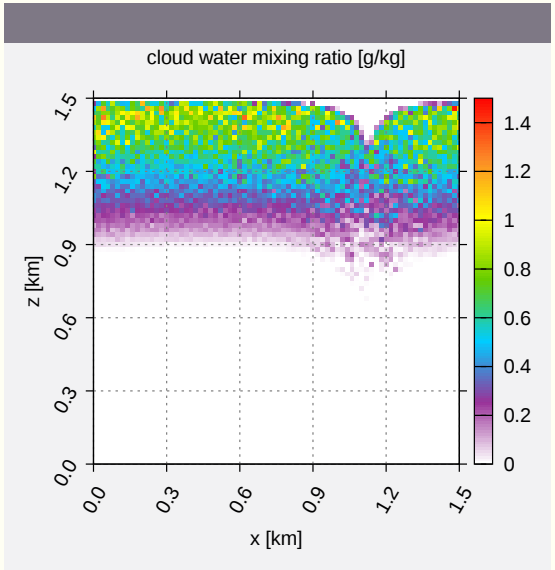

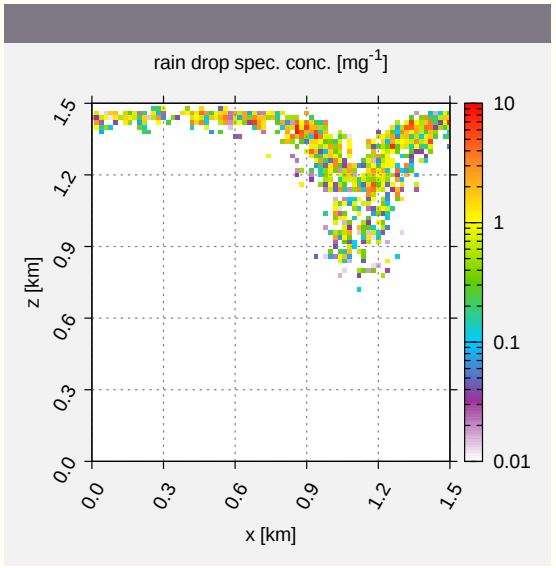

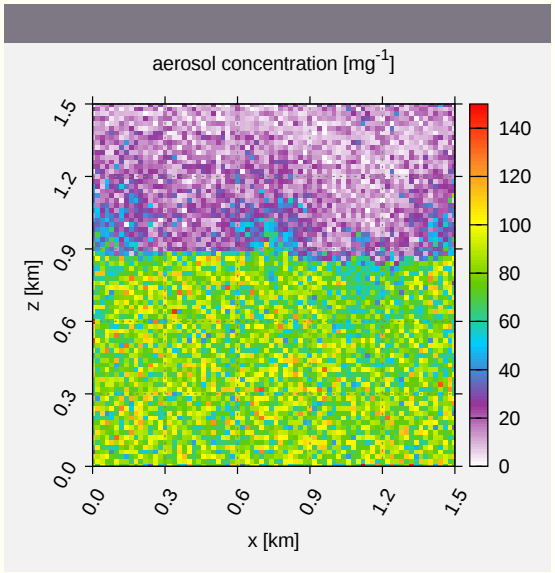

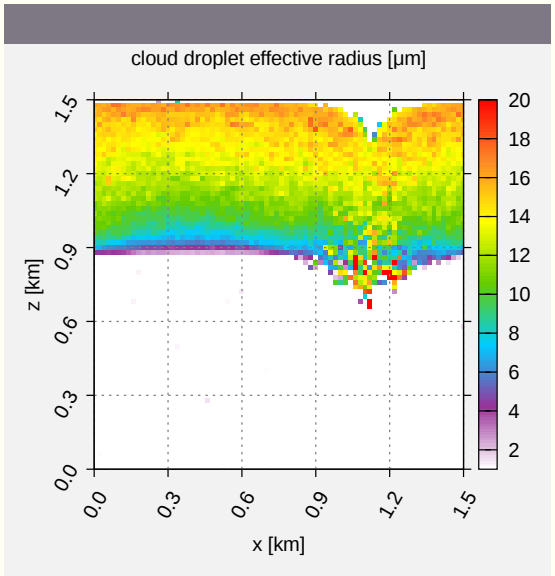

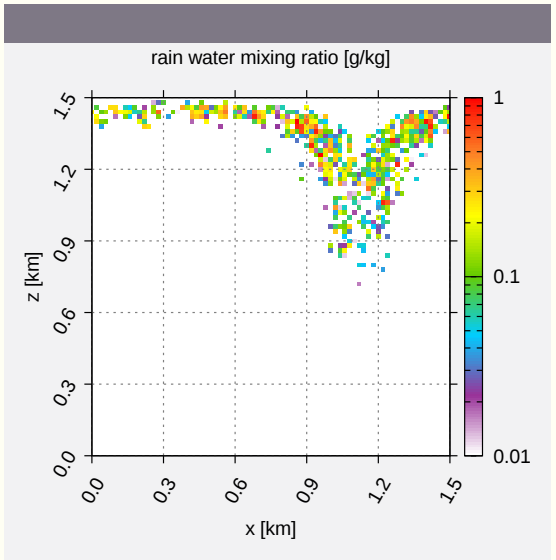

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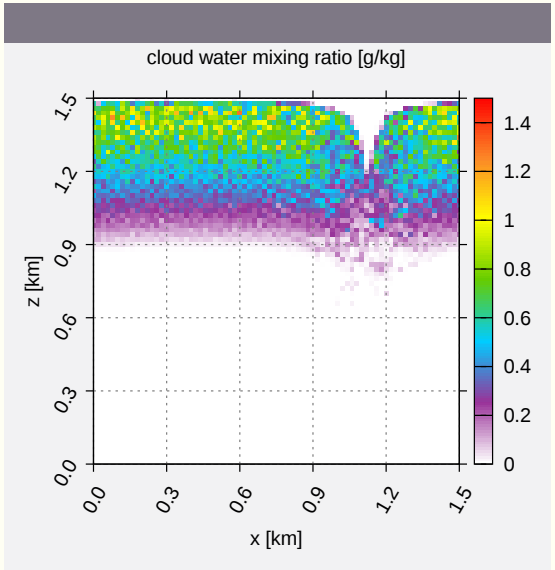

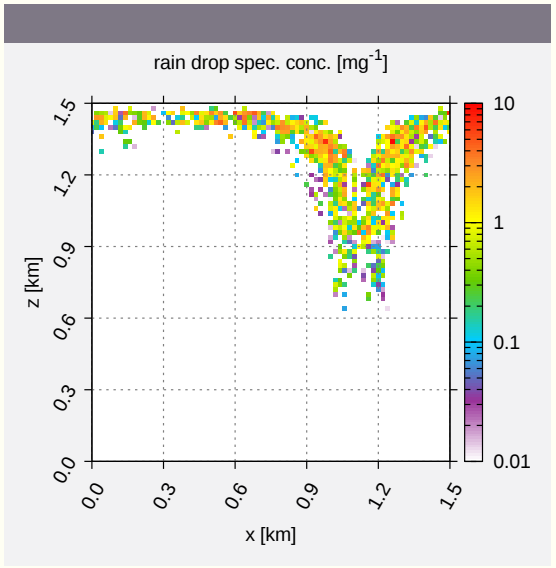

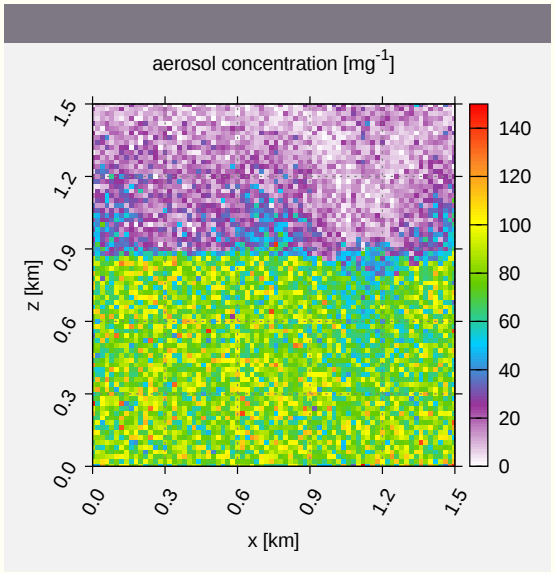

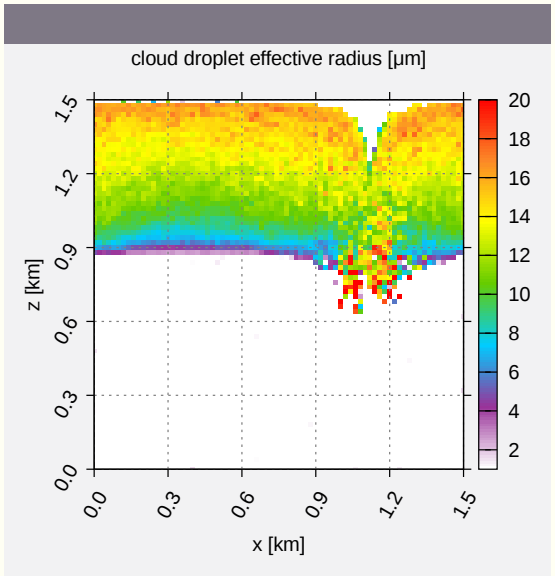

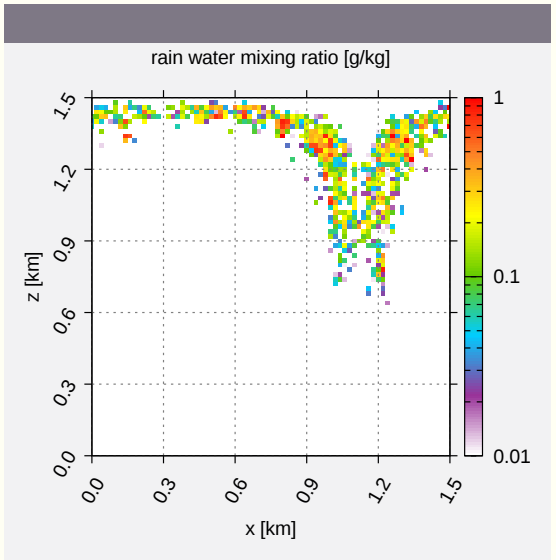

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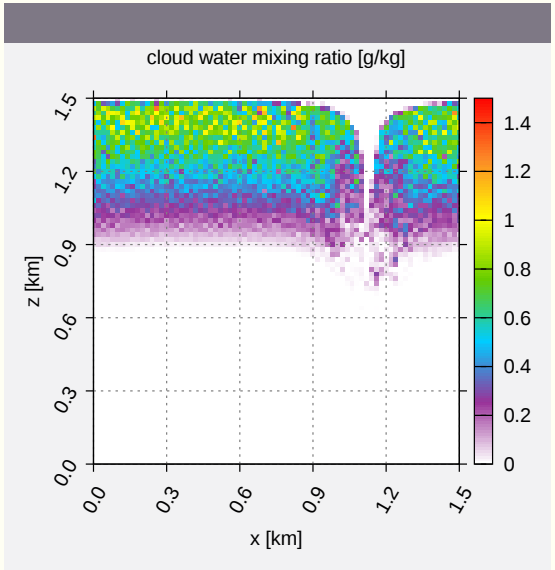

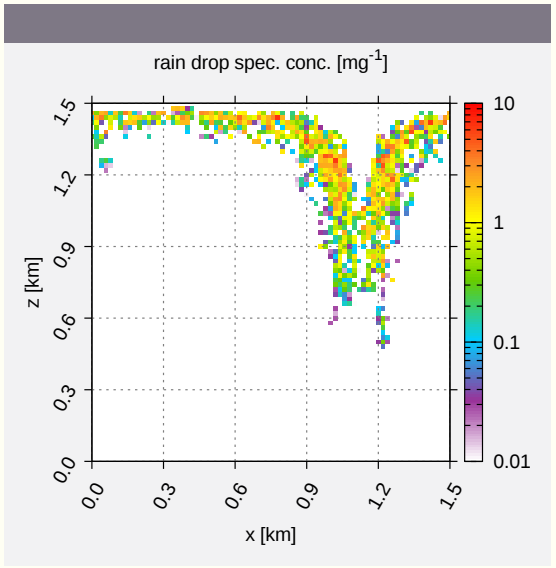

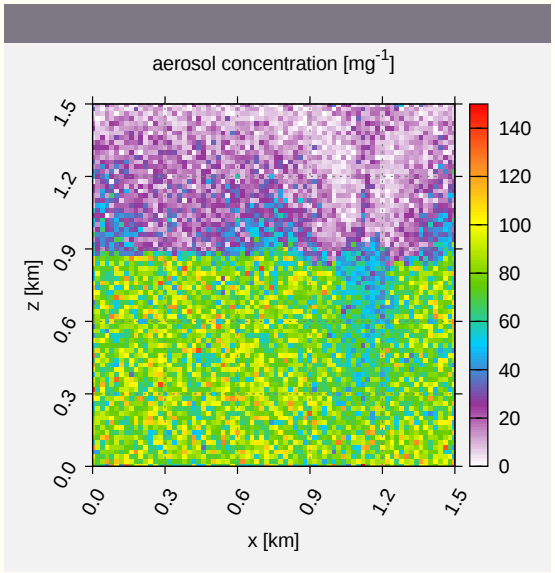

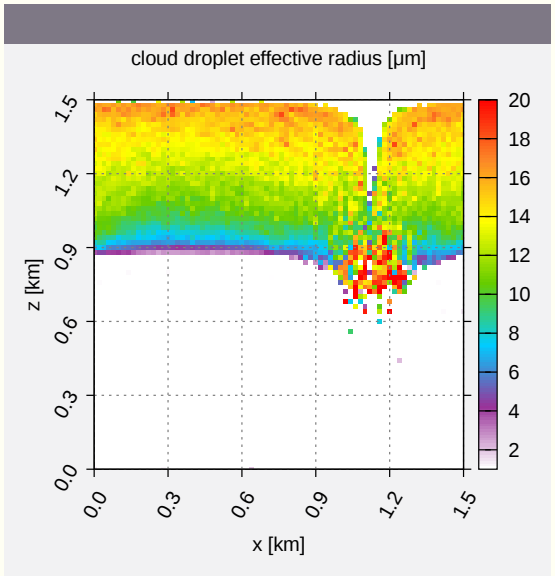

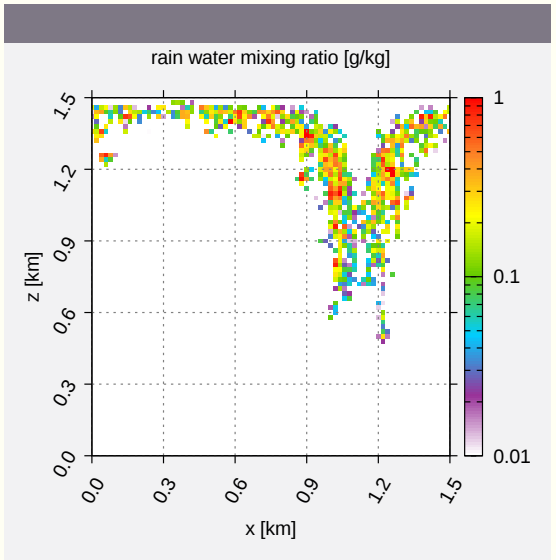

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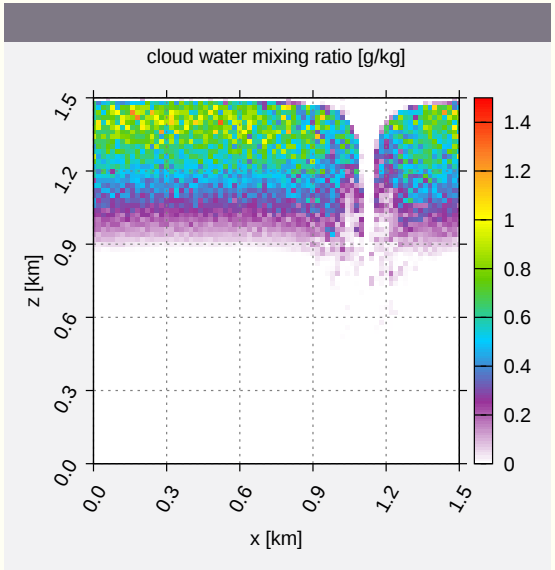

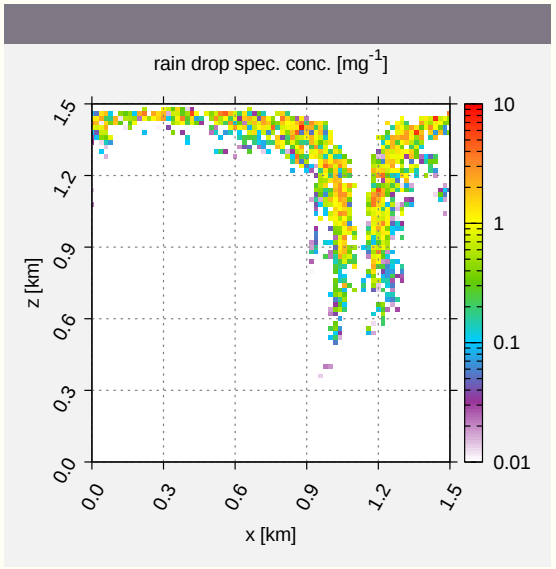

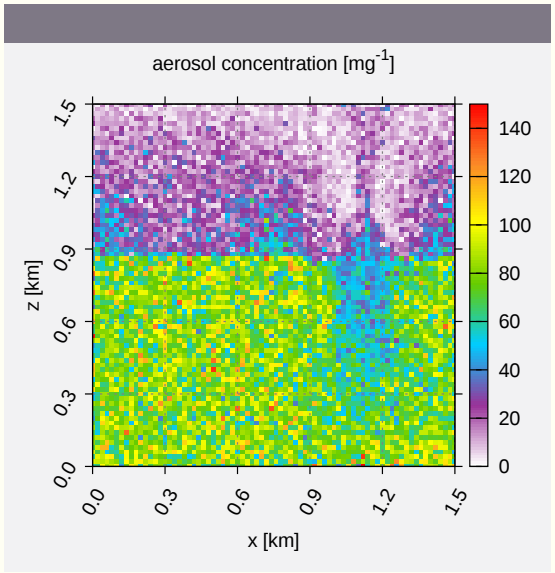

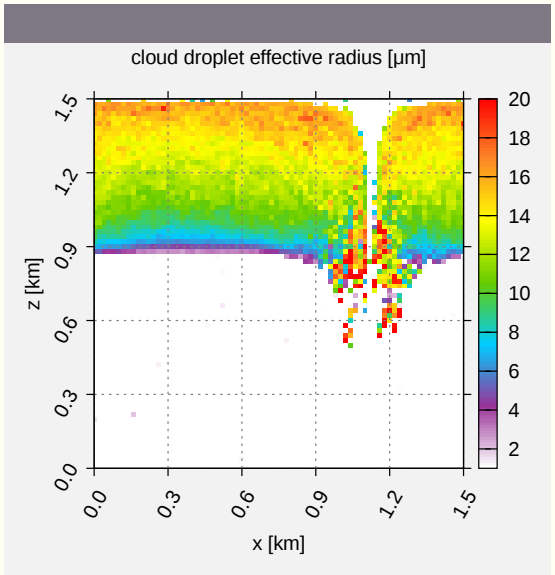

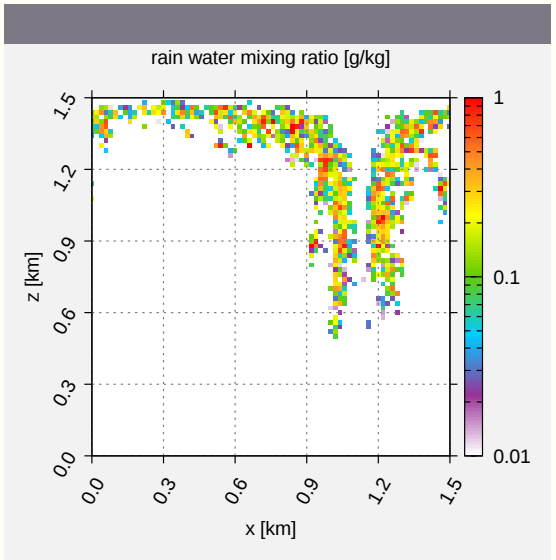

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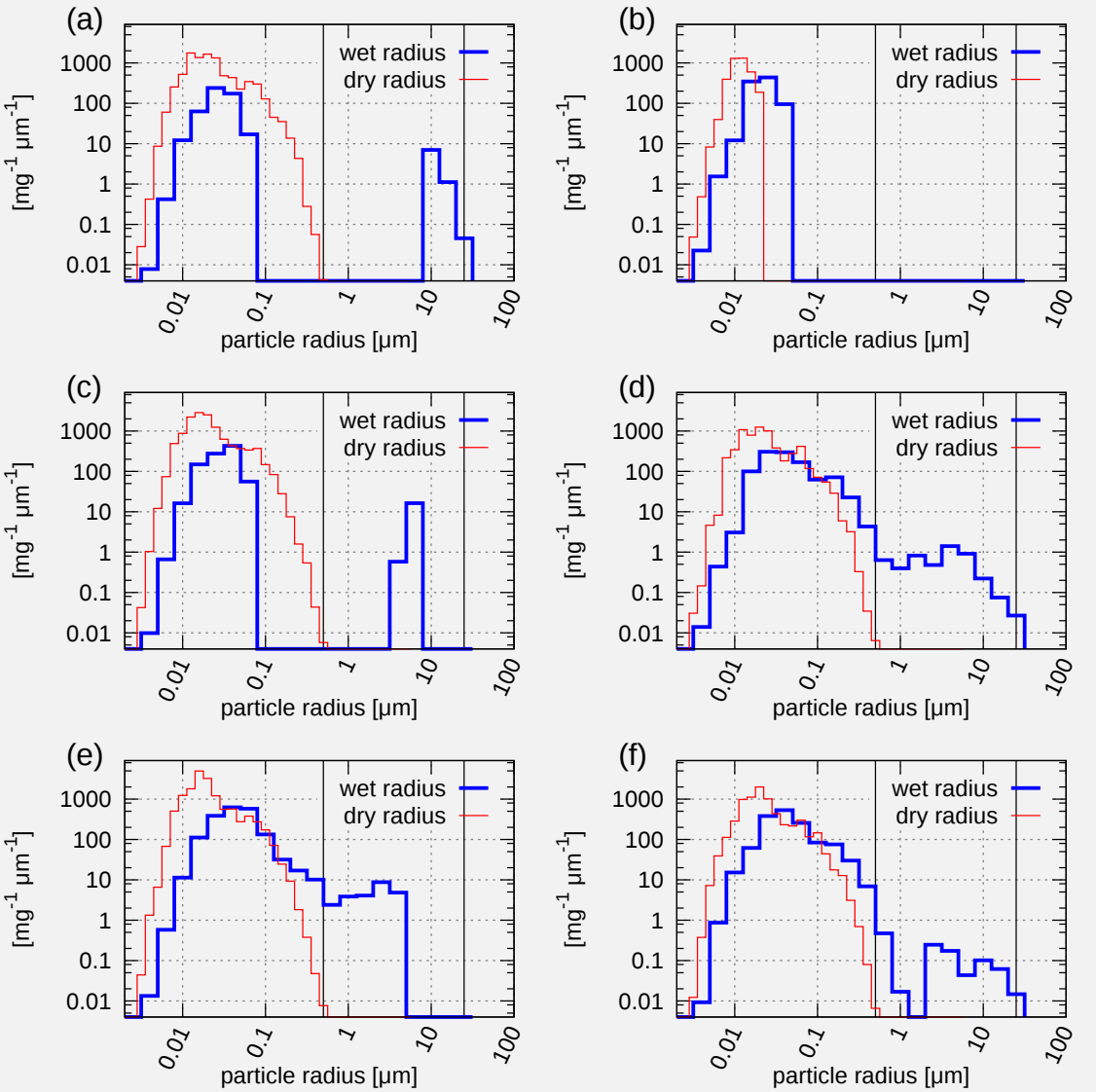
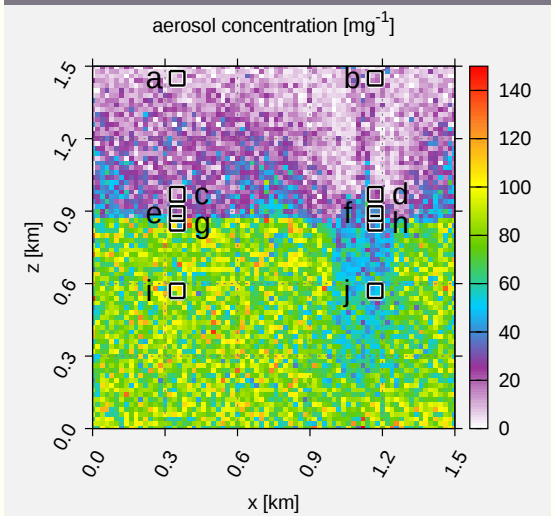
particle size spectra





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- Pencil-Code (`http://pencil-code.nordita.org`) from Nordita/UC,

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- ASAM (`http://asam.tropos.de/`) from TROPOS,
- UWLCM (`http://github.com/igfuw/UWLCM`) from Univ. Warsaw.

CReSS

highlights

- particle-based microphysics vs. praticle-based measurements
- new particle formation studies

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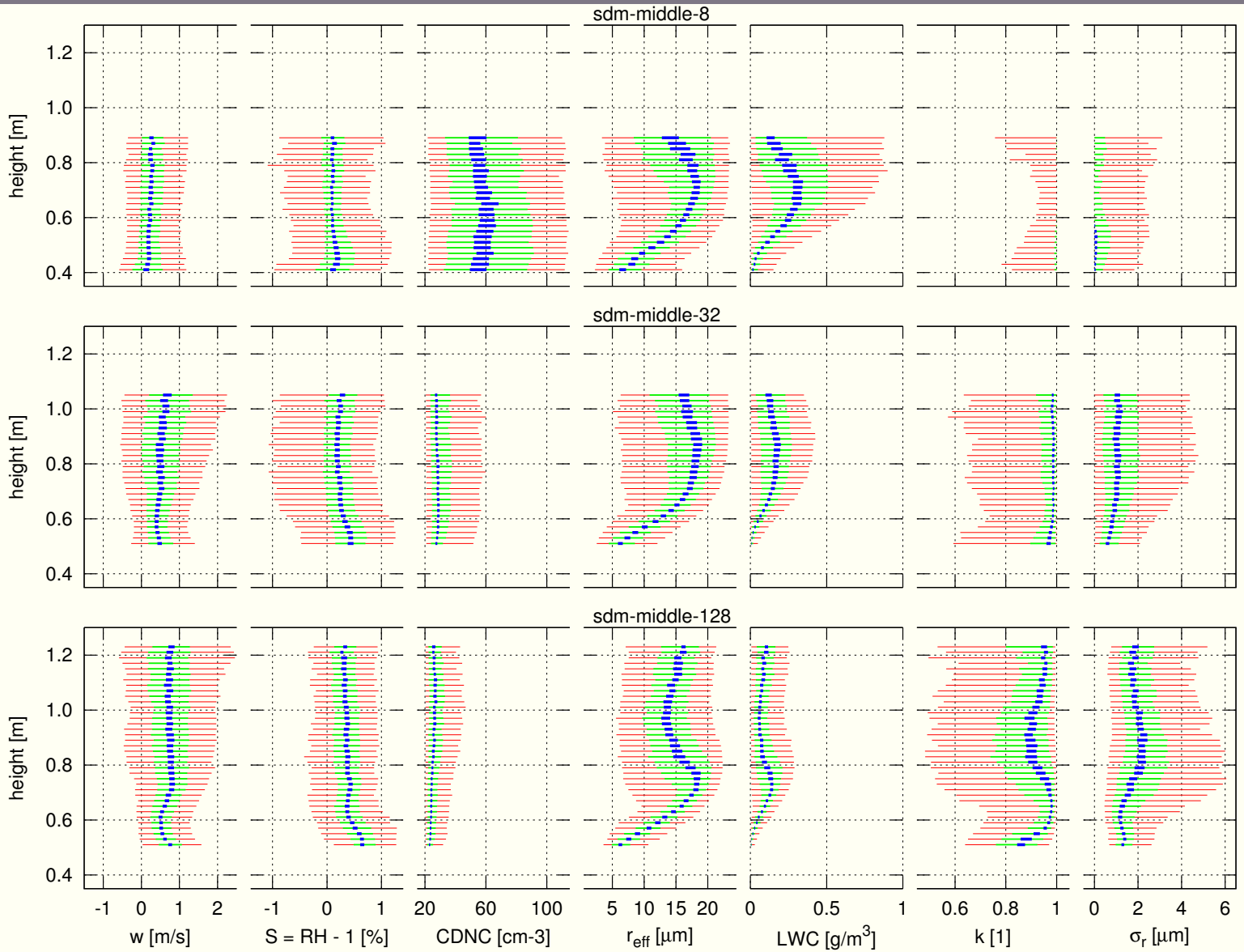
references

- **Arabas & Shima 2013** (JAS): *"Large Eddy Simulations of Trade-Wind Cumuli using Particle-Based Microphysics with Monte-Carlo Coalescence"*
- **Shima, Hasegawa & Kusano 2015** (EGU Vienna): *"Preliminary numerical study on the cumulus-stratus transition induced by the increase of formation rate of aerosols"*

CReSS - RICO 24h LES of cumulus cloud field



(Arabas & Shima 2013, JAS)

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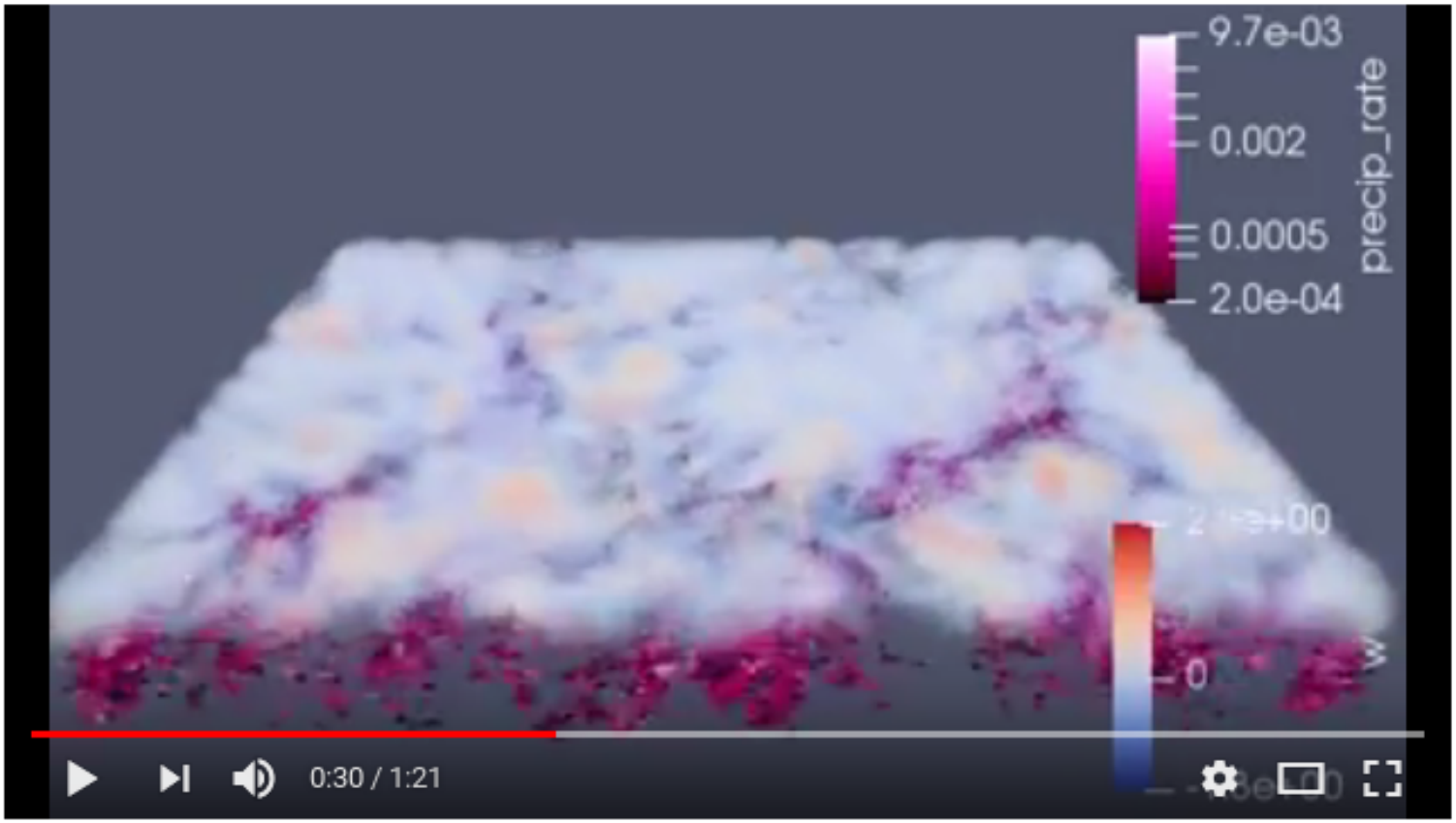
- **Arabas, Jaruga, Pawlowska & Grabowski 2015** (GMD): *"libcloudph++ 1.0: single-moment bulk, double-moment bulk, and particle-based warm-rain microphysics. . ."*
- **Jaruga & Pawlowska 2018** (GMD): *"libcloudph++ 1.1: aqueous phase chemistry extension of the Lagrangian cloud microphysics scheme"*
- **Dziekan & Pawlowska 2017** (ACP): *"Stochastic coalescence in Lagrangian cloud microphysics"*
- **Grabowski & Abade 2017** (JAS): *"Broadening of cloud droplet spectra through eddy hopping: Turbulent adiabatic parcel simulations"*
- **Grabowski, Dziekan & Pawlowska 2018** (GMD): *"Lagrangian condensation microphysics with Twomey CCN activation"*
- **Dziekan, Waruszewski & Pawlowska 2019** (GMD): *"University of Warsaw Lagrangian Cloud Model (UWLCM)..."*

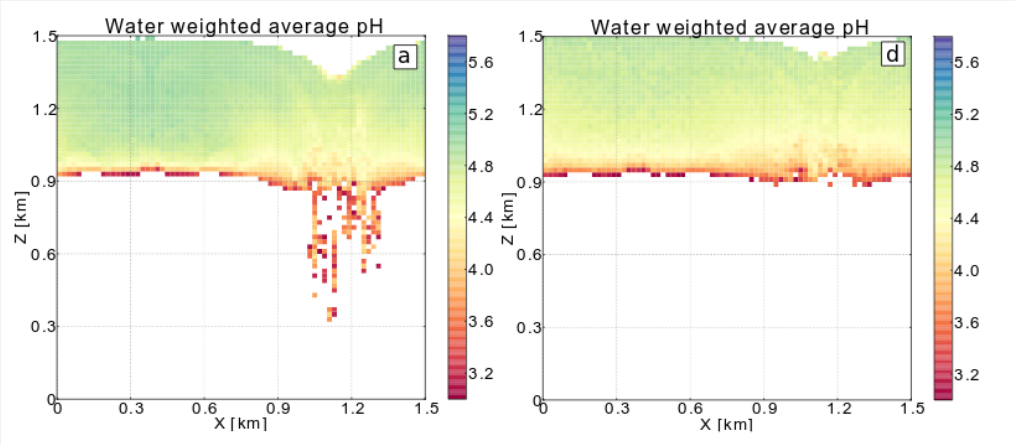
UWLCM - DYCOMS example



https://www.youtube.com/watch?v=BEidkhpw-MA

UWLCM: Hoppel-gap resolving particle-based μ-physics

Jaruga and Pawlowska 2018 (doi: 10.5194/gmd-11-3623-2018)



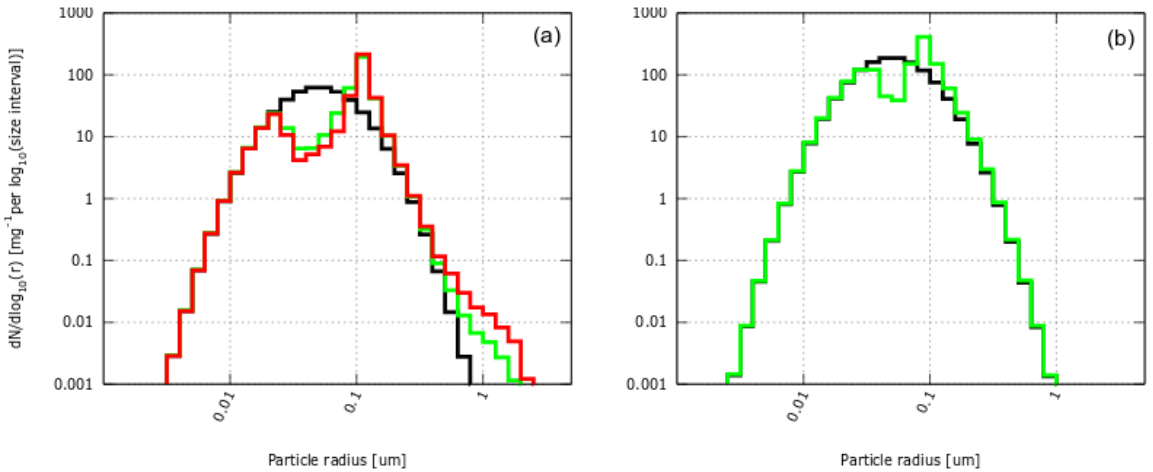


Figure 6. The size distributions of dry radii for the base case **(a)** and case3 **(b)**. The initial dry radius size distribution is marked in black, the final dry radius size distribution from grid cells with $r_c > 0.01\ \mathrm{g\,kg^{-1}}$ in green, and from grid cells with $r_r > 0.01\ \mathrm{g\,kg^{-1}}$ in red. See Tables 2 and 3 for a definition of simulation set-ups.

challenges ($\rightsquigarrow$ opportunities)

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news: BAMS super-droplet review (Grabowski et al. '19)

MODELING OF CLOUD MICROPHYSICS

Can We Do Better?

Wojciech W. Grabowski, Hugh Morrison, Shin-Ichiro Shima, Gustavo C. Abade, Piotr Dziekan, and Hanna Pawlowska

The Lagrangian particle-based approach is an emerging technique to model cloud microphysics and its coupling with dynamics, offering significant advantages over Eulerian approaches typically used in cloud models.

doi:10.1175/BAMS-D-18-0005.1

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Thank you!

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