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

Sylwester Arabas
Jagiellonian University

Jagiellonian University, Kraków, Poland

- founded in 1364 (coeval with the Ming Dynasty)
- among 20 oldest surviving universities in the world
- ca. 40 000 students, 7000 staff (4000 acad.), 16 faculties
- host to the Confucius Institute in Kraków (first in Poland)

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intro: plan of the talk

particle-based cloud microphysics:

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particle-based cloud microphysics:

- rationale

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particle-based cloud microphysics:

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- state of the art

intro: plan of the talk

particle-based cloud microphysics:

- rationale
- state of the art
- challenges ($\rightsquigarrow$ opportunities)

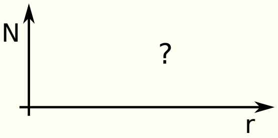
rationale

rationale: aerosol-cloud interactions

"Cloud and ship. Ukraine, Crimea, Black sea, view from Ai-Petri mountain"
(photo: Yevgen Timashov / National Geographic)

modelling nomenclature: aerosol, cloud & rain spectra

- single-moment bulk



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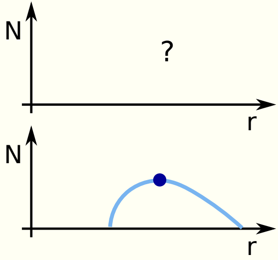

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- single-moment bulk
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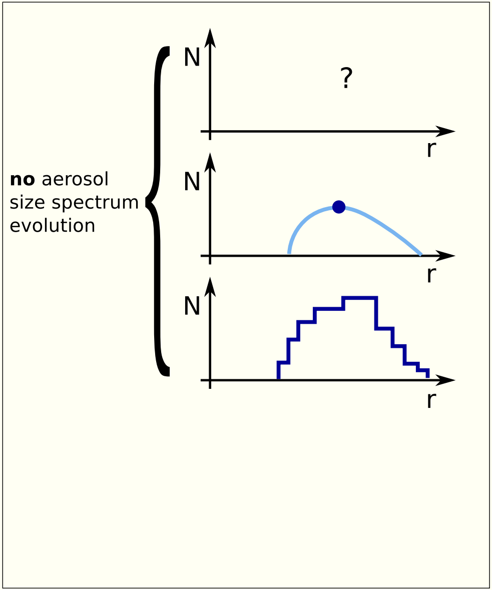
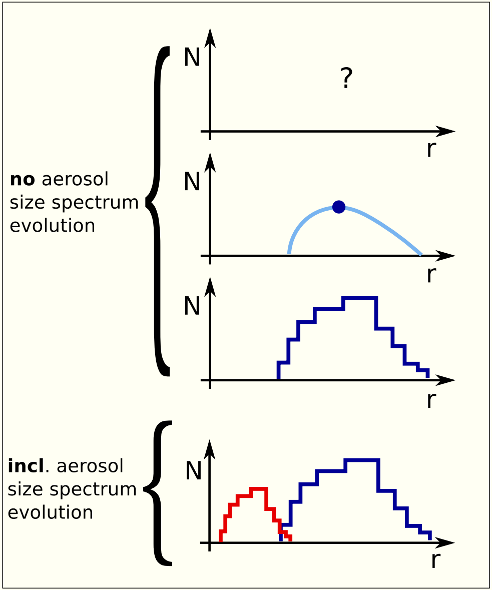
- „wet” size spectrum (bin)

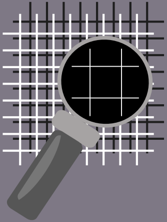

no aerosol
size spectrum
evolution

modelling nomenclature: aerosol, cloud & rain spectra

- single-moment bulk
- multi-moment bulk
- „wet" size spectrum (bin)
- „wet vs. dry" 2D spectrum



rationale: modelling aerosol-cloud interactions



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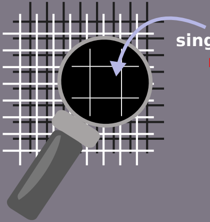

single-moment bulk:
no influence of aerosol on cloud

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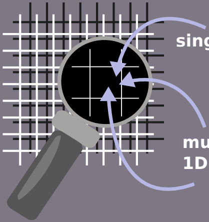

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aerosol may influence cloud
no "memory" of drop nuclei

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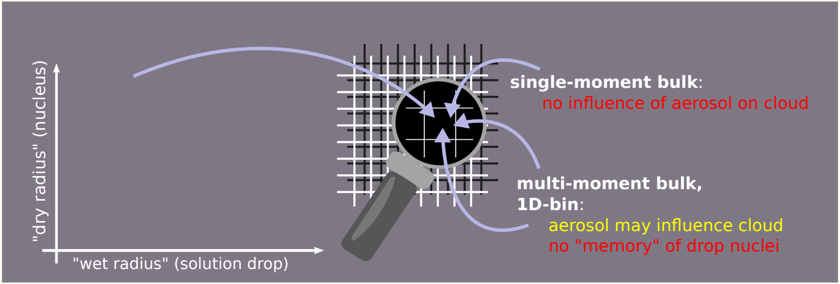

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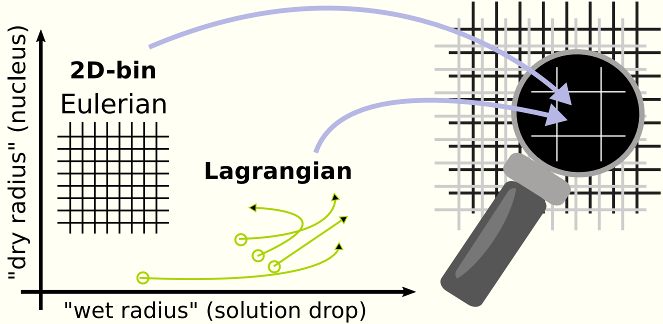

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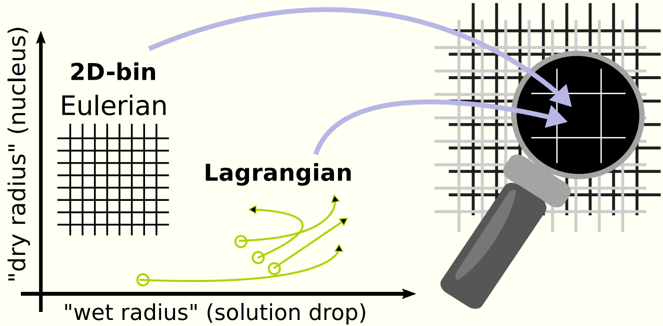

Lagrangian:

- parcel model
  ⇝ moving-sectional schemes (40-ties onwards: Howell, Mordy, . . .)

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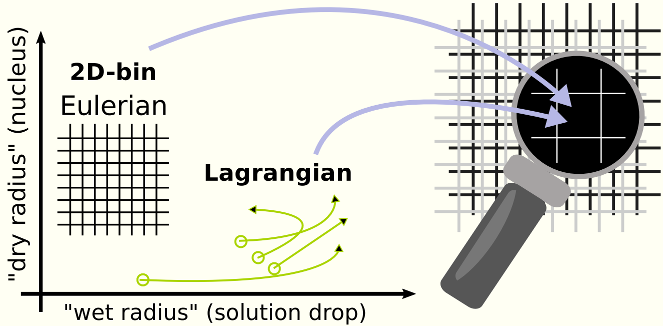
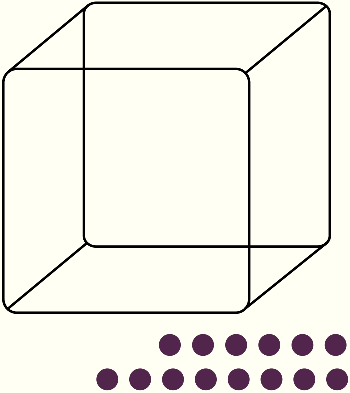


Lagrangian:

- parcel model
    ⇝ moving-sectional schemes (40-ties onwards: Howell, Mordy, . . .)
- LES + Lagrangian-in-space + coalescence
    ⇝ particle-based/super-droplet μ-physics (00-ties onwards: Shima, . . .)

particle-based μ-physics: key concepts



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

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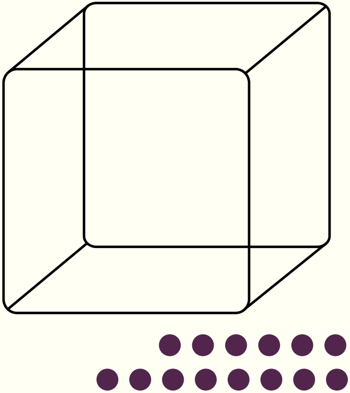

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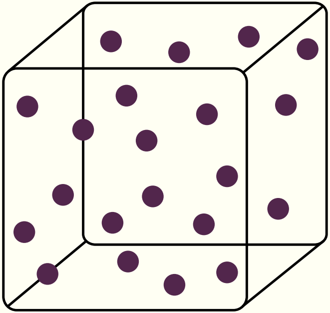

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carrier attributes:

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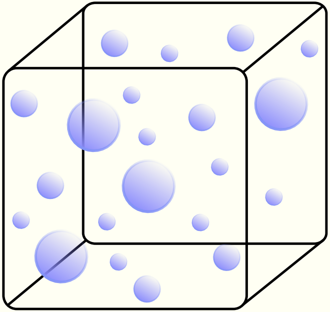

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carrier attributes:

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- wet radius

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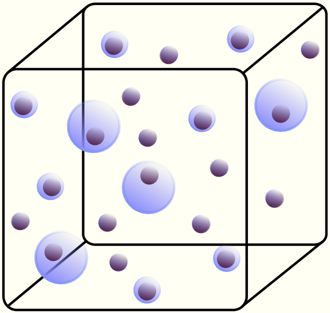

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carrier attributes:

- location
- wet radius
- dry radius

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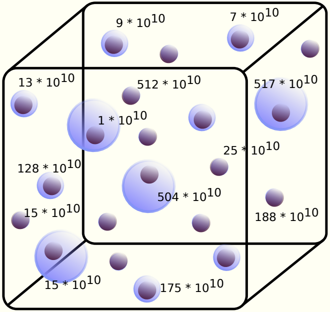

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carrier attributes:

- location
- wet radius
- dry radius
- multiplicity

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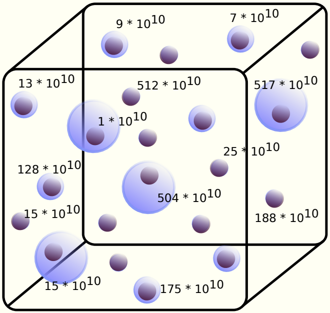

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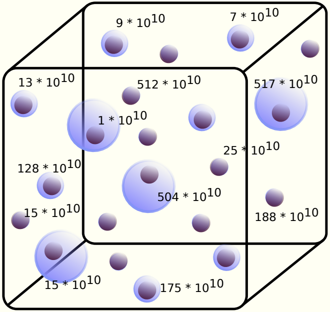

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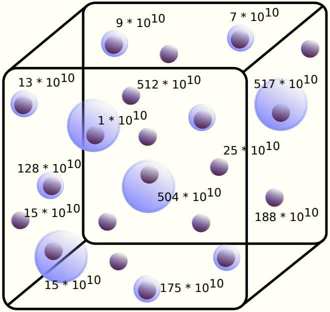

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advantage over Eulerian approach: adding attributes does not increase dimensionality (ice, chemistry, charge, isotopic composition, ...)

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

Eulerian / PDE	Lagrangian / ODE

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advection of heat	particle transport by the flow
advection of moisture	

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advection of moisture	condensational growth
	collisional growth
	sedimentation

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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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advection of trace gases	in-particle aqueous chemistry
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...	...

challenges:

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

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++

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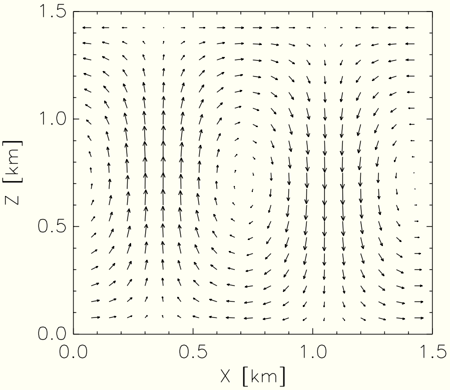

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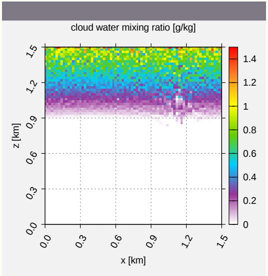
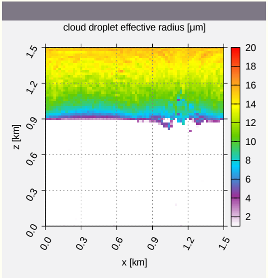
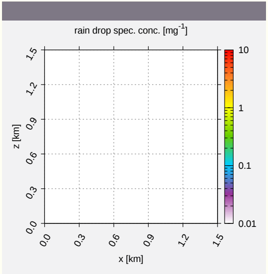
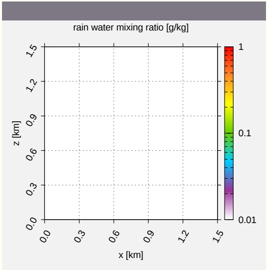

cloud water mixing ratio [g/kg]


cloud droplet effective radius [μm]


rain drop spec. conc. [mg^{-1}]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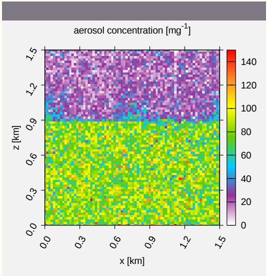
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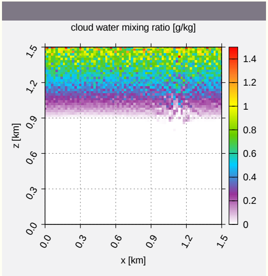
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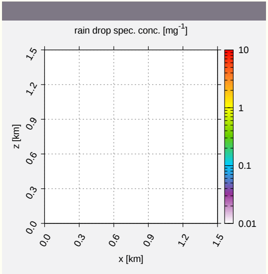
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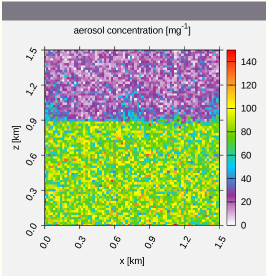
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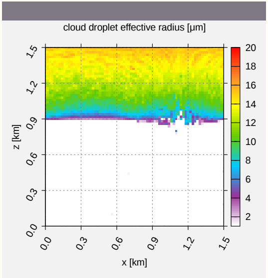
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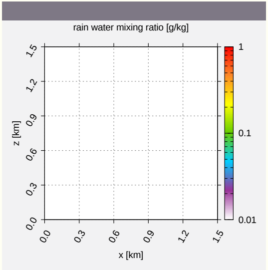
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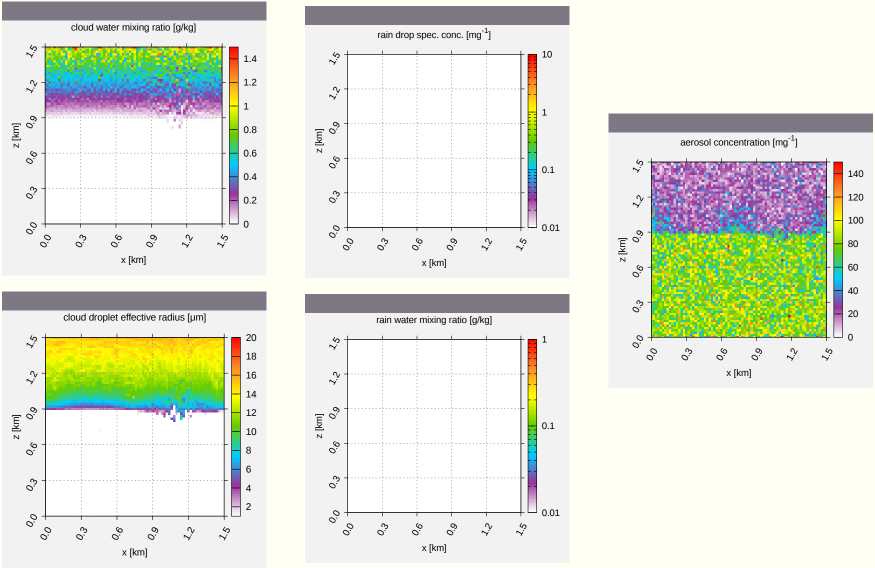

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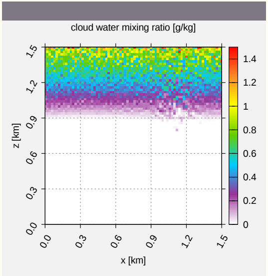

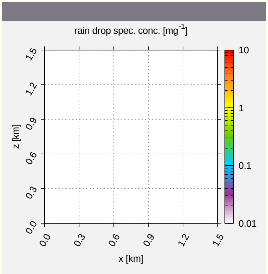

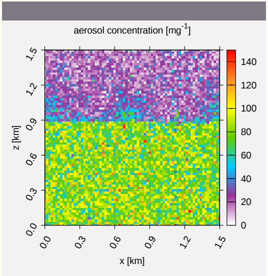

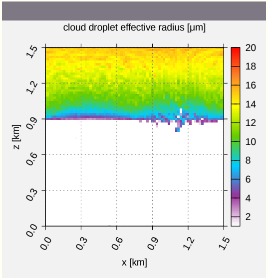

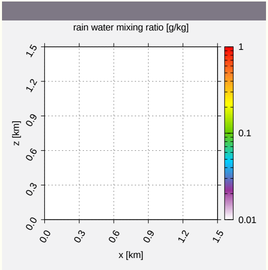

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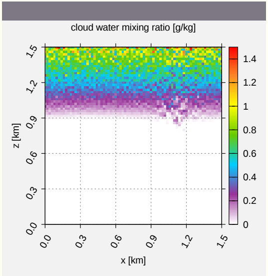
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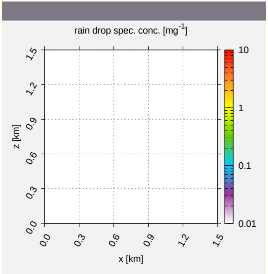
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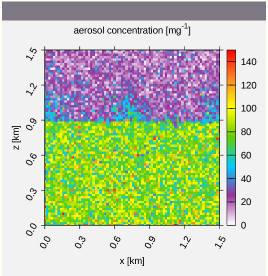
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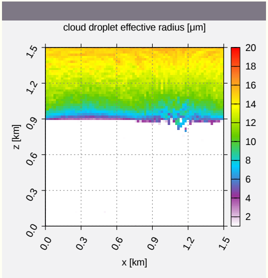
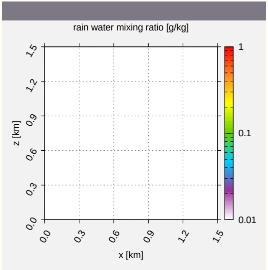

cloud droplet effective radius [μm]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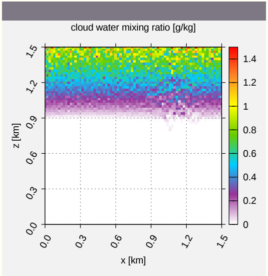
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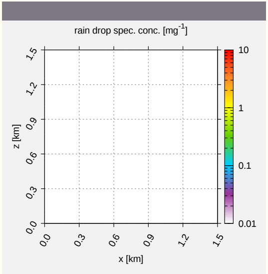
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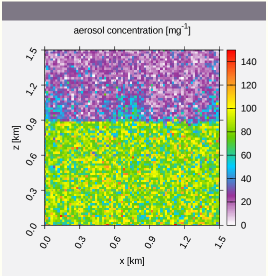
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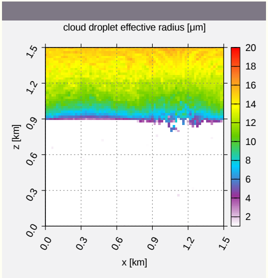
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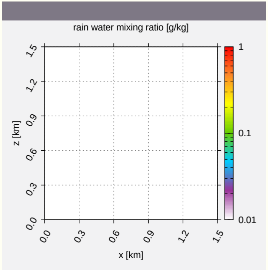
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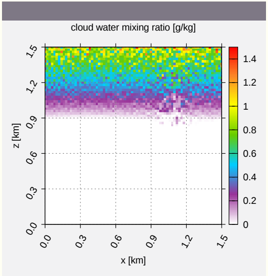
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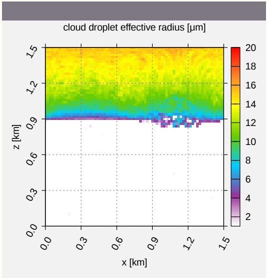
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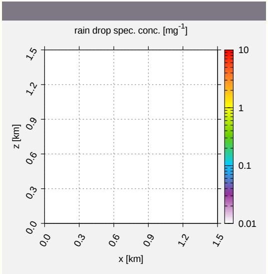
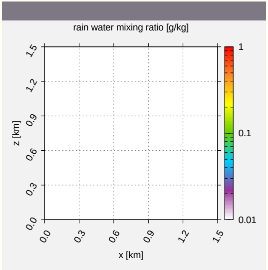
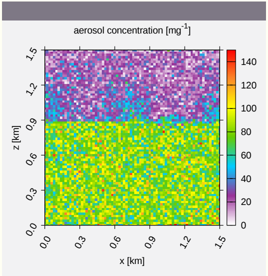
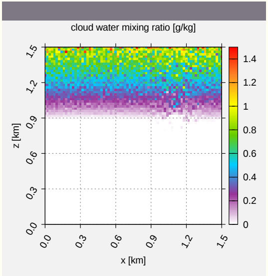
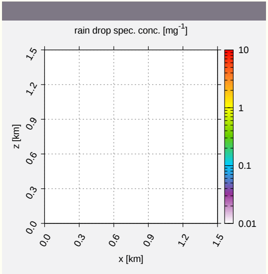

rain drop spec. conc. [mg^{-1}]

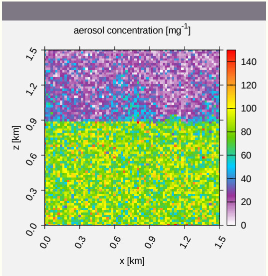

rain water mixing ratio [g/kg]

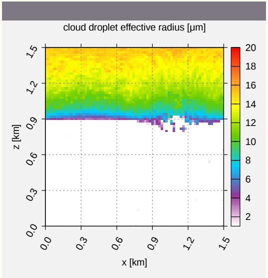

aerosol concentration [mg^{-1}]

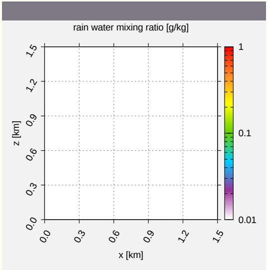
example simulation (Arabas et al. 2015, GMD)



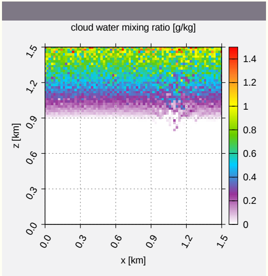




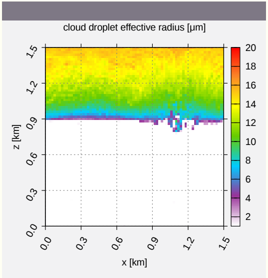




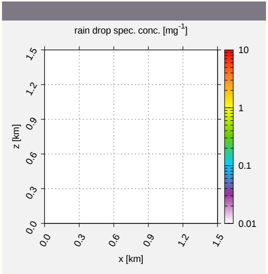
example simulation (Arabas et al. 2015, GMD)



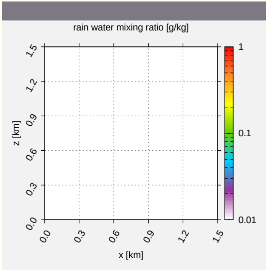
cloud water mixing ratio [g/kg]



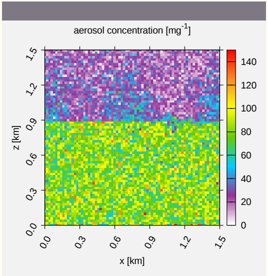
cloud droplet effective radius [μm]



rain drop spec. conc. [mg^{-1}]

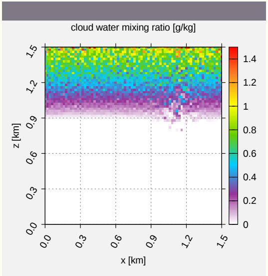


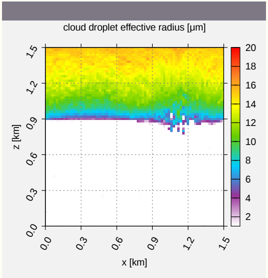
rain water mixing ratio [g/kg]

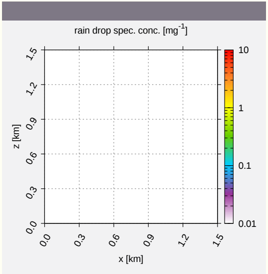


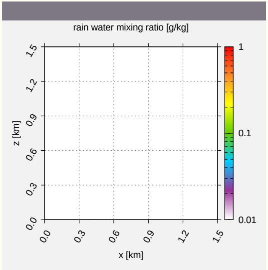
aerosol concentration [mg^{-1}]

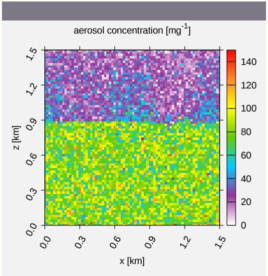
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

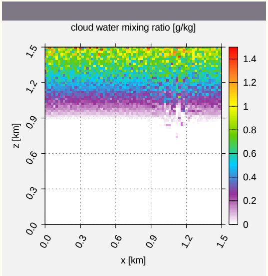

cloud droplet effective radius [μm]

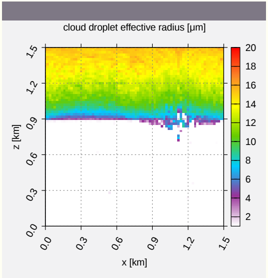

rain drop spec. conc. [mg^{-1}]

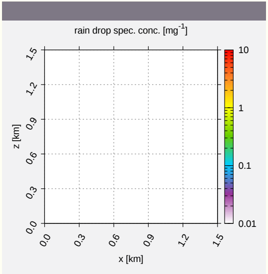

rain water mixing ratio [g/kg]

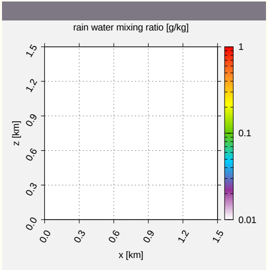

aerosol concentration [mg^{-1}]

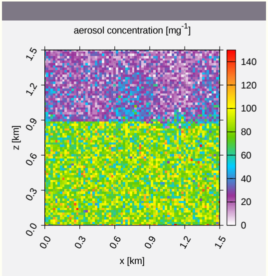
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

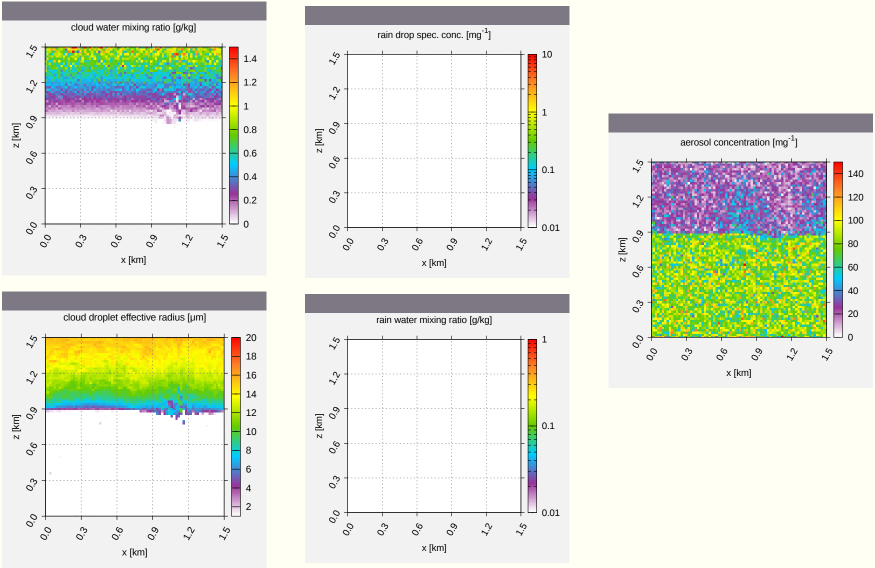

cloud droplet effective radius [μm]


rain drop spec. conc. $[\mathrm{mg}^{-1}]$

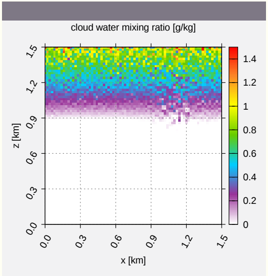

rain water mixing ratio [g/kg]

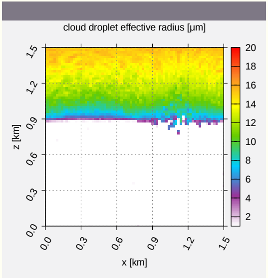

aerosol concentration $[\mathrm{mg}^{-1}]$

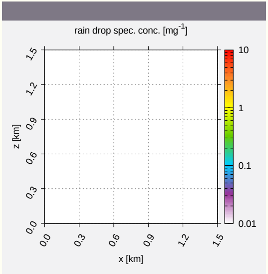
example simulation (Arabas et al. 2015, GMD)

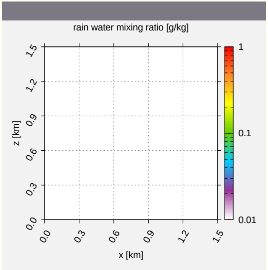


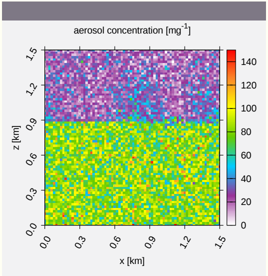
example simulation (Arabas et al. 2015, GMD)



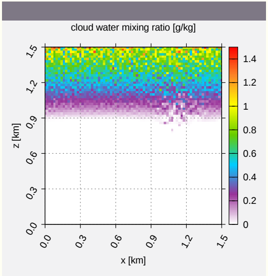


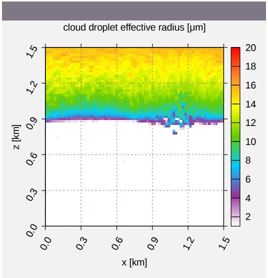


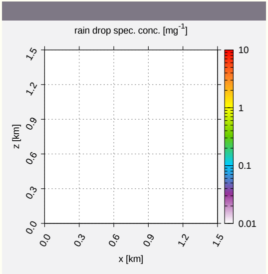


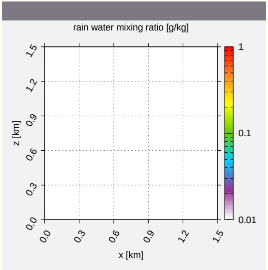


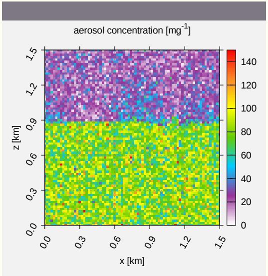
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

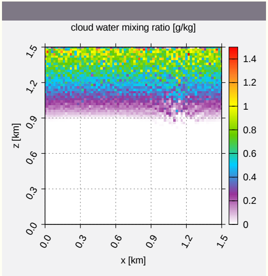

cloud droplet effective radius [μm]

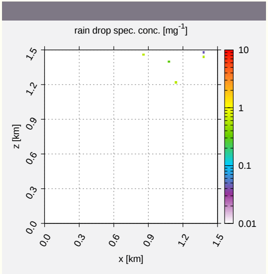

rain drop spec. conc. [$\mathrm{mg^{-1}}$]

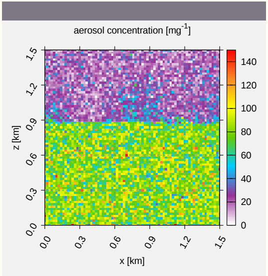

rain water mixing ratio [g/kg]

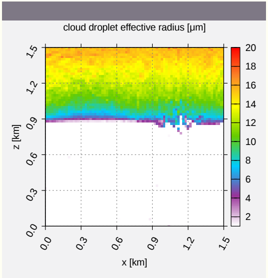

aerosol concentration [$\mathrm{mg^{-1}}$]

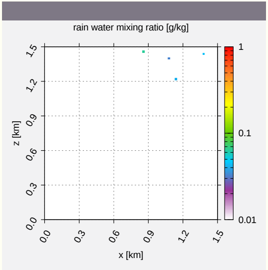
example simulation (Arabas et al. 2015, GMD)



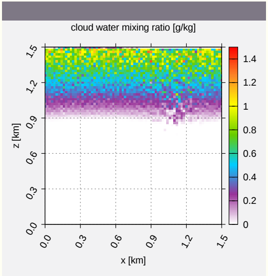


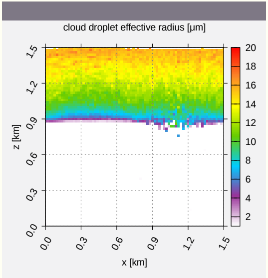


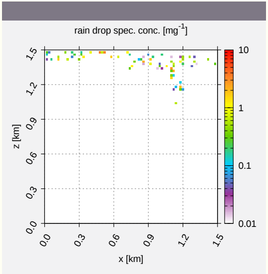


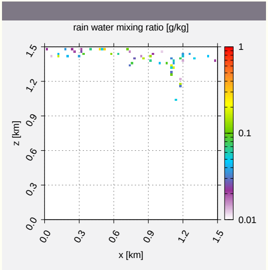


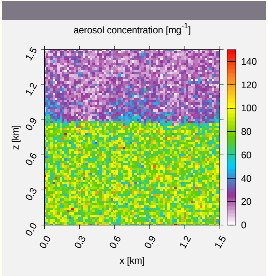
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

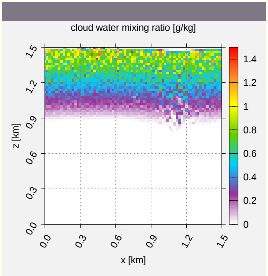

cloud droplet effective radius [μm]

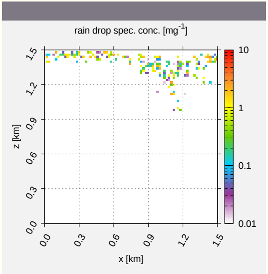

rain drop spec. conc. [mg^{-1}]

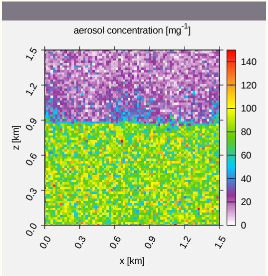

rain water mixing ratio [g/kg]

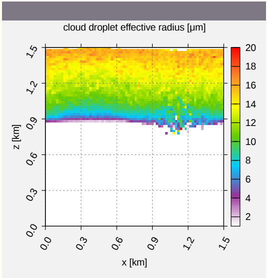

aerosol concentration [mg^{-1}]

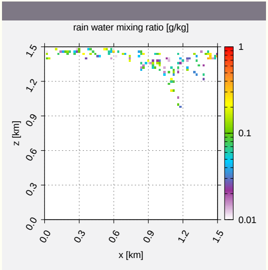
example simulation (Arabas et al. 2015, GMD)



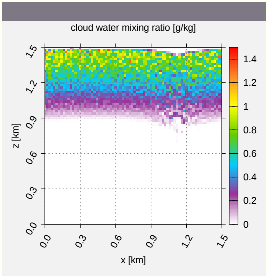


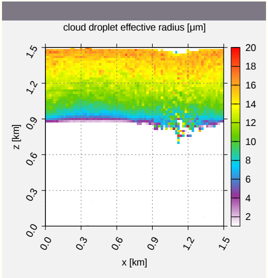


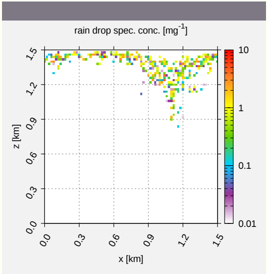


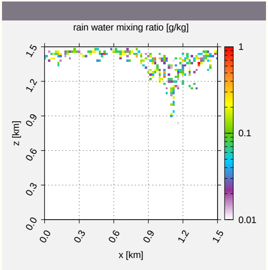


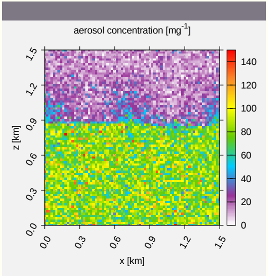
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

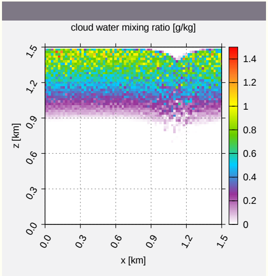

cloud droplet effective radius [μm]

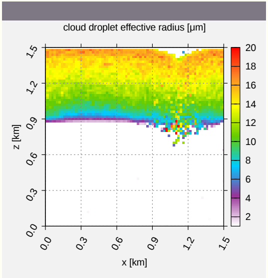

rain drop spec. conc. [mg^{-1}]

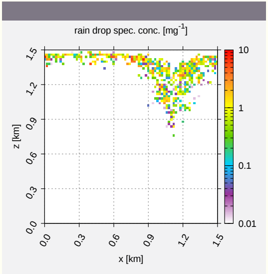

rain water mixing ratio [g/kg]

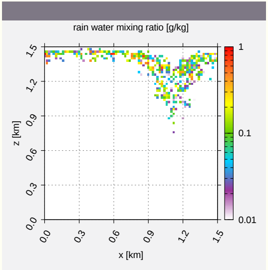

aerosol concentration [mg^{-1}]

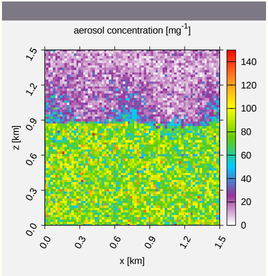
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

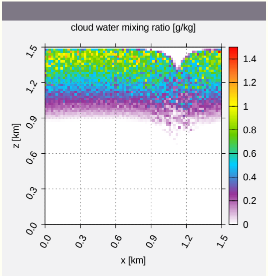

cloud droplet effective radius [μm]

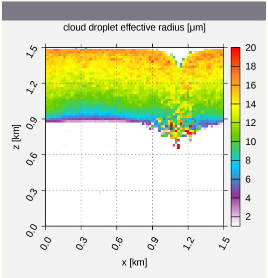

rain drop spec. conc. [mg^{-1}]

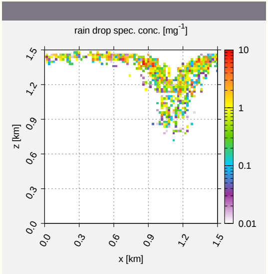

rain water mixing ratio [g/kg]

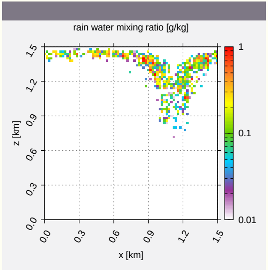

aerosol concentration [mg^{-1}]

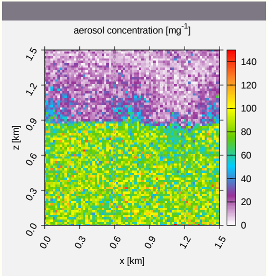
example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]

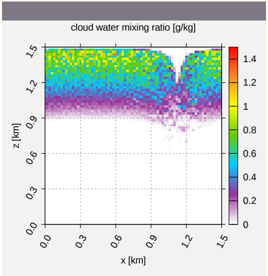

cloud droplet effective radius [μm]


rain drop spec. conc. [mg^{-1}]

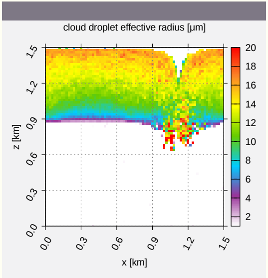

rain water mixing ratio [g/kg]


aerosol concentration [mg^{-1}]

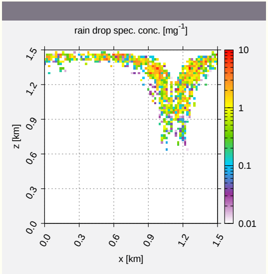
example simulation (Arabas et al. 2015, GMD)



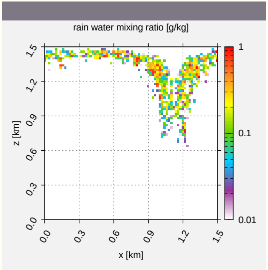
cloud water mixing ratio [g/kg]



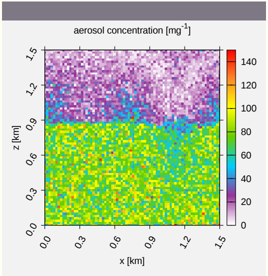
cloud droplet effective radius [μm]



rain drop spec. conc. [mg^{-1}]

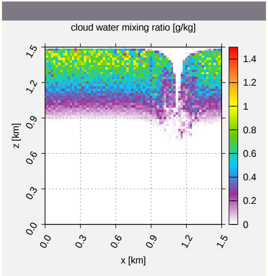


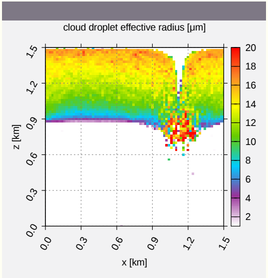
rain water mixing ratio [g/kg]



aerosol concentration [mg^{-1}]

example simulation (Arabas et al. 2015, GMD)


cloud water mixing ratio [g/kg]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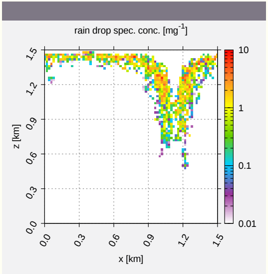
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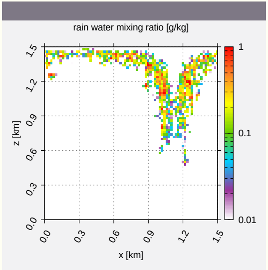
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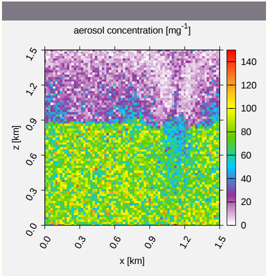
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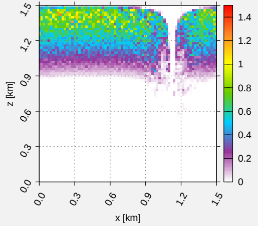

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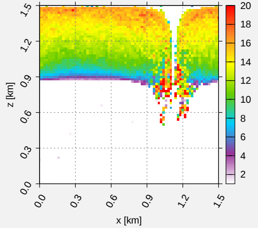

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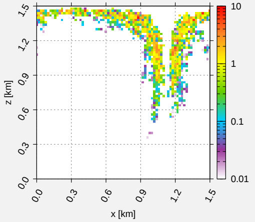

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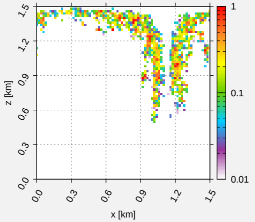

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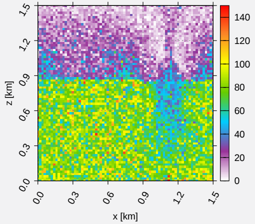

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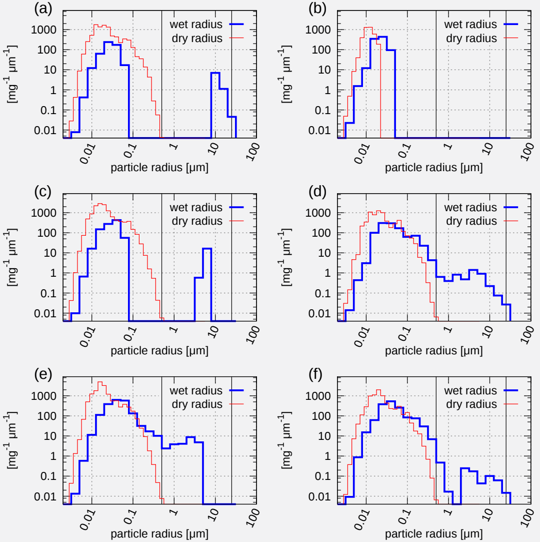
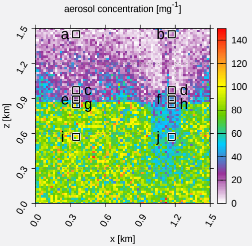
particle size spectra





state of the art

recent particle-based μ-physics software developments

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

INC/LCM

highlights

- soluble vs. non-soluble aerosol studies
- global-warming mitigation geoengineering studies

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references

- **Andrejczuk, Reisner, Jeffery 2006** (JAS): *"Comparison of analytical solutions for the growth of cloud droplets against Eulerian and Lagrangian numerical formulations"*
- **Andrejczuk, Reisner, Henson, Dubey & Jeffery 2008** (JGR): *"The potential impacts of pollution on a nondrizzling stratus deck: Does aerosol number matter more than type?"*
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- **Andrejczuk, Gadian, Blyth 2014** (AR): *"Numerical simulations of stratocumulus cloud response to aerosol perturbation"*

EULAG-LCM

highlights

- particle-based ice microphysics
- contrail-to-cirrus transition simulations

EULAG-LCM

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references

- **Sölch & Kärcher 2010** (QJRMS): *"A large-eddy model for cirrus clouds with explicit aerosol and ice microphysics and Lagrangian ice particle tracking"*
- **Unterstrasser & Sölch 2010** (ACP): *"Study of contrail microphysics in the vortex phase with a Lagrangian particle tracking model"*
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- **Unterstrasser 2014** (JGR): *"Large-eddy simulation study of contrail microphysics and geometry during the vortex phase and consequences on contrail-to-cirrus transition"*
- **Unterstrasser, Hoffmann & Lerch 2017** (GMD): *"Collection/aggregation algorithms in Lagrangian cloud microphysical models: Rigorous evaluation in box model simulations"*

PALM-LES

highlights

- turbulence-enhancement of coalescence, spectrum broadening
- derivation of autoconversion rates through ab-initio simulations
- Linear Eddy Model (LEM) $\rightsquigarrow$ mixing inhomogeneity

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references

- **Riechelmann, Noh & Raasch 2012** (NJP): *"A new method for large-eddy simulations of clouds with Lagrangian droplets including the effects of turbulent collision"*
- **Hoffmann, Raasch & Noh 2015** (AR): *"Entrainment of aerosols and their activation in a shallow cumulus cloud studied with a coupled LCM-LES approach"*
- **Hoffmann, Noh & Raasch 2017** (JAS): *"The route to raindrop formation in a shallow cumulus cloud simulated by a Langrangian cloud model"*
- **Schwenkel, Hoffmann & Raasch 2018** (GMD): *"Improving Collisional Growth in Lagrangian Cloud Models: Development and Verification of a New Splitting Algorithm"*
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- **Hoffmann, Yamaguchi & Feingold 2019** (JAS): *"Inhomogeneous Mixing in Lagrangian Cloud Models: Effects on the Production of Precipitation Embryos"*

CReSS

highlights

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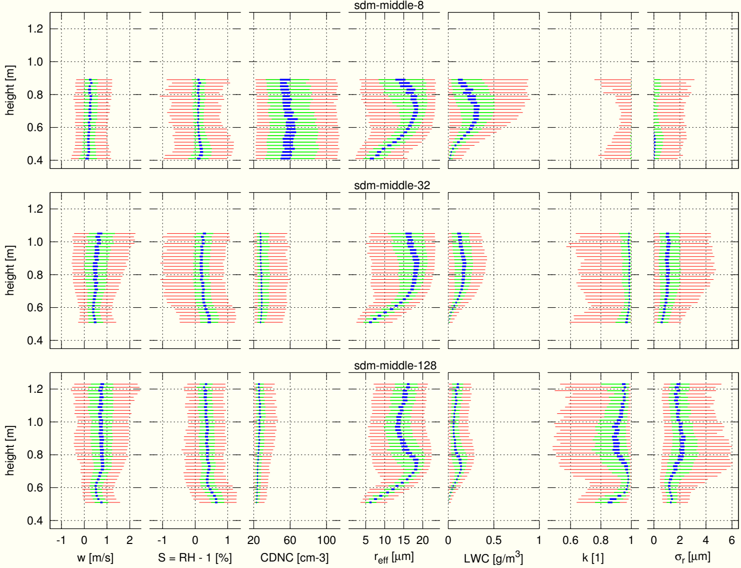
references

- **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)

UCLA-LES

highlights

- bulk cloud μ-physics + particle-based rain
- recirculation of raindrops

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- **Naumann & Seifert 2015** (JAMES): *"A Lagrangian Drop Model to Study Warm Rain Microphysical Processes in Shallow Cumulus"*
- **Naumann & Seifert 2016** (JAMES): *"Recirculation and growth of raindrops in simulated shallow cumulus"*
- **Naumann & Seifert 2016** (JAS): *"Evolution of the Shape of the Raindrop Size Distribution in Simulated Shallow Cumulus "*

Pencil-Code (DNS)

highlights

- turbulence effects on collisions
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- implemented in general-purpose CFD code

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- **Li, Brandenburg, Haugen & Svensson 2017** (JAMES): *"Eulerian and Lagrangian approaches to multidimensional condensation and collection"*
- **Li, Brandenburg, Svensson, Haugen, Mehlig & Rogachevskii (2018** (JAS): *"Effect of turbulence on collisional growth of cloud droplets"*
- **Li, Svensson, Brandenburg & Haugen 2019** (ACP): *"Cloud droplets growth due to supersaturation fluctuations in stratiform clouds"*

SCALE-SDM

highlights

- numerical convergence studies down to 12.5/10 m resolution
- ice particles represented by porous spheroids + Monte-Carlo
- deep convective studies
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- **Sato, Shima & Tomita 2017** (ASL): *"A grid refinement study of trade wind cumuli simulated by a Lagrangian cloud microphysical model: the super-droplet method"*
- **Sato, Shima & Tomita 2018** (JAMES): *"Numerical Convergence of Shallow Convection Cloud Field Simulations: Comparison Between Double-Moment Eulerian and Particle-Based Lagrangian Microphysics Coupled to the Same Dynamical Core"*
- **Shima, Sato, Hashimoto & Misumi 2018** (AMS Vancouver): *"Application of the Super-Droplet Method to Mixed-Phase Clouds Based on the Porous Spheroid Approximation of Ice Particles"*

ICON/McSnow

highlights

- Monte-carlo mixed-phase microphysics
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- **Brdar & Seifert 2018** (JAMES): *"A Monte-Carlo particle model for riming and aggregation of ice particles in a multidimensional microphysical phase space"*
- **Siewert, Seifert & Brdar 2018** (AMS Vancouver): *"The Novel Particle-based Microphysical Model McSnow: 1D and 3D Results"*

UWLCM

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references

- **Arabas, Jaruga, Pawlowska & Grabowski 2015** (GMD): *"libcloudph++ 1.0: single-moment bulk, double-moment bulk, and particle-based warm-rain microphysics..."*
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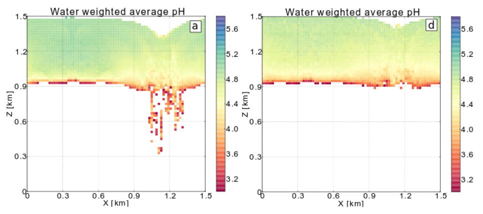
- **Dziekan, Waruszewski & Pawlowska 2019** (GMD): *"University of Warsaw Lagrangian Cloud Model (UWLCM)..."*

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

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



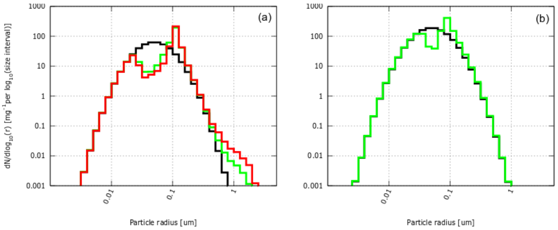


Figure 6. The size distributions of dry radii for the base case **(a)** and case3 **(b)**. The initial dry radius size distribution is marked in black, the final dry radius size distribution from grid cells with $r_c > 0.01\,\mathrm{g\,kg^{-1}}$ in green, and from grid cells with $r_r > 0.01\,\mathrm{g\,kg^{-1}}$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

challenges ($\rightsquigarrow$ opportunities)

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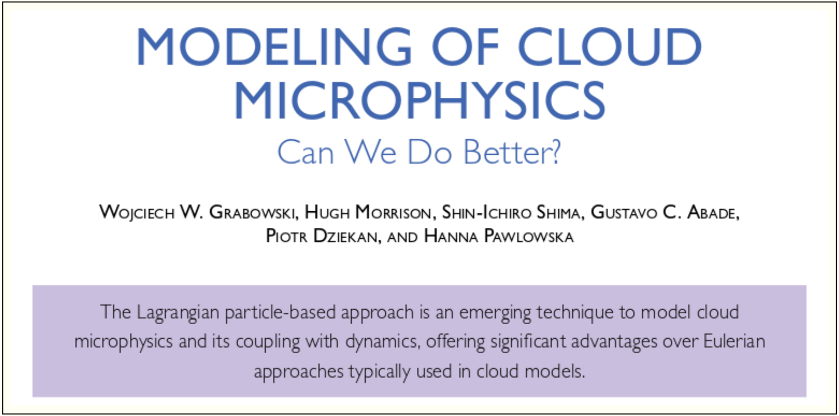
- **charge, isotopic ratio, ...**

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

谢谢大家的关注

Thank you for your attention!

funding acknowledgement:
Foundation for Polish Science / European Union