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

Sylwester Arabas

intro: speaker

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- alma mater: University of Warsaw (group of Hanna Pawłowska)

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- back to academia:
  - 2018–...: Jagiellonian University, Cracow (Math/CS Dept.)

particle-based cloud microphysics:

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- rationale

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- state of the art

particle-based cloud microphysics:

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

rationale

rationale: aerosol-cloud interactions

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background image: vitsly.ru / Hokusai

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- rain drops form through collisions of cloud droplets

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- aqueous chemical reactions irreversibly modify the drop composition

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rationale: aerosol-cloud interactions

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

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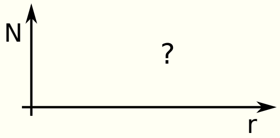
two-way interactions:
- aerosol characteristics influence cloud microstructure
- cloud processes influence aerosol size and composition

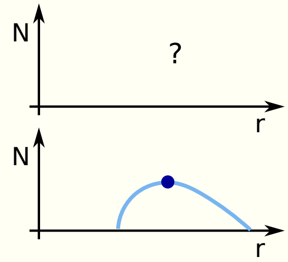
background image: vitsly.ru / Hokusai

- single-moment bulk



modelling nomenclature: aerosol, cloud & rain spectra

- single-moment bulk
- multi-moment bulk



modelling nomenclature: aerosol, cloud & rain spectra

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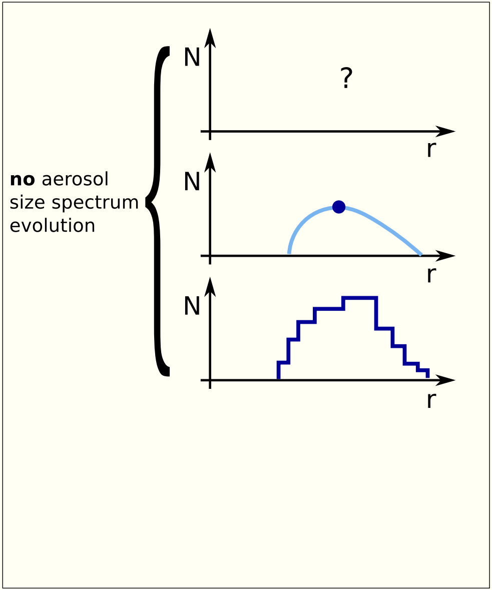
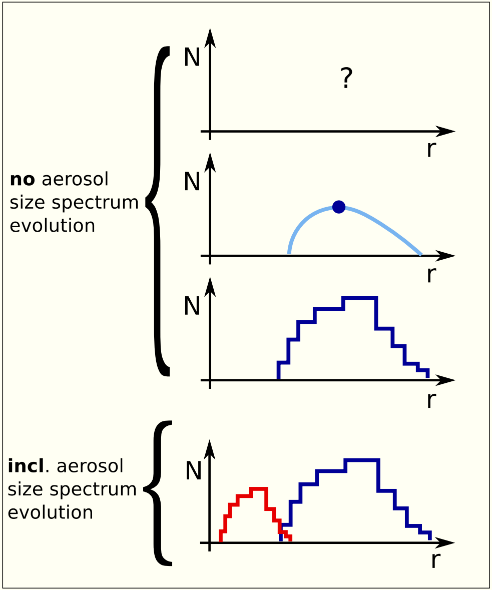
- multi-moment bulk
- „wet” size spectrum (bin)

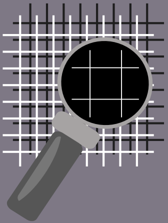


modelling nomenclature: aerosol, cloud & rain spectra

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



rationale: modelling aerosol-cloud interactions



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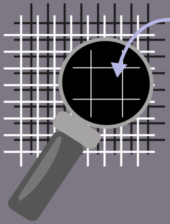
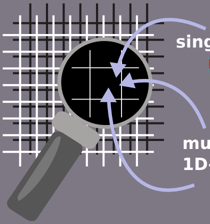
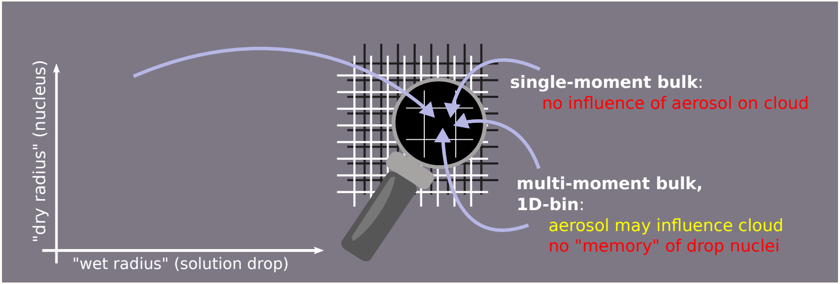


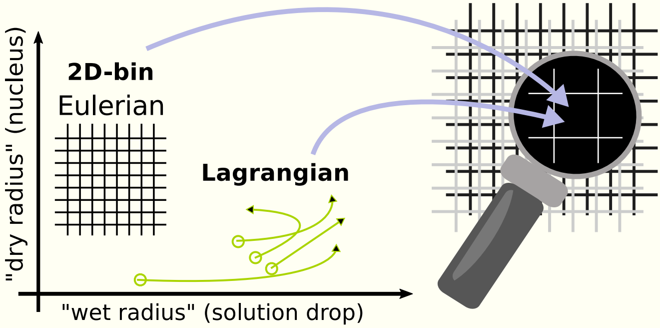
single-moment bulk:
no influence of aerosol on cloud


single-moment bulk:
no influence of aerosol on cloud
multi-moment bulk, 1D-bin:
aerosol may influence cloud
no "memory" of drop nuclei

rationale: modelling aerosol-cloud interactions



rationale: modelling aerosol-cloud interactions



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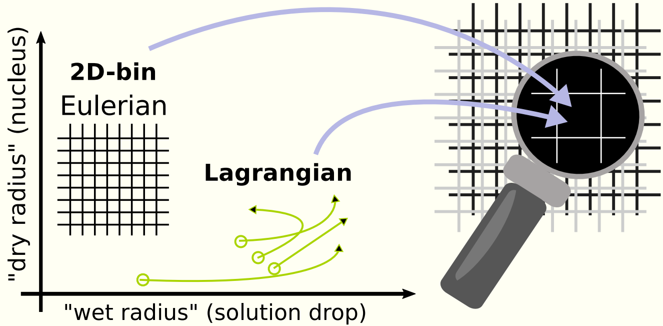

Lagrangian:

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

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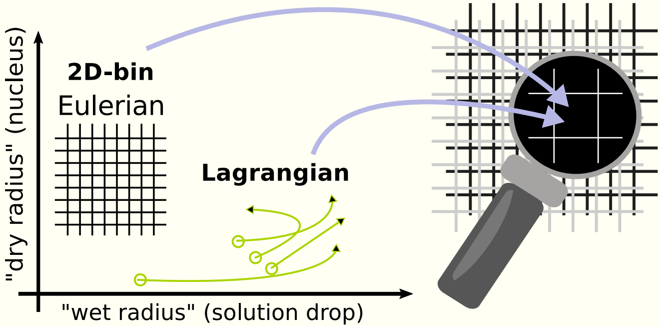
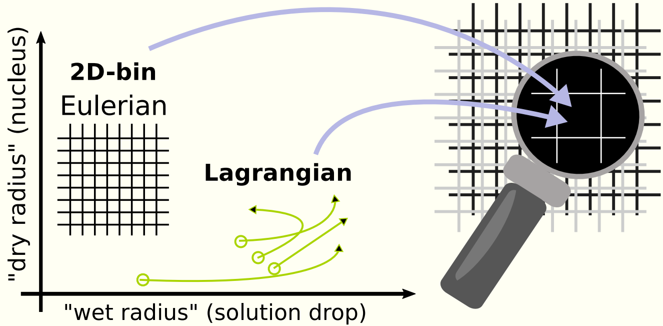


Lagrangian:

- 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, . . .)

rationale: modelling aerosol-cloud interactions



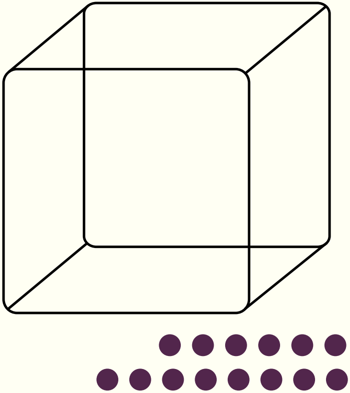
Pioneering warm-rain LES aerosol-cloud-interaction models:

Andrejczuk et al. 2010	
condensation:	Lagrangian
collisions:	Eulerian

Lebo & Seinfeld 2011	
condensation:	Eulerian
collisions:	Eulerian

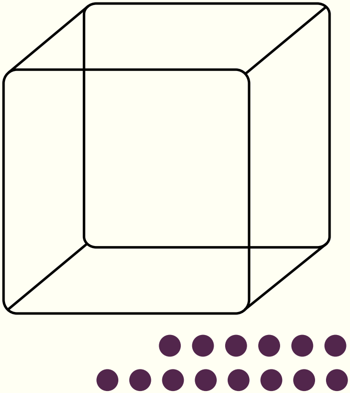
Shima et al. 2009	
condensation:	Lagrangian
collisions:	Lagrangian

particle-based μ-physics: key concepts



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

particle-based μ-physics: key concepts



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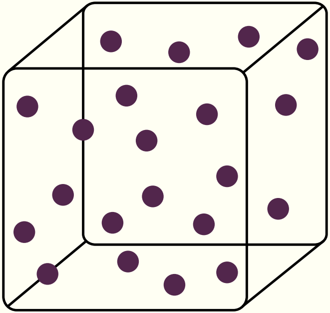
carrier attributes:



Domain randomly populated with
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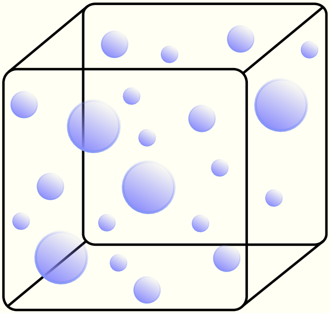
carrier attributes:

- location

particle-based μ-physics: key concepts



Domain randomly populated with "μ-physics information carriers"
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carrier attributes:

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- wet radius

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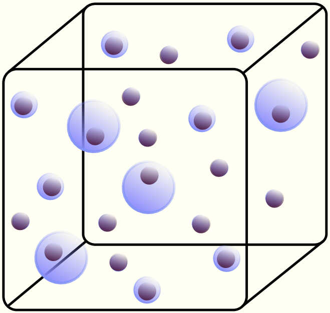

Domain randomly populated with "μ-physics information carriers" (super particles / super droplets)

carrier attributes:

- location
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- dry radius

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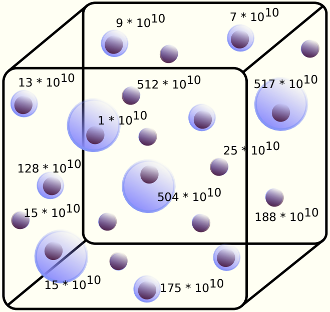
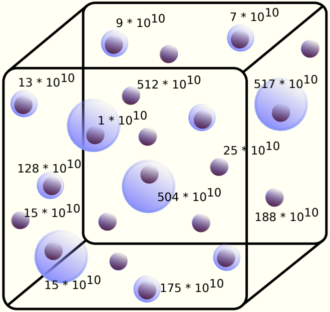


Domain randomly populated with "μ-physics information carriers" (super particles / super droplets)

carrier attributes:

- location
- wet radius
- dry radius
- multiplicity



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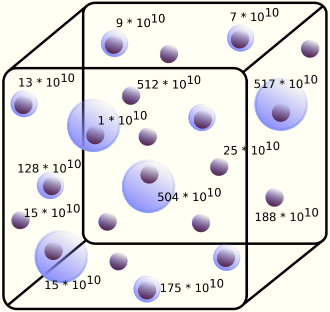

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advantage over Eulerian approach: adding attributes does not increase dimensionality

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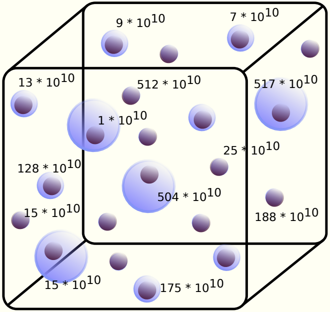

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carrier attributes:

- location
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- dry radius
- multiplicity
- ...

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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Eulerian / PDE	Lagrangian / ODE
advection of heat	particle transport by the flow
advection of moisture	

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Eulerian / PDE	Lagrangian / ODE
advection of heat	particle transport by the flow
advection of moisture	condensational growth
	collisional growth
	sedimentation

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

Eulerian / PDE	Lagrangian / ODE
advection of heat advection of moisture	particle transport by the flow condensational growth collisional growth sedimentation
$\partial_t(\rho_d r) + \nabla \cdot (\vec{v}\rho_d r) = \rho_d \dot{r}$	$\dot{r} = \sum_{\text{particles} \in \Delta V} \ldots$
$\partial_t(\rho_d \theta) + \nabla \cdot (\vec{v}\rho_d \theta) = \rho_d \dot{\theta}$	$\dot{\theta} = \sum_{\text{particles} \in \Delta V} \ldots$

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

Eulerian / PDE	Lagrangian / ODE
advection of heat	particle transport by the flow
advection of moisture	condensational growth
	collisional growth
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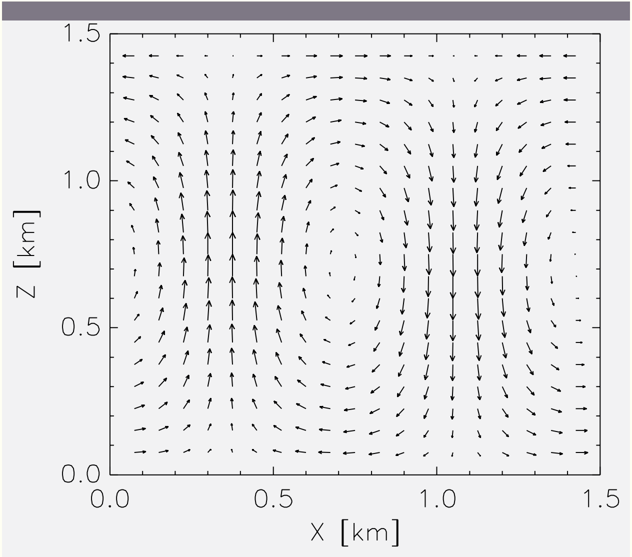
advection of trace gases	in-particle aqueous chemistry
...	...

example simulation (2D, prescribed flow)



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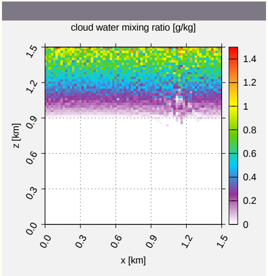

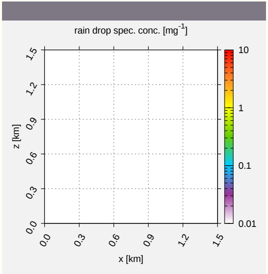

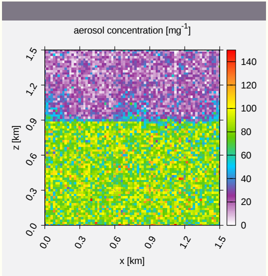

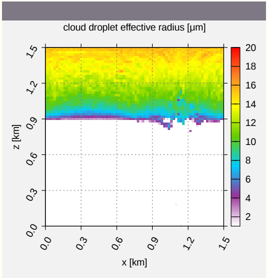

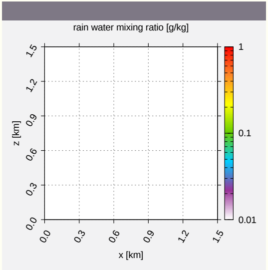

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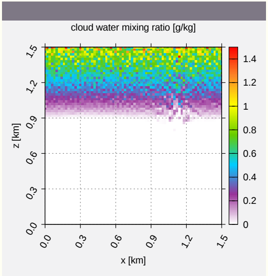

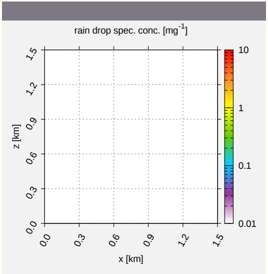

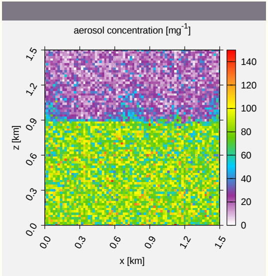

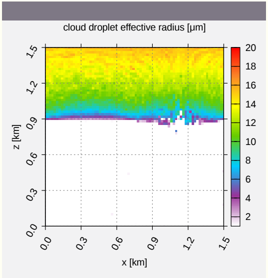

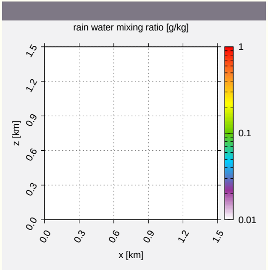

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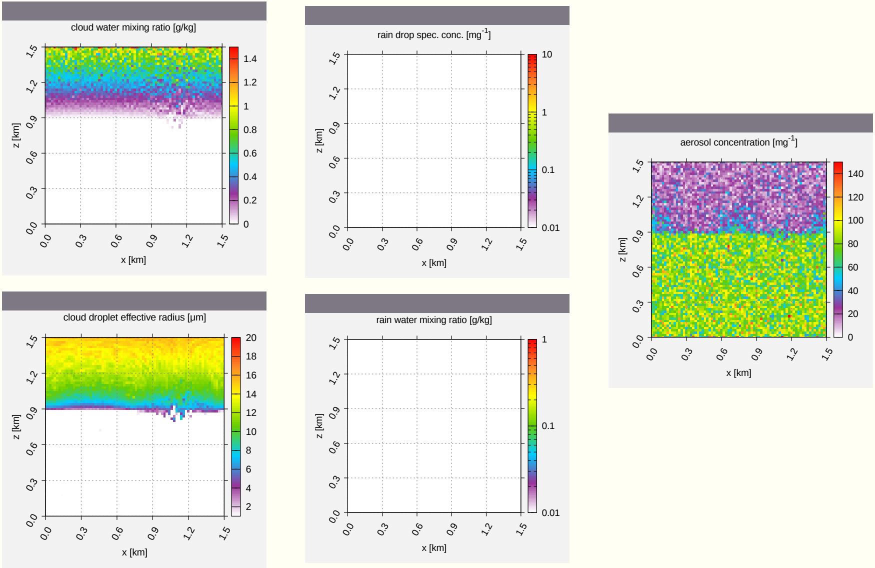

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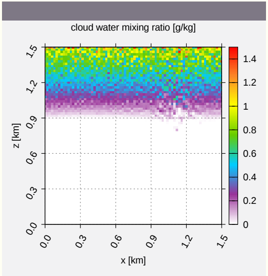

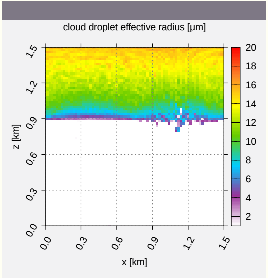

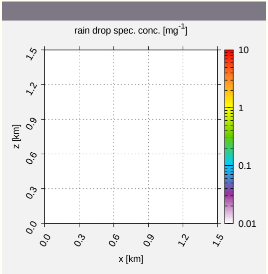

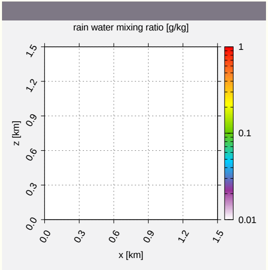

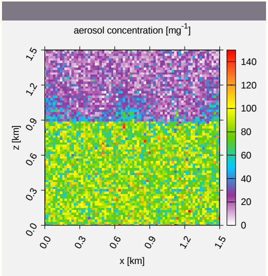

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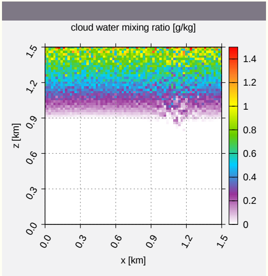

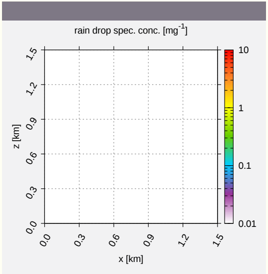

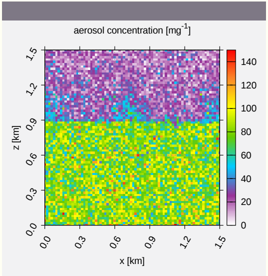

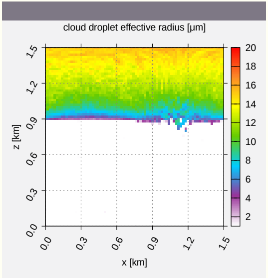

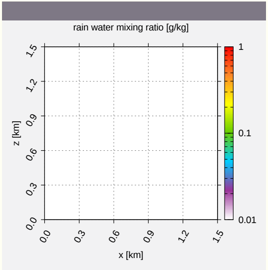

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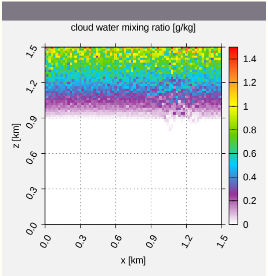

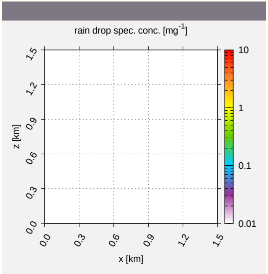

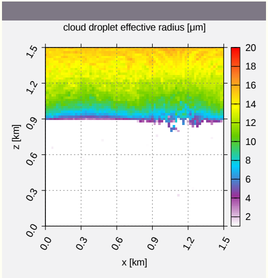

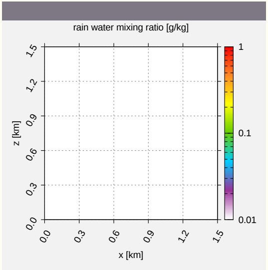

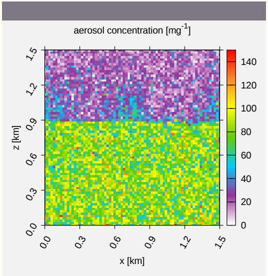

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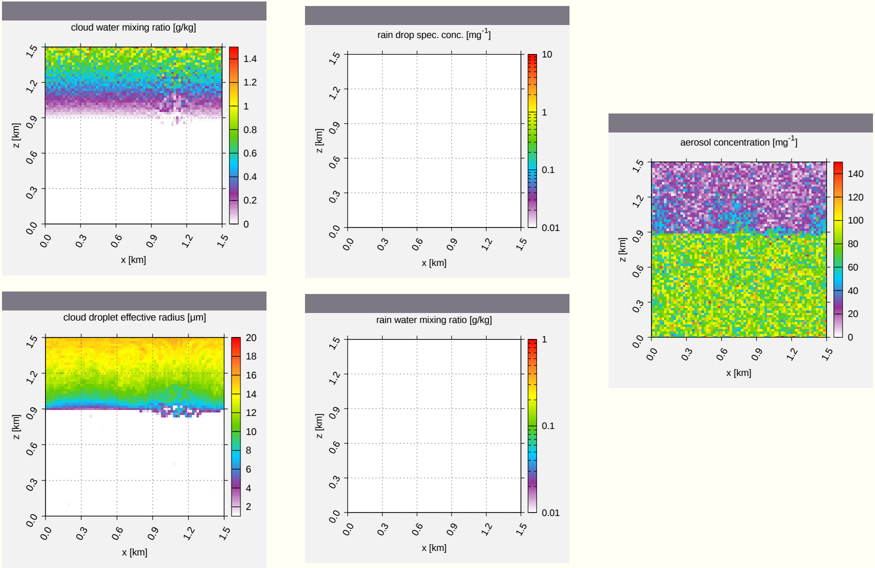
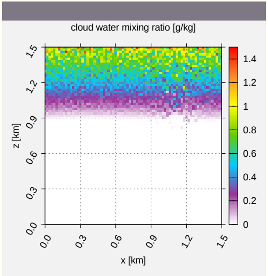
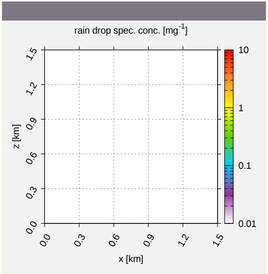
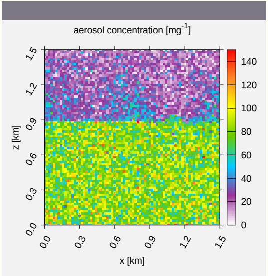
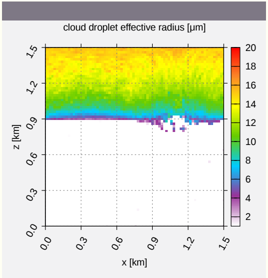


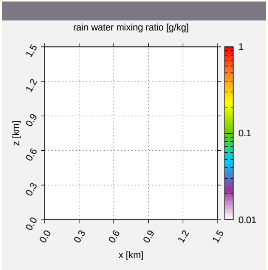
example simulation (2D, prescribed flow)



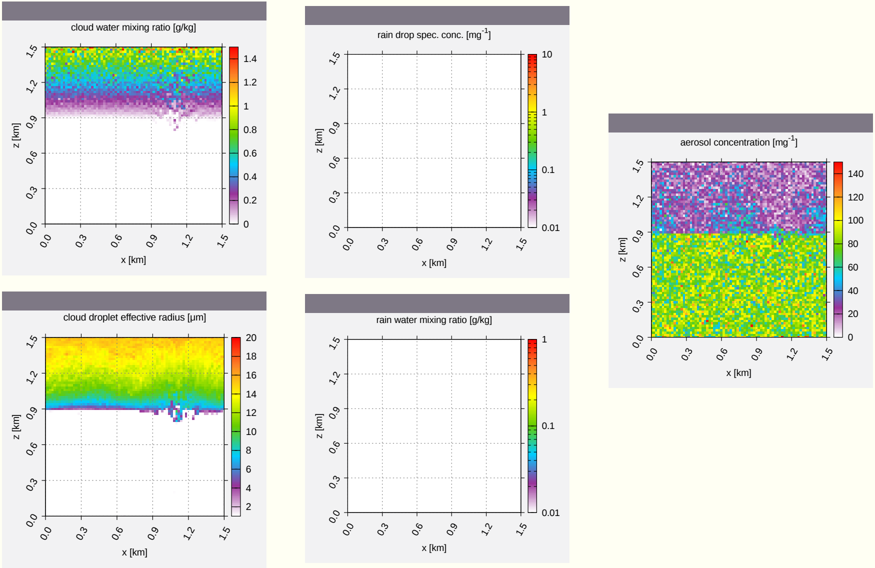








example simulation (2D, prescribed flow)



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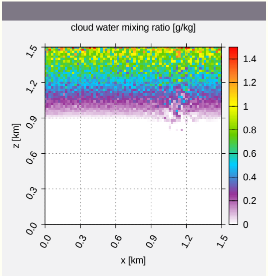

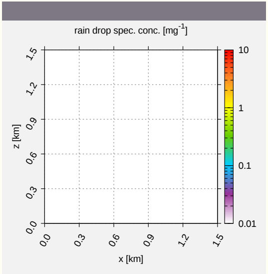

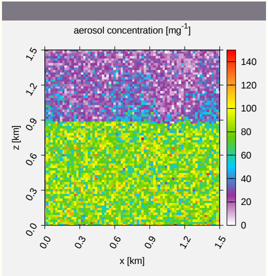

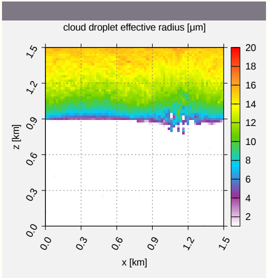

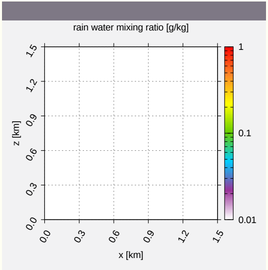

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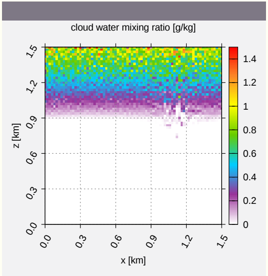

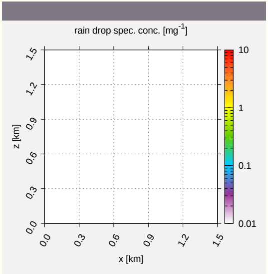

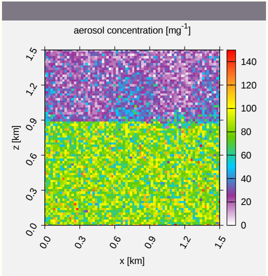

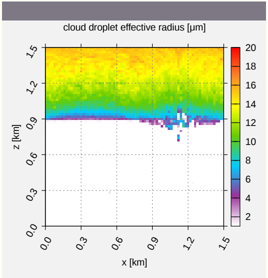

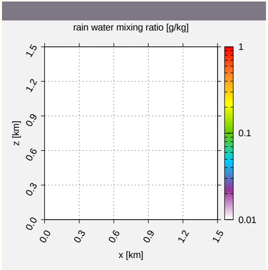

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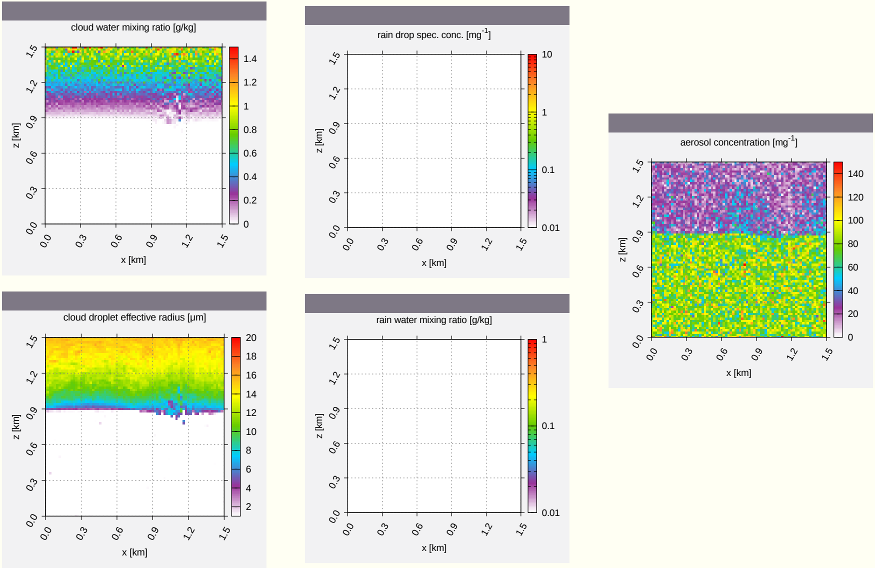

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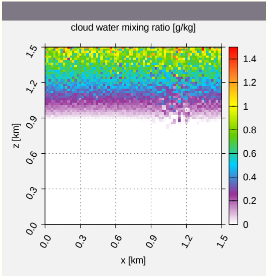

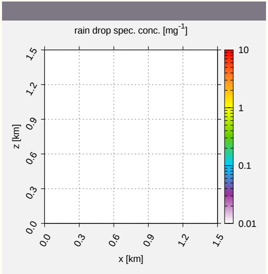

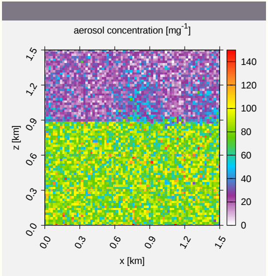

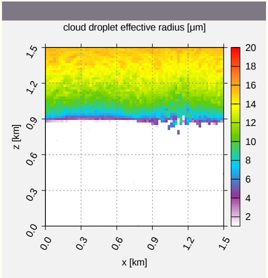

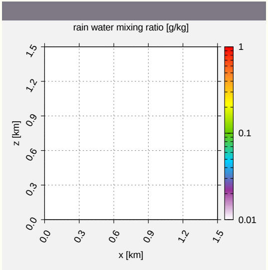

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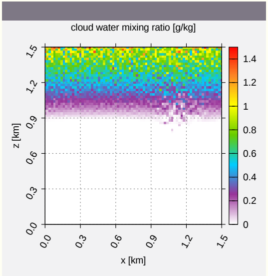

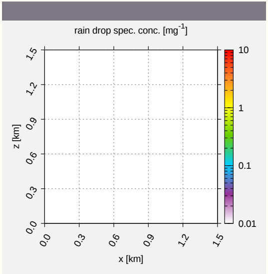

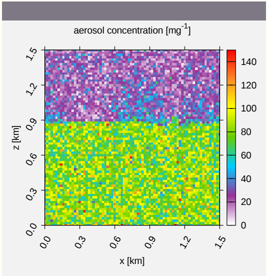

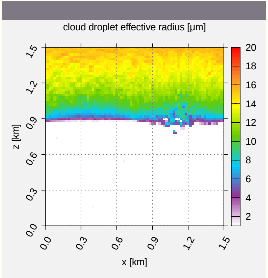

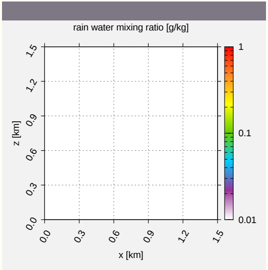

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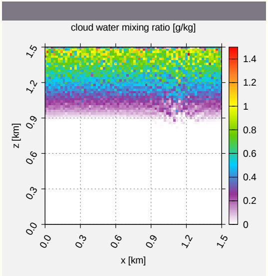

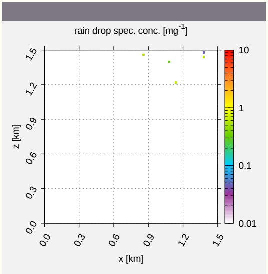

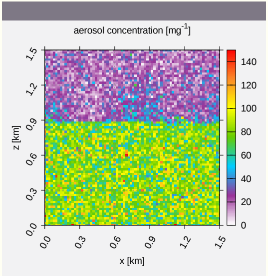

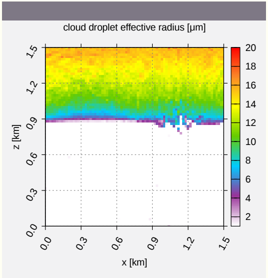

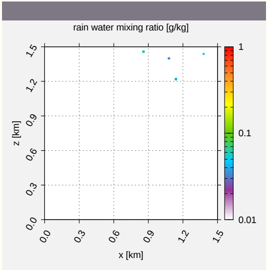

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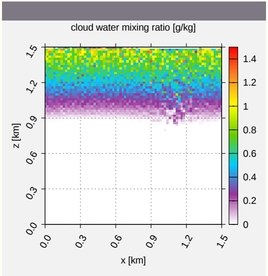

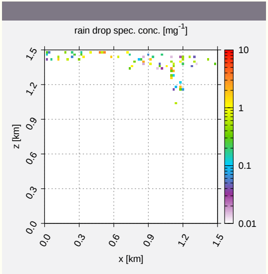

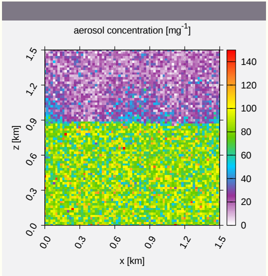

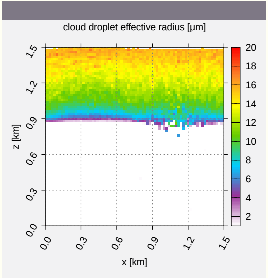

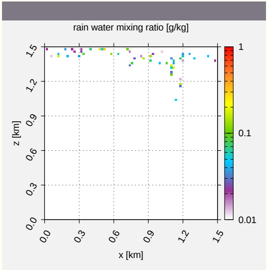

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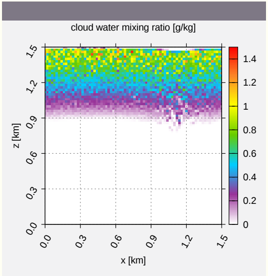

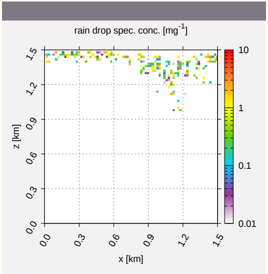

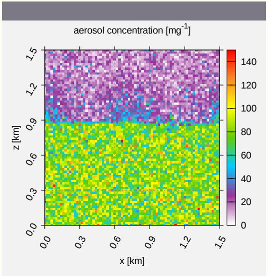

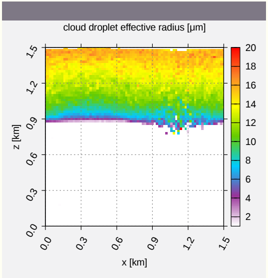

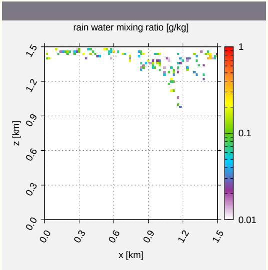

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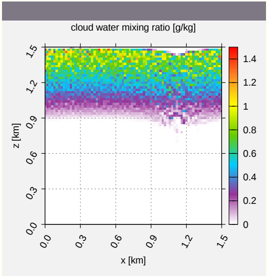

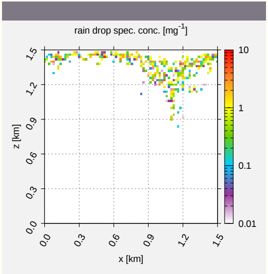

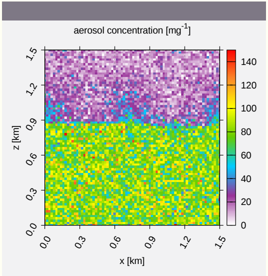

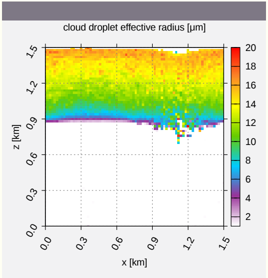

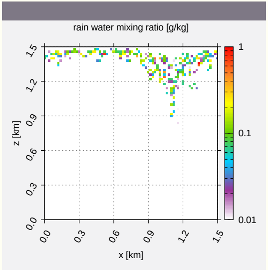

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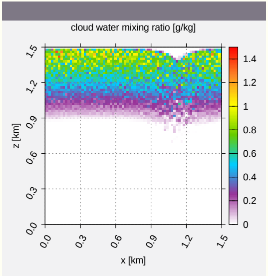

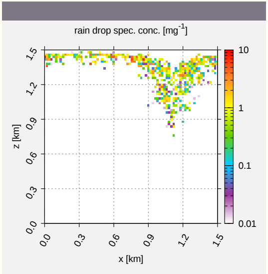

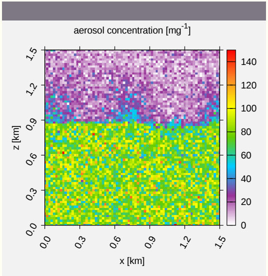

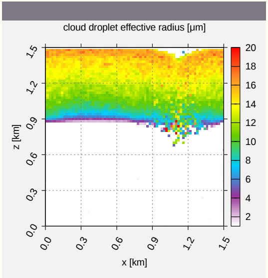

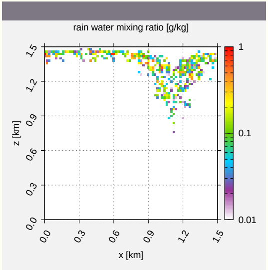

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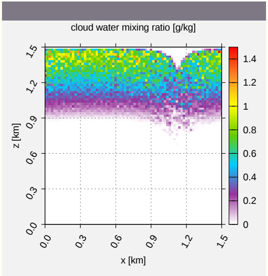

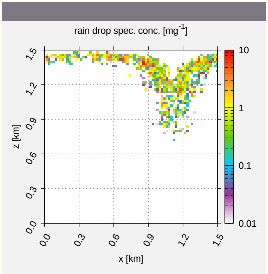

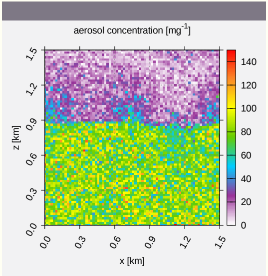

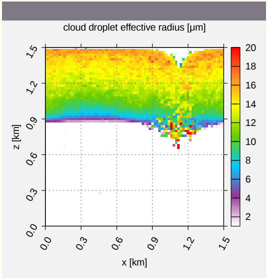

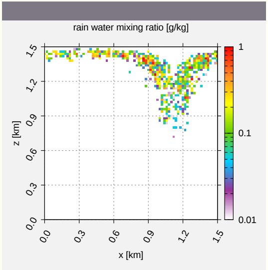

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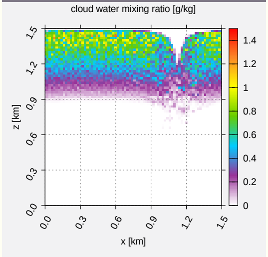

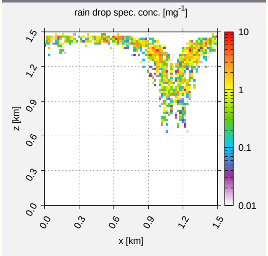

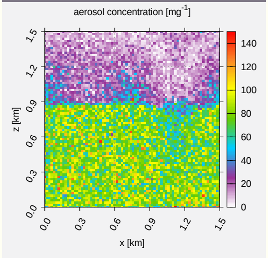

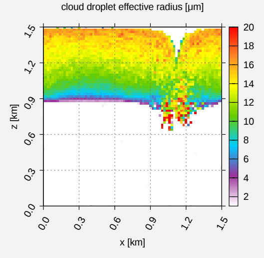

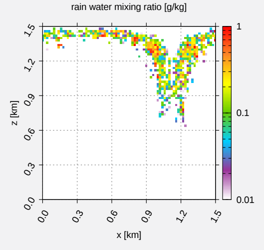

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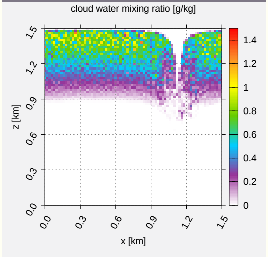

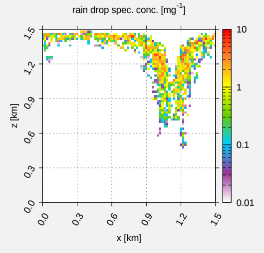

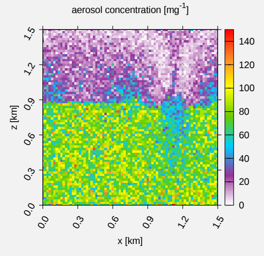

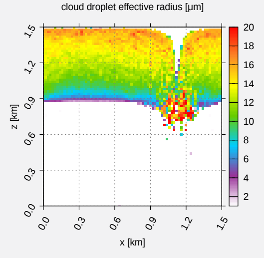

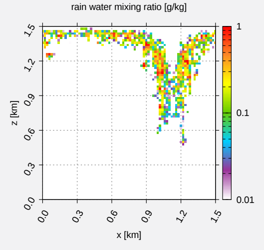

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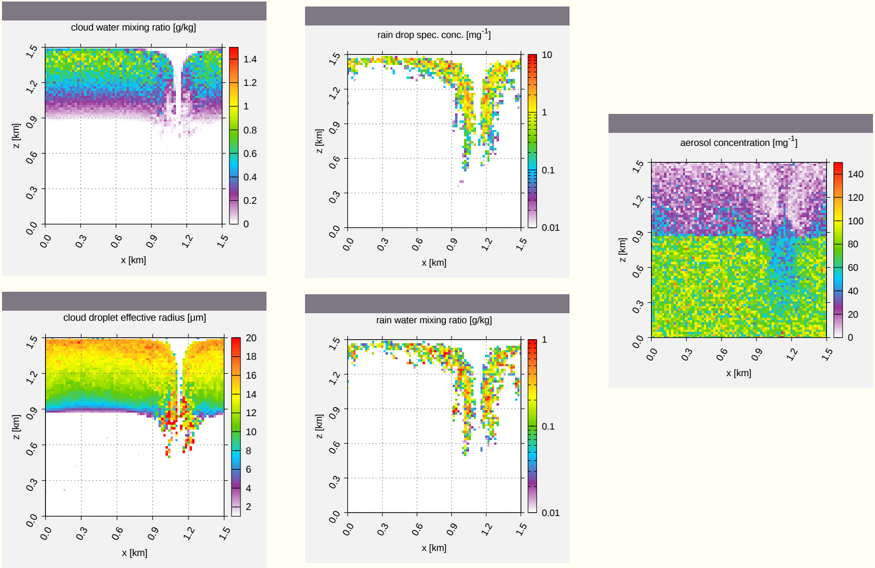
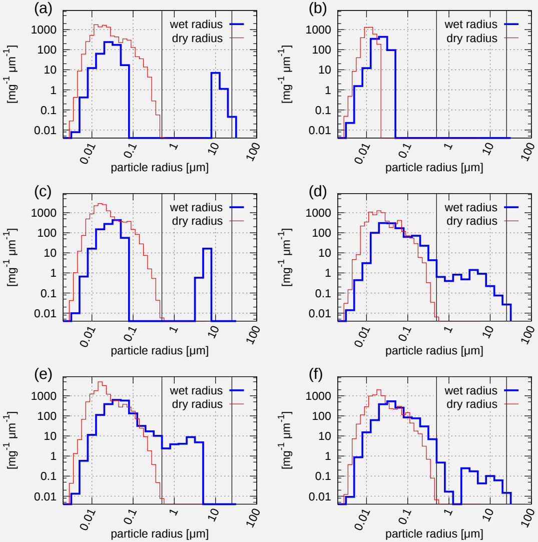
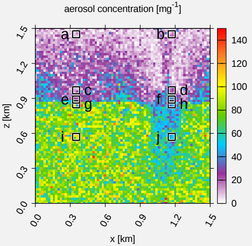


particle size spectra





state of the art

particle-based μ-physics for LES

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recent research software (re)developments:

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- CReSS (`http://www.rain.hyarc.nagoya-u.ac.jp/`) from Univ. Nagoya,

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- CReSS (http://www.rain.hyarc.nagoya-u.ac.jp/) from Univ. Nagoya,
- UCLA-LES (http://github.com/uclales) from UCLA/MPI-M,

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- ASAM (http://asam.tropos.de/) from TROPOS.

INC/LCM (and related works)

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?"*
- **Andrejczuk, Grabowski, Reisner & Gadian 2010** (JGR): *"Cloud-aerosol interactions for boundary layer stratocumulus in the Lagrangian Cloud Model"*
- **Andrejczuk, Gadian, Blyth 2014** (AR): *"Numerical simulations of stratocumulus cloud response to aerosol perturbation"*

EULAG-LCM (and related works)

highlights

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

EULAG-LCM (and related works)

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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"*
- **Unterstrasser & Sölch 2014** (GMD): *"Optimisation of the simulation particle number in a Lagrangian ice microphysical model"*
- **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 (and related works)

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"*
- **Noh, Oh, Hoffmann & Raasch 2018** (JAS): *"A Cloud Microphysics Parameterization for Shallow Cumulus Clouds Based on Lagrangian Cloud Model Simul."*
- **Hoffmann, Yamaguchi & Feingold 2019** (JAS): *"Inhomogeneous Mixing in Lagrangian Cloud Models: Effects on the Production of Precipitation Embryos"*

CReSS (and related works)

highlights

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

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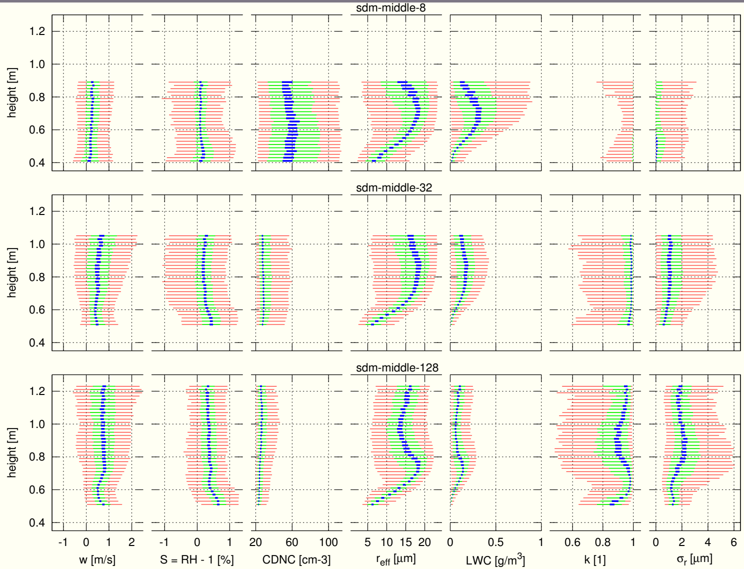
references

- **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)

UCLA-LES (and related works)

highlights

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

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references

- **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 (and related works)

highlights

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

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references

- **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 (and related works)

highlights

- numerical convergence studies down to 12.5/10 m resolution
- ice particles represented by porous spheroids + Monte-Carlo
- deep convective studies
- incorporation of aerosol sources (in progress)

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references

- **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"*

UWLCM (and related works)

highlights

- Hoppel-gap resolving aqueous chemistry
- GPU-resident (or multi-threaded) microphysics in C++

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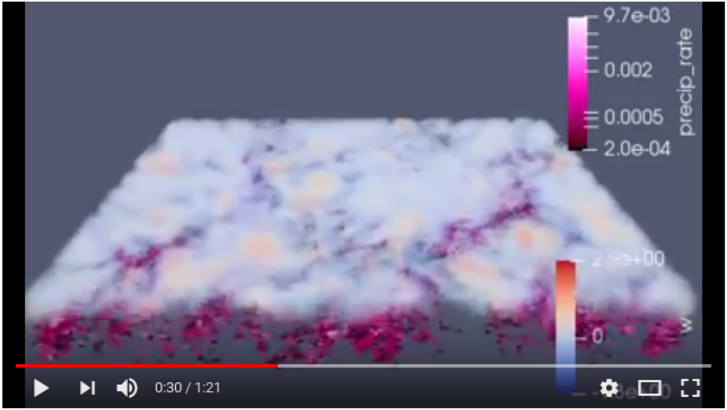
references

- **Arabas, Jaruga, Pawlowska & Grabowski 2015** (GMD): *"libcloudph++ 1.0: single-moment bulk, double-moment bulk, and particle-based warm-rain microphysics..."*
- **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`

ICON/McSnow (and related works)

highlights

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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"*

challenges ($\rightsquigarrow$ opportunities)

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

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

http://particle-based-cloud-modelling.network

particle-based-cloud-modelling.network

View on GitHub

Particle-Based Cloud Modelling Network Initiative

Mailing List

Venue for communications relevant to the development and applications of particle-based models of atmospheric clouds: announcements of meetings, calls for submissions, funding opportunities, scholarships, openings, software/data releases, publications and other notices warranting community-wide dissemination.

Archives and subscription management:
https://mailing.uj.edu.pl/sympa/info/particle-based-cloud-modelling

Event Calendar

Database of events announced on the mailing list:

Thank you for your attention!