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

Sylwester Arabas

Jagiellonian University

uj.edu.pl









founded in 1364, among 20 world oldest (in cont. operation)



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- host to Smoluchowski Institute of Physics
- 1917 Smoluchowski elected as Rector (professor since 1913)

Maurycy Pius Rudzki (1862–1916)

Maurycy Pius Rudzki

From Wikipedia, the free encyclopedia

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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Maurycy Pius Rudzki



"Principles of Meteorology" book (1917)

D^R M. P. RUDZKI profesor uniwersytetu jagiellońskiego, dyrektor obserwatoryum astronomicznego w krakowie.

ZASADY METEOROLOGII

WARSZAWA.

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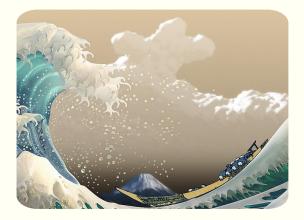
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particle-based μ -physics: rationale



background image: vitsly.ru / Hokusai



background image: vitsly.ru / Hokusai

 aerosol particles of natural and anthropogenic origin act as condensation nuclei



background image: vitsly.ru / Hokusai

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



background image: vitsly.ru / Hokusai

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- cloud droplets grow by water vapour condensation
- rain drops form through collisions of cloud droplets



background image: vitsly.ru / Hokusai

- aerosol particles of natural and anthropogenic origin act as condensation nuclei
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- aqueous chemical reactions irreversibly modify the drop composition



background image: vitsly.ru / Hokusai

- aerosol particles of natural and anthropogenic origin act as condensation nuclei
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- rain drops form through collisions of cloud droplets
- aqueous chemical reactions irreversibly modify the drop composition
- rain drops precipitate washing out aerosol

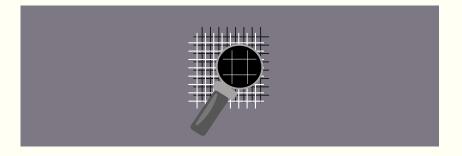


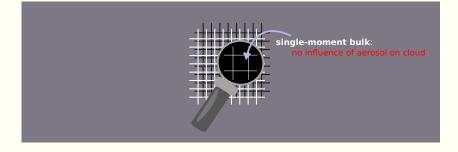
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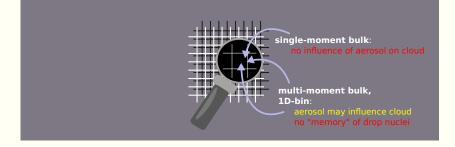
- aerosol particles of natural and anthropogenic origin act as condensation nuclei
- cloud droplets grow by water vapour condensation
- rain drops form through collisions of cloud droplets
- aqueous chemical reactions irreversibly modify the drop composition
- rain drops precipitate washing out aerosol
- rain drops evaporate into aerosol particles of potentially altered size and/or composition (collisions, chemistry)

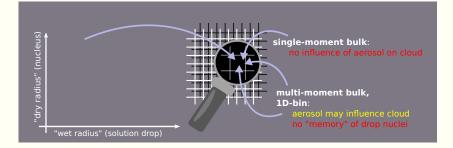


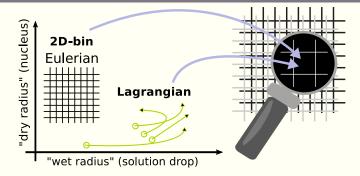
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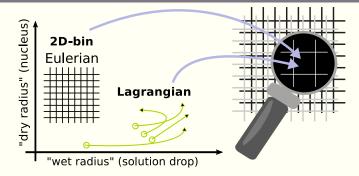








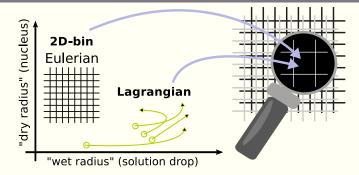
rationale: modelling aerosol-cloud interactions



Pioneering warm-rain aerosol-cloud-interaction models:

Andrejczuk et al. 2010	Lebo & Seinfeld 2011		Shima et al. 2009	
condensation: Lagrang	condensation:	Eulerian	condensation: Lagrangian	
collisions: Euleria	collisions:	Eulerian	collisions: Lagrangian	

rationale: modelling aerosol-cloud interactions

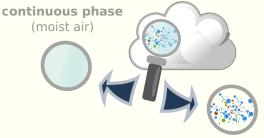


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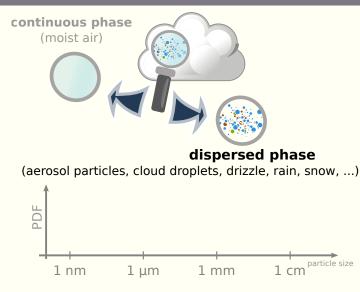
Shima et al.: stochastic coalescence and random phase-space sampling

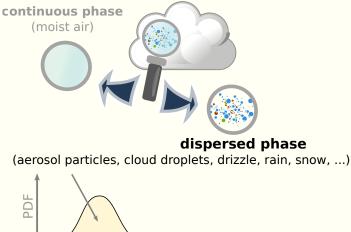




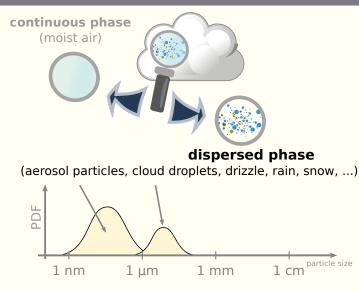
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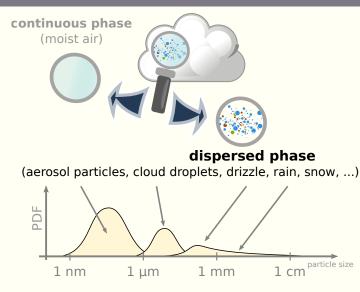
(aerosol particles, cloud droplets, drizzle, rain, snow, ...)

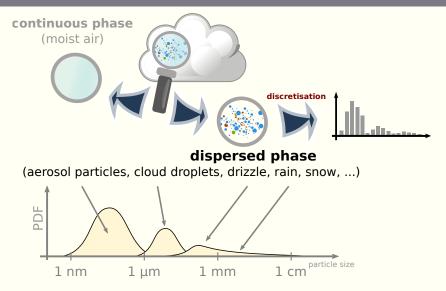


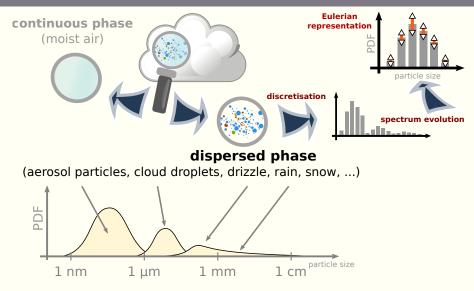


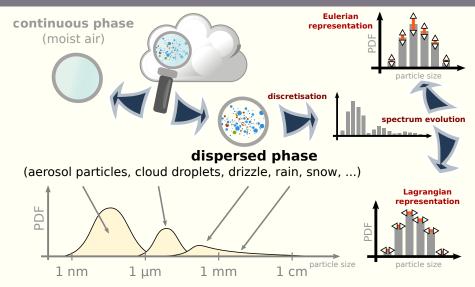
particle size 1 nm 1 µm 1 mm 1 cm



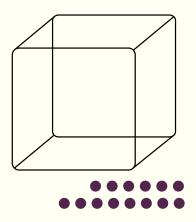


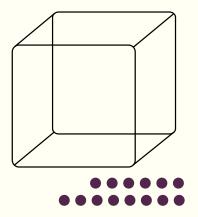




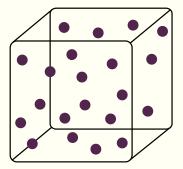


Domain randomly populated with " μ -physics information carriers" (super particles / super droplets)





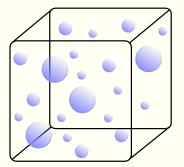
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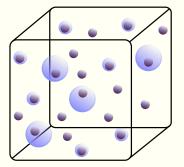
carrier attributes:

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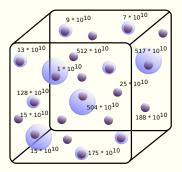
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- Iocation
- wet radius



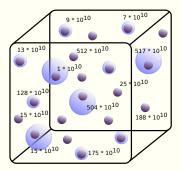
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- Iocation
- wet radius
- dry radius



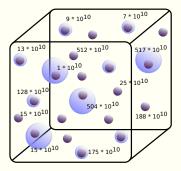
Domain randomly populated with " μ -physics information carriers" (super particles / super droplets)

- Iocation
- wet radius
- dry radius
- multiplicity



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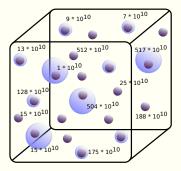


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advantages over Eulerian approach: no "categorisation"

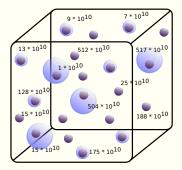


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Domain randomly populated with " μ -physics information carriers" (super particles / super droplets)

carrier attributes:

- Iocation
- wet radius
- dry radius
- multiplicity
- λ.

advantages over Eulerian approach: no "categorisation"; adding attributes does not increase dimensionality (ice, chemistry, charge, isotopic composition, ...)

Eulerian / PDE	Lagrangian / ODE

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

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

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advection of heat	particle transport by the flow
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	sedimentation
$\partial_t(\rho_d r) + \nabla \cdot (\vec{v} \rho_d r) = \rho_d \dot{r}$	$\dot{r} = \sum$
$\partial(z, 0) + \nabla(\vec{z}, 0) = \dot{0}$	particles $\in \Delta V$
$\partial_t(\rho_d\theta) + \nabla \cdot (\vec{v}\rho_d\theta) = \rho_d\dot{\theta}$	$\dot{\theta} = \sum_{\text{particles} \in \Delta V} \dots$

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

Eulerian / PDE	Lagrangian / ODE
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advection of trace gases	in-particle aqueous chemistry
challenges:	

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

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

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- each representing ξ real particles (aerosol/cloud/drizzle/rain)

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$$P_{ij} = max(\xi_i, \xi_j) \cdot \underbrace{\mathcal{E}(r_i, r_j) \cdot \pi(r_i + r_j)^2 \cdot |v_i - v_j|}_{\Delta V} \cdot \frac{\Delta t}{\Delta V}$$

coalescence kernel

where r - drop radii, $E(r_i, r_j) - collection efficiency, v - drop velocities$

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where r - drop radii, $E(r_i, r_j) - \text{collection efficiency}$, v - drop velocities

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}) → there's always a "bin" of the right size to store the collided particles

coalescence kernel

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where r - drop radii, $E(r_i, r_j) - \text{collection efficiency}$, v - drop velocities

- coalescence takes place following the latter of the two (consistent) scenarios:
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- collisions triggered by comparing a uniform random number with P_{ij}
- In/2] random non-overlapping (i,j) pairs examined instead of all (i,j) pairs cost: O(n²) → O(n), probability upscaled by n·(n-1)/[n/2]

example simulation (2D, prescribed flow)

Geosci. Model Dev., 8, 1677-1707, 2015 https://doi.org/10.5194/gmd-8-1677-2015 © Author(s) 2015. This work is distributed under the Creative Commons Attribution 3.0 License.



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. Arabas¹, A. Jaruga¹, H. Pawlowska¹, and W. W. Grabowski² ¹Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland

²National Center for Atmospheric Research (NCAR),

Boulder, CO, USA

example simulation (2D, prescribed flow)

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Model description paper | 09 Jun 2015

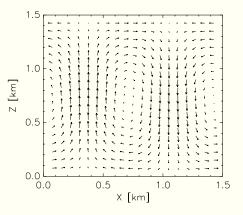
libcloudph++ 1.0: a single-moment bulk, double-moment bulk, and particle-based warm-rain microphysics library in C++

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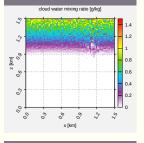
¹Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland

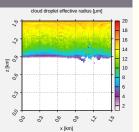
²National Center for Atmospheric Research (NCAR),

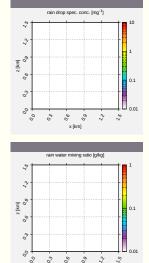
Boulder, CO, USA



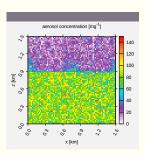
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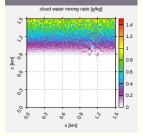


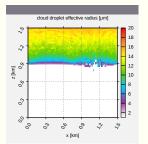


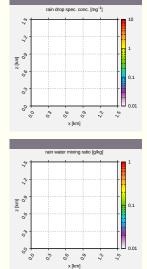


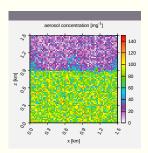
x [km]

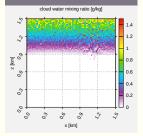


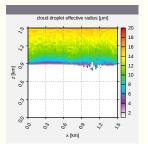


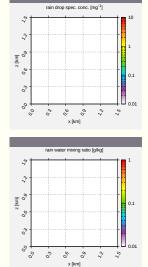


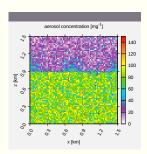


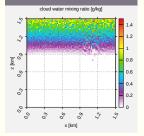


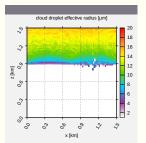


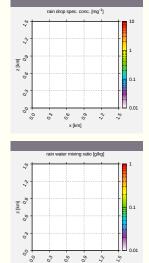




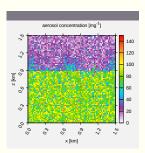


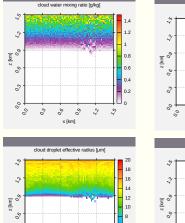






x [km]





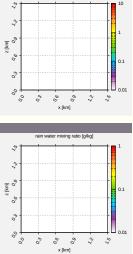
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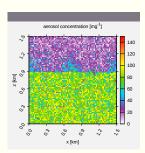
o: o:

80 V

x [km]

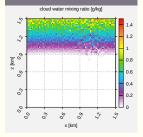


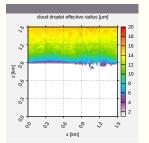
rain drop spec. conc. [mg⁻¹]

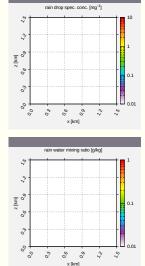


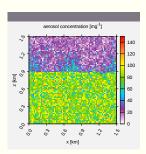
Particle-based cloud microphysics: rationale, state of the art and challenges

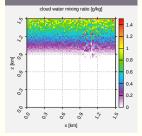
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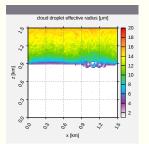


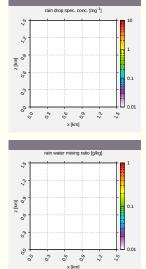


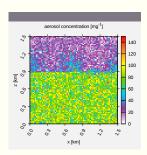












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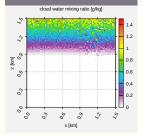
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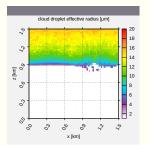
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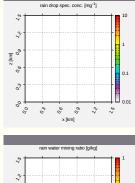
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°. °.

z [km]





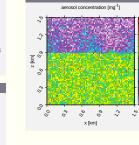


0.0 27 28 7

x [km]

0.1

0.01



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

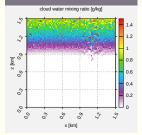
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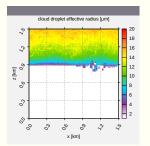
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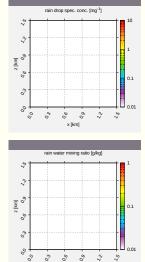
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60 40

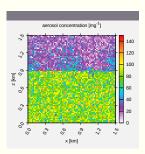
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x [km]

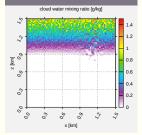


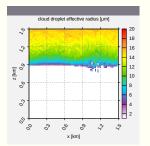
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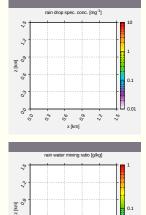
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0.0







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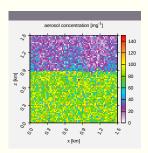
x [km]

2

00

0.01

6

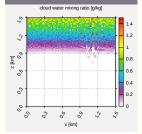


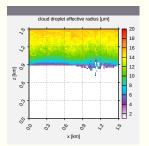
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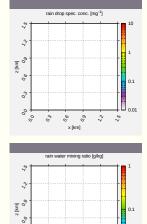
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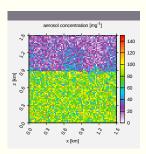


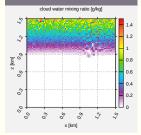


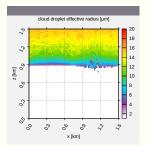
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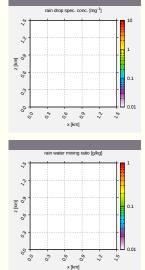
x [km]

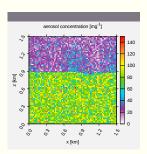
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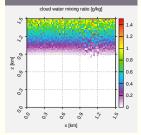


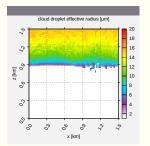


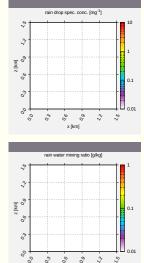






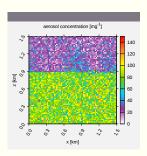






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x [km]

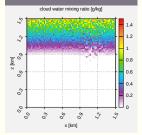


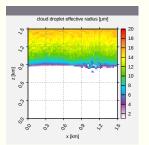
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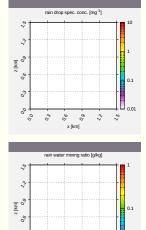
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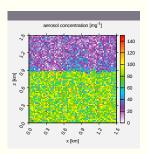
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x [km]

2

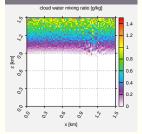
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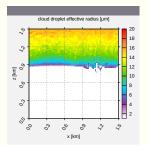
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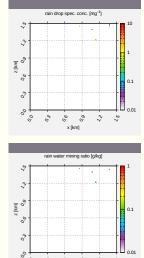


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°. °.

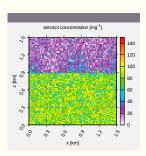






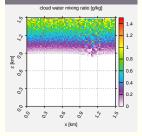
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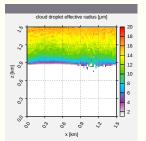
x [km]

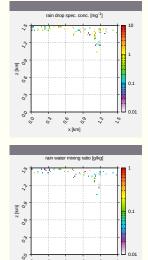


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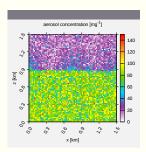






0.0 27 28 72

x [km]



z [km] 0.9

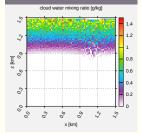
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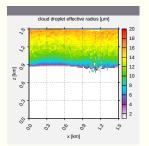
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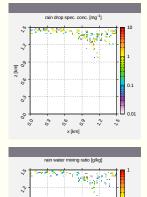
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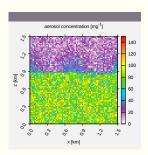
x [km]

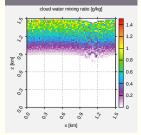
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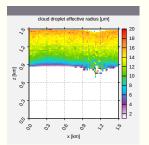
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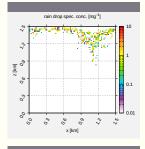
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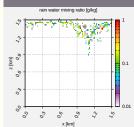
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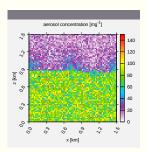


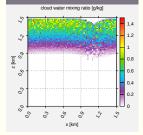


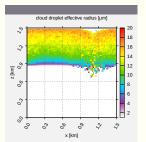


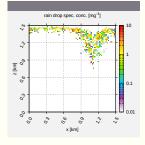


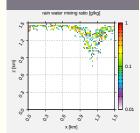


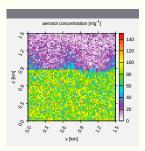


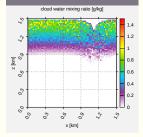


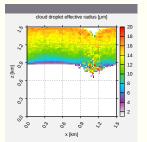


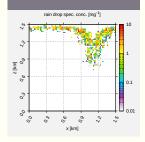


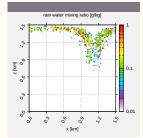


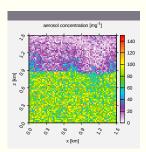


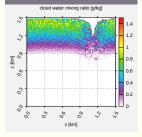


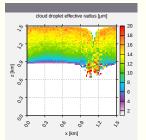


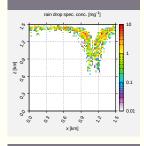


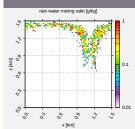


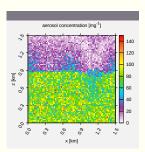


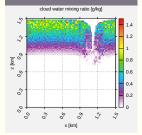


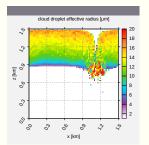


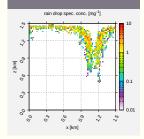


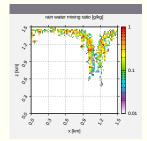


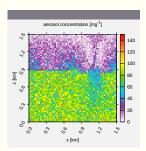


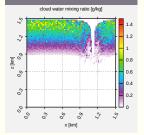


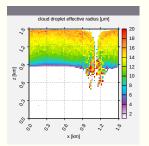


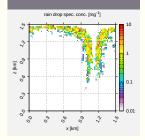


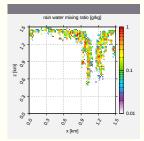


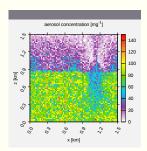




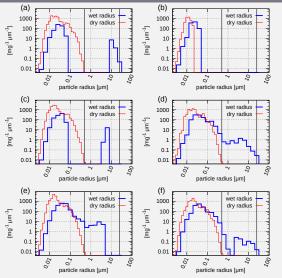


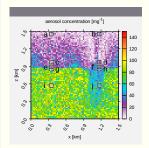






particle size spectra





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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

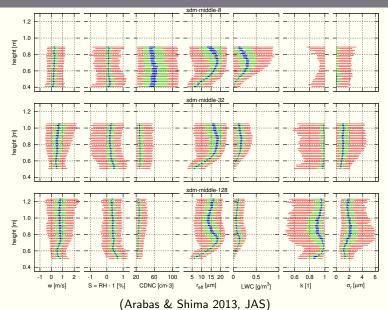
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references

- 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



UWLCM

highlights

- Hoppel-gap resolving aqueous chemistry
- GPU-resident 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

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

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

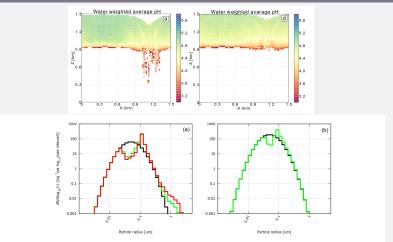


Figure 6. The size distributions of dry radii for the base case (a) and case3 (b). The initial dry radius size distribution is marked in black, the final dry radius size distribution from grid cells with $r_c > 0.01 \text{ g kg}^{-1}$ in green, and from grid cells with $r_r > 0.01 \text{ g kg}^{-1}$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

challenges (~~ opportunities)

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- **hybrid supercomputing** adaptable (GPU-resident particles)

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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

Merci! Thank you!

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