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

Sylwester Arabas

Michigan Tech, Houghton, US | July 19, 2018

# intro: speaker

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

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- challenges ($\rightsquigarrow$ opportunities)

# rationale

background image: vitsly.ru / Hokusai

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

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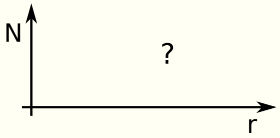
# modelling nomenclature: aerosol, cloud & rain spectra

- single-moment bulk



# modelling nomenclature: aerosol, cloud & rain spectra

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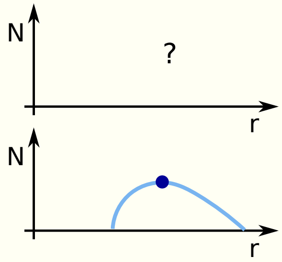
- multi-moment bulk



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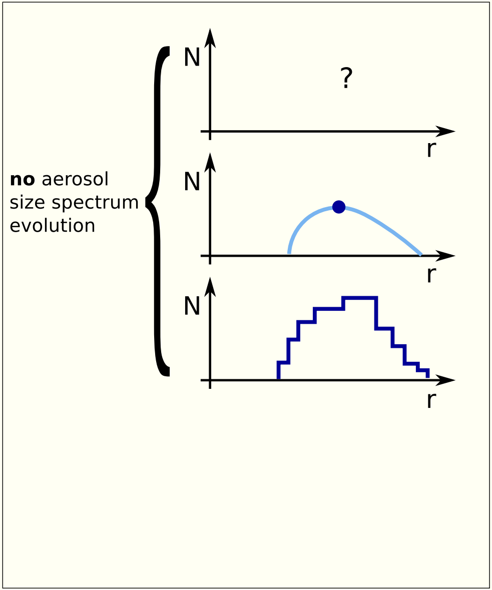

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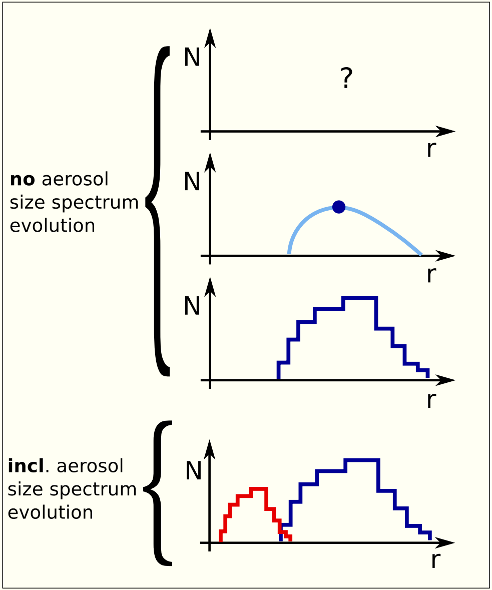
- multi-moment bulk
- „wet” size spectrum (bin)
- „wet vs. dry” 2D spectrum



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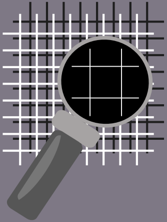

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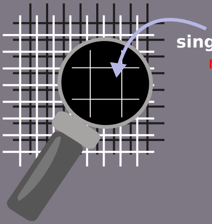
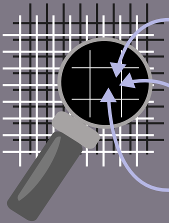


**single-moment bulk**:
no influence of aerosol on cloud

# rationale: modelling aerosol-cloud interactions



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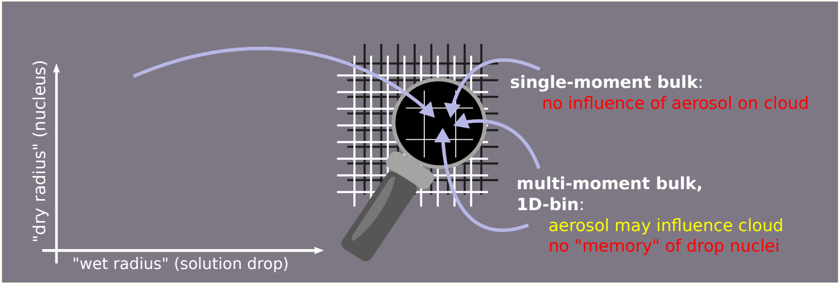

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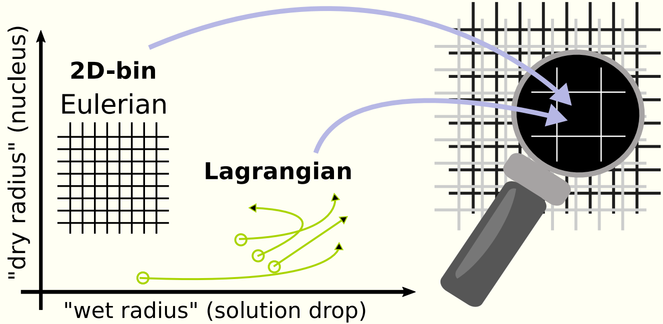

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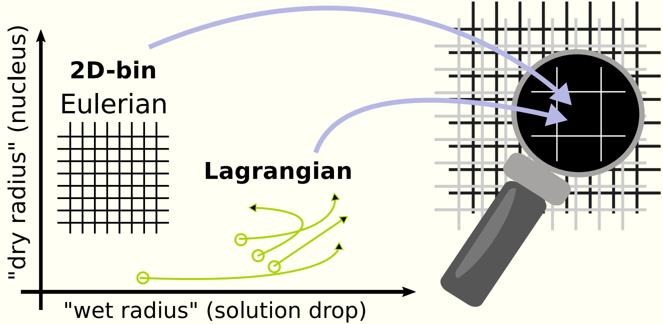


**Lagrangian:**

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

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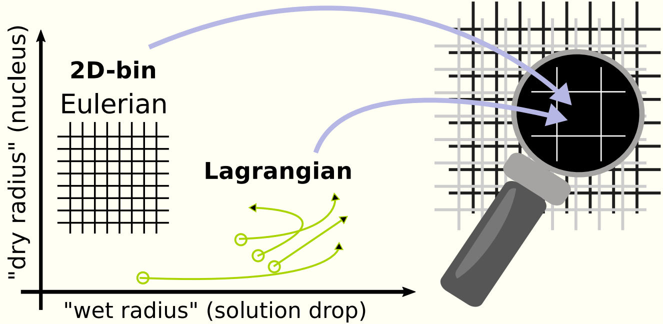


**Lagrangian:**

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

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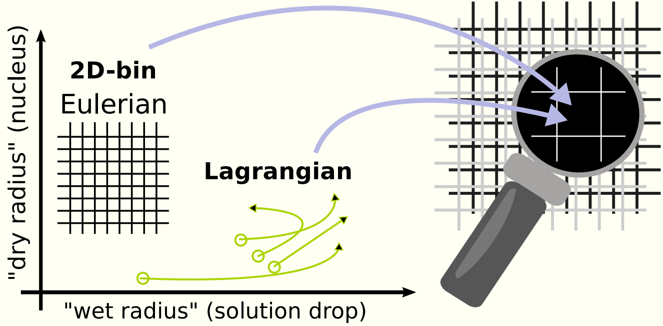


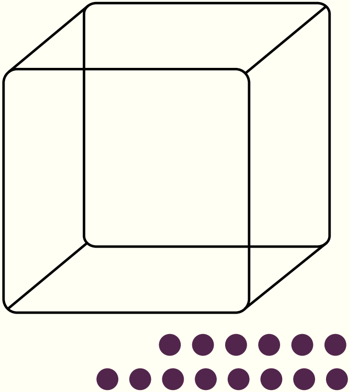

**Pioneering warm-rain LES aerosol-cloud-interaction models:**

| Andrejczuk et al. 2010 | |
|---|---|
| condensation: | Lagrangian |
| collisions: | Eulerian |

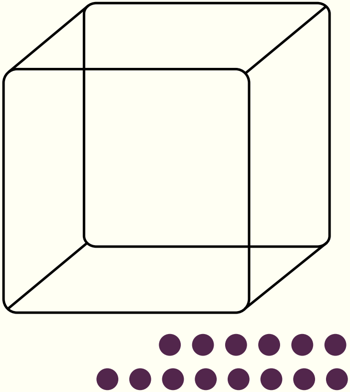
| Lebo & Seinfeld 2011 | |
|---|---|
| condensation: | Eulerian |
| collisions: | Eulerian |

| Shima et al. 2009 | |
|---|---|
| condensation: | Lagrangian |
| collisions: | Lagrangian |

# particle-based $\mu$-physics: key concepts



Domain randomly populated with "$\mu$-physics information carriers" (super particles / super droplets)



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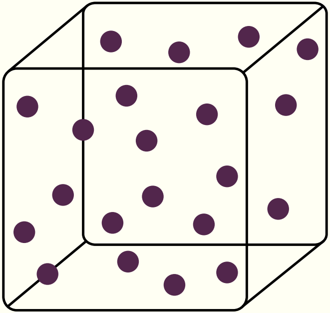

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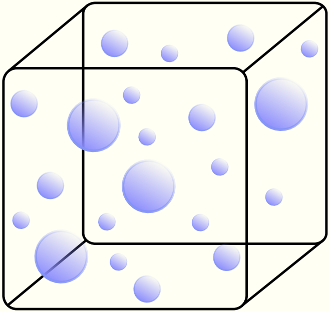

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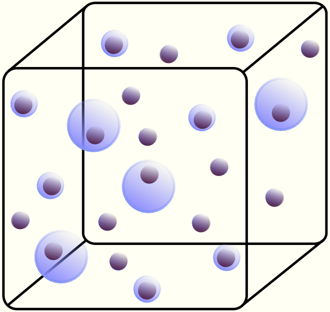

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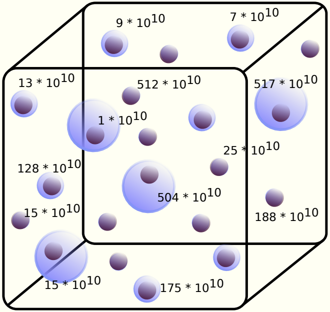


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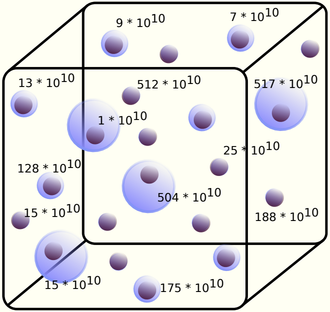


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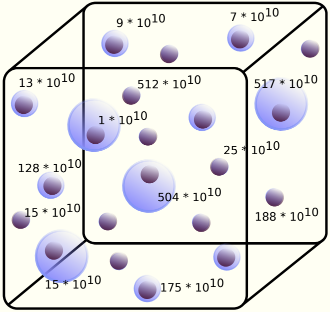


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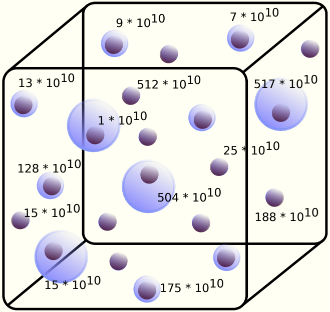


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- multiplicity
- ...

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

# particle-based $\mu$-physics: coupling with the host model

| Eulerian / PDE | Lagrangian / ODE |
| --- | --- |

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| advection of heat | particle transport by the flow |
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| $\partial_t(\rho_d r) + \nabla \cdot (\vec{v}\rho_d r) = \rho_d \dot{r}$ | $\dot{r} = \sum_{\text{particles} \in \Delta V} \ldots$ |
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| advection of trace gases<br>... | in-particle aqueous chemistry<br>... |

# state of the art

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- UWLCM (`http://github.com/igfuw/UWLCM`) from Univ. Warsaw,
- ICON/McSnow (`http://gitlab.com/sbrdar/mcsnow`) from DWD.

# 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

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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, subm.): *"Improving Collisional Growth in Lagrangian Cloud Models: Development and Verification of a New Splitting Algorithm"*
- **Noh, Oh, Hoffmann & Raasch 2018** (JAS, subm.): *"A Cloud Microphysics Parameterization for Shallow Cumulus Clouds Based on Lagrangian Cloud Model Simul."*
- **Hoffmann, Yamaguchi & Feingold 2018** (JAS, subm.): *"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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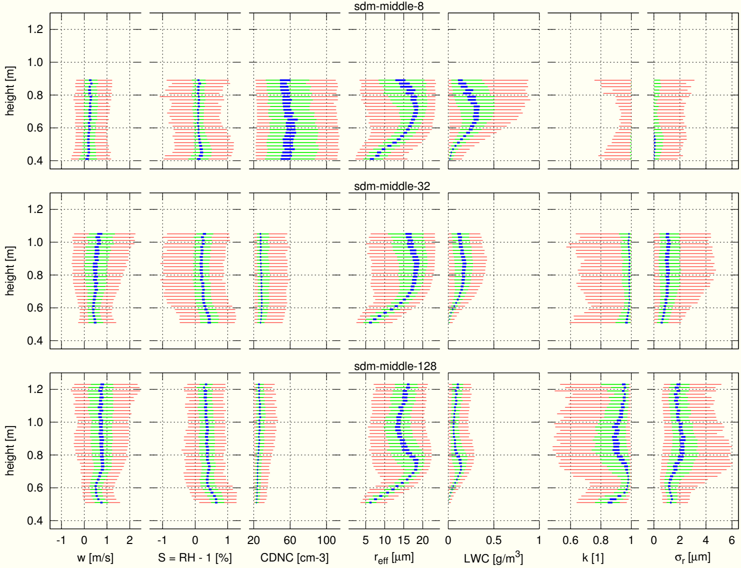
- new particle formation studies

## 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 $\mu$-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

# Pencil-Code (and related works)

## highlights

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

## references

- **Li, Brandenburg, Haugen & Svensson 2017** (JAMES): *"Eulerian and Lagrangian approaches to multidimensional condensation and collection"*
- **Li, Brandenburg, Svensson, Haugen, Mehlig & Rogachevskii (2017/18** (arXiv): *"Effect of turbulence on collisional growth of cloud droplets"*
- **Li, Svensson, Brandenburg & Haugen 2018** (arXiv): *"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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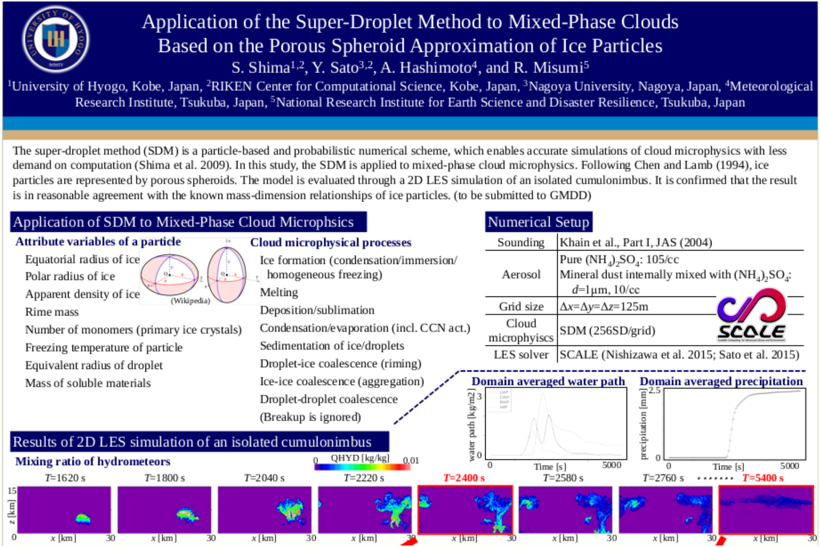
## references

- **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"*

# SCALE - cumulonimbus example



## Application of the Super-Droplet Method to Mixed-Phase Clouds Based on the Porous Spheroid Approximation of Ice Particles

S. Shima[1,2], Y. Sato[3,2], A. Hashimoto[4], and R. Misumi[5]

[1]University of Hyogo, Kobe, Japan, [2]RIKEN Center for Computational Science, Kobe, Japan, [3]Nagoya University, Nagoya, Japan, [4]Meteorological Research Institute, Tsukuba, Japan, [5]National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan

The super-droplet method (SDM) is a particle-based and probabilistic numerical scheme, which enables accurate simulations of cloud microphysics with less demand on computation (Shima et al. 2009). In this study, the SDM is applied to mixed-phase cloud microphysics. Following Chen and Lamb (1994), ice particles are represented by porous spheroids. The model is evaluated through a 2D LES simulation of an isolated cumulonimbus. It is confirmed that the result is in reasonable agreement with the known mass-dimension relationships of ice particles. (to be submitted to GMDD)

### Application of SDM to Mixed-Phase Cloud Microphysics

**Attribute variables of a particle**

- Equatorial radius of ice
- Polar radius of ice
- Apparent density of ice
- Rime mass
- Number of monomers (primary ice crystals)
- Freezing temperature of particle
- Equivalent radius of droplet
- Mass of soluble materials

(Wikipedia)

**Cloud microphysical processes**

- Ice formation (condensation/immersion/ homogeneous freezing)
- Melting
- Deposition/sublimation
- Condensation/evaporation (incl. CCN act.)
- Sedimentation of ice/droplets
- Droplet-ice coalescence (riming)
- Ice-ice coalescence (aggregation)
- Droplet-droplet coalescence
- (Breakup is ignored)

### Numerical Setup

| | |
|---|---|
| Sounding | Khain et al., Part I, JAS (2004) |
| Aerosol | Pure $(NH_4)_2SO_4$: 105/cc<br>Mineral dust internally mixed with $(NH_4)_2SO_4$: $d$=1μm, 10/cc |
| Grid size | $\Delta x=\Delta y=\Delta z$=125m |
| Cloud microphyiscs | SDM (256SD/grid) |
| LES solver | SCALE (Nishizawa et al. 2015; Sato et al. 2015) |

**Domain averaged water path**

water path [kg/m2]; 3; 0; Time [s]; 0; 5000

**Domain averaged precipitation**

precipitation [mm]; 2.5; 0; Time [s]; 0; 5000

### Results of 2D LES simulation of an isolated cumulonimbus

**Mixing ratio of hydrometeors**

QHYD [kg/kg] 0 – 0.01

T=1620 s, T=1800 s, T=2040 s, T=2220 s, T=2400 s, T=2580 s, T=2760 s, …… T=5400 s

z [km] 0–15; x [km] 0–30

https://ams.confex.com/ams/15CLOUD15ATRAD/webprogram/Handout/Paper346467/poster076.Shima.pdf

# UWLCM (and related works)

## highlights

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

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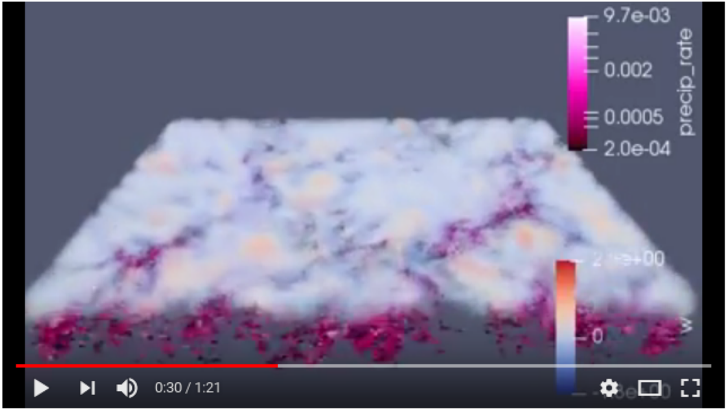
## references


- **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, Jaruga & Pawlowska 2018** (AMS, Vancouver): *"UWLCM: a Modern LES Model with Lagrangian Microphysics"*

# UWLCM - DYCOMS example




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

# ICON/McSnow (and related works)

## highlights

- Monte-carlo mixed-phase microphysics (5 particle attributes)
- deep convection studies

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## references

- **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)

# particle-based microphysics: recap/takeaways

- **no numerical diffusion** in radius space (also for coalesc. if Monte-Carlo)

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- **lucky-droplet & GCCN friendly** Monte-Carlo (non-SCE) coalescence

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

# news: BAMS super-droplet review (Grabowski et al. ’18)

**Modeling of cloud microphysics: Can we do better?**

Wojciech W. Grabowski[1], Hugh Morrison[1], Shin-ichiro Shima[2],

Gustavo C. Abade[3], Piotr Dziekan[3], and Hanna Pawlowska[3]

[1]Mesoscale and Microscale Meteorology Laboratory, NCAR*, Boulder, USA

[2]University of Hyogo and RIKEN Center for Computational Science, Kobe, Japan

[3]Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Submitted to BAMS

# news: super-droplet workshop 2019

## Workshop on Eulerian vs. Lagrangian methods for cloud microphysics

The cloud-aerosol modelling team at the Institute of Geophysics, Faculty of Physics, University of Warsaw, Poland organised a workshop aimed at bringing together researchers working on **modelling cloud microphysics**.

The workshop took place **in Warsaw on April 20-22, 2015**, in the CeNT building at the "Ochota Campus" of the University of Warsaw.

**TOPICS AND FORMAT**

The workshop topics covered formulation, implementation and validation of numerical models of aerosol, cloud and precipitation microphysics.

The axis of the workshop was the juxtaposition of the Eulerian (bulk or bin) and the Lagrangian (particle-based) methods for modelling clouds.

Follow-up workshop soon to be announced (Poland, Q2? 2019)
Organised by Jagiellonian University in Cracow and University of Warsaw

# acknowledgements

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Thank you for your attention!