Lagrangian (particle-based) cloud microphysics: super-droplet approach

Sylwester Arabas
Jagiellonian University

rationale

rationale: aerosol-cloud interactions

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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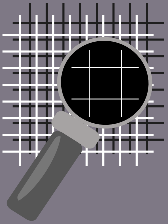
rationale: modelling aerosol-cloud interactions



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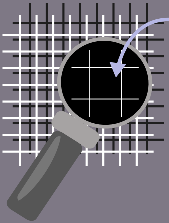

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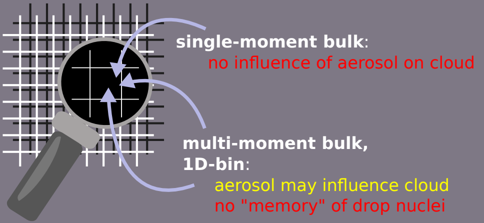

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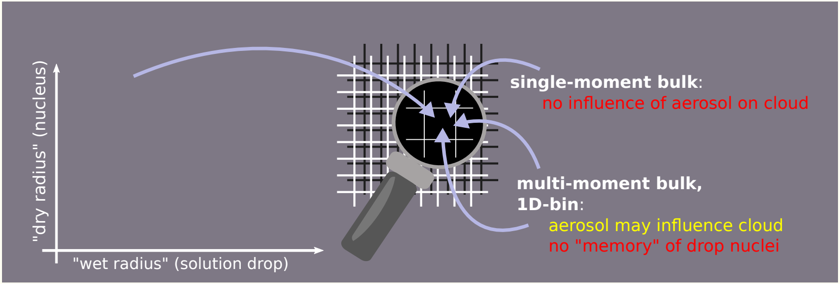

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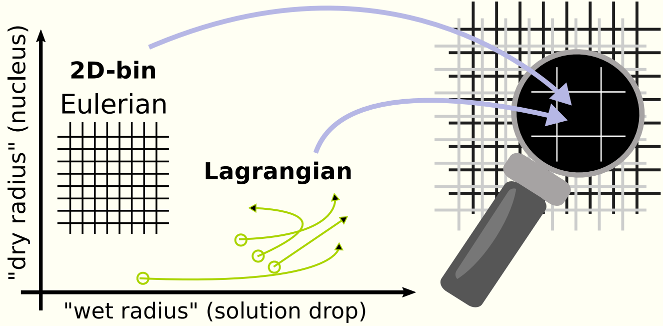
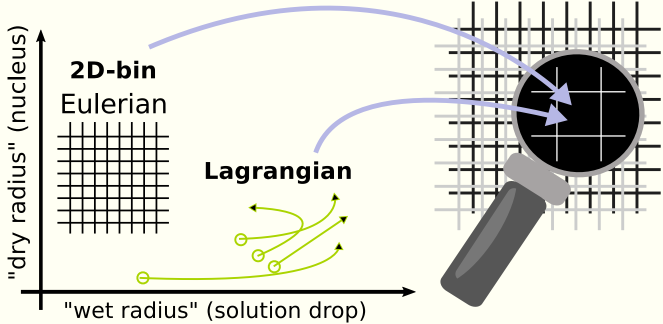
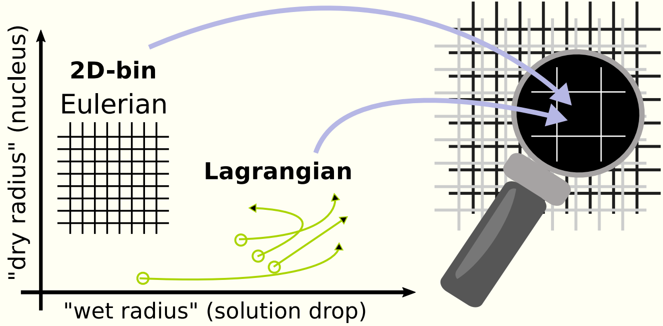




Lagrangian:

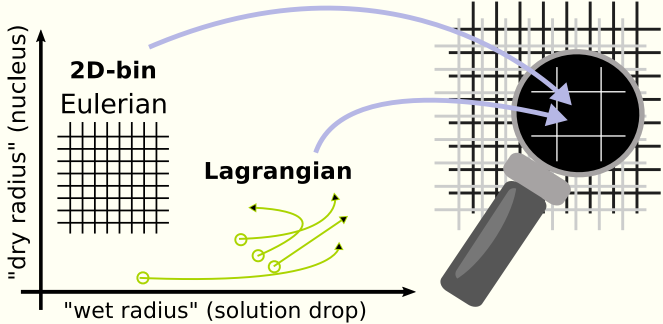
- parcel model
  ⇝ moving-sectional schemes (40-ties onwards: Howell, Mordy, ...)



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



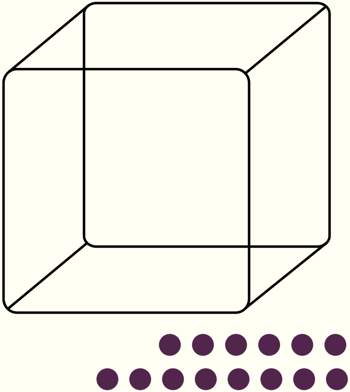
Pioneering warm-rain LES aerosol-cloud-interaction models:

Andrejczuk et al. 2010	
condensation:	Lagrangian
collisions:	Eulerian

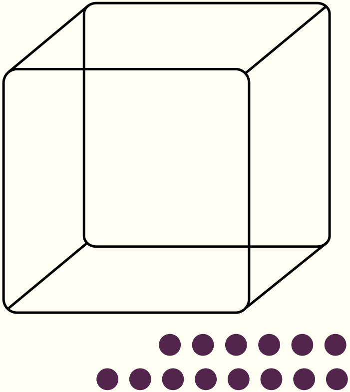
Lebo & Seinfeld 2011	
condensation:	Eulerian
collisions:	Eulerian

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)



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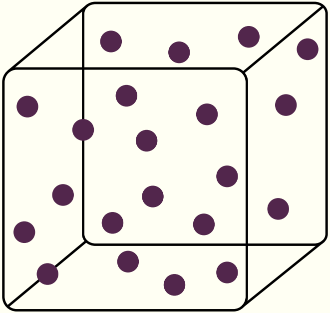

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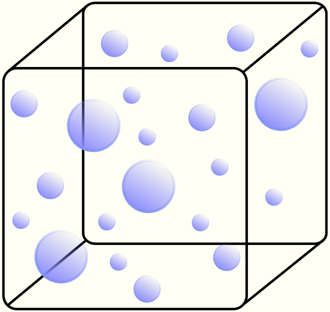
carrier attributes:

- location



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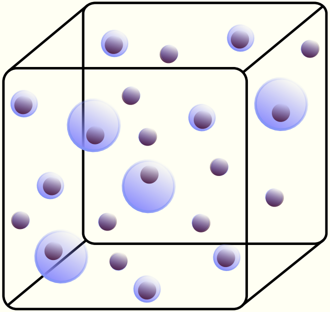
carrier attributes:

- location
- wet radius



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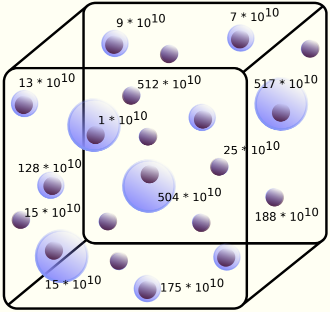
carrier attributes:

- location
- wet radius
- dry radius



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

carrier attributes:

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- dry radius
- multiplicity

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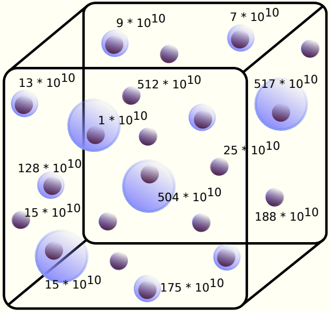

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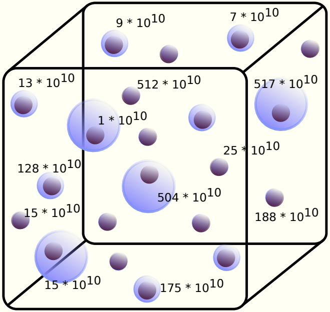

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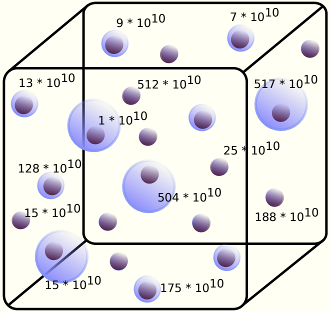
advantage over Eulerian approach: adding attributes does not increase dimensionality



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

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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	collisional growth
	sedimentation

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

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

state of the art

particle-based μ-physics for LES

recent research software (re)developments:

- INC/LCM from LANL/Leeds,

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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

PALM-LES (and related works)

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- derivation of autoconversion rates through ab-initio simulations
- Linear Eddy Model (LEM) ⇝ mixing inhomogeneity

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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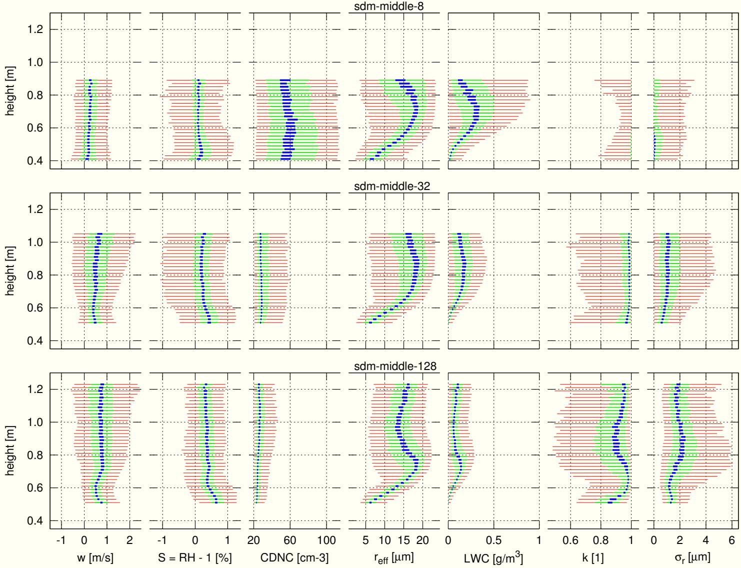
references

- **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"*



(Arabas & Shima 2013, JAS)

UCLA-LES (and related works)

highlights

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

UCLA-LES (and related works)

highlights

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

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 (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"*

UWLCM (and related works)

highlights

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

UWLCM (and related works)

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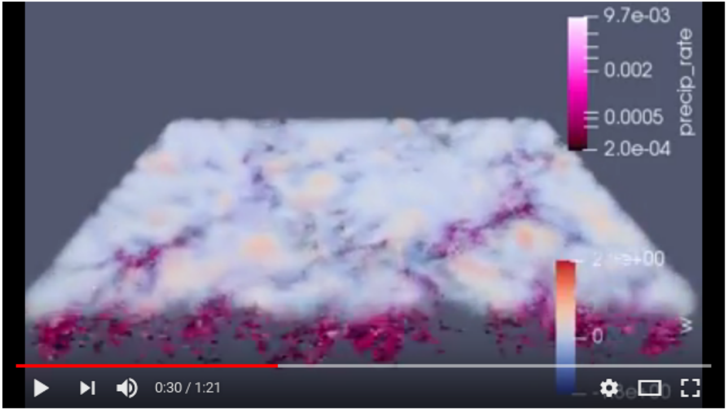
references

- **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 (Dziekan et al.)



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

ICON/McSnow (and related works)

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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

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- **subgrid cloud fraction** is effectively represented (robust wrt Eulerian grid)

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particle-based microphysics: recap/takeaways

- **no numerical diffusion** in radius space (also for coalesc. if Monte-Carlo)
- **by-design non-negativity** of the derived density/concentration fields
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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)

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Modeling of cloud microphysics: Can we do better?

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BAMS

SNOW GLOBE

Eulerian vs. Lagrangian microphysics workshop 2019

http://ww2.ii.uj.edu.pl/~arabas/workshop_2019/

WORKSHOP2019 WORKSHOP2019

Workshop on Eulerian vs. Lagrangian methods for cloud microphysics

The meeting is aimed at bringing together researchers working on **modelling cloud microphysics**. It is a follow up event to the workshop organised in Warsaw in 2015.

The meeting is organised jointly by:
- Division of Computational Mathematics, Faculty of Math. and CS, Jagiellonian University &
- Institute of Geophysics, Faculty of Physics, University of Warsaw.

The workshop will take place **in Cracow, Poland on April 15-17, 2019** (week after EGU GA in Vienna) in the ``Auditorium Maximum'' of the Jagiellonian University.

TOPICS AND FORMAT

The envisaged workshop topics range from formulation through implementation to validation of numerical models of aerosol, cloud and precipitation microphysics, and its interactions with turbulence, radiation, aqueous chemistry and atmospheric electricity.

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

Organised by Jagiellonian University in Cracow and University of Warsaw
Registration deadline: February 10!

`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!