Progress and Prospects of Lagrangian Particle-Based Cloud Modeling

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1. Lagrangian Particle-Based Method for Cloud Microphysics

It is an alternative to Eulerian bulk or bin methods

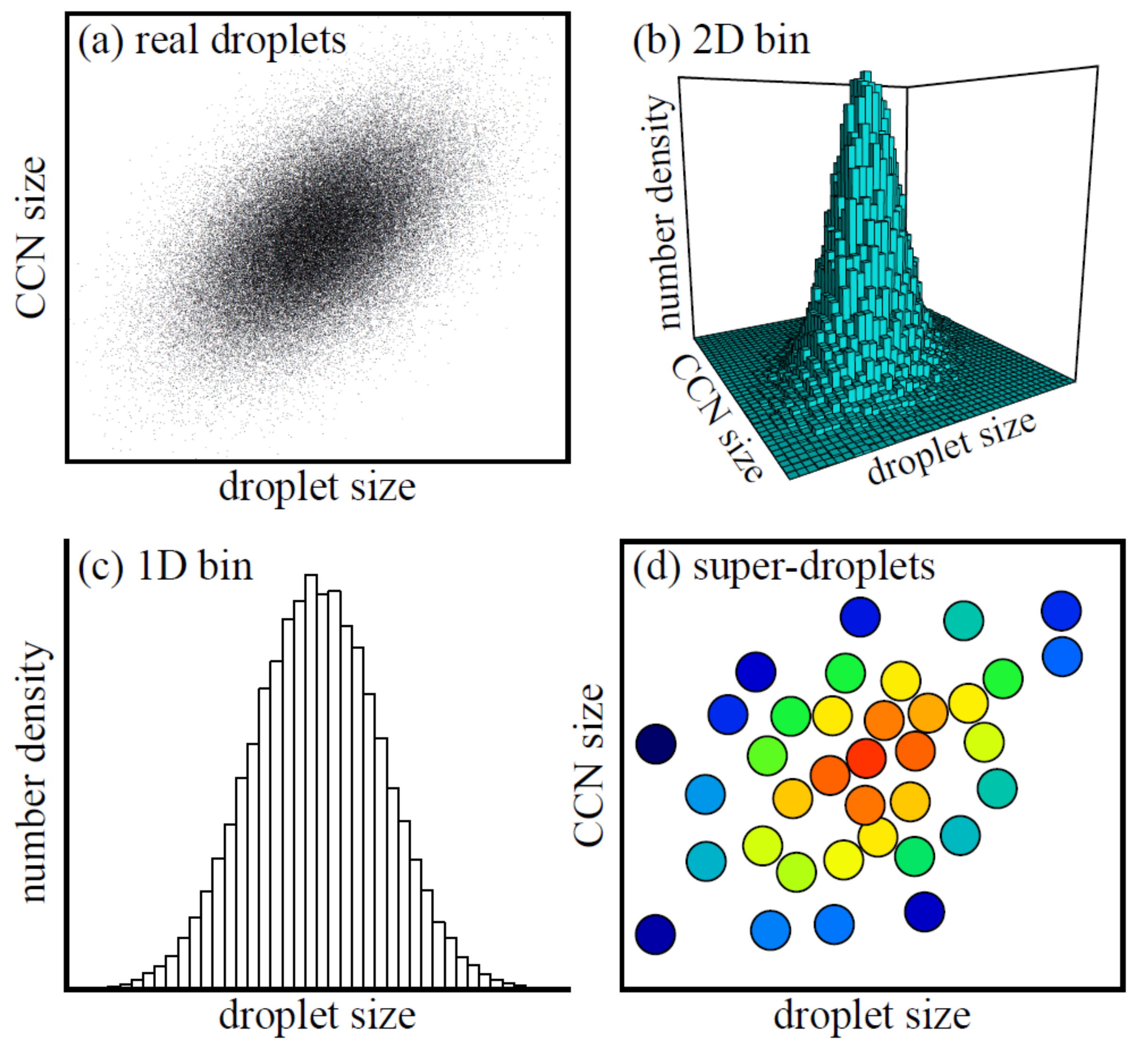


Fig.4 of Grabowski+'19 (created by Shima)

- Aerosol/cloud/precipitation particles are represented by super-droplets or super-particles
- See, e.g., Shima+('09,'20) for more details.
- **Particle-based schemes could resolve various issues of bin and bulk (Grabowski+'19)**

In bulk models, only the statistical properties (mass, number, etc.) of the particle size distribution are calculated.

Particle-based models are being used for various problems

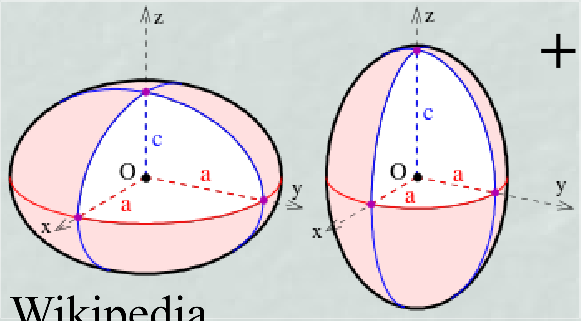
- Warm clouds: cumulus, cumulus congestus, fog,
  - Stratocumulus: Dziekan+'19, Hoffmann&Feingold'19, Dziekan+'21, Chandrakar+'22, Yin+'24
  - Marine cloud brightening: Hoffmann&Feingold'21, Kainz&Hoffmann'24
- Aerosol processing and aqueous/surface chemistry
  - Hoppel gap: Jaruga&Pawlowska'18
- Ice-/mixed-phase clouds
  - Cirrus and contrail: Sölch&Kärcher'10, Unterstrasser&Sölch'10, …, Unterstrasser+'17, and many
  - Model for mixed phase clouds and habit (ice shape) prediction:
    - McSnow: Brdar&Seifert'18, Welss+'24; PALM-LCM: Hoffmann'20; SCALE-SDM: Shima+'20; CM1-SDM: Chandrakar+'24
- Supersaturation fluctuation by SGS turbulence
  - By adding 4 new attributes (S',U',V',W') (Grabowski&Abade'17, Abade+'18)
  - By introducing Linear Eddy Model (Hoffman+'18)

2. Application to Mixed-Phase Clouds and Habit Prediction

Approach of Shima+'20

Porous spheroid approximation

(e.g., Chen&Lamb'94, Jensen&Harrington'15)



Wikipedia

+ apparent density ρ

+ rime mass, number of monomers

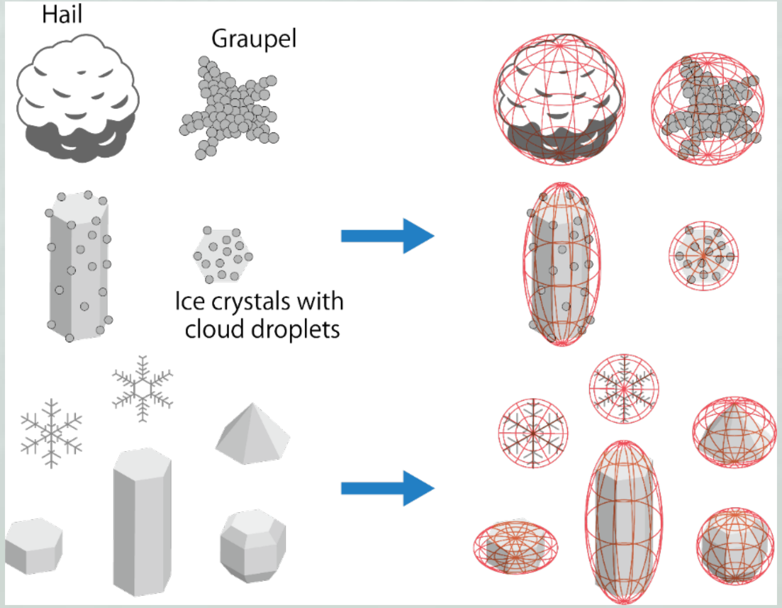
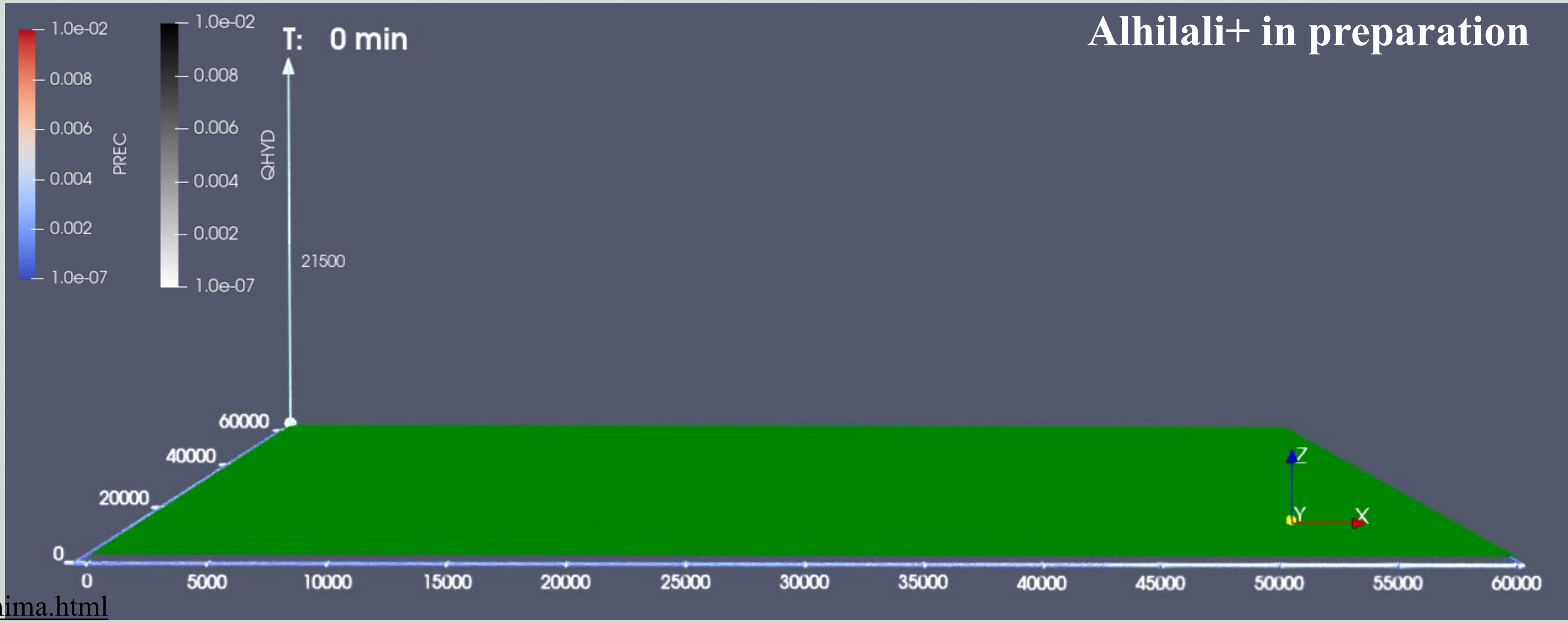


Fig.2 in https://moonshot8-modeldev.riken.jp/eng/theme/2-1_shima.html

Ice nuclei is represented by **freezing temperature attribute, based on INAS theory**

Can account for homogeneous, and condensation/immersion freezing

Cb simulation with SCALE-SDM



Improved habit prediction model (Welss+'24)

- Inherent growth ratio function of Chen&Lamb'94 is renewed
- Reexamination of Böhm's theory ('89,'92abc,'94,'99,'04) for terminal velocity and collision
- **Habit dependent ventilation model**

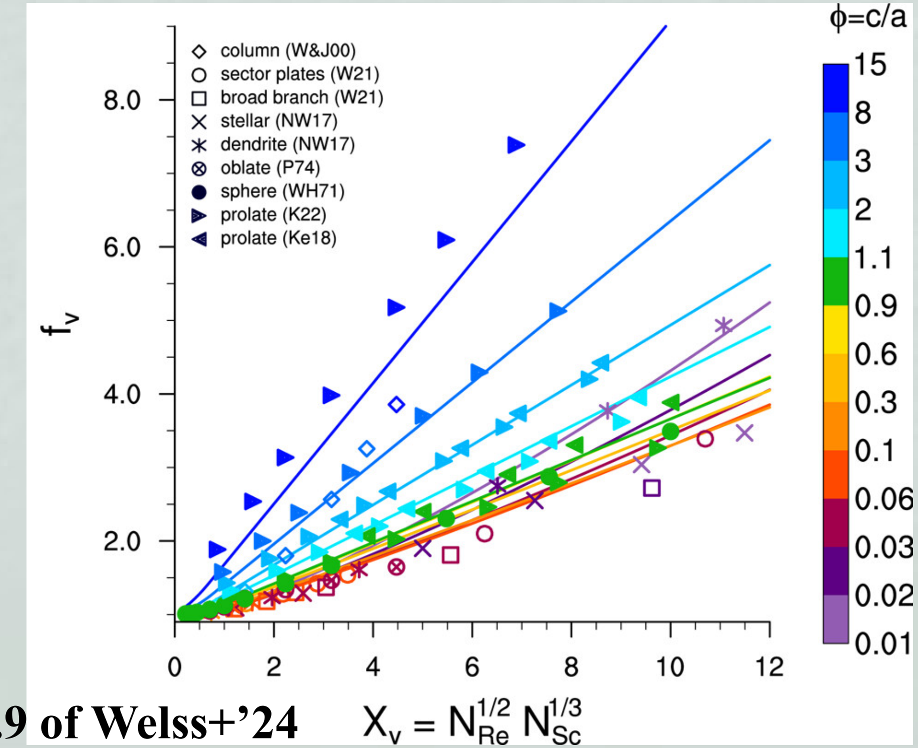
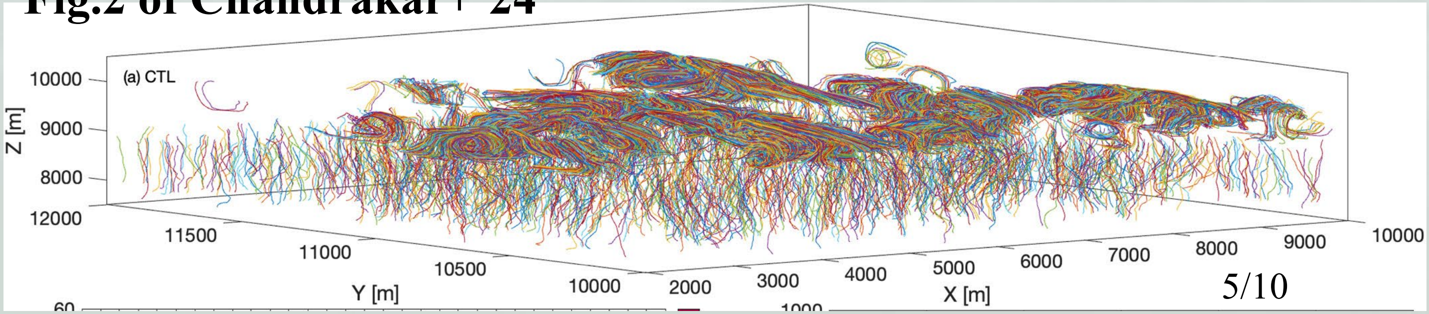


Fig.9 of Welss+'24

New crystal growth model and cirrus (Chandrakar+'24)

- **A new depositional growth model based on lab experiments** (Harrington+'19 and Pokrifka+'23) was implemented to CM1-SDM
- They found that the particle variability in cirrus is primarily driven by their thermodynamic histories

Fig.2 of Chandrakar+'24



3. Model Developments

Collisional breakup of droplets

SD number remain unchanged through coalescence (Shima+'09)

Collisional breakup poses a computational challenge

Bringi+'20's algorithm requires SD merging.

De Jong+'23 developed an algorithm that conserves the SD number, and implemented it to PySDM

Development of efficient algorithms for other breakup processes is important, such as ice-ice collisional breakup, rime splintering, shedding, shattering of freezing droplets.

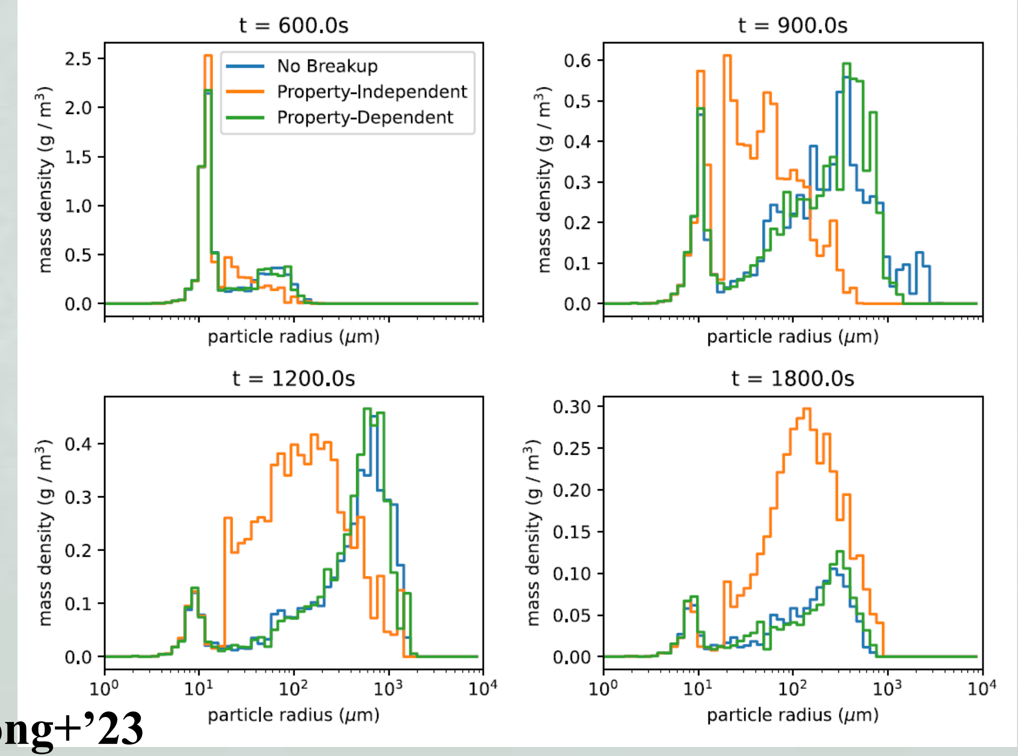


Fig. 11 of de Jong+'23

Performance optimization

Matsushima+'23 achieved **61.3 times speed-up** by improving the algorithm and optimizing the code. (Available only in his version.)

The elapsed time is comparable to a two-moment bulk scheme.

Numerical weather forecast with particle-based model would be feasible?

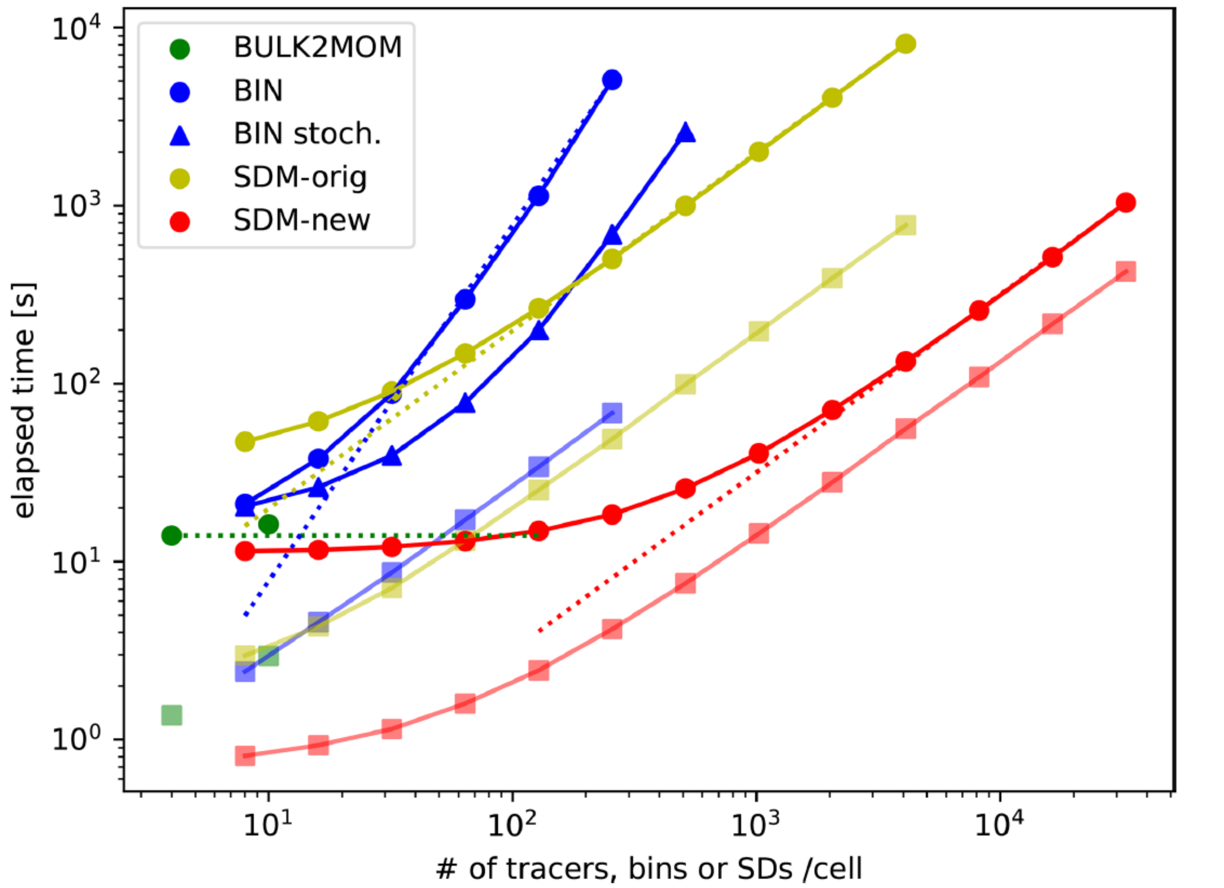


Fig. 4 of Matsushima+'23

CPU + GPU + MPI

Dziekan&Zmijewski'22 explored the performance of UWLCM.

Lagrangian and Eulerian calculations can be parallelized efficiently on GPU and CPU.

On 40 nodes, the wall time of CPU+GPU particle-based was twice that of CPU-only bulk.

Machine learning

Particle-based models can provide training data for machine learning (e.g., Seifert&Rasp'20, Sharma&Greenberg'24, Azimi+'24)

Seifert&Siewert'24 developed ML-based two-moment ice microphysics by learning 55 process rates using McSnow as reference

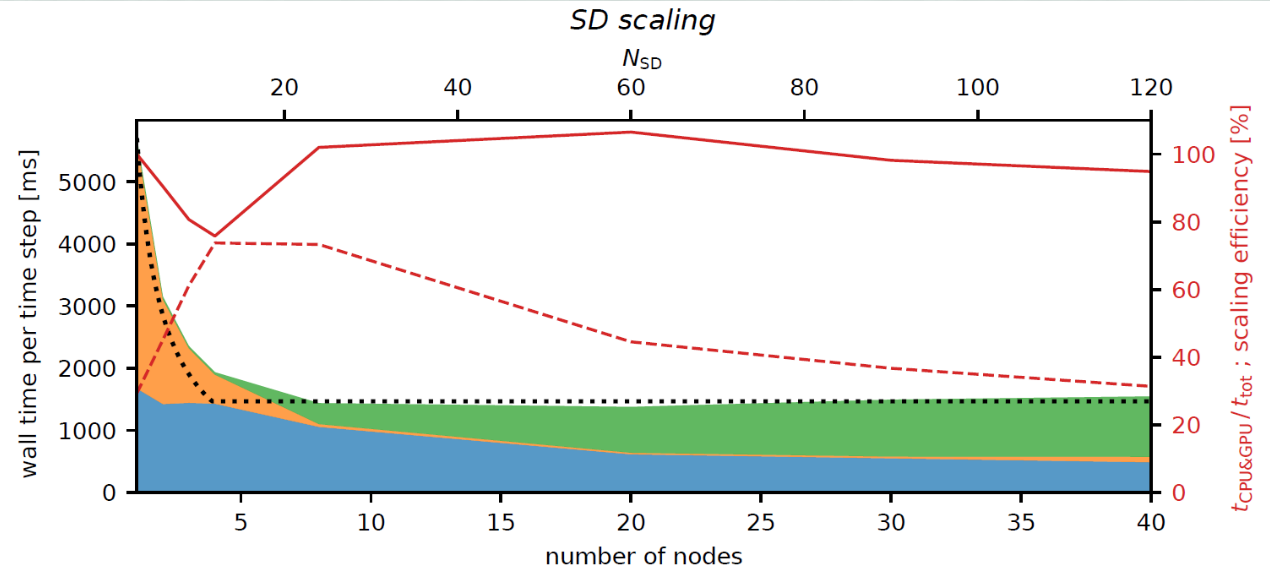


Fig.5 of Dziekan&Zmijewski'22

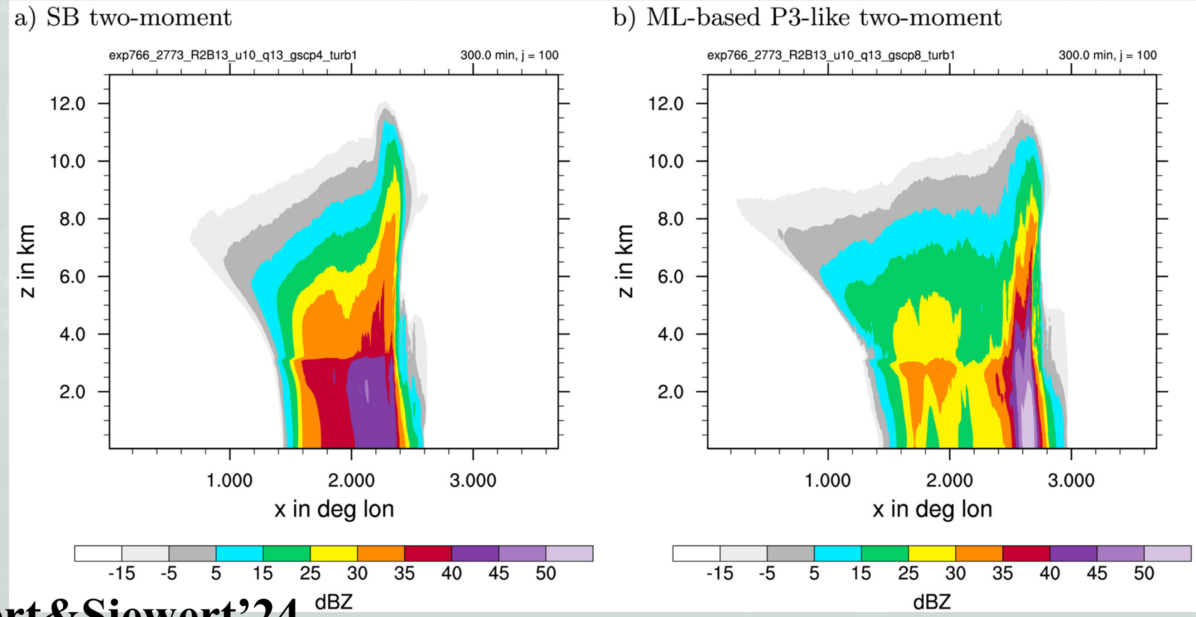


Fig.4 of Seifert&Siewert'24

4. Model Validations

Pi chamber model intercomparison

- Moist turbulent chamber in Michigan Tech
- ICMW2020 case for warm phase (Chen+'24); 2024 case for mixed phase
- **Qualitative agreement with lab experiment**
- Further study is needed to understand the remaining discrepancy

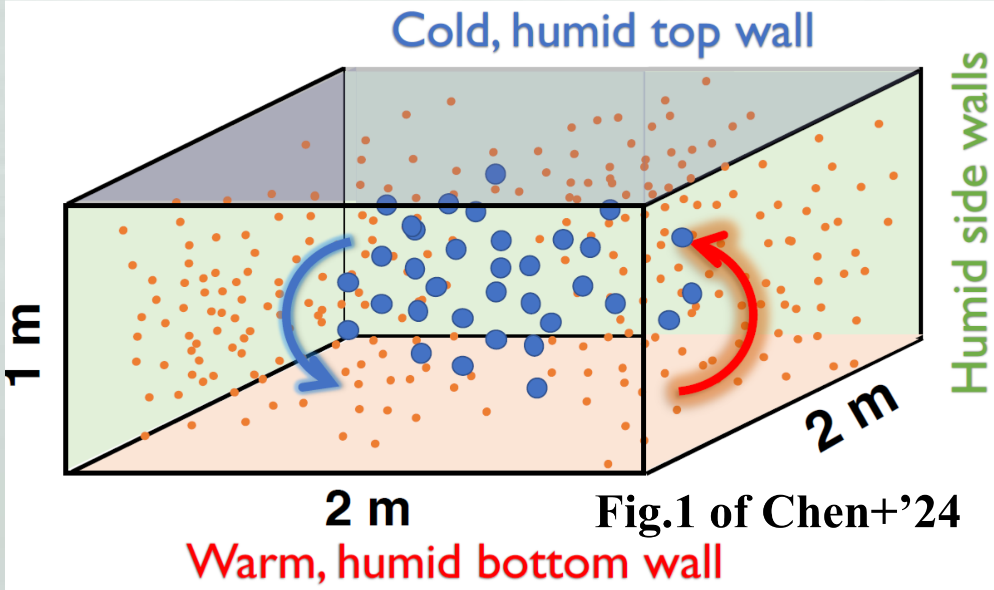


Fig.1 of Chen+'24

Evaluation of coalescence algorithms in 3D

- Morrison+'24 tested several coalescence algorithms for particle-based models in 3D LES of a cumulus congestus
- **SDM Monte-Carlo algorithm of Shima+'09 worked efficiently** (good convergence at 256SDs/cell)
- They uncovered the reason why some deterministic algorithms perform poorly
- **Flow variability due to turbulence is much larger than the stochasticity of the SDM algorithm** (see also Zmijewski+'24)

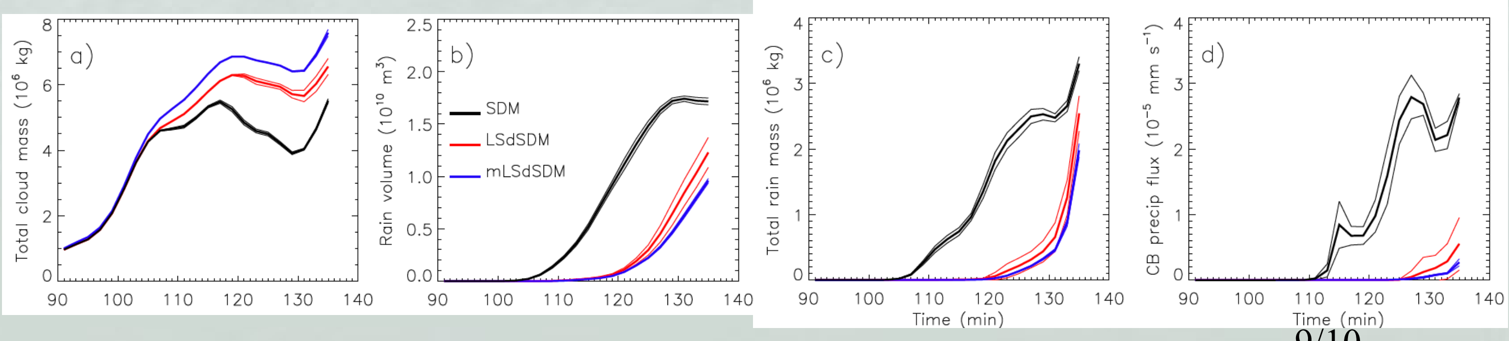


Fig.10 of Morrison+'24

5. Conclusions

Key messages

Lagrangian particle-based cloud models can seamlessly connect aerosol scale and cloud scale from the process level.

They serve as a unique tool to bridge the gaps between observations, modeling, lab studies, and theory.

Open source software

McSnow: https://gitlab.dkrz.de/mcsnow/mcsnow

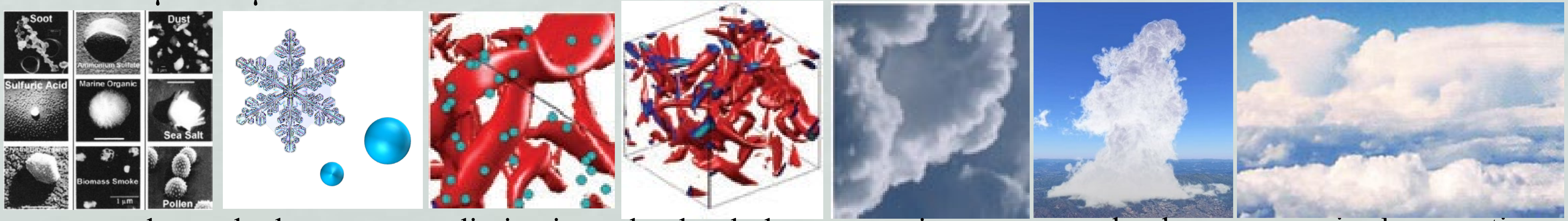
PySDM: https://github.com/open-atmos/PySDM

SCALE-SDM: https://github.com/Shima-Lab

UWLCM: https://github.com/igfuw/UWLCM

GMD/ACP special issue

https://gmd.copernicus.org/articles/special_issue1164.html



aerosol (Heintzenberg et al., 2003)
hydrometeors (SnowCrystals.com)
dissipation
cloud turbulence
entrainment
(Fig.1 of Grabowski and Wang (2013) with modification)
cloud (created by Matsushima)
organized convection (荒木健太郎, 2018: 世界でいちばん素敵な雲の教室より)