20th Anniversary of the Super-Droplet Method

Shin-ichiro Shima (Univ of Hyogo, Kobe, Japan)

富岳NEXT FS気象･気候分野公開研究会

第4回気象･気候 計算科学研究連絡会

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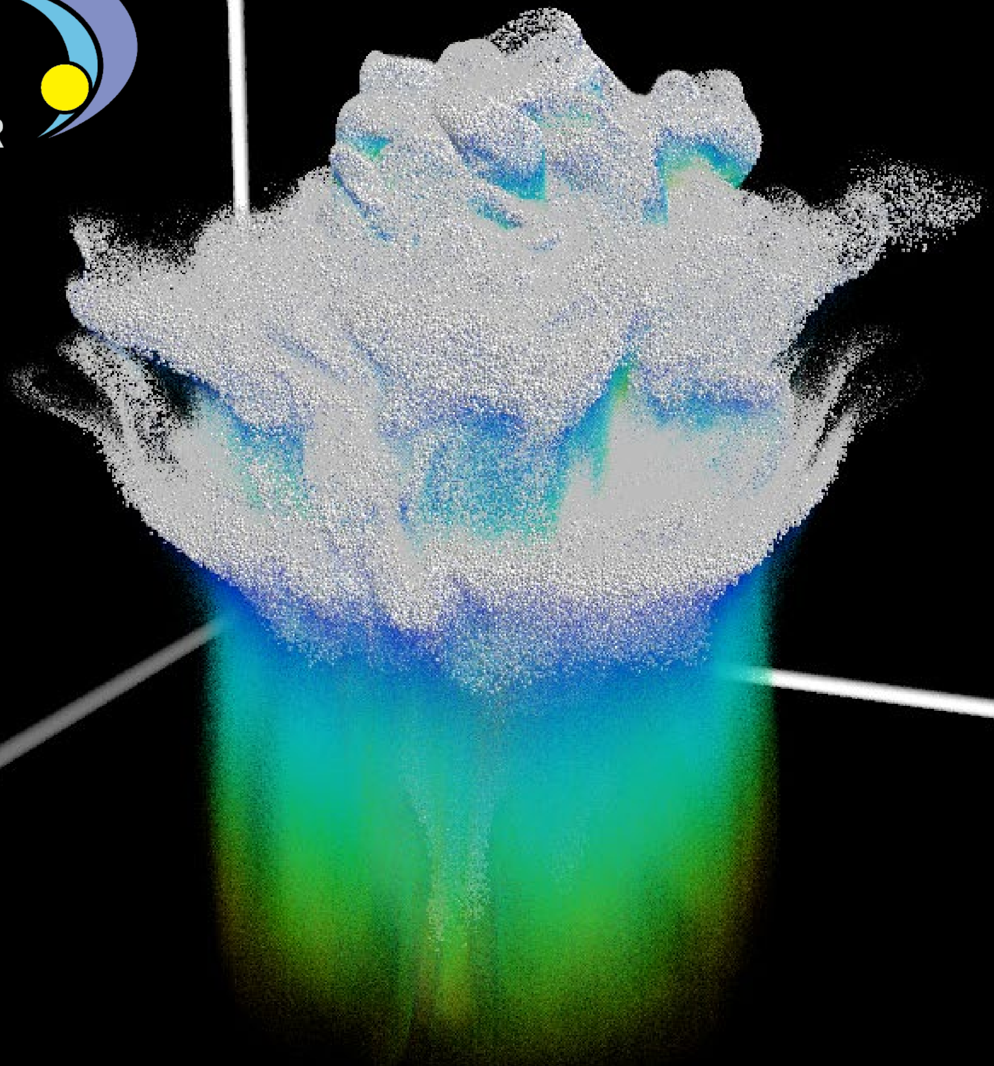

Innovative Atmospheric Model

Overview

In **2005**, when I joined Prof. Kusano's group at the Earth Simulator Center, JAMSTEC, the development of the **super-droplet method (SDM)** (SS+'09,'20) began.

Recently, **Lagrangian particle-based cloud modeling** has been gaining popularity.

The SDM has become synonymous with it.

Progress and prospects, including the activities of our group will be presented.

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1. What is Happening in Clouds?

In warm clouds

Cloud Dynamics

dry air, vapor, trace gas.

interaction

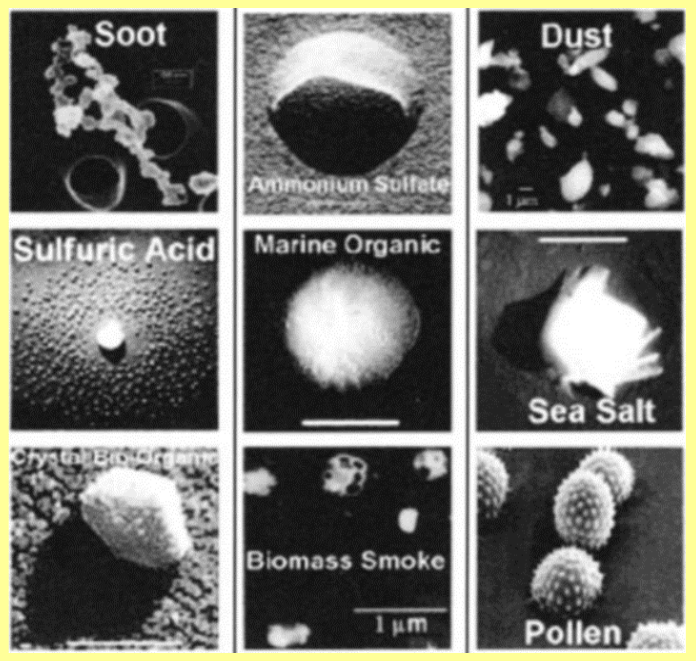
Cloud Microphysics

particles (aerosol/cloud/precipitation)

nucleation from gases
or rolling up of dusts

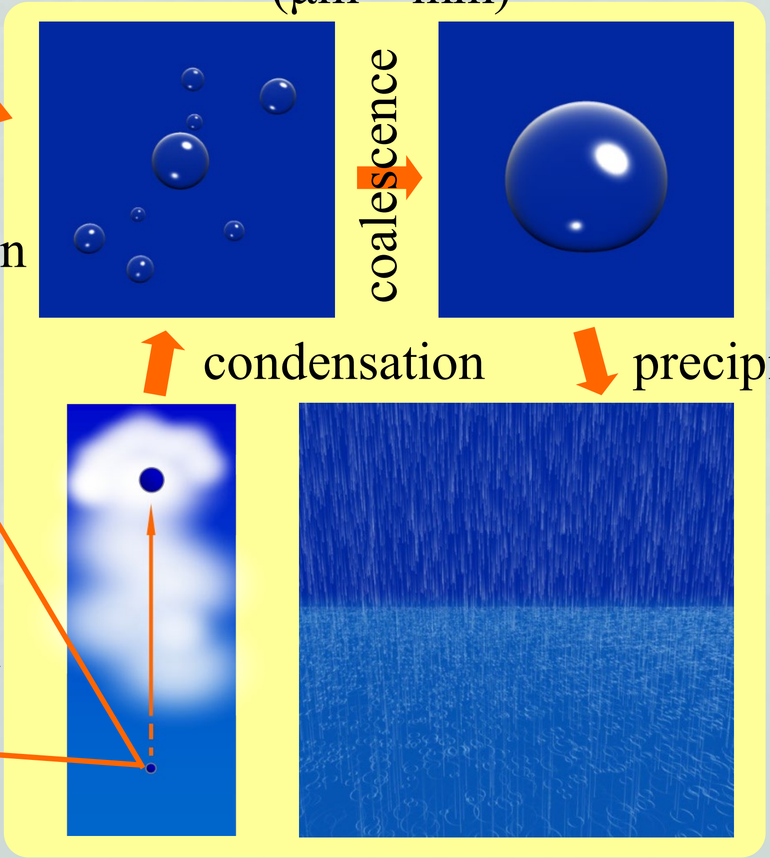
chemical
reactions

(μm〜mm)



evaporation

cloud-aerosol interaction



precipitation

Aerosol particles

Mixed-phase clouds are more complicated

Various ice nucleation pathways

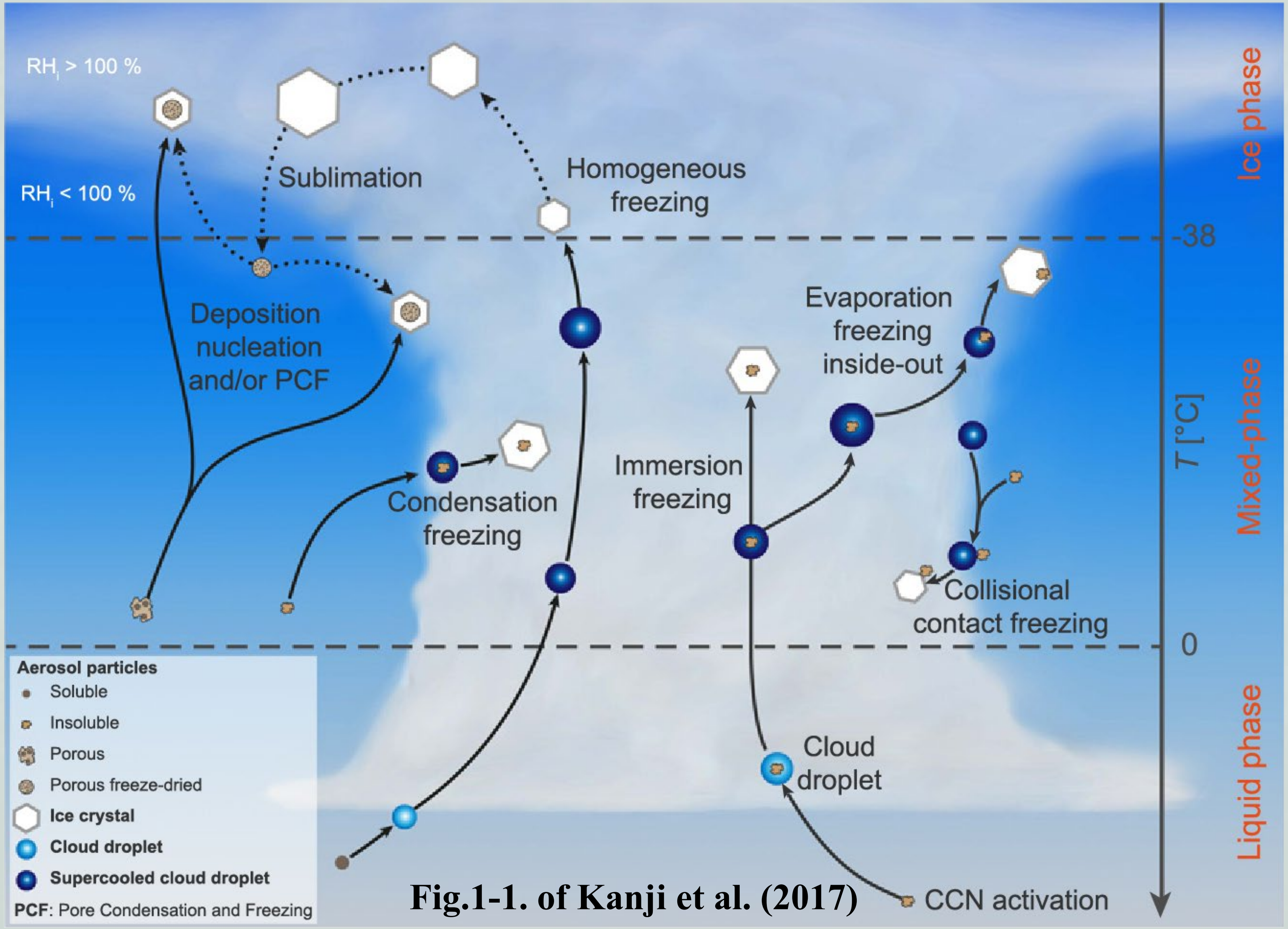


Fig.1-1. of Kanji et al. (2017)

… Mixed-phase clouds are more complicated

Various other processes

- Freezing
- Melting
- Deposition/sublimation
- Riming (ice-droplet)
- Aggregation (ice-ice)
- Breakup
- etc.

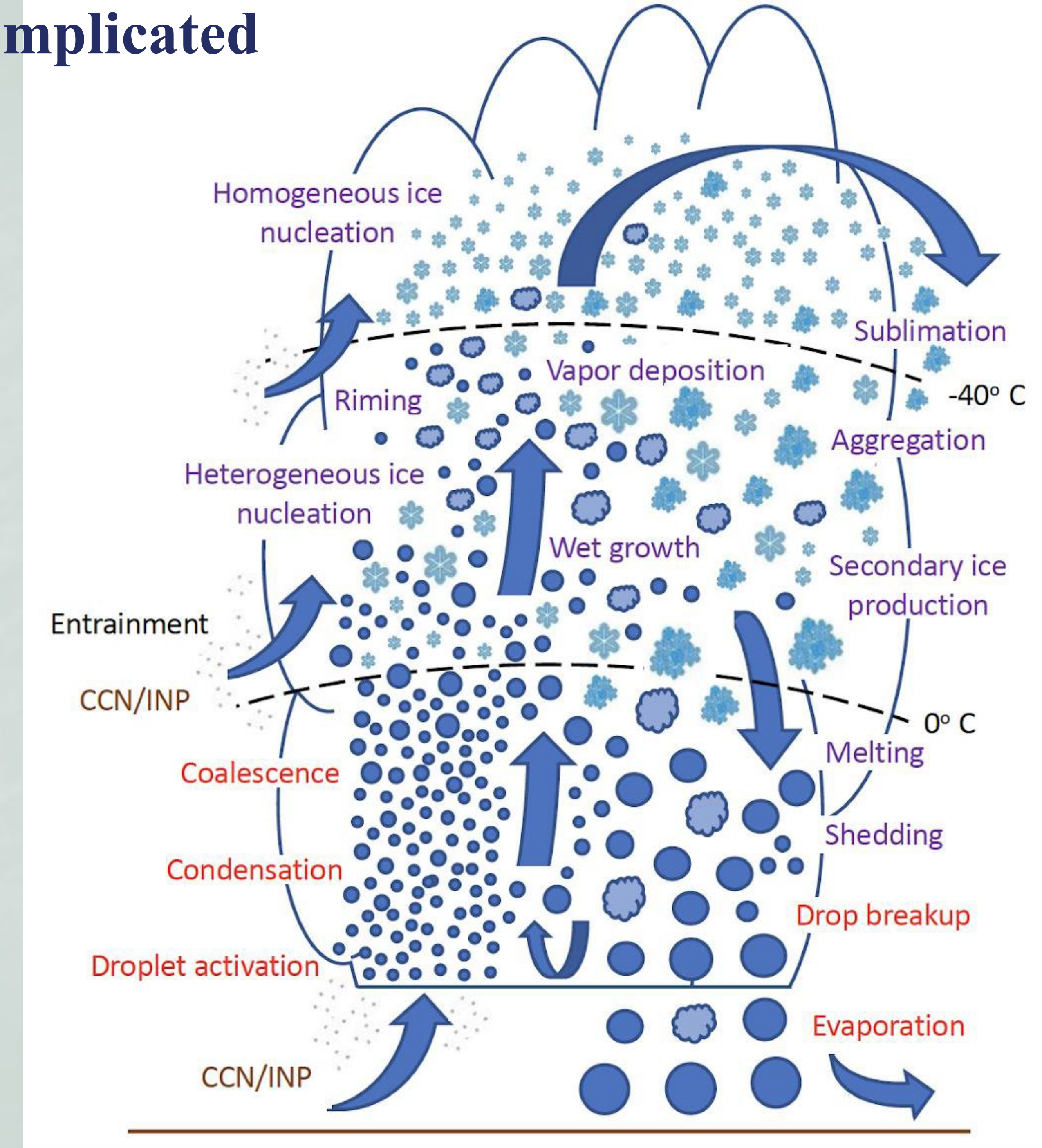
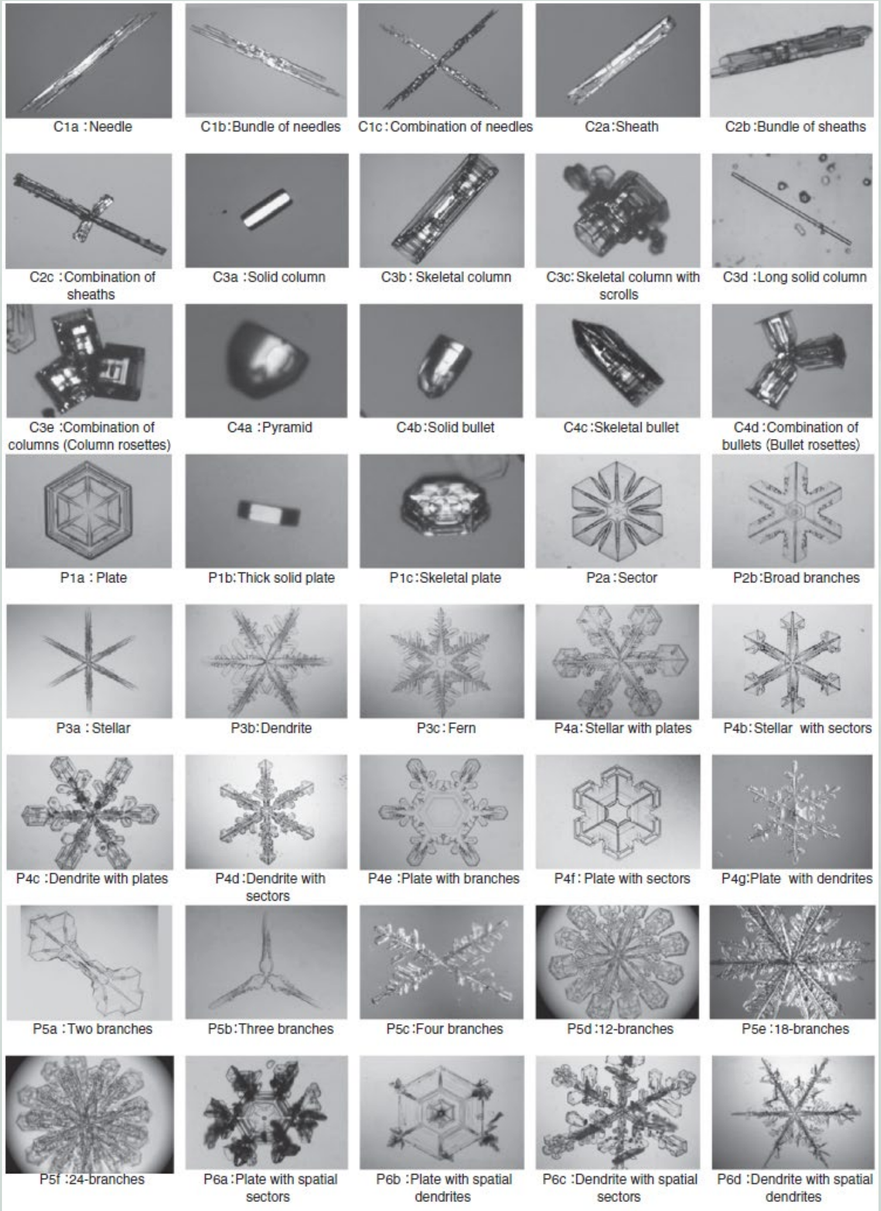


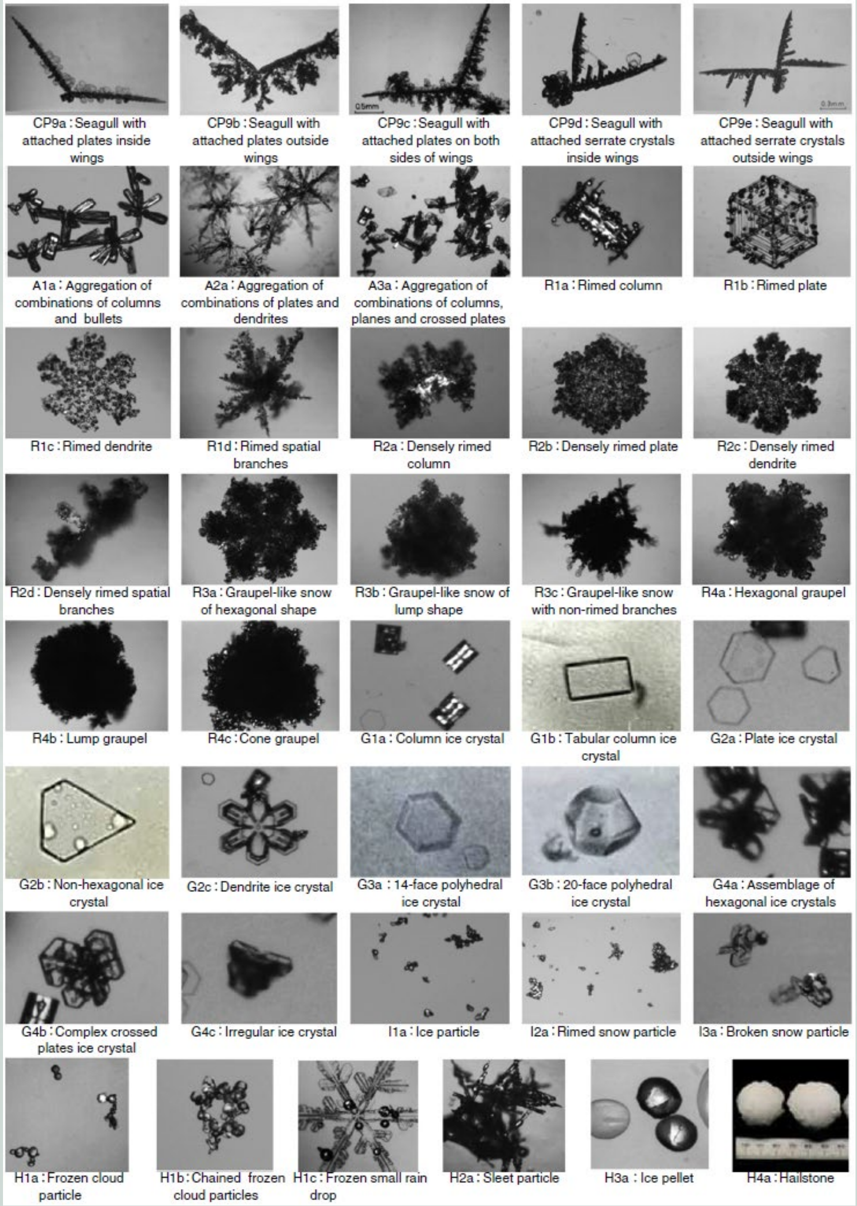
Fig. 1 of Morrison et al. (2020)

… Mixed-phase clouds are more complicated

Diverse morphology of ice particles

Fig. 1 of Kikuchi et al. (2013)





2. Lagrangian Particle-Based Cloud Modeling

It is an alternative to Eulerian bulk or bin method approach

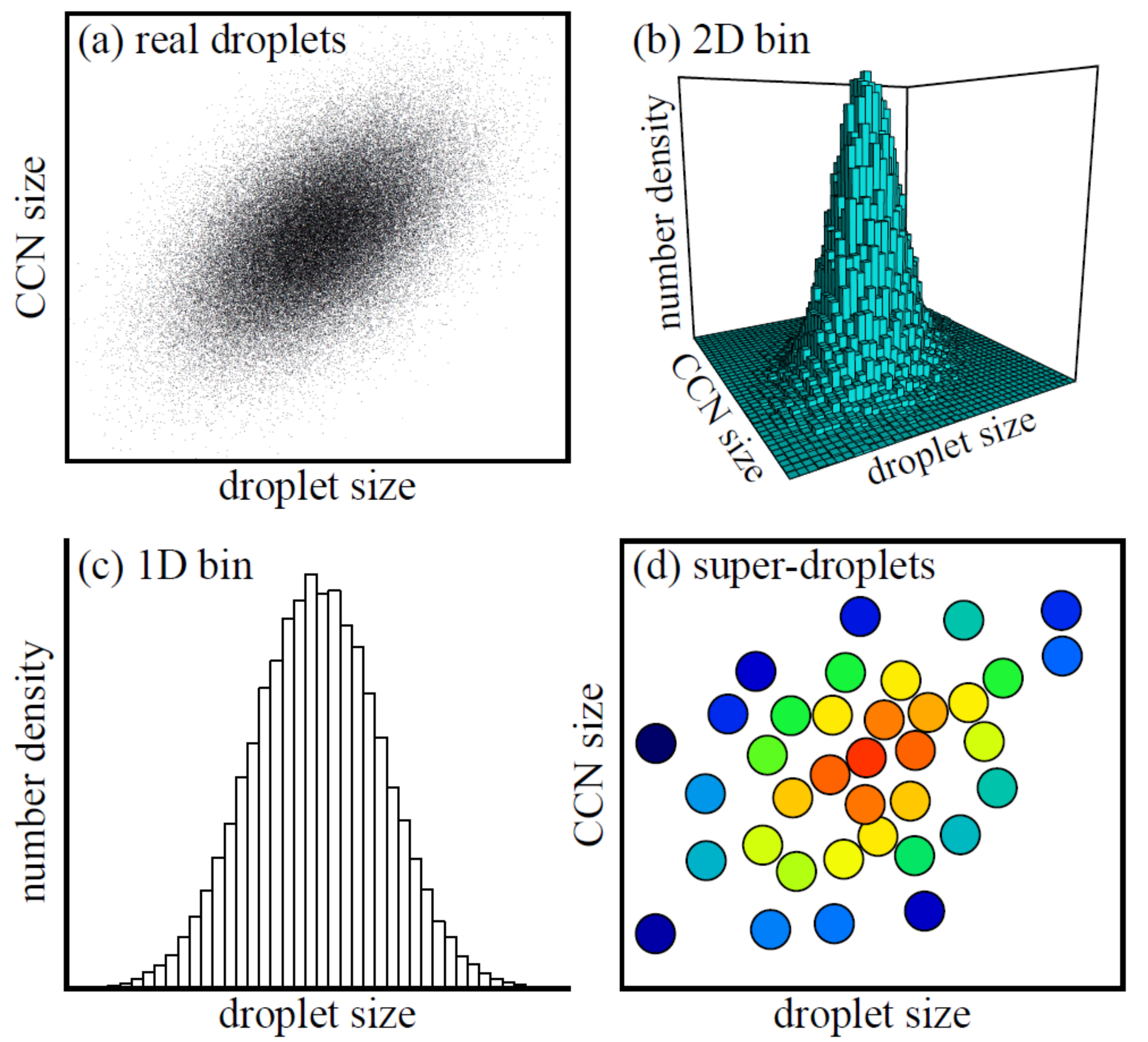
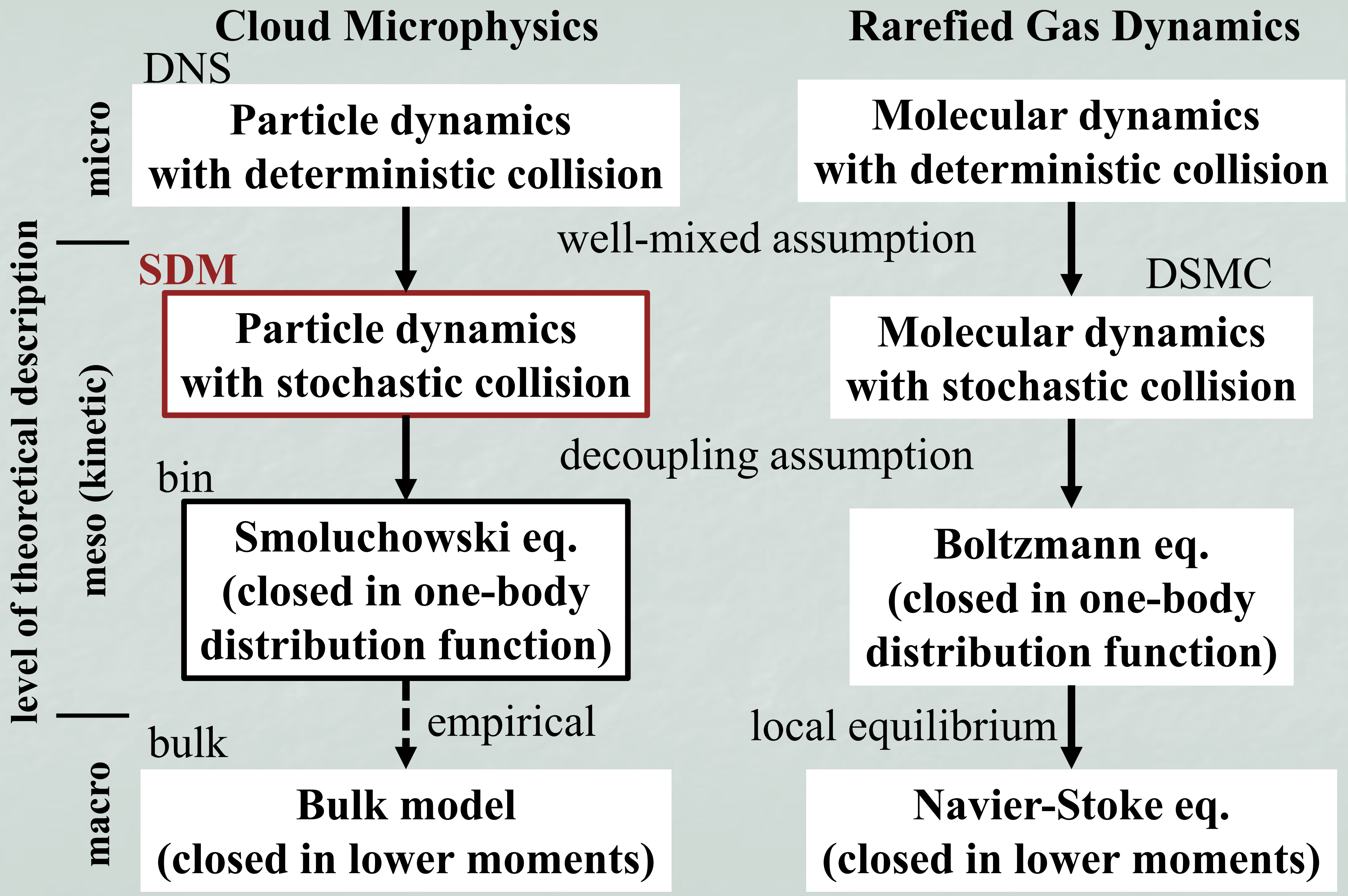


Fig.4 of Grabowski+'19 (created by SS)

- **It enables cloud microphysics simulation from the process level**
- Aerosol/cloud/precipitation particles are represented by super-droplets or super-particles
- See, e.g., SS+('09,'20) for more details.
- **Particle-based schemes have various advantages over bin and bulk (Grabowski+'19)**

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

Hierarchy of description in cloud microphysics



3. Progress and Prospects of Lagrangian Particle-Based Cloud Modeling

S. Shima, W.W. Grabowski, S. Arabas, K.K. Chandrakar, P. Dziekan,
@u-hyogo.ac.jp @ucar.edu @agh.edu.pl @ucar.edu @fuw.edu.pl

F. Hoffmann, E. de Jong, H. Morrison, A. Seifert, S. Unterstrasser
@uni-muenchen.de @caltech.edu @ucar.edu @dwd.de @dlr.de

(This part is based on our presentation at ICCP 2024 and AGU24)

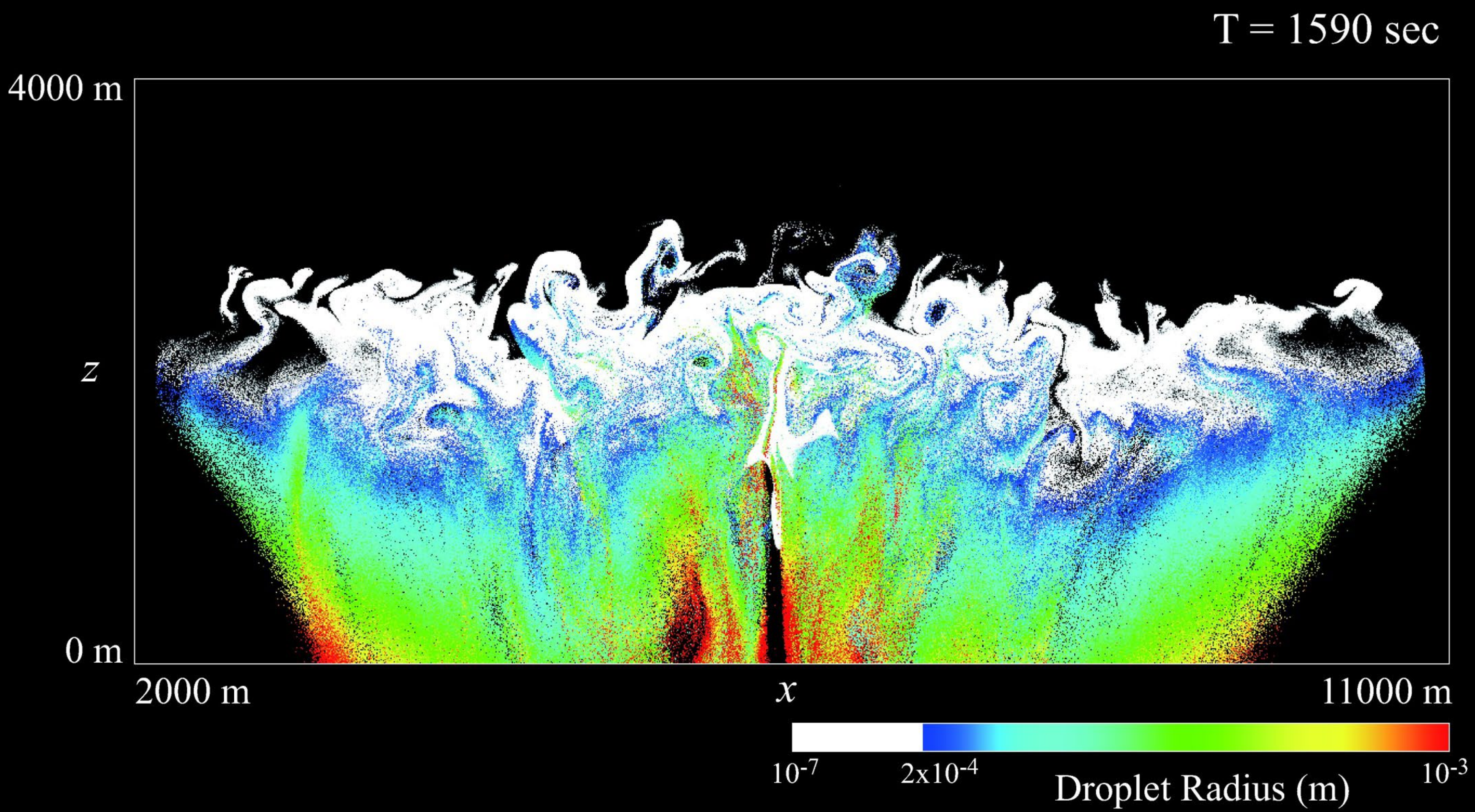
Particle-based models are being used for various problems

- 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: SS+'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)

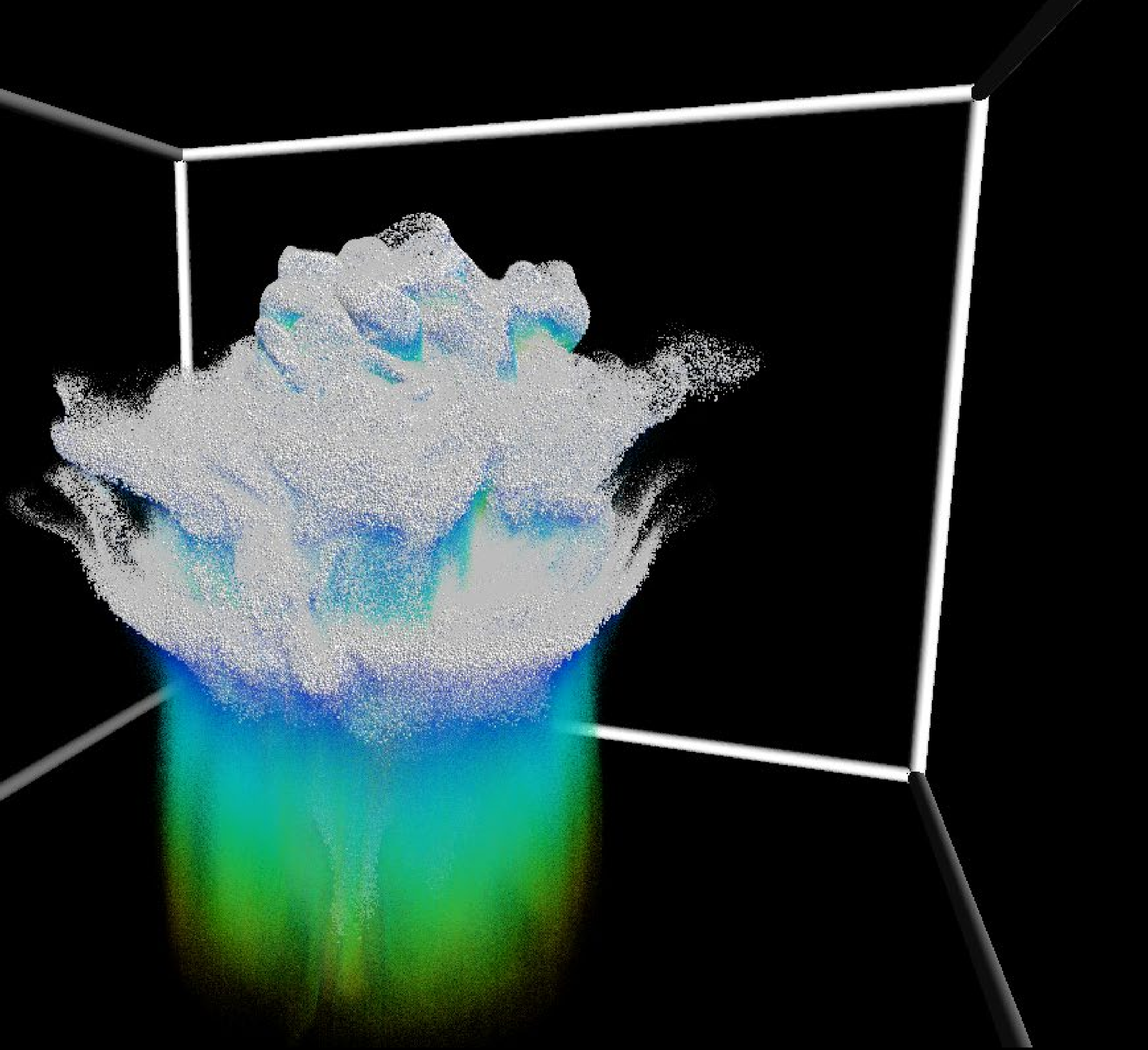
3.1. Application to Warm Cumulus Congestus

Shallow Cu simulation with SDM (2006)

2D, Δz=



Shallow Cu simulation with SDM (2006)



EARTH SIMULATOR

3D, Δz= 8 m,

grid: 624x1024x1024,

particles: #10^10,

ES 256 nodes

Non-precipitating cumulus congestus

Matsushima+'21 conducted a more **realistic simulation of a cumulus congestus** based on SCMS campaign using the K computer

Precipitating cumulus congestus

Chandrakar+'24 conducted a similar simulation based on CAMP^{2}Ex using CM1-SDM

With turbulence coalescence considered, the droplet size distributions agree well with observations

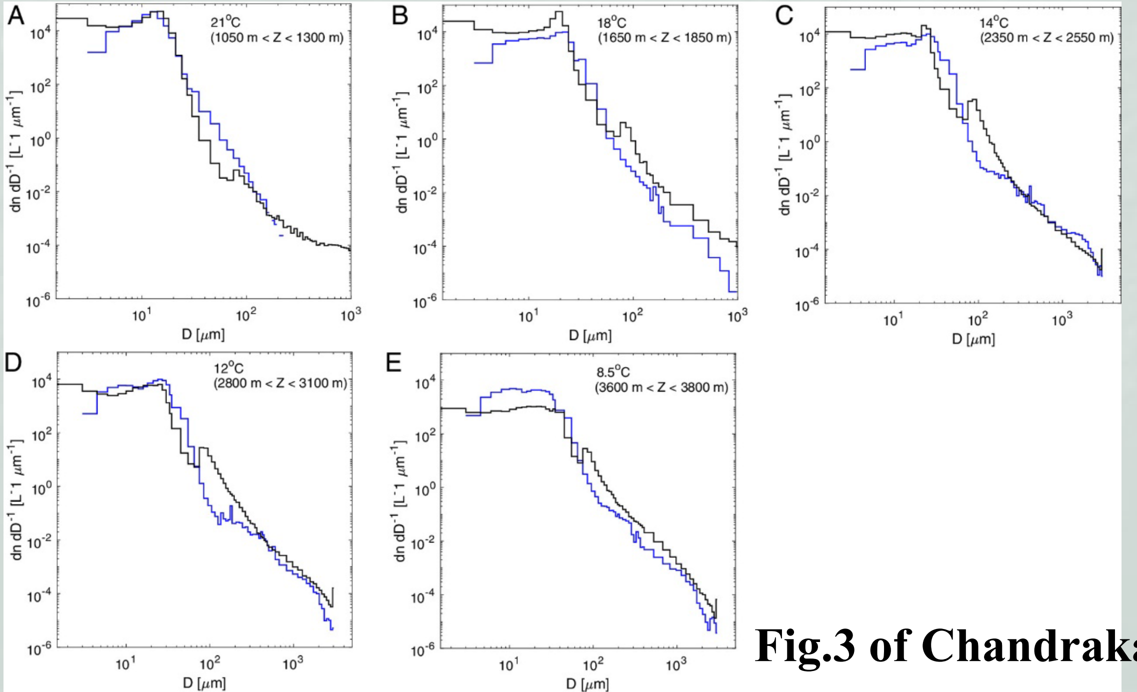


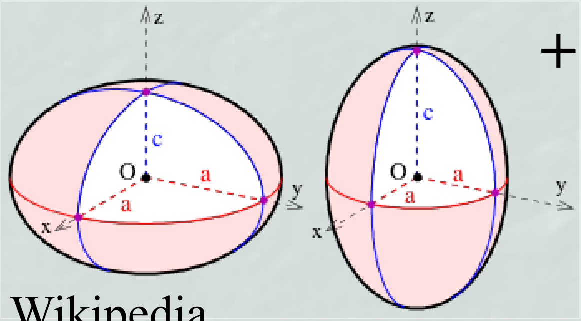
Fig.3 of Chandrakar+'24

3.2. Application to Mixed-Phase Clouds and Habit Prediction

Approach of SS+'20

Porous spheroid approximation

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



Wikipedia

+ apparent density ρ

+ rime mass, number of monomers

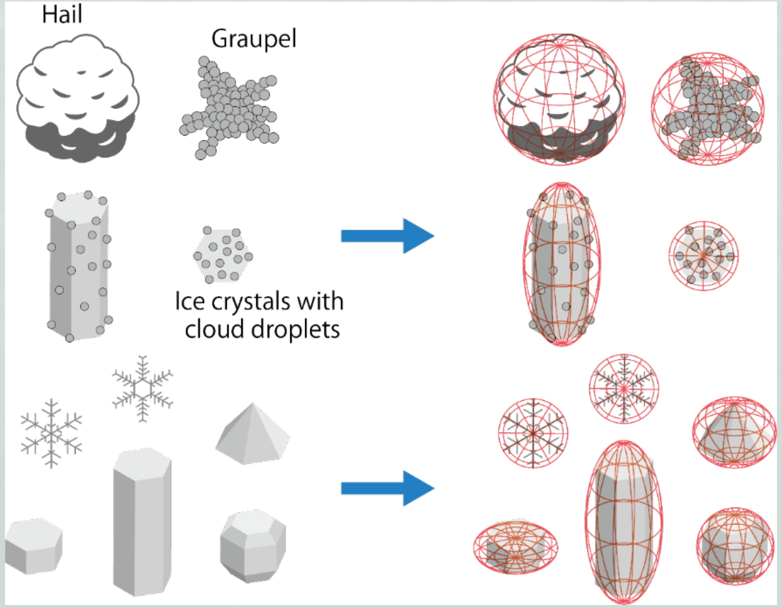
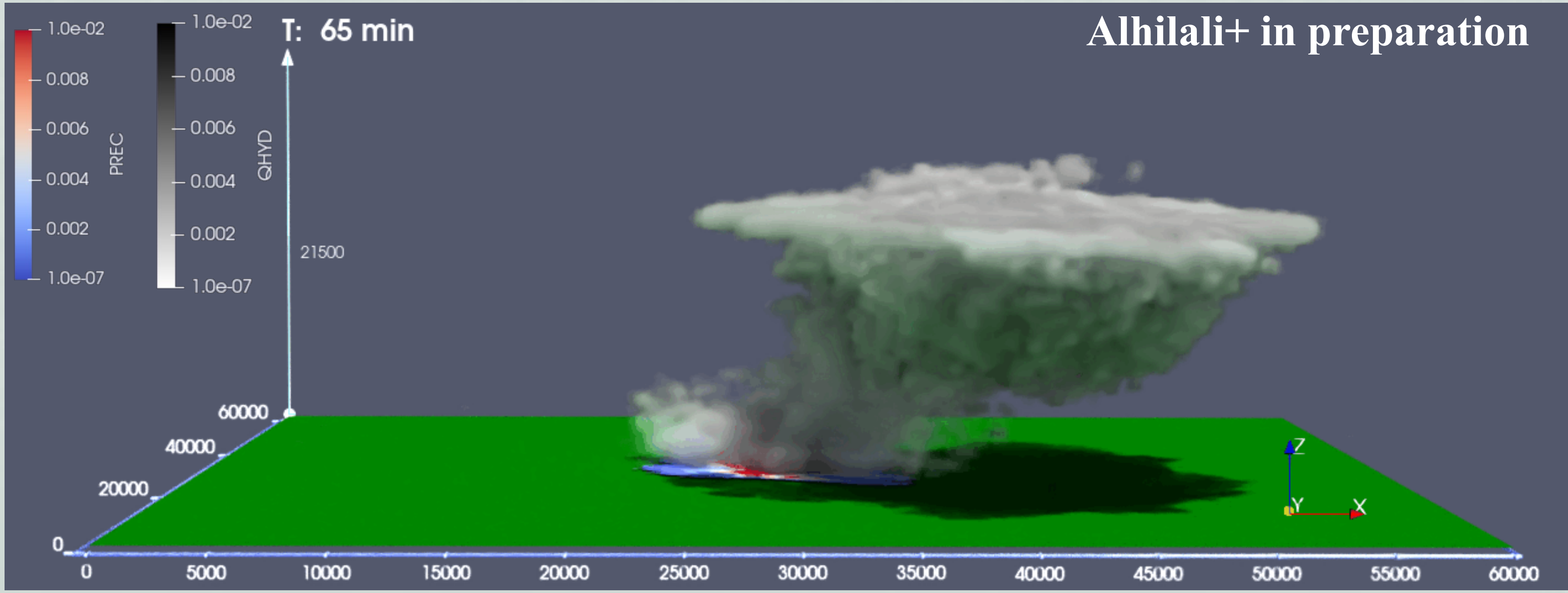


Fig.2 in https://moonshot8-modeldev.riken.jp/eng/theme/2-1_shima.html

Ice nuclei are 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**

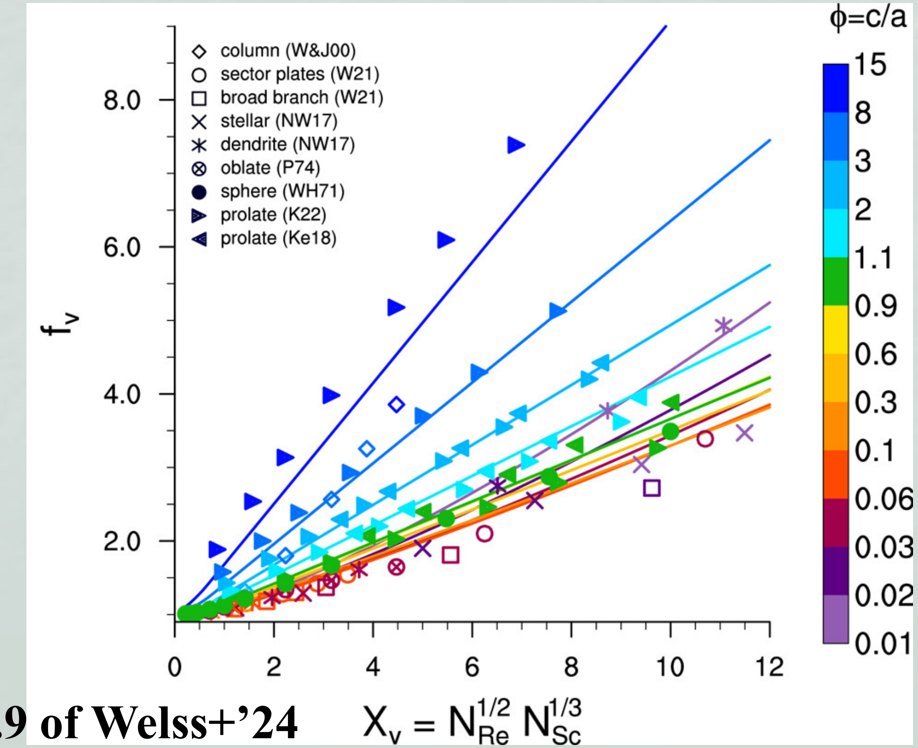
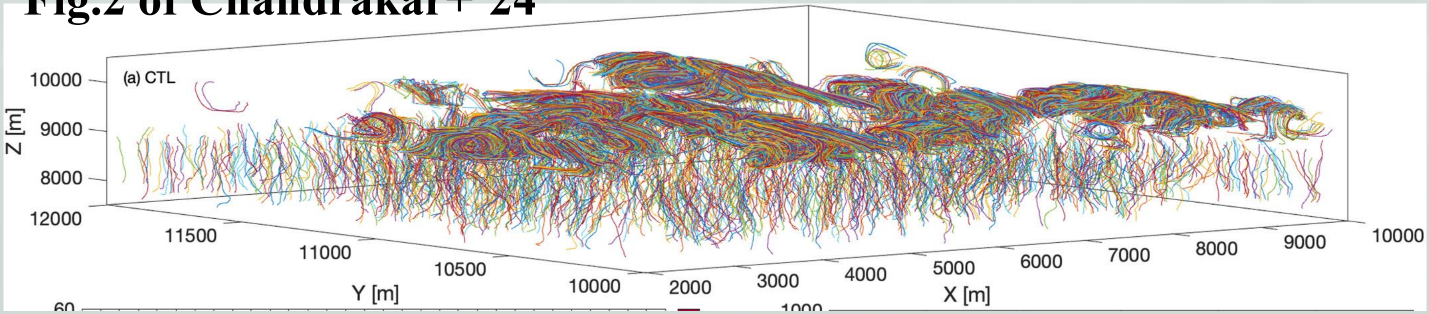


Fig.9 of Welss+’24 $X_v = N_{Re}^{1/2} N_{Sc}^{1/3}$

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



3.3. Model Developments

Collisional breakup of droplets

SD number remains unchanged through coalescence (SS+'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.

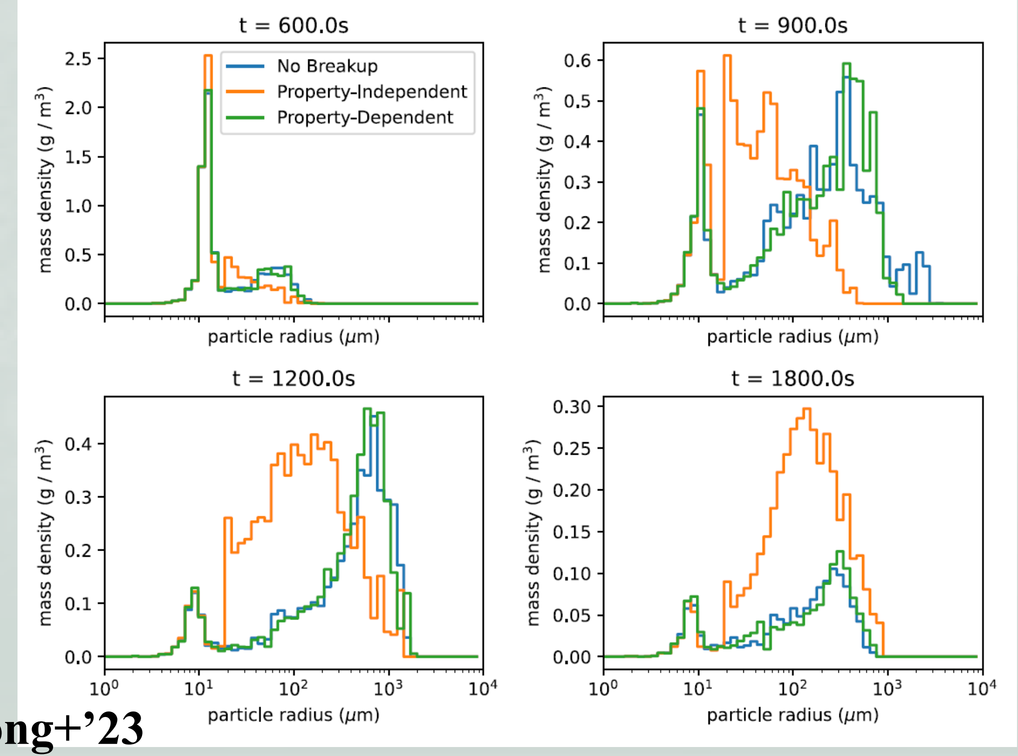


Fig. 11 of de Jong+'23

Performance optimization

Matsushima+'23 achieved **61.3 times speed-up** by improving the algorithm and optimizing the code for Fugaku. (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?

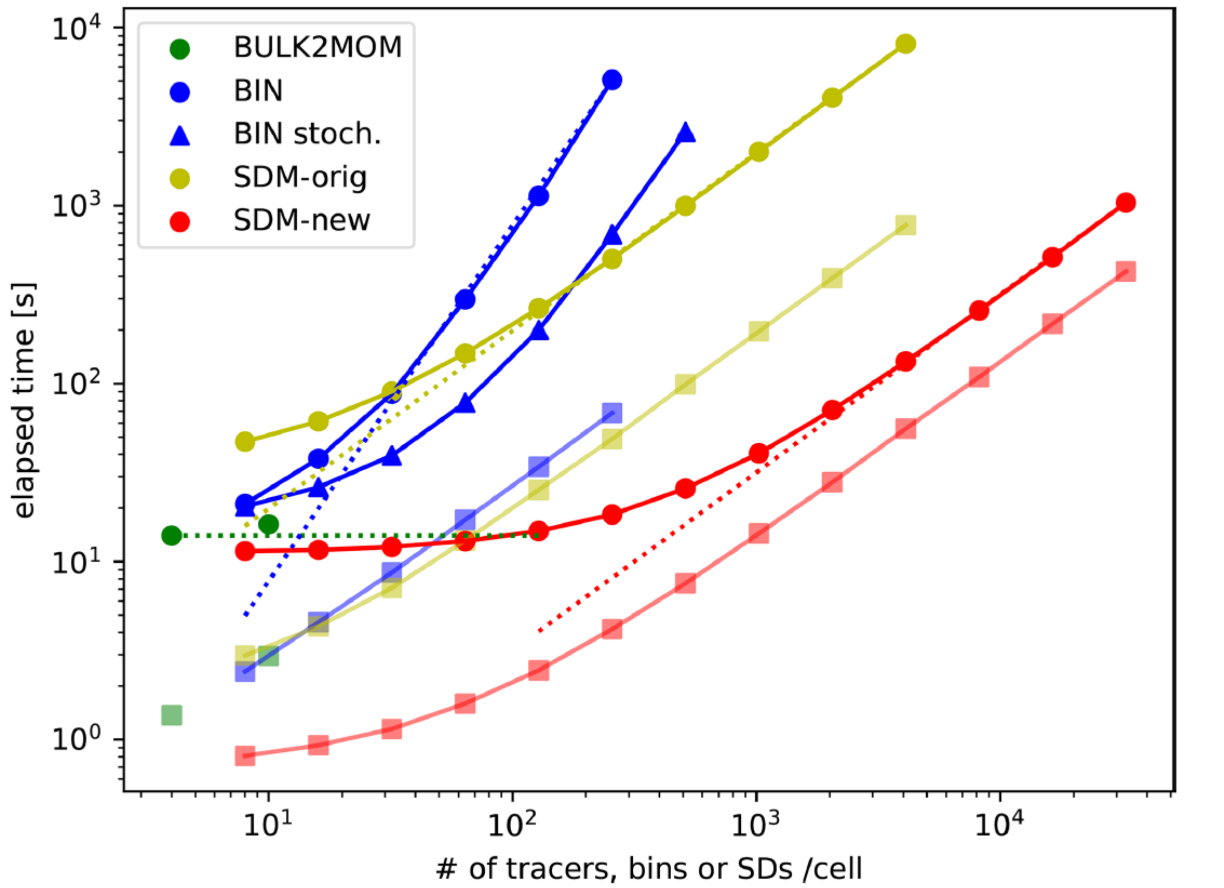


Fig. 4 of Matsushima+'23

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

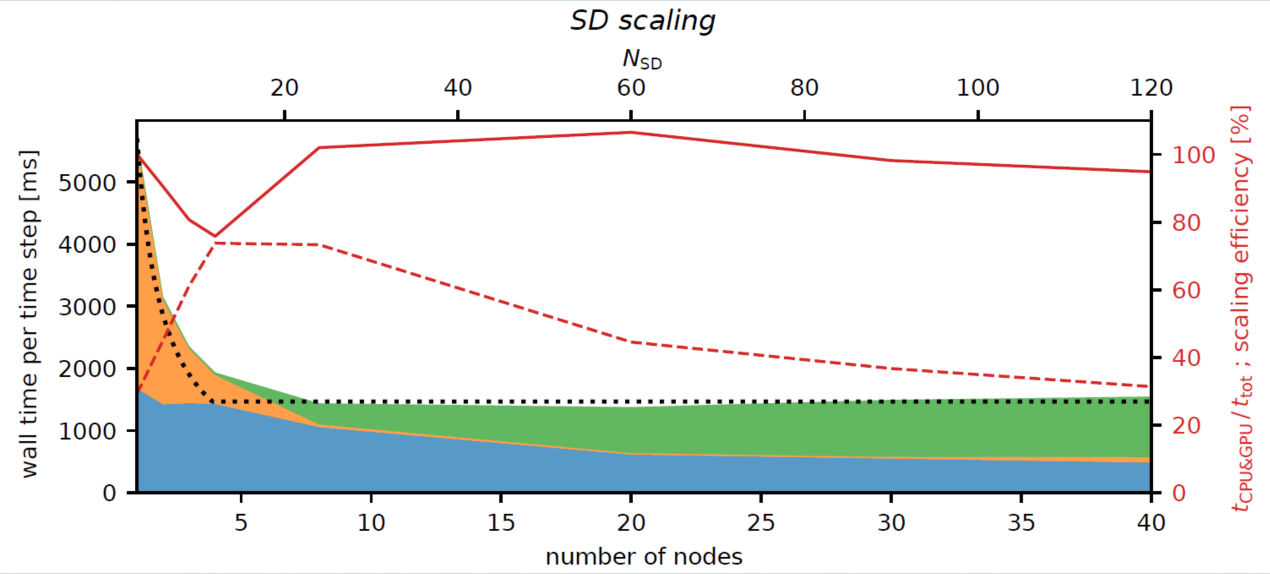


Fig.5 of Dziekan&Zmijewski'22

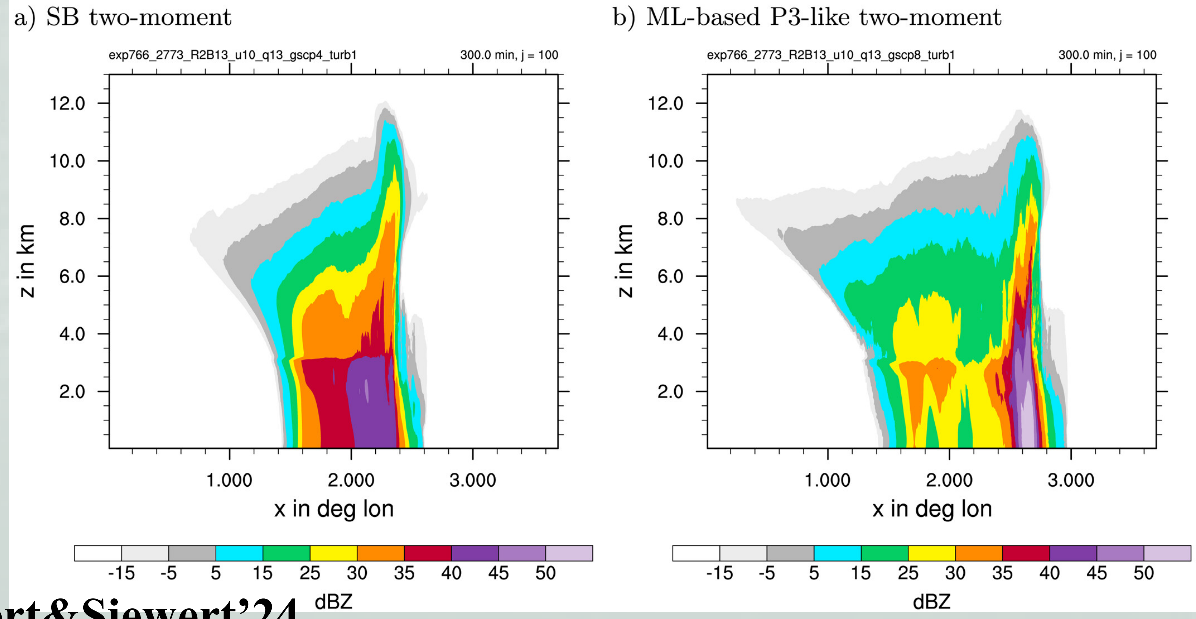


Fig.4 of Seifert&Siewert'24

3.4. 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

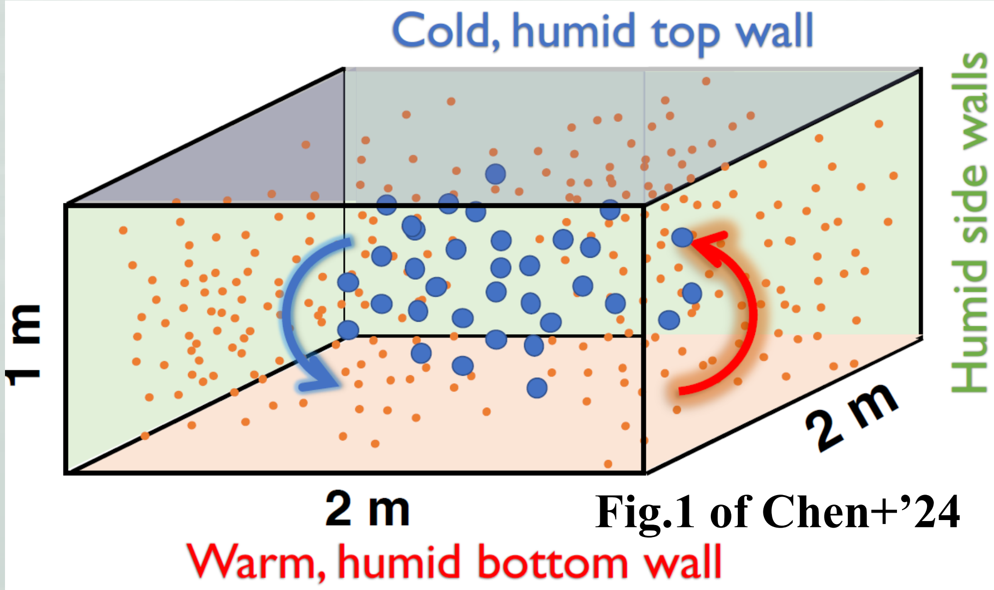


Fig.1 of Chen+'24

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 SS+'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)

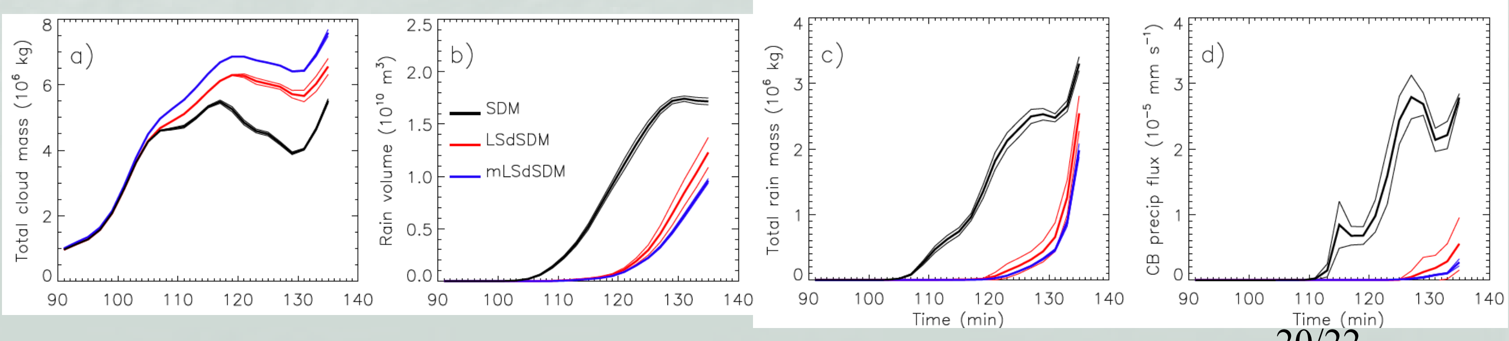


Fig.10 of Morrison+'24

4. General Perspectives

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

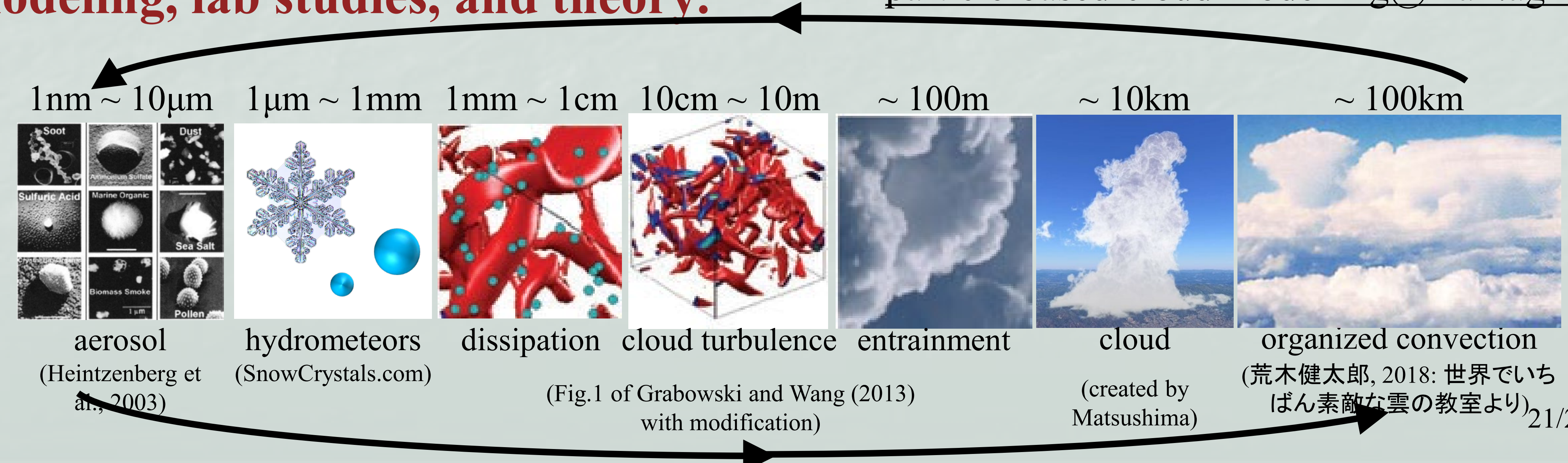
UWLCM: https://github.com/igfuw/UWLCM

GMD/ACP special issue

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

Mailing list

particle-based-cloud-modelling@mail.agh.edu.pl



5. Our Group's Next Plan

Our targets in the next 5 years

- **Real atmosphere simulations** (up to 1000 km scale, such as tropical cyclones?)
  - Past event simulations
  - Run SDM faster than real (or acceleration by AI?)
  - Numerical weather prediction? (simulation of the future)
- **Aerosol-cloud interaction and weather modification/control**

Related projects

- KAKENHI KibanA " From Particles to Precipitation: Toward a Deeper Understanding of Cloud Systems with the Super-Droplet Method "
- Moonshot Program 8 "Realization of a society safe from the threat of extreme winds and rains by controlling and modifying the weather by 2050" (PD: T. Miyoshi, R-CCS)
  - **Postdoc position open!**
- UAE Research Program for Rain Enhancement Science (UAEREP)
  - **Another postdoc position opening soon!**
- HANAMI project (for EU-Japan partnership in HPC)