Lagrangian Particle-Based Microphysics In Cloud Simulation: Progress & Prospects

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Background

LPBM – Lagrangian Particle-Based Microphysics models track the evolution (snigle- and many-particle physiochemical processes) and transport of notional particles, and are an alternative to Eulerian bulk or bin methods

Model developments

drop breakup

Collisional breakup poses a challenge to **LPBM** in terms of comp. scaling, as the fragments produced in collisions may have many different sizes. In [4], a Monte-Carlo scheme is proposed that avoids creating new superdroplets, respecting the physical probability of coalescence/breakup and the fragment size distribution.

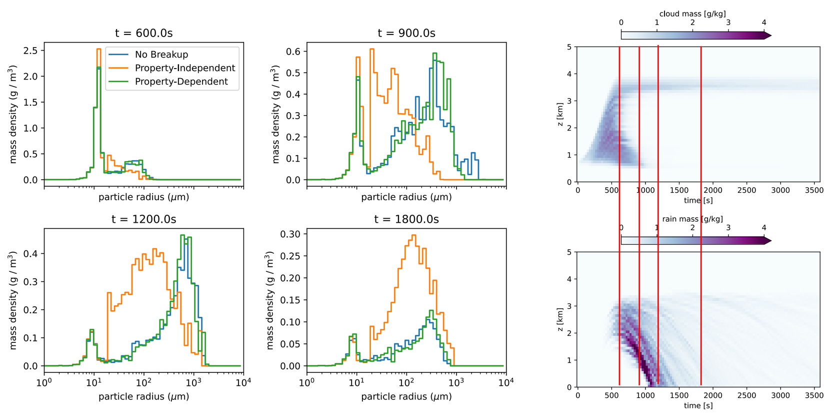

Fig. 1: Sample comparison of drop spectra with and without breakup in a single-column (KiD/**PySDM**) kinematic framework

habit prediction/ventilation

Being able to track the history of individual representative particles, **LPBMs** are well suited to tackle ice habits. Taking into account a habit dependent ventilation improves the physics of cirrus clouds [17].

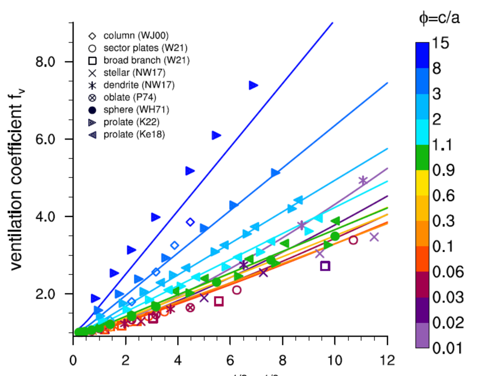

Fig. 2: Data evidence that columns experience stronger ventilation than spheres or plates. Solid lines: parameterization for **LPBM** that include habit prediction

performance optimizations

Optimizations discussed in [11] led to an **LPBM** module for **SCALE-SDM** with computational cost comparable to a 2-mom. bulk method (see Fig. 3). A 2m grid-length shallow cloud LES in a ~10 km^2 domain is used for performance evaluation; depicts path to turbulence and microphysics studies over wide range of scales.

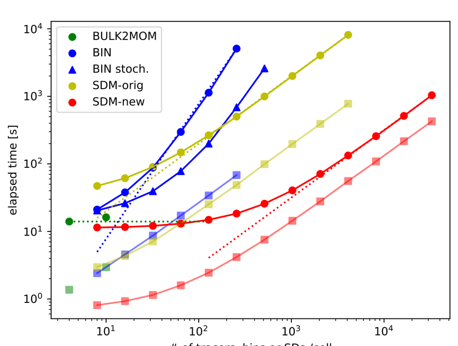

Fig. 3: Total simulation time (circles, triangles) and tracer advection and SD tracking time (squares) for bulk, bin, pre- (SDM-orig) and post-optimization (SDM-new)

CPU + GPU + MPI

In [7], the performance of hybrid MPI+threading+GPU mode of operation of **UWLCM** is explored, see Fig. 8. On 40 nodes, wall time of CPU+GPU **LPBM** is twice that of CPU-only bulk.

Validation

CM1-SDM/balloon-borne obs

Laboratory experiments of particle growth (tied to crystal morphology via vapor deposition density) are combined with **LES+LPBM** simulations to examine sources of microphysical variability in cirrus. Cirrus case from ARM Ice Cryo-Encapsulation by Balloon (ICE-Ball) campaign. Variability is dominated by particles' thermodynamic histories (see Fig. 4), however, diversity in crystal morphology notably increases spatial variability of mean particle size and density.

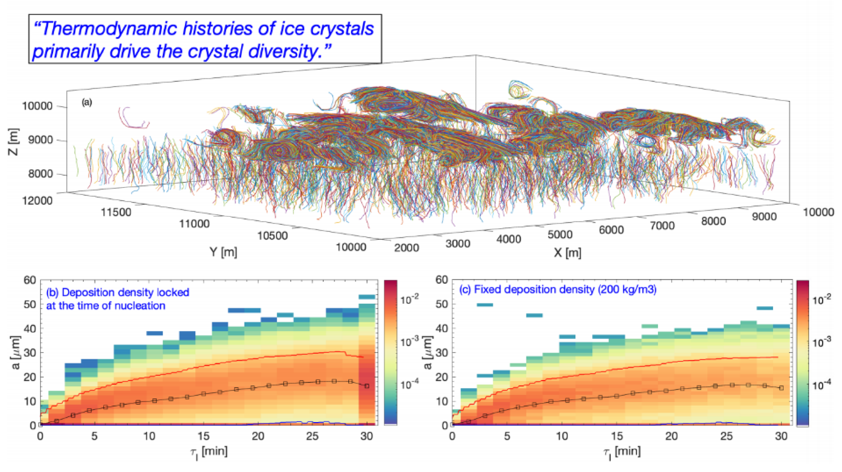

Fig. 4:(a) Selected ice particle trajectories sampled at 15 s intervals (trajectory length > 900 m). Evolution of the ice particle size distributions (b-c) with particle age after nucleation (τ_l). Color bars: probability; squares: mean values; black lines: running mean; red lines: 90th percentile; and blue lines: 10th percentile. See [2]

Π chamber

A model intercomparison study is underway within the framework of the ICCP International Cloud Modeling Workshop, including comparison of **LPBM** simulations with holographic particle size spectrometry inside the MTU **Π** chamber.

Monte-Carlo vs. deterministic collisions

In [12], three methods for drop coalescence in **LPBM** are compared: deterministic average impact method (AIM), Monte-Carlo (SDM), deterministic SDM (dSDM). Results highlight the critical role of statistical fluctuations ("lucky drops") in driving rain formation in warm clouds.

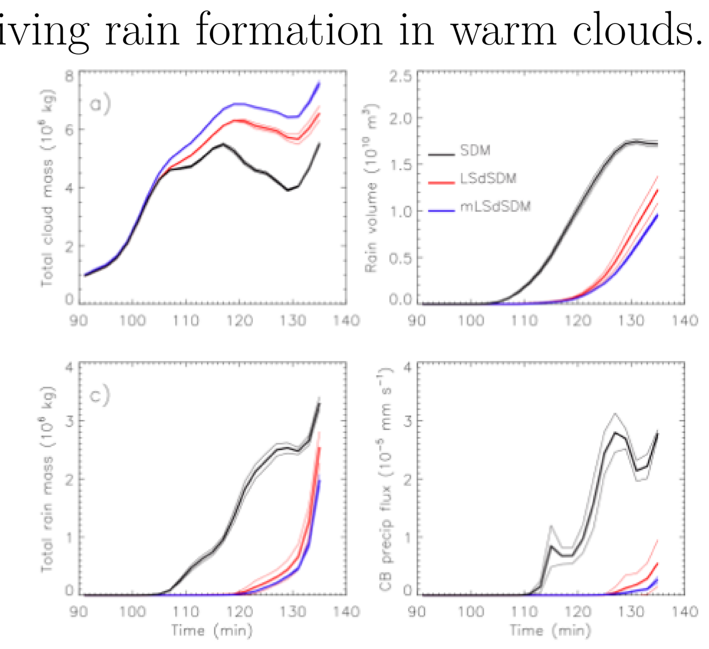

Fig. 5:Warm rain in LES of a Cu con cloud is substantially delayed using dSDM (red and blue lines, thick lines are mean and thin lines are $\pm\sigma$) versus SDM (black lines)

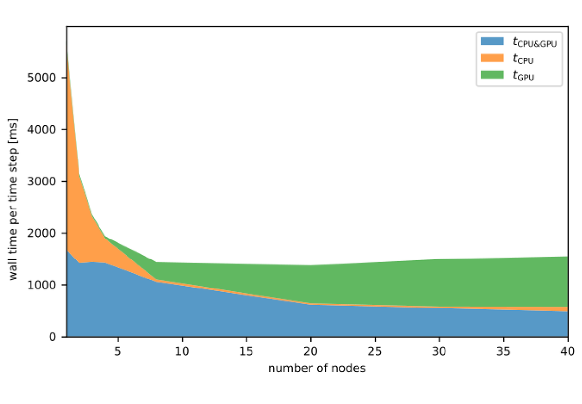

Fig. 8: Scaling of the time to complete a time step of **LPBM** LES on a CPU+GPU cluster

Applications

cirrus & contrail studies

In [16], **LES** of natural and contrail cirri were carried out. Scenarios where contrails were surrounded by later forming natural cirrus were investigated. An important question was to understand whether contrails (as an anthropogenic cloud) would remain distinguishable from natural cirrus when sampled in in-situ measurement campaigns. The analyses benefited from the use of **LPBM** (no numerical diffusion in space, freely evolving ice crystal size distributions, inexpensive tagging of origin).

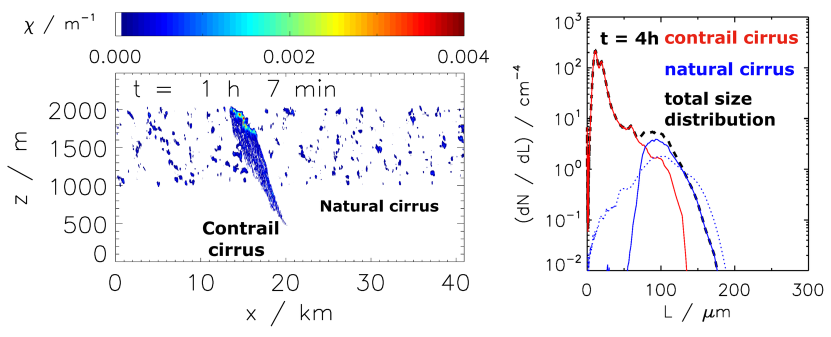

Fig. 6: L: snapshot of a contrail becoming surrounded by natural cirrus (extinction coefficient plotted); R: ice crystal size distribution of such a dual-origin ice cloud

marine cloud brightening

LPBM have been used to support assessment of marine cloud brightening as a viable climate engineering approach (through increasing the reflectance of clouds by artificially increasing the aerosol and hence droplet concentration). **LES+LPBM** setup allows simulating: the sprayers that disperse seawater droplets, evaporation of droplets to sea salt aerosols that are lifted to the cloud layer, where they activate; [9] addressed the optimal size distribution of sprayed particles; [10] their transport to the clouds (Fig. 7).

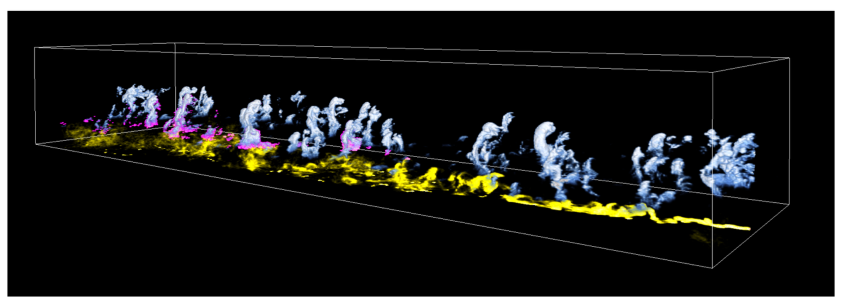

Fig. 7: Sprayed particle plume (yellow) is lifted to the clouds (white), where some of the sprayed aerosols activate (magenta).

marine stratocumulus

Recent **LES+LPBM** marine Sc studies: [6] assessed the impact of LES vs. iLES, whereas [8] applied Linear Eddy Model for subgrid RH; [5] found giant CCNs significantly increase precipitation; [3] studied the transition to open-cell; [18] investigated the grid convergence and a comparison with 2-moment.

machine learning

Particle-based models are used for simulations to provide training data for machine learning models: [13, 14, 15, 1]

Open Source LPBM Software

- **McSnow**: aims at understanding precipitation formation via mixed-phase processes `https://gitlab.dkrz.de/mcsnow/mcsnow`
- **PySDM**: tutorial notebooks based on 30+ papers `https://github.com/open-atmos/PySDM`
- **SCALE-SDM**: mixed-phase LES+SDM `https://github.com/Shima-Lab`
- **UWLCM**: hybrid MPI+CPU+GPU LES `https://github.com/igfuw/UWLCM`

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