Modeling of cloud microphysics: Can we do better?

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Introduction

Representation of cloud microphysics is the key ingredient of cloud simulation. From early days of cloud dynamics modeling, numerical models have relied on Eulerian "continuous medium" approach for all cloud thermodynamic variables, not only for the temperature and water vapor, but also for cloud condensate and precipitation applying density-like variables. As time passed, the sophistication of microphysics representation has been steadily increasing, from initial simple single-moment warm-rain bulk schemes, through double- and triple-moment warm rain and ice bulk schemes, to complex bin (spectral) schemes that predict evolution of cloud and precipitation size distributions. With increasing computational power, bin microphysics has become commonplace in nonhydrostatic cloud-scale modeling.

Is bin microphysics the ultimate approach in cloud modeling?

We do not think so.

FIRST, for warm-rain processes, bin microphysics cannot represent CCN processing unless multidimensional approach is used. The multidimensional bin microphysics is extremely expensive.

SECOND, for ice processes, bin representation of evolving ice particle properties (shape, density, fallspeed) during depositional, aggregation, and riming growth is a major challenge (as in all schemes). Most bin schemes represent the transition of particles from one type to another using different categories of ice hydrometeors such as pristine ice (or "cloud ice"), snow, graupel, and hail.

FIG. 1. Line-averaged vertical cross sections in (a) and horizontal cross sections at 2 km in (b) for (upper panels) observed NEXRAD radar reflectivity and derived from the model-predicted hydrometeor species for the simulations applying three different bin microphysics schemes. Reproduced with changes from Xue et al. (2017).

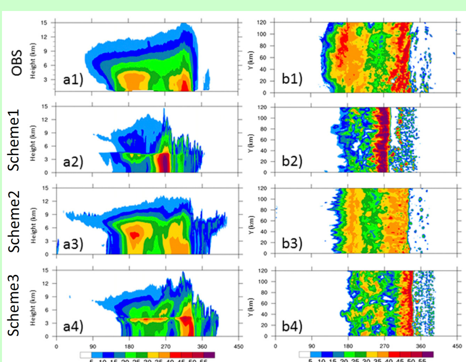
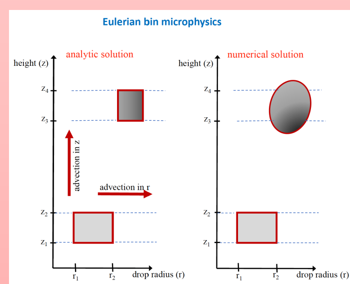


Figure 1 (see Xue et al. 2017 for more details) compares observations and results of simulations of a squall line event from the MC3E field project. The simulations applied three different state-of-the-art mixed-phase bin microphysics schemes coupled to WRF model. The figure shows fields of observed and model-predicted radar reflectivity fields (the details are given in Xue et al. 2017). All three schemes produce a squall line with features resembling the observed storm characteristics. However, there are significant differences in many aspects of the simulated convective systems. So which scheme should be taken as the ultimate one?

THIRD, there are significant challenges with the numerical integration of the bin microphysics equations when the representation of particles growth is combined with the transport in Eulerian physical space. Morrison et al. (2018) explored the impact of numerical diffusion for the case of the vertical advection of a droplet population and their growth by the diffusion of water vapor. They show that the combination of the advection in the physical space and advection in the radius space leads to unphysical effects when compared to benchmark analytic solutions. This is illustrated in Fig. 2.

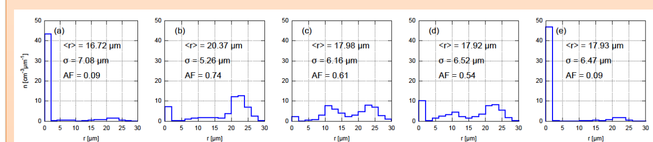
Fig. 2. Illustration of (left) analytical and (right) numerical solution of the growth of cloud droplets in a volume advected in the vertical. The initial one-dimensional (horizontally-uniform) cloud is located between levels z_1 and z_2. The initial spectrum of cloud droplets consists of droplets with the uniform nonzero number density function between radii r_1 and r_2. The cloud is advected upwards and cloud droplets grow due to adiabatic cooling of the cloud volume.



FOURTH, bin microphysics represents collisional growth of ice crystals and water drops by solving the Smoluchowski equation. The Smoluchowski equation is a mean field equation that cannot represent the truly probabilistic nature of particle collisions, see Dziekan and Pawlowska (2018) and references therein.

Can we do better?

The problems with the Eulerian bin microphysics can be addressed by employing a Lagrangian particle-based approach (e.g., Shima et al. 2009). The main idea is to use a judiciously selected ensemble of Lagrangian point particles, often called super-droplets or super-particles, to represent the enormous number of aerosol, cloud, and precipitation particles typically present in real clouds. These particles are followed in physical space applying the model-predicted flow field, and their growth mimics processes occurring in a natural cloud.



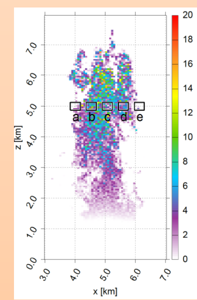


Fig. 3. Single-cloud simulation using the University of Warsaw Lagrangian Cloud Model. The panel to the left shows a map of the cloud water mixing ratio (in g kg^{-1}) in the vertical plane intersecting the 3D cloud. Droplet spectra derived from the simulated Lagrangian super-droplets present within grid boxes marked a to e in the left panel are shown above. The panels show the mean radius <r>, spectral width σ, and adiabatic fraction (AF).

To illustrate capabilities of the Lagrangian particle-based approach, we consider the classical problem of the droplet size distribution spectral width. Cloud observations show that the droplet spectra in cumulus clouds are typically wide and often multimodal. Cooper (1989) argued that the key mechanism capable in explaining the observed large spectral widths involves droplets arriving at a given location within a turbulent cloud following different trajectories through a cloud. This is naturally simulated by the Lagrangian particle-based approach. The simulated spectra are wide and multimodal as shown in Fig. 3.

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