Simulation of an isolated cumulus congestus cloud with collision-coalescence using Lagrangian and bin microphysics approaches

ICMW 2024, CASE D

Case leaders: Kamal Kant Chandrakar[1] & Noémi Sarkadi[2]

[1]kkchandr@ucar.edu; [2]*sarkadin@gamma.ttk.pte.hu*

Case overview and motivation:

Precipitation development is a critical process affecting the cumulus cloud lifecycle, the hydrological cycle, and cloud dynamics. Even after numerous investigations using observations and process modeling, understanding precipitation development in cumulus clouds and its appropriate representation in atmospheric models remains a challenge. This is partly due to the complexity of the droplet collision-coalescence process, which is highly dependent on droplet size distributions and their variability. Factors that shape the droplet size distributions, like turbulence and aerosol properties, increase the complexity of the problem under different environmental conditions. Overall, accurately representing precipitation formation in atmospheric models poses a significant challenge and is a critical source of uncertainty in weather and climate models. Advanced microphysics schemes (such as Eulerian bin and Lagrangian super-particle) have become standard tools for cloud physics research and parameterization development. However, this leads to a question: how well do these schemes represent precipitation development in clouds? Is there a true benchmark microphysics scheme? This model intercomparison project will focus on warm rain development in cumulus congestus clouds and how different models and microphysics schemes simulate this process. We will compare Eulerian bin and Lagrangian particle-based microphysics schemes in different dynamics cores using a well-constrained simulation environment.

In 2019, a NASA campaign, namely the Cloud, Aerosol and Monsoon Processes Philippines Experiment (hereafter CAMP^{2}EX), was performed near the Philippines. Its main goal was to understand aerosol-cloud interactions and climate feedback, as well as to provide a more detailed microphysical description of cumulus clouds. The measurement took place from 24th August to 5th October. Due to the comprehensive measurements, one of the measured cases was selected for this specific case study: 7th September 2019.

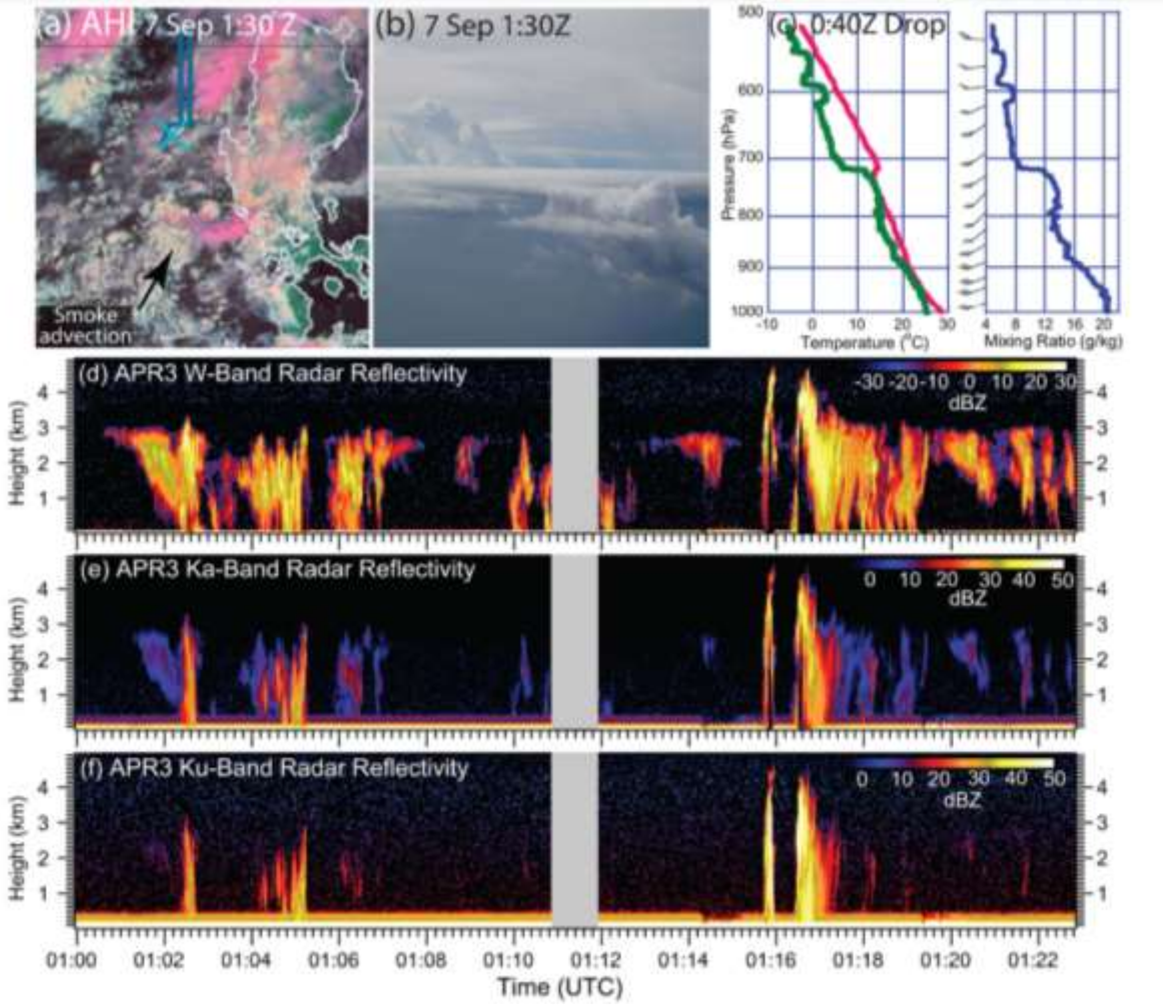

Figure 1: Fig. 7. from Reid et al., 2023, BAMS. "An example of a monsoon enhancement period but with strong regional subsidence sampled on 7 Sep 2019. (a) AHI "ice enhancement" image at 0130 UTC (0930 local time), where bright pink indicates ice clouds, coral implies large water droplets, and white small water droplets (RGB mapped to 2.2, 0.87, and 0.44 µm). The light blue × marks the P-3 location and ends the last 30min of track (blue); (b) a cockpit photo of multiple cloud layers taken at the end of this segment, demonstrating the complex trilevel cloudiness of the region; (c) dropsonde temperature, dewpoint, and water vapor mixing ratio demonstrate the presence of a strong 725-hPa inversion with corresponding moist layer below it; (d)–(f) APR-3W-, Ka-, and Ku-band cross sections from 0100 to 0123 UTC. The Ku-band radar is sensitive to large, precipitation-sized particles, while the Ka band is sensitive to smaller precipitation-sized particles and the W band is sensitive to cloud-sized particles."

Primary research question:

Do we have a reasonably accurate and consistent benchmark microphysics scheme for cloud parameterization developments?

Goals:

- Compare the performance of Lagrangian and bin microphysics schemes in this precipitating case (how well do they compare with observed cloud properties?)
- Identify the primary sources of deviation between Lagrangian and bin schemes (preferably for the same dynamics)
- Identify the primary sources of deviation between different Lagrangian schemes (preferably for the same dynamics model)
- Sensitivity of the results to the grid resolution
- Sensitivity of the results to the super-droplet number and bin resolutions
- Sensitivity of the results to the initialization methods
- Response to aerosol perturbations
- Do the details of droplet activation methods and curvature and solute effects matter for precipitation initiation?

General setup:

- Case setup: The Cloud, Aerosol and Monsoon Processes Philippines Experiment ($CAMP^2Ex$) sounding (Sep 7, 2019 case)
- Domain Size: 12 km X 12 km X 11 km (dx = dy = dz = 35-100 m)
- Initial super-droplet concentration: 32-320 SDs/grid box
- For bin scheme users: if it is possible modify the number or size of bins for sensitivity studies.
- Time steps: 0.5 s (dynamics) and 0.1 s (Lagrangian microphysics)
- Total integration time: 2.5 hrs
- Aerosol properties: bimodal log-normal distribution of Ammonium sulfate aerosols (n_1 = 680 cm^{-3}; n_2 =2.24 cm^{-3}; D_{m1} = 180 nm; D_{m2} = 1000 nm; sgm1 = 1.65; sgm2 = 1.65) and a vertical profile of aerosol concentration based on $CAMP^2Ex$ observations
- Sensitivity to aerosol concentration: scale the number for each mode by a factor of 0.5 (relatively clean case) and 1.5 (relatively polluted case) and remove large aerosol mode (sensitivity to giant CCN).
- Surface heat and moisture fluxes: uniform flux (sensible heat = 0.01 K m/s and moisture = $4.0e^{-5}$ kg/kg m/s) at the beginning hour and a Gaussian flux distribution afterwards (sensible heat peak = 0.3 K m/s and moisture flux peak = $2.4e^{-4}$ kg/kg m/s with horizontal length scale (the half-width of the distribution = 3000 m))

- Surface momentum flux: based on a constant friction velocity (0.28 m/s) and horizontal surface wind
- Hall collection kernel and the settling velocity parameterization from Beard (1976)
- Super-droplet initialization: random sampling from the input aerosol distribution (logarithmically uniform from a dry diameter range 10 nm – 10 μm) to determine super-droplet multiplicity and spatially uniform super-droplet number mixing ratio (super-droplet distributed vertically based on air density)
- Piggybacking framework (if available) or 5-10 realizations for the control case

Note -- We invite participants using either bin or Lagrangian microphysics schemes (or both). Also, we encourage contributions from different dynamics models and bin/Lagrangian schemes for a successful model intercomparison project.

Recommended outputs and format:

Outputs:

3D outputs are requested after t = 6000 sec. The main variables are listed in table below:

Variable name	Required	Optional
Dynamics		
Potential temperature	+	
Pressure	+	
Wind components (u,v,w)	+	
Sub-grid TKE		+
Dissipation rate		+
Buoyancy field		+
Microphysics		
Mass mixing ratios:		
Water vapor (Q_{vapor})	+	
Cloud water (Q_{cloud}) (droplet radius ≤ 25 μm)	+	
Rain water (Q_{rain}) (drop radius > 25 μm)	+	
Number mixing ratios/concentrations:		
Interstitial aerosol particles ($N_{aerosol}$)	+	

Cloud droplets (N_{cloud}) (droplet radius ≤ 25 μm)	+	
Rain drops (N_{rain}) (drop radius > 25 μm)	+	
DSD moments:		
First (R_m)		+
Second (R^2) and σ_R		+
Sixth (R^6)		+
Process rates:		
Activation		+
Condensation/evaporation		+
Autoconversion		+
Accretion		+
Self-collection		+

Plots for analysis:

- **Contoured Frequency by Altitude Diagrams (CFADs)** overlapped with horizontal average and 10th and 90th percentiles for grid scale cloud quantities (e.g., QC, QR, R_m (number mean radius in each grid cell), σ_R (standard deviation in each grid cell), R^6, N_{cloud}, N_{rain}, w) in cloudy grid cells (QC > 0.1 g/m^3)
- **Time series:** domain integrated cloud, rain and total water; average surface and cloud base precipitation flux; accumulated precipitation just below the cloud base and near the surface; cloud base and top
- Vertical profiles of cloud/rain quantities stratified based on vertical velocity
- Average drop size distributions at different levels (only cloudy grid cells, QC > 0.1 g/m^3)

Format:

- 3d/2d outputs in NetCDF (single file or one file per time)
- Figures: '.fig' (MatLab figure file); '.eps'; '.pdf'; '.png'

Case description and configuration setup for WRF users

(for WRFV4.3 and V3.7, latter with optional release with piggybacking method upon request: sarkadin@gamma.ttk.pte.hu)

Domain size and resolution:

The domain is 10 km x 10 km, and model top is 12 km. Horizontal resolution is 100 m, with a timestep of 0.5 sec. Number of vertical levels is 201, close to 60 m vertical resolution. If users are using finer horizontal and/or vertical resolution the time step suggested lowered to 0.25 sec.

Surface fluxes:

As in previous ICMW (An Isolated cumulus congestus based on SCMS campaign (case leaders: Shin-ichiro Shima and Wojciech W. Grabowski)) for the first hour of the simulation a uniform flux of heat and moisture are applied.

From the second hour the initially uniform surface fluxes are replaced by surface fluxes with an additional Gaussian distribution centered in the middle of the domain.

Currently, the surface layer scheme is set as sf_sfclay_physics = 1. Then, the above surface heat fluxes can be added in file phys/module_sf_sfclayrev.F.

Setup for aerosol:

For aerosol properties we use a bimodal log-normal distribution with the following:

Mode 1:
n_1 = 680 cm^{-3}
Dm_1 = 180 nm
sgm_1 = 1.65

Mode 2:
n_2 = 2.24 cm^{-3}
Dm_2 = 1000 nm
Sgm_2 = 1.65

Agenda:

Time	Goal
November 2023:	Officially announce the workshop and cases and start to invite interested parties to participate. (ICMW website should be set up and running then).
March 2024:	Collect outputs from participants.
January 2024:	ICMW registration, abstract submission, and hotel reservation open.
April 2024:	Abstract submission closes.
May 2024:	First draft of the ICMW agenda ready.
June 2024:	Final agenda ready.
July 8-12, 2024:	In-person workshop at Yonsei University.

References:

Reid et al., 2023: The Coupling Between Tropical Meteorology, Aerosol Lifecycle, Convection, and Radiation during the Cloud, Aerosol and Monsoon Processes Philippines Experiment ($CAMP^2Ex$), *BAMS*, https://doi.org/10.1175/BAMS-D-21-0285.1

Input sounding and aerosol concentration profile: Provided by the case leaders.

For WRF users: input sounding, sample namelist and coding sample are available upon request.