Towards improving high resolution NWP forecasts of convection using an explicit/ bin microphysics scheme to guide bulk microphysics scheme improvements

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1. Visit summary

Noémi arrived to NCAR at the middle of December 2017 and departed at the beginning of February, 2018. Most of the goals of the visit were successfully achieved, although some parts of the original research plan were not completed during the visiting time because of timing with other projects and code issues.

During the early summer of 2018 Noémi was able to visit the NCAR again secured by her own funding to support another 2-month visit. However, because of the fact that the abovementioned visit was related to another project limited time was available to work on previous missed points of the DTC project.

While this did mean that not all portions of the original research plan were finished, the opportunity to move ahead with those plans and the lessons learned in the process have already led to substantive changes to the Thompson et al (2008) bulk microphysics scheme and also modify the detailed microphysical scheme to improve the aerosol-cloud interactions (this part of the work mainly was done by István Geresdi).

This document is organized as follows. The primary sections of the original research plan are briefly revisited in subsections below and details of 12-month progress are noted. Then, the expected outcomes of the original plan are discussed in the context of what was partly or fully successful versus what work could be pursued in the future to achieve these outcomes.

2. Research Plan

a. Explicit/bin microphysics scheme

Between 2012 and 2014, the explicit/bin microphysics scheme of I. Geresdi (c.f., Geresdi, 1998; Rasmussen et al, 2002, Sarkadi et al, 2016) was incorporated and extensively tested in WRF v3.4.1. The bin scheme offers a significant advantage over the usual bulk schemes. It makes no *a priori* assumption concerning a functional form of any water species and predicts the number and mass mixing ratio of 36 individual size bins explicitly. As such, it contains a proper spectrum of fall speeds of water and ice particles whereas the bulk schemes must assume that all particles (of single water species) fall at a mass-weighted or number-weighted mean speed. These assumptions may be critical in the growth phase of convective towers because whereas the bin scheme properly simulates that only the largest particles are falling downward relative to the updraft, the bulk schemes may be producing far too much downward moving rain that prematurely evaporates below cloud to create the cold pool that ultimately propagates large-scale convective systems. Most notably, for only the second time in the world, a 2-moment bin microphysics scheme with ice has been run in a fully three dimensional simulation of a squall line. The run was performed using

NCAR's Yellowstone computer in Sep. 2013 using idealized 3D conditions following Case#2 of the 2012 WMO Cloud Modeling Workshop. Because of the fact that bin schemes have explicit bins of particle size, they have hundreds of total predictive variables rather than roughly 10 used by a typical bulk scheme. Until computing power reached its current state, we could only run 2D idealized simulations or water-only bin microphysics schemes to reduce computational cost. Now we have run a state-of-the-art bin scheme in a real-world squall line and other 3D cases. During István Geresdi's 2014 visit, which was partially supported by DTC visitor funds, we encountered some code errors that took far longer to diagnose and correct and we were, therefore, unable to complete the task of fully implementing the bin scheme into a public release of WRF. These issues have now been resolved and we would like to update and adapt the code infrastructure to the most current WRF version (v3.8.1).

b. Test & Evaluation plan

In this section originally the following plans were described:

1. Sensitivity experiment on aggregation of snowflakes within the melting layer, graupel/hail production and its subsequent fall velocity that brings it to the melting layer to create rain. Our aim was to compare the process rates and terminal velocities between the bin and bulk microphysics schemes.
2. Brief investigation on the model grid spacing similar to Bryan and Morrison (2012).
3. Convective cloud investigation: i) based on Fan et al (2017) and ii) a second type of convective cloud system from the most recent International Cloud Modeling Workshop held at the UK Met Office in July 2016.

c. Realization of the research

Unfortunately, the delays discussed previously slowed progress in this area. Fig. 1 shows the terminal velocity of the different type of particles (dry snowflakes, water drops and dry graupel particles) in the case of the bin scheme.

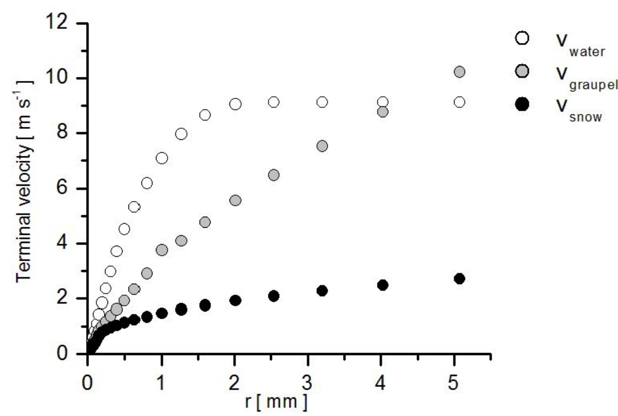


Figure 1. Terminal velocity of the particles (dry snowflakes, dry graupel particles, water drops) in the bin scheme.

Previous study showed that the Thompson bulk scheme (see reference Sarkadi et al, 2016) is sensitive to the modification of the terminal velocity properties. Table from Sarkadi et al, 2016 added as reference.

Point 2 was investigated by Greg Thompson with bulk microphysics scheme because of the high needs of computer capacity of the bin microphysical scheme.

Because of these expensive run times only 3/ii) was made. The following table (see Table 2) contains the sensitivity runs of the COPE case study. The case studies were run of Cheyenne supercomputer. One simulation took around 12 days to finish.

Table 1. Results of the sensitivity tests of the THOMPSON and BIN scheme with different terminal velocity (in the case of the Thompson scheme) and with and without collision-induced shedding (in the case of the bin scheme).

Applied microphysical scheme	Total amount of liquid precipitation [mm]	Average depth of the melting layer [m]	Total domain accumulated snow on the surface[mm]	Total domain accumulated graupel on the surface [mm]	Maximum mixing ratio of snowflakes [g m^{-3}]	Maximu m mixing ratio of graupel particles [g m^{-3}]
BINCIS	2163	675.7	0.1	8.7	0.44	0.53
BINWCIS	2267	676.8	0.2	2.6	0.44	0.62
BULK	2269	973.9	8.9	38.0	0.63	0.25
BULK1	936	606.6	0.0	8.3	1.25	0.22
BULK2	2229	808.8	0.0	35.7	0.60	0.26
BULK3	2168	956.6	4.1	72.4	0.51	0.33
BULK4	2161	795.7	0.0	70.0	0.51	0.33
BULK5	2576	773.8	0.2	47.1	0.55	0.28

BINCIS: original bin scheme

BINWCIS: bin scheme with collision-induced shedding

BULK: original Thompson bulk scheme;

BULK1: the terminal velocity of the melting snowflakes is equal to that of dry snowflakes, otherwise unchanged from BULK;

BULK2: the terminal velocity of the melting snowflakes depends linearly on the environmental temperature. At 0°C it is equal to the terminal velocity of dry snowflakes while at +5°C, it is equal to the terminal velocity of water drops;

BULK3: the transfer function from rimed snow to form graupel was made faster[1];

BULK4: both modifications used in BULK2 and BULK3 were combined together;

BULK5: the BULK4 modification was combined with collision-induced shedding for graupel-rainwater collision, only when temperature is greater than 0°C just as in BINCIS, the source equation for number concentration of rain drops formed from the melting of snowflakes and graupel particles altered to reduce the mean size and rain self-collection and break-up has a lower constant pre-factor to lessen the impact of melting and riming processes.

[1] The transfer function in BULK uses a linear relation from 5 to 75% of rimed snow mass converted to graupel as the rime growth to vapor deposition growth ratio increases from 5:1 to 30:1. In the BULK3 experiment, a linear relation from 5 to 95% of rimed snow mass converted to graupel as the rime growth to vapor deposition ratio increases from 2:1 to 30:1.

Table 2 shows the sensitivity simulation properties with bin microphysics scheme. The model setup was the following:

Time period: 3rd August 2013 06 UTC to 3rd August 2013 18 UTC

Domain centre (in Figure 2): 50.3928 °N and -5.6331 °E.

Fig. 2. shows the modeled domain and the smaller domain where the analysis was made (MODIS image also attached to the figure).

Table 2. Sensitivity simulations related to COPE case study.

	CTRL (CC)	NOHM (CC)	CTRL (DM)
Domain size in horizontal	830x700	830x700	830x700
Horizontal resolution	600 m	600 m	600 m
Domain size in vertical	71 (~ 20 km)	71 (~ 20 km)	71 (~ 20 km)
Vertical resolution	streched grid (~45-700 m)	streched grid (~45-700 m)	streched grid (~45-700 m)
Simulation time	12 h	12 h	12 h
Time step	3 s	3 s	3 s
Microphysical processes	**ALL** microphysics	Without **Hallett-Mossop** effect	**ALL** microphysics
Ice initiation process	Cooper, 1986	Cooper, 1986	DeMott et al., 2010

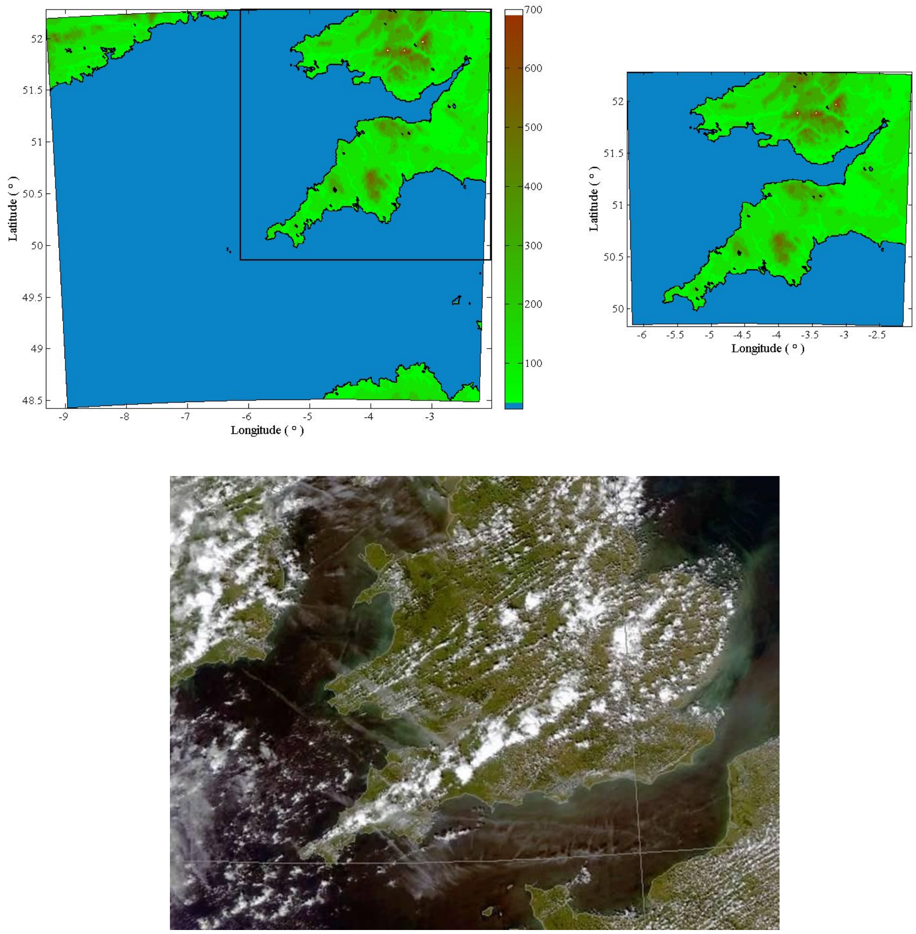


Figure 2. Simulated domain (top left), and smaller domain (top right) in which the domain-averaged values were calculated, and MODIS image of 14:00 UTC (bottom)

Comparison between results of different bulk models (see Fig. 3) with observations and comparison between bulk and bin (see Fig. 4) scheme shows large spread of data. Results of the bin scheme shows better agreement with the observations to catch the highest peak of light or moderate precipitation rates during the simulations. As Fig. 4 shows Hallett-Mossop effect has large impact on domain average precipitation intensity. Without this effect (green line) underestimation of the intensity occurs.

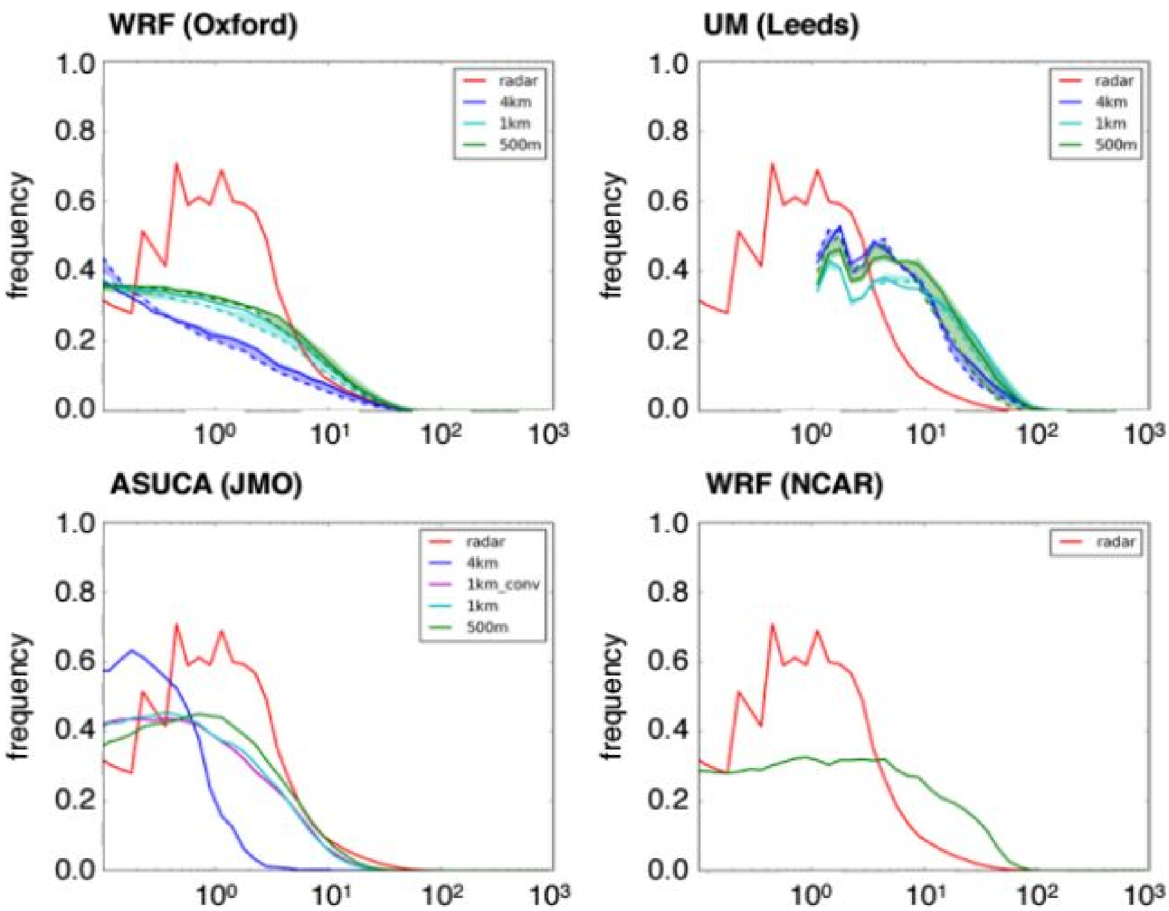


Figure 3. Four different model simulations of frequency of precipitation rate (mm h-1) as compared to radar data. All models under-estimate the light to moderate rain rates and most over-estimate the heaviest precipitation rates. Different colored curves represent models run with different grid spacings. Image courtesy of Annette Miltenberger (Univ. Leads).

This means that secondary ice production between -3 and -8°C plays an important role in surface precipitation formation.

Comparing the different bin schemes with observed radar reflectivity frequencies shows the model and measurements are in good agreement (Fig. 5 and Fig. 6).

Figures 7 and 8 show the simulated domain and time averaged microphysical profiles of different hydrometeors (water drops [both cloud water and rain], snowflakes, ice crystals, graupel particles). However, the different ice initiation schemes do not significantly affect the liquid water content in the clouds but have a large impact on the ice phase.

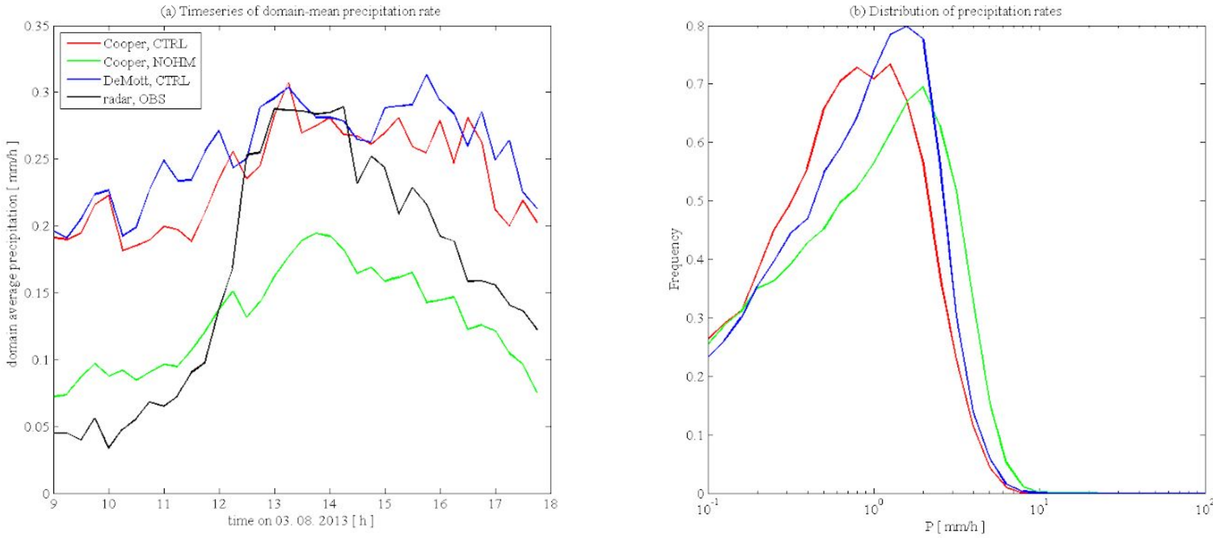


Figure 4. Timeseries of domain-mean precipitation rate (a) and distribution of precipitation rates (b) from model simulations (see different configurations in Table 2) and radar observations (black line in part (a)).

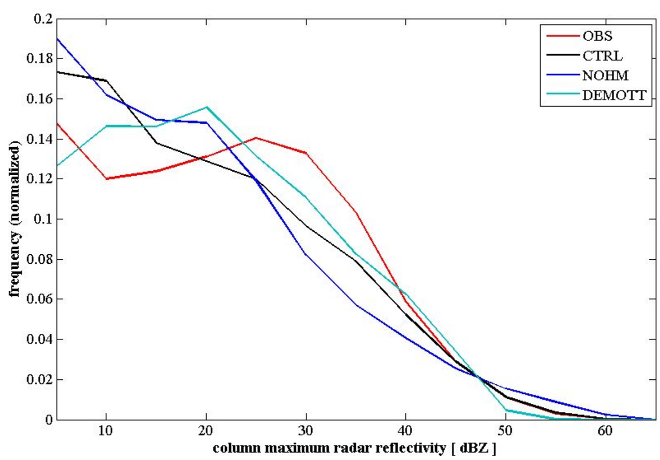
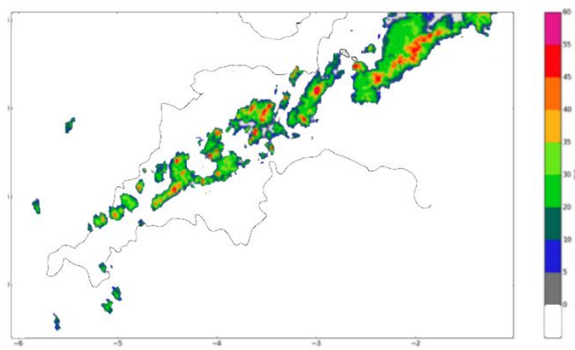
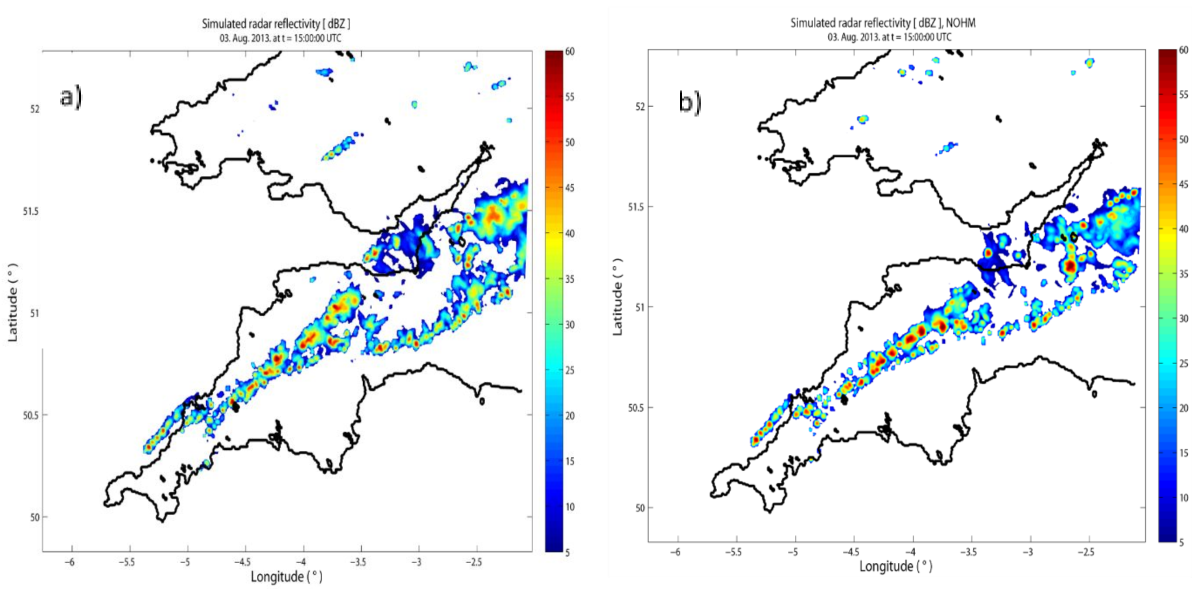


Figure 5. Distribution of column maximum reflectivity from radar observations (black) and model simulation (colors).




Simulated radar reflectivity [dBZ]
03. Aug. 2013. at t = 15:00:00 UTC
a)
Latitude (°)
Longitude (°)
Simulated radar reflectivity [dBZ], NOHM
03. Aug. 2013. at t = 15:00:00 UTC
b)
Latitude (°)
Longitude (°)

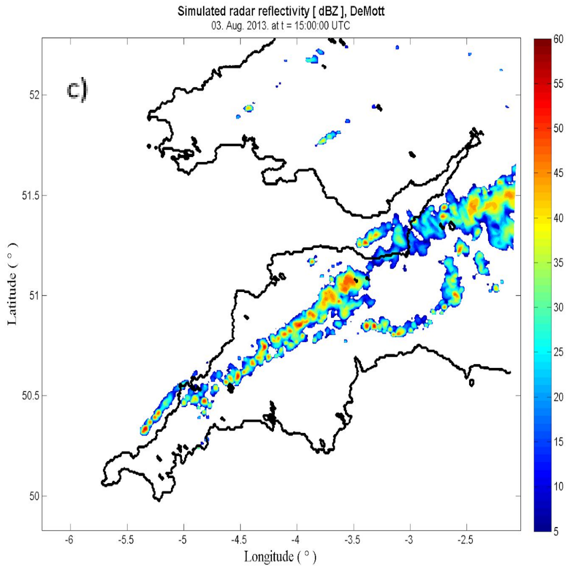


Figure 6. Observed (top middle), and simulated radar reflectivity fields (a) Cooper, CTRL, (b), Cooper, NOHM and (c) DeMott, CTRL at 03. Aug. 2013 15:00 UTC (each panel).

In the case of the ice crystals, the DeMott ice initiation scheme did not affect the mass of the formed ice crystals but did change the number concentration of ice. Because of a large change in the number concentration of the ice crystals, the number and mass of the generated snowflakes also increased. An interesting result is that the number of the falling graupel particles did not change from the DeMott ice initiation scheme, but the mixing ratio of the graupel particles significantly increased.

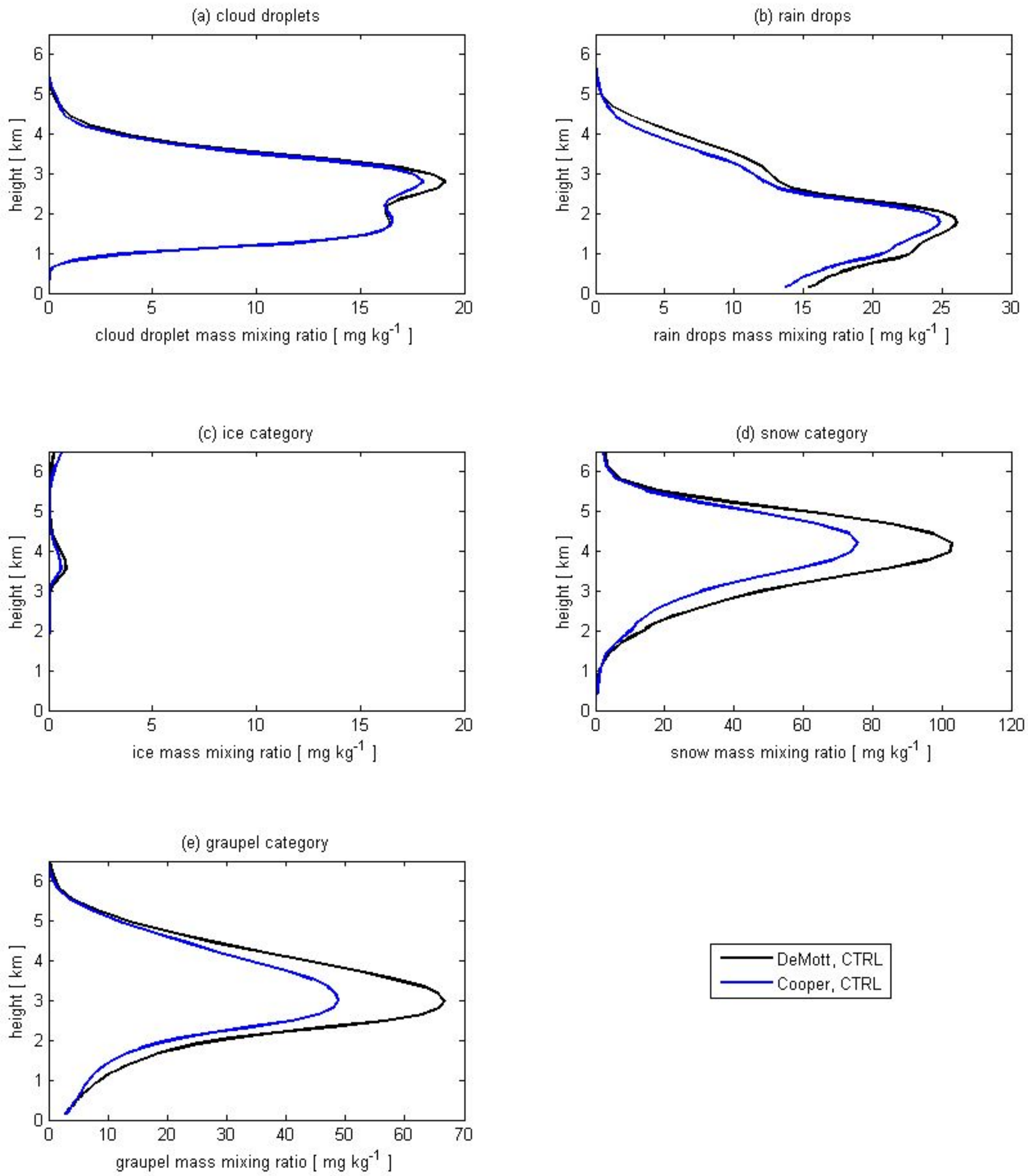


Figure 7. Profiles of hydrometeor mass mixing ratios averaged between 10-17:45 UTC over all gridpoints in the smaller domain: (a) cloud droplet, (b) rain drops, (c) ice crystals, (d) snowflakes, (e) graupel particles in [mg/kg].

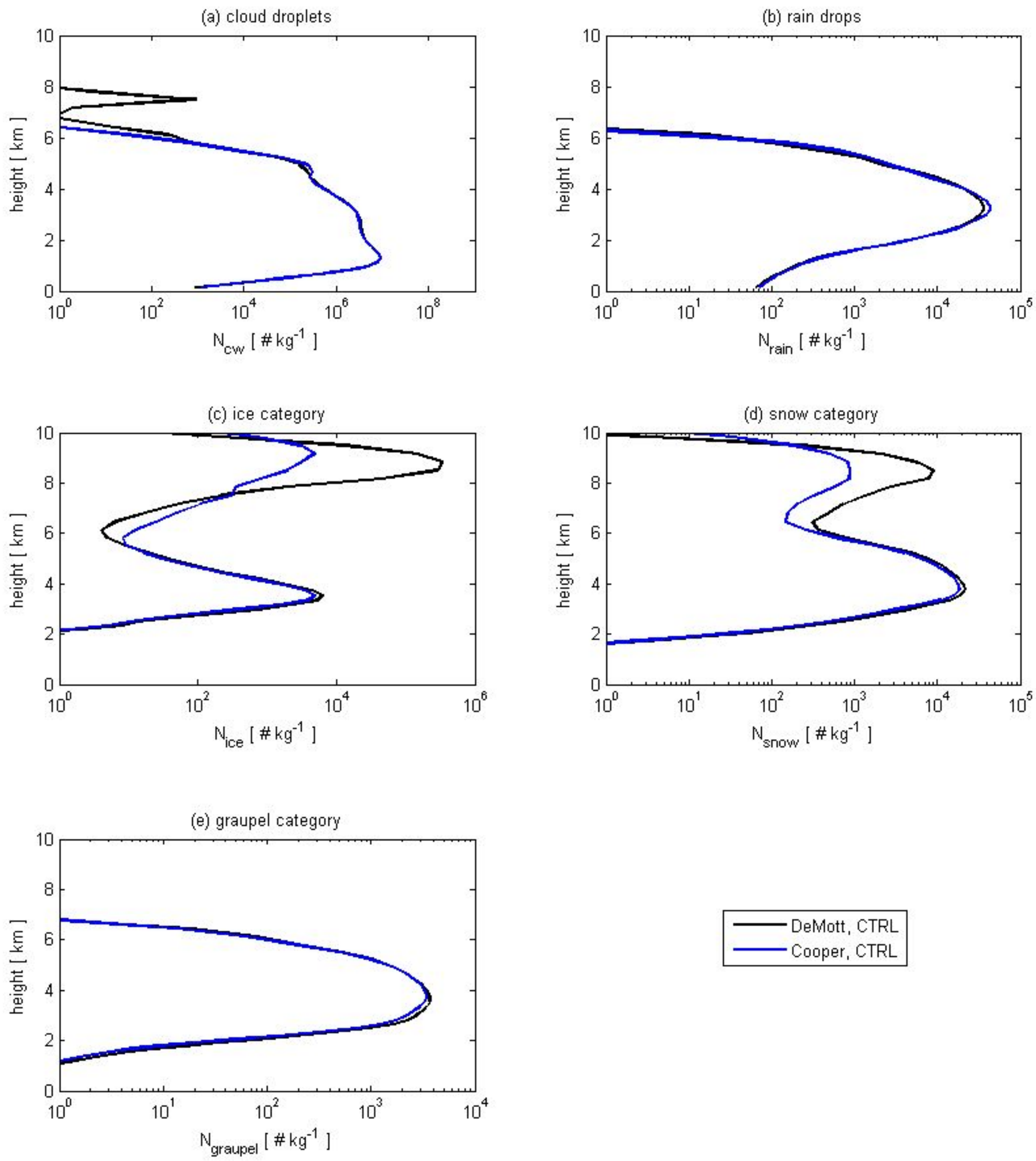


Figure 8. Same as Fig.7. but for number concentration.

3. Original Expected Outcomes

A number of positive outcomes are expected from the planned research:

- A state-of-the-art bin microphysics scheme with ice will be available to the WRF-ARW research community to serve for future improvements to bulk microphysics schemes.
- Improvements of high-resolution, high-fidelity convective forecasts.

Although not all of the planned tests were performed during the visit, the aforementioned outcomes favor considering the project a success. The following work was done during the visit:

- Implementation of a new ice initiation process (DeMott, 2010) into bin microphysics.
- Implementation of more detailed aerosol – cloud interactions in the bin scheme is under development. The addition of aerosol particles into the bin scheme are in progress by István Geresdi based on DeMott simulations.
- The bin scheme was successfully implemented into a newer version of WRF v3.7.1.
- Radar reflectivity calculations were post-processing in previous version and also required high computational resources. The radar reflectivity calculation was implemented and coupled with the WRF and the bin scheme. As a result data analysis became faster.
- Three different kinds of sensitivity studies were made by bin scheme and also with bulk scheme in COPE case study.

The final expected outcome will be a paper in high-ranking journal. The manuscript is being prepared, and the expected submission will be early summer in 2019.

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