Final Report of UCAR/NCAR activities of DOE ASR grant DE-SC0008648

"Evolution of Precipitation Particle Size Distributions within MC3E Systems and its Impact on Aerosol-Cloud-Precipitation Interactions"

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This grant supported several observational and modeling activities as reviewed below. Overall, over 20 papers (published, in press or still in preparation) acknowledge support from this grant; see the complete list at the end of this report. Note that some of these papers are not included in the narrative below.

1. ANALYSIS OF THE PARTICLE SIZE DISTRIBUTIONS OBSERVED AROUND MELTING LEVEL IN MC3E CLOUD SYSTEMS OVER SGP ARM/CART SITE

In the first year, we have analyzed in-situ measurements of cloud particle size distributions and particle shapes during the Mid-latitude Continental Convective Clouds Experiment (MC3E), with particular focus on aircraft spiral ascent/descents through the melting layer during stratiform and convective trailing stratiform events over the SGP ARM/CART site. Of the 23 spiral ascents/descents performed by the in-situ aircraft during MC3E, we identified five of them that measured the melting layer transition while within precipitation. As expected, we were able to measure the melting process by focusing on the evolution of particle *shape* distributions as the melting process proceeds below the 0-degree level. In all cases the smaller ice crystals melt first, producing a mixed-phase region composed of small liquid droplets coexisting with large ice particles. The melting then gradually proceeds to the larger particles until all particles are fully melted. During the analysis we found that the onset of the melting process appears to be dependent on the ambient relative humidity, with low humidity being able to delay melting until up to +2 degree Celsius, thus lowering the melting layer (and bright band characteristics) by several hundred meters.

We used the particle shape information, and its evolution through the melting layer, to significantly improve our estimates of particle density in mixed-phase regions. This in turn improves our estimates of all related bulk properties and moments within the melting layer, such as condensed water content, fall velocity, and mass flux. In the case of the April 27th stratiform rain event, we were able to compute a relatively constant mass flux through the entire melting level based on the measured size and shape distributions. This is a true milestone that gives us confidence in the measurements and estimates of bulk properties. This detailed knowledge of melting layer characteristics is essential for guiding our further modeling and radar observational efforts. They have been used in the comparison of bin microphysics simulations as discussed later in this report and in bin microphysics scheme enhancements.

In the second year of this project, we have made considerable progress on our observational study of the melting layer sampled by the University of North Dakota Citation aircraft during the Midlatitude Continental Convective Clouds, Experiment (MC3E) in South-Central Oklahoma, April 22-June 6, 2011. We have carefully examined the data acquired from four spiral descents from the ice regions, through the melting layer, and into the rain regions (or visa versa). The analysis includes data from the following microphysical probes: Cloud Droplet Probe, 2D-Cloud Probe, High Volume Precipitation Sampler Probe (HVPS-3), King Liquid Water Probe, Nevzorov Total and Condensed Water Probe, and the Rosemount Icing Probe. The improved image quality from the HVPS-3 allows us to see the melting processes in more detail than was previously possible by analyzing the shape of the particles over a wide size range in addition to measuring the size and area of the particles.

With decreasing temperatures from -4 to +1^{0}C and with relative humidities with respect to water of 90% or above, the PSD slope and intercept parameters uniformly decreased downward, while the maximum particle size of the largest particle continued to increase. Aggregation is responsible for these trends. Melting proceeded from the smallest to the largest particles, beginning at +0.5 to +1^{0}C and ending at about +2^{0}C. The aggregation process appears to be enhanced beginning at the top of the melting layer, possibly because the aggregates become more sticky on their bottom side and exterior surfaces as they melt, and since these are their collecting surfaces, this could enhance the aggregation process.

For highly subsaturated conditions and for temperatures from about –4 to +2^{0}C, the PSD slope and intercept parameters continued to decrease downwards, whereas the size of the largest particles either remained about the same or increased. There was relatively little melting until a temperature of +2^{0}C or above was reached. There is no apparent increase in the total concentrations of the ice particles or the particles larger than about 1 mm, suggesting that breakup of the particles during the melting process is not significant.

In the third year and during the no-cost extension, these efforts continued with the specific emphasis on the comparison of aircraft observations with bin microphysics simulations of the May 20 squall line case reported below.

2. THEORETICAL AND MODELING ACTIVITIES

Modeling efforts in the project involved various activities, from bin microphysics modeling of the MC3E May 20 squall line case applying three bin microphysics schemes, through improvements of existing microphysical schemes and developments of novel approaches to microphysics parameterization, studies concerning indirect aerosol impact on deep convection, to the development of the novel methodology to separate dynamical and purely microphysical impacts of aerosol on moist convection, the microphysical piggybacking. Theoretical studies of convective dynamics with implications to the scale-aware convective parameterization were also conducted. These efforts are summarized below.

2.1. Development of a new bulk microphysics scheme: the predicted particle properties (P3) scheme.

In years 1 and 2 we developed a new bulk microphysics scheme based on the approach of predicting particle properties rather than separating ice into various pre-defined categories with fixed properties. This work has its roots in previous work supported by DOE, in which we developed a microphysics scheme that separately predicts the mass mixing ratios of ice grown by vapor deposition and riming (Morrison and Grabowski 2008; 2010, JAS). The idea is to allow ice particle properties to vary smoothly in time and space as a function of prognostic flow-conserved microphysical variables (ice mass, rime mass, rime volume, number mixing ratios), rather than separating ice into pre-defined categories. In the traditional approach, conversion between different ice categories must rely on poorly constrained conversion parameters and thresholds. The new paradigm of predicting particle properties is the basis for the new microphysics scheme we call the Predicted Particle Properties (P3) scheme (Morrison and Milbrandt 2015). The four prognostic ice microphysical variables in this scheme allow it to simultaneously predict the mean particle size, rime mass fraction, particle density, and fallspeed. This scheme was implemented into the Weather Research and Forecasting model (WRF) and used to simulate two contrasting cases: a mid-latitude squall line and precipitation associated with an extratropical cyclone enhanced by orography, including comparison with other microphysics schemes in WRF (Morrison et al. 2015a). In year 3, P3 was extended to include multiple free categories, each of which has four prognostic ice variables that allow smooth evolution based on the history of particle growth conditions (Milbrandt and Morrison 2016). This scheme has also been tested in a real-time high-resolution (4 km grid spacing) weather forecast system as part of the NOAA NSSL Hazardous Weather Testbed in spring 2014 and 2015 (and continuing in spring 2016). P3 was found to compare well in terms of providing forecast guidance in severe convective weather events relative to existing, well-established schemes in WRF. In recent work, P3 has been assessed against observation for the May 20 MC3E case study as part of the MC3E cloud-resolving model intercomparison project described below. We plan to release P3 to the wider community, continuing our tradition of developing and maintaining microphysics codes in community models, likely by the spring 2017 release of WRF.

In year 3 we have further improved microphysics schemes by exploring a new approach for calculating transport (advection) of microphysical variables. This has involved developing a method we call Scalar Flux Vector Transport (Morrison et al. 2016), which calculates advection of mass mixing ratio variables using the host model's nonlinear, typically positive definite/monotonic advection scheme, and calculates advection of the other microphysical variables using a weighted scaling of the mass mixing ratio fluxes. This method gives similar results and overall accuracy compared to the traditional approach of applying the host model's full advection calculation to each microphysical variable independently, but with a reduced cost in terms of total model run time by 10-15%. This work has potential to substantially reduce the overall cost of using multi-moment bulk microphysics, bringing the cost closer to that using simpler one-moment microphysics schemes.

2.2 Theoretical and numerical studies of convective dynamics

This work investigated aspects of moist convective dynamics, including coupling of microphysics and convective dynamics. A theoretical study of perturbation pressure effects on convection led to new analytic expressions for the perturbation pressure and its effect on convective updraft velocities as a function of integrated buoyancy and updraft aspect ratio, with implications for improving the representation of vertical velocity in convection parameterizations and for interpreting the sensitivity of "cloud-resolving" model simulations to horizontal grid spacing in the "gray zone" (Morrison 2016a,b). This work was extended to develop theoretical expressions for a passive scalar, buoyancy, and vertical velocity in growing convective drafts including the effects of turbulent and dynamic entrainment (Morrison 2016c). This study explained the occurrence of plume-like versus thermal-like updraft structure as a function of updraft width and height and environmental relative humidity. It also showed that a transition between plume and rising thermal structures is controlled by dynamic entrainment (the organized inflow of environmental air associated with flow on the scale of the updraft itself), which sharpens horizontal gradients and enhances lateral turbulent mixing. Sensitivity of a simulated squall line to horizontal and vertical grid spacing in the "gray zone" using WRF was studied in Lebo and Morrison (2015) using a new method for performing very high resolution large domain simulations (~ 70 m spacing over a domain > 100 x 100 km^2), while concurrent sensitivities to horizontal grid spacing and microphysics scheme in WRF were investigated in Morrison et al. (2015c). Aerosol effects on idealized supercell storm dynamics and microphysical structure were documented in Kalina et al. (2014).

2.3 A cloud-resolving model intercomparison for MC3E

This project addresses the wide spread of model simulations of deep convection using different microphysics parameterizations and challenges in identifying causes of these differences. We have focused on the May 20 squall line case from MC3E, but plan to extend this to additional cases from MC3E (and potentially GO-AMAZON). This project builds upon previous ARM/ASR-supported model intercomparison projects (e.g., TWP-ICE), but allows us to isolate differences arising directly from the microphysics versus from microphysical-dynamics interactions using the "piggybacking" approach. The use of a common modeling framework (WRF) also allows for a more straightforward analysis of differences caused by using different microphysics schemes.

This collaborative work has analyzed model simulations using several different microphysics schemes in WRF, representing a range of complexity from a 1-moment bulk microphysics scheme to a detailed bin scheme (including the new P3 scheme described above, developed in part by ASR funding), using a "real case" setup of the May 20 squall line case. Results were presented at the 2014 and 2015 ASR Science Team Meetings (with a planned presentation at the upcoming 2016 meeting). It was found that simulations of convective characteristics, vertical velocity in particular, and distributions of surface precipitation are sensitive to different representations of microphysics, with preliminary work suggesting the importance of impacts on cold pools, in turn influencing convective dynamics. A focus is on comparison of model simulations with the wealth of observations available from MC3E. This work is currently being written up as a multi-part paper led by Dr. Jiwen Fan, with the first paper focusing on interactions between microphysics, cold pools, and convective characteristics, the second part on differences in stratiform rain characteristics and drop size distributions, with a third paper on results from the piggybacking. This is a longer-term project, and we expect to continue work on this project beyond the expiration of this grant.

2.4 Improving and testing bin microphysics schemes with MC3E observations

Comparisons between model results simulated by three bin schemes and various MC3E observations from the May 20, 2011 squall line case have been conducted. The results of these comparisons (C-Band radar reflectivity, radar derived vertical velocity, Mesonet temperature, relative humidity, precipitation, and in-situ aircraft measurements) were presented at the ASR 2015 Science Team Meetings. Although all three schemes produced a linearly organized convective system with similar structure, detailed comparisons among schemes and between model results and observations revealed considerable sensitivity of simulated storms to representation of microphysical processes in bin schemes. For instance, for the schemes that predict water mixing ratio or melting fraction of the partially melted ice particles, the calculated C-band radar reflectivity showed distinct bright band or enhanced reflectivity below melting layer. Mesonet comparisons indicated that some schemes produced too weak cold pools and slower moving speed while some generated strong downward rear inflow drying the lower atmosphere and reduced the stratiform precipitation. A detail analysis of the buoyancy budget within the model results showed that microphysics plays an important role in the cold pool evolution locally. But similar magnitude contributions from dynamics, especially the negative feedback of the rear inflow, were also found. The differences of storm dynamic and thermodynamic structures among schemes analyzed under the framework of "Rotunno-Klemp-Weisman (RKW) theory" trace back to the assumptions of the hydrometeor mass-size relationships and associated terminal velocity relationships that are applied in different schemes. The model-observation comparisons, storm dynamic and thermodynamic structure analysis and detailed comparisons of in-situ measured and modeled microphysics in the stratiform region are summarized in a two part paper series, which are in the final stages of preparation and will soon be submitted to *Journal of the Atmospheric Sciences* .

2.5 Microphysical piggybacking

Grabowski (2014, 2015) introduced a novel modeling methodology to separate purely microphysical effects from the impacts on cloud dynamics. Grabowski (2014) applied the methodology to simulations of shallow convection, whereas deep convection was considered in Grabowski (2015). The methodology is referred to as "microphysical piggybacking". The main idea is to apply two sets of thermodynamic variables (the potential temperature, water vapor mixing ratio, and all variables describing aerosol, cloud and precipitation particles) in a single cloud field simulation. The first set is coupled to the dynamics and drives the simulation, and the second set piggybacks the simulated flow and does not affect it. The methodology allows assessing the impacts with an unprecedented accuracy, and it is capable of detecting even minuscule impacts on bulk cloud properties such as the cloud cover, liquid and ice water path, and surface precipitation. It also allows comparing local cloud buoyancies between driving and piggybacking sets of thermodynamic variables, and thus exploring possible impacts on cloud dynamics. The impact on the dynamics is assessed by performing a second simulation with microphysical sets swapped, so the driving set becomes the piggybacking set, and vice versa. Modeling results discussed in Grabowski (2014, 2015) and in Grabowski and Jarecka (2015) document capabilities of the piggybacking methodology. This methodology is being used by Grabowski in follow-up studies and will provide the key tool in future studies concerning the impact of microphysical parameterizations on cloud dynamics.

2.6 Investigations into aerosol invigoration of deep convection.

This effort has extended work from our previous DOE ASR grant investigating cloud-aerosol-precipitation interactions in the context of feedback with the larger-scale environment using high-resolution cloud system resolving models (Grabowski and Morrison 2011; Morrison and Grabowski 2011). This study specifically examined the hypothesized "invigoration effect" of aerosols on deep convection due to increased latent heating in updrafts. We used an idealized framework to simulate this effect by increasing latent heating in updrafts and cooling in downdrafts with a perturbation magnitude consistent with previous studies of the invigoration effect. These heating and cooling perturbations led to an initial invigoration but convection returned to its unperturbed state because of adjustment of the larger-scale environment. In contrast, when perturbed conditions were only applied to part of the model domain invigoration was sustained during the entire simulation period. This was associated with a mean mesoscale circulation consisting of upper-level ascent (descent) and lower-level descent (ascent) in the perturbed (unperturbed) region. In contrast to recent studies, it is concluded that the invigoration effect is intimately coupled with larger-scale dynamics through a two-way feedback, and in the absence of alterations in the larger-scale circulation there is limited invigoration beyond the convective adjustment timescale. A paper describing this study (Morrison and Grabowski 2013) has been published in the *Journal of the Atmospheric Sciences*.

The hypothesized convective invigoration was studied in more detailed applying the piggybacking methodology and an idealized case of daytime convection development over land based on observations over Amazon rainforest during the LBA field project. Simulations with two single-moment bulk microphysics schemes (Grabowski 2015) show insignificant impact of assumed droplet concentration on cloud field bulk properties (e.g., cloud fraction profiles, surface rainfall) and on the convective dynamics. In contrast, simulations applying the double-moment scheme of Morrison and Grabowski showed a significant microphysical effect (e.g., much larger cloud fraction profiles of upper-tropospheric anvils). This is explained through the direct link between ice formation in convective updrafts aloft and cloud droplet concentrations below the freezing level. Interestingly, a small dynamical impact was not because of ice processes as originally hypothesized in the invigoration hypothesis, but due to differences in supersaturations below freezing level between pristine and polluted conditions. Note that the supersaturation is predicted in the double-moment scheme of Morrison and Grabowski, in contrast to the saturation adjustment (i.e., no supersaturation with respect to water) applied in most bulk schemes (including 1-moment schemes applied in Grabowski 2015). The manuscript reporting double-moment results (Grabowski and Morrison 2016) is under review, and follow-up investigations are underway.

Peer-reviewed papers acknowledging support from this grant:

Grabowski, W. W., 2014: Extracting microphysical impacts in large eddy simulations of shallow convection. J. Atmos. Sci., **71**, 4493-4499.

Grabowski, W. W., L.-P. and Wang, and T. V. Prabha, 2015, Macroscopic impacts of cloud and precipitation processes on maritime shallow convection as simulated by an LES model with bin microphysics. Atmos. Chem. Phys., **15**, 913-926.

Grabowski, W. W., 2015: Untangling microphysical impacts on deep convection applying a novel modeling methodology. J. Atmos. Sci., **72**, 2446-2464.

Grabowski, W. W., and D. Jarecka, 2015: Modeling condensation in shallow nonprecipitating convection. J. Atmos. Sci., **72**, 4661-4679.

Grabowski, W. W., and H. Morrison, 2015: Untangling microphysical impacts on deep convection applying a novel modeling methodology. Part II: Double-moment microphysics. J. Atmos. Sci. (conditionally accepted).

Heymsfield, A. J., A. Bansemer, M. R. Poellot, and N. Wood, 2015: Observations of ice microphysics through the melting layer. *J. Atmos. Sci.*, **72**, 2902-2928.

Kalina, E. A., K. Friedrich, H. Morrison, and G. Bryan, 2014: Aerosol effects on simulated supercell thunderstorms in different environments. *J. Atmos. Sci.*, **71**, 4558-4580.

Kumjian, M. R., Z. J. Lebo, and H. Morrison, 2015: On the mechanisms of rain formation in an idealized supercell storm. *Mon. Wea. Rev.*, **143**, 2754-2773.

Lebo, Z. J., and H. Morrison, 2013: A novel scheme for parameterizing aerosol processing in warm clouds. *J. Atmos. Sci.*, **70**, 3576-3598.

Lebo, Z. J., and H. Morrison, 2014: Dynamical effects of aerosol perturbations on squall lines with varying wind shear. *Mon. Wea. Rev.*, **142**, 991-1009.

Lebo, Z. J., and H. Morrison, 2015: Effects of horizontal and vertical grid spacing on mixing in simulated squall lines and implications for convective strength and structure. *Mon. Wea. Rev.*, **143**, 4355-4375.

Milbrandt, J. A., and H. Morrison, 2016: Parameterization of cloud microphysics based on the prediction of ice particle properties. Part 3: Introduction of multiple free categories. *J. Atmos. Sci.*, **73**, 975-995.

Morrison, H., and W. W. Grabowski, 2013: Response of tropical deep convection to localized heating perturbations: Implications for aerosol-induced convective invigoration. *J. Atmos. Sci.*, **70**, 3533-3555.

Morrison, H., and J. A. Milbrandt, 2015: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part I: Scheme description and idealized tests. *J. Atmos. Sci.*, **72**, 287-311.

Morrison, H., J. A. Milbrandt, G. H. Bryan, K. Ikeda, S. A. Tessendorf, and G. Thompson, 2015a: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part II: Case study comparisons with observations and other schemes. *J. Atmos. Sci.*, **72**, 312-339.

Morrison, H., A. Morales, C. Villanueva-Birriel, 2015b: Concurrent sensitivities of an idealized deep convective storm to parameterization of microphysics, horizontal grid resolution, and environmental static stability. *Mon. Wea. Rev.*, **143,** 2082-2104.

Morrison, H., 2016a: Impacts of updraft size and dimensionality on the perturbation pressure and vertical velocity in cumulus convection, Part 1: Simple, generalized analytic solutions. *J. Atmos. Sci.*, **73**, 1441-1454.

Morrison, H., 2016b: Impacts of updraft size and dimensionality on the perturbation pressure and vertical velocity in cumulus convection, Part 2: Comparison of theoretical and numerical solutions and fully dynamical simulations. *J. Atmos. Sci.*, **73**, 1455-1480.

Morrison, H., A. A. Jensen, J. Y. Harrington, and J. A. Milbrandt, 2016: Advection of coupled hydrometeor quantities in bulk cloud microphysics schemes. *Mon. Wea. Rev.* (submitted)

Morrison, H., 2016c: An analytic model for entrainment and mixing in growing deep cumulus updrafts. *J. Atmos. Sci.* (submitted).

Xue, L., Z. Lebo, J. Fan, W. Wu, I. Geresdi, A. Bansmer, X. Chu, H. Morrison, R. Rasmussen, W. W. Grabowski, A. Heymsfield, and G. McFarquhar, 2016: Idealized simulations of a squall line from MC3E field campaign applying three bin microphysics schemes. Part 1: Dynamic and thermodynamic structure of the simulated squall line. *J. Atmos. Sci.* (to be submitted).

Xue, L., W. Wu, A. Bansmer, I. Geresdi, Z. Lebo, J. Fan, H. Morrison, W. Grabowski, R. Rasmussen, A. Heymsfield, and G. McFarquhar, 2016: Idealized simulations of a squall line from MC3E field campaign applying three bin microphysics schemes. Part

2: Simulated microphysical properties in the stratiform region. *J. Atmos. Sci.* (to be submitted).