Final progress report
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Testing a Novel Stochastic Ice Microphysics Parameterization for Cloud and Climate Models using ARM Field Campaign Data

1. Participants

Dr. Hugh Morrison, NCAR (PI): overall project coordination and management, development of the stochastic ice microphysics parameterization, assistance in the testing the stochastic schemes in WRF.

Dr. Greg McFarquhar (co-PI), University of Oklahoma/University of Illinois: analysis of aircraft observations, development of the observationally-constrained stochastic scheme.

Dr. Adam Varble (co-PI), University of Utah: analysis of observational data for model evaluation, experiment design and configuration for WRF ensemble simulations, analysis of the WRF simulations; note moved to PNNL in summer 2018 and thereafter was an unfunded collaborator.

Dr. Wojciech Grabowski (co-I), NCAR: conceptual development of the stochastic approach, development of a Lagrangian cloud model including a stochastic condensation scheme, further development and application of the piggybacking modeling method.

Dr. Ed Zipser (co-I), University of Utah: guidance in modeling and observational analysis of convective cases.

Dr. Wei Wu (PhD student, awarded in 2017, post-doc, and research scientist), University of Oklahoma/University of Illinois: analysis of aircraft observations, development of the observationally-constrained stochastic scheme.

Dr. Joseph Finlon (PhD student, awarded in 2019), University of Illinois: analysis of aircraft and radar observations to characterize *a* and *b* parameter variability for the stochastic parameterization.

Dr. McKenna Stanford (PhD student, awarded in 2020), University of Utah: led development of the stochastic mixing scheme, analysis of observational data for model evaluation, experiment design and configuration for WRF simulations, running and analysis of WRF simulations.

Dr. Andrew Dzambo (post-doc), University of Oklahoma: analysis of in-situ aircraft and radar observations to characterize mass-size and fallspeed-size relationships.

Dr. Junshik Um (research scientist), University of Oklahoma/University of Illinois: analysis of microphysical observations, characterization of parameter variability for particle perimeter-size and area-size relationships (left project in 2018 after taking a faculty position in Korea).

2. Accomplishments

a. Major goals of the project

The major goals of this project, as stated in the project proposal, were: 1) use ARM field campaign measurements to characterize variability of important ice microphysical parameters; 2) based on the observational analysis, develop a scheme that stochastically varies these parameters, and implement the new scheme into the Weather Research and Forecasting model (WRF); 3) use WRF coupled with the new stochastic scheme to simulate ARM field campaign convective cases and analyze sensitivity to the parameter variability. Several other efforts were related to these core goals, including development of a stochastic subgrid-scale model for droplet condensation, further development and use of the piggybacking technique (initially developed under previous ASR funding), and investigation of convective dynamics providing context for a stochastic mixing parameterization.

b. Accomplishments under these goals

Significant progress was made on this project for each of the three main goals listed above. Each of the three institutions have focused on a particular aspect: observational analysis at Univ. Oklahoma/Univ. Illinois; parameterization development at NCAR; WRF simulations and analysis at Univ. of Utah. That said, this work was strongly collaborative. We had approximately bi-monthly skype project meetings for the duration of the project. McKenna Stanford, the Univ. of Utah Ph.D. student supported by this project, visited NCAR from April 30 to June 30, 2018 and again from March 13 to August 30, 2019 to work directly with PI Dr. Hugh Morrison and co-I Dr. Wojciech Grabowski on the stochastic parameterization and WRF simulations.

Accomplishments led by each institution are detailed below.

i) National Center for Atmospheric Research Contributions

The effort at NCAR focused on several modeling projects, as well as collaborative work with Univ. Oklahoma/Illinois and Utah to use ARM observations to constrain and evaluate models. Four efforts focused specifically on model evaluation using ARM data. These studies included a) testing of the new stochastic ice microphysics scheme with MC3E data; b) testing of the new stochastic subgrid-scale mixing scheme with MC3E and AMIE/DYNAMO data; c) initial testing of the Predicted Particle Properties (P3) microphysics scheme for the May 20, 2011 MC3E squall line case (P3 was used for developing the stochastic ice microphysics and stochastic mixing schemes); and d) testing of bin microphysics schemes for the same MC3E squall line case that provided additional context for the bulk simulations. The stochastic ice microphysics and mixing schemes are detailed later in "University of Utah" efforts and these efforts formed a major part of McKenna Stanford's Ph.D. thesis at the University of Utah.

Model intercomparison studies of the May 20, 2011 MC3E squall line

The studies of Fan et al. (2017) and Han et al. (2018) compared simulations using various bulk microphysics schemes in the Weather Research and Forecasting (WRF) model for the May 20, 2011 MC3E squall line (note that personnel from both NCAR and Utah are involved in this project). As noted above, this comparison includes the P3 microphysics scheme, which serves as the foundation for the stochastic ice microphysics parameterization for our project. Most of the microphysics schemes overestimate vertical velocity and radar reflectivity in convective updrafts as compared with observational retrievals. Simulated precipitation rates and updraft velocities have significant variability across the eight schemes, even in this strongly dynamically driven system. The spread in simulated updraft velocity correlates well with spreads in buoyancy and the low-level vertical perturbation pressure gradient, which appears related to cold pool intensity that is controlled by the evaporation rate. Simulations with stronger updrafts have a more optimal RKW (Rotunno-Klemp-Weisman theory) state, but only if the rear inflow jet strength is accounted for with cold pool strength and ambient low-level vertical wind shear. Updraft velocity variability between schemes is mainly controlled by differences in simulated ice-related processes, which impact the overall latent heating rate, whereas surface rainfall variability increases in no-ice simulations because of scheme differences in collision-coalescence parameterizations.

The study of Xue et al. (2017) compared simulations of the May 20 MC3E squall line applying three different bin (spectral) microphysics schemes in WRF (note that personnel from both NCAR and Illinois were involved with this project). Semi-idealized three-dimensional simulations in a “bowling alley” configuration were driven by temperature and moisture profiles acquired by a radiosonde released in the pre-convection environment at 1200 UTC in Morris, Oklahoma. MC3E observations were used to assess fidelity of model simulations. This study showed that the three bin microphysics scheme produced a squall line with features broadly consistent with the observed storm characteristics. However, substantial differences in the details of the simulated dynamic and thermodynamic structures were evident. These differences were attributed primarily to different assumptions of the hydrometeor properties, especially the ice particle mass, density, and terminal velocity relationships with size, and the resulting interactions between the microphysics, cold pool strength, and convective dynamics. We showed that bin microphysics schemes, designed to be conceptually more realistic and thus arguably more accurate than bulk microphysics schemes, still simulate a wide spread of microphysical, thermodynamic, and dynamic characteristics qualitatively similar to the spread of squall line characteristics simulated using various bulk schemes (for example, as shown in the Fan et al. and Han et al. studies noted above).

Development and testing of stochastic model physics parameterizations

As part of this project three efforts were undertaken to develop and test stochastic model parameterization schemes (for microphysics and sub-grid scale mixing). Parameterizations for stochastic ice microphysics and stochastic sub-grid scale mixing are described further in University of Utah’s contribution. The other project involved development of a stochastic condensation parameterization via a stochastic vertical velocity forcing to capture the mechanism referred to as “eddy hopping”, leading to droplet spectral broadening. This is described in Grabowski and Abade (2017), Abade et al. (2018), and Grabowski et al. (2018). The key idea, suggested a quarter century ago, is that droplets arriving at a given location within a turbulent cloud follow different trajectories and thus experience different growth histories, and that this leads to a significant spectral broadening. In this study, the adiabatic parcel model with super-droplets is used to contrast droplet growth with and without turbulence. Turbulence inside the parcel is described by two parameters: i) the dissipation rate of the turbulent kinetic energy ε, and ii) the linear extent of the parcel L. As expected, adiabatic parcels without turbulence produce extremely narrow droplet spectra. In turbulent parcels, a stochastic scheme is used to account for vertical velocity fluctuations that lead to local supersaturation fluctuations for each super-droplet. These fluctuations mimic the impact of droplets hopping turbulent eddies in a natural cloud. For L smaller than a few meters, noticeable spectral broadening is possible only for strong turbulence, say, $\varepsilon > 100$ cm^2 s^{-3}. For L typical for grid lengths of large eddy simulation (LES) models (say, between 10 and 100 m), the impact is significant even with relatively modest turbulence intensities. The impact increases with both L and ε. The representation of eddy hopping developed in this paper can be included in a straightforward way in the subgrid-scale scheme of a Lagrangian LES cloud model and may serve as a benchmark for the stochastic microphysics applied in simulations using the traditional Eulerian approach.

Microphysical piggybacking

We have also further refined and utilized the piggybacking methodology in Grabowski and Morrison (2017), Grabowski and Morrison (2018), Grabowski (2018), Grabowski and Prein (2018), Grabowski (2019), Grabowski and Morrison (2020), and Grabowski and Morrison (2021), initially developed under previous ASR funding from Grabowski and Morrison. The basic idea of piggybacking is to separate effects of changes in microphysics from changes in the dynamics and flow. Given rapid increase of magnitude in small perturbations, different flow realizations can obscure the sensitivity to a microphysical change such as aerosol loading. Piggybacking allows greater confidence in assessing such microphysical sensitivities, particularly when used with ensembles of different flow realizations. The studies above showed a limited impact of changes in cloud condensation nucleus concentrations above the freezing level, with a small impact on buoyancy below the freezing level due to increased droplet concentration and somewhat greater cloud condensation below the freezing level. Above the freezing level, reduced collision-coalescence in polluted conditions owing to smaller mean droplet size leads to greater latent heating from freezing, but this is closely balanced by the extra weight of carrying this water leading to almost no net impact on the buoyancy. Below the freezing level, our simulations showed increased latent heating from greater condensation in polluted conditions leading to a small increase in updraft core vertical velocities – a weak "warm invigoration effect".

Convective dynamics parameters for stochastic subgrid-scale mixing

Additional work led by NCAR has explored relationships among basic convective parameters, which provided guidance for the stochastic mixing scheme described below. Specifically, we explored convective parameters that strongly influence convective characteristics and evolution, such as updraft radius, height, turbulent mixing length, and environmental relative humidity. In work funded by ASR under a previous grant described in Morrison (2017, *JAS*), we developed simplified scaling relationships describing key aspects of moist convective dynamics. These relationships suggest how updraft characteristics, including the effects of entrainment, affect updraft properties. Under the current project, this work was extended to develop scaling relationships between moist updraft growth rates (ascent rates of convective clouds) and various convective parameters. This work is described in Morrison and Peters (2018). In follow up work, we further studied the behavior of moist deep convective updrafts using theory and large eddy simulations. This work focused particularly on *why* moist convection often has the structure of a series of rising thermals, which we called "thermal chains". We developed theoretical expressions describing why this thermal chain structure of convection occurs and showed its linkages to the traditional rising thermal and plume conceptual models of convective updrafts. These expressions were evaluated with idealized numerical updraft simulations directly compared to the theoretical expressions, and large eddy simulations of deep cumulus clouds. We showed that the thermal chain structure occurs because of feedbacks between pulses of entraining dry environmental air near the bottom of individual rising thermals, evaporation and/or reduction in condensation, reduction of buoyancy, and changes in the updraft flow structure. A more thermal-like structure occurs when the aspect ratio (width divided by height) is small and the background environmental relative humidity is dry, while plume-like updrafts occur when the aspect ratio is large and the environment is moist. This work is described in a two-part manuscript (Morrison et al. 2020; Peters et al. 2020).

Review papers on microphysical modeling

Papers led by either Grabowski or Morrison at NCAR summarized the above results in a broader context of cloud modeling with review papers on Lagrangian microphysics published in the *Bulletin of the American Meteorological Society* (Grabowski et al. 2019) and key challenges in microphysical modeling in the *Journal of Advances in Modeling Earth Systems* (Morrison et al. 2020).

ii) University of Utah[1]

Stochastic ice microphysics in WRF using the P3 microphysics scheme

Led by Ph.D. student McKenna Stanford, co-PI Dr. Adam Varble, and PI Hugh Morrison (with input from Dr. Judith Berner at NCAR leveraging non-DOE funding), we developed a new microphysical scheme that stochastically varies a handful of ice microphysical parameters within the P3 scheme in the Weather Research and Forecasting model (WRF). The initial focus was on 1) the *a* and *b* parameters in the ice particle power law mass-size relationship; and 2) ice particle fallspeed *V*. The *a* and *b* parameters were directly observationally-constrained based on work led by co-I Wei Wu, while the *V* parameter was chosen because previous studies have shown it has large impacts on deep convective cases using fixed perturbations (i.e., held constant over the domain and model integration time). The new stochastic scheme was applied to three cases observed during the ARM MC3E experiment. In order to place the sensitivity to stochastic microphysical perturbations into context, we have run additional ensembles with: 1) perturbed initial and boundary conditions using the GEFS-Reforecast members (ICBC); 2) fixed parameter perturbations (i.e. values held fixed across the entire domain and for the duration of the simulations); 3) small grid-scale Gaussian random noise in the low-level perturbation potential temperature field. The grid-scale noise is a "floor" on the expected sensitivity, representing the expected possible minimum ensemble spread due to error growth from tiny-amplitude small-scale noise.

Results showed that stochastic perturbations had a modest impact on surface precipitation compared to the other ensembles, but more substantial impacts on anvil microphysical properties and cloud radiative forcing (Fig. 1). The stochastic *a-b* parameter ensembles were the only simulations capable of capturing observed variability in the ice water path-optical depth relationship (Fig. 2). A paper on this work was published in *Journal of Advances in Modeling Earth Systems* (Stanford et al. 2019). This paper describes the new stochastic scheme, the WRF model configuration, and the ensemble results for the three MC3E cases.

[1]Note that co-PI Adam Varble's work on the project after he moved from Utah to PNNL in 2018 are included here.

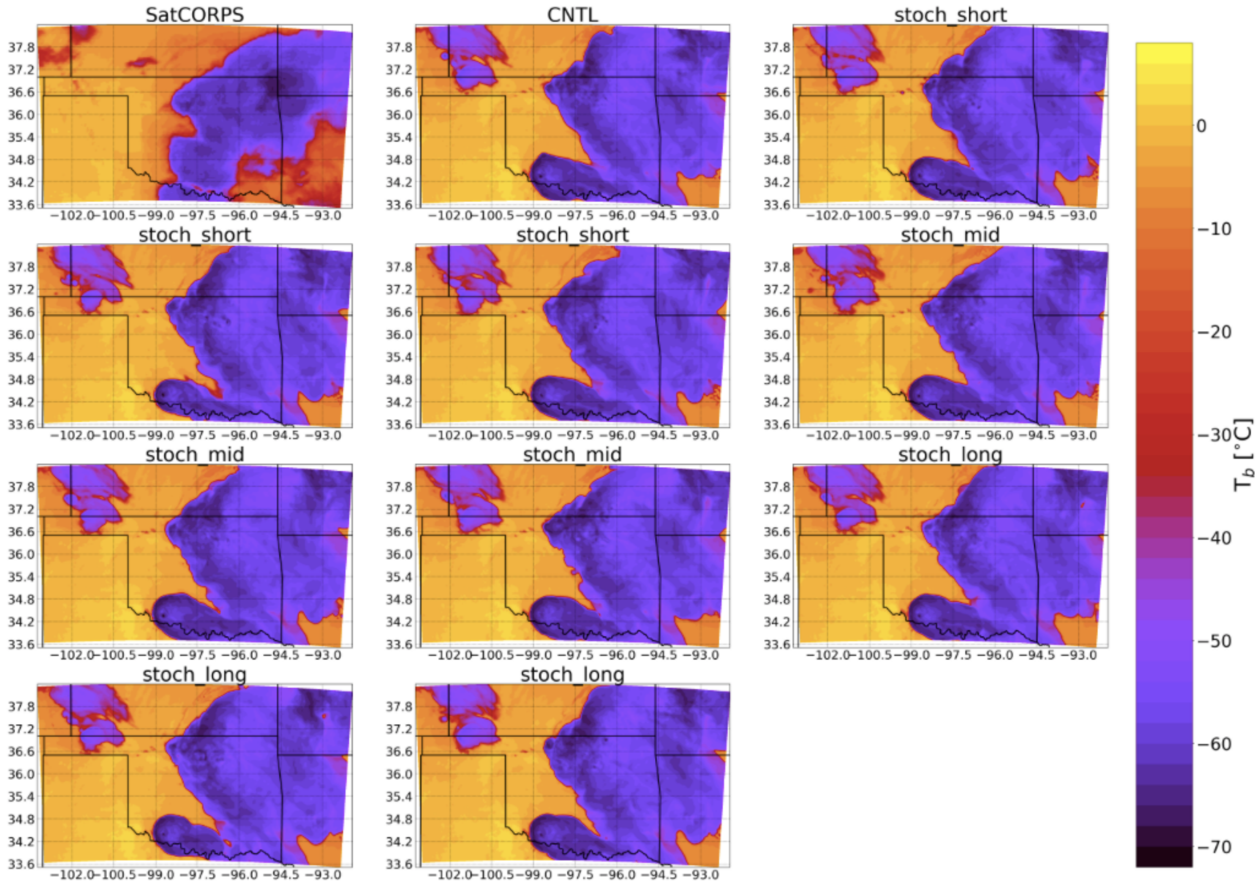

Figure 1. Example of horizontal cross-sections of brightness temperature from satellite (SatCORPS) and various stochastic *a* and *b* parameter ensembles with short, mid, and long spatiotemporal autocorrelation scales for May 23/24 MC3E case. The x and y axes are the longitude and latitude, respectively.

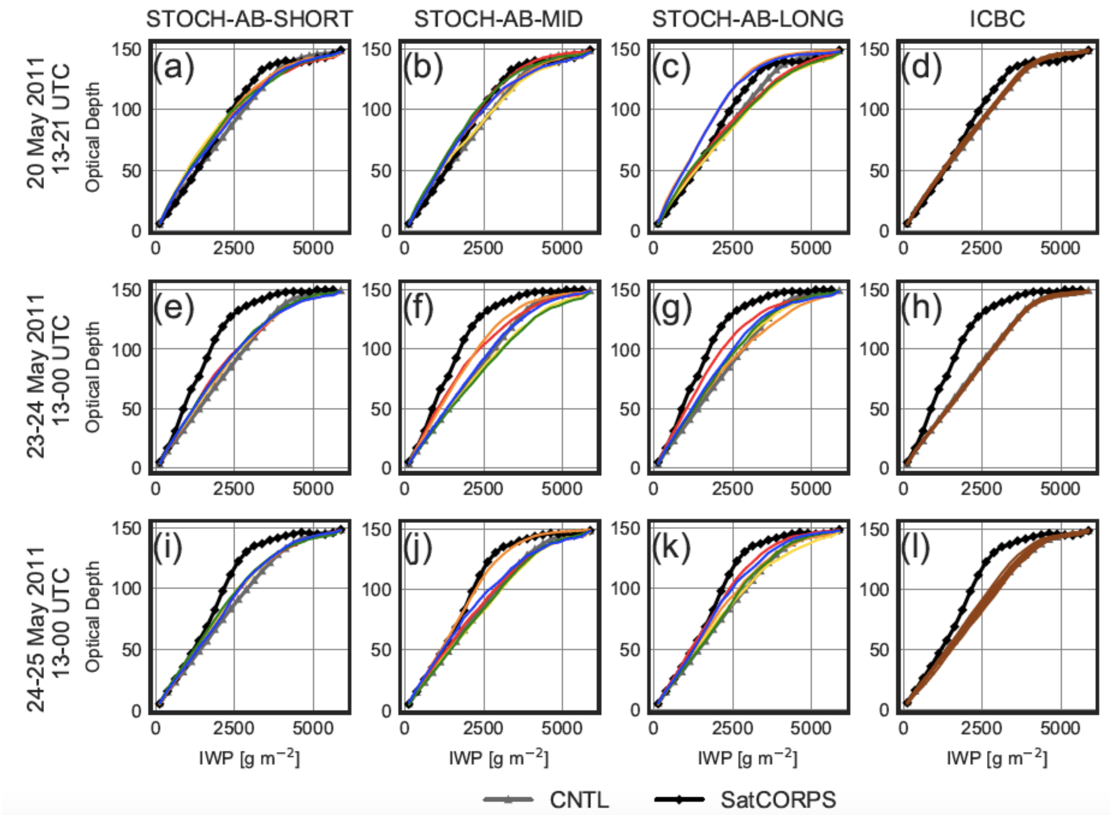

Figure 2. Average optical depth as a function of ice water path (IWP) for the stochastic *a-b* and ICBC ensemble WRF simulations for (a)-(d) 20 May, (e)-(h) 23-24 May, and (i)-(l) 24-25 May. Color coding indicates results for each of 5 stochastic microphysics ensemble members. “SHORT”, “MID”, and “LONG” indicates ensemble simulations using short, medium, and long spatiotemporal autocorrelation scales for the stochastic microphysical perturbations.

Stochastic subgrid-scale mixing in WRF

Ph.D. student Stanford, PI Morrison, and co-PI Varble developed a scheme to represent horizontal mixing stochastically in WRF and applied this in simulations of two MC3E convective cases, varying horizontal grid spacing from 500 m to 2 km. The “benchmark” was based on 100-m horizontal grid spacing large eddy simulations of these cases. Results showed some systematic effects of including stochastic mixing compared to non-stochastic control simulations, which in some cases brought results closer to benchmark large eddy simulations of these cases. Most notably, the stochastic simulations increased updraft dilution for a given updraft horizontal area compared to the control. The effects of stochastic mixing were generally largest at 2 km horizontal grid spacing, with somewhat less impact at 1 km and much less impact at 500 m, highlighting some “scale aware” behavior of the scheme. A paper covering this work was published in Monthly Weather Review (Stanford et al. 2020).

More recently, the stochastic subgrid-scale mixing scheme was tested in convection-permitting (3 km horizontal grid spacing) WRF simulations of a case from AMIE/DYNAMO. Two ensembles using the stochastic scheme with a short autocorrelation scale of the stochastic perturbations (STOCH_SHORT) and a long autocorrelation scale (STOCH_LONG) were compared with an ensemble with standard mixing scheme but small perturbations to the initial low level potential temperature (θ-pert), a simulation with no parameterized horizontal mixing (NO_MIXING), a simulation with eddy diffusion coefficient for horizontal mixing increased by a constant factor of 4 (4X), a 1 km simulation using standard mixing (BASELINE_1KM_CG), and AMIE/DYNAMO observations. The stochastic mixing scheme was found to generally increase mesoscale organization and convective intensity relative to a non-stochastic control simulation. Perturbations applied at relatively short autocorrelation scales induced differences relative to the control that were more systematic than those from perturbations applied at relatively long scales that yielded more variable outcomes (Fig. 3). The simulation with mixing enhanced by a constant factor of 4 significantly increased mesoscale organization and convective intensity, while turning off horizontal subgrid-scale mixing entirely decreased both (Fig. 4). Total rainfall was modulated by a combination of mesoscale organization, areal coverage of convection, and convective intensity. The stochastic simulations tended to behave more similarly to the constant enhanced mixing simulation owing to greater impacts from enhanced mixing as compared to reduced mixing. The impacts of stochastic mixing were robust, ascertained by comparison with the non-stochastic mixing ensemble that had grid-scale noise added to the initial thermodynamic field. Compared to radar observations and the higher resolution 1 km horizontal grid spacing simulation, the stochastic mixing seemingly degraded the simulation performance. These results imply that stochastic mixing produces non-negligible impacts on convective system properties and evolution but does not lead to an improved representation of convective cloud characteristics in the case studied here. A manuscript describing this work is in final stages of preparation with planned submission to *Monthly Weather Review* within the next month, authored by Stanford, Varble, and Morrison.

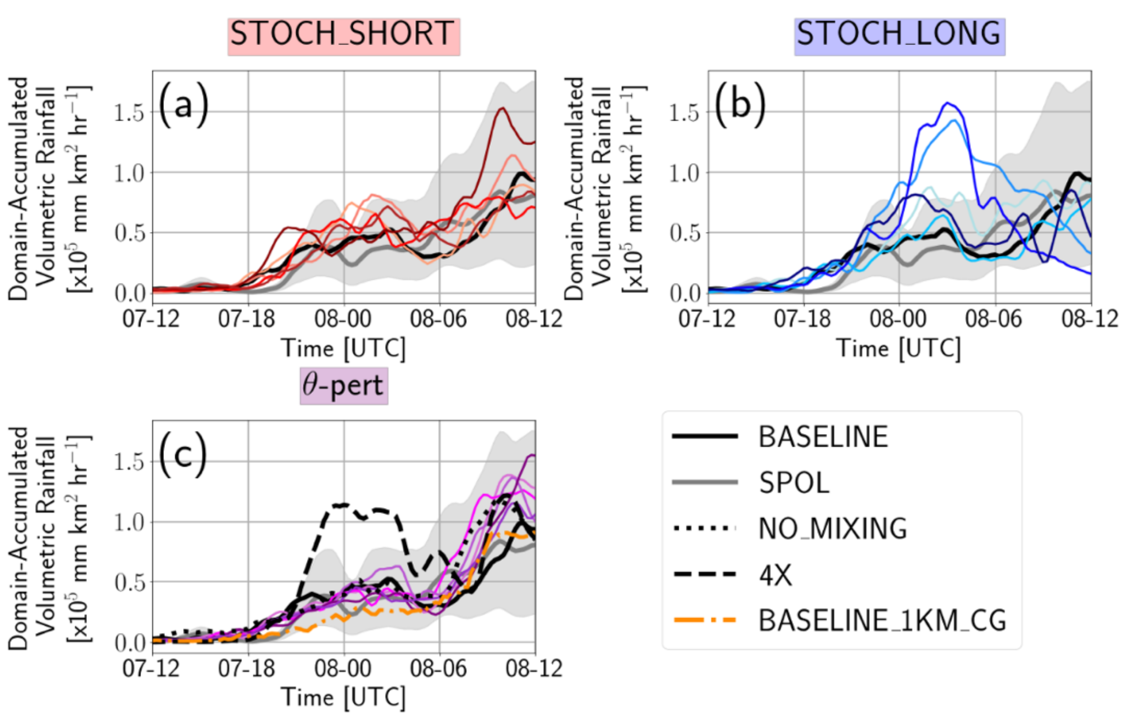

Figure 3. Time series of domain-total volumetric rainfall, limited to the SPOL domain, for the a) STOCH-SHORT, b) STOCH-LONG, and θ-pert ensembles. The other simulations with no parameterized horizontal mixing, 4 times mixing coefficient, and 1 km horizontal grid spacing simulation are shown in c).

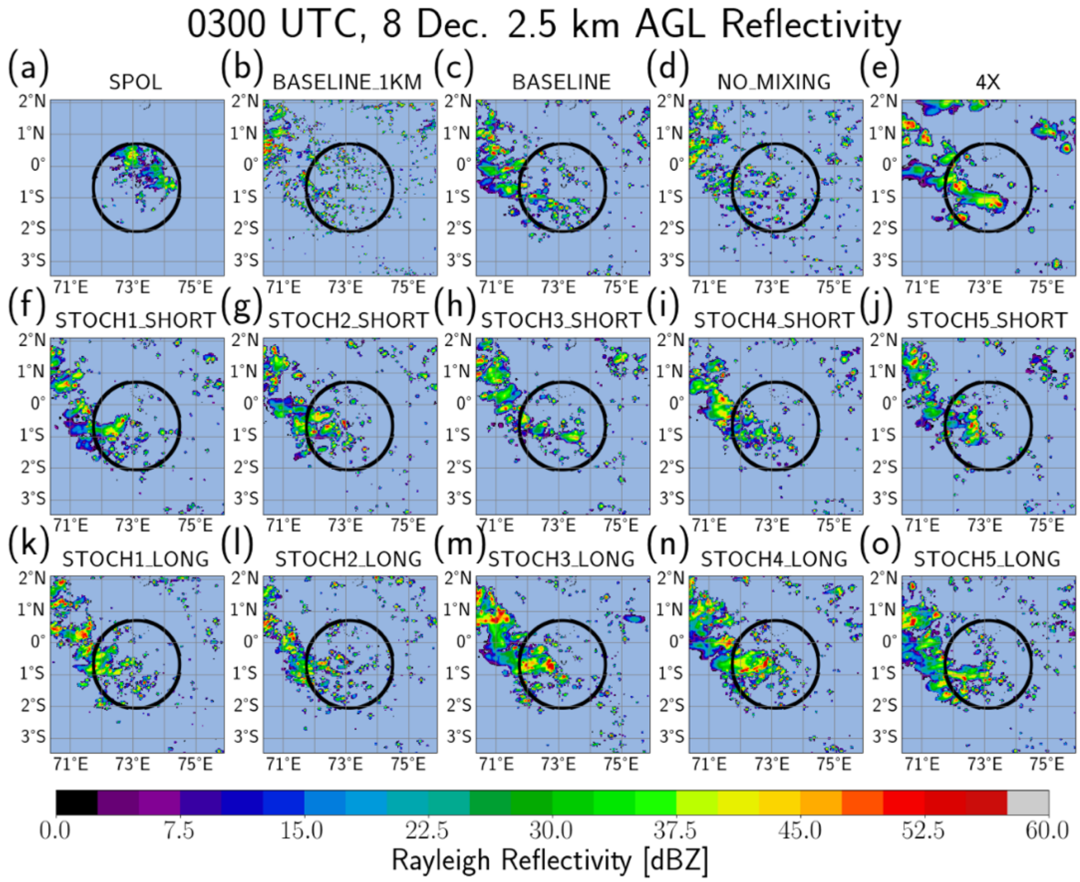

Figure 4. Horizontal cross sections at 2.5 km above ground level of a) observed and b-n) simulated radar reflectivity (using the P3 scheme in WRF) at 0300 UTC on 8 December. The SPOL 150-km radial distance range ring is shown by a black circle.

Effects of model grid spacing on updraft and downdraft dynamics for a MC3E squall line

A paper entitled "Effects of under-resolved convective dynamics on the evolution of a squall line" authored by co-PI Varble, PI Morrison, and co-I Zipser was published in *Monthly Weather Review*. This research was jointly supported by this grant, a previous ASR grant led by Zipser, and the ASR ICLASS SFA at PNNL. Motivated by increasing usage of cloud system resolving resolutions in weather and climate models, radar observations of a MC3E squall line event were used to evaluate the impact of WRF model horizontal grid spacing on squall line evolution. The higher resolution (250 m grid) run better reproduced the altitude and strength of the rear inflow and front-to-rear circulations in the squall line than the coarser resolution (750 m) run, which led to more upright deep convection like observed. This difference was traced back to the early stage deep convection that initiated before the squall line had formed. The 750-m simulation had a relatively greater number of wide and lesser number of narrow downdrafts than the 250-m run, a consequence of downdrafts being under-resolved in the 750-m run. This is consistent with previous literature highlighting a transition in convective draft properties between 500 and 250 m grid spacing for mid-latitude continental deep convection as typical convective draft sizes become resolved. Convective downdraft condensate mass, latent cooling, and downward motion all increase with downdraft area similarly in both simulations such that differences between the two runs are simply due to differences in the convective draft size distribution. Under-resolved downdrafts in the 750-m run are associated with under-resolved updrafts and transport mid-upper level zonal momentum downward to low levels too efficiently in the early stage deep convection. These results imply that under-resolved convective drafts in simulations may vertically transport air too efficiently and too far vertically, potentially biasing buoyancy and momentum distributions that impact mesoscale convective system evolution. The results also motivate the need for further research to determine how convective draft size biases in models with horizontal grid spacing of 0.5-5 km bias mesoscale convective evolution.

iii) University of Oklahoma/University of Illinois

The effort at Oklahoma/Illinois focused on analysis of observational data, comparison of bin-resolved simulations against observational data, use of statistical theory to describe the shapes of size distributions, and collaborative work with NCAR and Univ. Utah on the use of this analysis to develop parameterizations and evaluate model simulations. The four main thrusts of the work at Oklahoma/Illinois were as follows: a) use of maximum entropy theory to describe the analytical shapes of size distributions; b) examination of the effectiveness of bin-resolved simulations for predicting ice crystal size distributions and their variability; c) development of mass-dimensional relationships and their variability for use in model parameterization schemes; and d) development of velocity-dimensional relationships for use in model parameterization schemes. Other efforts involved using our knowledge of the MC3E observations to determine how incorporating aerosol profiles in simulations affect the predicted ice crystal properties (Fridlind et al. 2017) and how uncertainties in microphysical observations affect our understanding of mixed-phase clouds (Korolev et al. 2017).

Statistical theory on the analytical form of cloud particle size distributions

Several analytical forms of cloud particle size distributions (PSDs) have been used in numerical modeling and remote sensing retrieval studies of clouds and precipitation, including exponential distributions, gamma distributions, lognormal distributions, Weibull distributions, and others. However, prior to our work there was no satisfying physical explanation as to why certain distributions preferentially occur instead of others. Theoretically, the analytical form of PSDs can be derived by directly solving the general dynamic equation, but no analytical solutions have been found yet. Instead of the process level approach, the use of the principle of maximum entropy (MaxEnt) as a potential method for determining the analytical form of PSDs from the perspective of a system was examined. MaxEnt theory states that the probability density function with largest information entropy among a group satisfying the given properties of the variable should be chosen. Thus, we used MaxEnt theory to derive an analytic form of cloud PSDs. Our approach eliminated a problem related to the Gibbs/Shannon definition of entropy that existed in previous studies by using the concept of relative entropy. Our paper (Wu and McFarquhar 2018) showed that the 4-parameter generalized gamma distribution is the appropriate analytical form of PSDs using the principle of maximum (relative) entropy when assuming power law relations exist between state variables, and provided there is scale invariance and the constraint of one state variable. The four-parameter generalized gamma distribution is very flexible to accommodate various types of constraints that could be assumed for cloud PSDs. In a follow up paper, Wu and McFarquhar (2019) refuted fundamental misunderstandings about the principle of maximum entropy contained in a comment on the original paper.

Effectiveness of bin schemes for simulating PSDs and their variability

A mesoscale convective system (MCS) sampled on 20 May 2011 during MC3E was simulated using WRF with three different spectral bin microphysics schemes. The simulated ice cloud PSDs and their variability were compared against those measured in-situ using a two-dimensional cloud probe and a high volume precipitation spectrometer on the University of North Dakota Citation aircraft in the trailing stratiform region behind the MCS. The observed and simulated PSDs were fit to gamma distribution functions with three parameters using the incomplete gamma fit (IGF) routine to determine the intercept (N_0), slope (μ) and shape (λ) parameters. The dependence on environmental conditions of the gamma parameters as ellipsoids of equally realizable solutions in the parameter phase space (N_0, μ, λ) was compared between the three bin schemes and the in-situ observations. Large differences in PSDs were found among the three bin schemes and between the simulations and observations, including the median PSD form, their natural variabilities under similar environmental conditions and their dependence on temperature. Assumptions about the particle properties (such as mass/terminal velocity-dimensional relations, etc.) and representations of microphysical processes, such as nucleation, diffusional growth and aggregation growth, in different bin schemes were investigated to explain the differences between models and in-situ observation. This study was a major component of the Ph.D. Thesis of Wei Wu at the University of Illinois, and extended the analysis presented in Xue et al. (2017) described above.

Mass-Dimensional relationships for ice hydrometeors

Mass-dimension (*m-D*) relationships are used to derive bulk microphysical properties such as ice water content (*IWC*) and radar reflectivity (*Z*) within numerical models. The most common way of estimating *a-b* coefficients used in $m=aD^b$ relationships is to minimize the difference between the *IWC* or *Z* derived from number distribution functions and that directly measured by a bulk water probe or radar. These *a* and *b* values, however, can vary significantly based on meteorological conditions, particle habit, definition of particle maximum dimension *D*, probes used to obtain the data, or even the techniques used to process the cloud probe data. In order to investigate how these a and b values vary with environmental conditions, we (Finlon et al. 2019) used microphysical data collected by two-dimensional optical array probes (OAPs) installed on the University of North Dakota Citation aircraft during MC3E in conjunction with *TWC* data from the Nevzorov probe (the *TWC* is equivalent to *IWC* for ice-phase clouds) and ground-based radar data at S-band to test a novel approach that determines *m-D* relationships for a variety of environments. A surface of equally realizable *a* and *b* coefficients in (*a,b*) phase space was determined using a technique that minimizes the chi-squared difference between the *IWC* or *Z* derived from the size distributions measured by the OAPs and that directly measured by a *TWC* probe or radar, accepting as valid all coefficients within a specified tolerance of the minimum chi-squared difference. Figure 5 shows surfaces of equally realizable *a* and *b* coefficients for near constant temperature flight legs within trailing stratiform regions of MCSs sampled on different days during MC3E. The surfaces demonstrate how the environmental conditions and spatial and temporal variability within clouds control the *a*-*b* coefficients. This work was a large component of Joe Finlon's Ph.D. Thesis at the University of Illinois.

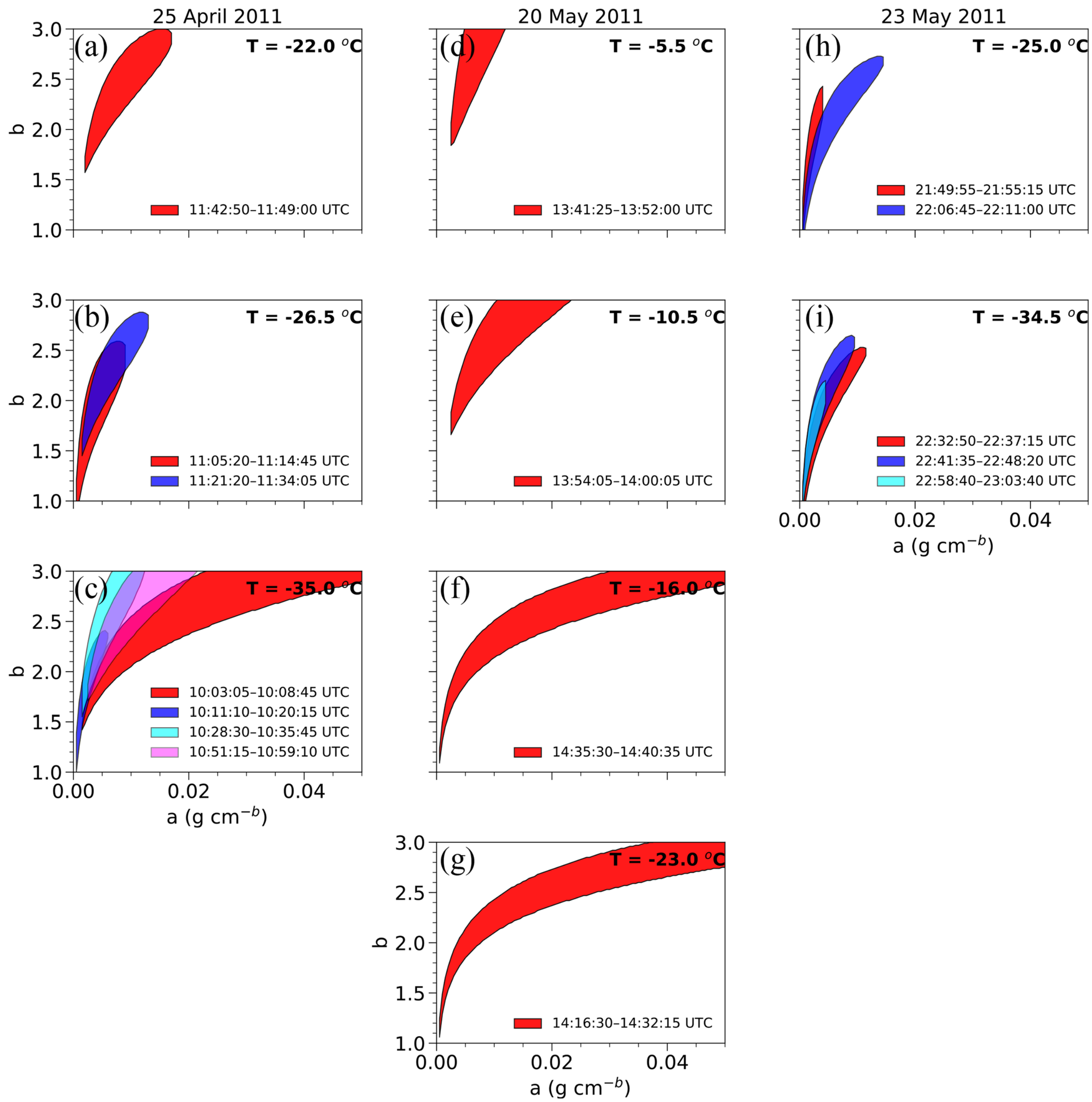

Figure 5: Surfaces of equally plausible a and b values for near-constant-temperature flight legs for (a–c) 25 April, (d–g) 20 May, and (h–i) 23 May 2011 events. Multiple legs occupying the same temperature are assigned a different color within a panel.

In order to use the surface of equally plausible realizations of (*a,b*) in model simulations, it is necessary to stochastically choose realizations of (*a,b*) and subsequently derive microphysical properties. However, it is also necessary to evaluate the spatial autocorrelation of properties derived from these stochastic (*a,b*) solutions because this may ultimately affect their use in model parameterization schemes. The spatial autocorrelation of median-mass diameter (D_{mm}), derived from 5 stochastic (*a,b*) solutions for one event during MC3E, is shown in Fig. 6. This analysis served as guidance for the stochastic simulations conducted at the University of Utah described above.

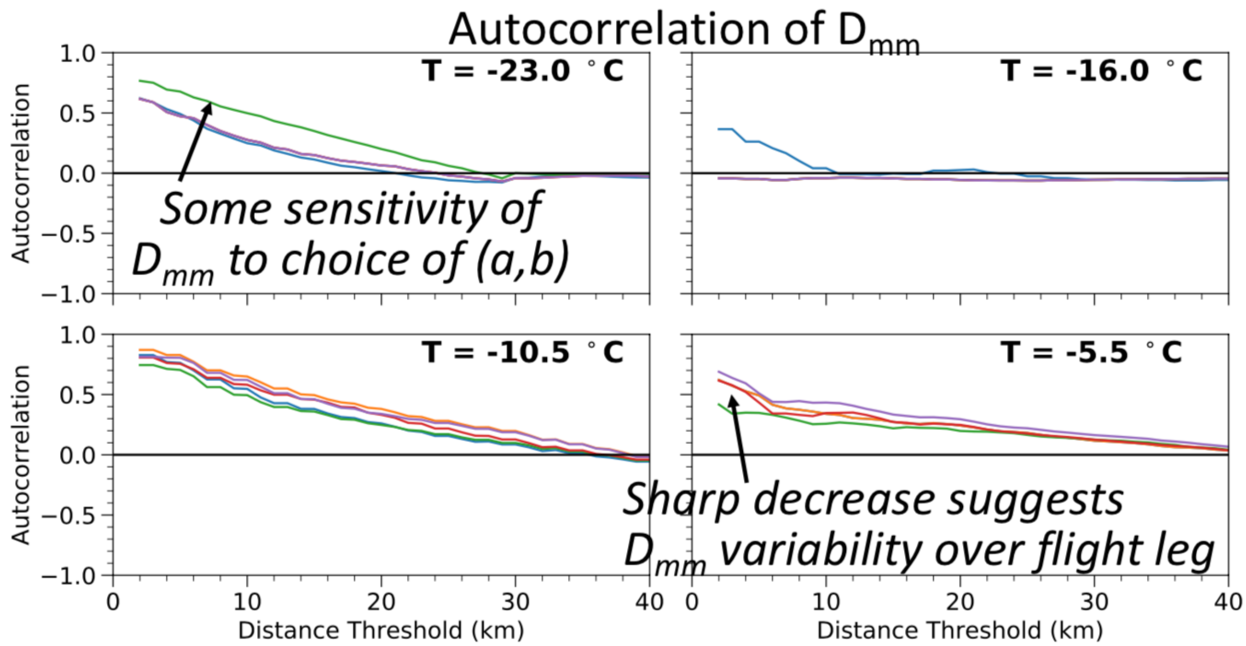

Fig. 6. *Autocorrelation of D_{mm} as a function of varying distance at which the autocorrelation is computed. Different colors represent 5 stochastic a-b solutions from surface of equally plausible solutions.*

Fall Velocity-Dimensional Relationships

Ice particle fall speed (V) is fundamental for determining microphysical processes, yet remains extremely challenging to measure. Current theoretical "best estimates" of ice particle terminal velocity (V_t) are available as functions of Reynolds number, area ratio (A_r) and maximum dimension (D_{max}), and thus not conducive for use in models. Many model parameterizations take the form $V=\alpha D_{max}^{\beta}$ where (α,β) depend on habit and D_{max}. Recently hired postdoctoral research associate Andrew Dzambo has extended the work started by Joe Finlon to develop fall velocity dimensional relationships using stochastic realizations of (α,β) parameters describing $V=\alpha D^{\beta}$. In a paper to be soon submitted to the *Journal of the Atmospheric Sciences*, Dzambo et al. (2021), the Finlon et al. (2019) framework is implemented to determine surfaces of equally plausible (α,β) coefficients, by combining 10-s averaged ice particle size and shape distributions obtained during two flights of MC3E with V_t estimates to determine mass- (V_m) or reflectivity-weighted (V_Z) velocities that calculated using (α,β) coefficients are forced to closely match using two approaches.

The first approach uses surfaces of equally plausible (a,b) coefficients describing mass (M)-dimension relationships (i.e. $M=aD_{max}^{b}$) to calculate 10-s mass- ($V_{M,SD}$) or reflectivity ($V_{Z,SD}$) weighted velocity from size/shape distributions that are then used to determine (α,β) coefficients giving best agreement between $V_{M,Z}$ and $V_{M,Z;SD}$. A wide range of (α,β) produce $V_{M,Z;SD}$ statistically similar to flight leg $V_{M,Z}$. The second approach investigates how uncertainties in A_r,

D_{max}, and PSDs affect $V_{M,Z}$. For seven of nine flight legs, variability exceeds uncertainties arising from different A_r assumptions in generating the (α,β) coefficients. The combined uncertainty between A_r, D_{max} and PSDs produced smaller variability in (α,β) coefficients compared to varying M(D). These results demonstrated the value of accurately quantifying M(D) to accurately model mass-weighted fall velocities. Results also demonstrate that the primary sources of uncertainty vary considerably between meteorological and environmental sampling conditions, and suggest that further studies are needed in a variety of geographic locations.

c. Opportunities for training and professional development

This project directly supported 3 PhD students at the University of Illinois, University of Utah, and University of Oklahoma (Wei Wu, McKenna Stanford, Joseph Finlon). Wu, Finlon, and Stanford completed PhDs during the course of this project. Mentoring was also provided to a postdoc at the University of Oklahoma (Andrew Dzambo) and to Wei Wu when he started his research scientist position at the University of Oklahoma.

d. Dissemination of results to communities of interest

See the list of papers published in "Products". This work has been presented at several conferences and workshops. Several ARM/ASR research highlights were also published based on the work supported from this project. We have developed the new stochastic microphysics and subgrid scale mixing parameterizations in a widely-used community model (WRF), which will facilitate dissemination of the code to other interested parties, and potentially the wider community if they are eventually made standard in the public version of WRF.

2. Products

Peer-reviewed papers acknowledging support from this grant:

Abade, G. C., W. W. Grabowski, and H. Pawlowska, 2018: Broadening of cloud droplet spectra through eddy hopping: turbulent entraining parcel simulations. *J. Atmos. Sci.*, 75, 3365-3379.

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3. Impacts

a. Impact on the development of the principal discipline of the project

Our project extended an approach previously developed to characterize the variability in ice particle size distributions to microphysical parameters that are explicitly represented in model parameterization schemes (i.e., relationships between mass and particle maximum dimension, and between fall velocity and particle maximum dimension). Our project is, to our knowledge, the first to apply observationally-constrained estimates of stochastic parameter variability describing mass-dimensional and fall velocity-dimensional in a modeling framework. Our results showed efficacy of the approach, evaluated using ARM observations. Similarly, to our knowledge, work in this project was the first to propose and evaluate in detail a stochastic subgrid-scale mixing scheme for convection-permitting model simulations against large eddy simulations and ARM observations. Results showed some promising behavior, particularly with increased mixing and dilution of deep convective updrafts bringing the stochastic simulations closer to the large eddy simulations; however, results were somewhat degraded using stochastic mixing compared to AMIE/DYNAMO observations. Work on this project also developed a stochastic condensation scheme designed for Lagrangian microphysics, which represents an important advance; Lagrangian microphysics is an emerging modeling approach that holds considerable promise as outlined in our review papers on microphysical modeling (Grabowski et al. 2019; Morrison et al. 2020). This project also supported additional work that further refined and applied a modeling methodology called "piggybacking" that can robustly separate dynamical and thermodynamic impacts of microphysical (or other model) changes, and model intercomparison studies based on cases developed from ARM observations. Finally, this project directly supported three graduate students who completed their PhDs as well as a postdoctoral research fellow.

b. Impact on technology transfer

This project contributed to developments of a new stochastic microphysical scheme in the WRF community model, and a stochastic mixing scheme in WRF. It also contributed to further development and testing of the P3 microphysics scheme in WRF (and more recently implemented in E3SM supported by the DOE).