Abstract

Detailed observations from DOE ARM field campaigns were used to evaluate and improve microphysical and dynamic fields simulated by 3D Cloud Resolving Models (CRMs), employing both bulk and size-resolved bin microphysics. One of the main challenges in bridging the gap between observations and models is placing the analysis in a common framework. To address this, a polarimetric radar simulator was built, consisting of a forward operator to calculate model-consistent polarimetric radar fields, and an analysis package to calculate microphysical and dynamic fields from radar data in a self-consistent manner. The assumptions required for the transformation from model output to radar parameters were carefully considered and tested. It was found that although rain is fairly well captured by the forward model, ice characteristics are difficult to constrain. This polarimetric radar simulator, POLArimetric Radar Retrieval and Instrument Simulator (POLARRIS), was then applied to WRF simulations and polarimetric C-band radar observations from Darwin, Australia and the SGP site in Oklahoma. These two locations contrast maritime and mid-latitude continental convection respectively. POLARRIS was used with NASA Unified WRF simulations of the same storms in order to compare the observed land and ocean contrasts in microphysics and dynamics. An improved model framework for dynamic downscaling of large-scale aerosol products was also developed and applied to the NASA Unified WRF (NU-WRF) cloud resolving model. This improved framework was used to explore the effects of thermodynamic and aerosol invigoration in deep land and ocean convection through a series of sensitivity studies by perturbating aerosol (CCN) and convective available potential energy (CAPE). It was found that increases in aerosol concentrations yielded increases in low-density graupel in the maritime case and high-density hail in the continental case through riming by increased supercooled water. This result implies that native differences in aerosol concentrations may enhance the inherent contrast in riming effects between deep convective systems in the maritime and continental conditions. Formal publications were generated describing this research.

Report Body:

The overall goal of this project was to use detailed observations from multi-sensor polarimetric radars from DOE ARM field campaigns to evaluate and improve microphysical and dynamical fields simulated by 3D Cloud Resolving Models (CRMs), using both bulk and size-resolved "bin" microphysics. We aimed to look at a variety of regimes, spanning continental convection to maritime convection. Utilizing the improved model framework (dynamic downscaling the large-scale aerosol products), we then evaluated the sensitivity of deep convection to varying aerosol (CCN) and convective available potential energy (CAPE) perturbations.

We have completed the development and evaluation of a polarimetric radar simulator for cloud resolving models, the POLArimetric Radar Retrieval and Instrument Simulator (POLARRIS) framework. POLARRIS is our primary means for validating cloud microphysical fields simulated by numerical models, that is, to compare the same quantities (such as w, mixing ratio, or hydrometeor identification) between model and observations (for the same case storm being simulated).

POLARRIS is composed of POLARRIS-f (forward radar simulator) and iPOLARRIS (the inverse radar algorithm) components. POLARRIS-f is capable of simulating polarimetric-radar observables (Z_h, Z_{dr}, K_{dp}, ρ_{hv}) as well as radial and Doppler velocities from NU-WRF output. We worked extensively to determine the most appropriate assumptions for the scattering calculations, including axis ratios and canting angle distributions which yielded the closest results to observations for the polarimetric radar parameters. However, we found that the breadth of K_{dp} and Z_{dr} in ice could not be captured with single axis ratio or canting angle assumptions. Direct solutions of T-matrix and Mueller matrix by integrating size and particle type required significant computational time (8 wall-clock hours with 1600 CPUs). Thus, we developed an extremely efficient look-up table approach to interpolate pre-computed T- and Mueller-matrix values as a function of radar frequency (X-, C- and S-band), elevation angle, temperature, and particle type (e.g., hail, graupel, snow aggregates, rain, etc.) for prescribed canting angle distributions and particle axis ratios. As a result, we realized a factor of 8000 in computational efficiency such that a single CPU can calculate radar observables from standard WRF output within a few minutes.

iPOLARRIS is a set of retrieval algorithms that can be executed on either simulated model data through POLARRIS-f output or on polarimetric and (multi-) Doppler radar observations. This streamlined framework allows for the mutual benefit of validating radar retrieval algorithms and /or model microphysics and dynamics. For example, polarimetric observations can be synthesized by fuzzy logic hydrometeor identification (HID) in order to identify the most dominant hydrometeor type within a radar echo volume. The assumptions made in the HID can be tested for consistency with model fields (such as mixing ratios of various species), and the simulated polarimetric HID can be analyzed against observations for understanding different model microphysical schemes. *The iPOLARRIS framework also allows for streamlined statistical analysis of model and observations, such as Constant Frequency by Altitude Diagrams (CFADs), echo top heights, and vertical velocity.*

We identified storm cases extracted from the Midlatitude Continental Convective Cloud Experiment (MC3E) and the Tropical Warm Pool – International Cloud Experiment (TWP-ICE) and conducted Weather Research and Forecasting (WRF) model simulations with the Goddard 4-ICE scheme and spectral bin microphysics (SBM) configurations. These simulations have been compared to field observations of these same cases using the POLARRIS framework described earlier. The WRF coupled with the SBM (WRF-SBM) model was updated including a unique interface for coupling between the model and the NASA-based Modern Era Retrospective-Analysis for Research and Applications Aerosol (MERRA) re-analysis package. The interface is based on the Aerosol Loading Interface for Cloud Microphysics In Simulation (ALICIS). The four-types of aerosols in MERRA Aerosol, i.e., dust, sea-salt, sulfates, organic/black carbon, are introduced with prescribed particle size distribution functions into WRF-SBM and used to calculate the nucleation process of cloud particles. This implementation enables more realistic cloud resolving simulation interacted with atmospheric aerosols through the dynamical downscaling approach using the aerosol re-analysis variables in MERRA Aerosol. The model improvements described above have greatly facilitated our work to investigate aerosol invigoration of deep convection.

Under support of this project, we have published two manuscripts with two additional papers conditionally accepted. The first paper, Dolan et al. (2018; *J. Atmos. Sci*.) used world-wide observations of drop size distributions to identify systematic microphysical processes across the low, mid- and high latitudes. The drop size parameters derived from this unique and robust dataset are used to underpin and inform drop size distributions assumptions in bulk models. The second paper, Matsui et al. (2019; JGR) reported on the model simulations, the development of POLARRIS, and POLARRIS applications to compare model and observations to assess the performance of the various model microphysical packages. The conditionally accepted paper, Iguchi et al. (2019; JGR) describes a modeling study to assess the impacts of aerosol (CCN) and CAPE perturbations on deep convection using cases observed during two DOE ARM field campaigns cases, MC3E and TWP-ICE. This paper applied a new approach using dynamic aerosol downscaling from global aerosol reanalysis to represent aerosol fields (base cases and aerosol perturbations) in WRF-SBM. It was found that increases in aerosol concentrations yielded increases in low-density graupel in the maritime case and high-density hail in the continental case through riming by increased supercooled water. This result implies that native differences in aerosol concentrations may enhance the inherent contrast in riming effects between deep convective systems in the maritime and continental conditions. The second conditionally accepted paper investigates differences between land and oceanic deep convection, and finds that both WRF bulk and size-resolved bin simulations are able to reproduce the contrast seen in radar observations. Sensitivity studies are conducted by swapping the aerosol profiles between the land and ocean cases to show that aerosols play an important role in shaping the land-ocean constrats.

The project provided support for one M.S. level graduate student. Julie Barnum was supported by this project starting Fall 2015, and she completed her M.S. thesis in November 2017. Ms. Barnum gained considerable knowledge about polarimetric radar data under this project support, as well as an introduction to modeling. She conducted a number of simulations to examine the sensitivity of polarimetric variables and Hydrometeor Identification algorithms to basic input parameters such as shape, orientation and bulk density. Her work has served to underpin the development of POLARRIS, our polarimetric radar translator used to derive a full suite of polarimetric variables from NU-WRF microphysical output.

Journal Publications

Dolan, B., B. Fuchs, S.A. Rutledge, E.A. Barnes, and E.J. Thompson, 2018: Primary Modes of Global Drop Size Distributions. *J. Atmos. Sci.,* **75**, 1453–1476, https://doi.org/10.1175/JAS-D-17-0242.1

Matsui, T., B. Dolan, S. A. Rutledge, W.-K. Tao, T. Iguchi, J. Barnum and S. Lang, 2019: Polarris APOLArimetric Radar Retrieval and Instrument Simulators, *J. Geophys. Res*., https://doi.org/10.1029/2018JD028317.

Matsui, T., **B. Dolan**, T. Iguchi, S. A. Rutledge, W.-K Tao, and S. Lang, 2019: Polarimetric radar characteristics of simulated and observed intense convective cores between continental and martime enviornments. *J. Hydromet., (conditionally accepted).* https://www.dropbox.com/s/48phe8kr4rqddgn/LO_Contrast_POLARRIS_BODY_SUBMIT.docx

Iguchi, T., S. A. Rutledge, W.-K. Tao, T. Matsui, B. Dolan, S. Lang, and J. Barnum, 2019: Impacts of aerosol and environmental conditions on maritime/continental deep convective systems: Control and sensitivity experiments using a bin microphysical model. *J. Geophys. Res.*, (conditionally accepted). https://drive.google.com/open?id=12Te0qGErDjVLRqkbl6upogvqEvuLvZYl

Conference proceedings:

Dolan, B., S. A. Rutledge, J. I Barnum, T. Matsui, W.-K. Tao, and T. Iguchi, 2017: Investigation of hydrometeor classification uncertainties through the POLARRIS polarimetric radar simulator. *Amer. Geo. Union Fall Meeting,* New Orleans, 11-15 December 2017.

Dolan, B., B. Fuchs, S. A. Rutledge, E. Barnes, 2016: GPM Ground Validation DSD variability as revealed from empirical orthogonal function analysis. *Amer. Geo. Union Fall General Meeting*, San Francisco, CA, 12-16 December 2016.

Matsui, T., B. Dolan, W.-K. Tao, S. A. Rutledge, T. Iguchi, J. I. Barnum, and S. E. Lang, 2017: Polarimetric radar characteristics of simulated and observed severe convective cores between MC3E and TWP-ICE . *USRI GASS,* Montreal, CA, August 19-26, 2017.

Matsui, T., B. Dolan, W.-K. Tao, S. A. Rutledge, T. Iguchi, J. I. Barnum, and S. E. Lang, 2017: Polarimetric radar characteristics of simulated and observed intense convection between continental and maritime environment. *American Geophysical Union,* New Orleans, 11-15 December 2017.

Matsui, T., B. Dolan, S. Rutledge, W.-K. Tao, T. Iguchi, S. Lang, J. Barnum, 2018: Land-ocean contrast of intense convection from TRMM satellite and polarimetric radar measurements. *Asia Ocean. Geo. Soc.*, 3-8 Jun, Honolulu, Hawaii.

Iguchi, T., T. Matsui, W-. K. Tao, S. Lang, S. A. Rutledge, B. Dolan, and J. Barnum, 2018: WRF-SBM simulations of maritime and continental deep convective systems through aerosol dynamical downscaling from MERRA global aerosol reanalysis. *AMS 15th Conference on Cloud Physics*, Vancouver, BC, 9 – 13 July 2018.

Rutledge, S. A., T. Iguchi, T. Matsui, J. Barnum, W.-K. Tao, B. Dolan and S. Lang, 2018: Investigating the Sensitivity of Tropical and Mid-latitude Deep Convection to CAPE and CCN Changes. *2018 ASR PI Meeting,* Tyson's Corner, VA, 19-23 March.

Theses:

Barnum, J., 2017: Investigations of the Uncertainties Associated with HID Algorithms and Guiding Input to a Novel, Synthetic Polarimetric Radar Simulator. M.S. Thesis, Atmospheric Science, Colorado State University, Fort Collins, CO, November 2017.

Software:

POLArimetric Radar Retrieval and Instrument Simulator (POLARRIS)
http://radarmet.atmos.colostate.edu/polarris/