Final Report

Project Title:
Improving parameterization of ice microphysical processes in Arctic clouds using a synergistic modeling and observational approach

Federal Award Identification Number:
DE-SC0018933

Project Period:
8/15/2018 – 8/14/2022

Principal Investigator Information:
Dr. Matthew R. Kumjian
Associate Professor of Meteorology
503 Walker Building
University Park, PA 16802
Email: kumjian@psu.edu
Contact: (814)-863-1581

Recipient Organization:
The Pennsylvania State University
110 Technology Center
University Park, PA 16802-7000, USA
DUNS: 003403953
EIN: 246000376

Submitting Official Information:
Dr. Matthew R. Kumjian
Associate Professor of Meteorology
503 Walker Building
University Park, PA 16802
kumjian@psu.edu
814-863-1581

ACCOMPLISHMENTS

1. What are the major goals of the project?

The primary goals of the project were to:

1) Improve the fundamental quantitative models of ice growth processes using ARM radar observations.
2) Better understand the growth of ice particle populations through vapor deposition, riming, and aggregation in Arctic clouds using a new particle-property microphysical model.
3) Robustly estimate and constrain key unknown model parameters using ARM radar observations combined with the particle-property model to develop an improved parameterization of ice growth processes for traditional bulk parameterizations used in cloud and climate models.

2. What was accomplished under these goals?

Over the course of the project, we made substantial progress towards achieving our main goals.

As a first step towards quantitatively using ARM radar observations for improving model physics, we developed a polarimetric radar forward operator for snow crystals (Schrom and Kumjian 2019, *JAMC*) that accounts for the natural variability in branched ice crystal shapes, allowing for probabilistic treatment of particle properties not accounted for in microphysical model. In this way, we respect the uncertainty of the mapping between the model and radar observables; other approaches rigidly constrain this uncertainty by *a priori* assumptions built into the forward operator.

We used this forward operator, coupled with XSAPR observations from the DOE site in the Arctic, to improve the formulation of vapor deposition density for growing ice crystals (Schrom et al. 2021, *JAS*). Using this new formulation, we demonstrated how a Bayesian inference framework known as Monte Carlo Markov Chain (MCMC) can be used to simultaneously estimate the values of numerous uncertain microphysical parameters in a detailed particle property growth model, as well as provide quantitative estimates of their uncertainty. This model was constrained by KAZR and XSAPR observations of a vapor deposition case in the Arctic (Schrom et al. 2021, *JAS*).

The team developed a new snow aggregation parameterization for use in the particle property model (Dunnavan et al. 2019, *JAS*), which was based on Multi-Angle Snow Camera (MASC) observations from the Arctic site. This parameterization better predicts the natural shape and density evolution of ice particles as they conglomerate into single aggregates. Further, a follow-on study (Dunnavan 2021, *JAS*) demonstrated how allowing for this natural variability in aggregate shape leads to feedbacks in terms of variability of snow particle fall speed and subsequent aggregation rates.

The combined improvements to snow aggregation and vapor growth models were used in conjunction with the MCMC framework to provide improved estimates of the model parameters as well as robust estimates of the parameter uncertainty (van Lier-Walqui et al. 2018, Kumjian et al. 2019a,b; Dunnavan et al. 2021, conference presentations). Using XSAPR and KAZR data from the Arctic, we showed how the combination of (i) ice production aloft, possibly owing to secondary ice production (SIP) processes, and associated aggregation, and (ii) ice nucleation below this layer leads to an often-observed polarimetric signature in snow-bearing clouds. This work has not been published yet.

The identification of model-indicated secondary ice production processes motivated our PhD student (Sara Wugofski) to explore the feasibility of using radar observations to identify these regions in Arctic clouds. Over the last year, Sara has developed and implemented a novel algorithm to use moment data from KAZR to identify possible times of secondary spectral modes. The algorithm can be run on years' worth of data rather quickly, helping to mitigate the massive spectral data downloads that has limited their use. As part of her analysis of several years' worth of KAZR data in the Arctic, Sara has found a large fraction of secondary spectral modes occur in the dendritic growth zone (temperatures roughly between -10 and -20 degrees Celsius). This suggests either active primary ice nucleation in this layer, or collisional fragmentation of branched planar crystals. Follow-up modeling efforts are underway to elucidate the processes leading to these signatures. Sara's work has been presented at several conferences (Wugofski et al. 2020, 2021a,b; 2022a,b,c), and a manuscript is under preparation for submission in Spring 2023.

The successful approach of combining Bayesian inference with radar observations (specifically, dual-polarization and/or Doppler radar observations) for quantifying microphysical model parameters and their uncertainty has also been highlighted in two review works (Morrison et al. 2020, *JAMES*; Kumjian et al. 2022, *Remote Sensing*).

3. What opportunities for training and professional development has the project provided?

The project supported the tail end of two PhD graduate students at Penn State (Robert Schrom and Lee Dunnavan). Both successfully defended their PhDs in the 2018-2019 academic year.

The project has also supported the PhD studies of Sara Wugofski, who joined the group in Fall 2019. The award supported Sara's travels and participation in several national conferences, including the annual ASR Science Team Meetings in 2021 and 2022. I am proud to note that Sara is active in outreach activities at Penn State, including having lead the department's Society for Supporting Women in Meteorology (SSWIM) for the 2021-2022 academic year.

4. How have the results been disseminated to communities of interest?

Our results have been disseminated to the community in 6 peer-reviewed articles that are published, as well as 10 conference or workshop presentations, including at the annual ASR Science Team Meetings. In addition, there is a manuscript under preparation to be submitted in Spring 2023 (Wugofski et al., in prep, to be submitted to *JTECH*). A complete list of these products has been updated and included in the DOE PAMS listing for this award; if there is an issue accessing these products, a list can be provided in standard bibliographic form.

IMPACT

What is the impact on the development of the principal discipline(s) of the project?

Our project was a novel synthesis of cloud microphysical modeling, advanced radar observations, and Bayesian inference. As such, we believe its impact was felt beyond the traditionally narrow scope of specialized research.

The improved vapor depositional growth and aggregation models are being used by other students at Penn State, and there are plans to incorporate the latest versions of these schemes into the ISHMAEL package (which is currently available in WRF). The effort towards this has slowed a bit since the main developer (Anders Jensen) quit NCAR and the field entirely, but co-PI Jerry Harrington is working with collaborators at NCAR to help see this through. We expect the improvements to these processes to lead to more realistic treatments of Arctic mixed-phase clouds in particular, but, because these processes are universal in cold clouds, there should be improvements to a wide range of cloud systems and models of different scales.

The Bayesian inference plus radar observational constraint framework we successfully demonstrated is exciting to many in the remote sensing and modeling communities because, for the first time, we may now *quantitatively* use microphysical fingerprinting to constrain or evaluate model parameterization schemes (see, e.g., Kumjian et al. 2022, *Remote Sensing*). Further, the information gained helps fill gaps of knowledge about fundamental microphysical processes (e.g., aggregation) that will be used widely in models and remote sensing retrievals.

The efficient method for identifying multimodal Doppler spectra will be widely applicable for researchers, including those interested in drizzle formation, secondary ice production, primary ice production, and other complex cloud systems known to exhibit bi- or tri-modal spectra. Sara's conference presentations have stirred up some excitement, particularly by folks in the radar community.