Final DOE-ASR Report for the Project "Advancing our Understanding and the Remote Sensing of Ice Clouds" Award No. DE-SC0008871

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Executive Summary

This project has evolved during its execution, and what follows are the key project findings. This project has arguably provided the first global view of how cirrus cloud (defined as having cloud base temperature T < 235 K) nucleation physics (evaluated through satellite retrievals of ice particle number concentration $N_{i,}$ effective diameter D_e and ice water content IWC) evolves with the seasons for a given temperature, latitude zone and surface type (e.g. ocean vs. land), based on a new satellite remote sensing method developed for this project. The retrieval method is unique in that it is very sensitive to the small ice crystals that govern the number concentration N_i, allowing N_i to be retrieved. The method currently samples single-layer cirrus clouds having visible optical depth ranging from about 0.3 to 3.0, using co-located observations from the Infrared Imaging Radiometer (IIR) and from the CALIOP (*Cloud and Aerosol Lidar with Orthogonal Polarization*) lidar aboard the CALIPSO (*Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation)* polar orbiting satellite, employing IIR channels at 10.6 µm and 12.05 µm. Retrievals of N_i are primarily used to estimate the cirrus cloud formation mechanism; that is, either homo- or heterogeneous ice nucleation (henceforth hom and het). This is possible since, in general, hom produces more than an order of magnitude more ice crystals than does het. Thus the retrievals provide insight on how these mechanisms change with the seasons for a

given latitude zone or region, based on the years 2008 and 2013. Using a conservative criterion for hom cirrus, on average, the sampled cirrus clouds formed through hom occur about 43% of the time in the Arctic and 50% of the time in the Antarctic, and during winter at mid-latitudes in the Northern Hemisphere, hom cirrus occur 37% of the time. Elsewhere (and during other seasons in the Northern Hemisphere mid-latitudes), this hom cirrus fraction is lower, and it is lowest in the tropics. Thus, the microphysical properties of cirrus clouds in the Polar Regions are much different than they are in the tropics; something unknown prior to this study. Moreover, the frequency of cirrus cloud occurrence in the Polar Regions varies strongly with season, peaking during winter in the Arctic and during spring in the Antarctic. Considering these seasonal changes in microphysics and inferred cloud coverage, this leads us to speculate that the buildup of Arctic cirrus during winter may significantly contribute to tropospheric heating in that region, possibly affecting winter jet-stream dynamics and mid-latitude weather patterns through the thermal-wind balance relationship.

This cirrus cloud research provides essential guidance for realistically representing cirrus clouds in climate models; guidance previously unavailable. For example, mid-latitude hom cirrus were widespread during winter over or nearby mountainous terrain, evidently due to mountain-induced waves that produce strong updrafts at cirrus cloud levels. The treatment of turbulent mountain stress and gravity waves will likely need to be improved in climate models in order to adequately represent cirrus clouds outside the tropics.

Another goal of this project was to develop a ground-based 94-GHz radar retrieval for winter snowstorms, based on (1) an improved analytical framework describing the interaction of radiation from radar with snowfall and (2) the development of a steady-state snow growth model that predicts the height-evolution of the ice particle size distribution through ice particle growth by vapor diffusion, aggregation and riming (i.e. the growth of snow through collisions with supercooled cloud droplets). Although activities (1) and (2) were completed, there was insufficient time to test and finalize the radar retrieval scheme. However, activity (2) provided a new method for relating ice particle mass “m” and projected area “A” to the ice particle maximum dimension “D”. The ice cloud microphysical processes (which determine ice cloud radiative properties) in climate models are parameterized in terms of these m-D and A-D relationships. By improving these relationships, the ice cloud radiative properties in Community Atmosphere Model version 5, or CAM5 (an atmosphere global climate model, or GCM) were improved.

Student funding from the University of Nevada, Reno, was combined with funds from this project to conduct some basic research on the mechanism of the North American monsoon, or NAM. Federal research on the NAM has dwindled since 2006, but atmospheric soundings taken during research vessel cruises in the Gulf of California (GC) during the North American Monsoon Experiment (NAME) were used to reveal a likely mechanism that explains the relationship between an intrusion of tropical warm water into the GC during late spring-early summer and the onset of relatively heavy NAM rainfall in northwest Mexico and the southwestern United States. These soundings, combined with reanalysis data, satellite sea surface temperatures and satellite measurements of outgoing longwave radiation were used to develop and provide evidence for a planetary-scale NAM mechanism. As far as we know, no other physical explanation has been offered for the spring-summer evolution of the NAM system.

1. Project Objectives and Actual Accomplishments

The research objectives described in the original proposal are as follows:

1) To understand and quantify the principle microphysical processes responsible for recent in situ observations of cirrus clouds
2) To improve the accuracy of existing ARM radar and radar-lidar retrievals of IWC and snowfall rate in cloud regions where the lidar signal is attenuated

Also under objectives in the original proposal: “Regarding (1), ice particle size distribution (PSD) analyses from recent cirrus cloud field campaigns suggests that cirrus clouds may be described by two microphysical regimes separated by the -40°C isotherm, especially for mid-latitude cirrus. This project would characterize the microphysical processes responsible for the differing microphysical attributes and enable their representation in climate models. This is the primary objective of this project. The second objective aims to improve ground-based 94 GHz radar retrievals of ice cloud effective diameter (D_e) and ice water content (IWC) where the radar-lidar ground-based retrieval method is not applicable due to lidar attenuation.”

These objectives were pursued throughout this project. The primary (1st) objective was fulfilled beyond expectations whereas the secondary objective was partially fulfilled. The primary objective had several components, including (1) determining the formation mechanism (mode of ice nucleation) for mid-latitude cirrus clouds based on aircraft measurements from the Small PARTicles In CirrUS (SPARTICUS) field campaign; (2) improve estimates of ice particle mass “m” and projected area “A” from the ice particle maximum dimension “D” (i.e. m-D and A-D relationships) using SPARTICUS measurements; (3) improve the treatment of ice particle aggregation in ice clouds. These three components were accomplished, although (1) was expanded to include the entire world. The secondary objective had two components: (1) development of the Rayleigh-Gans Approximation used to apply our radar retrieval equation (formulated from Rayleigh scattering theory) to larger ice particle sizes (i.e. beyond the Rayleigh regime) that are characteristic of winter snowfall near ground level, and (2) development and testing of a snow growth model used to estimate the sizes, areas and masses of ice particles (critical variables in the retrieval equation). Both of these two components were successfully developed, but there was insufficient time to combine them into a radar retrieval scheme.

The larger goal behind the primary objective is to improve the representation of ice clouds in global climate models (GCMs), and thus reduce the uncertainty in GCM estimates of climate sensitivity (i.e. the change in globally averaged surface temperature due to a doubling in CO_2 concentration at radiative equilibrium). It can be argued that there are two kinds of cirrus clouds; those formed through homogeneous and those formed through heterogeneous ice nucleation (henceforth hom and het). In general, hom produces ice crystal concentrations more than an order of magnitude higher than het does, resulting in considerably different radiative properties between hom and het cirrus clouds. Thus it is important to know whether mid-latitude cirrus clouds are formed primarily through hom or het, and when this occurs. In addition, many ice cloud microphysical processes in GCMs are parameterized using m-D and A-D relationships. By improving the accuracy and decreasing the uncertainty of these relationships as we did in this project, we were able to improve the accuracy of ice cloud microphysical processes in the GCM known as the Community Atmosphere Model version 5 (CAM5). This in turn improves the accuracy of ice cloud radiative properties in CAM5. Three papers have been published or submitted describing these two aspects of the primary objective. One paper has been submitted (and another soon to be submitted) describing progress towards the secondary objective.

Regarding objective (1) on the determination of whether mid-latitude cirrus were formed via hom or het, this was to be done using SPARTICUS field campaign data, but the water vapor measurements taken during SPARTICUS turned out to be corrupted. This forced us to develop a new strategy that did not require SPARTICUS data. It became apparent that whether hom or het dominated cirrus cloud formation ($T < 235$ K) would depend primarily on the cloud updraft velocity w and the concentration of ice nuclei or IN. These in turn would depend on latitude, season and surface type, and the only way to measure this dependence was through satellite remote sensing. Since no satellite retrieval method existed for this, one was invented. A satellite retrieval sensitive to the smallest ice crystals in cirrus clouds was developed that could estimate the ice particle number concentration N_i. Knowing N_i, the formation mechanism (hom vs. het) could be estimated. The application of this retrieval method has led to several discoveries and new hypotheses that are described in a paper submitted to Atmospheric Chemistry and Physics.

2. Project Activities

Year 2013:

Primary objective: Aircraft measurements from the SPARTICUS field campaign, primarily ice particle size distributions or PSDs, were obtained from SPEC, Inc. via our collaboration with Dr. Paul Lawson. Computer programs were written to analyze this PSD data in unique ways, providing evidence that hom dominated the microphysical properties of cirrus clouds not associated with deep convection, whereas anvil cirrus cloud microphysical properties appeared dominated by het. Later it was discovered by

Dr. Jay Mace's student that these PSD were not processed correctly, and SPEC reprocessed the data to correct it. This new SPEC data was then reanalyzed at DRI. The reanalysis removed one piece of evidence (relating to PSD projected area) supporting the conclusions on the roles of hom and het in non-convective and convectively generated cirrus clouds, thus making these conclusions tenuous.

Secondary objective: An analytical relationship between ice water content (IWC) and National Weather Service radar effective reflectivity Z_e, based on Rayleigh scattering theory, was developed during a previous DRI-ASR project. This relationship was modified in the current project to relate 94 GHz Z_e (no longer conforming to Rayleigh scattering theory) to IWCs typically found in wintertime mid-latitude snowstorms. This was done by applying the Rayleigh-Gans Approximation (RGA) as developed by Dr. Chris Westbrook at the University of Reading, UK. A new computer program was developed and tested that expressed the IWC in terms of the 94 GHz Z_e, the PSD slope parameter and the ice particle m-D power law (as developed under this project). To obtain the PSD slope and the m-D power law, a snow growth model (SGM) would be needed that could be initialized at cloud top based on the radar echo from cloud top (i.e. the cloud top Z_e). The required SGM was developed in the final year of this project.

North American monsoon research: This research was done during the first year of this project, and the results of this research have been published in the Journal of Geophysical Research, Atmospheres. The abstract for this paper is given here:

An understanding of the major governing processes of North American monsoon (NAM) is necessary to guide improvement in global and regional climate modeling of the NAM, as well as NAM's impacts on the summer circulation, precipitation, and drought over North America. A mechanistic understanding of the NAM is suggested by incorporating local- and synoptic-scale processes. The local-scale mechanism describes the effect of the temperature inversion over the Gulf of California (GC) on controlling low-level moisture during the 2004 NAM. The strong low-level inversion inhibits the exchange between the moist air in the marine boundary layer (MBL) and the overlying dry air. This inversion weakens with increasing sea surface temperatures (SSTs) in GC and generally disappears once SSTs exceed 29.5°C, allowing the moist air, trapped in the MBL, to mix with free tropospheric air. This leads to a deep, moist layer that can be transported by across-gulf (along-gulf) flow toward the NAM core region (southwestern U.S.) to form thunderstorms. On the synoptic scale, climatologies from 1983 to 2010 exhibit a temporal correspondence between coastal warm tropical surface water, NAM deep convection, NAM anticyclone center, and NAM-induced strong descent. A hypothesis is proposed to explain this correspondence, based on limited soundings at the GC entrance (suggesting this local mechanism may also be active in that region), the climatologies, and the relevant literature. The warmest SSTs moving up the coast may initiate NAM convection and atmospheric heating, advancing the position of the anticyclone and the region of descent northward.

Year 2014:

Primary objective: Through a collaboration with Dr. Jennifer Comstock, cirrus cloud relative humidity (RH) data was obtained that corresponded with the SPEC PSD data we were working with. Combined, the RH and PSD data providing compelling evidence that the cirrus clouds not associated with deep convection were formed primarily through hom, whereas the anvil cirrus clouds resulting from deep convection were formed through het processes. A method was developed to parameterize these findings and represent them in the CAM5 GCM. Based on these SPARTICUS results and five-year CAM5 simulations, it was found that changing the cirrus cloud formation mechanism from hom to het in CAM5 resulted in a change in cloud radiative net forcing of ~ 1 W m^{-2} outside the ± 30° latitude zone. This was a cooling effect where the longwave cooling was greater than the shortwave warming effect. A journal paper was written based on these results, only to be withdrawn due to news from Dr. Anne Fridlind that the SPARTICUS RH measurements could not be trusted. The NASA mentor of the SPARTICUS water vapor measurements felt that the RH measurements could be corrected, but he was not able to find sufficient time to carry out these corrections. Without the RH measurements, the evidence supporting the claims in the journal paper was deemed to be inadequate, which is why the paper was withdrawn.

This appeared to be a crushing blow to the project's main goal, which, generally speaking, was to understand the respective roles of hom and het in cirrus cloud formation. However, results from other studies in Europe and America were also making it clear that field campaigns would not be able to answer this question; some campaigns were showing het dominating while others indicated hom dominated the cirrus cloud microphysics. From theory, the formation mechanism will depend on the cloud updraft and IN concentration, which will depend on topography, latitude and season. Recognizing this, the PI decided to explore ways to estimate whether hom or het dominated cirrus cloud microphysics using satellite remote sensing, since that seemed to be the only approach that would answer this science question. The only defensible way of remotely sensing the formation mechanism was to retrieve the ice particle number concentration N_i, which should be relatively high when hom dominates. This meant measuring the concentration of the smallest ice crystals since they govern N_i. The best way to do this was to recognize that the difference in cirrus cloud emissivity between the 11 μm and 12 μm channels (measured by satellite instruments) was due to a process known as wave resonance, or equivalently, photon tunneling. That is, photon tunneling absorption is maximum when the absorbing particle is similar in size to the wavelength of the absorbed radiation. Thus, the 11 μm and 12 μm channels are ideal for the remote sensing of small ice crystals and N_i (see Mitchell et al., 2010, a product of previous ASR research). During the fall of 2014, a tight relationship was discovered between the 12 μm to 11 μm absorption optical depth ratio, denoted as β, and the N_i/IWC ratio, based on SPARTICUS field campaign measurements. Since the effective β (that includes the effects of scattering), β_{eff}, is a routine retrieval for the Infrared Imaging Radiometer (IIR) aboard the CALIPSO (*Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation)* polar orbiting satellite, retrievals of N_i/IWC could now be made during the period of CALIPSO's lifetime. The same could be done for the MODIS instrument aboard the AQUA and TERRA polar orbiting satellites. In the case of CALIPSO, these N_i/IWC retrievals were related to cloud temperature by using the CALIOP (*Cloud and Aerosol Lidar with Orthogonal Polarization*) lidar aboard CALIPSO (Garnier et al., 2012), while in the case of MODIS, cloud temperature can be retrieved using the method of Mitchell and d'Entremont (2012).

Year 2015:

Primary objective: During 2015, a method was developed in collaboration with Dr. Anne Garnier for retrieving N_i, D_e, IWC, ice water path (IWP) and cirrus cloud visible optical depth (OD) based on the CALIPSO IIR and CALIOP lidar. Based on β_{eff}, both N_i/IWC and D_e were retrieved using relationships obtained from SPARTICUS and TC4 (Tropical Composition, Cloud and Climate Coupling field campaign) PSD measurements. N_i was retrieved based on the following equation:

$$Ni = \frac{\rho_i}{3} \times \frac{\left[2/\overline{Q}_{abs}(12\mu m)\right]\tau_{abs}(12\mu m)}{\Delta z_{eq}} \times D_e \times \left(\frac{Ni}{IWC}\right) \qquad (1)$$

where ρ_i is the bulk density of ice (0.917 g cm^{-3}), τ_{abs}(12 μm) is the retrieved absorption optical depth from the IIR 12 μm channel, and Δz_{eq} is the effective cloud thickness. The quantity 2/ $\overline{Q}_{abs}$(12 μm) is obtained from β_{eff} via a regression equation obtained from SPARTICUS and TC4 PSD measurements, where 2 is the value of $\overline{Q}_{ext}$ for ice PSDs in the visible spectrum. This quantity converts τ_{abs}(12 μm) to an equivalent visible extinction optical depth (OD). The right hand side of (1), excepting the N_i/IWC term, is an expression for the layer-mean IWC. Since D_e, N_i/IWC and 2/ $\overline{Q}_{abs}$(12 μm) are retrieved from β_{eff}, N_i is sensitive to the smallest ice crystals. The effective cloud thickness Δz_{eq} accounts for the fact that the IIR instrument does not sense equally all of the cloud profile that contributes to thermal emission; see Mitchell et al. (2016) for these and other details.

Secondary objective: As noted, there are two components of this objective, and both components strongly benefit from improvements in the formulation of m-D and A-D relationships. A major research effort of this project was to improve these relationships that are extensively used in bulk microphysical schemes within climate models, as well as within ice cloud remote sensing algorithms used for the remote sensing of cloud properties. An article describing this research was published in Atmospheric Chemistry and Physics (ACP), and the abstract describing this paper is as follows:

Ice particle mass- and projected area-dimension (m-D and A-D) power laws are commonly used in the treatment of ice cloud microphysical and optical properties and the remote sensing of ice cloud properties. Although there has long been evidence that a single m-D or A-D power law is often not valid over all ice particle sizes, few studies have addressed this fact. This study develops self-consistent m-D and A-D expressions that are not power laws but can easily be reduced to power laws for the ice particle size (maximum dimension or D) range of interest, and they are valid over a much larger D range than power laws. This was done by combining ground measurements of individual ice particle m and D formed at temperature T <-20°C during a cloud seeding field campaign with 2-D stereo (2D-S) and cloud particle imager (CPI) probe measurements of D and A, and estimates of m, in synoptic and anvil ice clouds at similar temperatures. The resulting m-D and A-D expressions are functions of temperature and cloud type (synoptic vs. anvil), and are in good agreement with m-D power laws developed from recent field studies considering the same temperature range (-60°C < T < -20°C).

The findings from this paper formed the basis of a collaboration between DRI (i.e. the PI and his PhD student Ehsan Erfani) and NCAR (i.e. Dr. Hugh Morrison and his postdoc Dr. Trude Eidhammer). These findings were used to improve the CAM5 GCM, and an article describing how these m-D and A-D expressions were used to improve CAM5 has been published in the Journal of Climate; the abstract for this paper is as follows:

This paper describes a new approach for representing ice microphysics in climate models. In contrast with most previous schemes, this approach does not include separate categories for cloud and precipitating ice and instead uses a single two-moment category to represent all solid hydrometeors. Thus, there is no need for an ice "autoconversion" size threshold parameter, which has a critical impact on simulated climate in the Community Atmosphere Model (CAM5), yet is poorly constrained by theory or observations. Further, in the new treatment, all ice microphysical processes and parameters, including ice effective radius and mean fallspeed, are formulated self consistently and flexibly based on empirical ice particle mass-size and projected area size relationships. This means that the scheme can represent the physical coupling between bulk particle density, mean fallspeed, and effective radius, which is not possible in current schemes. Two different methods for specifying these relationships based on observations are proposed. The new scheme is tested in global simulations using CAM5. Differences in simulations using the two methods for specifying the mass- and projected area size relationships, particularly the cloud radiative forcing, are attributable mainly to the effects on mean ice particle fallspeed, impacting sedimentation and ice water path. With some tuning of parameters involved in calculating homogeneous freezing it produces a similar climate compared to the simulations using the original CAM5 microphysics. Thus, it can produce a comparable climate while improving the physical basis and self-consistency of ice particle properties and parameters.

Year 2016:

A one-year no-cost extension was granted by DOE for this project in order to complete the research in progress, which is why research during 2016 is reported.

Primary objective: This retrieval scheme was tested and validated against in situ measurements from five field campaigns (10 flights) as described in Mitchell et al. (2016), including N_i, N_i/IWC and IWC. Although not reported in this article, case study comparisons from the SPARTICUS field campaign were also made, with in situ measurements of N_i, D_e and IWC in relatively good agreement (within uncertainty estimates) with corresponding retrieved quantities. These results will be reported in a future publication.

There are many aspects to this CALIPSO retrieval research, and these are described in Mitchell et al. (2016). The abstract for this ACPD article is as follows:

There are two fundamental mechanisms through which cirrus clouds form; homo- and heterogeneous ice nucleation (henceforth hom and het). The relative contribution of each mechanism to ice crystal production often determines the microphysical and radiative properties of a cirrus cloud. A new satellite remote sensing method is described in this study to estimate cirrus cloud ice particle number concentration and the relative contribution of hom and het to cirrus cloud formation as a function of altitude, latitude, season and surface type (e.g. land vs. ocean). This method uses co-located observations from the Infrared Imaging Radiometer (IIR) and from the CALIOP (Cloud and Aerosol Lidar with Orthogonal Polarization) lidar aboard the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) polar orbiting satellite, employing IIR channels at 10.6 µm and 12.05 µm. The method is applied here to single-layered clouds of visible optical depth between about 0.3 and 3. Two years of Version 3 data have been analyzed for the years 2008 and 2013, with each season characterized in terms of 532 nm cirrus cloud centroid altitude and temperature, the cirrus cloud ice particle number concentration, effective diameter, layer-average ice water content and visible optical depth. Using a conservative criterion for hom cirrus, on average, the sampled cirrus clouds formed through hom occur about 43% of the time in the Arctic and 50% of the time in the Antarctic, and during winter at mid-latitudes in the Northern Hemisphere, hom cirrus occur 37% of the time. Elsewhere (and during other seasons in the Northern Hemisphere mid-latitudes), this hom cirrus fraction is lower. Processes that could potentially explain these observations are discussed, as well as the potential relevancy of these results to ice nucleation studies, climate modeling and jet-stream dynamics.

Secondary objective: The second component of this secondary objective was to develop a snow growth model (SGM) that would provide estimates for variables other than Z_e that would provide closure in the IWC retrieval equation. The SGM is similar to that published in Mitchell et al. (2006), but this new SGM includes the growth process of ice particle riming. Due to the complexity of the riming process (whereby supercooled cloud droplets freeze on impact when colliding with falling snowflakes or ice particles), this SGM development was a large undertaking. This SGM represents a novel solution to the ice particle number density equation, solved for steady-state snowfall conditions and ice particle growth by vapor deposition, riming and aggregation. As such, the SGM is analytically formulated, making it very efficient computationally as well as accurate. It has already found application in radar meteorology in the research of Dr. Alexander Ryzhkov at the National Severe Storms Laboratory in Norman, Oklahoma (who plans on using this SGM more extensively in the future). The motivation behind this collaboration is to better interpret polarimetric radar products and to improve quantitative precipitation estimates from polarimetric radars.

Due to the complexity of the riming process, it was decided to publish this SGM research in two publications; one devoted to representing the riming process in cloud-resolving models, and one describing the SGM itself. The paper describing how the riming process can be represented in cloud resolving models (including climate models with some modification) has been published in Atmospheric Chemistry and Physics Discussions (ACPD), and the abstract is as follows:

There is a long-standing challenge in cloud and climate models to simulate the process of ice particle riming realistically, partly due to the unrealistic parameterization of the growth of ice particle mass (m) and projected area (A) during riming. This study addresses this problem, utilizing ground-based measurements of m and ice particle maximum dimension (D) and also theory to formulate simple expressions describing the dependence of m and A on riming. It was observed that β in the m-D power law $m = \alpha D^{\beta}$ *appears independent of riming before the formation of graupel, with α accounting for the ice particle mass increase due to riming. This semi-empirical approach accounts for the degree of riming and renders a gradual and smooth ice particle growth process from unrimed ice particles to graupel, and thus avoids discontinuities in m and A during accretional growth. The treatment for riming is explicit, and includes the parameterization of the ice crystal-cloud droplet collision efficiency (Ec) for hexagonal columns and plates using hydrodynamic theory. In particular, Ec for cloud droplet diameters less than 10 μm are estimated, and under some conditions observed in mixed phase clouds, these droplets can account for roughly half of the mass growth rate from riming. These physically-meaningful yet simple methods can be used in models to improve the riming process.*

The two ACPD papers mentioned above are under peer review and will be improved for publication in ACP through the peer-review process. The paper describing the SGM is a chapter in the PhD dissertation of Dr. Ehsan Erfani, who conducted his PhD research through this ASR project. The SGM has been tested against aircraft Lagrangian descent measurements of PSD as the PSD evolved from cloud top to cloud base for two case studies, with favorable agreement found between predicted and measured PSD. This SGM paper will be submitted to the journal Atmospheric Chemistry and Physics in the near future, and the abstract for this paper is as follows:

A snow growth model for rimed snowfall (SGMR) was developed based on the growth processes of vapor deposition, aggregation, and riming. The SGMR is initialized by radar reflectivity (Z) at cloud top, and thereafter simulates the vertical evolution of size spectra. The SGMR is based on the zeroth- and second- moment conservation equations with respect to mass, and thus conserves the number concentration and Z, respectively. New mass- and area-dimension expressions suitable for synoptic clouds are utilized in the model, and therefore the assumption of specific ice particle shapes is not required. In addition, the new approach to parameterize riming has the advantage of a smooth and gradual growth of mass and area by riming. In general, the processes of vapor deposition and aggregation lead to larger ice particles that fall faster and therefore, produce larger snowfall rate (r_s). The r_s and ice water content with the inclusion of riming are significantly greater than that produced by the vapor deposition and aggregation alone. Moreover, r_s is sensitive to the cloud drop size distribution. The size spectra predicted by the SGMR were compared with those from two cases of Lagrangian spiral descent through frontal clouds, and good agreement is seen between the vertical profiles of SGMR and observations. This analytical SGMR, due to its accuracy and short running time, can be used in climate models and remote sensing.

3. Products Developed Under this Project

a. Journal Publications

Research conducted under this project has produced the following journal publications:

Erfani, E., and D. L. Mitchell, 2016: Development of a snow growth model for rimed snowfall. In preparation for Atmospheric Chemistry and Physics.

Mitchell, D. L., A. Garnier, M. Avery and E. Erfani, 2016: CALIPSO observations of the dependence of homo- and heterogeneous ice nucleation in cirrus clouds on latitude, season and surface condition. Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-1062.

Erfani, E., and D. L. Mitchell, 2016: Growth of ice particle mass and projected area during riming. Atmos. Chem. Phys. Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-455.

Eidhammer, T., H. Morrison, D. L. Mitchell, A. Gettelman, E. Erfani, 2016: Improvements in the Community Atmosphere Model (CAM5) microphysics using a consistent representation of ice particle properties. J. Climate, doi: 10.1175/JCLI-D-16-0050.1, in press.

Erfani, E., and D. L. Mitchell, 2016: Developing and bounding ice particle mass- and area-dimension expressions for use in atmospheric models and remote sensing. Atmos. Chem. Phys., 16, 4379–4400, doi:10.5194/acp-16-4379-2016.

Erfani, E., and D. L. Mitchell, 2014: A Partial Mechanistic Understanding of the North American Monsoon. J. Geophys. Res. Atmos., 119, 13,096–13,115, doi:10.1002/2014JD022038.

b. Conference presentations

Mitchell, D. L., Mejia, J. F., Kuebbeler, M., Lohmann, U., Xiao, M., 2013: Seeding of Cirrus Clouds to Reduce Global Warming, 19th Conference on Planned and Inadvertent Weather Modification, 93rd American Meteorological Society Annual Meeting: Austin, TX, January 6, 2013.

Mitchell, D. L., Lance, S., Lawson, R. P., 2013: Improving the Ice Optics in CAM5: Treatment of the Asymmetry Parameter, Oral presentation, Atmosphere Model Working Group, NCAR: Boulder, CO, February 10, 2013.

Erfani, E., Mitchell, D. L., Ivanova, D., 2013: A Mechanism for the Impact of Gulf of California Sea Surface Temperature on North American Monsoon, Poster presentation, Atmospheric System Research (ASR) 2013 Science Team Meeting: Potomac, MD, March 18, 2013.

Erfani, E., Mitchell, D. L., Ivanova, D., 2013: North American Monsoon: Progress Toward a Mechanistic Understanding, Poster presentation, 18th Annual CESM Workshop: Breckenridge, CO, June 17, 2013.

Erfani, E., Mitchell, D. L., Ivanova, D., 2013: Mechanisms Governing the Onset, Extent and Strength of the North American Monsoon, Poster presentation, 14th Annual WRF Workshop: Boulder, CO, June 24, 2013.

Erfani, E., Mitchell, D. L., Ivanova, D., 2013: Toward a Mechanistic Understanding of the Onset and Extent of the North American Monsoon, Poster presentation, Gordon Research Conference and Gordon Research Seminar on Radiation and Climat: New London, NH, July 6, 2013.

Mitchell, D. L., Mishra, S., Comstock, J., Mejia, J. F., Kuebbeler, M., Lohmann, U., 2013: Relevance of the negative Twomey effect for ice clouds, Poster presentation, Gordon Research Conference: Radiation and Climate: New London, NH, July 6, 2013.

Mitchell, D. L., Mejia, J. F., Kuebbeler, M., Lohmann, U., Mishra, S., Comstock, J., 2013: Constraining the Negative Twomey Effect for Cirrus Clouds, Poster presentation, Gordon Research Conference: Radiation and Climate: New London, NH, July 6, 2013.

Erfani, E., Mitchell, D. L., 2013: Mechanisms for the onset and evolution of North American monsoon, 38th NOAA Climate Diagnostics and Prediction Workshop Special Issue, Climate Prediction S & T Digest, NWS Science & Technology Infusion Climate Bulletin Supplement: College Park, MD, October 21, 2013.

Erfani, E., Mitchell, D. L., 2013: Air-sea interaction in the Gulf of California and its effect on the North American Monsoon, Oral presentation, Atmospheric System Research (ASR) 2013 Fall Meeting: Rockville, MD, November 4, 2013.

Mitchell, D. L., Mejia, J. F., Lohmann, U., Kuebbeler, M., Mishra, S., Comstock, J., Rasch, P., 2013: Microphysical and radiative impacts of the cirrus cloud negative Twomey effect in two GCMs based on SPARTICUS data, Oral presentation, Atmospheric System Research (ASR) 2013 Fall Working Groups,: Washington, D.C., November 4, 2013.

Erfani, E., Mitchell, D. L., Ivanova, D., Lavin, M., 2013: Poster presentation, AGU Fall Meeting: San Francisco, CA, December 9, 2013.

Mitchell, D. L., Erfani, E., Mishra, S., 2013: Convergence on ice particle mass- and area-dimensional expressions for ice clouds, Poster presentation, AGU Fall Meeting: San Francisco, CA, December 9, 2013.

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Mitchell, D. L., 2014: Globally mapping regions of homo- and heterogenous nucleation as a function of latitude and season: A potential strategy using CALIPSO. ASR Annual Meeting, 10-13 March, Potomac, Maryland.

<u>E. Erfani</u> and D. L. Mitchell, 2014: Improving a Snow Growth Model with Application to Radar Quantitative Precipitation Estimates. AMS Conference on Cloud Physics, Boston, 6-11 July 2014. (poster)

Mitchell, D. L., and E. Erfani, 2014: Developing and bounding ice particle mass- and area-dimensional expressions for use in atmospheric models and remote sensing.   AMS Conference on Cloud Physics, Boston, 6-11 July 2014. (poster)

Mitchell, D. L., M. A. Avery and A. Garnier, 2014: Inferred Differences in Ice Crystal Nucleation Rates between Continental and Maritime Deep Convective Clouds. *AGU Fall Meeting,* San Francisco, December 15-19, 2014. (poster)

Mitchell, D. L., M. A. Avery and A. Garnier, 2015: Inferred Differences in Ice Crystal Nucleation Rates between Continental and Maritime Deep Convective Clouds. 95th AMS Annual Meeting, Seventh Symposium on Aerosol–Cloud–Climate Interactions, session on “Aerosol Impacts on Cirrus Clouds”, Phoenix, AZ, 5-9 Jan. 2015. (poster)

Mitchell, D. L., 2015: On the ethics of climate engineering: An overlooked question? 95th AMS Annual Meeting, 20th Conference on Planned and Inadvertent Weather Modification and the Seventh Symposium on Aerosol–Cloud–Climate Interactions, joint session on “Human Alternation of Climate: Engineering, Ethics, and Politics”, 5-9 Jan. 2015. Oral presentation recorded at:
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Mitchell, D., A. Garnier and M. Avery, 2015: On the feasibility of cirrus cloud thinning: Dependence of homo- and heterogeneous ice nucleation as a function of latitude and season. Climate engineering: new insights from (Solar) Radiation Management studies, European Geosciences Union General Assembly, Vienna, Austria, 12 - 17 April 2015.

E. Erfani, D. Mitchell, and M. Avery, 2015: A partial mechanistic understanding of the North American monsoon. International Union of Geophysics and Geodesy (IUGG), 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

E. Erfani, D. Mitchell and M. Avery, 2015: The role of coastal mid-latitude air-sea interactions in exporting tropical energy to N. America during summer. International Union of Geophysics and Geodesy (IUGG), 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

Mitchell, D., A. Garnier and M. Avery, 2015: The seasonal dependence of climate on high latitude cirrus clouds. International Union of Geophysics and Geodesy (IUGG), 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

Mitchell, D., A. Garnier and M. Avery, 2015: On the feasibility of cirrus cloud thinning: Dependence of homo- and heterogeneous ice nucleation on latitude and season. International Union of Geophysics and Geodesy (IUGG), 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

Erfani, E., and D. Mitchell, 2015: Progress in representing microphysical processes in a mixed-phase snow growth model. International Union of Geophysics and Geodesy (IUGG), 26th IUGG General Assembly, Prague, Czech Republic, June 22 – July 2, 2015.

Mitchell, D. L., A. Garnier, and M. Avery, 2015: Cirrus cloud thinning: Do the right conditions exist, and how can it be tested with observations? Our Common Future Under Climate Change International Scientific Conference, 7-10 July 2015, Paris, France.

Mitchell, D., A. Garnier, M. Avery and E. Erfani, 2015: Satellite remote sensing of the dependence of homogeneous ice nucleation on latitude and season. *AGU Fall Meeting,* San Francisco, December 14-18, 2015. (poster)

Mitchell, D., A. Garnier, M. Avery and E. Erfani, 2016: The seasonal, latitude, temperature and surface roughness dependence of homogeneous ice nucleation. 96th AMS Annual Meeting, Eighth Symposium on Aerosol–Cloud–Climate Interactions, session on “Aerosol Impacts on Cirrus Clouds”, New Orleans, Louisiana, 11-15 Jan. 2016.

Mitchell, D., A. Garnier, M. Avery and E. Erfani, 2016: A novel cirrus cloud retrieval method for GCM high cloud validations. Atmosphere Model Working Group (AMWG), National Center for Atmospheric Research (NCAR), Boulder, Colorado, 8-10 February 2016.

Erfani, E., D. L. Mitchell, T. Eidhammer, H. Morrison and A. Gettelman, 2016: Progress on CAM5 microphysics using self-consistent ice particle mass- and area-dimension expressions. Atmosphere Model Working Group (AMWG), National Center for Atmospheric Research (NCAR), Boulder, Colorado, 8-10 February 2016.

Mitchell, D. L., 2016: Participant in the Workshop on Low Environmental Impact Solar Radiation Management Field Experiments, Institute of Advanced Sustainability Studies, Potsdam, Germany, 7-8 September 2016.

Mitchell, D., A. Garnier, M. Avery and E. Erfani, 2016: The Dependence of Cirrus Cloud Formation Mechanism on Latitude, Season and Surface Type. International Conference on Clouds and Precipitation, Manchester, United Kingdom, 25-29 July 2016.

Mitchell, D., A. Garnier, M. Avery and E. Erfani, 2016: The dependence of homo- and heterogeneously formed cirrus clouds on latitude, season and surface-type based on a new CALIPSO remote sensing method. AGU Fall Meeting, San Francisco, 12-16 December 2016.

Mitchell, D., A. Garnier and E. Erfani, 2016: Insights on the Feasibility, Modeling and Field Testing of Cirrus Cloud Thinning from Satellite Remote Sensing. AGU Fall Meeting, San Francisco, 12-16 December 2016.

c. Invited presentations

Mitchell, D.L., E. Erfani, D. Ivanova, M. F. Lavin, and A. S. Mascarenhas, Jr., 2013: Progress towards a mechanistic understanding of the North American monsoon. Guest speaker for seminar program at the National Weather Center, Norman Oklahoma.

Mitchell, D. L., 2014: An overview of cirrus cloud thinning and determining its scientific feasibility. Climate Engineering Conference 2014, Critical Global Discussions, Berlin, Germany, 18-21 August 2014.

Mitchell, D. L., E. Erfani, and D. Ivanova, 2014: Evolution of the North American monsoon: Potential large- and small-scale mechanisms. Pennsylvania State University, Dept. of Meteorology seminar series, 10 Dec. 2014.

Mitchell, D. L., E. Erfani, D. Ivanova, and M. Avery, 2015: Observational and Modeling Evidence for both Local- and Large-scale NAM Mechanisms. 3rd Annual Regional Climate and Meteorology Meeting for Northwest Mexico and the Southwest U.S., Centro de Ciencias de la Atmósfera, UNAM, Mexico City, 4-5 June 2015.

Mitchell, D. L., 2015: Panelist, "*Local vs Large-Scale Forcing and NAM Variability"*, 3rd Annual Regional Climate and Meteorology Meeting for Northwest Mexico and the Southwest U.S., Centro de Ciencias de la Atmósfera, UNAM, Mexico City, 4-5 June 2015.

Mitchell, D. L., 2015: Panelist, "What do the models need to get right?", 3rd Annual Regional Climate and Meteorology Meeting for Northwest Mexico and the Southwest U.S., Centro de Ciencias de la Atmósfera, UNAM, Mexico City, 4-5 June 2015.

Mitchell, D. L., A. Garnier and M. Avery, 2015: Cirrus cloud thinning: Do the right conditions exist, and how can it be tested with observations? Workshop 1. Solar Radiation Management: Foresight for Governance (SRM4G). Institute for Advanced Sustainability Studies (IASS), Potsdam, Germany, 13 July 2015.

Mitchell, D. L., 2015: Dependence of global sustainability on the degree of fear and aspiration. A Mindset for the Anthropocene project, Institute for Advanced Sustainability Studies (IASS), Potsdam, Germany, 14 July 2015.

Mitchell, D. L., A. Garnier, M. Avery and E. Erfani, 2016: Insights on the Feasibility, Modeling and Field Testing of Cirrus Cloud Thinning from Satellite Remote Sensing. Sixth GeoMIP Meeting, 21–22 June 2016, Norwegian Meteorological Institute, Oslo, Norway.

d. Websites exhibiting research results from this project

Website for North American monsoon research findings and monsoon tracking tools: http://www.dri.edu/monsoon/

e. Collaborations fostered

Strong collaborations were developed and sustained with the following groups: Dr. Paul R. Lawson at SPEC, Inc., Boulder, Colorado; Dr. Hugh Morrison at National Center for Atmospheric Research (NCAR), Boulder, Colorado; Dr. Anne Garnier at Science Systems and Applications, Inc., Hampton, Virginia; Dr. Melody Avery at NASA Langley Research Ctr., Hampton, Virginia. Each one of these collaborations was extremely productive and vital to the research accomplishments of this project.

f. Technologies developed under this project

A novel *satellite remote sensing method* that retrieves the ice particle number concentration, along with other ice cloud properties, was developed under this project. The PI has recently become a member of the NASA CloudSat-CALIPSO Science Team and is currently working with the NASA CALIPSO Project Office through Dr. Anne Garnier to further develop this CALIPSO retrieval method. Dr. Melody Avery at NASA Langley, a CALIOP lidar expert, is also part of this research effort. It is possible that this retrieval method could ultimately provide standardized retrievals of cirrus cloud properties for the scientific community via the NASA Data Archive.

Another important product of this project is the *snow growth model* (SGM) described under Year 2016 of Project Activities. An article that describes this SGM and tests it against aircraft observations from ice clouds has been written for the journal ACP; it will be submitted in

January of 2017. During the 2016 ASR Annual Meeting, the PI and Dr. Alexander Ryzhkov (at the National Severe Storms Laboratory in Norman, Oklahoma) decided to collaborate on interpreting polarimetric radar products from frontal storm systems and to improve corresponding quantitative precipitation estimates (QPE) from these polarimetric radars. This would be accomplished by initializing and testing this new SGM with radar-retrieved properties from frontal storm systems.

4. Potential Impact of the Research on Society

Over the last decade several radiation management (RM) climate intervention approaches have been suggested. One proposed RM climate intervention method is known as cirrus cloud thinning or CCT. CCT will not be possible if het cirrus dominate the high latitudes during the "cold season" where noontime solar zenith angles are relatively low or absent (Storelvmo et al., 2014). Recent GCM modeling studies (Penner et al., 2015; Gasparini and Lohmann, 2016) argue that CCT is not possible for this reason, but the findings from this project indicate that this is not the case; that hom cirrus clouds are common in the Arctic and Antarctic (at least 43% and 50%, respectively, based on a conservative criterion for hom cirrus). Thus, it may be possible to cool the entire planet by seeding cirrus clouds at high latitudes with efficient ice nuclei (IN), provided a workable strategy could be found for producing an optimal background IN concentration. The GCM coupled atmosphere-ocean modeling study of CCT by Storelvmo et al. (2014) produced a spatial and seasonal distribution of hom and het cirrus clouds similar to this CALIPSO study. Seeding just the high latitude hom cirrus clouds reduced the global mean surface temperature by 1.4°C, and it reduced high latitude surface temperatures by ~ 1°C to 5°C (averaging ~ 3°C). The results from this CALIPSO study show that the Storelvmo et al. (2014) results cannot be dismissed and that more research is needed to determine what the actual cooling impact of CCT is likely to be.

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