FINAL REPORT for "Improved Representations of Cloud Microphysics for Model and Remote Sensing Evaluation using Data Collected During ISDAC and TWP-ICE"

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We were funded by ASR (DE-SC0001279) to use data collected during ISDAC and TWP-ICE to evaluate models with a variety of temporal and spatial scales, to evaluate ground-based remote sensing retrievals and to develop cloud parameterizations with the end goal of improving the modeling of cloud processes and properties and their impact on atmospheric radiation. In particular, we proposed to:

1) Calculate distributions of microphysical properties observed in arctic stratus during ISDAC for initializing and evaluating LES and GCMs, and for developing parameterizations of effective particle sizes, mean fall velocities, and mean single-scattering properties for such models;
2) Improve representations of particle sizes, fall velocities and scattering properties for tropical and arctic cirrus using TWP-ICE, ISDAC and M-PACE data, and to determine the contributions that small ice crystals, with maximum dimensions D less than 50 μm, make to mass and radiative properties;
3) Study fundamental interactions between clouds and radiation by improving representations of small quasi-spherical particles and their scattering properties.

We were additionally funded 1-year by ASR (DE-SC0005507) to use RACORO data to develop an integrated product of cloud microphysical properties. We accomplished all of our goals as explained below.

1) Microphysical properties in Arctic stratus

The primary goal of ISDAC was to examine effects of aerosols on clouds that contain both liquid and ice water for clean and polluted environments. During ISDAC, the National Research Council (NRC) of Canada Convair-580 flew 27 sorties, collecting data using an unprecedented 42 state-of-the-art cloud and aerosol instruments for more than 100 hours on 12 different days. McFarquhar et al. (2011a) explain how these data are enabling a process-oriented understanding and statistical analysis of how aerosols affect the microphysical and radiative properties of arctic clouds in the context of varying meteorology.

To relate cloud microphysical properties to distributions of aerosol composition and size, accurate estimates of cloud properties are needed. We developed an integrated product of the best estimate of cloud microphysical parameters from the ISDAC data by comparing size distributions (SDs) measured by different probes in overlapping size ranges and conducting mass closure tests whereby the mass measured by bulk probes was compared against that derived by the size resolved probes (Jackson 2011; Jackson et al. 2012). As a result, we determined the optimum values of liquid and ice SDs, mass content, reflectivity, effective radius and median mass diameter at 30 s and 1 s resolution for all times and submitted this as a value added product to the ARM archive. In general, the Cloud Droplet Probe (CDP) was used to characterize particles with D < 50 μm, the Two-Dimensional Stereo Probe (2DS) for 50 < D < 300 μm, the Two-Dimensional Cloud Probe (2DC) for 300 < D < 800 μm, and the Two-Dimensional Precipitation Probe (2DP) for D > 800 μm. We found that habit-dependent mass-diameter relationships applied to the size distributions segregated according to shapes measured by a Cloud Particle Imager (CPI) gave masses most consistent with those measured by the bulk probes. However, different probes are sometimes used for different days because some probes did not operate correctly on some days. A technical document describing these data was submitted (McFarquhar and Jackson 2012) to the archive.

These products have been used in several studies, including remote sensing evaluation studies (Botta et al. 2011), model evaluation studies (Avramov et al. 2011) and fundamental studies of aerosol-cloud interactions (Earle et al. 2011). These data were also used by us to examine the influence of different mechanisms proposed to describe the effect of aerosols on mixed-phase clouds: the glaciation indirect effect (Lohmann 2002), the riming indirect effect (Borys et al. 2003), and the cold second indirect effect (Rangno and Hobbs 2001). Our work (Jackson et al. 2012) showed that a correlation of 0.75 between liquid cloud droplet concentration, N_l, and ambient aerosol concentration below cloud, N_{PCASP}, combined with increasing *LWC* with height above cloud base and the nearly constant profile of N_l suggest that liquid drops nucleated from aerosol at cloud base. No evidence of a riming indirect effect was observed, but a 0.69 correlation between ice crystal concentration N_i and N_{PCASP} above cloud was noted. Increases in IN concentration with N_{PCASP} above cloud combined with subadiabatic *LWC* profiles near cloud top suggest mixing of IN from cloud top consistent with the glaciation indirect effect. The higher N_i

and lower r_{el} for ISDAC compared to data collected in cleaner single-layer stratocumulus during M-PACE is consistent with the cold second indirect effect. However, we concluded that data in a wider range of surface and meteorological conditions, with greater variations in aerosol forcing, were required to identify the dominant aerosol forcing in mixed-phase arctic clouds.

We also investigated factors responsible for the longevity of arctic mixed-phase clouds using data measured above, below, and within single-layer stratocumulus on 8 and 26 April 2008 (Korolev et al. 2012). Observations with the NRC X-band radar showed small-scale structure in the clouds with regions of ascent of 1-2 m s^{-1} in close proximity to regions of descent of 1-4 m s^{-1}. Ramped ascents and descents through cloud showed the presence of small particles everywhere and nearly constant ice profiles. This, together with inhomogeneities in radar data, indicates vertical mixing driven by dynamics or turbulence. Simulations using Korolev and Isaac's (2003) and Korolev and Field's (2008) models show harmonic oscillations consistent with observed velocity fields and cloud top radiative cooling provide the conditions necessary for indefinitely long maintenance of mixed-phase clouds when no precipitation reaches ground.

High-resolution hydrometeor images measured during ISDAC and M-PACE were used to determine the phases of small particles between 35 and 60 μm in mixed-phase clouds (McFarquhar et al. 2013a). We found that particle shapes tended to be semi-spherical in ice dominated mixed-phase clouds whereas they were more spherical in water dominated clouds. This hence questions the assumption used in previous studies that small particles in mixed-phase clouds are supercooled droplets and may have important implications for calculating cloud scattering properties. We (Lindqvist et al. 2011) also developed a novel automatic method for identifying the habits of larger ice particles based on principal component analysis, and demonstrated that it worked well for ice clouds sampled during ISDAC, TWP-ICE and over the SGP.

2) Improved representations of tropical and arctic cirrus

For objective 2, we had previously used TWP-ICE data to quantify the contributions of small ice crystals with D < 50 μm to the mass and radiative properties of cirrus (McFarquhar et al. 2007a). This study was extended using ISDAC data collected in cirrus during transits from Fairbanks to Barrow to show that the shattering of large ice crystals on the tips of a forward scattering probe (FSSP) artificially amplified small ice crystal concentrations (McFarquhar et al. 2011b). Because the FSSP has been used to develop previous cirrus parameterizations (e.g., Ivanova et al. 2001) and because comparison against 2DS concentrations (with shattered particles removed) confirmed that the FSSP overestimate of small crystal concentration increased with large crystal concentration, this work has important ramifications for correcting prior cirrus parameterizations. This work was the subject of K. Bae's M.S. thesis (Bae 2010).

In order to better determine the concentrations of small ice crystals in tropical cirrus from TWP-ICE, we needed to use CPI SDs because much cirrus mass occurred in small sizes not well measured by optical array probes during that experiment due to their small and poorly defined depth of field for small crystals. To get the CPI SDs, we (Um et al. 2013) calibrated the DOE CPI at the University of Manchester with funding from the ARM Airborne Facility (AAF) using the technique of Connolly et al. (2007). We and many of our collaborators have also needed information about particle habits from the cirrus measured during TWP-ICE. We found that the aged cirrus was mainly composed of bullet rosettes and their aggregates, plates, and columns, whereas fresh anvils had more frequent plates, columns, occasional capped columns and aggregates of plates (Um and McFarquhar 2009). We (Protat et al. 2011) also developed a method to minimize errors associated with the density and projected area assumptions in bulk microphysics calculations using particle classifications from the CPI. The resulting *IWC* were virtually unbiased compared to those from a Counterflow Spectrometer and Impactor (CSI).

We (McFarquhar et al. 2013b) also developed an incomplete gamma fitting technique (IGF) for deriving the N_0, λ and μ that characterize SDs as gamma functions. This has important ramifications for modeling work underway within ASR because gamma distributions are used to represent SDs in mesoscale and cloud resolving models that predict one, two or three moments of hydrometeor species. We showed that N_0, λ and μ characterizing the gamma function are not independent, but rather exhibit mutual dependence. Although N_0, λ and μ are not highly dependent on choice of fitting routine, they are sensitive to the tolerance permitted by fitting algorithms, meaning a three-dimensional volume in N_0-λ–μ phase space is required to represent a single SD. Depending on the uncertainty in the measured SD and on how well a gamma distribution matches the SD, parameters within this volume of equally realizable solutions can vary substantially with N_0, in particular, potentially spanning several orders of magnitude. A method to characterize a family of SDs obtained in similar conditions as an ellipsoid in $N_0/\lambda/\mu$ phase space is described, with the associated scatter in $N_0/\lambda/\mu$ for such families comparable to scatter in fit parameters observed in prior field campaigns conducted in different conditions. This has big ramifications for the development of model cloud parameterization schemes and associated calculations of microphysical process rates, especially in the event that future models are able to take into account uncertainties in cloud parameterizations.

3) Fundamental Interactions between clouds and radiation

Um and McFarquhar (2011) developed a new idealized model, called a budding Bucky ball (3B), to describe the shapes of small ice crystals measured. The 3B is based on an ice analogue grown from sodium fluorosilicate solution on a glass substrate, with several columns emanating from a common center of mass, which appears quasi-circular when imaged by a CPI. Although its shape is very different from other quasi-spherical shapes (Chebyshev particles, Gaussian random spheres, droxtals) its shape is just as consistent with CPI images as the others. We compared the phase function and *g* of the different shapes at a visible wavelength. The scattering properties depended both on the choice of idealized model and area ratio used to characterize the small ice crystals. The *g* for different models varied by up to 25%, a significant difference given the accuracy needed for radiative flux calculations for climate models and retrieval algorithms.

The Um and McFarquhar (2011) study did not identify an optimum small crystal model. In an attempt to identify the habit and concentration of small crystals most consistent with observed radiative fluxes, Mauno et al. (2011) used similar representations of small crystal concentrations and shapes, based on microphysical data measured during the SGP 2000 Cloud IOP, to generate vertical profiles of optical properties. We combined existing wavelength-dependent single-scattering properties of different ice crystal models with 5 alternate size-shape distributions accounting for uncertainties in small ice crystals. The resulting profiles of g, ω_0, and τ were input to a radiative transfer model to simulate shortwave fluxes. Even though the fluxes depended substantially on assumptions about small ice, differences in modelled and measured fluxes were larger than those explained by variations in shape and concentration preventing us from determining an optimum shape model. Reducing *g* improved the agreement considerably, implying the presence of non-ideal crystals.

In a complementary study, we (Nousiainen et al. 2011) used TWP-ICE CPI images to investigate how small ice crystal shapes vary between mid-latitudes and Tropics. First, we showed that the infrequent occurrence of multiple particles in single CPI frames shows most imaged crystals were natural ice crystals rather than shattered artifacts. Then, the measured images were used to generate an ensemble of small, quasi-spherical ice crystals using the Gaussian random sphere geometry, and their scattering properties calculated using ray-optics at a visible wavelength. The tropical ice crystals were closer to spherical than their mid-latitude counterparts and, consequently, their *g* larger, but the differences were not significant from the standpoint of climate studies. Thus, using a single small quasi-spherical ice particle model may be justified.

Because the shapes of small ice crystals are poorly known, there is still need for computations of their scattering properties using different idealized models for use in radiative transfer sensitivity studies. Thus, there is a need to determine the optimal way to determine the average single-scattering properties of such crystals. Um and McFarquhar (2013) investigated the optimal orientation averaging scheme (regular lattice grid scheme or quasi Monte Carlo QMC method), the minimum number of orientations, and the corresponding computing time required to calculate the average single-scattering properties (i.e., asymmetry parameter (g), single-scattering albedo (ω_0), extinction efficiency (Q_{ext}), scattering efficiency

(Q_{sca}), absorption efficiency (Q_{abs}), and scattering phase function at scattering angles of 90˚ ($P_{11}(90˚)$), and 180˚ ($P_{11}(180˚)$) within a predefined accuracy level (i.e., 1.0%) were determined for four different non-spherical atmospheric ice crystal models (Gaussian random sphere, droxtal, budding Bucky ball, and column) with maximum dimension D=10 µm using the ADDA at λ=0.55, 3.78, and 11.0 µm. The QMC required fewer orientations and less computing time than the lattice grid. The calculations of $P_{11}(90˚)$ and $P_{11}(180˚)$ required more orientations than the calculations of integrated scattering properties (g, ω_0, Q_{ext}, Q_{sca}, and Q_{abs}) regardless of the orientations average scheme. The fewest orientations were required for calculating g and ω_0. The minimum number of orientations and the corresponding computing time for single-scattering calculations decreased with an increase of wavelength, whereas those were increased with the surface-area ratio that defines particle non-sphericity.

4) Dependence of Fair Weather Cumuli Properties on Aerosol Loading

An integrated product of cloud microphysical properties (*LWC*, β_e, r_e, and SDs) was developed for RACORO and submitted to the ARM archive. We identified problems with the original calibration of the FSSP so that corrected data were placed in the archive. In our product, CAS data represent small droplets because its calibration was steadier than that of the FSSP during RACORO. We verified that the CAS did not suffer errors from shattering in the presence of large drops by comparing drizzle and non-drizzle cases. The 1-d cloud imaging probe (CIP) was used to characterize droplets larger than those measured by the CAS because some artifacts in the 2-d CIP were manually identified.

We also showed that even though numerous studies have provided evidence of precipitation suppression and increased water contents in stratus and stratocumulus under enhanced aerosol loading, an opposite effect occurs in the 2337 shallow cumuli penetrations (85 h of data) during RACORO where LWC decreased with increased aerosol (Yang 2013; Yang and McFarquhar 2013). The decrease in LWC was correlated with a decrease in vertical velocity inside cloud. We are attempting to explain this result from the competition between moistening from decreased surface precipitation and boundary-layer drying associated with greater entrainment. This work was an invited oral presentation at the 2011 ASR science team meeting.

Other Activities

The PI has been an active member of ASR, attending all science team and working group meetings. We have developed Value Added Products (VAPs) of cloud properties using data collected during M-PACE, ISDAC and RACORO for use by scientists inside and outside of ASR. The PI organized the 2010 American Meteorological Society Cloud Physics Conference, where several ASR papers were presented. The PI represented DOE at the 2010 International Conference for Airborne Research on the Environment in France, and has made invited presentations on ASR research at the 2011 European Geophysical Union Meeting, the International Conference on Clouds and Precipitation, the National Center for Environment Prediction, and several universities. The PI served was co-lead for ISDAC and the aircraft component of TWP-ICE, flight scientist for the ER-2 during CLASIC, and served on the steering committees for RACORO and SPARTICUS. He is co-lead of the new “Ice properties and processes” interest group within ASR, with this group about to petition to become a focus group.

Papers Generated Using Funding from this Grant (Conference Proceedings not listed)

Avramov, A., A. S. Ackerman, A.M. Fridlind, B. van Diedenhoven, G. Botta, K. Aydin, J. Verlinde, A.V. Korolev, W. Strapp, **G. M. McFarquhar, R. Jackson**, S.D. Brooks, A. Glenn, and M. Wolde, 2011: Towards ice formation closure in Arctic mixed-phase boundary layer clouds during ISDAC. *J. Geophys. Res.*, doi:10.1029/2011JD015910.

Botta, G., K. Aydin, J. Verlinde, A.E. Avramov, A.S. Ackerman, A.M. Fridlind, **G.M. McFarquhar**, and M. Wolde, 2011: Millimeter wave scattering from ice crystal aggregates: comparing cloud model simulations with X- and Ka-band radar measurements. *J. Geophys. Res.,* **116**, doi:10.1029/2011JD015909.

Bromwich, D.H., J.P. Nicolas, J. Kay, T. Lachlan-Cope, D. Lubin, M. Lazzara, I. Gorodskaya, D.

Grosvenor, K. Hines, G. McFarquhar, E. Key, and N. Adams, 2012: Antarctic cloud characteristics. *Rev. Geophysics*, **50**, doi:10.1029/2011RF000363.

Earle, M.E., P.S. Liu, J. W. Strapp, A. Zelenyuk, N.C. Shantz, W.R. Leaitch, and **G.M. McFarquhar**, 2011: Observations of indirect effects in Arctic clouds during the Indirect and Semi-Direct Aerosol Campaign. J. Geophys. Res., **116**, D00T09, doi:10.1029/2011JD015887.

Fan, J., J. Comstock, M. Ovchinnikov, S. A. McFarlane, **G. McFarquhar** and G. Allen, 2010: Tropical anvil characteristics and water vapor of the tropical tropopause layer (TTL): Impact of heterogeneous and homogeneous freezing parameterizations. *J. Geophys. Res.*, **115**, D12201, doi:10.1029/2009JD012696.

Jackson, R., G.M. McFarquhar, A. Korolev, J.W. Strapp, M. Earle, and S. Brooks, 2012: The dependence of arctic stratus ice cloud properties on aerosol properties observed during ISDAC. *J. Geophys. Res.*, **117**, D15, doi:10.1029/2012JD017668.

Korolev, A., **G. McFarquhar**, J.W. Strapp, et al., 2013: Explaining the longevity of mixed-phase stratocumulus observed during ISDAC. *J. Geophys. Res.,* in preparation.

Lindqvist, H., K. Muinonen, T. Nousiainen, R. Makkonen, **J. Um**, P. Mauno, **G.M. McFarquhar**, and H. Hakkarainen, 2012: Ice-cloud particle habit classification with atmospheric radiation applications. *J. Geophys. Res.*, 117, D16206, doi:10.1029/2012JD017573.

Mauno, P., **G.M. McFarquhar**, T. Nousiainen, **M.S. Timlin**, M. Kahnert, and P. Raisanen, 2011: The influence of observed cirrus microphysical properties on shortwave radiation: a case study over Oklahoma. *J. Geophys. Res.,* 116, doi:10.1029/2011JD016058.

McFarquhar, G.M., and R. Jackson, 2012: ISDAC value added microphysics data set version 1.0. Available from http://www.arm.gov/data/pi/51.

McFarquhar, G.M. and Coauthors, 2011a: Indirect and Semi-Direct Aerosol Campaign: The impact of arctic aerosols on clouds, *Bull. Amer. Meteor. Soc.*, **92**, 183-201, doi:10.1175/2010BAMS2935.

McFarquhar, G.M., B. Schmid, A. Korolev, J. Ogren, P.B. Russell, J. Tomlinson, D.D. Turner, and W. Wiscombe, 2011b: Airborne instrumentation needs for climate and atmospheric research. *Bull. Amer. Meteor. Soc.,* doi:10.1175/2011BAMS3180.1

McFarquhar, G.M., J. Um, and R. Jackson, 2013a: Small cloud particle shape in mixed-phase clouds. *J. Appl. Meteor. Clim..*, **52**, 1277-1293

McFarquhar, G.M., T.-L. Hsieh, M. Freer, and **B.F. Jewett,** 2013b**:** An approach for quantifying uncertainties in fits to observed size distributions: implications for modeling studies. *J. Atmos. Sci.*, in preparation.

Morrison, H., P. Zuidema**, G.M. McFarquhar**, A. Bansemer, and A.J. Heymsfield, 2011: Snow microphysical observations in shallow mixed-phase and deep frontal Arctic cloud systems. *Quart. J. Roy. Meteor. Soc.*, **137**, 1589-1601.

Nousiainen, T., H. Lindqvist, **G.M. McFarquhar**, and **J. Um**, 2011: Small irregular ice crystals in tropical cirrus. *J. Atmos. Sci.*, **68**, 2614-2627.

Protat, A., **G.M. McFarquhar, J. Um**, and J. Delanoe, 2011: Obtaining best estimates for the microphysical and radiative properties of tropical ice clouds from TWP-ICE in-situ microphysical observations, *J. Appl. Meteor. Clim.*, **50**, 895-915.

Um, J., and **G.M. McFarquhar**, 2011: Dependence of the single-scattering properties of small ice crystals on idealized shape models. *Atmos. Chem. Phys.*,**11**, 3159-3171, doi:10.5194/acp-11-3159-2011.

Um, J., and **G.M. McFarquhar**, 2013:Optimal numerical methods for determining the orientation averages of single-scattering properties of atmospheric ice crystals. *J. Quant. Spect. Rad. Transfer.*, In press.

Um, J., **G.M. McFarquhar**, P.J. Connolly, C. Emersic, Z.J. Ulanowski, and M. Gallagher, 2013: A laboratory study to assess the performance of three generations of Cloud Particle Imagers, *J. Atmos. Ocean. Tech.*, in preparation.

Vogelmann, **G.M. McFarquhar**, and Coauthors, 2012: RACORO, extended-term, aircraft observations of boundary layer clouds. *Bull. Amer. Meteor. Soc.*, in press.

Yang, H.-J., and **G.M. McFarquhar,** 2013: Effects of aerosols on shallow cumuli sampled during RACORO. *Atmos. Chem. Phys.,* in preparation.

Thesis Produced with Funding from this grant

Um, J., 2009: The microphysical and radiative properties of tropical cirrus from the 2006 Tropical Warm Pool International Cloud Experiment (TWP-ICE), Ph.D. thesis, University of Illinois at Urbana-Champaign, 262 pp.

Bae, K., 2010: The microphysical properties of arctic cirrus, M.S. thesis, University of Illinois at Urbana-Champaign, May 2010, 83 pp.

Jackson, R., 2011: The dependence of vertical structure of arctic mixed-phase clouds on aerosol composition and concentration and meteorology, M.S. thesis, University of Illinois at Urbana-Champaign, December 2011, 78 pp.

Yang, H., 2013: Aerosol-cloud-radiation interactions in shallow cumuli, Ph.D. thesis, University of Illinois, anticipated December 2013.

Conference Proceedings

McFarquhar, G.M., S. Ghan, J. Verlinde, B. Schmid, J. Tomlinson, J. Hubbe, D. Ronfeld, S. Brooks, D. Collins, D. Cziczo, M. Dubey, I. Gultepe, G. Kok, A. Korolev, A. Laskin, P. Lawson, P. Liu, D.Lubin, C. Mazzoleni, A.-M. McDonald, W. Strapp, A. Zelenyuk, C. Flynn, D. Lubin, D. Mitchell, R. Ferrare, M. Shupe, D. Turner, M. Wolde, M. Ovtchinnikov, S. Xie, A. Fridlind, and X. Liu, 2009: Indirect and Semi-Direct Aerosol Campaign (ISDAC): The influence of arctic aerosols on clouds. *10th Conf. Polar Meteorology and Oceanography*, Amer. Meteor. Soc., Madison, WI.

McFarquhar, G.M., and J. Um, 2009: Calculated single-scattering properties of aggregate ice crystals using crystal images observed in-situ in the tropics and mid-latitudes. *International Symposium on Atmospheric Light Scattering and Remote Sensing*, Xi'an, P.R. China, July 13-17 2009.

McFarquhar, G.M., K. Bae, R. Jackson, M. Freer, A. Korolev, J.W. Strapp, M. Poellot, and P. Lawson, 2009: The microphysical properties of arctic cirrus derived from in-situ measurements during ISDAC and M-PACE: implications for the importance of small crystals. *Eos. Trans. AGU*, 90(52), Fall Meeting Supp., Abstract A43A-0168.

Mauno, P., T. Nousiainen, M. Kahnert, G.M. McFarquhar, and P. Raisanen, 2009: From in situ profiles of cirrus microphysics to radiative impacts: a case study of mid-latitude cirrus, *International Symposium on Atmospheric Light Scattering and Remote Sensing*, Xi'an, P.R. China, July 13-17 2009.

McFarquhar, G.M., and the ISDAC Science Team, 2010: Indirect and Semi-Direct Aerosol Campaign (ISDAC): The impact of arctic aerosols on clouds, *European Geophys. Union Annual Meeting*, Vienna, Austria.

McFarquhar, G.M., J. Um, K. Bae, M. Freer, H. Jonsson, A. Korolev, R> Jackson, M. Poellot, J.W. Strapp, H.-J. Yang, and G. Zhang, 2010: Integrated database of cloud microphysical properties from in-situ observations obtained during M-PACE, TWP-ICE, ISDAC and RACORO, *First Atmospheric System Research Science Team Meeting*, Bethesda, MD.

Mauno, P., T. Nousiainen, G.M. McFarquhar, M. Timlin, M. Kahnert, and P. Raisanen, 2010: Modeling of radiative impact of a cirrus cloud based on in-situ microphysical measurements. *12th Conf. on Electromagnetic and Light Scattering by Nonspherical Particles*, Helsinki, Finland, June 28 to July 2 2010.

Nousiainen, T., H. Lundqvist, and G.M. McFarquhar, 2010: Light scattering by quasi-spherical ice crystals in tropical cirrus. *12th Conf. on Electromagnetic and Light Scattering by Nonspherical Particles*, Helsinki, Finland, June 28 to July 2 2010.

Um, J., G.M. McFarquhar, P.J. Connolly, C. Emersic, Z. Ulanowski, and M. Gallagher, 2010: Intercomparison of the performance of three different versions of Cloud Particle Imagers (CPIs), *13th Conf. on Cloud Physics*, Amer. Meteor. Soc., Portland, OR

Um, J., and G.M., McFarquhar, 2010: The impacts of small ice crystal shape and concentration on the bulk scattering properties of tropical cirrus. *Proc. 13th Conf. Cloud Physics/13th Conf on Atmos. Radiation*, Amer. Meteor. Soc., Portland, OR.

Neumann, A.J., M.R. Poellot, G.M. McFarquhar, and G. Zhang, 2010: Airborne estimates of precipitation during the Mixed-Phase Arctic Cloud Experiment, *13th Conf. on Cloud Physics*, Amer. Meteor. Soc., Portland, OR

Korolev, A., G. McFarquhar, S.J. Ghan, J.W. Strapp, M. Wolde, J. Verlinde, B. Schmid, P. Liu, M. Ovchinnikov, and S.D. Brooks, 2010: In-situ observation of arctic mixed phase clouds during the ISDAC flight campaign, *13th Conf. on Cloud Physics*, Amer. Meteor. Soc., Portland, OR

Jackson, R., G.M. McFarquhar, A.V. Korolev, J.W. Strapp, and P. Lawson, 2010: Mass closure studies using size distributions and bulk water contents measured in arctic cirrus during the Indirect and Semi-Direct Aerosol Campaign (ISDAC), *13th Conf. on Cloud Physics*, Amer. Meteor. Soc., Portland, OR

Vogelmann, A., G.M. McFarquhar, J. Ogren, D.D. Turner, J.M. Comstock, G. Feingold, C.N. Long, H.H. Jonsson, A. Bucholtz, D.R. Collins, G. Diskin, H. Gerber, R.P. Lawson, R.K. Woods, J. Hubbe, J. Tomlinson, and B. Schmid, 2010: RACORO long-term systematic aircraft observations of boundary layer clouds, *13th Conf. on Cloud Physics,* Amer. Meteor. Soc., Portland, OR

Avramov, A., A.S. Ackerman, A.M. Fridlind, B. van Diedenhoven, A.V. Korolev, J.W. Strapp, G.M. McFarquhar, R. Jackson, S.D. Brooks, and A. Glen, 2010: Possible sufficiency of conventional ice nucleation mechanisms in a case study of arctic stratus: April 8th during ISDAC, *13th Conf. on Cloud Physics*, Amer. Meteor. Soc., Portland, OR

Botta, G., K. Aydin, J. Verlinde, A. Avramov, A. Ackerman, A. Fridlind, G. McFarquhar and M. Wolde, 2011: Millimeter wave scattering from ice crystal aggregates: comparisons with radar measurements at X- and Ka-band using cloud model simulations. *2nd Science Team Meeting of Atmospheric Systems Research Program*, San Antonio, TX.

McFarquhar, G.M., R. Jackson, P. Liu, M. Earle, and S. Brooks, 2011: Variation of the microphysical properties of arctic stratus clouds as a function of aerosol concentration: results from ISDAC. *2nd Science Team Meeting of Atmospheric Systems Research Program*, San Antonio, TX

Yang, H.-J., G. McFarquhar, and H. Jonsson, 2011: Effect of aerosols on shallow cumuli sampled during RACORO. *2nd Science Team Meeting of Atmospheric Systems Research Program*, San Antonio, TX

McFarquhar, G.M., and J. Um, 2011: Quantifying and reducing uncertainty in observed sizes, shapes and concentrations of small ice crystals: implications for derived scattering properties. *European Geophys. Union Annual Meeting*, Vienna, Austria.

Carpenter, J. M., P. J. DeMott, M. D. Branson, S. M. Kreidenweis, A. J. Prenni, A. Glen, S. D. Brooks, A. M. Fridlind, M. Ovchinnikov, A. Korolev, W. Strapp, M. Earle, P. Liu, M. Wolde, G. McFarquhar, and R. Jackson, 2011: Cloud-resolving model simulations of two Arctic cloud cases during the ISDAC campaign. *Amer. Assoc. Aerosol Research.*

McFarquhar, G.M., Considerations in the development of microphysical and single-scattering representations of ice clouds, Atmospheric Systems Research Cloud Lifetime Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

McFarquhar, G.M., H.-J. Yang, and H. Jonsson, 2011: Controls on the microphysical properties of shallow cumuli sampled during RACORO. Atmospheric Systems Research Cloud Lifetime Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

McFarquhar, G.M., and R. Jackson, 2011: ISDAC microphysics data analysis and applications to ice clouds. Atmospheric Systems Research Cloud-Aerosol-Precipitation Interactions Working Group fall Meeting, 12 to 16 September 2011, Annapolis, MD

McFarquhar, G.M., and R. Jackson, 2011: The dependence of arctic stratus ice cloud properties on aerosol properties observed during ISDAC. Atmospheric Systems Research Cloud-Aerosol-Preciptiation Interactions Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

McFarquhar, G.M., 2011: Overview of cirrus and shallow cumuli in pristine environments working group and update on Cirrus AErosol Shallow Cumuli Atmospheric Radiation Study (CAESARS). Atmospheric Systems Research Cloud-Aerosol-Preciptiation Interactions Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

Um, J., and G.M. McFarquhar, 2011: Atmospheric Systems Research Cloud Lifetime Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

Um, J., and G.M. McFarquhar, 2011: Atmospheric Systems Research Cloud Lifetime Working Group Fall Meeting, 12 to 16 September 2011, Annapolis, MD

Vogelmann, A., T. Toto, M. Jensen, W. Lin, C. Lu, G. McFarquhar, H. Jonsson, and Y. Liu, 2011: RACORO aircraft data case study development for FASTER. DOE Climate and Earth System Modeling PI Meeting, Washington, DC, 19-22 September 2011.

Hsieh, T.-L., G. McFarquhar, and M. Freer, 2012: An intercomparison of techniques used to fit gamma distributions to cloud particle size distributions. *11th Amer. Meteor. Soc., Student Conf. and Career Fair*, New Orleans, LA, 22 January 2012.

Earle, M.E., P.S.K. Liu, J.W. Strapp, G.M. McFarquhar, A. Zelenyuk, D. Imre, M. Ovchinnikov, N.C. Shantz, S.J. Ghan, and W.R. Leaitch, 2012: Droplet closure analysis of arctic stratocumulus clouds during ISDAC. *3rd Science Team Meeting of Atmospheric System Research (ASR) Program*, Arlington, VA, 12 to 16 March 2012.

Vogelmann, A., T. Toto, M. Jensen, W. Lin, C. Lu, G. McFarquhar, R. Jackson, H. Jonsson, and Y. Liu, 2012: RACORO aircraft data case study development for FASTER. *3rd Science Team Meeting of Atmospheric System Research (ASR) Program*, Arlington, VA, 12 to 16 March 2012.

McFarquhar, G., R. Jackson, A. Korolev, M. Earle, P. Liu, P. Lawson, S. Brooks, M. Wolde, A. Laskin, and M. Freer, 2012: The dependence of arctic mixed-phase stratus ice cloud microphysics on aerosol concentration using observations acquired during ISDAC. *3rd Science Team Meeting of Atmospheric System Research (ASR) Program*, Arlington, VA, 12 to 16 March 2012.

Ovchinnikov, M., A. Ackerman, A. Avramov, G. de Boer, A. Fridlind, J. Harrington, S. Ghan, A. Korolev, A. Lock, G. McFarquhar, H. Morrison, B. Shipway, and M. Shupe, 2012: ISDAC LES intercomparison: Case setup and preliminary results. *3rd Science Team Meeting of Atmospheric System Research (ASR) Program*, Arlington, VA, 12 to 16 March 2012.

Korolev, A., M. Ovchinnikov, and G. McFarquhar, 2012: Characterizing the structure of persistent mixed-phase Arctic clouds during ISDAC using in-situ observations and modeling. *International Polar Year Conference*, Montreal, Canada, 22-27 April 2012.

Jackson, R.C., G.M. McFarquhar, J. Stith, and J. Jensen, 2012: A comparison of bulk ice microphysical properties derived using 2D cloud probes with and without shatter reducing tips and correction algorithms. *16th Int. Conf. Clouds Precip.*, Leipzig, Germany, 28 July to 3 August 2012.

McFarquhar, G.M., T.-L. Hsieh, and M. Freer, 2012: The use of gamma distributions for characterizing cloud hydrometeor size distributions in hurricane models: Uncertainties and implications. *Amer. Meteor. Soc. 30th Conf. Hurricanes Trop. Meteor.*, Ponte Vedra Beach, FL, 15-20 April 2012.

Jackson, R.C., G.M. McFarquhar, J. Stith, D.C. Rogers, and W.A. Cooper, 2012: Resolving uncertainties in climate prediction by improving the treatment of small ice particles. *Lower Atmospheric Facilities Observing Workshop*, Boulder, CO, June 2012.

McFarquhar, G.M., T.-L. Hsieh, M. Freer, and B.F. Jewett, 2012: The characterizastion of hydrometeor size distributions fit to gamma functions as surfaces in $N_0/\lambda/\mu$ phase space: implications for microphysical process rates. *16th Int. Conf. Clouds Precip.*, Leipzig, Germany, 28 July to 3 August 2012.

McFarquhar, G.M., R.C. Jackson, A.V. Korolev, J.W. Strapp, M.E. Earle, P.S.K. Liu, A. Laskin, R.P. Lawson, S. Brooks, and M. Freer, 2012: The dependence of single-layer arctic stratus ice microphysical properties on aerosol properties observed during ISDAC and M-PACE. *16th Int. Conf. Clouds Precip.*, Leipzig, Germany, 28 July to 3 August 2012.

Um, J., G.M. McFarquhar, P.J. Connolly, C. Emersic, Z. Ulanowski, and M. Gallagher, 2012: Calibration of three generations of Cloud Particle Imagers (CPIs) to improve measurements of particle size distributions. *16th Int. Conf. Clouds Precip.*, Leipzig, Germany, 28 July to 3 August 2012.

Yang, H.-J., and G.M. McFarquhar, 2012: Effects of aerosols on shallow cumuli sampled during RACORO. *16th Int. Conf. Clouds Precip.*, Leipzig, Germany, 28 July to 3 August 2012.

McFarquhar, G.M., and J. Um, 2012: Quantifying and reducing uncertainty in observed sizes, shapes and concentrations of small ice crystals: Implications for derived scattering properties at visible wavelengths. *International Radiation Symposium*, Berlin, Germany, 6 to 10 August 2012.

Um, J., and G.M. McFarquhar, 2012: Optimal numerical methods for determining the orientation average of single-scattering properties of atmospheric ice crystals. *International Radiation Symposium*, Berlin, Germany, 6 to 10 August 2012.

Um, J., and G.M. McFarquhar, 2012: Single-scattering properties of small atmospheric ice crystals at absorbing wavelengths: Dependence on idealized models. *International Radiation Symposium*, Berlin, Germany, 6 to 10 August 2012.

Vogelmann, A., T. Toto, W. Lin, Y. Liu, C. Lu, M. Jensen, G. McFarquhar, R. Jackson, and H. Jonsson, 2012: RACORO Aircraft data case study development for FASTER. *Pan-GCSS Meeting*, Boulder, CO, September 2012.

Um, J., and G.M. McFarquhar, 2012: The dependence of the single-scattering properties of small ice crystals on orientation average, particle shape and wavelength. *Amer. Geophys. Union Fall Meeting*, December 2012.

Vogelmann, A.M., T. Toto, W. Lin, Y. Liu, M.P. Jensen, C. Lu, G.M. McFarquhar, R. Jackson and H. Jonsson, 2012: RACORO aircraft data case study development for FASTER. *Amer. Geophys. Union Fall Meeting*, December 2012.

Other References in Report

Borys, R. D., D. H. Lowenthal, S. A. Cohn, and W. O. J. Brown, 2003: Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.*, **30(10),** 1538, 1510.1029/2002gl016855.

Connolly, P. J., M. J. Flynn, Z. Ulanowski, T. W. Choularton, M. W. Gallagher, and K. N. Bower, 2007: Calibration of the cloud particle imager probes using calibration beads and ice crystal analogs: The depth of field. *J. Atmos. Ocean. Technol.*, **24,** 1860-1879.

Ivanova, D., D. L. Mitchell, W. P. Arnott, and M. Poellot, 2001: A GCM parameterization for bimodal size spectra and ice mass removal rates in mid-latitude cirrus clouds. *Atmos. Res.*, **59,** 89-113.

Korolev, A., and G. Isaac, 2003: Roundness and aspect ratio of particles in ice clouds. *J. Atmos. Sci.*, **60,** 1795-1808.

Korolev, A., and G. Isaac, 2003: Roundness and aspect ratio of particles in ice clouds. *J. Atmos. Sci.*, **60,** 1795-1808.

Lohmann, U., 2002: A glaciation indirect aerosol effect caused by soot aerosols. *Geophys. Res. Lett.*, **29,** 1052, doi:1010.1029/2001gl014357.

McFarquhar, G. M., J. Um, M. Freer, D. Baumgardner, G. L. Kok, and G. G. Mace, 2007a: Importance of small ice crystals to cirrus properties: Observations from the Tropical Warm Pool International Cloud Experiment (TWP-ICE). *Geophys. Res. Lett.*, **34,** L13803, doi:13810.11029/12007GL029865.

Rangno, A. L., and P. V. Hobbs, 2001: Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations. *J. Geophys. Res.*, **106,** 15065-15075.