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 \( r_{sd} \) 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 \( \mu \)m 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 \( D < 50 \mu \)m 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 \( N_0, \lambda \) and \( \mu \) 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 \( N_0, \lambda \) and \( \mu \) characterizing the gamma function are not independent, but rather exhibit
mutual dependence. Although \( N_0, \lambda \) and \( \mu \) 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 \( N_0-\lambda-\mu \) 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 \( g \), \( \omega_0 \), and \( \tau \) 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 \( \omega_0 \), extinction efficiency \( Q_{ext} \), scattering efficiency
absorption efficiency \((Q_{\text{abs}})\), and scattering phase function at scattering angles of 90° \((P_{11}(90^\circ))\), and 180° \((P_{11}(180^\circ))\) 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 \(D=10 \mu m\) using the ADDA at \(\lambda=0.55, 3.78, \text{and } 11.0 \mu m\). The QMC required fewer orientations and less computing time than the lattice grid. The calculations of \(P_{11}(90^\circ)\) and \(P_{11}(180^\circ)\) required more orientations than the calculations of integrated scattering properties \((g, \omega_0, Q_{\text{ext}}, Q_{\text{sca}}, \text{and } Q_{\text{abs}})\) regardless of the orientations average scheme. The fewest orientations were required for calculating \(g\) and \(\omega_0\). 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 \((LWC, \beta_e, r_e, \text{and } SDs)\) 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 as 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)


**Thesis Produced with Funding from this grant**


**Conference Proceedings**


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.


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-Precipitation 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-Precipitation 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


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.


Other References in Report


