Use of In Situ Observations to Characterize Cloud Microphysical and Radiative Properties: Application to Climate Studies

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Introduction

Cloud radiative feedback is the most important effect determining climate response to human activity. Ice clouds reflect solar radiation and absorb thermal emission from the ground and the lower atmosphere and emit infrared radiation to space. The representation of these processes in models affects future climate predictions and there is much uncertainty in the representation of these processes. The size and shape of ice crystals has a major impact on how ice crystals affect radiation. Although the single-scattering properties of pristine ice crystals are generally well known (e.g., Yang et al. 2000), the single-scattering properties of irregular ice crystals and those of clouds composed of mixtures of various shaped crystals are not well known. Here, relationships between cloud and radiative properties, and their effects on the Earth's energy budget, are explored.

Two-dimensional ice crystal images obtained from in situ probes are used to derive size and shape distributions. We examine how assumptions on the shapes of small ice crystals (maximum dimensions $D < 100$ μm) and derived size and shape distributions of larger crystals affect the single-scattering and microphysical properties of ice clouds. Parameterizations that account for these effects are incorporated into single-column models (SCMs) to determine how uncertainties in their representations scale up to uncertainties in predicted cloud radiative forcings (CRFs).

This paper describes how observations are used to derive the shapes and single-scattering properties of small ice crystals; describes how data from Stratton Park Engineering Company's (SPEC Inc.) cloud particle imager (CPI) are used in coordination with data from standard optical array probes to derive size and shape distributions for larger ice crystals; and shows the importance of crystal size and shape on predictions of CRF using the Scripps SCM.

Shapes of Small Ice Crystals

Images of small ice crystals were obtained in mid-latitude cirrus clouds in May 2000 over the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) site near Ponca City, Oklahoma. The ice particle images were recorded on the charged couple device (CCD) of a digital camera that is part of the CPI, a relatively new instrument designed by SPEC Inc. The resolution of the crystal images is 2.3 μm and the images are digitized using processing software available from SPEC Inc. During this 2000 cloud intensive operational period (IOP), the CPI was installed on the University of North Dakota (UND) Citation, which flew spiral descents through cirrus clouds over the SGP, allowing ice crystals to be sampled in cirrus at temperatures between –50° and –15°C. Thirteen such spiral descents were flown and large numbers of the quasi-spherical ice crystals were seen during each descent. Figure 1 shows examples of some high quality images of small crystals, most of which have a "quasi-spherical" shape. Although typical of crystals observed, there is no guarantee that these crystals are statistically representative. These quasi-spheres were typically mixed with larger crystals that had more pristine shapes (e.g., bullet rosettes, hexagonal columns, plates, side planes, or aggregates of such shapes). For this preliminary study, data obtained during a spiral descent of 45 minutes duration on March 9, 2000, are examined. Over 99% of the larger crystals appeared to be bullet rosettes, a unique finding for a cloud to exhibit such uniformity. However, the quasi-spheroidal shape of the small crystals observed on this day was very similar to shapes observed on other days. The images shown in Figure 1 are typical of those measured on other dates. Note the bright and dark zones around particles that are caused by diffraction and somewhat fuzzy particle boundaries.

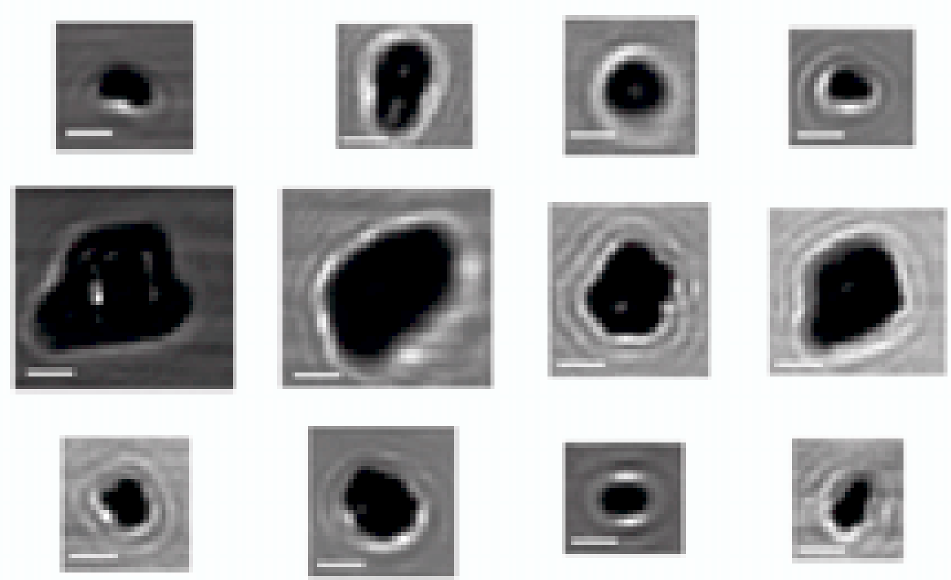

Figure 1. Example images of quasi-spherical ice particles as seen by the CPI during spiral descent of the UND Citation through cirrus over the SGP site, March 9, 2000. The horizontal bar on the images represents 25.3 μm.

The presence of these small quasi-spherical particles is not restricted to observations obtained during the 2000 cloud IOP. During the Central Equatorial Pacific Experiment (CEPEX), McFarquhar and Heymsfield (1996) observed that over 90% of the small particles they measured with a video ice particle sampler (VIPS) were quasi-spherical, where quasi-spherical was defined to mean that the projected areas of the particles were similar to those of circumscribed circles, yet their shapes exhibited substantial deviations from spheres. Since CEPEX, other investigators have found a plethoria of these quasi-spherical ice crystals in a wide variety of geographical regimes and meteorological situations.

Because the shapes of the small crystals are essentially deformed spheres, the Gaussian random sphere geometry (Muinonen 2000) can be used to describe the statistical properties of the measured ice crystals. From silhouettes of particles imaged by the CPI, the center of mass and the distance of the particle edge from the center of mass are computed. These set of radii are used to compute a covariance function, which is then used to generate model shapes that follow the same statistics as the observed shapes. Figure 2 shows examples of these generated shapes and can be compared to the actual crystal images shown in Figure 1.

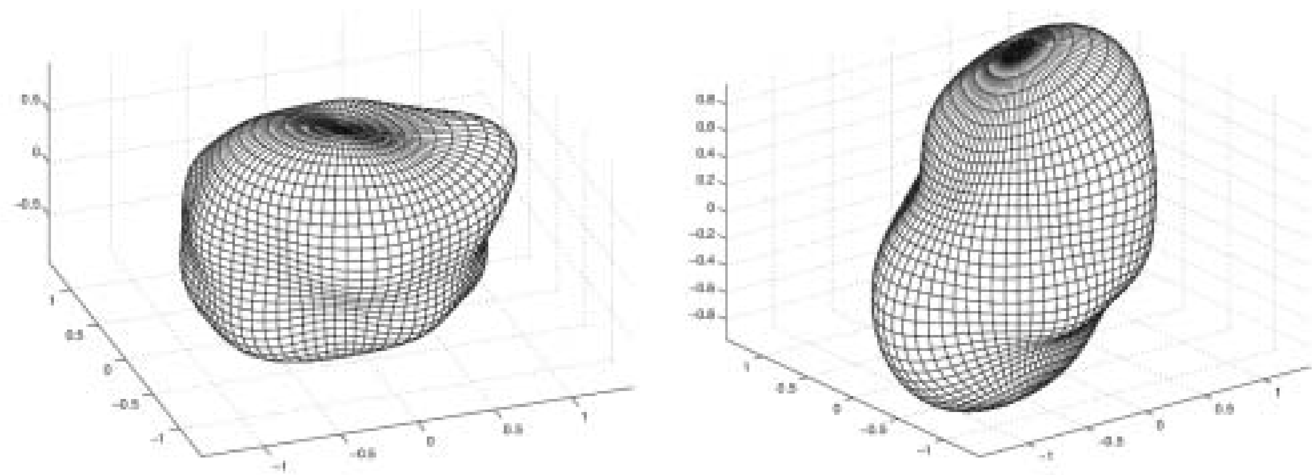

Figure 2. Example model shapes generated using the correlation function retrieved from the Gaussian random sphere approach; shapes consisting of 2 to 7 degree spherical harmonics displayed for crystals with relative standard deviation of radius of 0.165.

The single-scattering properties of the ice crystals are computed using a Monte Carlo geometric optics model (Nousiainen et al. 2002). For a wavelength of 550 nm, computed asymmetry parameters range from 0.795 to 0.837. These are similar to those estimated by McFarquhar et al. (2002) for Chebyshev particles, but somewhat higher than those estimated for pristine crystals (0.7 to 0.84). Current studies are examining the impacts of small-scale features on measured particles, and uncertainties in detection of particle boundaries on the calculation of these single-scattering properties.

Derived Shape Distributions of Large Ice Crystals

To calculate the microphysical and radiative properties of distributions of ice crystals, data from standard optical array probes, namely the two-dimensional cloud and precipitation probes, are typically used (e.g., McFarquhar et al. 2002). Habit identification using data obtained from these probes is plagued with uncertainty because the resolution of the crystal images is approximately 30 μm. Figure 3 shows examples of larger crystals measured by the CPI during the 2000 Cloud IOP. These images have much higher resolution and, hence, can be used to more accurately identify the ice crystal habits.

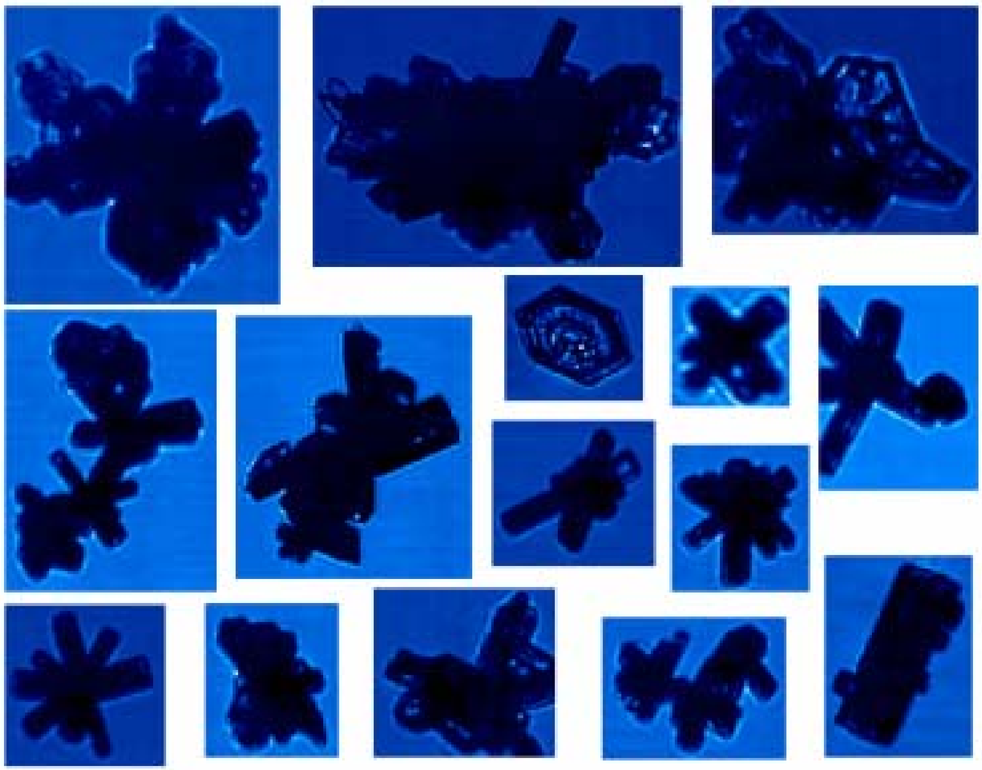

Figure 3. Examples of larger crystals imaged by the CPI during 2000 Cloud IOP over SGP site. Examples of bullet rosettes, aggregates, and irregular crystals are seen.

Ice crystal habits are identified from the CPI using software obtained from SPEC Inc. that is modified to account for the crystal characteristics observed during the 2000 Cloud IOP. For each size range, the percentage of crystals identified in different habit categories is combined with size distribution information obtained from the optical array probes to derive size and shape distributions for ice crystal populations, an example of which is shown in Figure 4. Analysis of different flight dates showed that there could be substantial variations in the size distributions and in the frequency of occurrence of different habits between dates, and even within a single date.

These derived size and shape distributions are then used to calculate the single-scattering radiative properties (asymmetry parameter, single-scatter albedo, extinction coefficient) for the distributions of ice crystals by weighting the single-scattering properties of individual ice crystals from the Yang et al. (2000) library according to the scattering cross-sections and observed number concentrations. Similarly, bulk microphysical parameters such as ice water content (IWC) and effective radius (r_e) are derived from the observed size and shape distributions using the projected areas and estimated masses of

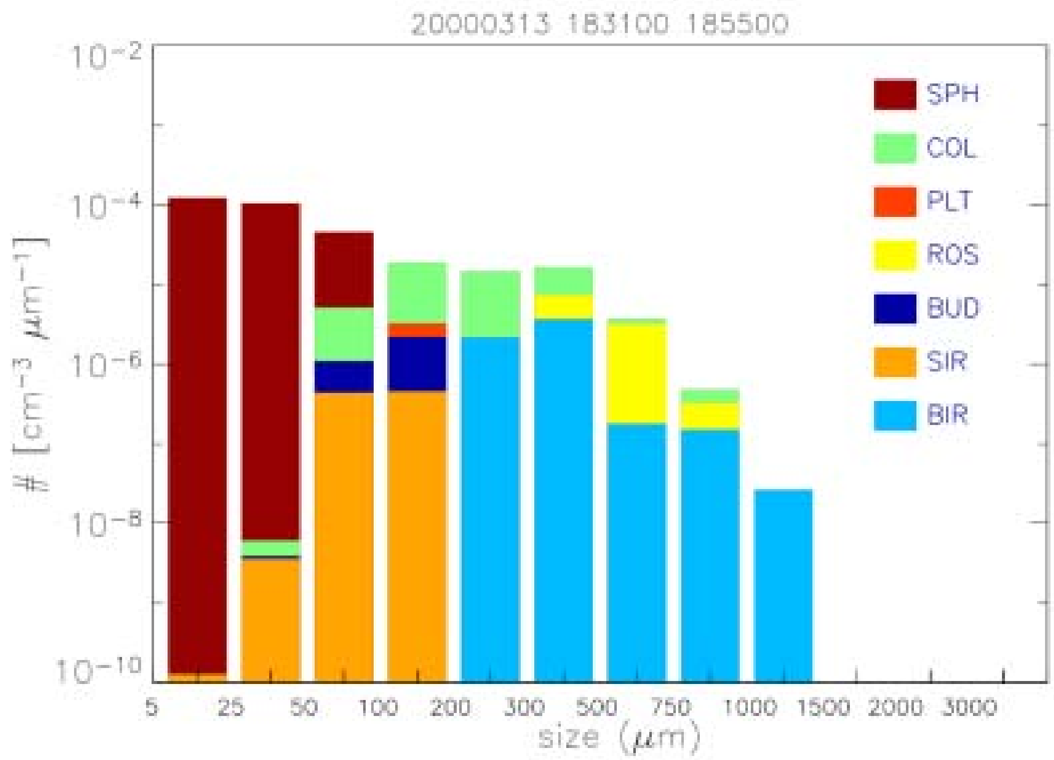

Figure 4. Number concentration of ice crystal distributions as a function of crystal maximum dimension; different-colored shadings refer to percentage of each sized crystal identified as different habits.

different crystal habits. These calculations of the single-scattering and microphysical properties of ice clouds give values that differ from those currently used in large-scale models, as existing calculations typically assume the existence of pristine habits, do not account for the occurrence of significant numbers of small ice crystals, and do not consider the effects of mixtures of different ice crystal habits on the mean scattering and bulk microphysical properties. McFarquhar et al. (2002) explain the procedures used to calculate the mean scattering properties in more detail, including the application of surface roughness to describe the aggregate crystals.

From the calculations of single-scattering and microphysical properties describing observed mixtures of ice crystals, parameterizations that describe how the mean scattering and mean microphysical properties can be developed; dependences on variables such as temperature, mass content, and r_e can be considered in this development. McFarquhar et al. (2002 and 2003) document such parameterizations for tropical clouds. Similar techniques are now being applied to determine how to represent the single-scattering and microphysical properties of mid-latitude clouds, and also to determine how these representations differ from those that have been previously derived for tropical clouds.

Impacts on Cloud Radiative Forcing

An examination is performed to determine how alternate representations of cloud and single-scattering properties affect estimates of CRF in large-scale models, using simulations that describe conditions observed at ARM's Tropical Western Pacific (TWP) site and parameterizations derived for tropical clouds (McFarquhar et al. 2002). In particular, it is examined how uncertainties in the derived parameterizations scale up to uncertainties in predictions of CRF. McFarquhar et al. (2003) describe the setup of the simulations using the Scripps SCM and the different numerical experiments performed.

McFarquhar et al. (2003) developed a parameterization that showed how r_e varied with IWC based on aircraft observations acquired during CEPEX. They also included alternate representations of the parameterization that accounted for variations of r_e one and two standard deviations above and below the mean or base value. As shown in Figure 5, these uncertainties in the parameterized r_e are associated with an estimated uncertainty in CRF of 20 W m^{-2}, when results averaged over the entire time period of this particular simulation. Variations for individual times within the simulation can be substantially larger, and average values for different simulations may differ. Until reasons for the unresolved variation in r_e that give rise to the uncertainties in the parameterization can be better understood and characterized by multi-variate dependence and until improved prognostic relations are incorporated into large-scale models, this uncertainty in r_e should be included in parameterizations and represented as a random error in model simulations.

Simulations are performed where r_e is randomly chosen at each time step to have a value within one or two standard deviations of the base parameterization. These simulations accounting for the parameterization uncertainty do not give the same CRF as simulations performed using the mean or base parameterization, as shown in Table 1. This occurs because of the non-linear relation between r_e, reflectance, and other variables and their effects on atmospheric heating. This finding may have important ramifications for modeling studies and the meaning of what a base parameterization should represent.

Table 1. Cloud radiative forcing (W m^{-2}) in solar (SW) and infrared (LW) wavelengths at surface (SFC) and top of the atmosphere (TOA).

Case	SW CRF TOA	SW CRF SFC	LW CRF TOA	LW CRF SFC
r_e,best	-88.8	-95.9	45.6	139.5
r_e,best ± 1 σ	-92.0 ± 4.7	-99.5 ± 5.6	47.0 ± 0.9	140.7 ± 2.3
r_e,best ± 2 σ	-93.7 ± 4.5	-101.4 ± 5.1	47.1 ± 0.9	140.5 ± 1.9

The variation of r_e affects CRF partly due to an enhanced reflection of solar radiation and partly due to the influence of r_e on cloud heating rates. Heating rates are also influenced by the representation of single-scattering properties. Figure 6 shows how representations of single-scattering properties affect CRFs at the TWP site. Average CRFs can vary by up to 14 W m^{-2}. This effect is comparable to the effect of varying r_e, and much larger than that due to random perturbations in temperature and pressure.

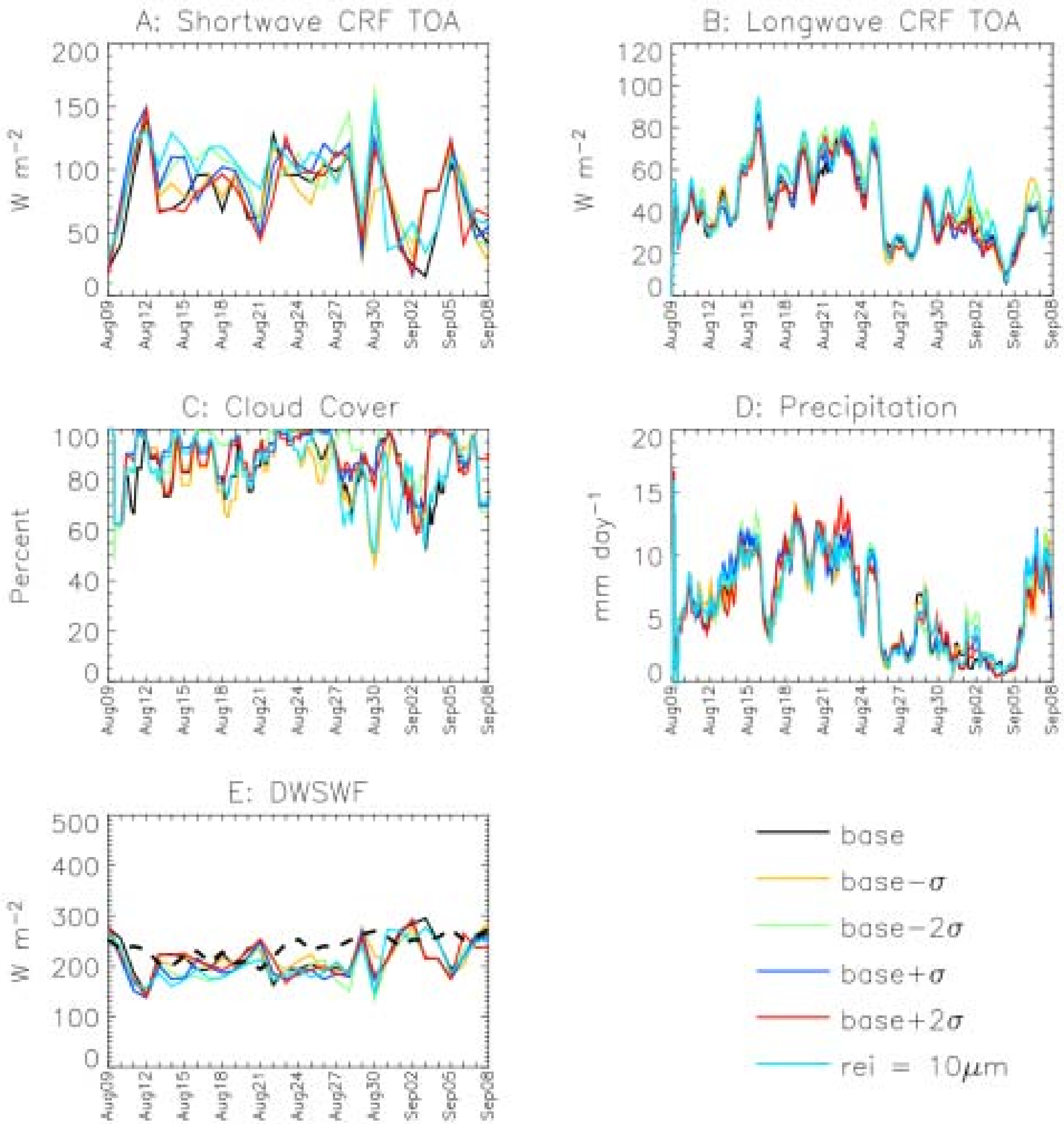

Figure 5. Computed cloud and radiative properties for 1-month simulations of conditions observed at ARM TWP site in August 2000. Different line colors represent different representations of micro-physics, ranging from simulation with base parameterization to those where parameterization based on conditions one or two standard deviations greater than or less than base parameterization (as derived from in situ microphysical observations).

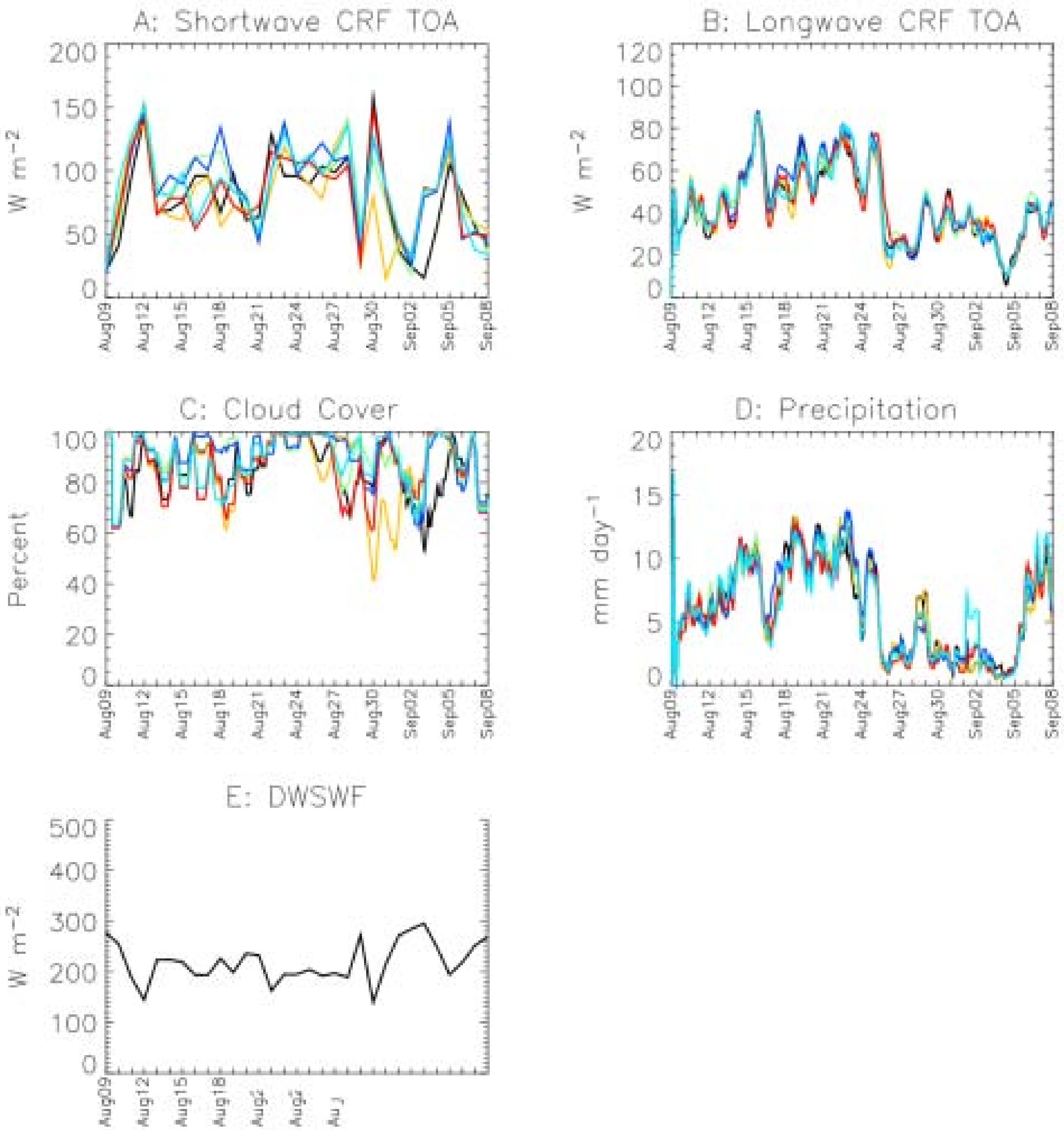

Figure 6. As in Figure 5, except different colors correspond to use of different parameterizations of cloud single-scattering radiative properties.

Summary

Impacts of cloud microphysical and radiative properties are felt at large scales. However, understanding mechanisms by which their influence scales upward is non-trivial. A better understanding of the microphysical composition of clouds, and how this composition dictates radiative properties, is a needed first step. Future work is examining these interactions for Arctic, tropical, and mid-latitude clouds.

Acknowledgments

This research was supported by the U.S. Department of Energy Atmospheric Radiation Measurement Program under Contract Numbers DE-FG03-00ER62913 and DE-FG03-97ER62338. Data was obtained from the ARM Program sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Environmental Sciences Division. Software from SPEC Inc. was used to process the CPI imagery. Mike Poellot was responsible for the collection of the microphysical data. We thank Ping Yang for the use of his library of computed single-scattering radiative properties.

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