The Microwave Radiative Properties of Falling Snow Derived from Nonspherical Ice Particle Models. Part II: Initial Testing Using Radar, Radiometer and In Situ Observations

WILLIAM S. OLSON,* LIN TIAN,† MIRCEA GRECU,† KWO-SEN KUO,# BENJAMIN T. JOHNSON,∗,** ANDREW J. HEYMSFIELD,†† AARON BANSEMER,†† GERALD M. HEYMSFIELD,‡‡ JAMES R. WANG,‡‡ AND ROBERT MENEGHINI‡‡

* Joint Center for Earth Systems Technology/University of Maryland, Baltimore County, Baltimore, Maryland
† Goddard Earth Sciences Technology and Research/Morgan State University, Baltimore, Maryland
# Earth System Science Interdisciplinary Center/University of Maryland, College Park, College Park, Maryland
†† National Center for Atmospheric Research, Boulder, Colorado
‡‡ NASA Goddard Space Flight Center, Greenbelt, Maryland

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ABSTRACT

In this study, two different particle models describing the structure and electromagnetic properties of snow are developed and evaluated for potential use in satellite combined radar–radiometer precipitation estimation algorithms. In the first model, snow particles are assumed to be homogeneous ice–air spheres with single-scattering properties derived from Mie theory. In the second model, snow particles are created by simulating the self-collection of pristine ice crystals into aggregate particles of different sizes, using different numbers and habits of the collected component crystals. Single-scattering properties of the resulting nonspherical snow particles are determined using the discrete dipole approximation. The size-distribution-integrated scattering properties of the spherical and nonspherical snow particles are incorporated into a dual-wavelength radar profiling algorithm that is applied to 14- and 34-GHz observations of stratiform precipitation from the ER-2 aircraftborne High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) radar. The retrieved ice precipitation profiles are then input to a forward radiative transfer calculation in an attempt to simulate coincident radiance observations from the Conical Scanning Millimeter-Wave Imaging Radiometer (CoSMIR). Much greater consistency between the simulated and observed CoSMIR radiances is obtained using estimated profiles that are based upon the nonspherical crystal/aggregate snow particle model. Despite this greater consistency, there remain some discrepancies between the higher moments of the HIWRAP-retrieved precipitation size distributions and in situ distributions derived from microphysics probe observations obtained from Citation aircraft underflights of the ER-2. These discrepancies can only be eliminated if a subset of lower-density crystal/aggregate snow particles is assumed in the radar algorithm and in the interpretation of the in situ data.

1. Introduction

In late February 2014, the Global Precipitation Measurement (GPM) Core Observatory satellite was launched into low Earth orbit in a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). The Core Observatory includes the Dual-Frequency Precipitation Radar (DPR) as well as the multichannel GPM Microwave Imager (GMI), and the complementary precipitation information provided by this combination of instruments has been described by Hou et al. (2008). The DPR, operating at frequencies of 13.6 and 35.5 GHz, can in principle be used to retrieve two parameters, typically the intercept and median volume diameter, of the precipitation particle size distribution (PSD) in each 250-m range gate within the near-vertical column observed by the radar (see Grechu et al. 2011; Seto and Iguchi 2011). The GMI radiometer, sensing upwelling radiances between 10.65 and 183.3 GHz, can provide information regarding the path attenuation by water vapor, cloud, and precipitation in the vertical...
column observed by the DPR. This additional information may be used to help attenuation correct the radar data (Haddad et al. 1997b; Grecu et al. 2004) and potentially provide information regarding the effective density (or habit) of ice particles along the radar line of sight (Grecu et al. 2011).

Most algorithms that combine radar and microwave radiometer data to estimate precipitation vertical profiles are physically based (see Haddad et al. 1997b; Grecu et al. 2004; Masunaga and Kummerow 2005; Grecu and Olson 2008; Munchak and Kummerow 2011). Therefore, it is crucial that the physical models used to describe the microwave single-scattering properties of the precipitation particles are unbiased; otherwise, biased estimates of precipitation could result. In particular, given their complex geometries, ice-phase and mixed-phase precipitation particles pose a significant challenge to modelers attempting to describe their single-scattering properties. Early attempts to describe the scattering properties of snow particles utilized equivalent homogeneous sphere models for snow that relied upon dielectric mixing formulas to describe the effective refractive index of the ice–air medium (see Meneghini and Liao 1996, 2000). The appeal of these spherical models is that once the effective refractive index is specified, the single-scattering properties of the particles can be calculated efficiently using Mie theory. However, with the introduction of faster computer processors and parallel-computing environments, methods such as the discrete dipole approximation have been used to accurately describe the properties of more realistic, nonspherical pristine ice crystals and aggregates of crystals (see Liu 2004; Kim 2006; Hong 2007; Weinman and Kim 2007; Grecu and Olson 2008; Petty and Huang 2010; Botta et al. 2010, 2011; Tynelä et al. 2011; Nowell et al. 2013; Bi and Yang 2014; Ori et al. 2014). As shown in these studies, snow particle shape has an impact on extinction for particles with equivalent size parameters (defined as $x_{eq} = \pi D_{eq}/\lambda$, where $D_{eq}$ is the liquid equivalent particle diameter and $\lambda$ is the wavelength of radiation) greater than $\sim 0.5$, and on the asymmetry of scatter for even smaller size parameters.

In Kuo et al. (2016, hereinafter Part I), pristine crystals were generated using a 3D growth model, and these crystals were aggregated using a self-collection algorithm to create a large set (6646) of crystal/aggregate snow particles. Taking advantage of parallel-processing techniques, the single-particle and bulk (polydispersion integrated) single-scattering properties of these particles were computed and simple radiative simulations were performed. Bulk reflectivities and radiance simulations were shown to be significantly different from those based upon spherical particle polydispersions, and it was demonstrated that the choice of an “effective” spherical particle density for the purpose of parameterizing the nonspherical snow particle scattering properties would not lead to consistent scattering properties across the spectrum of DPR and GMI channel frequencies.

The validity of different snow particle models has been tested using coincident radar and passive microwave observations by Kulie et al. (2010). They interpreted W-band (94 GHz) radar observations from CloudSat in terms of snow particle size distributions and then simulated upwelling microwave radiances at the 36-, 89-, and 157-GHz channel frequencies of the satelliteborne Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) and Microwave Humidity Sounder. In general, these authors obtained greater consistency between simulated and observed microwave radiances using nonspherical snow particle models as opposed to spherical snow models. Also, Leinonen et al. (2012) and Kulie et al. (2014) utilized radar data at 13.4, 35.6, and 94 GHz from the Wakasa Bay (Japan) experiment to demonstrate that nonspherical snow particle models were required to explain these simultaneous observations consistently.

The objective of the present study is to evaluate the spherical and nonspherical snow particle scattering models, described in Part I of this series, in the context of the dual-frequency radar and multichannel passive microwave radiometer observations that are available from GPM. During the Midlatitude Continental Convective Clouds Experiment (MC3E), an airborne radar, the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), and a radiometer, the Conical Scanning Millimeter-Wave Imaging Radiometer (CoSMIR), similar to the DPR and GMI, were deployed. Data from these instruments are utilized to test the consistency of the different snow particle models. Estimated snow particle size distributions from the airborne remote sensing instruments are further evaluated using microphysics probe observations from an underflying aircraft. To date, the set of airborne radar and radiometer observations from MC3E, as well as the GPM Cold Season Precipitation Experiment (GCPEX) and Integrated Precipitation and Hydrology Experiment (IPHEx), most closely resemble the data that are derived from the GPM core instruments.

The snow particle models and size distributions are briefly reviewed in section 2; see Part I for more complete descriptions. The testing framework, data, and analysis methods are presented in section 3. The particle models are examined using radar–radiometer observations and microphysics probe data in sections 4 and 5, respectively. A summary and concluding remarks are provided in section 6.
2. Pristine crystal and aggregate particle simulations

In Part I, the authors described the simulation (using the “snowfake” algorithm) of individual pristine crystals such as dendritic forms, needles, and “sandwich” plates, based upon a method pioneered by Gravner and Griffeath (2009). By prescribing different control parameters in snowfake, a pool of pristine crystals with different sizes and geometries was generated and their properties were cataloged. Drawing from this pool of ice crystals, a computer simulation of the crystal self-collection process was then performed to create aggregate snow particles. The single-scattering properties of the simulated crystal/aggregate snow particles were calculated using the discrete dipole approximation (DDA) as coded in DDSCAT 7.1 (see Draine and Flatau 1994). It was assumed that the orientation of all snow particles was random, and so the orientation-averaged properties of each particle were computed.

To calculate the bulk single-scattering properties of polydispersions of snow particles, the PSDs of the snow were assumed to be described by normalized gamma distributions, as in Testud et al. (2001; see Part I). In the normalized gamma distribution, the spectral concentration of particles $n(D_{le})$ for a particle liquid equivalent diameter $D_{le}$ is

$$n(D_{le}) = N_w f(\mu) \left(\frac{D_{le}}{D_{o-le}}\right)^\mu \exp\left(\frac{(3.67 + \mu)D_{le}}{D_{o-le}}\right),$$

where

$$f(\mu) = \frac{\Gamma(4)(3.67 + \mu)^{\mu+4}}{3.67^\mu \Gamma(\mu + 4)}.$$  (1)

Here, $N_w$ is the intercept, $D_{o-le}$ is the liquid equivalent median volume diameter, and $\mu$ is the shape factor of the normalized distribution. An advantage of (1) is that, for a given water content and $D_{o-le}$ value, $N_w$ is determined independent of $\mu$, whereas the traditional gamma distribution intercept varies strongly with $\mu$. Polydispersion bulk radiative properties, such as the extinction and scattering coefficients, asymmetry parameter, and radar reflectivity, are tabulated as functions of $N_w$, $D_{o-le}$, $\mu$, water content, and other PSD-derived parameters, for use in the applications that will be described in the following sections.

3. Testing framework

a. Field observations

During the MC3E, various ground-based and airborne remote sensing instruments were employed to produce a comprehensive view of convection over north-central Oklahoma and southern Kansas in the May–June 2011 period [see Jensen et al. (2010) for an overview]. The primary field campaign datasets utilized in the present study are derived from the enhanced sounding array, airborne radar and microwave radiometer, and airborne microphysics probes deployed on 20 May 2011. The focus of the current testing is stratiform precipitation that was observed on that date. Stratiform precipitation regions are chosen because of the quasi-uniform horizontal distribution of cloud and precipitation and the well-studied vertical structure of precipitation in similar regions based upon the accumulated evidence from numerous past field campaigns (see Houze 1981, 1989).

The HIWRAP was deployed on NASA’s ER-2 aircraft during MC3E. HIWRAP is a dual-wavelength radar operating at 13.9 GHz (Ku band) and 33.7 GHz (Ka band), and during MC3E, the antenna head for nadir viewing observations was utilized. In this configuration, the HIWRAP approximates the observing characteristics of the GPM DPR. However, a primary advantage of the HIWRAP, which is critical to the particle model testing of the present study, is that it has much higher sensitivity than the DPR. The minimum detectable signals of the HIWRAP are $-0.5$ and $-10.6$ dBZ at 13.9 and 33.7 GHz, respectively, at an altitude of 10 km (about 10-km range from the radar). This greater sensitivity makes it possible to detect ice-phase particle signals nearly to cloud top in the stratiform observations on 20 May 2011 in MC3E. The beamwidths of the 13.9- and 33.7-GHz channels are $3.0^\circ$ and $1.2^\circ$, respectively, and although the two channels have different resolutions, the quasi-uniform horizontal structure of the observed stratiform precipitation regions that are the focus of this study helps to mitigate channel resolution differences. A detailed description of the HIWRAP instrument may be found in G. M. Heymsfield et al. (2013).

Calibration of the HIWRAP for MC3E was carried out in two steps. First, to provide an absolute calibration of the 13.9-GHz radar channel, flights over the Gulf of Mexico were conducted on 7 May and 29 May 2011. The aircraft was banked to provide HIWRAP views at incidence angles ranging from $0^\circ$ to $24^\circ$. Over ocean surfaces, a minimum of the standard deviation of surface normalized backscatter cross section $\sigma^o$ is seen at off-nadir incidence angles (Meneghini et al. 2000; Meneghini and Jones 2011), and so an offset was applied to the HIWRAP data to bring the measured $\sigma^o$ at $9.75^\circ$ incidence angle into agreement with the reference value from Takahashi et al. (2003). The 33.7-GHz data are adjusted with respect to the 13.9-GHz data by assuming that the reflectivity in either channel approaches the small particle Rayleigh limit (essentially 0 reflectivity difference) at high altitude in stratiform precipitation...
regions. A similar calibration approach was used to calibrate 13.4- and 35.6-GHz radar observations from the Airborne Precipitation Radar-2 by Tanelli et al. (2006).

The CoSMIR was also deployed on the ER-2 during MC3E. It is a 9-channel radiometer operating at frequencies of 50.3 and 52.8 GHz (horizontal polarization), 89 and 165.5 GHz (vertical and horizontal polarizations), and 183.3 ± 7, 183.3 ± 3, and 183.3 ± 1 GHz (horizontal polarization). Of particular interest in the present study are the snow-sensitive channels at 89 and 165.5 GHz that operate in relative atmospheric windows, although background water vapor absorption does have an impact on these channels, and its influence increases with channel frequency. During MC3E, the CoSMIR was programmed to scan in a hybrid cross-track/conical mode, scanning cross track through nadir but then forward (or aft) conically at an incidence angle of 53.6° to complete one scan cycle. CoSMIR has a 4.3° beamwidth, which results in a footprint of 1.5 km at Earth’s surface at nadir view, based upon an ER-2 altitude of 20 km. The CoSMIR radiances are calibrated using two external calibration targets, one maintained at 328 K and the other at 250 K at the ER-2 cruising altitude. The instrument response to radiances is essentially linear, and so the calibration of the lowest nadir-view radiances in 20 May stratiform regions (~200 K) is expected to be ±1 K. A complete description of CoSMIR and its calibration during MC3E may be found in Wang et al. (2013).

HIWRAP and CoSMIR observations of predominantly stratiform precipitation on 20 May 2011 took place during ER-2 flight legs between 1356 and 1551 UTC. Since the HIWRAP and CoSMIR channels are sensitive to the gaseous environment as well as cloud and precipitation, sounding data contemporaneous with the ER-2 observations are also utilized in this study. During MC3E, sondes were launched every 3–6 h from the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains Central Facility at Lamont, Oklahoma, and from the surrounding stations at Pratt, Kansas; Chanute, Kansas; Vici, Oklahoma; Morris, Oklahoma; and Purcell, Oklahoma [see Jensen et al. (2010) and Fig. 1]. Vertical environmental profiles of pressure, temperature, and relative humidity are smoothly interpolated to the flight leg locations of the ER-2.

Microphysics probes were deployed on the University of North Dakota Citation aircraft during MC3E. The Citation carried a standard suite of meteorological instruments together with the microphysics instruments. The PSDs of cloud and precipitation in the 50–1000-μm size range were measured with a Particle Measurement Systems 2D-C or similar Droplet Measurement Technologies cloud imaging probe, while PSDs of larger particles (from 200 μm to >1 cm) were measured with a Stratton Park Engineering Company high-volume precipitation spectrometer (HVPS)-3 probe. Maximum dimension D is used to characterize the size of each particle in these measurements. On 20 May 2011 from 1330 to 1518 UTC, PSDs were collected in the same stratiform region between temperatures of −23° and 4°C. To avoid ambiguities in comparisons between the in situ probe PSDs and airborne remote sensing–estimated PSDs, the moments of the airborne PSDs in terms of D are computed directly from probe-derived histograms of particle sizes. The exceptional case is the water content, which is derived from the in situ data using an assumed mass–size relation, $m = 0.0061D^{2.05}$ in cgs units.

b. Airborne combined radar algorithm–radiometer simulator

The 13.9- and 33.7-GHz HIWRAP radar data are inverted to estimate parameters and moments of the particle size distributions of stratiform precipitation observed during MC3E. The algorithm used to retrieve precipitation information is the dual-wavelength radar method described in Grecu et al. (2011). In brief, this algorithm retrieves $N_w$ and $D_{v,le}$ of the precipitation size distribution given an assumed $μ$ value and atmospheric environment (temperature, pressure, humidity, and cloud water content). Procedurally, the algorithm does an analytical, forward iterative inversion of the 13.9-GHz radar profile given the environment, $μ$ value, and an a priori guess of the $N_w$ profile, to obtain a $D_{v,le}$ profile. The a priori parameters and estimated profile
are then used to simulate the reflectivities at 33.7 GHz as well as the column path-integrated attenuation at both 13.9 and 33.7 GHz. The observed reflectivities at 33.7 GHz and estimated path-integrated attenuation at 13.9 and 33.7 GHz [nominally, from the surface reference technique (SRT; Meneghini et al. 2000)] are then used to variationally adjust the original \(N_w\) profile, and the procedure is iterated until the simulations of reflectivities and path-integrated attenuations converge to the observed. However, since the applications of the current study are over land backgrounds, path-integrated attenuation estimates from methods such as SRT are unreliable, and so profile estimates are not constrained by path-integrated attenuation here. Since radar pulse attenuation is mostly confined to the liquid and mixed-phase precipitation layers, the lack of constraint by independent estimates of path-integrated attenuation does not have a significant influence on the estimation of snow microphysical properties, which are the focus of the present study.

The algorithm software for estimating precipitation profile PSD parameters is coupled to a forward radiative transfer model for the purpose of computing upwelling microwave radiances based upon the bulk scattering properties of the estimated precipitation profiles and environmental parameters, as well as surface properties. The radiative transfer method employed is Eddington’s second approximation (Weinman and Davies 1978), which includes the effects of microwave multiple scattering by precipitation. To account for the forward scattering peak of ice-phase particles at the higher microwave frequencies, the delta scaling of Joseph et al. (1976) is applied to the single-scattering parameters. In this way, the upwelling radiances at the CoSMIR channel frequencies/polarizations are computed. Idealized, single-layer radiative transfer solutions were performed in Part I, but here, the solutions account for the vertical layering of the atmosphere determined from the HIWRAP profile estimates. The HIWRAP profiles are resampled at 500-m resolution to make the radiative transfer calculations computationally efficient.

c. Testing strategy

The testing strategy is illustrated in Fig. 2. The ER-2 flies at a nominal altitude of 20 km, above the stratiform cloud and precipitation. The HIWRAP views only at nadir, observing a narrow slice of the atmosphere along the flight track. From the same platform, the scan pattern of CoSMIR allows it to view the same vertical column of the atmosphere at nadir view. The combined radar algorithm–radiometer simulator can be used to estimate vertical profiles of precipitation PSD parameters from HIWRAP and then simulate the vertically propagating microwave radiances at the CoSMIR channel frequencies.

![Fig. 2. Schematic of the snow particle model testing framework for stratiform precipitation. ER-2-based observations from HIWRAP and CoSMIR are at nadir view. In situ microphysics probe measurements are derived from Citation aircraft underflights. Typical extinction coefficients (orange line) and single-scattering albedos (green line) for spherical ice particles at 165.5 GHz are plotted as functions of altitude. Corresponding upwelling microwave radiances at 165.5 GHz for spherical snow particles (blue line) and nonspherical snow particles (red line) are also plotted as functions of altitude through the precipitation layer. Diamonds (crosses) indicates the upwelling radiances if extinction is doubled (halved) in the rain/mixed-phase layer.](http://journals.ametsoc.org/jamc/article-pdf/55/3/709/3586485/jamc-d-15-0131_1.pdf)}
air, and liquid. The proportions of ice, air, and liquid in each particle are determined using a thermodynamic melting model similar to the one described in Olson et al. (2001). The effective refractive indices of each mixed-phase particle are approximated using Bruggeman (1935) mixing, and Mie theory is then applied to compute the single-scattering properties of the particles. Tables of the scattering properties of snow polydispersions are computed for spherical, ice–air snow particles of different densities as well as nonspherical crystal–aggregate snow particles, as described in section 2.

The main question to be answered here is, what assumptions regarding the scattering properties of snow will lead to radar-derived PSDs and upwelling microwave radiances that are consistent with coincident observations from the CoSMIR? And, second, if a consistent scattering model for snow can be found, are the radar-estimated PSDs consistent with nearly coincident in situ microphysics probe observations from underflying aircraft? The first question can only be answered if variations in factors such as the environmental conditions, $\mu$, and assumptions regarding the characteristics of the mixed-phase and liquid precipitation layers and underlying Earth’s surface have limited impact on the radar estimates and subsequent radiometer simulations.

Sensitivity tests will confirm that the aforementioned factors and assumptions do not greatly impact the testing results; however, qualitatively, it may be first noted that the HIWRAP observations of ice-phase precipitation are largely unattenuated at 13.9 and 33.7 GHz, and so the radar signatures of snow are mainly due to particle size distribution and scattering effects (Liao et al. 2005). It follows that the estimated PSD parameters in the layer of ice-phase precipitation are largely unaffected by uncertainties of the attenuation correction by the radar algorithm. On the other hand, the radar estimates of precipitation distributions in the mixed-phase and rain layers are impacted by attenuation, particularly at 33.7 GHz, but the accuracy of the radar solutions in these layers is not so critical to the calculation of upwelling microwave radiances at the CoSMIR frequencies. This is because the upwelling radiation at the higher microwave frequencies is strongly absorbed/reemitted within the mixed-phase and rain layers because of the substantial optical depths of even light liquid precipitation layers at these frequencies, together with the relatively low single-scattering albedos of liquid precipitation (see Fig. 2).

To first order, then, the mixed-phase and rain layer act like a blackbody emitting at a temperature characteristic of the top of the mixed-phase layer (273 K), if the mean rain rate in the layer is at least 2 mm h$^{-1}$ (or $\approx$0.1 g m$^{-3}$ water content).

The profiles of simulated upwelling radiances at 165.5 GHz shown in Fig. 2 are based upon a fairly typical stratiform layer observed during 20 May of MC3E. The symbols at the top of the radiance plots indicate the small deviations of the upwelling radiance resulting from a halving or doubling of the optical depth in the mixed-phase and rain layer. The mixed-phase and rain layer, therefore, provide a fairly stable radiative background, and relative to this background, the microwave scattering depressions due to ice-phase precipitation can be used to discriminate different particle scattering models.

4. Radar–radiometer consistency tests

a. Case study

On 20 May 2011, from approximately 0700 to 1500 UTC, a northeast–southwest-oriented squall line propagated west to east, through central Oklahoma. Trailing the squall line was an extensive area of stratiform precipitation that passed over the ARM Central Facility at approximately 1400 UTC. During the period 1412–1418 UTC, the NASA ER-2 flew over this stratiform precipitation region along the flight track illustrated in Fig. 1.

In applying the dual-wavelength radar algorithm to the HIWRAP data from this flight leg, and in subsequent radiance simulations at the CoSMIR frequencies, uncertainties in the observed environmental conditions and gamma distribution $\mu$ assumptions are represented by randomly generating values of the environmental and $\mu$ profiles. The inversion of a given HIWRAP reflectivity profile, and the subsequent radiance simulations based upon the estimated PSD profile, are repeated for each set of randomly generated environmental–$\mu$ profiles, and a total of 40 sets of environmental–$\mu$ profiles are therefore used to create a 40-member ensemble of estimated PSD profiles–radiance simulations corresponding to each reflectivity profile.

Regarding environmental conditions, soundings collected from 20 May are smoothly interpolated to a single composite profile at the location of the flight leg (see Fig. 3). However, the large-scale composite profile derived from the sounding data does not necessarily represent the mesoscale variation of the environment that is expected in the vicinity of the squall line and trailing stratiform region. In particular, the humidity of the environment will have the largest impact on radar attenuation and subsequent radiometer channel simulations. For this reason, random perturbations of relative humidity with a standard deviation of 20% relative to the composite profile of humidity are added to that profile. In convective clouds, nonprecipitating cloud liquid water is expected to have a significant impact on radar pulse attenuation and microwave emission. However, since the indicated ER-2
flight leg is approximately 150 km from the convective leading edge of the squall line, nonprecipitating cloud liquid water contents are expected to be low (see Houze and Churchill 1987; Stith et al. 2002; Heymsfield et al. 2002), and so they are neglected in the current analysis. Regarding the assumed \( \mu \) profile, estimates of \( \mu \) in ice-phase precipitation based upon microphysics probe data by A. J. Heymsfield et al. (2013) indicate the bulk of \( \mu \) values are clustered near a value of 0 with a standard deviation \( \sim 2 \). Therefore, random \( \mu \) values drawn from a uniform distribution \([-2, +2] \) are assumed. A. J. Heymsfield et al. (2013) also note a dependence of \( \mu \) on the slope of the PSD (inversely proportional to \( D_o \)) and environmental conditions. Such \( \mu \) dependencies will be considered in future work, as these relationships become better established for snow particles. Finally, variations of microwave surface emissivity do not have an appreciable impact on upwelling radiances at frequencies of 89 GHz and higher because of the strong absorbing effect of rain layers at these frequencies. Therefore, variations in the prescribed emissivity, assumed to have a value of 0.9, are neglected.

HIWRAP 13.9- and 33.7-GHz reflectivity observations from the case study flight leg are illustrated in Fig. 4. The vertical distributions of reflectivity are quasi-uniform in the horizontal, with weaker reflectivities due to ice-phase precipitation aloft, a brightband maximum associated with melting particles just below the freezing level at \( \sim 3.8 \) km, and stronger reflectivities due to liquid precipitation below the bright band. Above the freezing level, the difference of 13.9- and 33.7-GHz reflectivities (DFR) is correlated with snow median volume diameter (see Liao and Meneghini 2011). In view of Fig. 4, a local maximum of snow median volume diameters is expected near 5.0 km just after 1415 UTC. In the melting layer and below, the DFR is primarily a function of the difference of attenuation at 13.9 and 33.7 GHz.

Shown in Fig. 5 are estimates of the logarithm of the particle total number concentration \( N_p \), median volume diameter \( D_o \), and precipitation water content derived from the dual-wavelength radar algorithm. Note here that the \( D_o \) values are based upon the maximum dimension of the particles instead of the liquid equivalent diameter, as in (1). The estimated precipitation quantities in the mixed-phase and rain layers are similar in both the left- and right-hand panels, since identical
models for mixed-phase and liquid precipitation are assumed in the radar algorithm. However, the estimates of ice-phase precipitation quantities in the left-hand panels are calculated assuming gamma-distributed spherical snow with a constant density (0.1 g cm\(^{-3}\)), while those in the right-hand panels are calculated using gamma-distributed nonspherical snow particles, as described in section 2. Note that the estimated log\(_{10}(N_T)\) values derived using the nonspherical snow particles are less than the values derived using the spherical snow, while values of \(D_o\) are substantially greater for the nonspherical particles relative to the spherical particles. The combined effect of the different snow PSDs and particle geometries is estimated precipitation water contents that are somewhat lower for the nonspherical particles. The water content estimates based upon the constant-density spheres are, however, sensitive to the assumed density. The specification of higher-density spheres leads to estimated log\(_{10}(N_T)\) and \(D_o\) that decrease, and estimated precipitation water contents that also decrease (not shown). The opposite trends occur if the assumed density of the spherical snow particles is reduced.

Regardless of the assumed density of the constant-density spherical snow particles, simulated upwelling microwave radiances computed from the corresponding radar-estimated snow distributions cannot match the observed radiances from CoSMIR (see Fig. 6). As the assumed density increases, the simulated radiances decrease, particularly at 165.5 GHz, since microwave scattering by snow is generally stronger at that frequency. However, it is evident from Fig. 6 that the radiances at 165.5 GHz do not decrease to the extent needed to match the observed radiances from CoSMIR. Larger ice-phase precipitation particles with densities greater than 0.3 g cm\(^{-3}\) are highly unlikely in stratiform regions far from convection (see Stith et al. 2002; Heymsfield et al. 2002). Moreover, the assumption of spherical ice–air particles with such high densities results in unrealistically low radar-estimated water contents. On the other hand, the precipitation distributions estimated using the nonspherical snow particles lead to simulated upwelling radiances that are reasonably consistent with those observed by CoSMIR. In the region of strongest ice scattering, simulated 165.5-GHz upwelling radiances based upon the nonspherical snow particles are in agreement with the observations, considering the range of uncertainty in the simulations, while the simulated radiances based upon the 0.1 g cm\(^{-3}\) spherical particles are \(~40\)K higher than the CoSMIR observations.
The difference in the spherical and nonspherical particle radiance simulations can be primarily attributed to the lower asymmetry parameters of the nonspherical snow particles relative to those of the spherical snow particles, particularly at 165.5 GHz (see Figs. 4, 8, and 10 of Part I). Because of the lower asymmetry parameters, the nonspherical snow particles scatter less in the forward direction than ice–air spheres of the same mass, leading to a large reduction of the microwave radiances upwelling from the mixed-phase layer. The vertical profiles of simulated upwelling radiances based upon spherical and nonspherical snow particles shown in Fig. 2 illustrate this effect. Increasing the density of the spherical particles within plausible limits leads to some reduction of upwelling radiances, but this reduction is not nearly enough to explain the microwave scattering depressions sensed by the CoSMIR at 165.5 GHz.

b. Composite statistics

On 20 May 2011, the ER-2 flew over predominantly stratiform precipitation on 16 flight legs from 1356 to 1551 UTC; see Table 1 for times and locations of these legs. For each of these legs, the HIWRAP data are used to estimate the vertical profiles of ice-phase precipitation based upon different snow particle models, and upwelling radiances at the CoSMIR 89- and 165.5-GHz channel frequencies are simulated and compared with the observed radiances, as described previously in section 4a. Composite bivariate statistics of these comparisons are presented in Table 2. Note that regardless of the type of snow particle model that is assumed, the correlations between the simulated and CoSMIR-observed radiances are quite high. On the other hand, the bias between the simulated and observed radiances for these legs is much reduced if nonspherical snow particles are assumed instead of spheres. This is particularly true of the comparison at 165.5 GHz, for which the bias is reduced from tens of kelvins using the spherical models to about 3 K using nonspherical snow. So, although this is a limited sample of data from one day of observations, the spherical snow models clearly lead to inconsistencies with the radar–radiometer observations, while the nonspherical snow particle model does not.

<table>
<thead>
<tr>
<th>Flight leg</th>
<th>Time period (UTC)</th>
<th>Lat/lon of endpoints (°min N°min W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1411–1412</td>
<td>36:12/97:12–36:19/97:12</td>
</tr>
<tr>
<td>3</td>
<td>1412–1418</td>
<td>36:19/97:13–37:02/97:16</td>
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<td>1437–1440</td>
<td>36:46/97:15–37:02/97:16</td>
</tr>
<tr>
<td>7</td>
<td>1443–1444</td>
<td>37:00/97:31–36:56/97:31</td>
</tr>
<tr>
<td>10</td>
<td>1454–1501</td>
<td>36:13/97:12–37:02/97:16</td>
</tr>
<tr>
<td>12</td>
<td>1515–1522</td>
<td>36:11/97:12–37:02/97:16</td>
</tr>
<tr>
<td>15</td>
<td>1540–1543</td>
<td>36:42/97:14–37:03/97:16</td>
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<tr>
<td>16</td>
<td>1547–1551</td>
<td>37:00/97:32–36:34/97:29</td>
</tr>
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</table>
5. Comparisons with in situ data

Although the HIWRAP-estimated vertical profiles of precipitation based upon the nonpherical snow particle model show general radiative consistency with simultaneous passive microwave observations from the CoSMIR, that does not guarantee that the estimated profiles are necessarily accurate. Therefore, as a rough quality check, the estimated snow PSDs are compared with near-simultaneous, in situ PSDs from the Citation aircraft (see section 3a).

On May 20, the Citation flew underneath flight paths of the ER-2 from 1355 to 1400 UTC at 5.9-km altitude (ER-2 leg 1), from 1457 to 1502 UTC at 5.1-km altitude (ER-2 leg 10), and from 1508 to 1516 UTC at 4.1-km altitude (ER-2 leg 12). Each Citation underflight was only under a portion, or segment, of the corresponding ER-2 flight leg. Because of the different speeds of the aircraft, there were time mismatches on the order of a few minutes between the ER-2 and Citation observations along a given flight segment; see Table 1 for a listing of the ER-2 flight leg periods. Also, despite best efforts to coordinate the ER-2 and Citation flight paths, spatial mismatches of the flight segments of ~1 km occurred. For these reasons, and because the sampling volumes of the HIWRAP radar targets and microphysics probes are significantly different, only comparisons of flight-segment-mean PSD quantities are attempted here. Since the precipitation structures selected in this study are all stratiform, errors due to temporal and spatial mismatches are minimized.

Presented in Table 3 are the mean estimated and in situ PSD-derived parameters over the indicated flight segments. Note that aside from the mean liquid water content, the in situ parameters are derived solely from the PSD without any additional assumptions; these include the mean median volume diameter \( D_{\text{m}} \) and mean logarithmic moments \( \log_{10}(M_0) \), \( \log_{10}(M_2) \) and \( \log_{10}(M_3) \) of the PSDs. The mean liquid equivalent water content \( \text{LWC} \) is derived from the in situ data using a mass–size relation, \( m = 0.0061D^{2.05} \), in egs units. A regression fit to the ensemble of simulated nonspherical snow particles developed in this study yields a mass–size relation of \( m = 0.0082D^{2.14} \); that is, the mean density of a simulated snow particle is greater than that of the corresponding in situ particle of the same size for particle sizes greater than \( \sim 500 \mu m \).

From Table 3, it may be noted that the estimated \( D_{\text{m}} \) values based upon constant-density spherical particles are significantly lower than the in situ observed \( D_{\text{m}} \) values, while the estimated \( D_{\text{m}} \) based upon the nonpherical snow particles, although still lower than the in situ, are much closer in magnitude. The correspondence of the estimated and in situ mean logarithmic moments is somewhat more ambiguous, although the nonspherical model leads to PSD estimates with a fourth moment that is consistently higher than that of the constant-density particles, and closer to the in situ.

The values of LWC estimated using either the constant-density spherical or nonpherical snow models tend to be substantially lower than the in situ. This result is not surprising, because the second moments of the estimated PSDs, which are essentially proportional to the water mass, are also consistently lower. Since the \( 0.1 \text{ g cm}^{-3} \) constant-density spheres generally lead to the highest LWC values, and since the simulated nonpherical particles tend to be denser for the same particle size than the assumed in situ mass–size relation, \( m = 0.0061D^{2.05} \), would suggest, the distribution of nonpherical particles shown in Fig. 3 of Part I is filtered to select particles that are, on average, half the mean density of the original simulations; that is, \( m = 0.0041D^{2.14} \). As seen in Table 3, these filtered, “lower-density nonpherical” particles typically yield estimated PSD parameters that are closer to the in situ than the original distribution. For example, in leg 12, where the Citation flew just above the freezing level, the lower-density nonpherical snow particles yield an estimated
LWC of 0.47 g m\(^{-3}\) as opposed to 0.45 g m\(^{-3}\) for the original nonspherical snow distribution. If the same mass–size relation used to filter the aggregates is applied to the in situ data instead of the standard relation, then the in situ water content becomes 0.46 g m\(^{-3}\). So better agreement is obtained using the filtered nonspherical particles, but at the same time, these particles lead to only a relatively small increase in the positive radiative bias relative to the CoSMIR observations (see Table 2). A final sensitivity test, in which the maximum particle size for a given PSD is imposed using the A. J. Heymsfield et al. (2013) relation, does not lead to a general improvement in consistency of estimated and in situ parameters, relative to what is obtained using the lower-density nonspherical particles.

6. Summary and concluding remarks

The primary objective of this study is to make an initial assessment of the ability of different snow particle models to yield a reasonable fit to simultaneous dual-wavelength radar and passive microwave radiometer observations. The data utilized in this assessment are 13.9- and 33.7-GHz nadir-view observations from the HIWRAP radar and 89- and 165.5-GHz nadir-view radiometer observations from the CoSMIR. These observations are analogs of the Ku–Ka-band DPR observations and higher-frequency GMI observations that are currently provided by the GPM core satellite mission. The HIWRAP and CoSMIR instruments were deployed on the ER-2 during the MC3E field campaign, and on 20 May 2011, observations were collected during ER-2 overpasses of stratiform precipitation on 16 flight legs.

The primary snow particle models evaluated in this study are homogeneous, constant-density ice–air spheres and nonspherical crystal/aggregate particles. The single-scattering properties of the spherical particles are calculated using Mie theory, while the DDA is used to calculate the properties of the nonspherical particles. Both particle types are distributed in size using normalized gamma distributions. It is demonstrated that upwelling radiance simulations based upon HIWRAP-estimated vertical profiles of the spherical snow particles are not consistent with simultaneous CoSMIR observed radiances, and adjustments of the assumed particle
density do not lead to consistency. On the other hand, radiance simulations based upon HIWRAP-estimated vertical profiles of the nonspherical snow particles are generally consistent with CoSMIR observations, with only a small positive bias over all of the 20 May 2011 flight legs from MC3E.

The evaluation of HIWRAP-estimated snow size distributions properties using in situ observations from microphysics probes deployed on the Citation aircraft is less conclusive. Although the median volume diameters estimated using the nonspherical snow model are closer to the corresponding in situ diameters than those derived using the spherical snow model, the higher PSD moments of the estimated spherical and nonspherical particle distributions are low-biased, leading to substantial underestimates of equivalent liquid water content. However, in situ estimates of liquid water content are sensitive to the assumed mass–size relation of the observed particles, and if lower-density particles are assumed both in the HIWRAP estimation and in the interpretation of the in situ particle distributions, then significantly better agreement of water contents is obtained. At the same time, the lower-density simulated nonspherical particles lead to only a small increase of the bias in simulated radiances relative to the CoSMIR observations.

The results of the present study, together with previous work by Kulie et al. (2010, 2014), Leinonen et al. (2012), and others, demonstrate fairly conclusively that particle single-scattering properties derived from nonspherical snow particle models are generally required to explain simultaneous radar/radiometer observations over the microwave spectrum, while scattering properties derived from spherical snow particle models may be applicable in limited contexts. The added value of the current study is that the particle models are constrained by dual-wavelength radar as well as passive microwave observations, and therefore the PSDs of the particles, which have essentially 2 degrees of freedom (see Haddad et al. 1997a,b), are strongly constrained by the radar data, yet they must also explain observed scattering signatures at much higher microwave frequencies.

The comparison of spherical and nonspherical snow particle single-scattering properties in Fig. 4 of Part I suggests that GPM precipitation algorithms applied to 14- and 36-GHz dual-wavelength radar alone could utilize spherical snow particle models without incurring large errors. However, GPM radar–radiometer remote sensing applications span a wide range of microwave frequencies (10–183 GHz), and in these applications, nonspherical snow particle models are needed because spherical models are not electromagnetically consistent over such a range. In particular, the asymmetry parameters of spherical snow particles at higher microwave frequencies can be significantly higher than those of nonspherical particles. This leads to excessive forward scatter by spherical particles and high-biased radiances relative to observed radiances. Since radiative consistency with the MC3E data is achieved using the nonspherical snow particle models, and since the tables of nonspherical snow bulk scattering properties described in section 2 are designed to be used in current GPM estimation algorithms, additional consistency tests of the nonspherical snow particle models using spaceborne observations are recommended.

Considering the difficulty of comparing remotely sensed and in situ PSDs, it is not surprising that some discrepancies between the two are seen in this study. In addition to the requirement that the radars and radiometers utilized in field studies of this kind should be rigorously calibrated, tight coordination of remote sensing and microphysics-probe aircraft should be maintained to avoid collocation errors. Also, independent in situ water content data from an instrument such as the Nevzorov probe are needed to reduce ambiguities in water content estimates derived directly from PSD data. Unfortunately, the Nevzorov probe deployed during MC3E did not function reliably, and so these data are not utilized in the present study.

Still, much work should be done to reconcile the remaining uncertainties in ice-phase precipitation particle models. For example, commonly observed pristine crystals such as bullet rosettes and capped columns are not simulated in the present study. Also, each nonspherical snow particle simulated in the current study is derived from component crystals with only a single habit, whereas aggregates of ice crystals with different habits, depending on environmental conditions, are observed (see Kikuchi et al. 2013). Rimed aggregates or graupel may be more prevalent depending on the proximity to convection. Also, in the present study, all melting ice particles are assumed to be spherical homogeneous mixtures of ice, air, and liquid water. Although spherical shell models (Liao et al. 2009) represent an obvious improvement over homogeneous models, work by the authors is under way to calculate the single-scattering properties of nonspherical melting snow particles based upon the database of crystals/aggregates simulated here. In addition, the current focus is on stratiform precipitation because the data collocation and radiative transfer calculations are simplified. Convection presents a significant challenge because the horizontal nonuniformity of precipitation would require remote sensing instruments with matched spatial resolution, and 3D radiative transfer methods, such as the Monte Carlo method, would be required to realistically simulate microwave radiances.

The use of field campaign data to gain a better understanding of the physical basis of remote sensing
measurements and estimation algorithms is demonstrated by the current study. Obviously, a single field campaign does not prove the general applicability of any particular physical parameterization, but multiple campaigns may indicate plausible parameterizations, and such parameterizations can then be tested or even optimized within the context of a satellite algorithm using substantial volumes of input satellite data and ground observations. Data from the GCPEX, IPHEX, and recent Olympic Mountains Experiment (OLYMPPEX) field campaigns may also be used to help evaluate current ice precipitation particle models, with ramifications not only for GPM but also for remote sensing in the anticipated Earth Clouds, Aerosols, and Radiation Explorer (EarthCARE) and Aerosol/Cloud/Ecosystems (ACE) missions.

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