TRMM Common Microphysics Products: A Tool for Evaluating Spaceborne Precipitation Retrieval Algorithms

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ABSTRACT

A customized product for analysis of microphysics data collected from aircraft during field campaigns in support of the Tropical Rainfall Measuring Mission (TRMM) program is described. These "common microphysics products" (CMPs) are designed to aid in evaluation of TRMM spaceborne precipitation retrieval algorithms. Information needed for this purpose (e.g., particle size spectra and habit, liquid and ice water content) was derived by using a common processing strategy on the wide variety of microphysical instruments and raw native data formats employed in the field campaigns. The CMPs are organized into an American Standard Code for Information Interchange (ASCII) structure to allow easy access to the data for those less familiar with microphysical data processing and without the tools to accomplish it. Detailed examples of the CMP show its potential and some of its limitations. This approach may be a first step toward developing a generalized microphysics data processing—initiatives that would likely broaden community access to, and use of, microphysics datasets.

1. Introduction

Precipitation estimation from spaceborne remote sensors has been an active area of research for the past 30 years. One of the primary motivations for these investigations has been the desire to augment limited or nonexistent surface-based precipitation measurements over the oceans and inaccessible parts of landmasses. Initial studies focused on deducing precipitation information from the visible and infrared wavelengths (e.g., Griffith et al. 1978; Arkin 1979). Recognizing the limitations of these measurements, a segment of the community began to focus on techniques that involve passive microwave radiometers (e.g., Weinman and Guetter 1977; Wilheit et al. 1982; Spencer 1986). The Tropical Rainfall Measurement Mission (TRMM) was conceived in the mid-1980s (Simpson et al. 1988) to extend and enhance these efforts. Most unique in the TRMM instrument package (Kummerow et al. 1998) is the addition of an active microwave remote sensor [the TRMM precipitation radar (PR)] to go along with a high-resolution, multichannel passive microwave radiometer [the TRMM Microwave Imager (TMI)]. The combination of passive and active microwave measurements is beneficial because it places additional constraints on precipitation retrievals.

Assumptions regarding the microphysical characteristics of precipitating clouds are one of the largest uncertainties in the suite of TRMM precipitation retrieval algorithms. The parameterization of raindrop size distributions is an important component in the correction of attenuated radar reflectivity and the conversion of reflectivity to rain rate for the TRMM PR (Iguchi et al. 2000). The vertical profiles of mixing ratios of precipitation-sized particles, cloud-sized particles, and water vapor largely determine the column-integrated scattering and absorption measured by the TMI. In the physically based microwave precipitation retrieval employed by the TRMM satellite algorithms, numerical cloudmodel simulations of storms are used to construct an archive of mixing ratio profiles, which are in turn used as input to forward radiative transfer calculations to yield brightness temperatures at each of the TMI frequencies (Smith et al. 1992; Kummerow 1998). In situ

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observations of cloud microphysical structures can be used to refine cloud models and to address uncertainties in radiative transfer calculations related to the treatment of precipitation variability at scales smaller than the satellite field of view. This latter issue is often termed the beam-filling problem and refers to a breakdown in the assumption that the resolution volume is filled with a uniform distribution of scatterers. Radiative transfer calculations are sensitive to assumptions about the relative amounts of liquid and ice in the region within and just above the melting layer, and to the habit, size distribution, and density of ice particles. Direct observations of these quantities can be used to constrain the assumptions and to evaluate cloud model outputs. Last, surface precipitation estimates from active and passive remote sensor sampling volumes well above the surface require assumptions about hydrometeor characteristics at low levels, particularly in the subcloud layer. Lowlevel microphysical measurements are needed to refine these assumptions.

In recognition of the fact that new observational datasets were required to validate and improve precipitation retrieval algorithms, the TRMM program planned and executed several field campaigns in the Tropics and subtropics during 1998 and 1999 (Kummerow et al. 2000). Airborne collection of in situ cloud microphysical datasets was a primary emphasis in four of these campaigns: the Texas and Florida Underflights (TE-FLUN)-A (Texas) and -B (Florida), the TRMM component of the Brazilian Large-Scale Biosphere-Atmosphere (TRMM-LBA) experiment, and the Kwajalein Experiment (KWAJEX) in the Marshall Islands. Although there is a large disparity with the sample volume of the spaceborne measurements, these in situ data were deemed of great importance for constraining algorithm uncertainty. Four aircraft participated in these efforts: a Learjet operated by the Stratton Park Engineering Company (SPEC), the University of North Dakota (UND) Citation, the University of Washington (UW) Convair, and the National Aeronautics and Space Administration (NASA) DC8. Microphysical instruments on these aircraft included optical array probes (OAP; e.g., Knollenberg 1970; Korolev et al. 1998a) and digital photographic probes (e.g., Lawson and Cormack 1995; Lawson et al. 2001) for the quantification of cloud and precipitation particle size and shape, hot-wire devices (e.g., King et al. 1978; Biter et al. 1987) for the measurement of cloud liquid water content, and forwardscattering probes (e.g., Dye and Baumgardner 1984; Baumgardner et al. 1985) for the characterization of cloud droplet and small ice particle spectra.

Principal investigators from several universities and laboratories were responsible for collection of the datasets, most with their own specialized data formats and processing routines. Historically, processing techniques employed by different investigators have varied considerably, which increases the likelihood of inconsistent calculation of key variables such as cloud and precipitation particle number concentration and water content. This diversity of formats and processing algorithms was potentially a hindrance to the use of the datasets for evaluation of TRMM algorithms. To permit maximum utility by the broader TRMM validation community, not all of whom are intimately familiar with the complexities of microphysical data analysis, the TRMM field campaign microphysics datasets needed to be formatted with a common and relatively simple structure and processed using a consensus algorithm. This article describes the steps taken to achieve these objectives. We first outline the aircraft sampling strategies employed during the field campaigns and provide specifications for the primary microphysical instruments. The scientific and engineering issues involved in processing these microphysics datasets are then explored, leading to the development of the "common microphysics product" (CMP) structure, the format of which is described in detail. Second, the method for generation of the CMPs is discussed and examples are presented. Third, future applications of the CMP concept are proposed, with an emphasis on developing an even more generalized microphysics format and an associated community-oriented, nonproprietary software package for microphysics data processing. Although geared toward TRMM, these efforts are intended to be a first step toward making cloud microphysical data analysis more accessible to the broader atmospheric sciences community.

2. Microphysics data collected during the TRMM field campaigns

A detailed accounting of aircraft participation in the field campaigns is provided in Table 1. The number of aircraft for microphysical measurements varied from project to project, reflecting the relative emphasis on microphysical data collection in each of the projects. The Kwajalein field campaign, with three such aircraft, had the strongest microphysical focus.

The most desired microphysics sampling strategy during the field campaigns was to collect data beneath an overpass of the TRMM satellite. The coincidence of an overpass with a precipitating cloud system was a rare event within the sampling domains of the various projects. Anticipating this problem, each project deployed one or two aircraft with downward-pointing remote sensors that served as proxies for the TRMM PR and TMI. These aircraft, the NASA ER2 and DC8 (Table 1), either flew above or at the highest levels of the precipitating cloud. The microphysics aircraft then flew coordinated patterns beneath the remote sensing aircraft. Figure 1 shows one set of patterns used in the Kwajalein campaign. This stacked pattern is the most optimal configuration of flight tracks because it provides near-simultaneous microphysical data collection at multiple levels in a precipitating cloud, allowing assumptions in the TRMM algorithms concerning the vertical distribution of hydrometeors to be evaluated. In the absence of sev-

	TRMM field campaigns			
	TEFLUN-A (Apr–May 1998)	TEFLUN-B (Aug–Sep 1998)	TRMM-LBA (Jan–Feb 1999)	KWAJEX (Jul–Aug 1999)
Aircraft for microphysical	measurements			
SPEC Learjet UND Citation UW Convair	Х	Х	Х	X X
NASA DC8		Х		Х
Aircraft for remote sensing	g measurements			
	ER2	ER2, DC8	ER2	DC8

TABLE 1. Aircraft participation in the TRMM field campaigns.



(b) Horizontal View



FIG. 1. Schematic of flight patterns used by the NASA DC8, UND Citation, and UW Convair during the KWAJEX field campaign. (a) The side view shows that the Convair focused on sampling at low to midlevels of the precipitating cloud, and the Citation sampled at mid- to high levels. The DC8 was usually near the top of the cloud. Representative profiles of height and temperature are provided on the left. (b) The plan view shows that the aircraft were ideally stacked on top of each other. Adapted from Yuter et al. (2005).

TABLE 2. Primary airborne microphysical instruments used in the TRMM field campaigns grouped by instrument type. Dynamic range and (resolution) are indicated. Data formats for the different instrument category and aircraft combinations are also shown. Acronyms are defined in the text or in the appendix.

	SPEC Learjet	UND Citation	UW Convair	NASA DC8 (Florida)	NASA DC8 (Kwajalein)
Hot wire: Cloud liquid was	ter content				
PMS KLWC DMT LWC	$0-5 \ g \ m^{-3}$	$0-5 \text{ g m}^{-3}$	$0-3 \ g \ m^{-3}$		
Forward scattering: Cloud	droplet and small ice p	particle spectra			
PMS FSSP DMT CPS	2–47 µm (3 µm)	2-47 µm (3 µm)	2–47 µm (3 µm)		2–47 μm (1.1 μm)
Digital photographic: Clou	d and precipitation par	ticle size and shape			
SPEC CPI	10 μm—2 mm (2.3 μm)	10 μm—2 mm (2.3 μm)	10 μm—2 mm (2.3 μm)		10 μm—2 mm (2.3 μm)
Optical array: Cloud and p	recipitation particle siz	e and shape			
PMS 2DC	33–1056 μm (33 μm)	30–960 μm (30 μm)	25–800 μm (25 μm)	25–800 μm (25 μm)	
PMS 2DP			100–3200 μm (100 μm)	200–6400 μm (200 μm)	
DMT 2D-CIP					25–1600 μm
DMT 2D-PIP					$(25 \ \mu m)$ 100-6400 μm $(100 \ \mu m)$
SPEC HVPS	$200 \ \mu m$ —4.2 cm ($200 \times 400 \ \mu m$)	$200 \ \mu m$ —4.2 cm ($200 \times 400 \ \mu m$)	$200 \ \mu m$ —4.2 cm ($200 \times 400 \ \mu m$)		()
Data format					
Hot wire	SEA	SEA	UW		
Forward scattering	SEA	SEA	UW	SEA	DMT
Digital array Digital photographic	SEA SPEC CPI	SEA SPEC CPI	UW, SPEC HVPS SPEC CPI	SEA	SPEC CPI

eral aircraft for microphysical measurements, such as in Texas and Brazil (Table 1), spiral descents of a single aircraft were often used to examine vertical variations of hydrometeor characteristics.

The microphysics aircraft probed a broad spectrum of precipitating cloud systems during the field campaigns, as manifested by their areal extent, depth, and intensity. These clouds were composed of both convective and stratiform regions (Houze 1997). The goal was to give equal emphasis to the sampling of both regions. However, safety considerations led to more stratiform precipitation being sampled than convective. This bias is acceptable from a TRMM validation standpoint because the area of stratiform precipitation far exceeds the area of convective precipitation globally (Schumacher and Houze 2003). In terms of altitudeoriented priorities, the mixed-phase portions of the clouds, at and just above the \sim 4.5-km freezing level, were probed most intensively because algorithm assumptions are most uncertain in these regions.

The most critical microphysical instruments for TRMM validation can be grouped into four categories: hot wire, forward scattering, optical array, and digital photographic. Among the four microphysics aircraft, there was great variety in the dynamic range and resolution of instruments utilized within each category (Table 2). In fact, the NASA DC8 deployed different instruments in the Florida and Kwajalein campaigns. Instruments designed and manufactured by Particle Measuring Systems, Inc. (PMS), have been in use for more than 30 years. In contrast, instruments designed and manufactured by SPEC and Droplet Measurement Technology, Inc. (DMT), are relatively new, having been in use for about the last five years. SPEC and DMT claim that these instruments generally have better performance characteristics (i.e., greater precision and/or resolution, larger dynamic range, larger sample volume, faster processing) than the PMS probes. However, because the SPEC and DMT instruments, and the software for processing their data, are less well tested than the PMS instruments, they are subject to potentially greater uncertainties.

Also apparent in Table 2 is the great diversity of data formats that were utilized. The most common format is associated with a data acquisition system developed by Scientific Engineering Associates, Inc. (SEA). Although intended to be uniform, specific implementations of the data system by the SPEC Learjet, UND Citation, and NASA DC8 in the Florida campaign led to subtle but important differences in the output format of the data. The SPEC format actually refers to two separate formats: one for the High-Volume Precipitation Spectrometer (HVPS) optical array-type probe and another for the Cloud Particle Imager (CPI) digital photographictype probe. The UW format is an in-house, customized format developed and used by the Cloud and Aerosol Research Group for many years. The DMT format incorporates a new run-length encoded compression scheme for storage of data from the high-resolution, high-speed two-dimensional cloud-imaging probe (2D-CIP) and precipitation-imaging probe (2D-PIP). In addition to the difficulties associated with manipulating these disparate data formats, the wide range of microphysical instrument characteristics complicates the issue of data processing. We address this problem in the next section.

3. Development and description of the CMP format

After the TRMM field campaigns, it was clear that the microphysical datasets collected in tropical and subtropical precipitating cloud systems were unprecedented in detail and comprehensiveness. A meeting of the TRMM algorithm investigators and the TRMM microphysics investigators was held in February of 2000 to address how the processing of these datasets should proceed. The result of this meeting was a set of recommendations on the types of microphysical parameters that would be of most value for evaluating the TRMM algorithms. Size and area spectra of hydrometeors were deemed of great importance. Habit discrimination of the sampled hydrometeors, particularly ice versus liquid and high density versus low density, was also a high priority. Ice and liquid water contents for populations of both cloud- and precipitation-sized hydrometeors were emphasized as critical variables to be estimated. There was consensus that all of these parameters should be processed with a consistent method. In addition, the participants at the meeting who were less familiar with microphysical data analysis expressed their concerns about manipulating the datasets in their native formats. Therefore, another recommendation from the meeting was that the desired parameters should be processed and stored in a common American Standard Code for Information Interchange (ASCII) format to simplify subsequent analysis and use.

The TRMM microphysics investigators were charged with the responsibility of devising the specific processing strategy to generate the desired microphysical parameters for the CMP. This activity was initiated at the aforementioned meeting and continued at subsequent TRMM meetings over the next 18 months. Quality control of raw data, particularly from the optical array probes, was one of the first issues to be addressed. Algorithms for rejecting artifacts such as streakers and gapped images (Heymsfield and Baumgardner 1985) were proposed and agreed upon. Streakers are anomalously long images in the direction of flight (x dimension) as compared with the size of the image across the diode array (y dimension). Images oriented in this manner with aspect ratios (x/y) greater than 5 were rejected. Gapped images often result from intermittent malfunctions of individual diode elements in the array and are not necessarily spurious. It was decided to reject images with gaps in the x dimension and accept images with gaps in the y dimension because the latter were thought to yield more useful and reliable information than the former. Sizing of optical array probe images was also a topic of discussion. For particles entirely within the diode array of the probes, the maximum dimension of the image along any orientation was selected as the sizing metric in response to feedback from TRMM algorithm investigators. To increase the effective sample volume of these probes, it was also decided that partial images, occulting one or both edge diodes of the array, should be sized using a reconstruction technique based on circular symmetry arguments (Heymsfield and Parrish 1978; Korolev et al. 2000).

Quantitative processing of digital photographic imagery from the CPI, still in its infancy, was complicated by a poorly calibrated particle detection system—the mechanism used to trigger the camera when a particle is in focus. This resulted in gross sample volume uncertainties and erroneous particle concentrations. To address this problem, CPI particle concentrations were scaled to two-dimensional cloud probe (2DC)/2D-CIP particle concentrations in the 150–500- μ m size range. The 2DC/2D-CIP measurements become less reliable near the lower size limit because of depth-of-field uncertainties (Korolev et al. 1998a; Strapp et al. 2001). Near the upper size limit, the numbers of particles sampled by the CPI usually become statistically insignificant over time scales of less than 60 s.

A single set of size and area bins was defined for the CMP to best match the characteristics of the microphysical instruments utilized in the field campaigns. The forward-scattering, digital photographic, and optical array categories of probes measure increasingly larger sizes of particles with increasingly coarser resolution (Table 2). Within the optical array category, there are two modalities to particle sizing and resolution: one for the cloud probes (2DC, 2D-CIP) and another for the precipitation probes [two-dimensional precipitation probe (2DP), 2D-PIP, HVPS]. Therefore, the forward-scattering, digital photographic, and optical array categories of probes have associated with them four particle size and resolution regimes. It is these four regimes that are the basis for the CMP size bins detailed in Table 3. The first regime (5–40 μ m) is within the size range of the two forward-scattering probes. The second regime (40-150 μ m) spans the size range of both the CPI and optical array cloud probes. CPI data were used for this regime because of the aforementioned uncertainties in 2DC and 2D-CIP performance below about 150 μ m. The large size end of the third regime was terminated at 1000 μ m because of poor performance of optical array precipitation probes below this threshold and because of its nearness to the upper size limits of the various optical array cloud probes. Although the nominal size range for some of the 2DC probes does not extend to 1000 μ m, reconstruction of partial images provides the necessary

TABLE 3. Size and area bins implemented for the TRMM CMP and the probes used for each size and area bin regime.

Size		Area		
Range (µm)	Bin width (µm)	Range (µm ²)	Bin width (μ m ²)	Probe
5-40	5	_		FSSP/CPS
40-150	10	1.60×10^{3} - 2.25×10^{4}	1.90×10^{3}	CPI
150-1000	50	2.25×10^{4} - 1.00×10^{6}	5.75×10^{4}	2DC/2D-CIP
1000-25 000	400	1.00×10^{6} - 6.25×10^{8}	1.04×10^{7}	HVPS/2DP/2D-PIP
>25 000	_	$>6.25 \times 10^{8}$	—	HVPS

information to contribute to the bins on the larger size end of the regime. The large size end of the fourth regime was terminated at 2.5 cm because of the rarity of particles observed above this threshold. An oversize category was implemented to keep track of any exceptionally large particles that may have been sampled. For the first three size regimes, bin widths a little larger than the native resolutions of the relevant probes were selected to improve sampling statistics. The bin width for the largest size regime was set at 400 μ m, the native resolution of the HVPS along the direction of flight for the true airspeeds commonly employed by the UND Citation and UW Convair.

Area bins were derived from the size bins for the second regime through the fourth regime. The area range limits were determined by squaring the corresponding size range limits. Area bin widths for each regime were calculated by dividing the area range by the number of size bins.

Habit discrimination from the optical array probes was accomplished by examining the area ratio, which is the area of a particle divided by the area of a circle that circumscribes the maximum dimension of a particle. Although this recognition technique has limitations that can lead to errors in classification, it was favored over others (e.g., Hunter et al. 1984; Holroyd 1987; Duroure et al. 1994; Korolev et al. 2000) because of its simplicity and emphasis on particle habits critical to TRMM validation. The area ratio A_r is defined as

$$A_r = A/[(\pi/4)D_{\max}^2],$$
 (1)

where A is the area of a particle image and D_{max} is its maximum dimension. Values of A_r increase as imaged particles become increasingly circular, asymptotically approaching 1.0. Over the last 25 years, several studies have been able to correlate A_r , with certain particle habits (e.g., Heymsfield and Parrish 1979; Heymsfield and Kajikawa 1987; Heymsfield and McFarquhar 1996; Heymsfield et al. 2002a). Because of their almost circular two-dimensional cross section, raindrops most often have A_r near 1.0. Graupel particles can have a wide range of A_r values, from about 0.5 to almost 1.0, depending upon their degree of riming and embryonic origin. Aggregates of ice crystals slightly overlap the graupel-particle A_r parameter space, ranging from 0.3 to 0.7. Elongated particles, such as columns and needles with aspect ratios of 0.1-0.3, have A_r values between 0.1 and 0.4. For platelike crystals, A_r values can vary considerably (0.2–1.0) because their apparent shape differs substantially as a function of how the particle is oriented as it passes the diode array. If the edge of the plate is viewed by the array, the resulting image will look like a column and have a relatively small A_r . In contrast, if the face of the plate is viewed by the array, the resulting image will look like a graupel particle or perhaps a raindrop and have a relatively large A_r .

Final A_r thresholds for optical array probe habit recognition were selected to optimize discrimination of liquid and frozen hydrometeors, as well as relatively high density (graupel) and relatively low density (aggregate) ice particles. The first of these two requirements was addressed by setting an A_r threshold of 0.95 to distinguish raindrops from graupel particles. There is some overlap in these regimes, and so the possibility of improper classification still exists. This threshold was set fairly high to minimize the number of graupel particles that may be inappropriately placed in the raindrop category. However, a potentially negative side effect of this choice is the improper classification of raindrops as graupel when raindrops become ellipsoidal in shape at sizes larger than about 1-2 mm. At smaller sizes, raindrops can also take on an artificially ellipsoidal shape as a result of irregular flow around wing-mounted probes. The second basic requirement was addressed by setting an A, threshold of 0.7 to distinguish graupel from aggregates. With this threshold value, the graupel defined in the CMP would best be described by the lump, hexagonal, or conical varieties in Figs. 2a-c from Locatelli and Hobbs (1974). In contrast, aggregates are characterized by more jaggedness and porosity, traits evident in aggregates of dendrites, bullets, columns, plates, and side planes (Figs. 2f-g and 2p-r of Locatelli and Hobbs 1974). The 0.7 threshold, at the top end of the aggregate regime and in the middle of the graupel regime, was chosen to minimize the number of rimed aggregates, such as graupel-like snow of lump or hexagonal form (Figs. 2d-e of Locatelli and Hobbs 1974), categorized as graupel. Needles and columns were classified when A_r was less than 0.3. A fifth category, indeterminate particles, was activated when a particle image contained less than 25 pixels, the minimum deemed necessary to classify particle shape adequately. No contingency was implemented to account for platelike crystals being inappropriately classified as columns or graupel particles. However, the maximum dimension of platelike crystals is rarely larger than 1 mm (Heymsfield and Kajikawa 1987), suggesting that, even if inappropriately classified, their contribution to total water content would be relatively small.

Habit recognition from the CPI followed a geometric strategy similar to that for the optical array probes but with enhancements for its higher intensity resolution (i.e., 256 shades of gray vs black and white). Graupel and aggregates were not classified because these habits are unlikely in the 40–150- μ m CPI size range used for the CMP. This size range also rendered the indeterminate category unnecessary because there were always at least 25 pixels of CPI data at 40 μ m. Images with A, values greater than 0.75 and radii that deviated by no more than 10% from the mean radius of the image were classified as water droplets. Images whose maximum dimension was at least 3 times the transverse dimension were classified as columns and needles. Shapes that differed from these two categories were classified as irregular ice, a category used only with CPI imagery.

Determination of cloud liquid water content from the hot-wire probes was a fairly straightforward analog-todigital conversion (King et al. 1978) after eliminating spurious signals resulting from contact with, and subsequent melting of, ice particles (Korolev et al. 1998b). However, calculation of precipitation water content was more complicated and perhaps more error prone because it was derived from particle size spectra provided by the digital photographic and optical array probes rather than directly measured with total water content instruments such as a Nevzorov probe (Korolev et al. 1998b) or a counterflow virtual impactor (Twohy et al. 1997), which were not used on the aircraft that participated in the TRMM field campaigns. This complication is exacerbated in mixed-phase clouds. Heymsfield et al. (2002b) and Korolev and Strapp (2002) have performed intercomparisons of precipitation water content using direct measurements and calculations from particle size distributions and have found that, although large differences are possible, there is usually reasonable agreement between the measurements. In our calculations, particle size spectra from the digital photographic and optical array probes were first stratified by their different particle habits. Relationships between mass and particle size specific to each of the classified particle habits (Fig. 2) were then applied to these different spectra to derive integrated water content. This calculation was performed separately for the digital photographic probe size regime and the optical array probe size regime. Massdimension relationships for aggregates and needles/columns were based on results from Heymsfield et al. (2002b); the relationship for graupel was based on results from Heymsfield and Kajikawa (1987), whose dataset was composed primarily of lump and conical graupel. Figure 2 shows that the density of aggregates is lower than bulk ice over the size range for which aggregates are classified ($D_{\rm max} >$ 150 $\mu {\rm m})$ and that the effective density of aggregates decreases from 0.1 to



FIG. 2. Relationships between mass and maximum dimension for the various particle habits that are classified in the CMP. The rain curve (solid) assumes a liquid water density of 1 g cm⁻³, graupel (long dashed) is from Heymsfield and Kajikawa (1987), aggregates (short dashed) and needle/columns (dot–dot–dashed) are from Heymsfield et al. (2002b), indeterminates (dot–dashed) are from Brown and Francis (1995), and irregulars (dotted) are from Mitchell et al. (1990). As a reference, the thick gray line indicates the curve for bulk ice density (0.917 g cm⁻³).

0.03 g cm⁻³ as maximum dimension increases. The needle/column relationship also displays this trend but has a lower effective density at all sizes. In contrast, graupel density slightly increases as maximum dimension increases, ranging from 0.1 to 0.2 g cm⁻³. Graupel density exceeds aggregate density at sizes greater than 400 μ m. Few, if any, graupel were classified at smaller sizes. At temperatures above -40°C, particles classified as raindrops were associated with a mass-dimension relationship based on the density of liquid water. At relatively low air temperatures (below -40° C), mass-dimension relationships for graupel or bulk ice were used for this category, depending upon the size of particles involved. Large particles in this situation were observed with the optical array probes and were assumed to be graupel. Smaller particles in this scenario were observed with the CPI and were assumed to be frozen cloud droplets characterized by bulk ice density. Mass-dimension relationships for small indeterminate particles from the optical array probes and irregular particles from the CPI were also variable. At temperatures greater than 0°C, liquid water density was assumed; at temperatures less than 0°C, generic mass-dimension relationships for ice were implemented. The relationship given by Brown and Francis (1995) was used for indeterminate particles (Fig. 2). It is similar to the aggregate relationship but has a somewhat higher effective density, especially at smaller sizes. The relationship given by Mitchell et al. (1990) was used for irregular particles. It is also similar to the aggregate relationship but has a somewhat lower

TABLE 4. Basic structure of the TRMM CMP forma	at.
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Line 1	Summary statistics for a given averaging period:
Block 1	Date and time at center of averaging period
Block 2	Lat, lon, and alt at center of averaging period
Block 3	Air temperature, true air speed, ground speed, static pressure, dewpoint temperature, and vertical air velocity
Block 4	Total counts and concentrations for each of the FSSP/CPS, CPI, 2DC/2D-CIP, and HVPS/2DP/2D-PIP probes
Block 5	Number, area, and mass-weighted percentages of objectively determined particle habits (raindrops, graupel, aggregates, column/needles, and small/indeterminate particles) for each of the CPI, 2DC/2D-CIP, and HVPS/2DP/2D-PIP probes
Block 6	Water and ice masses measured from the KLWC/LWC and derived from the CPI and composite 2DC/ 2D-CIP/HVPS/2DP/2D-PIP spectra
Block 7	Mass-weighted mean particle size and radar reflectivity derived from the composite 2DC/2D-CIP/ HVPS/2DP/2D-PIP spectra
Block 8	Number-weighted percentage of artifacts from the 2DC/2D-CIP and HVPS/2DP/2D-PIP probes
Lines 2-3	Area spectra for all particles: counts (line 2) and concentrations (line 3)
Lines 4-5	Size spectra for all particles: counts (line 4) and concentrations (line 5)
Lines 6-7	Size spectra for raindrops: counts (line 6) and concentrations (line 7)
Lines 8-9	Size spectra for graupel: counts (line 8) and concentrations (line 9)
Lines 10-11	Size spectra for aggregates: counts (line 10) and concentrations (line 11)
Lines 12–13	Size spectra for column/needles: counts (line 12) and concentrations (line 13)

effective density, remaining at or below bulk ice density throughout the CPI size regime of 40–150 μ m.

The size and mass spectra were used to derive two additional quantities, mass-weighted mean particle size $\overline{D}_{\text{mass}}$ and equivalent radar reflectivity factor Z_e . Particle size $\overline{D}_{\text{mass}}$ is defined by

$$\overline{D}_{\text{mass}}(\mu \text{m}) = \frac{\sum_{b=1}^{B} M_b D_b}{\sum_{b=1}^{B} M_b},$$
(2)

where *M* is the precipitation water content (g m⁻³), *D* is the bin size (μ m), and the *B* summation is over all OAP size bins (i.e., >150 μ m). Reflectivity factor Z_e was derived in the same manner as in Heymsfield et al. (2002a). In this approach, Rayleigh scattering is assumed and melted particle diameter (D_{melt}) is used in the calculations:

$$D_{\text{melt}} (\text{mm}) = \left(\frac{6M}{\pi \rho_{w} N}\right)^{1/3}, \qquad (3)$$

where *N* is concentration (L⁻¹) and ρ_w is the density of liquid water (g cm⁻³). The equation employed for calculation of Z_e was

$$Z_e (\mathrm{mm}^6 \mathrm{m}^{-3}) = \frac{3.6 \times 10^4}{\pi^2 \rho_w^2} \sum_{h=1}^H \sum_{b=1}^B \frac{M_{h,b}^2}{N_{h,b} k_h}, \quad (4)$$

where the *H* summation is over all classified habits. A dielectric correction factor k_h of 4.7 is applied for all ice habits, whereas a value of 1.0 is used for raindrops. The choice of k_h for indeterminate particles is based on air temperature. The value for ice is assumed for air temperatures below 0°C, otherwise, the value for liquid water is applied. In these calculations, the possible mixed-phase nature of individual particles (e.g., water-

coated spheres, water-soaked aggregates, or graupel) is ignored, which may add uncertainty to the derived values, especially at levels where melting or wet growth is occurring.

The results of CMP calculations were output to ASCII files in a time series format. Each sampling interval is characterized by 13 lines of information (Table 4). The first line contains summary statistics, such as time, navigation, state parameters, and derived microphysical parameters. The remaining lines contain particle spectra information, both counts and concentrations, using the bins defined in Table 3. Lines 2 and 3 detail area spectra for all particles. Lines 4–13 describe size spectra for all particles and individually for the raindrop, graupel, aggregate, and needle/column particle habit categories.

The CMPs for the TRMM field campaigns can be accessed (at the time of writing) at the NASA Goddard Distributed Active Archive Center (available online at http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/TRMM_ FE/index.shtml). This site can also be used to obtain information about accessing native-format microphysical datasets and particle imagery.

4. CMP generation and examples

The process of taking several native-format data files and generating a single CMP file for a given aircraft and time period followed a systematic blueprint. First, a "common flight product" (CFP) file was produced that principally contained the beginning and ending times for analysis, as well as the sampling interval. This interval was based on a 1-km separation between samples, the minimum scale of interest for algorithm testing. The CFP file also included information that was often absent from binary OAP and CPI data files, such as navigation and state parameters and hot-wire and forward-scattering probe data. Next, the CFP file was used as input to software packages designed for processing OAP data (developed by Sky Tech Research, Inc.) and CPI data (developed by SPEC). The output from these programs was then merged to generate the final CMP.

a. Example CMP within stratiform precipitation

Figure 3 shows the three-dimensional radar precipitation structure for a three-aircraft flight leg from the KWAJEX field campaign on 23 August 1999 that is used to illustrate an example of the variety of information available in a CMP. This \sim 40-km-long leg transected a region of stratiform precipitation, with intensities ranging from moderate on the western two-thirds to weak on the eastern end. Radar echo tops varied between 8 and 9 km. The UW Convair, UND Citation, and NASA DC8 flew straight and level legs at the -5° , -15° , and -50° C temperature levels, respectively. Mass-weighted mean particle sizes derived from the OAPs on these aircraft indicate that the western end of the leg at each altitude was characterized by the largest particles (Fig. 4). In descending from top to bottom, particle sizes increased slightly from the DC8 level to the Citation level, and they increased greatly from the Citation level to the Convair level. Total concentrations derived from the Citation CMP 2DC spectra (henceforth all CMP-derived total concentrations will be referred to simply as total concentrations) showed a distinct maximum at about the midpoint of the leg, whereas the DC8 2D-CIP and Convair 2DC maxima were less distinct (Fig. 5). However, there is the suggestion that the 2DC/ 2D-CIP maxima occurred progressively farther west with increasing altitude. This suggestion is consistent with the vertical echo structure in Fig. 3, which indicates that the axis of maximum reflectivity tilted slightly westward with height. Fall streaks (Battan 1973) may be responsible for this pattern. The resolution of the radar data at this range (120 km) is too coarse to test this hypothesis. Total concentration maxima from the Citation HVPS and Convair 2DP (the DC8 2D-PIP was not functioning on this leg) appear to be shifted systematically west of the 2DC total concentration maxima and are smaller by a factor of $\sim 10-20$ (Fig. 6). If the vertical echo pattern can be attributed to fall streaks, then this shift may be a result of size sorting, with the HVPS- and 2DP-sensed particles falling out of the fall streak faster than the 2DC-sensed particles. The CPI total concentrations, available only on the Citation, were larger than the 2DC total concentrations by a factor of \sim 20 but show no clear relationship with the trends seen in the 2DC and HVPS traces (Fig. 7). In examining the vertical structure of total concentrations from this leg (Figs. 5 and 6), absolute values were largest at the Citation level and decreased substantially at the Convair level. In combination with the particle size trend between these two levels (Fig. 4), this result suggests that an aggregation process was active between -15° and −5°C.

Particle size spectra from a 1-km segment near the midpoint of the leg indicate that the Citation data are more steeply sloped and have a larger intercept than the Convair data, with a crossover at about 1 mm (Fig. 8). There is a slight discontinuity in the size spectra at 1 mm where the input data to the CMP makes a transition from the cloud OAP to the precipitation OAP in the Citation and Convair data. In the absence of 2D-PIP data, the DC8 spectra were truncated at 1 mm, which may bias the mass-weighted mean particle size shown in Fig. 4 toward smaller values. Despite this fact, an extrapolation of the DC8 spectra to larger sizes suggests that this impact should be minimal. Because of the truncation of the Citation CPI size spectrum, its continuity with the 2DC spectrum is not clear. However, the CPI spectrum appears to have a distinctly different slope than the 2DC spectrum. Although they do not incorporate uncertainties stemming from probe digitization, response time, and out-of-focus images (Korolev et al. 1998a; Strapp et al. 2001), the Poisson standard deviation departures associated with these spectra suggest that they are statistically distinct from each other, except at the Citation-Convair crossover near 1 mm.

Habit discrimination along this leg, based on 2D-CIP, 2DC, 2DP, and HVPS imagery, is shown in Fig. 9, and selected samples of particle images are shown in Fig. 10. The raindrop and column/needle categories were minor contributors (<10%) and are, thus, absent from this illustration. For the western two-thirds of the DC8 leg, aggregates were the most commonly observed habit, with graupel and indeterminate particles being roughly equal secondary regimes (Fig. 9a). In contrast, the concentration of indeterminate particles slightly exceeded the aggregates over the eastern third of this leg, likely a result of the relatively small particles present (Fig. 4). The various habit concentrations from the Citation show much less variability with respect to each other (Figs. 9b,c). For the 2DC, graupel was the most common habit (Fig. 9b), which is somewhat surprising given the stratiform nature of the radar echo. Of interest is that the concentration of indeterminate particles exceeded the concentration of aggregates. The elevated indeterminate concentration is probably a result of the relatively coarser resolution in the Citation 2DC as compared with the DC8 2D-CIP and Convair 2DC (Table 2). For the Citation HVPS (Fig. 9c), indeterminate particles were the overwhelmingly dominant habit that was classified, because of the coarse resolution of the probe and the dearth of particles larger than 2-3 mm. This combination led to many images with less than 25 pixels. However, more of the larger particles were categorized as aggregates than as graupel. As a result of finer resolution, indeterminate particles were present in much lower concentrations in the Convair data (Figs. 9d,e), especially from the 2DP. As observed with the Citation, graupel concentrations are again higher than expected. The graupel and aggregate concentration traces for the 2DC display two distinct trends (Fig. 9d). On



FIG. 3. (a) Horizontal and (b) vertical cross sections of reflectivity from the Kwajalein island S-band radar at 0209 UTC 23 Aug 1999 during KWAJEX. In (a), flight tracks of the NASA DC8 (yellow), UND Citation (magenta), and UW Convair (red) for the period 0154–0209 UTC are overlaid. The white diamond and cross indicate the start and end, respectively, of the defined flight leg. In (b), the altitudes of the three aircraft are overlaid, along with the associated air temperatures at those altitudes. The blue line indicates the level of the 0°C isotherm. Relative west–east distance along the leg is shown at the bottom.



FIG. 4. Spatial cross section of CMP mass-weighted mean particle size derived from the OAPs on the three aircraft. Data were collected along the leg defined in Fig. 3. Values from the UND Citation, UW Convair, and NASA DC8 are indicated by the solid, dashed, and dot-dashed lines, respectively. Relative west–east distance along the leg is shown at bottom. Vertical gray bar indicates location from which the mean size spectra shown in Fig. 8 were derived.

the western half of the leg, the concentrations of graupel and aggregates were approximately equal, whereas, on the eastern half, the concentration of graupel clearly exceeded the concentration of aggregates. In contrast, the trend in the graupel and aggregate concentration traces for the 2DP are reversed (Fig. 9e), with graupel concentrations largest on the western half of the leg and equal to aggregate concentrations on the eastern half of the leg.

Imagery from the DC8 2D-CIP probe, the Citation 2DC and HVPS probes, and the Convair 2DC and 2DP probes (Fig. 10) provides some context for these ob-



FIG. 5. Same as Fig. 4 but for 2DC/2D-CIP total particle concentration.



FIG. 6. Same as Fig. 4 but for HVPS/2DP total particle concentration measured from the UW Convair and UND Citation.

jective classifications. The examples from the DC8 2D-CIP (Fig. 10a) are from a region of the leg where aggregates were the dominant objectively determined habit (Fig. 9a). Most of the images have relatively sharp edges, are somewhat elongated, and occasionally display porous structure—characteristics that are consistent with those of aggregates. In contrast, the Citation 2DC imagery (Fig. 10b) shows less-elongated particles with smoother edges and relatively limited porosity, suggestive of rimed aggregates or, in some images, graupel, the habit that was dominant in the objective classification (Fig. 9b). There was an absence of cloud liquid water at this level (not shown) as inferred by a Rosemount, Inc., icing detector¹ (Cober et al. 2001) on the

¹ The hot-wire probes for cloud liquid water measurement on the Citation and Convair were inoperative on this leg.



FIG. 7. Same as Fig. 4 but for CPI total particle concentration measured from the UND Citation.



FIG. 8. Mean particle size spectra measured from the NASA DC8 (thin black), UND Citation (thick black), and UW Convair (thick gray) averaged in the region indicated by the gray bars in Figs. 4, 5, 6, and 7. The CPI, 2DC/2D-CIP, and HVPS/2DP size regimes are separated by the vertical dashed lines; ± 1 std dev departures from these curves, based on Poisson statistics, are indicated by the filled triangles (DC8), squares (Citation), and circles (Convair) at selected particle sizes.

Citation, suggesting that any graupel present would have grown in other parts of the cloud. Citation HVPS imagery (Fig. 10c) shows a large number of small, almost indistinguishable particles, which is consistent with the overwhelmingly indeterminate classification in Fig 9c. Imagery from the Convair 2DC and 2DP (Figs. 10d,e) indicates the existence of generally larger particles in comparison with the Citation imagery. Subjective interpretation of their shapes suggests numerous aggregates and only limited amounts of graupel, which appears to contradict the objective classifications shown in Figs. 9d,e. Forward-scattering spectrometer probe (FSSP) measurements from the Convair (see footnote 1) indicated less than 0.1 g m⁻³ of cloud liquid water on this leg. However, this result is tempered by the fact that FSSP measurements in mixed-phase clouds are often suspect (Gardiner and Hallett 1985; Gayet et al. 1996).

There is uncertainty regarding the fraction of graupel on this leg. The more rounded images in Fig. 10, with area ratios between 0.7 and 0.95, may be associated with particles that have undergone riming and could be characterized as lump graupel or graupel-like snow of lump form (Magono and Lee 1966; Locatelli and Hobbs 1974). Alternatively, these particles may be unrimed aggregates composed of compact, unbranched crystals such as plates and short columns. In addition, some of the smaller (<1 mm) particles could be single platelike crystals. CPI imagery from the Citation (not shown) indicates the presence of such ice crystal habits. An artifact of the objective habit discrimination algorithm may also be influencing the fraction of categorized graupel. As has been discussed, aggregates are typically

characterized by area ratio values between 0.3 and 0.7. However, this relationship is primarily valid when the images are completely within the diode array. When the particles occult one or both edge diodes, values of area ratio will be biased toward 1.0 because of the circular symmetry assumptions used in the reconstruction technique. This will increase the effective area ratio of many aggregates to the point of exceeding 0.7 so that they will be improperly classified as graupel. As is apparent from Fig. 10, many of the 2D-CIP, 2DC, and 2DP images occult one edge of the diode array. Over the length of the leg, these so-called partial images constitute 10%-50% of the total number of images, with the DC8 having the smallest fraction and the Convair having the largest fraction. With the Convair data, the relative fraction of graupel and aggregates illustrated in Figs. 9d,e is correlated well with the fraction of partial images. When the fraction of graupel is high, such as on the eastern end of the leg for the 2DC and on the western end of the leg for the 2DP, the fraction of partial images is relatively high (not shown). Although this habit classification scheme is somewhat crude, it was the best approach available for deriving reasonable total water contents from the optical array probes.

Total water contents derived from the OAP spectra (Fig. 11) increase as altitude decreases, a trend that is consistent with the vertical precipitation echo structure (Fig. 3b). The biggest increase in total water content occurs from the DC8 altitude (Fig. 11a) to the Citation altitude (Fig. 11b). The total water contents derived from the Convair measurements (Fig. 11c) are about 10%–20% greater than those derived from the Citation measurements. The percentage contribution to total water content by graupel also increases as altitude decreases. Over the western two-thirds of the DC8 leg, graupel was responsible for $\sim 35\%$ of the total water content, even though the graupel concentration in this area only contributed $\sim 20\%$ to the total 2D-CIP concentration (Fig. 9a). This results from the fact that the mass-dimension relation used for graupel implies a higher density than the relation used for aggregates. At the Citation level (Fig. 11b), graupel contributed to approximately one-half of the total water content; at the Convair level (Fig. 11c), graupel was responsible for $\sim 85\%$ of the total water content. The trend in percentage contribution to total water content by aggregates as a function of altitude is reversed. Indeterminates only contribute significantly to total water content in the Citation data $(\sim 20\%)$, primarily as a result of the HVPS data (Fig. 9c).

Comparison of the observed radar reflectivity (Fig. 3) with effective radar reflectivity derived from the habit-discriminated OAP particle spectra associated with the CMP (Fig. 12a) provides a way to assess the realism of derived total water contents. The derived values of -10-0 dBZ_e for the DC8 are below the detectability threshold of the radar at 120-km range, which explains the lack of echoes at the DC8 flight level of 11.5 km



FIG. 9. Spatial cross section of total particle concentration (solid line) along the leg defined in Fig. 3 for the (a) NASA DC8 2D-CIP, (b) UND Citation 2DC, (c) UND Citation HVPS, (d) UW Convair 2DC, and (e) UW Convair 2DP. The long-dashed, short-dashed dot–dashed, dot–dot–dashed, and dotted lines indicate contributions from graupel, aggregates, indeterminates, needle/columns, and raindrops, respectively. Relative west–east distance along the leg is shown at bottom. Gray bars indicate locations for which the selected particle images shown in Fig. 10 were extracted.

MSL (Fig. 3b). The trend of derived reflectivity for the Citation shows some general consistency with the observed pattern of radar reflectivity at the Citation flight level (7 km MSL), with the largest values occurring on the western half of the leg. Peak observed values are $5-6 \text{ dBZ}_e$ lower than, and shifted 5–7 km west of, the broadest peak in derived values. There are larger differences in the comparison involving the Convair. The observed radar reflectivity at the Convair flight level of 5 km MSL reaches its peak near the midpoint of the

leg, whereas the derived values of reflectivity maximize on the western end of the leg. Magnitudes also differ considerably. Peak values of observed reflectivity near the leg midpoint are $8-9 \ \text{dBZ}_e$ lower than the peak derived values at the same location.

Discrepancies between the pattern and magnitude of observed reflectivity and that derived from the Convair and Citation microphysical measurements may be partially attributable to beam filling in the radar data, particularly if fall streaks were present. However, the re(a) DC8 23 August 1999 2D-CIP X=17 km



FIG. 10. Selected particle images from the (a) NASA DC8 2D-CIP, (b) UND Citation 2DC, (c) UND Citation HVPS, (d) UW Convair 2DC, and (e) UW Convair 2DP probes at the locations indicated by the gray bars in Fig. 9.

DC8

CMP (a)

Observed

Rain

Citation

→Graupel (b)

→Aggregates (c)

30

40

Observed

Convair



FIG. 11. Spatial cross section of OAP-derived water content along the leg defined in Fig. 3 for the (a) NASA DC8, (b) UND Citation, and (c) UW Convair. The solid lines indicate total water content while the contributions from graupel, aggregates, indeterminates, raindrops, and needle/columns are indicated by the long-dashed, short-dashed, dot-dashed, dotted, and dot-dot-dashed lines, respectively. Relative west-east distance along the leg is shown at bottom.

FIG. 12. Spatial cross section of OAP-derived effective reflectivity along the leg defined in Fig. 3 for (a) the default CMP, (b) the default CMP modified by treating categorized raindrops as graupel, and (c) the default CMP modified by treating categorized raindrops and graupel as aggregates. Values from the UND Citation, UW Convair, and NASA DC8 are indicated by the solid, dashed, and dot-dashed lines, respectively. Observed ground-based radar reflectivity along the Citation and Convair flight paths is indicated by the solid and dashed thick gray lines, respectively. Relative west-east distance along the leg is shown at bottom.

20

flectivity derivation procedure from the microphysical observations, particularly as it relates to habit discrimination, is also likely contributing to the differences. Although particles classified as raindrops from the Citation and Convair OAPs contribute less than 15% to the total water content (Figs. 11b,c), their influence on derived reflectivity is important because of the much larger dielectric factor for liquid water as compared with ice. Given the stratiform nature of the cloud, the previously discussed lack of cloud liquid water, and the relatively low air temperatures at the levels of sampling $(-15^{\circ} \text{ and } -5^{\circ}\text{C})$, it is unlikely that raindrops were actually sampled by these aircraft. Under these conditions, the very rounded images ($A_r > 0.95$) classified as raindrops are more properly placed in the graupel category. In making this change, the calculation of raindrop contribution to total water content employs the mass-dimension relation appropriate to graupel (Fig. 2). This information is then applied in the derivation of reflectivity, except that the dielectric factor for ice is used instead of that for liquid water. The resulting total water contents are reduced by less than 10% (not shown), but the derived reflectivities are reduced more significantly, with a $5-10 \text{ dBZ}_{e}$ decrease for the Convair and a 3-6 dBZ_e decrease for the Citation (Fig. 12b). Note that these derived reflectivities are in better agreement with the observed reflectivities.

The influence of graupel classification uncertainties on the reflectivity comparison was also examined. Categorized graupel particles and the categorized raindrops that were subsequently placed in the graupel category were treated like aggregates in terms of mass-dimension relation (Fig. 2) and dielectric factor. With these assumptions, total water contents for the DC8, Citation, and Convair (Fig. 13) are reduced by 14%, 39%, and 72%, respectively, relative to the default CMP values (Fig. 11). The results show a suspicious trend that indicates decreasing total water content in descending from the Citation level to the Convair level. Reflectivities derived with these assumptions (Fig. 12c) are also much smaller than the default CMP values (Fig. 12a) and the values where raindrops are treated like graupel (Fig. 12b), especially those associated with the Convair, whose values are $10-15 \text{ dBZ}_{a}$ lower than observed. Although many of the categorized graupel particles look like they may be aggregates, these comparisons suggest that their density must be larger than that assumed in the mass-dimension relation employed for aggregates (Fig. 2). Therefore, the most realistic results for the leg on 23 August 1999 occur in association with the modified CMP for which the mass and dielectric properties of graupel particles are used as proxies for categorized raindrops.

b. Example CMP within convective precipitation

Convective precipitation provides a different perspective on CMP habit discrimination and total water



FIG. 13. Same as Fig. 11 except that categorized raindrops and graupel are treated as aggregates.

content calculation. To illustrate, CMP data from a Convair flight leg on 27 August 1999 during KWAJEX are examined. This leg penetrated a 10–15-km-diameter convective cell with peak reflectivity of \sim 34 dBZ_e. Flight-level air temperatures during the penetration were on average -1.5° C, and cloud liquid water contents exhibited occasional peaks of 0.4–0.5 g m⁻³. Habit dis-



FIG. 14. Spatial cross section of total particle concentration (solid line) for the (a) UW Convair 2DC and (b) UW Convair 2DP over the period 2222–2224 UTC 27 Aug 1999. The long-dashed, short-dashed, dot–dashed, dott–dashed lines indicate contributions from graupel, aggregates, indeterminates, raindrops, and needle/columns, respectively. A scale for horizontal distance is provided at the bottom of each plot. Gray bars indicate locations for which the selected particle images shown in Fig. 15 were extracted.

crimination along this leg based on the Convair 2DC and 2DP imagery is shown in Fig. 14. The analysis from both probes indicates that graupel was the most commonly occurring habit, which is consistent with the convective nature of the echo and the large cloud liquid water contents encountered on the leg. However, graupel was not the overwhelmingly dominant habit, because aggregates were close secondary contributors. Imagery from the portion of the leg containing peak total concentrations (Fig. 15) shows that most of the particles have smooth edges and virtually no porosity, traits that are suggestive of graupel. On the other hand, many of the images have shapes that deviate considerably from circles, which is why the area-ratio-based objective classifications include so many aggregates.

Graupel is responsible for more than 75% of the total water content derived from the OAPs in the default CMP for this leg (Fig. 16a). The corresponding derived re-

flectivity (Fig. 17) maximizes at $\sim 29 \text{ dBZ}_{e}$, about 5 dBZ_{e} below the observed peak. It is likely that this difference is even larger because of beam filling, because the convective cell under examination is about 150 km away from the ground-based radar. Although it is plausible for aggregates to exist within and in close proximity to convection (Heymsfield et al. 2002a), their relatively large concentration fraction in a population of images that mostly have the appearance of graupel leads to speculation that graupel may be undercounted on this leg. To investigate the impact of this supposition, categorized aggregates on this leg were treated as graupel in terms of mass-dimension relation. With this assumption, peak total water content is increased by 25% (Fig. 16b), but peak derived reflectivity is virtually unchanged (Fig. 17). This relationship suggests that the categorized aggregates must be much smaller than the categorized graupel. The next most plausible explana-



(b) Convair 27 August 1999 2DP



FIG. 15. Selected particle images from the (a) UW Convair 2DC and (b) UW Convair 2DP probes at the locations indicated by the gray bars in Fig. 14.



FIG. 16. Spatial cross section of OAP-derived water content for the UW Convair over the period 2222–2224 UTC 27 Aug 1999. Results are subdivided by (a) the default CMP, (b) the default CMP modified by treating aggregates as graupel, and (c) the default CMP modified by treating graupel as if it had a density of 0.7 g cm⁻³. The solid lines indicate total water content while the contributions from graupel, aggregates, indeterminates, raindrops, and needle/columns are indicated by the long-dashed, short-dashed, dot–dashed, dotted, and dot–dot–dashed lines, respectively. Note that the vertical scale



FIG. 17. Spatial cross section of OAP-derived effective reflectivity for the UW Convair over the period 2222–2224 UTC 27 Aug 1999. Results from the default CMP, the default CMP modified by treating aggregates as graupel, and the default CMP modified by treating graupel as if i had a density of 0.7 g cm⁻³ are indicated by the solid, dashed, and dot–dashed lines, respectively. The observed peak in ground-based radar reflectivity along the Convair flight path is indicated by the thick solid gray line. A scale for horizontal distance is provided at the bottom of the plot.

tion for underestimating derived reflectivity relative to the observations is use of an inappropriate mass-dimension relation for graupel. Recall from Fig. 2 that the graupel mass-dimension relation (Heymsfield and Kajikawa 1987) implies a particle density of 0.1-0.2 g cm⁻³. However, the smoothness of many of the images in Fig. 15 gives the impression of higher-density graupel particles, perhaps having frozen drops as embryos (Heymsfield and Hjelmfelt 1984). Also, the existence of relatively large amounts of cloud liquid water at an air temperature of -1.5° C suggests that the graupel may be in a wet accretional growth mode (Heymsfield 1982). As a result, the particles may be spongy and, therefore, denser than graupel particles undergoing dry accretional growth at colder temperatures. A range of particle densities in excess of 0.2 g cm⁻³ were applied to the graupel data on this leg. Derived reflectivity agreed most closely with the observed reflectivity when a graupel density of 0.7 g cm⁻³ was employed (Fig. 17). The associated total water content (Fig. 16c) was more than 3 times the values derived in the default CMP, indicating the extreme sensitivity of this parameter to assumed graupel particle density.

FIG. 16. (*Continued*) for (c) is expanded by a factor of 3 as compared with (a) and (b). A scale for horizontal distance is provided at the bottom of the plot.

5. Summary and future applications

A customized product has been developed for use and analysis of microphysics data collected from aircraft during field campaigns in support of the TRMM program. These so-called common microphysics products are designed to help evaluate TRMM spaceborne precipitation retrieval algorithms. Information needed for this purpose (e.g., particle size spectra, particle habit discrimination, and total water content) was derived using a common processing strategy on the wide variety of microphysical instruments and native data formats employed during the field campaigns. The CMP are available in an ASCII structure to allow easy access to the data for those less familiar with microphysical data processing techniques.

Detailed examples of the CMP showed its potential and some of its limitations. In a stratiform precipitation region, a small number of particles were inappropriately classified as raindrops rather than graupel. Although the impact of this improper classification on derived total water content was minimal, it anomalously increased derived reflectivity by 5–10 dB Z_e . Also, graupel were objectively classified in larger numbers than expected from subjective interpretation of the OAP imagery, which primarily indicated the presence of aggregates. Despite this apparent problem, reflectivities derived assuming that these particles were graupel agreed much better with observed reflectivity measured with a ground-based radar than did assuming these particles were aggregates. Therefore, if these particles were aggregates, they were likely heavily rimed and characterized by a density appropriate for graupel. The opposite trend was observed in a region of convective precipitation, where many particles were classified as aggregates when the imagery showed a predominance of graupel. This issue was rendered moot when a sensitivity test revealed that derived reflectivity was unchanged if all of the classified aggregates were treated as graupel. However, comparisons between derived and observed reflectivity showed that the density assumed for graupel was too low by a factor of 4-5. Analysis of additional CMPs from microphysics data collected in both convective and stratiform precipitation is currently under way. Through this effort we will assess whether additional variables and changes to the CMP default parameters for habit discrimination and total water content calculation are warranted.

The necessity for the CMPs was based on the fact that many in the TRMM community are not familiar with microphysical data processing and do not have the tools to accomplish the task—a limitation that is applicable to a large fraction of the broader atmospheric sciences community. Our field was faced with a similar challenge regarding the processing and analysis of Doppler radar data in the late 1970s and early 1980s. In response, the community came together to develop common radar formats; first, universal format (UF) was implemented (Barnes 1980), and then, more recently with the expansion of airborne radar platforms, Doppler radar exchange (DORADE) has become the standard (Lee et al. 1994). Complementing these activities was the development of community software for display and analysis of Doppler radar data (e.g., Oye and Carbone 1981; Mohr et al. 1986; Oye et al. 1995). As a result of these efforts, a much larger fraction of the atmospheric sciences community has become involved in radar-oriented studies of atmospheric phenomena. Broader community access to microphysics data will require a similar commitment. A more generalized version of the CMPs described in this paper is one option that could be explored. Such a product would need to address a wider array of applications such as cloudradiation feedbacks, orographic precipitation processes, and validation of microphysical parameterizations in forecast models. A limitation to this approach is the lack of flexibility in adjusting processing parameters once the products are generated. The CMP strategy also implies the need for software to generate the products. With these issues in mind, the development of a community-oriented, nonproprietary software package for microphysics data processing seems essential. This software package could implement several peer-reviewed processing techniques, thus providing a degree of uniformity while still allowing some flexibility. A logical component of this activity would be to design a common format for describing two-dimensional arrays of particle imagery, with the ability to translate easily to this format from various existing native formats.

Whatever the approach, this subject needs to be addressed in the near term. It is becoming increasingly clear that an improved understanding of cloud microphysical processes is one of the primary keys to advance knowledge in our field. Expanding the accessibility of microphysics data to a larger fraction of our community will be vital in addressing this challenge.

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APPENDIX

List of Abbreviations

2DC	Two-dimensional cloud probe
2D-CIP	Two-dimensional cloud-imaging probe
2DP	Two-dimensional precipitation probe
2D-PIP	Two-dimensional precipitation-imaging
	probe
A_r	Area ratio [see Eq. (1)]
CFP	Common flight product
CMP	Common microphysics product
CPI	Cloud Particle Imager
CPS	Cloud Particle Spectrometer
\overline{D}_{mass}	Mass-weighted mean particle size
$D_{\rm max}$	Maximum dimension of a particle
$D_{\rm melt}$	Melted particle diameter
DMT	Droplet Measurement Technology, Inc.
DORADE	Doppler radar exchange format
FSSP	Forward-scattering spectrometer probe
HVPS	High-Volume Precipitation Spectrometer
k	Dielectric correction factor
KLWC	King liquid water content
KWAJEX	Kwajalein Experiment
LBA	Large-Scale Biosphere-Atmosphere ex-
	periment
Μ	Precipitation water content
Ν	Particle concentration
NASA	National Aeronautics and Space Admin-
	istration
OAP	Optical array probe
PMS	Particle Measuring Systems, Inc.
PR	Precipitation radar
SEA	Scientific Engineering Associates, Inc.
SPEC	Stratton Park Engineering Company, Inc.
TEFLUN	Texas and Florida Underflights experiment
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
UF	Universal format
UND	University of North Dakota
UW	University of Washington
Z_e	Equivalent radar reflectivity factor

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