Observations and Parameterizations of Particle Size Distributions in Deep Tropical Cirrus and Stratiform Precipitating Clouds: Results from In Situ Observations in TRMM Field Campaigns

Andrew J. Heymsfield,* Aaron Bansemer,* Paul R. Field,† Stephen L. Durden,# Jeffrey L. Stith,@ James E. Dye,@ William Hall,@ and Cedric A. Grainger&

*National Center for Atmospheric Research, Boulder, Colorado
†Meteorological Research Flight, Met Office, Farnborough, United Kingdom
#Jet Propulsion Laboratory, Pasadena, California
@National Center for Atmospheric Research, Boulder, Colorado
&University of North Dakota, Grand Forks, North Dakota

(Manuscript received 9 July 2001, in final form 28 May 2002)

ABSTRACT

This study reports on the evolution of particle size distributions (PSDs) and habits as measured during slow, Lagrangian-type spiral descents through deep subtropical and tropical cloud layers in Florida, Brazil, and Kwajalein, Marshall Islands, most of which were precipitating. The objective of the flight patterns was to learn more about how the PSDs evolved in the vertical and to obtain information of the vertical structure of microphysical properties. New instrumentation yielding better information on the concentrations of particles in the size (D) range between 0.2 and 2 cm, as well as improved particle imagery, produced more comprehensive observations for tropical stratiform precipitation regions and anvils than have been available previously. Collocated radar observations provided additional information on the vertical structure of the cloud layers sampled.

Most of the spirals began at cloud top, with temperatures (T) as low as ~50°C, and ended at cloud base or below the melting layer (ML). The PSDs broadened from cloud top toward cloud base, with the largest particles increasing in size from several millimeters at cloud top, to 1 cm or larger toward cloud base. Some continued growth was noted in the upper part of the ML. Concentrations of particles less than 1 mm in size decreased with decreasing height. The result was a consistent change in the PSDs in the vertical. Similarly, systematic changes in the size dependence of the particle cross-sectional area was noted with decreasing height. Aggregation—as ascertained from both the changes in the PSDs and evolution of particle habits as observed in high detail with the cloud particle imager (CPI) probe—was responsible for these trends. The PSDs were generally well-represented by gamma distributions of the form \( N = N_{\infty}D^{\mu}e^{-\lambda D} \) that were fitted to the PSDs over 1-km horizontal intervals throughout the spirals. The intercept \( (N_{\infty}) \), slope \( (\lambda) \), and dispersion \( (\mu) \) values were derived for each PSD. Exponential curves \( N = N_0e^{-\lambda D} \), \( \mu = 0 \), were also fitted to the distributions. The \( \lambda_0 \) values for given spirals varied systematically with temperature as did the values of \( \lambda \) (exponential), and the data generally conformed to values found in previous studies involving exponential fits to size distributions in midlatitude frontal and cirrus layers. Considerable variability often noted in the PSD properties during the loops of individual spirals was manifested primarily in large changes in \( N_{\infty} \) and \( N_0 \) but \( \mu, \lambda_0 \), and \( \lambda \) remained fairly stable. Temperature is not found to be the sole factor controlling \( \lambda_0 \) or \( \lambda \) but is a primary one. Direct relationships were found between \( \lambda_0 \) and \( N_{\infty} \), \( \lambda_0 \) and \( \lambda \), \( \mu \), for the gamma distributions, and \( \lambda \) and \( N_0 \) for the exponential. The latter relationship was not found as distinctly in earlier studies; observed PSDs in this study had better fidelity with less scatter. The \( \mu \) values changed monotonically with \( T \) over the range of temperatures and were directly related to \( N_{\infty} \) or \( \lambda_0 \), thereby reducing the number of variables in the PSD functional equation to two. In the upper part of the ML, \( N_{\infty} \), and \( \lambda \) continued to decrease, and in the lower part these values began to increase as the largest particles melted.

General expressions relating various bulk microphysical, radar, and radiative-transfer-related variables to \( N_{\infty} \) and \( \lambda \) were developed; they are useful for both tropical and midlatitude clouds. These relationships facilitate the specification of a number of bulk properties in cloud and climate models. The results presented in this paper apply best to temperatures between 0°C and ~40°C, for which the measured radar reflectivities fall in the range of 0 to 25 dBZ.

1. Introduction

During 1998 and 1999, four field campaigns were conducted by the Tropical Rainfall Measuring Mission (TRMM) to evaluate the performance of the TRMM radar and radiometer retrieval algorithms. These field programs also provided validation data for TRMM mesoscale and regional-scale models. The experiments were conducted in subtropical and tropical regions: Texas and Florida [Texas–Florida Underflights (TEFLUN-A and -B)], Brazil [Large Scale Biosphere–Atmosphere Experiment (LBA)], and Kwajalein, Marshall Islands.
Table 1. Instruments used in earlier tropical ice cloud studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>Probe</th>
<th>Range (µm)</th>
<th>Study</th>
<th>Probe</th>
<th>Range (µm)</th>
<th>Study</th>
<th>Probe</th>
<th>Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Griffith et al. (1980)</td>
<td>1D-C PMS probe</td>
<td>70–460</td>
<td>Knollenberg et al. (1982)</td>
<td>2D grey</td>
<td>40–2500</td>
<td>Knollenberg et al. (1993)</td>
<td>FSSP</td>
<td>0.1–78</td>
</tr>
</tbody>
</table>

* Particle measuring systems
* Forward-scattering spectrometer probe
* Video ice particle sampler
* Cloud particle imager

[{
Kwajalein Experiment (KWAJEX)]. Measurements were acquired using multipolarization ground-based Doppler radars, rain gauges, and in situ and overlying aircraft. As part of the validation effort, in TEFLUN-B, LBA, and KWAJEX, the University of North Dakota (UND) Citation aircraft employed state-of-the-art instrumentation to acquire in situ measurements. In this study, we report on microphysical data acquired by the Citation in deep tropical anvils and stratiform precipitating clouds and develop parameterizations for use by the remote sensing and modeling communities.

Past in situ microphysical observations in tropical ice clouds over the range \(-80 \leq T \leq -20^\circ C\) have provided indications of total particle concentrations \(N_T\) and ice water contents (IWC). In the primary studies, listed in Table 1, particles with minimum diameter of between 10 and 100 µm up to about 1 mm were measured. Griffith et al. (1980) found that the IWCs in three cirrus cloud decks sampled at multiple levels during the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) generally increased from near cloud top (11.5 to 13.0 km) to near cloud base (7 to 9.5 km); peak, level-averaged IWCs reached 0.05 g m\(^{-3}\). Knollenberg et al. (1982, 1993) reported IWCs as high as several hundredths to several tenths gram per cubic meter, and IWC, cross-sectional area, and median mass-weighted diameter increased downward below cloud top. Stith et al. (2002), from the TRMM field campaigns, showed that there was a wide variety of particle types observed both in the convective and stratiform regions of tropical ice clouds at temperatures from 0\(^°\) to about \(-20^\circ C\), using data primarily from the cloud particle imager and Particle Measuring System 2D-C probes. Aggregation was observed to be a primary growth process, as was also the case in the Heymsfield and McFarquhar (1996) study.

Although remote sensing and modeling applications require knowledge of the PSDs in tropical clouds, relatively little data have been available to develop parameterizations for these PSDs. The PSDs of cirrus anvils and detached cirrus sampled during CEPEX were characterized by McFarquhar and Heymsfield (1997, hereafter MH97). They parameterized concentration in terms of the melted equivalent diameter \(D_{me}\) as a function of IWC and \(T\). A limitation of the dataset was that concentrations of particles with size above approximately 0.1 cm were generally below the detection limit of the 2D-C probe.

This discussion of previous studies implies important gaps in our knowledge of tropical ice cloud microphysical properties. In particular, few observations have been made of PSDs for particle sizes above 0.1 to 0.2 cm, or for \(T\) in the range 0\(^°\) to \(-20^\circ C\). There are also few observations of how PSDs vary in the vertical—other than those made by combining horizontal flight legs at different altitudes—or of microphysical properties as related to radar echoes. Furthermore, little information is available on particle habits. The data in this study fill some of these gaps. Spiral descents were used to characterize microphysical properties in the vertical for temperatures in the range \(-5^\circ\) to \(-2^\circ C\). Recently developed probes that provide high-quality particle habit information, especially for the smaller particle sizes, were used. Also, considerably larger sampling volumes
in the larger sizes provided more reliable measurements of PSDs than those previously obtained for tropical ice clouds.

In section 2, we describe new instrumentation used for this study. We present our observations in section 3. IWCs and other bulk properties derived from the PSDs are given in section 4; we also develop parameterizations to represent these properties. In section 5, we compare our results to earlier observations in mid-latitude and tropical ice clouds. We conclude, in section 6, by summarizing the results of this study. A list of symbols used for the different cloud microphysics variables is given in appendix A, and the methods used to calculate particle mass and terminal velocity are given in appendix B.

2. Instrumentation and data processing

The microphysical datasets collected during the TRMM field campaigns probably constitute the most complete set of in situ data in subtropical and tropical clouds to date. On the UND Citation aircraft, particle shapes were imaged and size distributions measured from about 20 \( \mu \text{m} \) to >2 cm.

A Stratton Park Engineering Company, Inc. (SPEC), cloud particle imager (CPI) probe provided detailed information on the shapes and sizes of particles from approximately 20 \( \mu \text{m} \) to above 1 mm, with 2.3-\( \mu \text{m} \) resolution. Because the CPI sampling volume is relatively small and is still the subject of study, the particle size distributions (PSD) obtained from the CPI are not used here.

PSDs, along with low-resolution particle imagery, were obtained from the Particle Measuring Systems (PMS) 2D-C and the SPEC high volume particle spectrometer (HVPS) probes. The PSDs were measured from 33 \( \mu \text{m} \) to above 1 mm in 33-\( \mu \text{m} \) increments by the 2D-C, and from 0.2 mm to about 5 cm in increments of 0.2 mm from the HVPS, with composite PSDs generated from the two probes by finding a point at which the size distributions from each overlapped, or where the concentrations were comparable. The overlap size usually occurred from 1 to 2 mm. The nominal 2D-C probe sample volume is given by the probe’s array width (about 1 mm) times the separation between the probe’s arms (6.1 cm) times the Citation’s true airspeed (about 120 m s\(^{-1}\)), or about 71 s\(^{-1}\). The “particle reconstruction” technique was used to extend this sample volume by an amount that increased roughly linearly with size (see sample volume values in Heymsfield and Parrish 1978), by considering particles that were partially outside of the 2D-C probes’ sample volume. The HVPS swept out a sample volume given by the array width (about 5 cm) times the separation between the probes’ arms of about 20 cm, times the aircraft’s true airspeed, or about 1 m\(^3\) s\(^{-1}\).

Key imaging probe data required for our analysis included the maximum particle diameter (\(D\)), cross-sectional area (A), area ratio (\(A_i = A/(\pi/4)D^2\)), and concentration per size bin (\(N\)). The diameter was derived as the “true” maximum diameter—not the maximum diameter along the array or flight direction axes, as in previous calculations.

State parameters were obtained from the aircraft’s standard suite of instruments. The \(T\) measurement, from a heated Rosemount sensor, is accurate to approximately \(\pm 0.5^\circ\text{C}\). A more complete discussion of the Citation state parameter instrumentation appears in Stith et al. (2002).

We used Doppler radar data from the NASA ER-2 and DC-8 aircraft to characterize the reflectivity structure of the cloud layers during the Citation sampling, and ground-based S-band (10.7 cm) radar data to examine temporal evolution of the cloud layers during the spirals. The ER-2 Doppler radar (EDOP) transmits at a wavelength of 3.1 cm (Heymsfield et al. 1996), whereas the airborne mapping Doppler radar (ARMAR) on the DC-8 transmits at a wavelength of 2.2 cm (Durden et al. 1994). The vertical resolution of these radars is 80 m (ARMAR) and 75 m (EDOP); the minimum detectable reflectivity as used here is approximately \(-10 \text{ dBZ}\); and the precision of the velocity estimate (particle fall velocity + air velocity) is 0.1 m s\(^{-1}\). The vertical motions of each aircraft have been subtracted from the velocity estimates by using the Doppler velocity information in the lowest (surface) rangegate, together with the aircraft navigational system data to remove the aircraft vertical motion. Some random components of vertical motion could not be subtracted but were eliminated through averaging,\(^1\) which resulted in an absolute accuracy of the Doppler velocities of 0.5–1.0 m s\(^{-1}\) for the ARMAR radar, and 0.5–1.0 m s\(^{-1}\) for EDOP. The accuracy of the reflectivity measurements from each aircraft radar was approximately \(\pm 1 \text{ dB}\). No aircraft Doppler data were available for three of the flights examined later, but data from the ground-based radar for these flights was available. The ground-based radars included the National Center for Atmospheric Research (NCAR) S-band polarimetric radar (S-pol) radar during TEFUN-B and LBA and a similar S-band radar during

\(^1\) Possible upward motions in and above the vicinity of the radar bright band of order 10 cm s\(^{-1}\) would not have been eliminated by averaging, but will not significantly influence the results.
KWAJEX. (The characteristics of the KWAJEX radar are presented in Schumacher and Houze 2000.)

3. Observations

a. Sampling strategy and limitations

The data reported here were collected primarily in anvils and dissipating thick stratiform precipitation regions. As pointed out of Field (1999, hereafter F99), “it is quite common for an aircraft run at a given height to encounter a cloud that thins, breaks, and perhaps thickens again. If microphysical data are averaged over such a traverse it becomes difficult to disentangle the effects of differing local conditions on the evolution of the particle population.” It is therefore difficult to assess how the properties of a cloud change in the vertical from data averaged for different levels.

To examine vertical variability but particularly particle evolution in the vertical, each case studied here involved a Lo and Passarelli (1982, hereafter LP82)-type Lagrangian spiral descent through a cloud to observe the evolution of the PSDs. A vertical profile using this technique starts aloft in a horizontally extensive ice cloud area, and an aircraft is placed in a constant bank angle at a constant descent rate of about 1 m s\(^{-1}\). The aircraft spirals downward at approximately the mean fall speed of the snow and the loops of the spiral drift with the wind. Ideally, if conditions are quasi steady and the properties of the atmosphere are fairly uniform over a length scale somewhat larger than the diameter of the loops, then the aircraft largely samples particle evolution from the height change in the size distribution properties. The analysis of particle size spectra can be performed by averaging spectra over a complete loop of the spiral. This serves to average any horizontal inhomogeneities. Another approach is to compare particle size spectra at various heights that occurred in the same aircraft heading or sector of different loops. Ideally, if all the loops are the same size and the aircraft descends at about 1 m s\(^{-1}\), then each point of the aircraft trajectory corresponds to the trajectory of a 1 m s\(^{-1}\) particle.

Horizontal gradients in wind velocity, wind shear, and dispersion of ice particle fall speed creates a difficult sampling problem under the best of circumstances. For example, even if the cloud dynamics and microphysics are in a quasi-steady state, there are usually mesoscale areas of precipitation embedded within widespread cloud layers, which move and change with time. Our observations are much more prone to sampling errors and misinterpretation than earlier studies that used Lagrangian spiral descents to sample stratiform cloud layers. This is in part because temporal evolution was much more pronounced—the durations of the spirals were comparable to the life cycles of the convective clouds that generated the cloud layers, such that the upper portions of the cloud we sampled could have evolved substantially by the time we sampled the lower portions of the clouds. Furthermore, horizontal inhomogeneities are possibly more pronounced than in widespread cloud layers—small convective elements could have contributed concentrated but small-scale regions embedded within broader cloud layers.

The vertical variations in the PSD properties that are presented in this section therefore may not represent the properties at any given time. What is being observed is the changes downwards in the part of the PSD falling at the descent velocity of the aircraft, whether or not there is substantial evolution of the cloud properties above the sampling level. For each case studied, the extent of evolution of the radar echoes over the course of the descents will be characterized and the impact discussed in section 5. Note also that horizontal variability in the properties of the PSDs during the course of each spiral may be more extensive than in earlier studies, a factor that will also be discussed in sections 3c and 5. And lastly, the spiral descents occupied less than 5 h of aircraft flight time whereas there is almost 100 h of data collected during horizontal traverses. This broader set of data will be used in the future to study the relationship between radar reflectivity and properties of the PSD for tropical ice clouds in forthcoming articles planned by a number of investigators.

b. Overview of the cloud layer properties

The cloud-top and cloud-base heights and temperatures measured by the aircraft during the spirals, the cloud optical depths estimated from the microphysical probes, and the changes in the radar reflectivities of the regions of the clouds sampled during the spirals are presented in Table 2. Most spirals commenced at cloud top, with four descents initiating at temperatures below \(-35^\circ C\) and five above \(-20^\circ C\) (Table 2). In the coldest case, \(T = -50^\circ C\). The spirals ended at cloud base, or in rain when the cloud base was below the melting layer (ML), and spanned a cloud depth that was usually between 3.0 and 4.5 km. When possible, aircraft descent rates \(d(\text{Alt})/dt\) were adjusted to match the approximate mean particle fallspeeds both in the ice (1 to 2 m s\(^{-1}\)) and rain (5 to 7 m s\(^{-1}\)) regions. These attempts were successful in KWAJEX but not in LBA (Table 2; \(d(\text{Alt})/dt\)).

Each loop of the spiral spanned a diameter of 5 to 10 km, with the number of loops varying from 3 to 23, exceeding 10 for all KWAJEX cases. The Citation drifted several tens of kilometers with the wind during the sampling periods (Fig. 1), ranging from 6 to 45 min, with most in the 25- to 45-min range.

An average optical depth for each spiral descent was derived by integrating downwards from the top to the base of the spiral, twice the cross-sectional area of the particle population as measured by the 2D-C and HVPS probes (Table 2). The cloud layers sampled were close to or exceeded the value of 23 necessary to be consid-
Table 2. TRMM Lagrangian spiral descents.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Times (UTC)</th>
<th>Altitude (m)</th>
<th>Temperature (°C)</th>
<th>d(Alt)/dt (m s⁻¹)</th>
<th>Loops (No.)</th>
<th>Optical depth (Average)</th>
<th>Surface precipitation—any?</th>
<th>Surface reflectivity &gt;18 dBZ?</th>
<th>Reflectivity change (dBZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>980905</td>
<td>Fl4</td>
<td>213251 215040</td>
<td>7923 3632</td>
<td>−19</td>
<td>6</td>
<td>2.7</td>
<td>6</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>990217</td>
<td>Brazil4</td>
<td>194224 195601</td>
<td>10 042 4602</td>
<td>−38</td>
<td>0</td>
<td>6.7</td>
<td>4</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>990219</td>
<td>Brazil4</td>
<td>201335 201934</td>
<td>6091 4379</td>
<td>−10</td>
<td>2</td>
<td>4.8</td>
<td>3</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>990188</td>
<td>Kwajalein</td>
<td>035139 040701</td>
<td>8508 5695</td>
<td>−26</td>
<td>−5</td>
<td>3.1</td>
<td>7</td>
<td>24</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>990189</td>
<td>Kwajalein</td>
<td>220448 225000</td>
<td>6950 3370</td>
<td>−14</td>
<td>7</td>
<td>1.3</td>
<td>23</td>
<td>37</td>
<td>Yes</td>
<td>Early</td>
</tr>
<tr>
<td>990822</td>
<td>Kwajalein</td>
<td>212049 220451</td>
<td>11 206 6983</td>
<td>−50</td>
<td>−16</td>
<td>1.6</td>
<td>14</td>
<td>22</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>990823</td>
<td>Kwajalein</td>
<td>031450 034550</td>
<td>10 341 6094</td>
<td>−42</td>
<td>−9</td>
<td>2.3</td>
<td>10</td>
<td>25</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>990830</td>
<td>Kwajalein</td>
<td>201056 203730</td>
<td>7376 3685</td>
<td>−18</td>
<td>6</td>
<td>2.3</td>
<td>13</td>
<td>29</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>205332</td>
<td>212120 7319 3685</td>
<td>−17</td>
<td>5</td>
<td>2.2</td>
<td>13</td>
<td>25</td>
<td>Yes</td>
<td>Yes</td>
<td>−25</td>
<td></td>
</tr>
<tr>
<td>990911</td>
<td>Kwajalein</td>
<td>194955 203121</td>
<td>10 055 4514</td>
<td>−39</td>
<td>7</td>
<td>2.2</td>
<td>11</td>
<td>30</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*YYMDDD Format.
*Two digits each to represent h, min, and s.
*Near Cape Kennedy.
*Near Puerto Velho.
*Not available or unknown.

...ered within the “deep convection” cloud category according to the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999). Our clouds did not fall within the optically thinner categories of “cirrus” or “cirrostratus.”

As shown in Table 2 from the ground-based S-band radars, 9 of the 10 spiral descents were associated with precipitation (deduced from radar) at some time during the spirals. Most of the clouds would have had surface reflectivities above the 18 dBZ, or so, necessary to be detected by the TRMM radar. (TEFLUN-B data courtesy Ed Brandes; LBA data courtesy Walt Petersen; KWAJEX data courtesy Sandra Yuter.)

Coincident vertical profiles of the measured radar reflectivities (dBZₚ) and reflectivity-weighted Doppler particle fallspeeds (Vₓ; positive downward) were available from overflying aircraft during seven of the spirals. The measured Vₓ values are the sum of the air and particle velocities. The ARMAR or EDOP provided information during or shortly before these spirals (Fig. 1). Note that the radar data were nearly instantaneous, although the Citation spirals required 30 min or so and involved aircraft drift. While a one-to-one comparison of the radar and in situ measurements is therefore not possible, pertinent information on cloud structure, measured dBZₚ, Vₓ, and presence of significant updrafts were obtained, at least for some portion of the spirals. Periods were identified when the Citation and DC-8 or ER-2 tracks overlapped (bold lines, Fig. 1), and radar data during and near these periods were examined to assess the adjacent cloud structure.

Averaged vertical profiles of measured dBZₚ and Vₓ for various periods of aircraft coincidence are shown in Fig. 2, left and right panels. The dBZₚ in the ice regions (4.5 km above mean sea level) fell in the 5–25 dBZₚ range and generally increased downward. The trend differed for the 990819 case (top panels), in which the dBZₚ values were nearly constant with height. The Vₓ in ice were 1 to 2 m s⁻¹ and also usually showed an increase downward. Vertical air motions may have been present in the data from individual radar scans, but averaging over the relatively long horizontal intervals probably canceled out up- and downdrafts, with the exception of possible local upward motions of order 10 cm s⁻¹ at and above the melting layer. Vertical air motions also contributed to the ±1σ bounds of 50 to 100 cm s⁻¹ shown in the figure. Lower Vₓ generally coincided with lower dBZₚ. Bright bands—for example, melting layers—were noted in the data at approximately 4.5 km in five of the cases. Below 4.2 km in rain, the Zₑ values were 20 to 30 dBZₑ, except on 990911, when lower values for dBZₑ were measured. The values for Vₓ in rain were about 6 m s⁻¹.

To place some bounds on the extent of temporal evolution during the spirals, airborne and ground-based radar measurements were used to loosely examine the change in the mean radar reflectivity at the Citation aircraft midspiral height and location at several times during each spiral. We use the EDOP and S-pol data for the 980905 spiral; the S-pol radar data for 990217 and 990219; the ARMAR data for 990819 and 990830; and the Kwajalein radar data for 990822, 990823, and 990911. The changes in the mean radar reflectivity values, shown in increments of 5 dBZₑ in the last column of Table 2, were generally 5 dBZₑ or below. As shown in section 4, changes in dBZₑ of about 5 dBZₑ correspond to changes in the ice water content or precipitation rate by a factor of about two. This change is modest and therefore we conclude that the spiral descents provide not only an indication of the evolution of the PSD in the vertical but an indication of the approximate properties in the vertical over the time periods of the spirals.

There was also considerable horizontal inhomoge-
neity over the course of the various loops of the spirals, and the variability ($\pm 1\sigma$ bounds) about the mean values of measured dBZ in Fig. 2 (left panels) was also often 5 dB.

c. Particle size distribution properties in the vertical

In KWAJEX, the rate of descent of the Citation coincided roughly with Doppler radar-measured particle fallspeeds. The particles dominating the measured reflectivities were presumably at the larger end of the PSDs and their evolution in the vertical was therefore captured by the Lagrangian spiral descents. However, evolution in the small end of the PSDs was not captured although aspects can be inferred from changes in the size distributions.

PSDs averaged over various loops for the spiral of 990819 are plotted in Fig. 3. The 2D-C and HVPS data overlapped reasonably well at about a particle diameter of 0.2 cm, thus providing nearly continuous PSD measurements for particles from tens of microns in size to centimeters. Most particles were below 0.2 cm. For particles above 0.04 to 0.06 cm, the concentrations (plotted on logarithmic axes) decreased linearly with size (linear axes), indicating that at sizes above 0.04 to 0.06 cm, the PSDs were exponential. Below 0.04 to 0.06 cm, the PSDs were linear when plotted on logarithmic axes, indicating that particle concentrations in this part of the distribution were distributed by a power law. The maximum particle size increased downward until the ML, then decreased below as a result of melting.

PSDs plotted as in Fig. 3 do not capture the horizontal and vertical variability observed during the spirals. We developed a different type of plot to capture these trends.
The left panels in Figs. 4 and 5 show height–time cross sections of dBZ, along the tracks of the DC-8 (KWAJEX) and ER-2 (LBA) as these aircraft flew near to and over the Citation. The boxes in the panels depict approximate locations of these overpasses if they had occurred over a period of about 2 min, for reference purposes only, but in fact they occurred over a 30 or so minute period (Table 2). The right panels show color-coded renditions of the PSDs during the spirals. Composite PSDs, as in Fig. 3, were color-coded to denote concentration per unit diameter $N(D)$ with higher $N$ in red and lower $N$ shown in blue. Colors represent $N(D)$ (the color key is at the right), and the $D$ scale is along the abscissa. The spirals used in Figs. 4 and 5 were selected because they contained both reliable $N(D)$ information and coincident radar data. An exception is the 990217 spiral (bottom panel, Fig. 5), where some loss of PSD information occurred because of a probe malfunction.

Inspection of the right panels in Figs. 4 and 5 shows the presence of cyclical fluctuations, indicating horizontal variability. This conclusion is supported by the radar imagery in the left panels, which indicates horizontal variability within the Citation domain sampled, sporadic bright band signatures, embedded convection, and distinct fall streaks. It is, therefore, not necessarily meaningful to infer particle growth from loop averages for PSDs, and there are questions related to whether horizontal inhomogeneity is atypical of tropical stratiform precipitating regions and anvils and if the observations are representative of tropical cloud layers.

Beginning at cloud top, particles as large as 2 mm (990911) to 6 mm (990819, 990830) were observed. The sizes of the largest particles in the PSDs increased downward, a feature shown by the decrease downward in the width of the dark blue color in the right panels of Figs. 4 and 5. Figure 6 shows images from the HVPS probe for each of the 14 loops of the Citation as it spiraled from cloud top to base on 990822. The particles shown for the first few loops were at most a few millimeters in size and reach up to 1 cm in diameter during the lower loops.

The diameters of the largest particles increased downward at 0.1 to 0.3 cm km$^{-1}$, with lesser increases for the colder cases and greater increases for the warmer cases. As the Citation descended at a rate similar to the fall velocity of the largest particles, the broadening of the PSDs can be attributed to growth of the larger particles and not to size sorting. Although large particles could have been injected into the lower levels, giving the illusion of growth, the measured dBZ, profiles adjacent to the spiral locations do not suggest the presence of nearby sources of large particles. However, on 990822, the proximity to convection may suggest local sources of particles.

The concentrations of small ice particles, which dominated the total concentration $N_T$, were greater near cloud top but generally decreased appreciably downward in the cloud (Fig. 7). Aggregates, examples of which appear in the lower panels of Fig. 8, were almost certainly responsible for the preponderance of this decrease, although a portion of the decrease may have been the result of sublimation and size sorting.

The PSDs changed markedly through the ML (Figs. 4 and 5: 990819, 990830, and 990911 spirals). The tops...
Fig. 3. Average PSDs for various loops of the 990819 spiral. (heavy lines) 2D-C. (light lines) HVPS.

of the ML—marked with “0C,” in these figures for the 990819, 990830, and 990911 spirals—occurred at about 4.5 km. The size of the largest particles, $D_{\text{max}}$, initially increased from about 1 to 1.5 cm, while the $N$ of particles under 0.5 cm decreased significantly (see Figs. 4, 5, and 7). Aggregation in the upper parts of the ML accounts for these observations.\(^2\) The bases of the ML, as defined by the height at which the sizes of the largest particles no longer changed appreciably, occurred at about 3°C (3.95 km), where the largest raindrops were 0.3–0.4 cm.

\(d\). Particle habit variations in the vertical

The CPI provided information on how the particle habits varied in the vertical and the relationship of these to the measured reflectivity structures shown in Figs. 4 and 5. This instrument is best suited for characterizing the habits of the particles smaller than 2 mm; larger particles are not detected as its sample volume is too

\(^2\) Some decrease in the total concentration could have been caused by the smaller particles decreasing in size below the 2D-C detection threshold by melting, resulting in increased fall velocities and decreased concentrations, or by evaporation of the small drops by preferential deposition of condensate on the larger ice particles. Calculations indicate that these were not significant factors.
Fig. 4. Measured reflectivities (left) and representations of the PSDs (right) during Lagrangian spiral descents on 3 days during KWJAEK. ARMAR measurements were obtained from DC-8 in nadir-viewing mode, with abscissa showing time. The boxes in the left panels show the top, bottom, and approximate horizontal positions of the Citation as if the spiral occurred during the overpass period (see text).
Fig. 5. Same as Fig. 4, except that bottom panels show data from EDOP on the ER-2 (data courtesy of G. Heymsfield) during LBA. Data for 990830 are from the first spiral listed in Table 2.
small to sample the larger particles. On 990819 (as shown in Fig. 8), numerous vapor-grown crystals were observed in the intermediate (400 to 600 μm) and large (>800 μm) sizes—including columns, capped columns, hexagonal plates, and branched crystals—whereas the habits of the small (<100 μm) particles were not identifiable. Aggregates, with some riming in the larger sizes, were also observed, especially just above and near the top of the ML. No supercooled liquid water was detected. The presence of the bright band for this spiral (top left panel, Fig. 6) indicated that updrafts were weak (because strong updrafts would disrupt the bright band). Weak updrafts are conducive to growth primarily through diffusion rather than riming. Radar echo-top heights of 8 to 9 km (from $-20^\circ$ to $-25^\circ$C) led to the initial formation of columns, then of capped columns as particles fell through the planar-crystal growth regime where $T$ ranged from $-12^\circ$ to $-18^\circ$C. In contrast, particles observed on 990822 (shown in Fig. 9) were rimed in the intermediate and large sizes with some aggregates evident, and these appeared more spherical in the small sizes. Measured radar reflectivities (Fig. 4, middle left panel) and $V_Z$ (not shown), from which vertical velocities above a few meters per second could be assessed, indicated the presence of deep updrafts, which led both to extensive riming and to complex crystal shapes often associated with the freezing of cloud droplets at low temperatures.

The relationship between particle habits, the measured radar reflectivities, and the proximity to convection was also observed in the other cases. The deep anvil generated from nearby deep and extensive convection on 990217 (Fig. 5, lower left panel; and EDOP data, not shown) produced complex rimed crystals and aggregates of rimed crystals (upper panels, Fig. 10). No supercooled liquid water was measured on 990217; thus, riming must have been acquired in the convective regions, then particles were advected into the anvil. Conversely, for the poorly organized and weak updrafts associated with the 990823 spiral (lower panel, Fig. 4), habits consisted of pristine cirrus-type crystals (e.g., unrimed side planes and bullet rosettes), reflecting the low cloud-top $T$, and capped columns, reflecting additional growth around $-15^\circ$C.

e. Derived moments of the size distributions

Various bulk properties were computed from the PSDs, including the ice water content, precipitation rate $R$, radar reflectivity factor $Z$, radar reflectivity assuming equivalent water spheres $d\text{B}_Z$, and mean mass and reflectivity-weighted particle terminal velocity $V_m$, $V_Z$, as in Heymsfield (1977). In this subsection, we present calculations of these parameters.

1) Estimation of ice particle density and mass

Calculation of each of these variables depends on a knowledge of the ice particle density and mass as a
Fig. 7. Concentration (number per liter) of particles 100 \( \mu \) and above vs altitude (km) as measured by the 2D-C probe during five of the Lagrangian spiral descents (dates given at top of each panel). The distinct spikes at some points in the \( N \) traces in the ML are probably an artifact of the 2D-C probe.
Fig. 8. Examples of particles vs altitude (km) and temperature (°C) imaged in three size ranges (<100, 400–600, >800 μm) by CPI probe on 990819. Magnification between different size ranges is not the same.
function of $D$, and a knowledge of the terminal velocity $V_t$, which are needed to calculate $R$, $V_z$, and $V_w$. The $V_t$, in turn, depends on $m$, the ice particle cross-sectional area ($A$) normal to its fall direction, and the drag coefficient. Obtaining the area is straightforward; $A$ was measured directly by the 2D and HVPS probes, which were oriented to measure the particles’ horizontal cross sections.

Calculation of $m$ is more problematic. Mass is obtained from the general relationship

$$m = \frac{\pi}{6} \rho_e D^3,$$

where $\rho_e$ is the effective density (particle mass divided by the volume of a circumscribed sphere). No direct measurements of IWC were available from the TRMM observations to constrain the estimates of $\rho_e$, and the ARMAR and EDOP measurements were not sufficiently collocated with those of the Citation to constrain the calculations from the radar reflectivity. Although $\rho_e$ can be estimated for some particles with pristine habits, little direct information could be ascertained for the more complex, rimed, and aggregated particles. A comprehensive study was used to estimate $\rho_e$, encompassing a combination of calculations, ARMAR observations, and observations of ice particle terminal velocities at the surface. We describe this effort in appendix B. The following relationship was developed from this analysis and from the work of Heymsfield et al. (2002, hereafter H02):

$$\rho_e = k A_r \rho_s D^n,$$

where $A_r$ is the area ratio $A_r/(\pi/4)D^2$ (number of shadowed 2D-C or HVPS pixels divided by the number of pixels in a circle with the same $D$), $k = 0.07$, $n = 1.5$, and $\alpha = -0.5$ (cgs units). The $A_r$ provided some information about $\rho_e$ (see H02), and the $D$ dependence accounted for observations that the $\rho_e$ for aggregates generally decreases with $D$. Although this relationship fit a number of observational datasets (described in appendix B), the variability in $\rho_e$ can nevertheless be large. We infer that using Eq. (2) with these coefficients provides an accuracy of $\pm 50\%$ of the true IWC, as ascertained by comparing values for $\text{dBZ}_e$ ($\equiv m^2$) as calculated from the PSDs with those measured by the ARMAR on the same days during KWAJEX. An optimistic uncertainty in the mean $\rho_e$ of $\pm 25\%$ leads to the following approximate uncertainties: IWC, $\pm 25\%$; $R$, $\pm 45\%$; dBZ$_e$, $\pm 10\%$ (for positive dBZ$_e$); $V_z$, $\pm 12\%$; and $V_w$, $\pm 15\%$. We have not accounted for Mie scattering effects in these estimates.

2) Derived IWCs and Other Moments

Vertical profiles of IWC, $R$, dBZ, $V_w$, and $V_z$ as calculated from the PSDs for three spirals (shown in Fig. 11) were selected as representative of the findings for the ice regions of all spirals. The equations used to calculate these properties are presented and parameterized in section 4c and listed in Table 3. The calculations are derived for temperatures 0°C and below to avoid ambiguities associated with particle mass in the melting layer. Our main findings were as follows.

1) The magnitudes of the IWCs are mostly from 0.1 to 0.5 g m$^{-3}$, and change by only about a factor of two or three with height, much less than is observed for synoptically generated ice clouds over comparable vertical depths (see section 5 and Fig. 18). The horizontal variability noted in the IWC values of less than 50% during the course of a spiral is comparable to that observed in earlier Lagrangian spiral descents reported on by LP82 and F99. The magnitudes of the IWCs, and associated calculated values for dBZ$_e$, were comparable to those for midlatitude anvils (Heymsfield 1986).

2) The precipitation rates changed by less than a factor of two over the course of the various loops of each spiral, and by less than a factor of three over the cloud depths, with the exception of the 990822 case. This result is good given that our goal was to sample the same population of particles as they fell from upper to lower cloud levels, implying a nearly constant $R$ with height.

3) The trends of calculated dBZ, with height differed markedly from the radar observations, shown in Fig. 2. This is not surprising given that the radar data were acquired over only part of the Citation track and for a very limited portion of each spiral. The calculated peak values of dBZ$_e$, however, were comparable to the radar measurements. Mie scattering effects should be included in cases where calculations and measurements of dBZ$_e$ can be made directly.

4) The $V_w$ were of the order 1 m s$^{-1}$—very reasonable for the calculated IWCs and $R_s$.

4. Properties and parameterizations of the PSDs

The focus of this section is to develop general relationships for the PSDs, and between the PSDs and various microphysical and radar-measured properties for use in cloud resolving models, climate models, and remote sensing applications.

a. Form of the ice PSDs

In this subsection, we use curves fitted to the PSDs to quantify how the PSDs from the Lagrangian spirals varied with temperature and height, and to quantitatively assess how horizontal variability influenced the PSD. Not all spirals were used in this analysis, because a complete set of 2D and HVPS data was not always available.

Based on the work of Kosarev and Mazin (1991),
Mitchell (1991), and others, gamma distributions of the form

$$N = N_0 D^m e^{-\lambda_D D}$$

(3)

were fitted to the PSDs with diameters 66 µm or two 2D-C probe size bins and above for each 1 km of horizontal distance, or about 20 m in the vertical and 8–9 s of flight. The intercept ($N_0$), slope ($\lambda_D$), and dispersion ($\mu$) values were derived for each PSD by matching three moments (Kozu and Nakamura 1991; Zhang et al. 2001). We have chosen to use the first, second, and sixth moments, as this set provided the best fit over the entire measured particle size range. (Symbols in the discussion that follows are defined in appendix A.)
Fig. 10. Same as Fig. 8, except for 990217 (LBA; top) and 0823 (KWAJEX; bottom). The 990217 case shows riming near to convection and the 990823 case shows pristine cirrus-type crystals reflecting short-lived convective elements and low temperatures.
The fit coefficients were derived as follows. The $p$th moment $M(p)$ of the observed PSD is given by

$$M(p) = \int_0^{D_{\text{max}}} p(D)D^p \ dD.$$  \(4\)

The parameter $\mu$ can be derived by finding the only real root of the quartic polynomial

$$(1 - F)\mu^4 + (8 - 18F)\mu^3 + (24 - 119F)\mu^2 + (32 - 342F)\mu + (16 - 360F) = 0,$$  \(5\)

where $F = [M(2)]^3/[M(6)][M(1)]^4$. The other fit parameters are derived from

$$\lambda_F = \frac{M(1)(\mu + 2)}{M(2)},$$  \(6\)

and

$$N_{\text{of}} = \frac{M(1)\mu^{\mu+2}}{\Gamma(\mu + 2)}.$$  \(7\)

This method produces a fit that is also in good agreement with other moments that are not used in the fitting routine, such as the third moment, used for computing IWC. Also fitted were exponential curves ($\mu = 0$) in Eq. (3), for reference to earlier studies. Hereafter, the fit coefficients for the exponential will be noted by $\lambda$ and $N_0$, and for the gammas by $\lambda_F$, $N_{\text{of}}$, and $\mu$.

The values of $\lambda$ and $\lambda_F$ obtained for the various spirals showed a correlation with $T$ (Figs. 12a and 12b), and with each other (Fig. 13a), although there was considerable variability. The $\lambda$ and $\lambda_F$ values were about the same (Fig. 13a), except below $\lambda$ and $\lambda_F$ less than 15 cm$^{-1}$ and above $\lambda$ and $\lambda_F$ greater than 70 cm$^{-1}$. The solid line in the figure (and the fitted equation) shows where the values deviate.

For $T \approx -15^\circ$C, the $\lambda$ and $\lambda_F$ values were usually greater than 20 cm$^{-1}$, with the exception of the 990822 case, which differed, presumably because of the proximity of the sampling to convection and possibly because it was an anvil. For values of $T$ between $-5$ and $-15^\circ$C, the $\lambda$ values decreased to between 12 and 20 cm$^{-1}$ while the $\lambda_F$ were somewhat lower. As $T$ increased toward $0^\circ$C, the $\lambda$ values were asymptotic at 8 to 10 cm$^{-1}$, similar to findings in earlier studies (Houze et al. 1979; LP82), which indicated that $\lambda$ values did not decrease below 8 to 10 cm$^{-1}$. The $\lambda_F$ values in this range resulted from poor curve fits, as ascertained from the correlation coefficients for the curve fits.

For individual spirals, the $\lambda$ versus $T$ values and the $\lambda_F$ versus $T$ curves fell along nearly straight lines, with slopes ($d\lambda/dT$ or $d\lambda_F/dT$) that were within a factor of two of each other over all cases. Within loops of individual spirals, the $\lambda$ or $\lambda_F$ values usually fluctuated by, at most, $\pm 50\%$—far less than the changes noted over the course of a spiral (see insert, Fig. 12b). The $\lambda$ values conformed quite closely to the $\lambda$ equation from Ryan (2000) for midlatitude ice clouds that has been converted to an exponential form here:

$$\lambda(\text{cm}^{-1}) = c_0 \exp^{-(\lambda_F/C)},$$  \(8\)

where the $c_0$ and $c_1$ values adapted from the coefficients in Ryan are 12.1 cm$^{-1}$ and $-0.0564$, respectively, and the curve is plotted in Fig. 12a. Coefficients $c_0$ and $c_1$ were derived from fits to the median TRMM values of the distribution of $\lambda$ versus $T$ and $\lambda_F$ versus $T$ shown in Figs. 12a and 12b, along with curves fitted to the $\pm 1\sigma$ values. (The data from the outlying 990822 case was omitted from the fitted dataset, and two curves were fitted to the $\lambda_F$ versus $T$ data.) Curves representing these equations are plotted in Figs. 12a and 12b and are listed at the bottom of Table 3. In and below the ML, $\lambda$ and $\lambda_F$ values again increased, in much the same way as was shown for $\lambda$ values by Houze et al. (1979).

We can assess how accurately $T$ would have predicted $\lambda_F$ by using the TRMM temperatures in the spirals and comparing the predicted to measured $\lambda_F$ (Fig. 13b). As is shown in the figure, this approach to predicting $\lambda_F$ leads to considerable scatter, especially for the outlying case on 990822, where virtually all of the points deviate widely from the line in Fig. 13b—thus, $T$ is not an ideal predictor of $\lambda_F$ (or $\lambda$) values. A similar interpretation results if the Ryan (2000) relationship is used to estimate $\lambda$.

The $N_0$ and $N_{\text{of}}$ values also decreased systematically with increasing $T$ (Figs. 12c and 12d). However, there is no strong dependence of $N_0$ or $N_{\text{of}}$ on $T$, which is why Ryan (2000) also found no clear relationship between $N_0$ and $T$, only noting that “the parameter $N_0$ is a less systematic function of $T$ with local geographic variations being evident.” Furthermore, there is considerably more scatter than was found for $\lambda$ and $\lambda_F$, especially over individual loops, where $N_0$ or $N_{\text{of}}$ often varied by up to one or two magnitudes (insert, Fig. 12d).

Since IWC is proportional to $N_0$ and $N_{\text{of}}$ (section 4c), the variability of the $N_0$ and $N_{\text{of}}$ represents IWC variability, and indicates that there are large fluctuations in IWC across the loops of the spirals.

The correlation coefficients ($r$) for the exponential fits (Fig. 12e) were generally high for $T$ values between $-35^\circ$ and $-5^\circ$C but not outside of this range. For $\lambda$ values above 80 cm$^{-1}$ or below 15 cm$^{-1}$, the quality of the exponential curve fits decreased. Nevertheless, the $r$ value averaged over all exponential fits was 0.96, signifying that the exponential fits were quite good. The gamma distribution fits produced even better correlation coefficients (not shown) with an average $r$ value of 0.98, and eliminated the problem areas at high and low $\lambda$.

At the larger values of $\lambda_F$, the $\mu$ tended to have positive values (subexponential distributions), whereas at the lower values of $\lambda_F$ $\mu$ had negative values (Fig. 13c; superexponential distributions). Fluctuations in the $\mu$ values during the loops of individual spirals were of
order of 1.0 (insert, Fig. 12f), signifying that there was considerable variability in the shape of the PSD in small sizes. The $\mu$ values were close to $-1$ in the range $25 < \lambda < 70$ (Fig. 13c), which is why the correlation coefficients for the exponential were relatively high in this range. The exception was noted on 990822, where $\mu$ values fell below $-1$. The values of $\mu$ were highly correlated with both
Incomplete gamma function:

$\text{Simplified equations for Kinematic viscosity:}$

$\text{Effective density:}$


term in Eq. (3) and reduce the number of unknown variables in Eq. (3) to two. The fits were derived with and without the data for the 990822 case, with little difference found.

An indirect relationship was found between the max-
imum measured particle size $D_{\text{max}}$ and $\lambda$ or $\lambda_T$ (Fig. 14). At least two particles were required in a given HVPS size bin to find a $D_{\text{max}}$. The $D_{\text{max}}$ at high $\lambda$ or $\lambda_T$ (low $T$) values were several millimeters and at low values were 1 cm or above. Curves fitted to the mean and standard deviation values are indicated in the figure and listed at the bottom of Table 3, with little difference found with and without the inclusion of the 990822 data. Extrapolation of the $D_{\text{max}}$ curve in Fig. 14a to 2 cm or above returns $\lambda$ values of only 6 or 7 cm$^{-1}$. We speculate that the absence of $\lambda$ values of less than 8 or 9 cm$^{-1}$ in earlier studies is due to a rarity of aggregates larger than 2 cm.

The $N_t$ and $\lambda$ or $N_{g0}$ and $\lambda_T$ values were highly correlated for individual spirals (Figs. 15a and 15b) and tended to decrease from large values at the top of the spirals to small values in the upper parts of the ML (indicated by large circles in each panel). Broadening of the PSDs with distance below cloud top by aggregation and with a corresponding decrease in $N_t$ or $N_{g0}$ by depletion of the smaller particles can account for this trend, although there are issues related to whether evolution of small particles was actually being observed during the Lagrangian spirals. The increase in $D$ by diffusional growth is very slow for large particles even if the environment was supersaturated with respect to ice and cannot account for these observations.

The 0°C level was denoted by a marked change in the trend of the $N_t$ versus $\lambda$ or $N_{g0}$ versus $\lambda_T$, points with temperature (Figs. 15a and 15b). Between 0° and 1.5°C, corresponding to the first several hundred meters, the $\lambda$ or $\lambda_T$ values decreased slightly, reflecting slight increases of $D_{\text{max}}$ and decreases in the total crystal concentration (Figs. 4 and 5; 990819, 990830, and 990911 cases). Broadening in the large end of the PSDs is consistent with previous observations by Yokoyama (1985) and Willis and Heymsfield (1989), who reported that aggregational growth continued several hundred meters into the ML. The decrease in $N_t$ or $N_{g0}$ is only partially accounted for by ice particles melting to sizes below the 2D-C detection threshold because particles of sizes of 50 μm and below have high densities and do not change their $D$ values much by melting. Most of the decrease is attributable to depletion by aggregation.

The lower part of the ML was characterized by a marked change in the trend of the $N_t$ versus $\lambda$ or $N_{g0}$ versus $\lambda_T$, points with temperature (Figs. 15a and 15b). Between 0° and 1.5°C, corresponding to the first several hundred meters, the $\lambda$ or $\lambda_T$ values decreased slightly, reflecting slight increases of $D_{\text{max}}$ and decreases in the total crystal concentration (Figs. 4 and 5; 990819, 990830, and 990911 cases). Broadening in the large end of the PSDs is consistent with previous observations by Yokoyama (1985) and Willis and Heymsfield (1989), who reported that aggregational growth continued several hundred meters into the ML. The decrease in $N_t$ or $N_{g0}$ is only partially accounted for by ice particles melting to sizes below the 2D-C detection threshold because particles of sizes of 50 μm and below have high densities and do not change their $D$ values much by melting. Most of the decrease is attributable to depletion by aggregation.

The lower part of the ML was characterized by an increase in the $N_t$ and $N_{g0}$ values (from the large circle to large triangle symbols in Figs. 15a and 15b). These increases suggest that there is little breakup of partially melted individual aggregates to multiple particles in this region, as the total concentration, from $N_t = N/\lambda$ (for an exponential; Sekhon and Srivastava 1970), remained essentially constant. The increases in the $\lambda$ or $\lambda_T$ values in the lower part of the ML resulted from a dominance of melting by the larger, lower-density aggregates. At this height in the ML, most of the smaller ice particles have melted, thus, their size is basically unchanged. The diameters of the larger, relatively low-density aggregates changed significantly. Thus, the $\lambda$ and $N_t$ or $N_{g0}$ values increased slightly.

### b. Parameterizations of the ice particle shapes

The area ratio is an important property in our estimates of ice particle density given by Eq. (2) and in parameterizing area-related properties (terminal velocity, extinction) of the PSDs. The $A_t$ is expressed as a power-law function of $D$: $A_t = aD^b$. The coefficients $a$ and $b$ can be derived through curve fits to the $A_t$ versus $D$ data from the imaging probes, collected over 1-km intervals during the spirals. As shown in Figs. 16a to 16d, the $a$ and $b$ coefficients are a strong function of altitude and temperature, and not surprisingly tend toward spheres ($a = 1$, $b = 0$) in the melting layer. The height trends conform to the tendencies found for mid-latitude cirrus clouds by Heymsfield and Miloshevich (2003), who attributed the changes in height or temperature to aggregation and sublimation. Points for the 990822 case, shown as grey symbols in Fig. 16, differ somewhat from those for the other cases. Given that the $\lambda$ values decrease downward, it can be inferred that the height and temperature tendencies are consistent with changes in $\lambda$. This result is confirmed in Fig. 16e, which shows the changes in the coefficient $a$ with $\lambda$. A nearly monotonic relationship is found between $b$ and $\lambda$, or between $a$ and $b$ (Fig. 16f), with relatively little scatter. Curve fits between $a$ and $\lambda$, and $a$ and $b$, are shown in Table 3, both to the mean values and standard deviations to indicate the extent of the scatter in the values.

### c. Parameterizations of the moments of the PSDs

The set of equations used to calculate the bulk properties of the particle population, including the IWC, $R$, $Z$, $V_m$, $V_z$, the extinction coefficient $\epsilon$, and the effective radius $r_e$, are shown in Table 3, with the symbols identified in appendix A. They use as input the values from the relationship between the various properties of the gamma distributions and temperature reported in section 4a; these equations are listed at the bottom of Table 3. The equations make use of PSDs represented by gamma distributions [Eq. (1)], which provides an accurate representation of the TRMM PSDs, although they can readily use exponential if the value of $\mu$ is taken to be 0. The equations listed under “full equations” in the table are general and can use many of the earlier measurements of the properties of exponential size distributions for ice particles reported later in section 5. Particles below the 2D-C probe detection threshold are included implicitly through the use of the gamma distributions.

---

1 Decreasing $\lambda$ or $\lambda_T$ values and hence increasing spectral breadth will generally lead to an increase in $D_{\text{max}}$. The measured $D_{\text{max}}$ also depends on the probe sampling volume and $N_t$ or $N_{g0}$ (which displace the PSDs upward or downward), and this relationship embodies these factors implicitly.
but the accuracy in these sizes cannot be estimated. The resulting errors might have a major affect on the lower moments (primarily on total concentration and cross-sectional area) of the distributions but not on the higher moments (IWC or dBZ).

The IWC can be expressed as

$$\text{IWC} = \frac{\pi}{6} k N_0 \int_0^{D_{\text{max}}} A_4 D^{(m+n+\alpha)} e^{-\lambda D} \, dD,$$

(9)

using the coefficients $\alpha$, $k$, and $n$ identified in section 4a and at the bottom of Table 3. The resulting solution to the integral of Eq. (9) is shown in column 2 of Table

Fig. 12. Fit parameters for exponential (left) and gamma (right) distributions as functions of $T$ from 1-km PSDs: (top) $\lambda$ and $\lambda_r$, fit from Ryan (2000), and to the TRMM data in left panel, and to TRMM data in right panel, shown with solid line. Fits exclude 0822 case. (middle) $N_0$ and $N_{0r}$. (bottom left) Correlation coefficient. (Bottom right) $\mu$ versus $T$. Different colors represent different days. Inserts in (b), (c), (d): data for 0911 case.
3 for integration from 0 to $\infty$ (complete gamma function). We also integrated this equation over the range 0 to $D_{\text{max}}$ (incomplete gamma function), with a generic solution shown at the bottom of the table. For given $N_{0\Gamma}$ and $\lambda_{\Gamma}$ values, IWCs returned from the complete and incomplete gamma functions differed insignificantly. A simplified relationship derived using the values of $\alpha$, $k$, and $n$ are presented in column 3.

The relative accuracy of the estimates of IWC using the exponential and gamma PSDs is shown in Figs. 17a and 17b. The numerators given in each of these panels were derived by taking the IWCs, as calculated from Eq. (9), using the fitted $N_{0\Gamma}$ and $\lambda$ or $N_{0\Gamma}$ and $\lambda_{\Gamma}$ values and the TRMM average $A_{\Gamma}$ versus $D$ relationship. The denominators are the IWCs derived directly from the PSDs and measured $A_{\Gamma}$ values. Using exponential size distributions to derive IWC values leads to significant departures in the ratios from unity. Dramatic improvements were noted through the use of gamma distributions, yielding values generally close to unity. Therefore, the gamma distributions provide a much better representation of the PSDs than do the exponential.

If IWC is known from measurements or prognosed in a general circulation model (GCM), the corresponding $N_{0\Gamma}$ and $\lambda$ or $N_{0\Gamma}$ and $\lambda_{\Gamma}$ values can be readily found. The relationship between $\lambda$ and $T$ or $\lambda_{\Gamma}$ and $T$ at the
to the distribution of ice mass with size, can be found by modifying the results presented in Mitchell (1991) and is a function of \( \lambda_\gamma \), \( \mu \), and the coefficients in the exponent of \( D \) in Eq. (9). The equation is presented in Table 3.

The radar reflectivity \( (Z) \) can be calculated from

\[
Z = \int_0^{D_{\text{max}}} N(D)D^\alpha dD, \tag{10}
\]

where \( D_{\text{max}} \) is the melted equivalent diameter, found using the expression for \( \rho_s \) as given in Eq. (2). Equation (10), for \( Z \), is analogous to Eq. (9) for IWC, with the results shown in Table 3. Mie scattering effects are small at wavelengths above 5 cm and are estimated for a wavelength of 2.1 cm in Table 3. As with IWCs, the gamma distributions provide a better match to the values calculated from the PSDs than do the exponential (see Figs. 17d and 17e). Given values for \( Z \) and \( T, N_o \) or \( N_{\text{eq}} \) can be found in a similar manner to that described for calculating IWC. However, this method may lead to very large errors (Fig. 17f). The equivalent radar reflectivity dBZ, listed in Table 3 is derived assuming equivalent water spheres (Smith 1984).

The precipitation rate \( (R) \) was calculated by incorporating the following \( A_\gamma \)-dependent \( V_r \) relationship from HO2 inside the integral in Eq. (9):

\[
V_r = a_r \left( \frac{4gk\rho_s^{-1}}{3\rho_o} \right)^{b_r} \mu^{(1-2b_r)}D^{(3+b(n-1)+a(2b_l-1))}
= CD^\gamma, \tag{11}
\]

where \( \nu \) is the kinematic viscosity of air, \( \rho_o \) is the density of air, and \( a_r \) and \( b_r \) are the coefficients used in fall velocity relationships of the form introduced by Mitchell (1996) and recently modified by HO2 to account for aggregates. To solve Eq. (11), only one set of \( a_r \) and \( b_r \) coefficients can be used at this time to represent all sizes. We carefully examined the use of appropriate \( a_r \) and \( b_r \) coefficients, and selected those shown in Table 3. The integrated equations for \( R \) appear in Table 3.

Equations for \( V_z \) and \( V_m \) also follow the development used for Eqs. (9) and (11). The \( V_z \) given by Eq. (11) is included in the integral in Eq. (9) and normalized by the IWC to obtain \( V_m \); \( V_z \) in Eq. (11) is incorporated in the integral in Eq. (10) and normalized by \( Z \) to obtain \( V_m \). Solutions of these equations appear in Table 3. Note that these fall velocity expressions do not depend directly on \( N_0 \) but do depend on \( \mu \) and thus indirectly on \( N_0 \). Also note that different sets of the \( a_r \) and \( b_r \) coefficients are used for \( V_m \) and \( V_z \) resulting from different parts of the PSD contributing to each. The \( V_m \) equation predicts values that are accurate to \( \pm 20\% \) (mostly slight overestimates) for \( D_{\text{max}} \) above 0.03 cm (>90% of the points) and the \( V_m \) equation predicts values that are accurate to \( \pm 20\% \) for \( D_{\text{max}} \) from 0.02 to 0.2 cm (83% of the points).
Given $V_z$ and $Z$ values, the $V_z$ expression can be used to derive $\lambda_r$, $N_{ef}$, and $\mu$ values. With the use of $Z$ or IWC, the full properties of the exponential PSDs are known. Vertically pointing Doppler radar data, with some time averaging to remove small-scale vertical motions, can therefore be used to obtain direct measurements of $\lambda_r$ and $N_0$ without the need to make assumptions about the temperature dependence of $\lambda_r$.

The total cross-sectional area of a population of particles ($A_c$) is given by

$$A_c = \frac{\pi}{4} \int_0^{D_{\text{max}}} N(D) A_c D^2 \, dD,$$

and the extinction coefficient in visible wavelengths (when particles are large compared to the wavelength) is calculated from $\kappa = 2A_c$. Solutions for these integrals are listed in Table 3, where the $a$ and $b$ coefficients can be taken directly from either the relationship to $\lambda$ shown in the bottom of Table 3, or from the average values of each coefficient listed in the table.
The effective radius \( r_e \), a parameter that characterizes the radiative size of a population of particles, can be written, according to Fu (1996), as

\[
r_e = \frac{\sqrt{3} \text{IWC}}{3 \rho_r A_e},
\]

where \( \rho_r = 0.91 \text{ g m}^{-3} \). Solution of this equation derives from Eqs. (9) and (12) and is given in Table 3. For the TRMM spirals, the absence of measurements from small particles is not thought to significantly affect the \( r_e \) values. Heymsfield and McFarquhar (1996), who did have measurements of size spectra down to about 10 \( \mu \text{m} \) in size, showed that the \( r_e \) at the warmer temperatures in tropical anvils were dominated by the larger particles.

5. Discussion

Lagrangian spiral-type descents and ascents have been used previously to examine the evolution of PSDs in mid-latitude layered and frontal clouds by Passarelli (1978 hereafter P78), LP82, Gordon and Marwitz (1986, hereafter GM86), and F99. In these studies, values for \( T \) at cloud top (\(-30^\circ \text{C}\)) and base (\(2^\circ \text{C}\)) were comparable to those of the TRMM observations. PSDs were measured using 1D-P (P78, LP82); or 2D-C and 2D-P (GM86); or the 2D-C and HVPS probes (F99). Diffusional and aggregational growth predominated in each of the spirals.

The parameters \( N_0 \) and \( \lambda \) of the exponential fitted to their PSDs by each of the authors are plotted in Fig. 18. More scatter was evident in the \( N_0 \) versus \( \lambda \) values.

Fig. 16. Coefficients \( a \) and \( b \) in the relationship \( A_r = aD^b \) as derived by fitting the \( A_r \) vs \( D \) data from the imaging probes. (a), (b) Height dependence. (c), (d) Temperature dependence. (e) Dependence of \( a \) on \( \lambda \). (f) Relationship between \( a \) and \( b \) coefficients. Points for the 0822 case in gray.
than we found for the exponential in our spirals because the probe sample volumes and upper size detection limits in all but the F99 study were significantly smaller than those used in our study. For reference, the $T$ values at cloud top and base are shown in each panel, and the approximate envelope of the $N_p$ versus $\lambda$ values from the TRMM observations are given in the lower right panel. Also plotted in two of the panels are the $\lambda$ values
The $N_0$ vs $\lambda$ points measured during Lagrangian spirals by GM86, LP82, P78, and F99. Unless otherwise noted, data are from descents. The listed values in GM86 (2D-C probe) and the values extracted from the graphical plots in P78 and LP82 (1D-P probe) are plotted. Temperatures at top and bottom of each spiral are shown. The dotted lines show IWCs calculated using the BF95 $\rho_0 - D$ relationship. The dashed lines in the lower right panel show an envelope of the observations from TRMM. The lines labeled “Ryan” use the $\lambda - T$ relationship from Eq. (8) to predict $\lambda$ from $T$, plotted at the measured value of $N_0$.

derived from the measured $T$ from the TRMM observations (bottom of Table 3).

The following similarities and differences may be noted between these and the TRMM observations as shown in Fig. 15a.

1) The $\lambda$ values generally fell in the range 10 to 50 cm$^{-1}$, similar to the TRMM observations over the same $T$ range.

2) The trends in the $N_0$ versus $\lambda$ values were similar to those we observed. One of the GM86 and two of the LP82 cases first showed an increase in the $N_0$ value with a decrease in the value of $\lambda$ at cloud top. This pattern was attributed by the authors to particles growing by diffusion into the size-detection threshold of the 1D-P and 2D-C probes and to ice nucleation.

3) The TRMM parameterization does a reasonably
good job of predicting the value of \( \lambda \) when \( \lambda \) decreases with \( T \), at \( T \) below 0°C, and when sublimating bases are not present.

4) The \( N_0 \) values for most, but not all, cases were comparable to the TRMM \( N_0 \). Above 0°C, \( N_0 \) values for the two GM86 cases and those from the TRMM observations corresponded closely. It is in this region that the probe sampling volume issues are probably minimized. Values for \( N_0 \) for several of the LP82 and P78 cases were below those measured during TRMM. We believe that this results from an underestimate of the concentrations of crystals in the smaller size range of the 1D-P, a conjecture confirmed by comparisons in GM86 of \( N_0 \) values from the 2D-C and 2D-P probes. As reported in GM86, the ratio \( N_0(2D - P)/N_0(2D - C) = 0.21 \), whereas the ratio \( \lambda(2D - P)/(2D - C) = 0.72 \); thus, \( N_0 \) changes appreciably but \( \lambda \) does not.

5) The range of IWCs sampled from these various spirals was comparable to those from the TRMM spirals. The lines of constant IWC in Fig. 18 were derived from IWC(\( g \ m^{-3} \)) = (\( \pi/6 \))(\( N_0 \eta \Gamma(4 + \eta) \times 10^6 \))/(\( \lambda(4 + \eta) \)), which comes from Sekhon and Srivastava (1970), with \( y = 0.0056 \) and \( \eta = -1.1 \) taken from Brown and Francis (1995, hereafter BF95). For a given constant value of IWC and a value of \( \lambda \), \( N_0 \) values were derived and the lines of constant IWC were plotted.

6) Most importantly, the gamma functions would have provided better estimates of the PSDs for \( \lambda \) below 20 to 30 cm\(^{-1}\).

Sekhon and Srivastava (1970) derived the following relationships for snowfall collected at the ground:

\[
N_0 = 2.50 \times 10^{-2}R^{-0.94} \text{ (cm}^{-4}\text{)},
\]

\[
\lambda = 22.9R^{-0.45} \text{ (cm}^{-1}\text{)},
\]

where \( N_0 \) and \( \lambda \) are for the resulting melted PSDs. Although no direct relationship between \( N_0 \) and \( \lambda \) was derived, this relationship can be estimated by eliminating \( R \) in Eq. (11), yielding

\[
N_0 = 3.61 \times 10^{-5}\lambda^{2.09}.
\]

We could have developed a more accurate relationship than that given by Eq. (15) if the original \( N_0 \) versus \( \lambda \) data points were available. In Fig. 19, Eq. (15) is plotted over the range of \( R \) reported in that study. Also shown in the figure are the \( N_0 \) versus \( \lambda \) points for the 990822 spiral and the corresponding “melted” \( N_0 \) versus \( \lambda \) points. These were obtained by fitting exponential curves to the concentration versus melted equivalent diameters [from \( \rho_e \) in Eq. (2)] for each PSD.

Our melted \( N_0 \) versus \( \lambda \) points differed somewhat from points along the curve given by Eq. (15), possibly for the following reasons. At \( T \) above approximately \(-5^\circ\text{C} \), the \( \lambda \) values for the unmelted and partially melted spectra remain relatively constant at 9 cm\(^{-1}\). This regime could not be discerned from the small number of points used in the Sekhon and Srivastava analyses. Furthermore, partially melted snow and/or raindrops were included in about half of the samples. Inspection of Fig. 11 shows that for a narrow range of \( T \) values between...
0° and 3°C (for each spiral within this range, the $R_\lambda$ values were approximately constant), the $\lambda$ values varied by a factor of 2–2.5. Thus, for partially melted snow, there is no unique $R$ versus $\lambda$ relationship, and the data points within the region of melting are suspect.

MH97 recently developed a parameterization for the PSDs of tropical ice clouds (produced by outflows of deep convection) as functions of $T$ and IWC, with stated ranges of validity $-70 \leq T \leq -20$°C and for $10^{-4} \leq$ IWC $\leq 1$ g m$^{-3}$. The intention of McFarquhar and Heymsfield was to produce reliable measures of both IWC and cross-sectional area. The authors emphasized in this paper the small particles that often dominate cloud extinction and optical depth. The PSDs, which were measured from about 10 $\mu$m to a size larger than 1 mm, depending on the particle concentration (Table 1), were converted to $N(D_e)$ for $D_e \leq 1000$ $\mu$m through use of mass–diameter relationships. They were then represented as the sum of a first-order gamma function, describing ice crystals with $D_e \leq 100$ $\mu$m, and a log-normal function, describing larger crystals. The percentage of the IWC comprising small particles, $D_e < 100$ $\mu$m, decreased with increasing IWC values. For IWCs of order 0.001 g m$^{-3}$, this portion from small particles was 80%, whereas for IWCs of order 0.1 g m$^{-3}$, this fraction decreased to less than 30%.

We fitted the PSDs generated by the MH97 parameterization to gamma distributions using Eqs. (4) to (7) to permit a qualitative comparison with our observations. The range of temperatures and IWCs at which the CEPEX and TRMM observations overlapped were examined: $-20$° to $-50$°C and 0.01 to 1 g m$^{-3}$. Throughout this range, single gamma distributions did a good job of representing the two curves used for the MH97 parameterization, reliably capturing the inflections in the curves.

It was difficult to compare the two sets of observations directly, because in MH97 the parameterization was derived in terms of the melted equivalent diameter, which involved assumptions about the particle density that differed from those made in this paper. Nevertheless, drawing upon the results of the comparison of $\lambda$ and the melted equivalent $\lambda$ in Fig. 19, we were able to note similarities and differences in $\mu$ and $\lambda_T$. Whereas our observations indicated that $\lambda_T$ and $\mu$ were primarily functions of $T$, the same coefficients using the MH97 parameterization were primarily functions of IWC, and only somewhat functions of $T$. The range of $\mu$ were comparable, $-1$ to 2.5, for the fits to the MH97 parameterization, whereas the $\lambda_T$ values from the parameterization were larger than would be expected by melting our spectra. More direct comparisons of the CEPEX and TRMM results will be the subject of a future study.

6. Summary and conclusions

In this study, we have examined the characteristics and evolution of the PSDs in stratiform precipitating regions and anvils during the TRMM field campaigns in Florida, Brazil and Kwajalein, Marshall Islands, emphasizing data from Kwajalein because the microphysical probes used for those observations performed better.

Cloud layers were sampled through the use of slow Lagrangian spiral descents, most of which commenced near cloud top and ended near cloud base (or at temperatures above 0°C). This flight pattern facilitated investigation of how the PSDs changed in the vertical, both within the ice regions and in the melting layer. The patterns provided information on the vertical distribution of cloud microphysical properties, although the profiles could have changed temporally in a way partially characterized using radar data over the course of the spirals. While our Lagrangian spiral descents are far from perfect in assessing the evolution of particles in the vertical and in characterizing the properties of particle size distributions because of horizontal variability and temporal evolution, we believe that the results are a step toward increasing the understanding of how tropical ice cloud properties vary in the vertical.

The use of new instrumentation, allowing more accurate measurements of the concentrations of larger particles and better definition of particle habits, has provided a dataset that is more complete than has been previously available. The following summarizes the main findings:

- Relatively large particles were measured at cloud top, from 2 mm (990911) to 6 mm (990819, 990830), even at $T$ values as low as $-50$°C. Such large particles have not been observed near the tops of layer clouds in the past. Particles of these sizes fall rapidly, above 1 m s$^{-1}$. Rapid fallout, coupled with the particles’ increased growth downward through aggregation, which will generally further increase their fallspeeds, would indicate that there is rapid transport of moisture from upper tropospheric levels to mid and lower levels.
- With distance below cloud top, the PSDs broadened, with some particles in the upper part of the ML reaching sizes exceeding 1 cm. Aggregation, which produced this growth, also led to depletion of particles smaller 0.1 cm, conforming to the observations of F99 and others of how the aggregation process works.
- Changes in the characteristics of the PSDs were quantified through the use of gamma distributions of the form $N = N_0 D_\lambda e^{-D_\lambda}$ fitted to the PSDs, using a technique that matches the errors in the first, second, and sixth moments of the distributions. Exponential ($\mu = 0$) were also fitted to the PSDs. From cloud top to cloud base, or the top of the ML, the $N_0$ and $\lambda_T$ values were found to decrease monotonically. A similar tendency was observed for the exponential fits, with the results showing remarkable similarity to results from earlier studies of deep ice clouds as well as of cirrus clouds. Horizontal inhomogeneities over the course of individual loops of the spirals is manifested primarily in variations in $N_0$ or $N_\lambda$. The $\mu$ changed systemat-
ically with height, from positive (subexponential) in the upper parts of the clouds to negative (superexponential) in the lower parts of the clouds. The $N_{\text{air}}$ and $\mu$ values were highly correlated, and an expression developed between the two parameters eliminated one unknown in the gamma distribution form.

- The $N_{\text{air}}$ values first decreased by about one order of magnitude near the top of the ML, whereas the $\lambda_{\text{f}}$ values decreased only slightly. Both the $\lambda_{\text{f}}$ and $N_{\text{air}}$ values then increased abruptly in the lower part of the ML until the base was reached.

- The $\lambda_{\text{f}}$ and $\lambda$ values were generally a function of $T$, and curves were fitted to the data, although there was considerable scatter. The curve was similar to that reported by Ryan (2000) for midlatitude synoptically and frontally generated ice clouds. We showed that the $\lambda_{\text{f}}$ versus $T$ relationship could be used to estimate $N_{\text{air}}$ when either IWC or dBZ can be measured, although errors in $N_{\text{air}}$ of up to a factor of three might result from this method. However, this extent of error is no worse than errors resulting from the parameterizations of the PSDs used in other studies. More accurate estimates may be possible through the use of vertically pointing Doppler radar data.

- Exponential curves fitted to our PSDs for tropical clouds that formed in association with convective forcing had $\lambda$ and $N_{\text{air}}$ values that were similar to earlier studies for midlatitude clouds formed primarily through synoptic forcing. The monotonic relationship found between $N_{\text{air}}$ and $\lambda$ or $N_{\text{air}}$ and $\lambda_{\text{f}}$ may be applicable to a wide variety of cloud types and geographical locations.

- We developed general expressions between a number of macroscale and remote sensing variables (e.g., IWC, $Z$, $V_{\text{m}}$, $V_z$, $R$, $\varepsilon$, $r_c$) and $N_{\text{air}}$ and $\lambda_{\text{f}}$. These expressions reduce to exponential if $\mu$ is taken to be zero. The free variable in these expressions is $N_{\text{air}}$, a term that will largely compensate for variations in IWC or dBZ, at a given temperature. Terms needed to derive the coefficients in the relationship—specifically the dependence of ice particle density on size—were derived using some new techniques. Because these expressions are general, they can be modified as new information on ice particle density becomes available.

- It was shown that the variable $V_z$ is fundamentally a function of the spectral slope $\lambda$ or $\lambda_{\text{f}}$. The distribution of $V_z$ with dBZ, we examined in the stratiform regions in appendix B provided implicit information on the distribution of $\lambda$ and $\lambda_{\text{f}}$ with dBZ. A similar analysis of ARMAR radar observations from three days from the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) cirrus cloud observations, two of which appear in Heymsfield et al. (1998), show a similar $V_z$ vs dBZ, pattern, suggesting that the distribution of $\lambda$ with dBZ is similar between the two datasets.

- Although a plethora of ice particle shapes were observed—extending all the way from complex rimed crystals and rimed aggregates to pristine particles—much of the variability could be explained by examining the Doppler radar data and quantified through use of the area ratio parameter. Rimed ice particles were sampled near deep convective clouds with sustained convection as evidenced by the presence of deep and horizontally extensive anvils. Small (sub millimeter), pristine particles were observed in clouds formed by more transient convection, with cloud-top temperatures controlling the habits: at low values of $T$, cirrus-type crystals, in some instances, evolved into the capped columns that usually reflect growth at warmer temperatures; at high values for $T$, planar-type crystals and capped columns dominated. Most particles of the larger sizes were aggregates. Relationships between the ice particle area ratio and diameter were used to describe the changes in the ice particle shapes with height, temperature, and $\lambda_{\text{f}}$.

- Our PSDs, after melting them to obtain equivalent water PSDs and then fitting exponential curves to them, compared reasonably well with those of Sekhon and Srivastava (1970). We surmised that any differences resulted from the few samples (only 14) that were available to those researchers to capture the $\lambda$ versus $N_{\text{air}}$ dependence in the critical regime where $\lambda$ values asymptote to about 9 cm$^{-1}$. Also, about half of their samples were collected in the ML, where no direct relationship is evident between $\lambda$ and $N_{\text{air}}$ values. Although we could not directly compare our gamma size distributions to the tropical cirrus PSD parameterization represented in terms of the melted equivalent diameter for $T < -20^\circ$C by MH97, a cursory examination showed that these have similar characteristics. The latter parameterization is clearly superior in low-IWC regimes and at low temperatures, whereas the parameterizations we developed are more flexible, are based on better measurements of the size distributions in larger sizes, and are better suited to the warmer temperatures and higher-IWC regimes.

- Given the range of conditions sampled, the results of our study apply to physically thick stratiform precipitation regions and anvils with temperatures from 3°C to about $-40^\circ$C. The observations apply to clouds falling into the category of “deep convection” according to the ISCCP optical-depth and height-related cloud classification scheme. The observations also apply to the range of IWCs from 0.01 to 1 g m$^{-3}$, and radar reflectivities, as measured from overlying aircraft, in the range of 0 to 25 or 30 dBZ.

The expression that we developed between IWC and the properties of the PSD [Eq. (9)] could have been substantially improved if direct measurement of IWC had been available. With direct measurements, assumptions that had to be made about ice particle density (the
coefficients $k$, $n$, and $\alpha$, and their variation within the ML) might not have been necessary. Also, questions about whether $\lambda_1$ depends on both temperature and IWC could have been addressed. Future direct measurements of IWC—along with PSD measurements from the probes—are needed.

In closing, we would like to point out that there was considerable horizontal variability throughout most of our Lagrangian spiral descents and that the melting layers associated with four of our spirals were not horizontally extensive or homogeneous as might be the case in tropical mesoscale convective systems. A comparison of the ARMAR $V_T$ versus dBZ, relationships from the KWAIEX and TOGA COARE datasets suggests that the observations apply to a broad range of tropical ice clouds. However, more tropical observations of PSD properties are clearly needed. We also want to point out that the TRMM satellite radar, which detects a minimum reflectivity of about 18 dBZ, would have seen some of the ice clouds we sampled on 990905 (TEFLUN-B), 990217 (LBA), 990819, and 990830 (KWAIEX). Our observations may therefore be useful in understanding the properties of the ice clouds and associated melting layers that the TRMM radar often detects.

Acknowledgments. This research was supported by the NASA TRMM Project Office through Grants NAG5-7743 and NAG5-9715. A portion of this research was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. The authors are grateful to Martin Brown and the UND Citation crew for their help over the course of this study, and Andy Detwiler and Rand Feind for use of their software to process HVPS data. The authors also wish to thank Sandra Yuter, Sharon Lewis, and two anonymous reviewers for their thorough reviews. Thanks go to Greg McFarquhar for allowing us to use his CEPEX parameterization code, and to Beverly Armstrong for editorial assistance.

APPENDIX A

List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Particle cross-sectional area; for example, the particle’s area projected normal to its fall.</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Total cross-sectional area of particle population ($\text{cm}^{-2}$).</td>
</tr>
<tr>
<td>$A_r$</td>
<td>Area ratio–particle area divided by area of circle with the same $D$.</td>
</tr>
<tr>
<td>$a, b$</td>
<td>Coefficient, exponent in the fit of the area ratio versus diameter data from 1-km imaging probe data.</td>
</tr>
<tr>
<td>$a_r, b_r$</td>
<td>Coefficients, exponents in Mitchell (1996) and H02 best number vs Reynolds number relationships.</td>
</tr>
<tr>
<td>$C$</td>
<td>Coefficient in the terminal velocity relationship.</td>
</tr>
<tr>
<td>$c_0, c_1$</td>
<td>Coefficient, exponent in equation relating $\lambda$ to $T$.</td>
</tr>
<tr>
<td>$D$</td>
<td>Maximum particle dimension, found by projecting its cross section onto a horizontal plane normal to its fall direction.</td>
</tr>
<tr>
<td>$D_m$</td>
<td>Melted equivalent diameter.</td>
</tr>
<tr>
<td>$D_{\text{max}}$</td>
<td>Maximum measured particle size in a given 10-s sample.</td>
</tr>
<tr>
<td>$F$</td>
<td>Parameter related to the gamma fitting function.</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration.</td>
</tr>
<tr>
<td>$\text{IWC}$</td>
<td>Ice water content.</td>
</tr>
<tr>
<td>$k$</td>
<td>Coefficient in equation for effective density.</td>
</tr>
<tr>
<td>$M$</td>
<td>Moment number for fitting function.</td>
</tr>
<tr>
<td>$m$</td>
<td>Ice particle mass.</td>
</tr>
<tr>
<td>$N$</td>
<td>Concentration per unit diameter as a function of $D$ ($\text{cm}^{-3}$).</td>
</tr>
<tr>
<td>$N_{i}$</td>
<td>Concentration in probe size bin $i$.</td>
</tr>
<tr>
<td>$N_{i0}$</td>
<td>Concentration intercept parameter, exponential, gamma distribution.</td>
</tr>
<tr>
<td>$n$</td>
<td>Exponent in effective density relationship.</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure (hPa).</td>
</tr>
<tr>
<td>$\text{PSD}$</td>
<td>Particle size distribution.</td>
</tr>
<tr>
<td>$p$</td>
<td>Parameter giving the moment number for gamma fit.</td>
</tr>
<tr>
<td>$R$</td>
<td>Precipitation rate (mm h$^{-1}$).</td>
</tr>
<tr>
<td>$r_e$</td>
<td>Radius used to describe the radiative properties of a particle population.</td>
</tr>
<tr>
<td>$r$</td>
<td>Correlation coefficient.</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature ($^\circ$C).</td>
</tr>
<tr>
<td>$V_T, V_m, V_Z$</td>
<td>Ice particle terminal velocity, mean mass-weighted, and mean reflectivity-weighted velocities of ice particle size spectra.</td>
</tr>
<tr>
<td>$y$</td>
<td>Coefficient in mass versus diameter relationship.</td>
</tr>
<tr>
<td>$Z, \text{dBZ}$</td>
<td>Radar reflectivity factor, equivalent radar reflectivity (dB).</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Exponent in effective density relationship.</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Extinction coefficient.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Exponent in mass versus diameter relationship.</td>
</tr>
<tr>
<td>$k$</td>
<td>Exponent in the terminal velocity versus diameter relationship.</td>
</tr>
<tr>
<td>$\lambda, \lambda_f$</td>
<td>Slope parameter of size distribution for exponential, gamma PSDs.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dispersion of gamma particle size distribution.</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity.</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Air density.</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>Effective ice particle density.</td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>Density of solid ice.</td>
</tr>
</tbody>
</table>
APPENDIX B

Estimation of Ice Particle Mass and Terminal Velocity

The ice particle mass—a necessary input into calculations of the IWC, dBZ, and the mass- and reflectivity-weighted fall velocities ($V_a$ and $V_z$)—can be derived from Eq. (1). As no measurements of the IWC were obtained to provide constraints on the estimated $\rho_r$ in Eq. (2), a comprehensive effort was undertaken to develop reliable estimates of $\rho_r$ and hence $m$. This effort involved three independent approaches.

1) We compared calculations of the terminal velocities with observations of snow crystal $V_a$ values at the ground, a meaningful test of the $\rho_r$ relationship because $V_a \propto \rho_r^{0.4}$ to $\rho_r^{0.8}$.

2) We compared the comprehensive set of dBZ and $V_z$ values from the ARMAR (nadir viewing) on the DC-8 with calculations of these variables from the PSDs on the same days. The DC-8 generally avoided convection and measurements in convective cells that might have confounded this comparison.

3) We compared calculations of rain PSDs, using as input snow PSDs near the top of the melting layer, with measured rain PSDs at the base of the ML during spirals. This method proved inconclusive, because of continued particle growth in the larger sizes and depletion in the smaller sizes.

Our goal was to find a single relationship between $\rho_r$ and $D$ across the full range of observed particle sizes to simplify the development of parameterizations of the PSDs in terms of macroscale variables (e.g., IWC) as presented in section 5. Three techniques (shown in Table B1) satisfied this requirement. The one-parameter approach ($\rho_r \propto D$; Table B1), employing the coefficients presented in BF95, fit direct measurements of IWC and applied to ice clouds when particles were relatively dense and up to several millimeters in size. We also tested the two-parameter “area ratio” ($A_r$) approach, in which $\rho_r$ is a function of $D$ and $A_r$ (H02). It is our belief—and supported by the observations by Hanesch (1999)—that there is inherent information on $\rho_r$ in the $A_r$. The $A_r$ two-parameter technique often reduces to a one-parameter technique because $A_r$ is usually approximately related to $D$ by a power law. The two sets of coefficients shown for the $A_r$ technique in Table B1 were developed for low $\rho_r$ [$A_r$ (I)], and for relatively high $\rho_r$ associated with bullet rosettes up to about 0.1–0.2 cm [$A_r$ (BR)]. A third technique, a hybrid of the one- and two-parameter techniques, was also attempted, as it captured the inherent information available in the two-parameter technique and the general decrease in $\rho_r$ with $D$, which is commonly found in transitions from single crystals at small sizes to aggregates at large sizes. For the hybrid technique, we used two sets of coefficients, consistent with earlier observations of aggregates at the ground (designated as H[I] and H[II] in the table.

From the images of some of the particles shown in Figs. 8–10 as well as and others not shown, some inferences about the $\rho_r$ may be made. Drawing upon observations in H01, the hexagonal plate and platelike crystals in the 400–600-μm range shown in Fig. 9, and larger than 800 μm in Fig. 15, have $\rho_r$ values of 0.03–0.05 g cm$^{-2}$. The capped columns in Figs. 8–10 have $\rho_r \approx 0.15$ g cm$^{-3}$, and the columns in Fig. 10 have $\rho_r \approx 0.07$ g cm$^{-3}$. Inspection of the particles smaller than 100 μm indicate that they are not solid ice spheres. The $\rho_r$ for the more complex, partially rimed crystal shapes cannot be ascertained from the images alone.

The $\rho_r$ values as a function of $D$ for the three techniques are plotted in Fig. B1a using the coefficients given in Table B1. Using the second and third approaches, we derived $A_r$ from $A_r = 0.4D^{-0.09}$, which represents an average relationship for the TRMM spirals. Use of the BF95 approach produced unrealistically large $\rho_r$ values below about 500 μm and too-small $\rho_r$ values above 0.5 cm. Use of the $A_r$ (I) technique resulted in intermediate $\rho_r$ values at small sizes and relatively large $\rho_r$ values at large sizes. The $A_r$ (BR) technique, plotted over the applicable range of sizes, yielded relatively large $\rho_r$. Using the two sets of coefficients (I) and (II) for the hybrid approach shown in Table B1 produced comparable results, with relatively large $\rho_r$ at small sizes and low $\rho_r$ at large sizes.

The $V_a$ was calculated as a function of $D$ using the $\rho_r$ from each approach. These calculated terminal velocities were then compared to a large set of $V_a$ mea-

<table>
<thead>
<tr>
<th>Technique</th>
<th>Equation</th>
<th>Designation</th>
<th>Coefficients</th>
<th>Simplified equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-parameter</td>
<td>$\rho_r = AD^a$</td>
<td>$A_r$</td>
<td>$a = 0.00561$</td>
<td>$\rho_r = 0.0182 D^{-0.225}$</td>
</tr>
<tr>
<td>Two-parameter</td>
<td>$\rho_r = k(A_r)^n$</td>
<td></td>
<td></td>
<td>$\rho_r = 0.029 D^{-0.465}$</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$\rho_r = k(A_r)^nD^a$</td>
<td>A$_r$(I)</td>
<td>$k = 0.09$</td>
<td>$\rho_r = 0.0067 D^{-0.508}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A$_r$(BR)</td>
<td>$k = 0.48$</td>
<td>$\rho_r = 0.0109 D^{-0.620}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H(I)</td>
<td>$k = 0.03$</td>
<td>$\alpha = -0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H(II)</td>
<td>$k = 0.07$</td>
<td>$\alpha = -0.5$</td>
</tr>
</tbody>
</table>

* See appendix B for discussion of nomenclature
measurements for snowflakes that fell to the surface in Japan at $T$ of $\approx -5^\circ$C (reported in Muramoto et al. 1993; Fig. B1b). The shaded region in the figure shows the $\pm 1\sigma$ bounds of the $V_t$ observed in that study; are consistent with observations by many others. We particularly plotted the data from the Muramoto study because these extend to somewhat smaller sizes. The $V_t$ were calculated from Eq. (11).

The calculated $V_t$ generally increased with $D$ (Fig. B1b), with less of an increase above about 0.4 cm, marking a change in the $a_r$ and $b_r$ (drag related) coefficients. The curve shown in the figure for BF95 data suggests that values in that study were $\rho_r$ are overestimated for aggregates in the small sizes and underestimated in the large sizes. The $V_t$ trends with $D$ for the $A_r$ technique suggest that the $\rho_r$ values were are overestimated for $D$ smaller than 0.05 cm using $A_r$(BR) and overestimated for $D > 0.5$ cm for AR(I). The $V_t$ trends with $D$ for both hybrid approaches agreed well with the measured $V_t$ for the larger sizes. The $V_t$ below about 0.1 cm for the H(II) technique appear to be larger than observed for aggregates.

As a means of evaluating the estimates of $m$ from Eqs. (1) and (2), we used the PSDs for all spirals and Eq. (1) to calculate the $\text{dBZ}_e$ ($\approx m^2$) and $V_Z$ (related both to $\text{dBZ}_e$ and terminal velocity), then compared the results to the same parameters measured by the ARMAR (nadir viewing) on the same days (Fig. B2). In the calculations of $\text{dBZ}_e$, 7.2 dB was subtracted from the reflectivities to account for the differences in the dielectric constants between water and ice. Note that there may
be some residual mesoscale ascent of order 10 cm s\(^{-1}\) just above the ML in these plots that is not averaged out. The mean values from ARMAR were obtained above the ML during those periods when the DC-8 was in level flight and in most instances avoided convection. The four panels in the figure show the values calculated using the three techniques for obtaining \( \rho_z \); the single-parameter technique \( \rho_z \approx D_z^2 \); here \( b \) is a power \( [n=0 \ 	ext{in Eq. (2)}] \); the \( A \) technique, \( \rho_z = ka^n [a=0 \ 	ext{in Eq. (2)}] \); and the hybrid technique with two sets of coefficients. (The explicit equations used to derive \( \rho_z \) from the average TRMM \( A \), versus \( D \) relationship are given in Table B1). Although the standard deviations of the \( V_z \) are fairly large, a systematic increase of \( V_z \) with \( \text{dBZ} \) is noted, but with some natural variability and some variability resulting from vertical motions.

Comparison of calculated and measured \( \text{dBZ} \) versus \( V_z \) indicates that when the particles were small and the \( \text{dBZ} \) and \( V_z \) were relatively low, the one-parameter technique, using the coefficients from BF95, produces results that underestimated \( V_z \); the \( A \) technique produced results that agreed moderately well with the radar data; and the hybrid (I) technique’s calculations agreed well with the data for both sets of coefficients. When relatively large particles were present, at large \( \text{dBZ} \) and \( V_z \), the one-parameter technique significantly underpredicted the \( V_z \); the \( A \) (I) technique significantly overpredicted the \( V_z \); and the two hybrid approaches produced reasonable \( V_z \) (I) and overpredicted the \( V_z \) (II).

From these comparisons, we conclude that the hybrid (I) technique appears to give the most reasonable results.

REFERENCES


Field, P. R., 1999: Aircraft observations of ice crystal evolution in an altostratus cloud. J. Atmos. Sci., 56, 1925–1941.


Stith, J. L., J. E. Dye, A. Bansemer, A. J. Heymsfield, C. A. Grainger,