Vertical Variability of Cloud Hydrometeors in the Stratiform Region of Mesoscale Convective Systems and Bow Echoes

by

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Abstract

During the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX), the NOAA P-3 research aircraft executed 17 spiral descents to the rear of convective lines to document the vertical variability of hydrometeors above, within, and below the stratiform melting layer. Ten spirals were behind lines that exhibited bowing at some stage in their evolution. Although quick descents on some spirals forced sampling of different particle zones, clear trends with respect to temperature were seen. For 16 spirals, the ambient relative humidity with respect to ice (RHi) ranged from 100±4% at temperatures between -10°C and the melting layer, but exhibited steady decreases below the melting layer to an average relative humidity with respect to water (RHw) of 77±15% at 9°C. In contrast, one spiral conducted on 29 June 2003 directly behind a developing bow echo had RHi averaging 85% at heights above the 0°C level and RHi further decreased below the 0°C level to a minimum RHw of 48% at 9°C.

Vertical profiles of particle shapes, size distributions (SDs), total mass contents (TMC), number concentrations (Nt), and parameters of gamma distributions fit to SDs were computed using optical array probe data in conjunction with measurements of radar reflectivity from the P-3 X-band tail radar. For spirals with humidity at or near saturation above the melting layer, melting particles occurred through about 300 m of cloud depth between 0 and 2 or 3°C. Above the melting layer, Nt, dominated by smaller crystals, decreased at 19±10% °C⁻¹, faster than the 10±7% °C⁻¹ decrease of TMC dominated by larger particles. Increases in numbers of crystals with D < 2 mm (N<2) and in the slope parameter (λ) with temperature also occurred. To the extent that in cloud heterogeneity did not complicate observed trends, these trends suggest aggregation dominated the
evolution of SDs. Observations on 29 June differ from other days and are explained by the unique position and timing of the spiral in sub-saturated air behind a developing bow. On 29 June the presence of an isothermal layer at 2.5°C suggested that sublimative cooling delayed the onset of melting. Ice at 7°C showed melting particles were present through 500 m of cloud depth. A slight decrease in $N_{-2}$, but no decrease in $\lambda$, with temperature suggested sublimation modified the impact of aggregation.

Sublimative cooling would only have been significant at the location of the 29 June spiral. For other spirals, evaporative cooling below the melting layer in sub-saturated regions was the most important diabatic processes in the stratiform regions at the time of the observations.
1. Introduction

Microphysical processes such as sublimation, melting and evaporation influence the structure and dynamics of mesoscale convective systems (MCSs). Biggerstaff and Houze (1991) and Braun and Houze (1994) showed that cooling associated with these processes provides enough negative buoyancy to drive downdrafts observed near the melting level in MCS transition zones. Braun and Houze (1996) also showed that the development of a rear inflow jet, a mesoscale circulation feature that flows from the rear of an MCS stratiform region forward and transports cool, dry air to lower levels, developed following the onset of strong sublimation and cooling at the back edge of a squall line observed on 10-11 June 1985. Their model showed that the strength of the jet was strongly influenced by the modeled microphysical processes.

Other modeling studies have also illustrated that incorporating microphysical processes, in particular those involving ice, are required to produce realistic stratiform areas behind MCSs (e.g., Gamache and Houze 1982, Rutledge and Houze 1987, Nicholls 1987, Fovell and Ogura 1989, Tao and Simpson 1989, Szeto and Cho 1994, Caniaux et al. 1995) and to explain the development and intensity of the rear inflow jet (Yang and Houze 1995). Sublimation and evaporation within the stratiform region can also generate strong subsidence and a wake low (Gallus 1996; Haertel and Johnson 2000). Despite these and other advances in the understanding of MCSs, processes leading to the extreme surface winds that accompany some MCSs remain poorly understood (Weisman 2001).

In order to validate hypotheses arising from model simulations about MCS morphology and severe wind generation in convective systems, information on the vertical and horizontal variability of the sizes, shapes and phases of hydrometeors is
required to quantify the contributions of sublimation, melting and evaporation to latent cooling and the dynamics of the stratiform regions of MCSs. The vertical profile of humidity and particle size distributions (SDs) impacts melting, sublimation, evaporation, riming and aggregation rates, which in turn modify the distributions themselves. The validity of assumptions about SDs in parameterization schemes for numerical models (Lin et al. 1983; Rutledge and Hobbs 1983; Straka and Mansell 2005) of MCSs is unknown because few observations of SDs exist. These assumptions affect simulated storms through dynamical effects associated with latent heating and cooling.

Unique data on the vertical variability of the size, shape and phase of hydrometeors in stratiform regions behind MCSs were obtained during the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX, Davis et al. 2004). During BAMEX, the Naval Research Laboratory (NRL) P-3 and the National Oceanic and Atmospheric Administration (NOAA) P-3 flew coordinated patterns, documenting the evolution of MCSs and bow echoes while sampling the area ahead of and behind convective lines (Wakimoto et al. 2004). In addition to making dual and quad-Doppler measurements (Jorgensen et al. 1996) of the convective lines and stratiform regions, the NOAA P-3 executed 17 spiral descents on 11 days to document the vertical variability of cloud microphysical structure in the stratiform regions behind the convective lines.

In this paper, vertical profiles of hydrometeor shapes, sizes, phases, and concentrations above, within, and below the melting layer of the stratiform regions of MCSs observed during BAMEX are presented. These are the first such profiles obtained in stratiform regions immediately behind bow echoes. The observed SDs were fit to gamma distributions. Other bulk cloud parameters, such as total mass content (TMC),
were also calculated using the SDs in conjunction with data from the NOAA X-band tail radar. The data are compared against observations in stratiform clouds behind other convective systems (Churchill and Houze 1984a; Willis and Heymsfield 1989; Gamache 1990; Heymsfield et al. 2002b). The location of the 29 June 2003 spiral was unique in that the P-3 penetrated into a notch behind a bowing convective line while the stratiform region and a bow echo were just developing (Grim et al. 2005). The effect of the sub-saturated air on aggregation, melting, sublimation, and the evolution of the SDs are examined at the location of this spiral.

This paper represents the first in a series examining the BAMEX microphysical data. Future papers will present high-resolution observations of the rapid development and decay of the 29 June 2003 squall line and examine how microphysical properties are related to the position and timing of spirals relative to the radar evolution.

2. Instrumentation and Data Processing

During BAMEX the NOAA P-3 was equipped with a two-dimensional Particle Measurement Systems (PMS) cloud probe (2DC), nominally sizing particles between 50 and 1600 μm, a two-dimensional PMS precipitation probe (2DP), sizing particles between 200 and 6400 μm (Knollenberg 1981) and a forward scattering spectrometer probe (FSSP) measuring particles smaller than 50 μm. The probes were serviced and calibrated before the project at Droplet Measurements Technology Inc. and performed well throughout the project with the exception of 22 June 2003 when the 2DP did not record useable data. For this reason, the 22 June spiral was excluded from the analysis.

On some flights, false occultation of one or two photodiodes on the 2DC and 2DP occurred sporadically. These erroneous signals were likely induced by vibrations of the
pods on which the probe canisters were mounted. To minimize problems induced by the vibrations, the 2DC and 2DP were carefully aligned and focused before each flight. As a result, the vibrations and erroneous images were not sufficiently frequent to swamp the data system and prevent calculations of concentrations. For the 147,319 2DC and 142,554 2DP data records obtained during spirals, 8,853 2DC and 21,958 2DP records, representing 6 and 15% of the records respectively, were rejected due to the sum of the particle inter-arrival times not being within 20% of the record duration; this mismatching in time is indicative of stuck bits and did not occur frequently enough to represent a problem.

Data were acquired using a Science Engineering Associates (SEA) data system. The SDs were calculated using software designed by William Hall at the National Center for Atmospheric Research (NCAR) and subsequently modified at Illinois to accommodate the NOAA data structures. For particles with maximum dimension $D < 160 \mu m$, the assumed sample volume depended on the inverse of the square of particle size (Heymsfield and Parrish 1978). Particles were sorted into bins according to $D$, defined here as the dimension of a particle in any direction or the diameter of the reconstructed particle, and according to the area ratio $AR$, the projected area of the particle divided by the area of a circumscribed circle (Eq. 1, McFarquhar and Heymsfield 1996). A lower limit of 0.2 was used for area ratio because particles with smaller area ratios were often artifacts. For the overlap region of 1.0 to 1.6 mm where both the 2DC and 2DP registered enough counts to give 10% uncertainties in the number distribution function ($N(D)$), $N(D)$ for the 2DP agreed within $9 \pm 41\%$ of the 2DC values, suggesting consistency between probes. Here, the 2DC was used to describe particles with $D < 1.2$
mm and the 2DP for 1.2 mm < D < 7 mm. Because of inadequate statistical sampling of particles with D > 7 mm, fits to the observed SDs for D < 7 mm were constructed and extended to larger D as described in Appendix A.

To investigate physical processes occurring in stratiform regions, accurate estimates of total mass content (TMC) are needed, where

\[
TMC = \sum_{i=1}^{M} m(D_i)N(D_i)\Delta D_i
\]

(1)

with \(N(D_i)\) the number concentration of particles in size bin \(i\), \(m(D_i)\) the mass of one particle in size bin \(D_i\), and \(D_1\) and \(D_M\) the smallest and largest hydrometeors considered in the construction of the SDs. Particles with \(D < 0.128\) mm did not make significant contributions to TMC (Appendix A) and hence were not included in the analysis.

A relationship between a particle’s mass and D of the form \(m = aD^b\) was assumed (e.g., Locatelli and Hobbs 1974) for \(m(D)\). Because ice particles are non-spherical there was uncertainty in the \((a, b)\) coefficients that should be used. Many values have been published depending on hydrometeor shape and density (e.g., Brown and Francis 1995; Mitchell 1996; Heymsfield et al. 2002b). Direct observations of \(Z_e\) deduced from the NOAA tail radar provided an independent measure of a quantity that can be estimated by integrating over the observed SDs using the assumed \((a,b)\) coefficients. Hence, the \((a, b)\) coefficients that minimized the difference between \(Z_e\) estimated from the SDs as

\[
Z_e = \sum_{i=1}^{M} m^2(D_i)N(D_i)\Delta D_i ,
\]

(2)

and the \(Z_e\) measured by the tail radar were determined. Because \(Z_e\) from the NOAA radar could not be determined at the exact location of the aircraft, the fore and aft scans of the tail radar were interpolated from either side of the aircraft to estimate \(Z_e\) at the aircraft
Grim et al. (2005) describe this approach and show that the standard deviations in $Z_c$ averaged in a region ±3 km on either side of the NOAA P-3 were between 1.6 and 3.9 dBZ, with an average of 2.4±0.4 dBZ. Appendix B discusses the algorithm used to determine the (a,b) coefficients. Separate coefficients were derived for each spiral because different mixtures of particle habits, which impact (a, b), were present in separate spirals. The (a,b) derived were then used with measured SDs in Eq. (1) to estimate TMC.

Other data collected by the P-3 relevant to this study include air temperature (T) measured by the Rosemount 102 total temperature sensor, the dew-point temperature measured by the General Eastern chilled-mirror hygrometer and latitude and longitude measured by the inertial navigation equipment. The temperature and moisture sensors may have suffered from occasional instrument wetting (Heymsfield et al. 1979; LeMone 1980). Eastin et al. (2002) investigated the accuracy of the flight-level thermodynamic data from 666 radial legs in 31 hurricanes, showing T measured by the Rosemount probe was significantly lower than T measured from a CO$_2$ radiometer, with maximum errors of 1 to 3°C below the melting level and 2 to 5°C near the freezing level. They found that a correction method proposed by Zipser et al. (1981) reduced the errors by 30 to 50% on average. Here, the Zipser et al. (1981) correction was applied to the T measurements which are henceforth denoted $T^*$. This is sufficient for separating times when the P-3 was in sub-saturated conditions versus in saturated or nearly saturated conditions.

3. Sampling Strategy

To map the profile of hydrometeor shapes, sizes and phases above, within and below the melting layer, 17 spiral descents were performed through MCS stratiform areas. The spiral descent sampling technique, originally used by Lo and Passarelli (1982),
has been used in numerous studies that seek to describe the processes by which cloud particles evolve during their fall (e.g., Willis and Heymsfield 1989, Field 1999). During these descents, the NOAA P-3 flew circles of about 6 km radius drifting with the background wind at the location of the aircraft. For spirals on or before 10 June, the P-3 descended at approximately 1 m s$^{-1}$ above the melting layer and 5 m s$^{-1}$ below to match the expected fall speeds of hydrometeors. To increase the number of spirals and to reduce problems associated with aircraft charging, the descent rate above the melting layer was increased to around 5 m s$^{-1}$ after 10 June. Overall, the spirals covered T* between –10°C and +10°C with considerable variation in the range of T* sampled on different dates.

Although the 1 m s$^{-1}$ spirals roughly followed particle zones and their evolution, the 5 m s$^{-1}$ spirals above the melting layer can not be considered Lagrangian. In these, the P-3 descended quicker than most particles. Hence, different particle zones were sampled throughout the spiral even though the P-3 advected with the background wind. In fact, the P-3 descended more quickly than small particles and more slowly than large particles for the 1 m s$^{-1}$ spirals (Lo and Passarelli 1982; Field et al. 2006). Further complicating the analysis, sampled particles represent some combination of particles advected from the convective line and those nucleated in stratiform regions. Hence, although the analysis can not be used to identify microphysical processes affecting the evolution of specific particle populations, height or temperature-dependent trends still offer insight into processes occurring in stratiform regions.

Figure 1a shows a spiral performed on 29 June when the complete life cycle of a bowing segment of a MCS was sampled over north-central Kansas. The cells in the system were tracking eastward during the spiral and the NOAA P-3 was located about 35
km behind the bowing segment of the line. Before this spiral, the NOAA tail radar indicated a significant tilt or slope in the radar bright band, with the melting layer extending to progressively lower heights closer to the line. Although the shape of the mini-bow did not change during the 14 minute descent, the reflectivity did increase. Most importantly, Fig. 1a shows that an extensive stratiform area had yet to develop even at the end of the spiral because of the short time after convective development. The observations were made in a descending rear inflow jet (Grim et al. 2005). Figure 1b shows a spiral from 10 June in an extensive stratiform area behind a mature bow echo over Nebraska. There was no major change in either the shape or intensity of the radar pattern during this 24 minute spiral descent.

Examination of radar imagery at times of other spirals showed all except the 29 June case were conducted at locations further from convective lines or at times when stratiform areas were broader in extent than for 29 June. Hence, data obtained on 29 June within the notch behind a rapidly developing bow echo are compared against the data obtained during other spirals in more extensive stratiform regions.

Table 1 summarizes all BAMEX spirals which overall covered the T* range from -12°C to +17°C. Table 2 gives average characteristics for those parts of the spirals where T* < 0°C, including the descent speed, the average and standard deviation of relative humidity with respect to ice (RHÎ) and the average and standard deviation of total number concentration (N_t) and TMC. Table 3 lists similar quantities for parts of the spirals for T* > 0°C, with the exception that relative humidity is computed with respect to water (RHw) and the average and standard deviation of TMC for are not included because a more complex method than developed here is required to compute TMC in the melting layer.
Figure 2 further shows that the 29 June spiral was unique in that the RHi was substantially less than RHi observed during other spirals. The RHi averaged 85±9% above the melting layer. For all other spirals the smallest value of RHi for T* < 0°C was 95% and RHi averaged 100±4% suggesting parts of stratiform regions were supersaturated with respect to ice. For flights conducted in MCS stratiform regions during the Oklahoma-Kansas PRE-STORM experiment, Willis and Heymsfield (1989) also found RHi close to saturation above the 0°C level. In general, RHw started to decrease below the freezing level for most BAMEX spirals. Willis and Heymsfield (1989) observed a similar decrease below 0°C. The 21 June and the first spiral on 6 July differed from other spirals in that RHw decreased faster with increasing T* below 0°C.

Although the NOAA P-3 did not have a Rosemount icing detector for unambiguously identifying the presence of supercooled water, FSSP SDs can be used to speculate on its presence. A strong peak between 5 and 20 μm typically corresponds to water droplets whereas broader distributions indicate ice (e.g., Gardiner and Hallett 1985; McFarquhar and Cober 2004). FSSP SDs for T* < 0°C did not exhibit strong peaks for any spiral. Further, FSSP concentrations averaged 12±7 cm⁻³, lower than typical cloud droplet concentrations (e.g., Miles et al. 2000). Thus, no evidence suggests supercooled water was present in the stratiform regions sampled.

Figure 3 shows how T* varied with altitude for all spirals. Although there were many small-scale fluctuations from a linear decrease in T* with altitude, for T* > 2°C and T* < -1°C the lapse rate averaged over intervals of 500 m varied by only 13% from the mean lapse rate of the spiral. Some small-scale variations are expected because different parts of the environment were sampled during the spiral descent. Isothermal or nearly
isothermal layers, where the rate of decrease of $T^*$ with altitude was significantly reduced, are seen in Fig. 3. For example, for the 24 May, 10 June (first spiral) and 2 July spirals there were isothermal layers around $0^\circ C$ that were 300, 500 and 250 m thick respectively. The only exception to these isothermal layers occurring around $0^\circ C$ was the 29 June spiral where a 250 m thick layer at $2.5^\circ C$ was seen. Even when isothermal layers did not occur, a layer of reduced lapse rate around the $0^\circ C$ level was frequently observed. For example, on the second spiral on 2 June there was a layer 700 m thick, starting at $0^\circ C$ where the lapse rate was only $2.9^\circ C$ km$^{-1}$ compared to lapse rates of $5.6^\circ C$ km$^{-1}$ and $8.2^\circ C$ km$^{-1}$ for layers between 0 and -5$^\circ C$ and between +2 and +7$^\circ C$, respectively. On average, the change of $T^*$ with altitude between 0 and 2$^\circ C$ was $4.7\pm1.5^\circ C$ km$^{-1}$, less than average lapse rates of $5.1\pm0.9^\circ C$ km$^{-1}$ for $T^* < -1^\circ C$ and of $6.3\pm2.2^\circ C$ km$^{-1}$ for $T^* > 2^\circ C$.

These nearly isothermal layers, which are similar to those documented in a variety of MCSs (e.g., Willis and Heymsfield 1989) especially in the Tropics (Johnson et al. 1996), correspond to the onset of the melting layer as verified by inspection of the particle images. However, there was no reduction in lapse rate between $0^\circ C$ and $2^\circ C$ for some spirals, such as on 10 June (second spiral) and 4 July (second spiral), even though melting was observed. Cloud horizontal inhomogeneity and measurements of different parts of the stratiform regions for faster spirals may have precluded the detection of isothermal layers on these days. The isothermal layer at $2.5^\circ C$ on 29 June can be more readily explained because sub-saturated air probably delayed the onset of melting. Rasmussen and Pruppacher’s (1982) laboratory experiments showed that the temperature at which ice spheres of sizes between 200 to 3000 $\mu m$ start to melt is greater than $0^\circ C$ due
to evaporative cooling at the particle’s surface. Based on their findings, melting would have started between 2 and 3°C.

4. Observed Vertical Profiles

a. Vertical Variability of Particle Habits

Hydrometeors imaged by the 2DC and 2DP were visually inspected to eliminate times where artifacts dominated. Plots illustrating the vertical variability of particle habits were then constructed for each spiral by selecting representative images at each T*. Figures 4 and 5 show examples of hydrometeors imaged by the 2DC and 2DP for the first spiral on 29 June when the P-3 was in the sub-saturated air behind a bowing segment of a convective line. Figure 6 and Figure 7 show examples of hydrometeors imaged by the 2DC and 2DP for the second spiral on 29 June when a more extensive and mature stratiform region was present with saturated air above the melting layer.

The most notable feature when comparing Figs. 4 and 5 against Figs. 6 and 7 is the presence of ice, noted from the quasi-spherical shapes of crystals, at T* as high as +7°C for the first spiral on 29 June compared to only about +2°C for the second spiral. Examination of all particles imaged during the other spirals showed ice only occurred at T* as high as +2 to +3°C except for the first spiral on 6 July when it occurred at T* as high as +4°C. The presence of nearly isothermal layers starting at 0°C and the existence of ice up to T* of +2 to +3°C for most spirals indicates that melting typically occurred at T* between 0 and +2 to +3°C. For comparison, observations in stratiform areas of mesoscale systems made during the Summer Monsoon Experiment (SMONEX) showed that ice particles falling below 0°C abruptly melted to form drops (Houze and Churchill 1987). The existence of ice at +7°C on 29 June combined with the onset of the melting at
+2 or +3°C shows melting particles existed over deeper and warmer layers at the location of this spiral, the onset of melting delayed because of the sub-saturated environment. The existence of ice at +4°C on 6 July is also consistent with this explanation as RHw averaged 88% between 0 and +4°C compared to 95% for the 13 spirals conducted on the days with higher RHw. On 29 June data were collected in a descending rear inflow jet (Grim et al. 2005), accelerating the descent of the ice and providing less time for the ice to melt for a given fall distance.

In Figs. 4-7 large aggregate crystals are noted as well as quasi-spherical shapes that may be indicative of graupel. Most particles had indeterminable shapes, consistent with observations in winter monsoon cloud clusters (Houze and Churchill 1984). Houze and Churchill (1987) also found few pristine shapes and a dominance of aggregates right above the freezing layer.

Because the majority of crystals had indeterminable shapes, particle morphology was examined to determine if particle mixtures varied between spirals. Figure 8 shows the average area ratio derived by averaging the 10-s area ratios collected over each spiral for -4 < T* < 0°C as a function of D. Reconstructed particles were excluded from the analysis in Fig. 8. Because the 2DC and 2DP images have coarser resolution than images from the Cloud Particle Imager (CPI) used in Heymsfield and Miloshevich’s (2003) analysis, there was high uncertainty in area ratio estimated for D < 0.2 mm and 1 < D < 2 mm where the switch between the 2DP and 2DC was made. Nevertheless, there was sufficient resolution for determining if differences existed between spirals. For D < 1 mm, the average area ratio for 29 June was 39% compared to 41% for all other spirals; the drier 6 July case also had lower area ratios. For 1 mm < D < 7 mm, the average area
ratio for 29 June was 42% compared to 40% for other spirals. However, there was no significant trend in how area ratio varied with diameter for the 29 June spiral compared to other spirals. Hence, no systematic variations in particle morphologies between spirals were detected from this analysis.

The (a, b) coefficients characterizing the m-D relations were also examined in an effort to determine variations in particle types between spirals. Figure 9 shows the relationship between (a, b) for each spiral together with coefficients for graupel and aggregate snowflakes (Locatelli and Hobbs 1974; Mitchell 1996; Heymsfield et al. 2002b). With the wide spread in (a, b) values, even for coefficients describing a single particle type like graupel, it was difficult to determine whether specific spirals consist of more graupel or aggregates compared to other spirals. Thus, the (a, b) coefficients were only used to estimate TMC.

b. Horizontal and Vertical Variability of SDs

To examine vertical profiles of cloud properties, SDs were plotted as a function of T*. Figure 10 shows the variation of SDs with T* for the second spiral flown on 2 June behind a small bowing segment of a MCS over southeast Arkansas. This was one of the few spirals where the NOAA P-3 descended at 1 m s⁻¹ for T* < 0°C, permitting sampling of the same particle zones throughout the spiral and allowing horizontal inhomogeneities in the stratiform region to be seen through pulsations in time series of SDs. Clear minima in the number concentrations of both large (e.g., 3 mm) and small (e.g., 300 μm) hydrometeors were seen at 2114, 2119, 2124, 2128, 2132, 2137, 2141, 2146 and 2150 UTC which correspond well with times when the P-3 was in a thinner stratiform region.
further west of the convective line. These horizontal variations correspond to a roughly 5
minute period, the time required for one complete turn of the P-3.

There was a gradual decrease in N(D) with increasing T* for particles with D < 3
mm. For example, local maxima in N(D) for 0.5 mm (2 mm) particles varied from 0.98
(0.022) to 0.60 (0.016) to 0.12 (0.007) cm⁻⁴ for T* of —7.9, -4.5 and —1.1°C. There was
also an increase in N(D) for particles with D > 5 mm as seen by the extension of the light
blue color to larger D with increasing T*. The maximum particle size where N(D)
exceeded 10⁻⁵ cm⁻⁴, approximately 7.0 mm, was relatively invariant with T*. The
decrease in N(D) of the small crystals and some increases of N(D) for larger D suggests
that aggregation was occurring in the stratiform region.

SDs changed significantly (Fig. 10) once melting was completed. At 2°C, a
decrease in N(D) for 4 mm particles from 2.2x10⁻⁷ to 1.8x10⁻⁸ cm⁻⁴ occurred in a level
only 240 m thick. No large reduction in N(D) occurred at 0°C when the melting started.
This shows that melting had the biggest impact on the SD when melting was almost
completed, and the particles collapsed into raindrops. Four mm was the size of the largest
raindrops sampled.

Variations in SDs within the stratiform layer can be partly explained in terms of
the ambient humidity. RHi oscillated above 0°C for the 2 June spiral depicted in Fig. 10
with a frequency given by the turning radius of the P-3 and an amplitude of up to 10%,
the RHi ranging between 92% and 105%. Figure 11 shows the concentrations of particles
with 128 < D < 512 μm, N_{128-512}, as a function of RHi when T* < 0°C. Decreases in N_{128-}
_{512} were well correlated with RHi suggesting sublimation was important. The correlation
between RHi and concentrations of particles with D > 2 mm, N_{>2}, of 0.542 was not as
large as the 0.806 value for correlations between RHi and $N_{128-512}$. Gu and Liou (2000) and others have shown that sublimation preferentially removes smaller particles, flattening the SD. This correlation between RHi and $N_{128-512}$ is consistent with sublimation causing the horizontal inhomogeneities in Fig. 10.

The variation of SDs with $T^*$ in Fig. 10, corresponding to an older stratiform region, can be contrasted with the variation of SDs with $T^*$ sampled in sub-saturated air at the time a bow was developing on 29 June as depicted in Figure 12. A difference from Fig. 10 is that $N(D) > 10^{-6}$ cm$^{-4}$ are seen from the fits for $D > 8$ mm at $T^*$ of approximately 7°C in Fig. 12. As seen in Figs. 6 and 7, the large particles seen in Fig. 12 were ice and show that the melting layer extended to low levels. As in Fig. 10, decreases with increasing $T^*$ in $N(D)$ for hydrometeors with $D < 2$ mm above the 0°C level are seen in Fig. 12. For example, $N(D)$ for 500 μm (2 mm) hydrometeors decreased from 0.12 (0.015) at -6.8°C to 0.07 (0.008) cm$^{-4}$ at -0.8°C. The presence of aggregates in the crystal images in Fig. 4 and Fig. 5 shows aggregation was occurring on 29 June even though the sizes of the hydrometeors did not increase with $T^*$. Thus sublimation in the sub-saturated air was probably not only decreasing $N(D)$ of ice crystals with $D < 2$ mm but was probably also limiting the size of aggregates.

Vertical profiles of SDs were constructed for all other spirals. Patterns in other profiles most closely matched patterns seen in Fig. 10 with melting completed at $T^*$ between 2 and 3°C, a gradual decrease in $N(D)$ for small hydrometeors with increasing $T^*$, and a gradual increase in $N(D)$ for large hydrometeors. Since the 29 June spiral was unique in that it was conducted in sub-saturated air, it suggests that the low RHi had a major role in determining the SDs observed during that spiral.
c. Vertical Variability of Bulk Parameters

Figures 13 and 14 show how \( N_t \) and TMC varied with \( T^* \) for all spirals. \( N_t \), proportional to \( D^0 \), was dominated by concentrations of small hydrometeors, whereas TMC, proportional on average to \( D^{2.0} \), was dominated by larger hydrometeors. Particles with \( 0.128 < D < 0.512 \) mm contributed \( 82\pm5\% \) to \( N_t \) and particles with \( 1 < D < 7 \) mm contributed \( 47\pm14\% \) to TMC. Oscillations in \( N_t \) and TMC were caused by horizontal inhomogeneities in the trailing stratiform region and by the sampling of different particle populations during faster spirals. A linear least squares procedure was used to determine the average rate at which \( \log_{10} TMC \) and \( \log_{10} N_t \) varied with \( T^* \) from which the fractional rate of decrease of \( N_t \) and TMC could be derived. Table 4 summarizes these rates. For example, on 2 June \( N_t \) decreased at a faster rate of \( 18\% \, ^{\circ}\text{C}^{-1} \) compared to the TMC decrease of \( 16\% \, ^{\circ}\text{C}^{-1} \). This was consistently seen for most spirals with TMC decreasing at an average rate of \( 10\pm7\% \, ^{\circ}\text{C}^{-1} \) and \( N_t \) decreasing at a rate of \( 19\pm10\% \, ^{\circ}\text{C}^{-1} \).

Comparing the fractional rate of decrease with \( T^* \) of \( N_t \) to that of TMC gives information about the relative rates of decrease with \( T^* \) of small and large particle numbers. To the extent that sampling of different particle zones does not complicate the analysis, these rate decreases can be interpreted in the context of processes dominating particle evolution. Aggregation leads to faster mass-weighted fall speeds and hence reductions in TMC (Field and Heymsfield 2003; Field et al. 2006) and \( N_t \). The faster decrease of \( N_t \) than TMC and the associated increase in particle size previously discussed was likely caused by aggregation.

There were two exceptions to these general trends. For the 24 May spiral behind a mesoscale convective vortex (MCV) center, TMC decreased while \( N_t \) increased.
Behavior for this spiral may be unique because it was not performed in a trailing stratiform region of a squall line and frequent pristine columnar crystals were noted. This spiral was excluded from the following analysis. For the 29 June spiral in sub-saturated air, \( N_t \) decreased at a rate of only 9.4% °C\(^{-1}\) and TMC at a rate of 5.4% °C\(^{-1}\), rates substantially less than those observed in most other spirals. The slower decreases of \( N_t \) and TMC suggests that particle fall speeds were increasing at slower rates on 29 June than on other days. This would be associated with slower increases in the size of particles and hence suggests that aggregation was not acting as efficiently as for other cases.

The TMC and \( N_t \) were also compared against values derived from observations made behind MCSs during PRESTORM and in deep stratiform precipitating tropical clouds during the Large Scale Biosphere-Atmosphere Experiment (LBA). Figure 15 shows a normalized frequency distribution of TMC derived from all BAMEX spirals for \( T^* < 0 \)°C. The mode of TMC peaked between 1 and 3 g m\(^{-3}\) with an average of 1.44±0.89 g m\(^{-3}\). This value is higher than TMC of 0.01 to 1 g m\(^{-3}\) noted by Heymsfield et al. (2002a), 0.1 to 1 g m\(^{-3}\) by Willis and Heymsfield (1989), 0.1 to 0.3 g m\(^{-3}\) by Churchill and Houze (1984b), and 0.01 to 1 g m\(^{-3}\) by McFarquhar and Black (2004) in tropical cyclones. However, the mean BAMEX TMC is similar to observations in maritime tropical systems (Heymsfield et al. 2004). Direct comparison between BAMEX and other observations is difficult because BAMEX data were collected closer to the generating convection.

5. Fits to Observed SDs

The observed SDs were fit to analytic functions to quantify the dependence of SDs on \( T^* \), to compare observations made in different meteorological conditions, and to
place observations in a form conducive for use by numerical models. These fits are especially valuable because previous observations in stratiform regions behind frontal systems or in other meteorological conditions may not represent conditions immediately behind mid-latitude continental MCSs. Although exponential functions are commonly used to represent SDs in mesoscale models, gamma functions given by

\[ N(D) = N_0 D^\mu e^{-\lambda D} \]  

(3)

where \( N_0 \) is the intercept parameter, \( \mu \) the order of the fit and \( \lambda \) the slope parameter, best characterized the BAMEX SDs. The \( \chi^2 \) fits were weighted by the total number of particles observed in each bin rather than by the total mass in each bin as used in Appendix A. A non-linear Levenberg-Marquardt technique was used to minimize \( \chi^2 \). Comparison of fit parameters against those obtained by weighting by particle mass showed that the number weighted fits gave a better representation of \( N(D) \) for small \( D \).

Figure 16 shows a typical fit to a 60-s averaged SD observed at \(-4^\circ C\) on 29 June. The fit with a \( \mu \) of approximately \(-1\) matched the observed SD over the range of sizes where data were obtained and the negative \( \mu \) shows there were more small hydrometeors than could be represented in an exponential distribution.

Figure 17 illustrates the variation of the \( \lambda \) against \( T^* \) for all spirals. Each data point corresponds to a 60-s average so that small-scale fluctuations in \( \lambda \) do not obscure trends in the variation of \( \lambda \). There was a clear decrease of \( \lambda \) with \( T^* \) above the melting layer for most spirals. This decrease in \( \lambda \) is consistent with increases in crystal size with temperature noted above the melting layer in stratiform areas behind mesoscale clusters during SMONEX. Gamache (1990) hypothesized this occurred due to aggregation and deposition. A sharp decrease in \( \lambda \) at \( T^* \) of around \(-3^\circ C\) was noted for some spirals, for
example from 8 cm\(^{-1}\) to values approaching 0 cm\(^{-1}\) on 2 June and from about 13 cm\(^{-1}\) to 5 cm\(^{-1}\) on 31 May. This decrease was likely associated with an increase in aggregation efficiency at temperatures of around -3\(^\circ\)C. Although there have been few studies of the temperature dependence of aggregation efficiency, Pruppacher and Klett (1997, p. 610) showed that the aggregation efficiency increases for ice surface temperatures greater than -5 to -3\(^\circ\)C. Thus, an increase in aggregation would be expected at these temperatures if other conditions needed for aggregation were present, such as the presence of planar dendritic crystals or spatial dendrites (Rauber 1987).

The only exceptions to the decrease of \(\lambda\) with \(T^*\) were for spirals conducted 31 May, 10 June (first spiral) and 29 June. For the 29 June spiral conducted in sub-saturated conditions, \(\lambda\) had an almost constant value around 5 cm\(^{-1}\) for \(T^* < 6^\circ\)C and then increased to about 30 cm\(^{-1}\) after melting was completed. On 31 May, there was a slight increase in \(\lambda\) for \(T^* < -3^\circ\)C after which there was a sharp decrease, and on 10 June there was also a slight increase in \(\lambda\) with \(T^*\). Since the 29 June and 31 May spirals were in environments with lower RHi, this suggests the different evolution of the SDs was associated with the drier air. The 10 June spiral was not associated with low humidity as RHi averaged 98% above 0\(^\circ\)C level.

Using data from all spirals, the solid line in Fig. 17 shows the best fit of \(\lambda\) to \(T^*\) given by

\[
\lambda = 3.58 \exp(-0.115T^*)
\]  

(4)

The \(\lambda\) values generally fell in the range of 0-20 cm\(^{-1}\), less than the range of 10 to 50 cm\(^{-1}\) observed in deep tropical cirrus and precipitating stratiform clouds during LBA (Heymsfield et al. 2002b). The difference in \(\lambda\) between projects was larger than the
scatter in the BAMEX data. Larger $\lambda$ correspond to a faster decrease in $N(D)$ with increasing $D$, showing more large particles occurred behind the convective lines in BAMEX than in stratiform regions further behind convective lines measured in other projects. The reduced range of $\lambda$ during BAMEX may have occurred because the spirals started at $T^*$ of around $-10^\circ$C, unlike spirals reported by Heymsfield et al. (2002a) that started at $T^*$ as low as $-50^\circ$C. The BAMEX observations, however, were consistent with observations from Heymsfield et al. (2002b), Gordon and Marwitz (1996) and Lo and Passarelli (1982) in that the decrease of $\lambda$ with $T^*$ showed that the fractional contributions of large hydrometeors increased with increasing $T^*$.

Fig. 17 shows that $\lambda$ continued to decrease with increasing $T^*$ for $T^* > 0^\circ$C. Then raindrops appeared producing a large increase in $\lambda$ at $T^*$ of 2 to 3°C on most days and at 6 to 7°C on 29 June. The decrease of $\lambda$ for $0^\circ$C < $T^*$ < $2^\circ$C suggests aggregation continued to be important until the hydrometeors completely melted. The continuation of aggregation after the onset of melting is consistent with observations of Yokoyama (1985), Willis and Heymsfield (1989) and Heymsfield et al. (2002a).

The other fit parameters of the gamma distributions, $N_0$ and $\mu$, were not independent of $\lambda$. Figure 18 shows the relationship between $N_0$ and $\lambda$ for the spirals individually and for all spirals combined. Consistent with findings of Heymsfield et al. (2002a), $N_0$ and $\lambda$ were well correlated with little scatter in Fig. 18. The relationship between $N_0$ and $\lambda$ is given by

$$\log_{10} N_0 = -4.14 \exp(-0.082\lambda),$$  \hspace{1cm} (5)$$

which includes all points above the melting layer. For most spirals, larger $\lambda$ and hence $N_0$ were found for decreasing $T^*$. But, $\lambda$, and hence also $N_0$, increased with increasing $T^*$.
for the 31 May, 10 June and 29 June spirals discussed above. The larger $N_0$ values offset from the line given by Eq. (5) correspond to SDs measured in rain.

The relationship between $\lambda$ and $\mu$ is illustrated in Figure 19. A strong relation between $\lambda$ and $\mu$ is noted for points above the melting layer, with a best fit given by

$$\mu = 0.93 \lambda^{0.314} - 3.05$$

A comparison with a similar relationship derived by Heymsfield et al. (2002a) shows that for all but the smallest $\lambda$ that occur infrequently, $\mu$ values from BAMEX were larger than those from LBA. This indicates that the BAMEX distributions were closer to exponential distributions than the super-exponential distributions of LBA. This is consistent with observations of a greater fraction of larger particles during BAMEX because the drop off in small hydrometeor numbers was responsible for super-exponential distributions and negative $\mu$ values in LBA. The values of $\mu < -1$ obtained from BAMEX will be difficult to incorporate in double moment parameterization schemes (e.g., Straka and Mansell 2005) that predict the evolution of total particle number and mass because the gamma function is not integrable for $\mu < -1$. However, these super-exponential distributions should be accounted for in some manner when developing future parameterizations.

In the simplest form of microphysical parameterization schemes, single moment schemes (e.g., Lin et al. 1983; Rutledge and Hobbs 1983) are used where only the mass contents of different species are prognosed. Hence, relationships between $N_0$, and $\lambda$ in terms of TMC were developed. Figure 20 shows $N_0$ as a function of TMC using SDs measured above the melting layer. Although there was considerable scatter in the data with a correlation of 0.46 between $\log_{10}(N_0)$ and $\log_{10}(\text{TMC})$, $N_0$ increased with TMC,
consistent with McFarquhar and Black’s (2004) analysis of hurricane data. A best fit is given by

\[ N_0 = 3.6 \times 10^{-3} TMC^{1.23} \]  

(7)

and is represented by the solid line in Fig. 20. Figure 21 shows \( \lambda \) as a function of TMC. The best fit for data obtained above the melting layer is given by

\[ \lambda = 4.06 \log_{10} TMC + 7.13 \]  

(8)

with a correlation coefficient of 0.29 between \( \lambda \) and \( \log_{10}(N_0) \). An implication of Eq. (7) and Eq. (8) is that although the total number of hydrometeors increased with TMC above the melting layer, the increase of the numbers of large particles with TMC occurred at a faster rate than that of the smaller particles.

6. Summary/Conclusions

During BAMEX, an unique set of data were collected during 17 spiral descents of the NOAA P-3 in stratiform areas of MCSs, some of which were directly behind bowing line segments. In this paper, the vertical and horizontal variability of microphysical properties were characterized based on data collected during spiral descents. These data represent the first observations of the microphysical properties of the stratiform regions behind bow echoes and included one unique spiral where the NOAA P-3 descended in a sub-saturated region directly behind a bowing segment of the line where ice was seen at temperatures as high as +7°C. The microphysical data were analyzed to describe how particle habits, size distributions (SDs), total number concentration (\( N_t \)), total mass content (TMC) and fit parameters to gamma functions (slope parameter \( \lambda \), intercept \( N_0 \) and order of fit \( \mu \)) varied with temperature \( T^* \) and ambient humidity. The observed trends were compared against observations obtained in stratiform regions during other field
campaigns. Although the 5 m s⁻¹ descent of the NOAA P-3 prevented tracking particle zones for some spirals, trends in the variation of hydrometeor shape, $N_t$, TMC $\lambda$, $\mu$, and $N_0$ with $T^*$ suggest which physical processes dominate the microphysical evolution in stratiform regions behind MCSs. The principal conclusions are as follows:

1) For 15 of 16 spirals, the environment for $T^* < 0^\circ C$ was at or near saturation with respect to ice. The relative humidity with respect to water (RHw) decreased at an average rate of 3% $^\circ C^{-1}$ below the melting layer. For the 29 June spiral in a notch behind a developing bow, the relative humidity with respect to ice (RHi) averaged 85% for $T^* < 0^\circ C$ and further decreased to 48% at 9°C at a rate of 4.5% $^\circ C^{-1}$.

2) Horizontal inhomogeneities were characterized using data from the slower 1 m s⁻¹ spiral descent on 2 June with $N_t$ (TMC) varying by a factor of 3 (8) and concentrations of hydrometeors with $D < 2$ mm ($> 3$ mm) by a factor of 3 (8) over the 6 km turning radius. The correlation between RHi and concentrations of particles with $D < 512 \mu$m ($> 2$ mm) was 0.806 (0.542).

3) The TMCs measured in the stratiform regions averaged 1.44±0.89 g m⁻³ and were an order of magnitude higher than those measured in deep tropical stratiform precipitating clouds and tropical cyclones during many past campaigns. The differences were attributed to the proximity of the BAMEX observations to the generating convective cells.

4) Averaged over all spirals, $N_t$ decreased at a rate of 19±10% $^\circ C^{-1}$, faster than the rate of decrease of TMC of 10±7% $^\circ C^{-1}$. The faster decrease in $N_t$, which was dominated by small particles, indicates that small crystals were being removed at a quicker rate than larger crystals, consistent with aggregation and sublimation.
5) When fit to gamma functions, the slope parameters $\lambda$ above the melting layer ranged between 0 and 20 cm$^{-1}$, intercept parameters $N_0$ from $10^{-4}$ and $10^{-1}$ cm$^{(3+\mu)}$ $\mu$m$^{-1}$, and the fit order $\mu$ from -2 to 0. The values of $\lambda$ and $N_0$ were smaller and $\mu$ larger than those measured in stratiform regions of other systems, showing that larger hydrometeors were prevalent during BAMEX.

6) For 13 of 16 spirals, $\lambda$ above the melting layer decreased with increasing $T^*$, showing that hydrometeor sizes increased with $T^*$. This, combined with the decrease in numbers of particles with $D < 2$ mm, suggests aggregation was occurring in the stratiform regions. A large decrease in $\lambda$ at $-3^\circ$C was noted for some spirals and may have been caused by enhanced aggregation efficiency.

7) For observations in highly sub-saturated air above the melting layer on 29 June, $\lambda$ and $\mu$ were relatively constant despite a reduction in $N_t$ and TMC. For the 31 May spiral with RHi between 85 and 95%, $\lambda$ increased with temperature for $T < -3^\circ$C, after which $\lambda$ sharply increased.

8) The fit parameters of the SDs exhibited dependence on T and TMC.

In summary, sublimation would have only had a significant influence on latent cooling at the time of the 29 June spiral conducted in sub-saturated air behind a developing bow; the other spirals were all conducted in near saturated conditions above the melting layer. For spirals at other locations and times in the evolution of the convective lines, melting and evaporation in sub-saturated air below the melting layer were the only processes contributing to latent cooling at the time of the observations. However, sublimation may have contributed to latent cooling above the melting layer at earlier stages in the life cycles of these systems. Smith (2006) also explains differences in
microphysical properties between spirals in the context of a conceptual model of the development of a MCS. With this context, the BAMEX observations should further the understanding of the role of microphysical processes in MCSs and bow echo evolution.

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Appendix A: Determining Size Distributions Outside Range of In-Situ Probes

To understand uncertainties in parameters derived from in-situ observations, the range over which the 2DC and 2DP provided sufficiently accurate SDs were determined, and SDs estimated outside this range. Following Hallett (2003), uncertainties in SDs were determined by computing the number of particles sampled in different size bins. Figure A1 shows uncertainties in N(D) for a 10 s integrated SD at -1.5°C during the first spiral on 2 June and the distance the P-3 would have traveled to get a sample of 100±10 particles in each bin. For D < 7 mm, the P-3 had to travel < 1.5 km to get 100 particles in each bin, corresponding to uncertainties of less than 10% in the SDs. For D > 7 mm, the P-3 had to travel > 1.5 km to get 10% uncertainty with, for example, a distance of 58 km required for a bin centered at 12 mm. Similar trends were seen at other time periods. There was not only large uncertainty in the concentrations of particles with D > 7 mm, but also in the estimate of D for D > 7 mm due to the use of reconstruction techniques to estimate the sizes of particles occurring on the photodiode edges.

Particles with D < 0.128 mm were also not well represented in the SDs as the 2DC does not reliably measure their concentrations at typical P-3 speeds (Baumgardner and Korolev 1997). To investigate whether such small and large particles were needed for calculations of TMC, the mass distribution function m(D) and the cumulative mass were plotted as functions of D for all spirals. Appendix B describes how the (a,b) coefficients, defining the mass of an individual particle as m=aD^b, were determined. Figure A2 shows m(D) for the 2 June spiral at 214230 UTC when T* was –1.5°C. Large particles would contribute most to mass near the melting layer (see Sec. 3). In Fig. A2, particles with 0.128 < D < 0.3 mm contributed 15% to TMC and those with D < 0.128 mm would make
even smaller contributions. Because $m$ was weighted by $D^{1.4}$ for this spiral (Appendix B), one of the smaller weightings of $D$ for any spiral, small hydrometeors would be expected to make larger contributions to TMC provided no systematic variations in SDs occurred. Thus, particles with $D < 0.128$ mm were ignored since the TMC estimates from in-situ measurements are accurate within 20% at best (Heymsfield et al. 2002b).

In Fig. A2, $m(D)$ peaked at $D$ between 3 and 4 mm and particles with $5.2 < D < 7$ mm contributed 5% to the total mass between 0.128 mm and 7 mm. However, since the 1.4 weighting of $D$ was one of the smaller weightings for any spiral, contributions of particles with $5.2 < D < 7$ mm to TMC were expected to be greater for other spirals. The exact contributions of particles with $D > 7$ mm to TMC could not be derived from Fig. 2 since uncertainties in SDs were large. Thus, hydrometeors with $D > 7$ mm needed to be included in the SDs for accurate determinations of TMC. Fits to SDs for $D < 7$ mm were thus made and the resulting fit parameters used to extend the SDs to larger sizes. As discussed in Sec. 5, observed SDs were best represented by gamma functions. For the fits needed to extend the SDs to $D > 7$ mm, the $\chi^2$ difference between the observed and fitted $N(D)\Delta D$ was minimized by weighting according to the total mass of particles in each bin estimated as $N(D)\Delta D D^2$. The exponent of 2.0 represents the median value of how $m$ scaled with $D$ (Appendix B). Mass weighting was necessary because fits weighted according to particle number typically overestimated $N(D)$ for $D > 4$ mm. Extending these fits to $D > 7$ mm led to overestimates of mass and reflectivity from such particles. Given that the best possible estimates of mass and reflectivity from the SDs are needed to derive the $(a,b)$ coefficients that best matched the radar observed reflectivity, these number-weighted fits were hence inadequate for estimating the SDs for $D > 7$ mm.
It should also be noted that fits based on mass-weighting did not provide good representations of \( N(D) \) for \( D < 1 \) mm and hence could not be used in Sec. 5 to investigate how processes like aggregation and sublimation affect \( N_t \) and smaller particle numbers. Attempts to derive fit parameters using moments directly calculated from the in-situ SDs following the equations of Heymsfield et al. (2002a) gave higher values of \( \chi^2 \) than fits using the Levenberg-Marquardt algorithm, and again did not well represent particles with \( D > 4 \) mm. In reality, the lack of a single fit to characterize particles with \( D < 1 \) mm and > 4 mm suggests either two gamma functions or a more complex function would better characterize the data. However, the use of multiple free parameters to better match the observed SDs would detract from the physical meaning of fit parameters and would prevent easy comparisons of the BAMEX data with previous in-situ observations.

**Appendix B: Determining Optimum Mass-Diameter Relationships**

To calculate TMC from in-situ SDs, assumptions on how the hydrometeor mass, \( m \), varies with \( D \) and other measures of hydrometeor morphology must be made. Locatelli and Hobbs (1974), Brown and Francis (1995), Mitchell (1996) and others have derived relations of the form \( m = aD^b \) to characterize this relationship. Heymsfield et al. (2002a) enhanced these techniques by deriving relationships that characterize how \( m \) varies with \( D \) and area ratio for different crystal habits.

Direct observations of the equivalent radar reflectivity factor (\( Z_e \)) deduced from the NOAA tail radar were used to determine the (a, b) coefficients needed to estimate hydrometeor mass and TMC. Figure B1 compares \( Z_e \) estimated at the aircraft location from the fore and aft scans of the tail radar (Grim et al. 2005), hereafter \( Z_{er} \), against \( Z_e \).
derived from the in-situ SDs using Eq. (2), hereafter $Z_{ei}$, using (a, b) coefficients from Locatelli and Hobbs (1974) for graupel like snow of lump type and aggregates of rimed dendrites for the first spiral executed 29 June 2003. Fig. B1, restricted to times when the P-3 was above the melting layer to avoid complications from partially melted crystals, shows that $Z_{ei}$ can vary by over 7.5 dBZ depending on the assumed habit, with $Z_{ei}$ from graupelike snow higher than that from aggregates of rimed dendrites. Tabulated relationships of (a, b) were not used to estimate TMC because a mixture of shapes was observed during each spiral and tabulated (a, b) values are for single shapes. In addition, published (a, b) coefficients are mostly based on observations in frontal cloud systems that may poorly represent hydrometeors observed in stratiform regions behind MCSs.

Instead a non-linear Levenberg-Marquardt fitting algorithm (Press et al. 1992) was used to minimize the $\chi^2$ difference between $Z_{ei}$ and $Z_{er}$ with respect to varying (a, b) coefficients, with $\chi^2$ defined by

$$\chi^2 = \sum_{i=1}^{N} \frac{(Z_{ei,i}(a,b) - Z_{er,i})^2}{N-1}$$

(A1)

where $Z_{ei,i}$ is $Z_{ei}$ for the ith 1-minute averaged SD and $Z_{er,i}$ is $Z_{er}$ for the same time. An initial guess of the (a,b) values for aggregates of rimed dendrites was made, and then an iterative procedure was followed whereby (a,b) were adjusted and $\chi^2$ recomputed until $\chi^2$ was reduced by less than 0.1% in successive time steps. The (a,b) coefficients were calculated separately for each spiral because different mixtures of hydrometeor shapes occurred on different days. Any variation of (a,b) coefficients throughout a spiral was not considered because around 10 SDs are ideally needed to get a statistically significant sample to calculate $\chi^2$ in Eq. (A1) and because any change in the (a,b) coefficients within
a spiral could cause large changes in TMC making it difficult to see trends in how TMC changed with temperature. The use of a single set of (a, b) coefficients implies that the mixture of hydrometeor shapes did not change with respect to temperature which naturally invokes some uncertainty in the calculation of TMC.

Table B1 lists the values that were determined for all spirals. Following McFarquhar (2004), confidence limits for the (a, b) coefficients were determined by constructing constant $\chi^2$ boundaries in the two-dimensional phase space of (a, b). The equation of the elliptical boundary of the confidence region encompassing the uncertainty estimates was determined from the eigenvalues and eigenvectors of the inverse of the covariance matrix generated by the fitting routine (Press et al. 1992) assuming a 68.3% confidence level following the approach of McFarquhar et al. (2002).

Once the (a, b) coefficients were determined for the spirals, the TMC was computed following Eq. (1). Because the (a,b) coefficients were set to most closely match $Z_{cr}$ which is weighted proportional to the square of the mass, the contributions of the largest hydrometeors in the observed SDs have a greater weight in determining TMC than they would if (a, b) were calculated using an independent measure of mass content (e.g., Heymsfield et al. 2002a). The influence of these large particles is likely responsible for the large range of b values from 1.2 to 2.2. The uncertainty in the (a,b) coefficients is hence larger than that from studies with direct measures of TMC. However, no probe directly measuring mass was used during BAMEX. Nevertheless, tuning the (a, b) coefficients against independent measures of $Z_c$ significantly reduced the uncertainty in computing mass concentration by avoiding uncertain assumptions about which shapes or mixtures of shapes should be applied to the SDs.
References:


*Smith*, A.M., 2006: Explaining the variability of cloud microphysics in stratiform regions of BAMEX MCSs using high-resolution radar and optical array probe


Table Captions

Table 1: Locations of spiral descents and minimum and maximum temperatures (T*) measured during descents.

Table 2: For parts of spiral at temperatures < 0°C, average descent rate, mean and standard deviation of RHi, average and standard deviation of total number concentration (Nt), and average and standard deviation of total water content (TMC).

Table 3: For parts of spiral with T* > 0°C, mean descent rate, mean and standard deviation of RHw, and mean and standard deviation of total number concentration (Nt).

Table 4: Rate of increase of Nt and TMC with increasing temperature for T* < 0°C for all spirals performed during BAMEX.

Table B1: Maximum likelihood estimates of (a,b) coefficients that describe the relationship between m and D according to m=aD^b. Length of the principal axis (l_a, l_b) and orthonormal vectors (v_a, v_b) describing principal axis of ellipse that represents surfaces of equally likely solutions are also shown.
Figure Captions

Figure 1: Flight tracks of NOAA P-3 and NRL P-3 ahead of and behind bow echoes at times just before, during and just after the spiral descents performed on (a) 29 June 2003 and (b) 10 June 2003. The flight track for the slow spiral on 10 June has had the system motion, given as grid motion on figure top, subtracted out; no adjustment has been made for the faster spiral on 29 June because the system did not move significantly during the course of the observations. In Fig. 1a, purple line with added wind barbs added at location of aircraft represents track of NOAA P-3 and red line with added wind barbs represents location of NRL P-3 (red line with wind barbs). In Fig. 1b, pink lines represent location of NOAA P-3 and red lines for NRL P-3. The time range of the flight tracks are given on the top in red (NRL) and purple/pink (NOAA), while the time of the composite radar image is given at the top in black.

Figure 2: Relative humidity as a function of T* for all spirals executed during BAMEX. For T < 0°C, RHi is plotted; for T > 0°C, RHw is plotted. Dark dashed line shows RHi for water saturation for T < 0°C. Specific spirals discussed in text indicated in legend.

Figure 3: Temperature at the location of NOAA P-3 as function of altitude for 16 spirals conducted during BAMEX. Specific spirals discussed in text indicated in legend.

Figure 4: Examples of particles imaged by 2DC as a function of temperature for the spiral descent executed 29 June 2003, 0525 to 0539 UTC.

Figure 5: As in Fig. 4, except particles imaged by 2DP are displayed.
Figure 6: As in Fig. 4, except for particles imaged by the 2DC during the second spiral executed on 29 June 2003 between 0729 to 0741 UTC.

Figure 7: As in Fig. 6, except for particles imaged by 2DP.

Figure 8: Mean area ratio as function of D for each spiral for T* < 0°C. Specific spirals discussed in text indicated in legend.

Figure 9: Relationship between (a, b) parameters, from m=aD^b for different spirals flown during BAMEX. Previously published (a,b) coefficients for graupel (asterisks) and aggregates of snowflakes (diamonds) are also shown.

Figure 10: N(D) from 2DC (D < 1.2 mm), 2DP (1.2 mm < D < 7.0 mm), and fits (7 < D < 12 mm) as function of time and temperature for second spiral conducted on 2 June 2003 between 2110 and 2203 UTC.

Figure 11: a) Concentration of particles with 0.128 mm < D < 0.5 mm as a function of RHi for the 2 June 2003 spiral for T* < 0°C; each point represents a 10 s average. b) As in a), except for concentrations of particles with 2 mm < D < 12 mm.

Figure 12: As in Fig. 10, except for the second spiral conducted on 29 June 2003 between 0525 and 0539 UTC.

Figure 13: The dependence of N_t on T* for all spirals executed during BAMEX. Specific spirals discussed in text indicated in legend.

Figure 14: As in Fig. 13, except for TMC.

Figure 15: Normalized frequency distribution of TMC for all measurements acquired during BAMEX above the 0°C level.

Figure 16: Gamma fit to 1-minute time-averaged size distribution measured at a temperature of –4°C on 29 June 2003 between 0525 and 0526 UTC. Histograms
represent observed number concentrations, thick solid line represents the best fit gamma distribution \( (N_0 = 5.5 \times 10^{-3} \text{ cm}^{-4}, \lambda = 6.6 \text{ mm}^{-1}, \mu = -0.99) \)

Figure 17: Variation of \( \lambda \) obtained for 1-minute fits to observed SDs as function of \( T^* \).

Upper left panel includes \( \lambda \) derived from SDs that occur above the melting level, solid line represents best fit to data (Eq. 5), and dashed line represents variation of \( \lambda \) as function of temperature obtained by Heymsfield et al. (2002a). Other panels represent data from each spiral labeled on top of figure, where solid circles represent data above the melting layer and unfilled diamonds represent data collected at melting layer or below.

Figure 18: As in Fig. 17, except for variation of \( N_0 \) against \( \lambda \) for all spirals. Solid line represents best fit to the data using only SDs measured above the melting layer.

Figure 19: As in Fig. 17, except describing the relationship between \( \lambda \) and \( \mu \). Solid line represents best fit to the data using only SDs measured above the melting layer. Dashed line represents fit from Heymsfield et al. (2002a).

Figure 20: As in Fig. 17, except for dependence of \( N_0 \) on TMC. Solid line represents best fit to data given by Eq. (7).

Figure 21: As in Fig. 20, except for dependence of \( \lambda \) on TMC. Solid line represents best fit to data given by Eq. (8).

Figure A1: \( N(D) \) measured by 2DC (\( D < 1.2 \text{ mm} \)) and 2DP (\( D > 1.2 \text{ mm} \)) between 214500 and 214510 on 2 June 2003 at \( T^* \) of \(-1.1\text{\degree C}\). Vertical error bars represent uncertainty in \( N(D) \), where lines run between \( N(D) \) calculated using \( N \pm N^{1/2} \) where \( N \) is number of particles measured in each size bin over the 10 s period. Horizontal bars represent distance that NOAA P-3 would have had to travel to get
10\% uncertainty in N(D), that is to sample 100 particles in the given size bin (horizontal axis corresponding to distance embedded in upper right part of figure).

Figure A2: m(D) versus D for same time period plotted in Fig. 1 (214500 to 214510 UTC on 2 June 2003). Thick solid line represents normalized cumulative mass distribution function for size ranges included in the histogram.

Figure B1: Reflectivity as function of time for spiral conducted on 29 June 2003. Z_{ci} represents Z calculated from in-situ size distributions using the maximum likelihood estimate of (a,b) coefficients, Z_{er} represents Z derived from NOAA tail radar, and Z_{c(agg)} and Z_{c(graup)} represent Z derived assuming (a,b) coefficients representative of aggregates and graupel respectively.
Table 1: Locations of spiral descents and minimum and maximum temperatures (T*) measured during descents.

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<th>Latitude</th>
<th>Longitude</th>
<th>Minimum T [°C]</th>
<th>Maximum T [°C]</th>
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<td>-8.6</td>
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Table 2: For parts of spiral at $T^* < 0^\circ$C, average descent rate, mean and standard deviation of RHi, average and standard deviation of total number concentration ($N_t$), and average and standard deviation of total water content (TMC).

<table>
<thead>
<tr>
<th>Spiral</th>
<th>Mean Descent rate [m s$^{-1}$]</th>
<th>Mean RHi [%]</th>
<th>$\sigma$ RHi [%]</th>
<th>Mean $N_t$ [l$^{-1}$]</th>
<th>$\sigma$ $N_t$ [%]</th>
<th>Mean TMWC [g m$^{-3}$]</th>
<th>$\sigma$ TMC [g m$^{-3}$]</th>
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Table 2: For parts of spiral at $T^* < 0^\circ$C, average descent rate, mean and standard deviation of RHi, average and standard deviation of total number concentration ($N_t$), and average and standard deviation of total water content (TMC).
Table 3: For parts of spiral with T* > 0°C, mean descent rate, mean and standard deviation of RHw, and mean and standard deviation of total number concentration (Nt).

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<th>Spiral</th>
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<th>Mean RHw [%]</th>
<th>σ RHw [%]</th>
<th>Mean Nt [l(^{-1})]</th>
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Table 4: Rate of increase of $N_t$ and TMC with increasing temperature for $T^* < 0^\circ C$ for all spirals performed during BAMEX.

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<th>Spiral</th>
<th>$dN_t/dT^*$ [% $\circ C^{-1}$]</th>
<th>$dTMC/dT^*$ [% $\circ C^{-1}$]</th>
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Table B1: Maximum likelihood estimates of \((a, b)\) coefficients that describe the relationship between \(m\) and \(D\) according to \(m = aD^b\). Length of the principal axis \((l_a, l_b)\) and orthonormal vectors \((v_a, v_b)\) describing principal axis of ellipse that represents surfaces of equally likely solutions are also shown.
Figure 1: Flight tracks of NOAA P-3 and NRL P-3 ahead of and behind bow echoes at times just before, during and just after the spiral descents performed on (a) 29 June 2003 and (b) 10 June 2003. The flight track for the slow spiral on 10 June has had the system motion, given as grid motion on figure top, subtracted out; no adjustment has been made for the faster spiral on 29 June because the system did not move significantly during the course of the observations. In Fig. 1a, purple line with added wind barbs added at location of aircraft represents track of NOAA P-3 and red line with added wind barbs represents location of NRL P-3 (red line with wind barbs). In Fig. 1b, pink lines represent location of NOAA P-3 and red lines for NRL P-3. The time range of the flight tracks are given on the top in red (NRL) and purple/pink (NOAA), while the time of the composite radar image is given at the top.
Figure 2: Relative humidity as a function of $T^*$ for all spirals executed during BAMEX. For $T < 0^\circ C$, $RHi$ is plotted; for $T > 0^\circ C$, $RHw$ is plotted. Dark dashed line shows $RHi$ for water saturation for $T < 0^\circ C$. Specific spirals discussed in text indicated in legend.
Figure 3: Temperature at the location of NOAA P-3 as function of altitude for 16 spirals conducted during BAMEX. Specific spirals discussed in text indicated in legend.
Figure 4: Examples of particles imaged by 2DC as a function of temperature for the spiral descent executed 29 June 2003, 0525 to 0539 UTC.
Figure 5: As in Fig. 4, except particles imaged by 2DP are displayed.
Figure 6: As in Fig. 4, except for particles imaged by the 2DC during the second spiral executed on 29 June 2003 between 0729 to 0741 UTC.
Figure 7: As in Fig. 6, except for particles imaged by 2DP.
Figure 8: Mean area ratio as function of D for each spiral for $T^* < 0^\circ C$. Specific spirals discussed in text indicated in legend.
Figure 9: Relationship between (a, b) parameters, from $m = aD^b$ for different spirals flown during BAMEX. Previously published (a,b) coefficients for graupel (asterisks) and aggregates of snowflakes (diamonds) are also shown.
Figure 10: $N(D)$ from 2DC ($D < 1.2 \text{ mm}$), 2DP ($1.2 \text{ mm} < D < 7.0 \text{ mm}$), and fits ($7 < D < 12 \text{ mm}$) as function of time and temperature for second spiral conducted on 2 June 2003 between 2110 and 2203 UTC.
Figure 11: a) Concentration of particles with $0.128 \text{ mm} < D < 0.5 \text{ mm}$ as a function of RH$i$ for the 2 June 2003 spiral for $T^* < 0^\circ\text{C}$; each point represents a 10 s average. b) As in a), except for concentrations of particles with $2 \text{ mm} < D < 12 \text{ mm}$. 
Figure 12: As in Fig. 10, except for the first spiral conducted on 29 June 2003 between 0525 and 0539 UTC.
Figure 13: The dependence of N_t on T* for all spirals executed during BAMEX. Specific spirals discussed in text indicated in legend.
Figure 14: As in Fig. 13, except for TMC.
Figure 15: Normalized frequency distribution of TMC for all measurements acquired during BAMEX above the 0°C level.
Figure 16: Gamma fit to 1-minute time-averaged size distribution measured at a temperature of –4°C on 29 June 2003 between 0525 and 0526 UTC. Histograms represent observed number concentrations, thick solid line represents the best fit gamma distribution ($N_0 = 5.5 \times 10^{-3} \text{ cm}^{-3.01}$, $\lambda = 6.6 \text{ cm}^{-1}$, $\mu = -0.99$)
Figure 17: Variation of $\lambda$ obtained for 1-minute fits to observed SDs as function of $T^\ast$. Upper left panel includes $\lambda$ derived from SDs that occur above the melting level, solid line represents best fit to data (Eq. 5), and dashed line represent variation of $\lambda$ as function of temperature obtained by Heymsfield et al. (2002a). Other panels represent data from spiral labeled on top of figure, where solid circles represent data above the melting layer and unfilled diamonds represent data collected at melting layer or below.
Figure 18: As in Fig. 17, except for variation of $N_0$ against $\lambda$ for all spirals. Solid line represents best fit to the data using only SDs measured above the melting layer.
Figure 19: As in Fig. 17, except describing the relationship between $\lambda$ and $\mu$. Solid line represents best fit to the data using only SDs measured above the melting layer. Dashed line represents fit from Heymsfield et al. (2002a).
Figure 20: As in Fig. 17, except for dependence of $N_0$ on TMC. Solid line represents best fit to data given by Eq. (7).
Figure 21: As in Fig. 20, except for dependence of $\lambda$ on TMC. Solid line represents best fit to data given by Eq. (8).
Figure A1: N(D) measured by 2DC (D < 1.2 mm) and 2DP (D > 1.2 mm) between 214500 and 214510 on 2 June 2003 at T* of –1.1°C. Vertical error bars represent uncertainty in N(D), where lines run between N(D) calculated using N ± N^{1/2} where N is number of particles measured in each size bin over the 10 s period. Horizontal bars represent distance that NOAA P-3 would have had to travel to get 10% uncertainty in derived number concentration, that is to sample 100 particles in the given size bin (horizontal axis corresponding to distance embedded in upper right part of figure).
Figure A2: $m(D)$ versus $D$ for same time period plotted in Fig. A1 (214500 to 214510 UTC on 2 June 2003). Thick solid line represents normalized cumulative mass distribution function for size ranges included in the histogram.
Figure B1: Reflectivity as function of time for spiral conducted on 29 June 2003. $Z_{ei}$ represents $Z$ calculated from in-situ size distributions using the maximum likelihood estimate of $(a,b)$ coefficients, $Z_{er}$ represents $Z$ derived from NOAA tail radar, and $Z_{e(agg)}$ and $Z_{e(grau)}$ represent $Z$ derived assuming $(a,b)$ coefficients representative of aggregates and graupel respectively.