4.5 A STUDY OF ICE−PHASE MICROPHYSICS IN TRMM−LBA DEEP CONVECTIVE CLOUDS

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1. INTRODUCTION

Although the sun is the ultimate source of energy for the motions in the Earth's atmosphere, most of this energy has to be first processed by convection to become available to the atmospheric circulations. In fact, it is recognized that the latent heat released in clouds, especially the convective clouds over the tropics drives atmospheric motions from local to global scales.

In tropical regions, the atmospheric thermodynamics is mostly ruled by deep convective action. In opposition to surface processes and shallow convection, deep convective clouds produce a net latent heating through the depth of the troposphere, as they transport energy upward. Deep convection serves as a bridge that connects the free atmosphere and the boundary layer as well.

Although in a large scale perspective deep convection can be seen in a state of quasi−equilibrium with a large−scale, destabilizing forcing (Arakawa and Schubert 1974), multiple scales are important to shape the characteristics of convection. This includes forcings on the mesoscale, cloud−scale circulations, turbulence and, on the extreme, microphysical processes. As pointed out by Emanuel (1994), the effect of cumulus convection on the redistribution of the water vapor in the atmosphere strongly depends on the detrained water substance and, therefore, is very sensitive to the cloud microstructure. In fact, it is at the scale of microphysical processes that the latent heat associated with convection is actually exchanged. Microphysical variables such as hydrometeor size, fall velocity and shape (in the case of ice particles) can influence evaporation and sublimation and hence the water vapor transport and the heating profile. Those uncertainties can place severe limitations to our capabilities of modeling tropical convection.

Even in a framework in which the heating and moistening is controlled by an imposed forcing on the large−scale, such as cloud−resolving simulations, the microphysics is also important when coupled to the radiation, as shown, for instance, by Grabowski et al. (1999) and Wu et al. (1999).

Surprisingly, however, there are only few and insufficient microphysical observations in the tropics. Among those observations are some microphysical studies performed during the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE, e.g., Takahashi et al. 1995), measurements in tropical cumulonimbi during the Stratosphere−Troposphere Exchange Project (STEP, Knollenberg et al. 1993) and microphysical data collected during the Central Equatorial Pacific Experiment (CEPEX, Chen et al. 1997). Those observations generally revealed important peculiarities in the microphysical evolution of tropical convective clouds, such as extremely high concentrations of ice crystals.

In Brazil, microphysical data are even scarcer. The Ceará Experiment in 1994 (Costa et al. 2000) provided information on the microphysics of clouds over Northeast Brazil, but focused on warm−phase microphysical processes only. No significant microphysical studies were performed over the Amazon region until recently, especially concerning mixed−phase (liquid water and ice) convective clouds.

Convection over the Amazon Basin has unique characteristics in terms of its organization and heating patterns. For instance, Greco et al. (1994) show that Amazon coastal squall lines exhibit heating profiles that depart from both oceanic convection and convection from other continental regions.

Amazon convection has very distinctive features related to the presence of the forest and some of them have direct impact over the characteristics of convection, such as the strong heat fluxes (e.g., Abreu Sá et al. 1988, Martin 1988, Viswanacham et al. 1990) and the significant production of aerosols by both natural and burning emissions (e.g., Kaufman et al. 1998, Ramer et al. 1998, Artaxo et al. 1998, Echalar et al. 1998). This justifies a thorough analysis not only of the dynamics and thermodynamics of Amazon convection but also of its microphysics.

To what extent the microphysics of Amazon convection is influenced by its dynamics and can in turn influence the larger scales is still unknown. In this context, the Tropical Rainfall Measuring Mission Large Scale Biosphere−Atmosphere Experiment in Amazonia (TRMM−LBA) provided the first opportunity to extensively investigate the microphysical structure of Amazon convection.

Using the TRMM−LBA data, important uncertainties regarding the microphysical aspects of Amazon convection can be addressed, for instance, the characteristic number concentration and size, size distribution and more common shapes of the ice crystals.

In this paper, microphysical observations of cumulus convection microphysics over Amazonia collected during the TRMM−LBA are analyzed with emphasis on the ice phase. Its outline is as follows. Section 2 describes the instrumentation used in the TRMM−LBA microphysical field campaign. Sections 3 and 4 show results from one case

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study: convection formed on 10 February 1999. A general discussion and conclusions are presented in Section 5.

2. INSTRUMENTATION

The TRMM LBA experiment was a major field campaign designed to obtain integrated information on meteorological and hydrological processes on multiple scales, carbon storage and exchange, biogeochemical processes and influences of land use changes over the Amazon. Most of the efforts were conducted over the Brazilian state of Rondônia, located between 8−13S and 60−65W.

A large variety of instrumentation was available, including two Doppler radars, wind profiler, radiosondes and tethered balloons and a pair of research aircrafts: NASA's ER−2, capable of flying at very high altitudes, and the Citation, from the North Dakota University. The data analyzed in this paper was collected on board the latter.

The following probes were used to sample the cloud and acquire microphysical data for a range of hydrometeor sizes: the Forward Scattering Spectrometer Probe (FSSP−100), the two−dimensional cloud probe (2DC), the one−dimensional precipitation probe (1DP) and the High Volume Particle Spectrometer (HVPS).

3. CASE STUDY: 10 FEBRUARY 1999

Most of the flight focused on a convective system, between 1740 and 2010 UTC. The aircraft approached the convective system at about 7.6 km, sampling the first ice crystals at that height at about 1805 UTC, then ascended to approximately 8.8 km. At that level, a penetration in the form of a long (more than 100 km), almost straight line toward the northwest was performed, between 1820 and 1840 UTC. The aircraft returned to the previous level (~7.6 km) and traversed the cloud system twice, between 1845 and 1915 UTC, again following nearly linear paths. After the line penetrations were concluded, two "bow−tie" trajectories were performed, a long one and a short one, at about 10 km (1925 to 1940 UTC) and 8.8 km (1945 to 1953 UTC), respectively. Finally, the aircraft performed a descending spiral down to the 5.5 km level. A summary of the flight characteristics is show in Table 1. The track is depicted in Figure 1 and radar images of the convective system are shown in Figure 2.

As the Citation approached the cloud system at the 7.6 km level, it flew almost parallel to it, ahead (to the west) of the active convection. Passing across a relatively dry region, with no significant vertical motions, the aircraft found relatively small concentrations of ice crystals at 1606 UTC. The crystals were mostly planar, with some large dendritic/stelar−type particles and aggregates. The dominant habit (planar) shows agreement with the temperature range of −17 to −19ºC.

Departure and Landing Times	*Maximum Altitude (km)*	*Minimum Temperature (oC)*
17:26:20 − 20:49:59	10.1	−38.9

Table 1− Flight characteristics (departure and landing time, maximum altitude and minimum temperature)

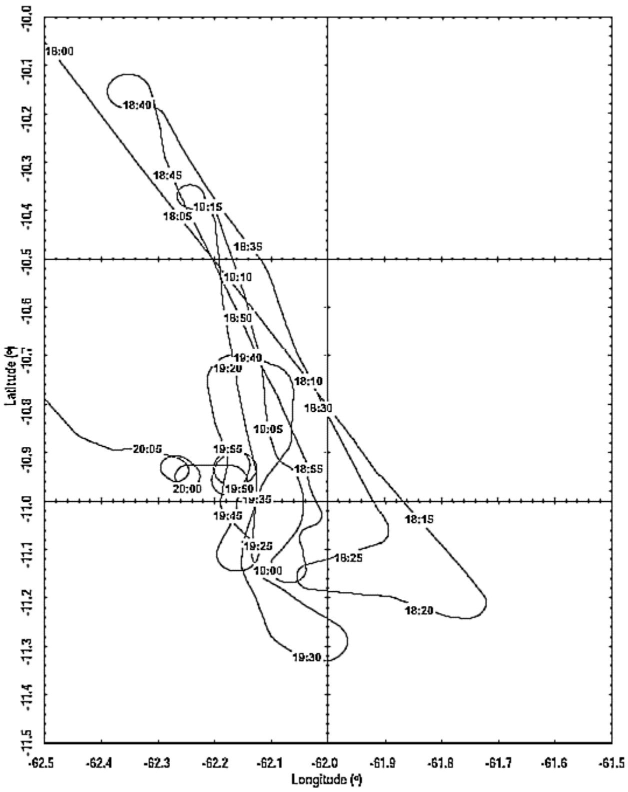

Figure 1 − Trajectory of the Citation aircraft between 1800 and 2010 UTC on 10 February 1999 with times indicated.

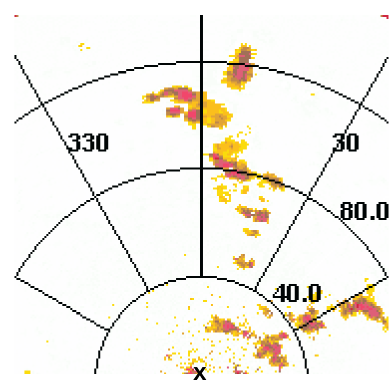

Figure 2 − SPOL radar showing a convective system observed during TRMM−LBA (10 February 1999, 1740 UTC). The "x" indicates the radar position (11S, 62W). Distance from the radar (in km) and angles are indicated.

The following passage was actually inside the convective system, at the 8.8km level. Most of the regions show saturation with respect to water and very high supersaturations with respect to ice. The dominant hydrometeor types were crystals of irregular shapes, such as graupel particles, and smaller columnar crystals, particularly at the southern portion of the system. The columnar habit agrees with the temperature range of −27 to −30ºC and a significant supply of water vapor. Other crystal shapes such as rosettes, bullets and planar crystals were also found. Relatively weak updrafts were found (less than 6 ms^{-1}) along with concentrations of FSSP, 2DC and 1DP greater than 10 cm^{-3}, 200 l^{-1} and 20 l^{-1}, respectively. Especially at the northern portion of the cloud system, the particles sampled by the FSSP were small (mean diameter of the order of 10um).

After traversing the system at about 8.8km, the Citation descended back to approximately 7.6km were two line penetrations were performed. During that penetration, the relative humidity was of the order of 80% in most regions, which means saturation or slight subsaturation with respect to ice. Nonetheless, such a pattern presented sharp discontinuities, due to the presence of strong updrafts, some of them exceeding 10ms^{-1} (including a very vigorous cell, which was penetrated twice by the aircraft, in which the vertical motion reached 20ms^{-1}. Those updrafts were warmer and moister than their surroundings, reaching saturation (or even supersaturation) with respect to water. The highest values of vertical velocity and the maxima of particle concentration (detected particularly by the FSSP) were generally co−located. The less active regions were characterized by crystal habits similar to the ones found during the first pass, at the same level, i.e., planar crystals, many of them with dendritic extensions, and aggregates of those crystals. In the more active regions, however, graupel particles were dominant. The high number concentration of hydrometeors and the supersaturated environment with respect to water may suggest that riming was taking place, contributing to the growth of the ice particles. A very large number of cloud particles was present within the major core updraft, with FSSP concentrations in excess of 200 cm^{-3}. At the same time (approximately 19:04:40), 2DC and 1DP concentrations were more than 150 l^{-1} and 20 l^{-1}, respectively. In the neighboring region, the FSSP and the 2DC concentrations dropped, while the 1DP concentration increased, suggesting a change to a small−particle to a large−particle regime. Later at the same passage, at the northern portion of the system (characterized by weak drafts and close to saturation with respect to ice), a group of CP2a and similar crystals were found, as discussed later, indicating habit superposition. Apparently, there were not new ice crystals being nucleated in that region, therefore no dominance of planar crystals (expected at temperatures of −17 to −18ºC) was found. Instead, several columnar crystals, probably formed in other regions of the cloud (e.g., aloft) were found, with or without the superposition of the planar habit.

Next, the Citation performed a bow−tie trajectory at the highest level in the entire flight (above 10 km). The aircraft encountered saturation/supersaturation with respect to water throughout almost the entire penetration. The high supersaturation with respect to ice (exceeding 40%) was accompanied by a background of 20−30 cm^{-3} FSSP, ~200 l^{-1} 2DC and ~20 l^{-1} 1DP concentrations. The mean diameters measured by the probes were also fairly uniform (of the order of 25 mm for the FSSP, 250 mm for the 2DC and 600 mm for the 1DP). The greatest changes in the particle concentration were found at a very strong updraft (the same that was penetrated in the previous straight line pass). Inside the core updraft (maximum vertical velocity close to 20 $m.s^{-1}$), FSSP concentrations nearly reached 150 cm^{-3}, i.e., more than five times greater than in the rest of the level. Despite the very sharp increase in the FSSP concentration, the 1DP concentration was only twice as large in the updraft than in other regions and the 2DC concentration changed only slightly. A mix of small crystals, double plates and irregular particles was found durring that penetration.

Following the pass above the 10 km level, the aircraft returned to an altitude of approximately 8.8 km, where it performed a short bow−tie trajectory. The temperature range was between −29 and −27oC and there were problems in the measurements of vertical wind at that time. The relative humidity was in excess of 90%, which meant supersaturations with respect to ice greater than 20%. Particle concentrations were up to 30 cm^{-3} (FSSP), 200 l^{-1} (2DC) and 50 l^{-1} (1DP) and mean diameters were of the order of 30 um (FSSP), 300 um (2DC) and 600 um (1DP). A significant variety of crystal shapes was found, with graupel−like particles, columnar crystals and double planar crystals coexisting in the same region.

Finally, the Citation entered a descending spiral trajectory, in which the cloud system was sampled from about 8km to down to roughly 5km (corresponding to a temperature range of approximately −30ºC to −2ºC). During that passage, ice crystals of a variety of habits were found, with only a weak agreement between the actual observed shape and the expected habit.

In order to illustrate the occurrence of different crystal habits within the 10 February 1999 cloud systems, 2DC images obtained during the first three penetrations are shown in Figure 3. Panel 3a depicts some ice crystals sample during the first pass. As discussed earlier, aggregates of dendritic crystals were the most prominent ice particle shape found in that region. In panel 3b, ice particles from the convectively active part of the cloud system are depicted. Relatively high concentrations of irregular shape particles were found, with distinction to graupel particles of a wide range of diameters. Columnar crystals were also found in the second pass. Finally, in the third penetration, as pointed out previously in this Section, crystals formed via habit superposition are quite common (panel 3c).

4. CONCENTRATION, MEAN DIAMETER AND SIZE DISTRIBUTIONS OF ICE PARTICLES

Despite the strong variability in the microphysical parameters (associated with the inhomogeneous nature of convection's dynamic and thermodynamic), it was observed that the maximum concentration and the dominant mean diameter were mostly uniform with height inside the 10 February 1999 cloud system.

Figure 10 depicts the observations of concentrations from the FSSP (left), 2DC (center) and 1DP (right). A tendency of exhibiting values respectively larger than 200 cm^{-3}, 0.30 cm^{-3} and 0.050 cm^{-3} is clear in all levels. Apparently, the maximum concentration tend to decrease between 6 and 7.5km, probably in association with aggregation of dendritic crystals. Concurrently, mean diameters of the order of 30 um (FSSP), 300 um (2DC) and 600 um (1DP) are predominant, although a slight decreasing tendency with height was observed, as shown in Figure 11. The presence of larger crystals at lower levels can be attributed to the joint influence of gravitational settling of larger particles, collection and aggregation processes and changes in the ice crystal habit.

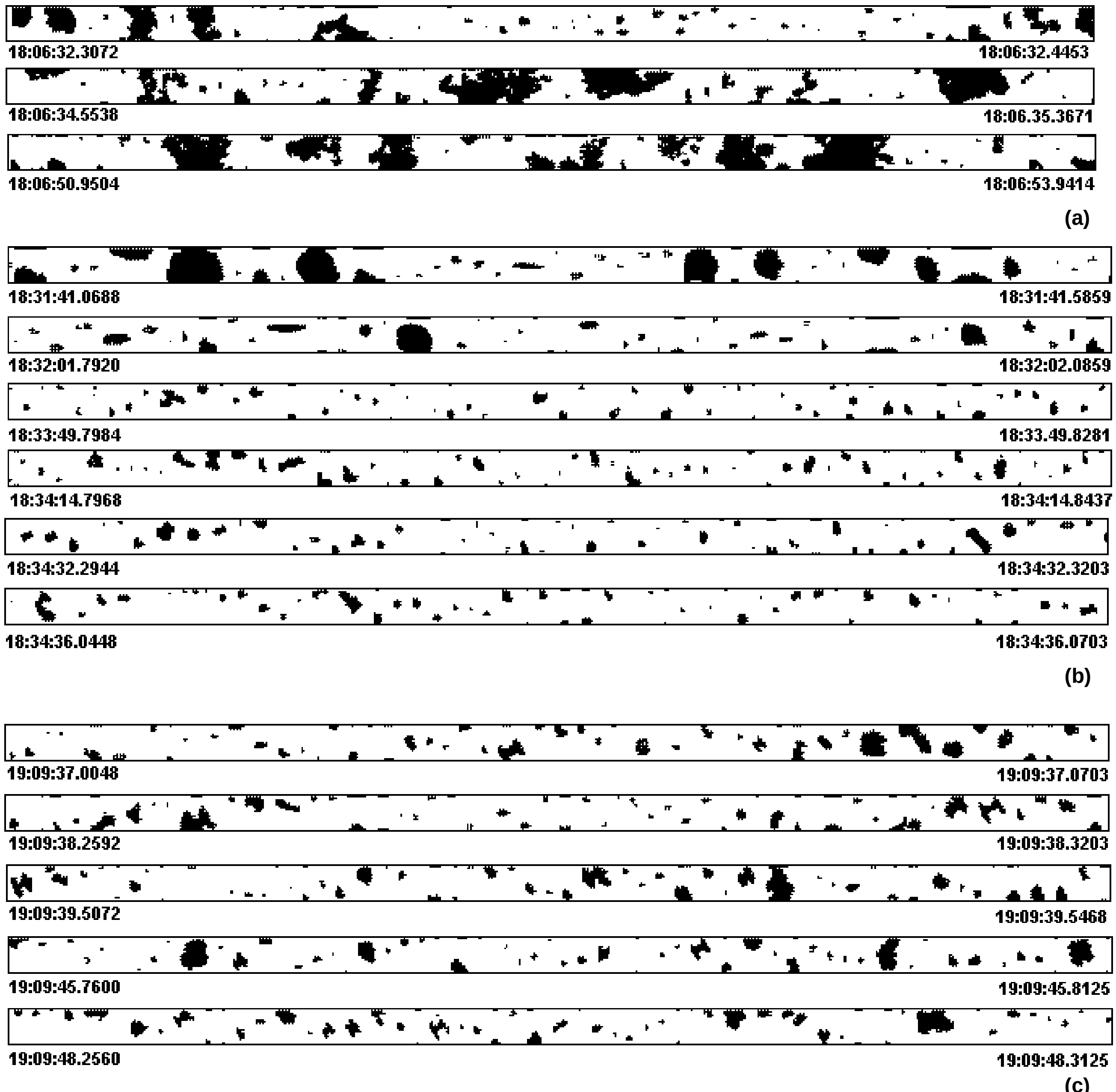

Figure 3 − 2DC images for the 1st, 2nd and 3rd pass.

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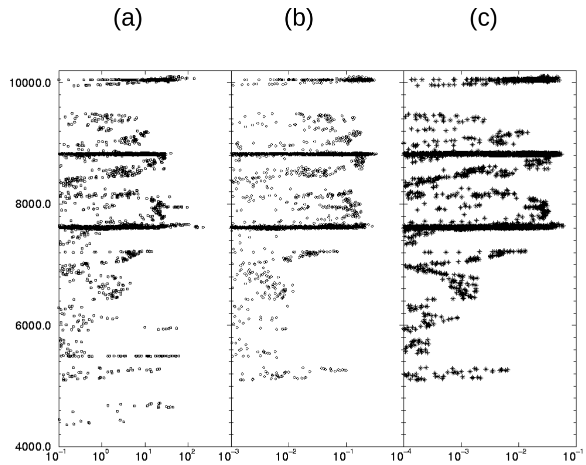

Figure 4 − Particle concentrations, in cm^{-3}, with height: (a) FSSP, (b) 2DC and (c) 1DP

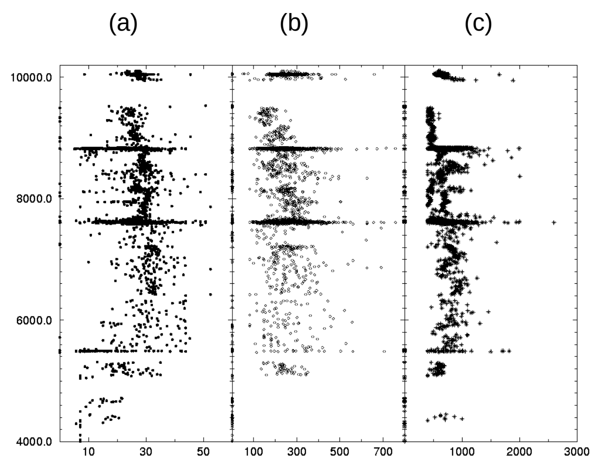

Figure 5 − Mean diameters, in um, with height: (a) FSSP, (b) 2DC and (c) 1DP

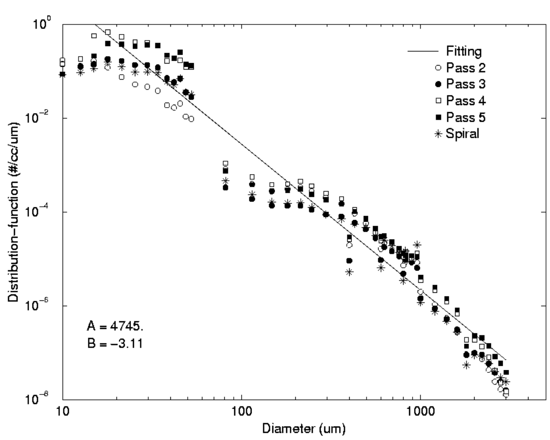

Figure 6 − Observed distribution−functions of hydrometeors for passes 2 (white circles), 3 (black circles), 4 (white squares), 5 (black squares) and descending spiral (stars), and fitting by a power law (straight line at the log−log diagram). The regression coefficients are indicated.

The size distribution of the particles larger than 10 um was also surprisingly uniform in the entire cloud and at different stages of its life cycle. Figure 6 depicts the distribution−function of hydrometeors for passes 2 to 5 and the descending spiral, as well as the best fitting for the entire set of observations. It is shown that a good fitting for the distribution of particles larger than 10 um can be attained using a power law in the form:

$$f(D) = aD^{b}$$

where a = 4745. and b = − 3.11 and D is given in um. The slope of the distribution (b) was actually close to the values found by Auer (1972) for the size distributions of graupel particles in storms over the United States, although the intercept for the Amazon system was about one order of magnitude larger.

5. CONCLUSIONS

There are significant uncertainties associated with the little knowledge on the microphysical structure of tropical convection that limit the current capability to properly model tropical precipitating cloud systems.

The Amazon convective system studied in this paper showed high particle concentrations at all levels, especially inside core updrafts. FSSP concentrations of several hundreds particles per cubic centimeter and 2DC concentrations of hundreds of ice crystals per liter were found, suggesting the existence of one or more mechanisms of massive ice nucleation within the cloud system. It is not clear what is the actual process that leads to the emergence of large concentrations. The extremely low cloud top temperatures in Amazon convective clouds can initiate homogeneous nucleation of ice from the liquid phase at higher altitudes within the cloud systems. On the other hand, at lower levels, the cloud environment was also capable to activate the riming−splintering mechanism, but the existence of very strong updrafts (as high as 20 $m.s^{-1}$) and plenty of water vapor available may suggest that the appearance of localized high supersaturations with respect to liquid water play a significant role. The break−up of crystals such as rosettes and dendrites can also respond for a minor part of the multiplication of ice.

A large variety of ice crystal habits was encountered, including combinations of superposed primary habits. A good agreement between the expected primary habit and the environmental temperature was found in the early stages of the observations. Seemingly, in later stages of the evolution of the squall system, the relationship between actual crystal shape and temperature weakened. As the squall line maturated and evolved toward dissipation, the transport of ice crystals by the cloud drafts and the settling of the larger particles allowed the appearance of ice particles with shapes other than the expected from the ambient temperature. The superposition of habits also suggests that some crystals underwent more than one growing process within the cloud system.

In contrast with the diversity of ice crystal shapes, however, the squall line exhibited a fairly uniform behavior with respect to the maximum particle concentration, mean diameter and size distribution in the vertical, which is a positive aspect looking at the issue of representing its microphysics in cloud−resolving to larger scale models.

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