P5.8 *IN SITU* MEASUREMENTS OF PARTICLE SIZE DISTRIBUTIONS IN HURRICANE HUMBERTO

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1. INTRODUCTION

Microphysical measurements were acquired aboard the NASA DC-8 aircraft during the Fourth Convection and Moisture Experiment (CAMEX-4) field campaign in August and September of 2001. A suite of particle imaging instruments recorded ice particle images, sizes, and concentrations across a large size range. We present measurements that were made by these instruments during an intensive 3-day study of Hurricane Humberto on September 22, 23, and 24. Observations include surprisingly high particle concentrations and large particles (7 mm) at altitudes up to 39000 feet. While previous reports of particle observations within hurricanes exist (e.g. Black and Hallett 1986, Houze, et al, 1992), they are focused in the lower portions of the storms at temperatures above –10 C. This report focuses on the upper portions of the storm, where the microphysical effects on satellite observations and cloud-top radiation are most important.

2. INSTRUMENTATION

The probes considered in this report include the Particle Measurement Systems (PMS) 2D-C and 2D-P imaging probes, both of which have been upgraded by Droplet Measurement Technologies (DMT) for modern electronics and 64-element diode imaging arrays. The pixel resolution of these probes is 25 µm and 100 µm, respectively, and together they cover a size range from roughly 50 µm to several centimeters. The images recorded by these probes were sized by the maximum diameter in any direction, and a reconstruction technique (Heymsfield and Parrish, 1978) was used measure particles that touched the edges of the imaging array. The particle sizes and concentrations in the overlap range between these two probes (roughly 500-1500 µm) compare extremely well in most cases. The size spectra reported here use the 2D-C concentrations up to 1000 µm, and the 2D-P concentrations above 1000 µm. An FSSP-100, also upgraded by DMT, was also on board the NASA DC-8 and recorded particle sizes and concentrations from 3 µm to 45 µm.

Several other probes were also on board, including a SPEC, Inc. Cloud Particle Imager for high-resolution imagery, a Nevzorov condensed water content sensor, and a Counterflow Virtual Impactor, which measures condensed water content and residual solid particles from evaporated cloud particles. Results from these probes will be presented in future publications.

3. OBSERVATIONS AND RESULTS

a. September 22, 2001: Humberto was a tropical depression roughly 500 km SSW of Bermuda at the time of takeoff, and strengthened to tropical storm intensity during the flight. The DC-8 flew at an altitude of about 8500 meters (-27 C) for the first half of the flight, then climbed to 9500 meters (-35 C) for the remainder of the flight. About 3 hours of continuous in-cloud data were recorded as the DC-8 flew multiple patterns within the storm. The 2D-C worked well and recorded over 15 million particles, but the 2D-P was only working sporadically and is not shown here. Concentrations recorded by the 2D-C from 75-2000 µm are shown in Fig. 1a. Peak concentrations are generally around 750/L, with one brief spike up to 2000/L, probably indicating the presence of a large updraft. Particle images during the spike consist of large numbers of small (less than 200 µm) irregularly-shaped particles interspersed with a few large, rounded, graupel-like particles in the 1-2 mm size range. The FSSP 3-45 µm data also show very high cloud droplet concentrations (Fig. 1b), often topping 60/cc with the largest spike above 170/cc, which is coincident with the spike in the 2D-C concentrations.

b. September 23, 2001: Humberto strengthened to hurricane intensity during the course of this flight as it passed about 250 km to the west of Bermuda. The flight followed a 'bow tie' shaped pattern, in which the entire storm was transected 3 times (see Fig. 2). The first pass through the center of the storm occurred while the aircraft was climbing from an altitude of 8000 meters (-23 C) to 10700 meters (-45 C). The aircraft then climbed to 11900 meters (-57 C) for the remaining two passes. Peak 2D-C and FSSP concentrations (Figs. 1c and 1d) are comparable to the previous day, even though the aircraft was flying at a much higher altitude and was in-cloud for a much shorter length of time. Each pass through the center of the storm is characterized by 2D-C concentrations of about 1000/L, and FSSP concentrations of about 50/cc. The 2D-C was temporarily inoperational during the second pass, as was the FSSP during the third pass. The 2D-P

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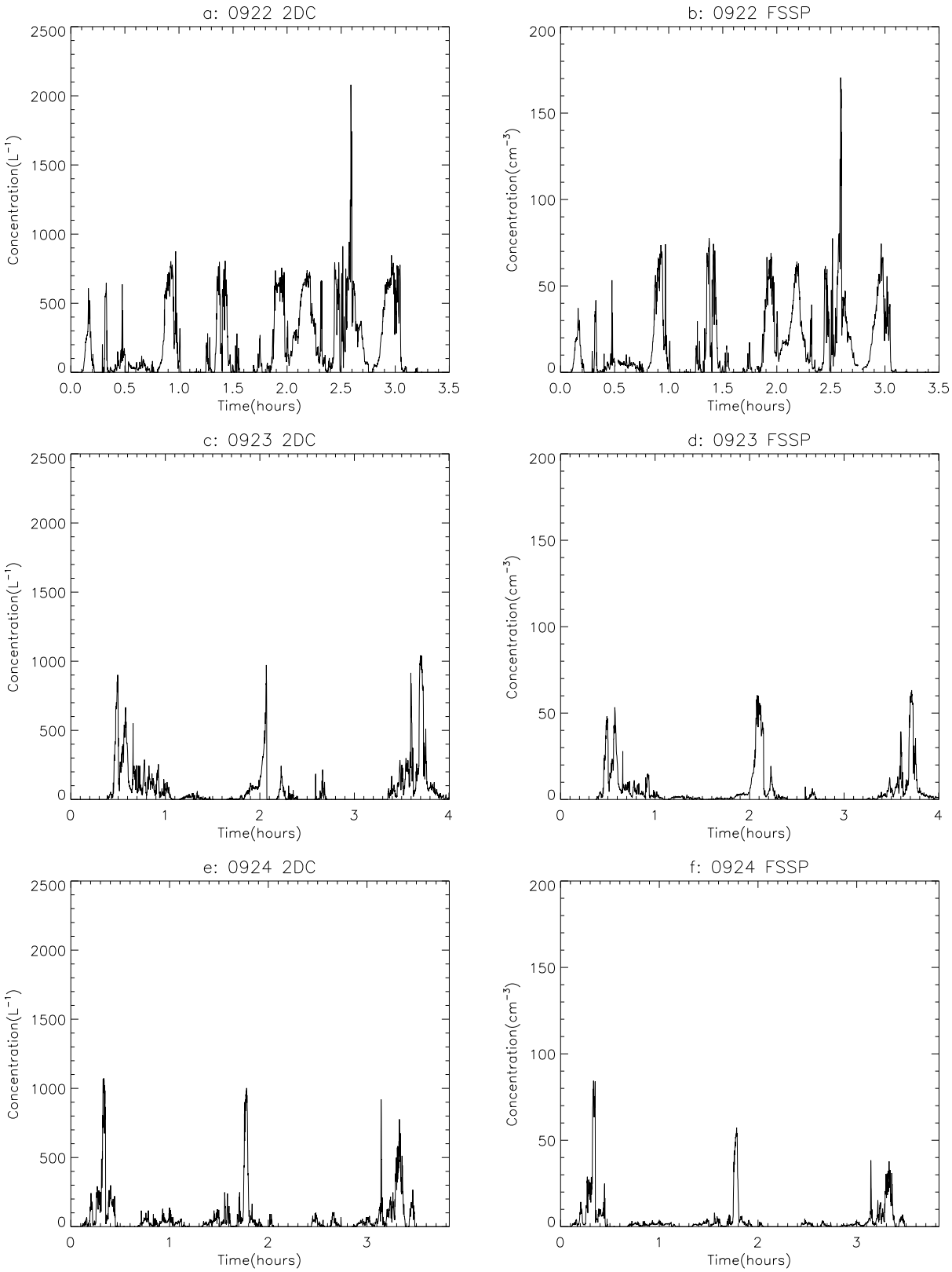

Figure 1. Time-series plots for 2D-C concentrations (75-2000 microns) and FSSP concentrations (3-43 microns) for Sept 22, 23, and 24.

worked well during this flight, so more information regarding the larger particles is available.

A composite 2D-C + 2D-P spectral plot is shown in Fig. 3. Concentrations are color coded, with high concentrations shown in red colors, and low concentrations in blue colors. Particle diameter is indicated on the y-axis and elapsed time is shown on the x-axis. The aircraft flew through the center of the storm at the 500-second mark indicated on the plot. High concentrations of small particles are found on both sides of the storm center in bands that are roughly 50 km wide. The storm center itself is characterized by markedly lower concentrations of small particles than the surrounding convective bands, yet concentrations of particles greater than 1000 µm remained comparable to other areas of the storm. Additionally, the largest particles were found about 70 km from the storm center, suggesting that they are not necessarily coincident with large concentrations of small particles.

Ice water content (IWC) has been derived from the particle concentration measurements following the methods in Heymsfield, et al (2002). IWC peaks at over 2.5 g/m^3 in the first pass, and at about 1.0 g/m^3 in the final two passes.

Strongly bimodal spectra are present in two regions roughly 150 and 230 km north of the storm center (at 1200 and 1550 seconds in Fig. 3). Particles with sizes in the 100-400 µm range are severely depleted, while there is a simultaneous enhancement in the concentration of particles greater than 1000 µm. The derived IWC values in this area are relatively steady, suggesting that the bimodalities could be the result of enhanced aggregation in the 100-400 µm range.

c. September 24, 2001: Hurricane Humberto had started moving to the northeast, and was located about 350 km north of Bermuda. The flight pattern was identical to the one flown on September 23, but at a nearly constant altitude of 11300 meters (-51 C). The 2D-C and FSSP maximum concentrations (Figs. 1e and 1f) are still similar to the previous day, but the extent of these regions appears to be much shorter, indicating that the storm updrafts may have been weakening.

A colorized plot of the particle size spectra during the first pass is shown in Fig. 4. The storm center is at about 500 seconds as indicated on the plot. The concentric nature of the storm is obvious from this plot, showing alternating bands of high and low concentrations as one moves radially outward from the center. Particles in the 2-3 mm size range are regularly observed (often in the shape of capped columns), with particles as large as 7 mm being found in one convective band. Some of the very large (> 1 cm) particles shown in Fig. 4 appear to be instrument artifacts. Again, the presence of high concentrations of small particles is not required for the existence of larger particles.

Computations of derived ice water content peak at 2.2 g/m^3 for this pass (in the area of the largest particles), and peak at about 1.0 g/m^3 during the following two passes. No bimodal spectra of the type observed on Sept. 23 have been found.

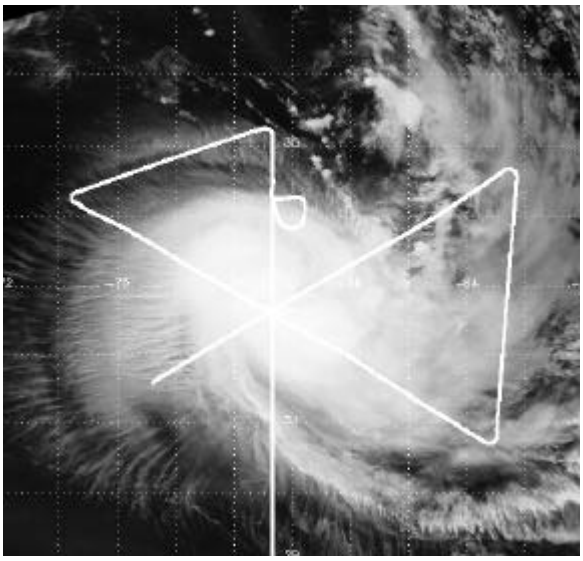

Figure 2. Flight track on September 23. The first leg went from south to north. Satellite data provided by NOAA/NCDC.

4. SUMMARY

Microphysical particle data for a 3-day period have been collected in the upper regions of an intensifying tropical storm. Results show that very high concentrations of small particles can exist at these altitudes, as can particles with diameters up to at least 7 mm. Passes through the center of the storm on September 23 and 24 show that the strongest parts are characterized by IWC values of at least 1 g/m^3, FSSP concentrations of at least 50/cc, and 2D-C concentrations of about 1000/L at temperatures as cold as –57 C. Regions of large particles and strongly bimodal spectra also exist away from the storm center.

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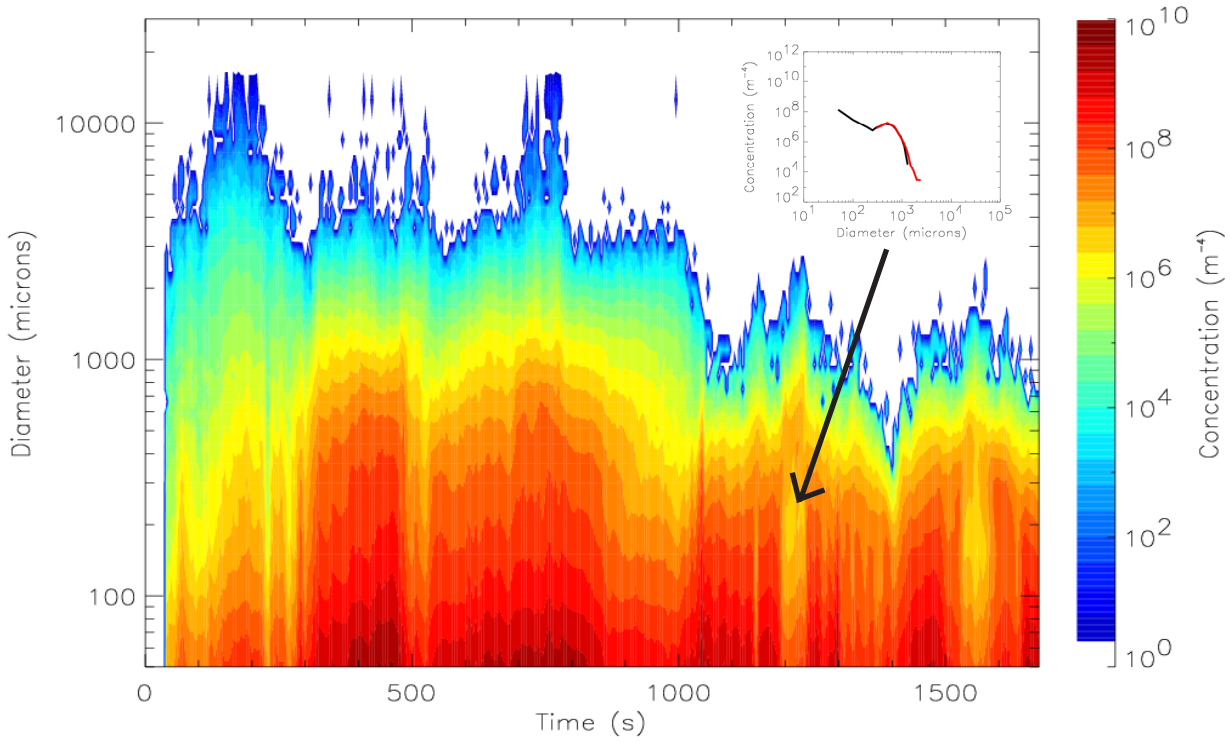

Figure 3. Particle size distributions on first pass through storm center on Sept. 23. Center is at 500 seconds. Bimodal size distributions are at 1200 and 1550 seconds. The aircraft was flying at approximately 220 m/s. Inset shows a more detailed view of a bimodal distribution. 2D-C probe is shown in black, 2D-P probe is in red.

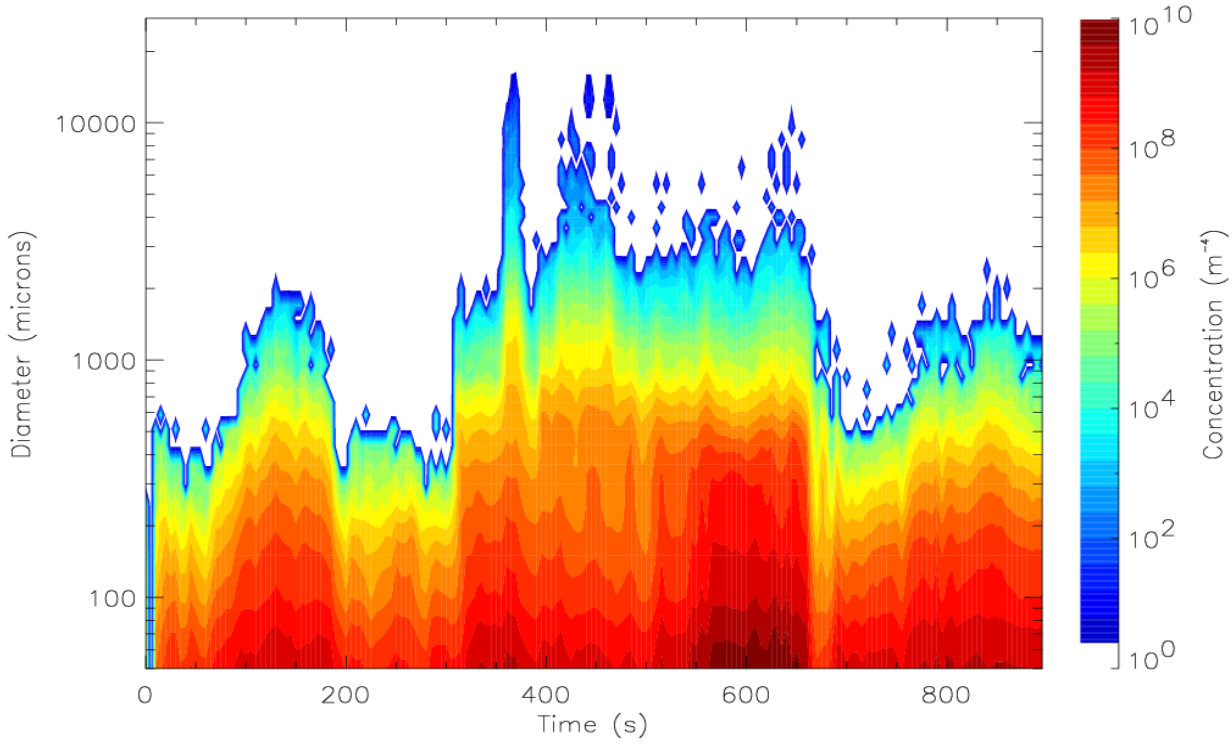

Figure 4. Particle size distributions on first pass through storm center on Sept. 24. Center is at 500 seconds. The aircraft was flying at approximately 220 m/s.