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MESOSCALE PATTERNS OF ICE PARTICLE CHARACTERISTICS IN HURRICANE NORBERT

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1. Introduction

The precipitation in the inner-core region of a hurricane (i.e., the region within about 50-100 km of the of the eye) is characterized by a ring of heavy eyewall rain and a surrounding region of lighter stratiform precipitation. Marks (1985) and Marks and Houze (1987) have found that about 60 % of the inner-core precipitation falls in the surrounding annular zone of stratiform rain. Black and Hallet (1986) found that hurricanes are glaciated everywhere above the -5°C level and that convective updrafts in the eyewall region contain graupel along with some supercooled drops while convective downdrafts adjacent to the updrafts tend to be characterized by high concentrations of small ice particles, many of which are columns and needles. The stratiform areas are characterized by aggregated snowflakes. Columnar crystals are also found in the stratiform areas, but only within 10-15 km of convective updrafts. Black and Hallet surmised that much of the ice in the stratiform regions originates through secondary nucleation within the eyewall updrafts and is then redistributed throughout the storm by the upper and midlevel radial outflow component of the secondary circulation associated with the hurricane vortex. Marks and Houze (1987) have shown that the ice particles advected from the upper levels of the eyewall by the radial flow are carried as many as 1 1/2 times around the storm by the strong tangential flow (i.e. the primary circulation) of the vortex before they reach the melting level. Thus, ice particles generated in and detrained from the top of convection at a particular location along the eyewall form a slowly descending plume that spirals gradually outward from the eyewall while winding around the entire storm. In this way, convection at one point in the eyewall seeds the precipitation pattern in the annular region surrounding the eyewall.

Since ice-particle image data are typically collected along an aircraft flight path, and because the routes followed are usually designed to collect a variety of data, of which cloud microphysical measurements are only one part, the horizontal patterns of ice-particle data on which previous results are based have generally been determined only for limited areas of storms. To fill this observational gap, flights in Hurricane Norbert (which occurred off the west coast of Mexico in 1984) were conducted with one NOAA WP-3D aircraft dedicated to mapping the microphysical characteristics of the inner-core region of the storm at the 6 km level (0 to -10°C), which was the highest level at which the aircraft was able to fly on this occasion. (At the same time a second WP3D was operating at a lower level, collecting Doppler radar data to document the kinematic structure of the storm.)

The objectives of the study are to determine the horizontal distribution of ice particle types, concentrations and sizes throughout the inner-core region of the storm at the 6 km flight-level and to infer from these horizontal patterns the influence of the eyewall convection on seeding the annular region around the eyewall.

2. Data and methods of analysis

Two PMS probes were on the aircraft. The "precipitation probe" (2DP) has a diameter range of 0.2-6.4 mm in 0.2 mm steps, while the "cloud probe" (2DC) has a range of 0.05-1.6 mm in 0.05 mm steps. Particles were classified by size according to the equivalent circle diameters of the images on each probe. On the 2DC, the categories were: *2DC-small*— 0.05 to 0.5 mm; *2DC-medium*— 0.55 to 1.05 mm; and *2DC-large:* > 1.05 mm. On the 2DP, they were: *2DP-small*— 0.2 to 2 mm; *2DP-medium*— 2 to 4 mm; and *2DP-large:* > 4 mm. Many particles were observed in each of these size categories, except for 2DP-large, in which category only very few particles were observed. The 2DC-medium and large particles were further subdivided according to particle shape. Particles for which the eccentricity of an ellipse fitted to the image was > 0.9 (length to width ratio ≈ 3.5:1) were called *columns*, since their images appeared qualitatively to be columnar crystals, while particles for which the eccentricity was < 0.4 were referred to as *nearly round* . Medium and large 2DC images not classified as either columns or nearly round appeared to have been aggregates of ice crystals. The nearly round particles appeared to have been graupel when seen in regions of active convection and aggregates when seen in stratiform regions devoid of significant liquid water.

Only a few images of drops were obtained at the 6 km level, and these were all found in crossings of the eyewall, where the flight-level temperature was maximum. No cloud-liquid water was observed with the Johnson-Williams probe except at these locations. Drops and all bad images as defined by Black and Hallet (1986) were deleted. In addition, "broken" images, which are said to occur if more than one shadow is found between time marks, were deleted.

The number concentrations of particles have been determined for each of the five size categories (2DC-small, medium and large, and 2DP-small and medium) and for the total of all particles seen on both the 2DC and 2DP. In addition, number concentrations of columns and needles (as defined above) were determined. Mass concentrations for the 2DC and 2DP data were computed using the equivalent circle diameters of the images and an ice-particle density of 0.1 g cm^{-3}.

The flight track of the upper-level aircraft consisted of a sequence of overlapping wedge-shaped circuits extending radially outward from the eye and covering all portions of the storm, but emphasizing the most active southwestern quadrant (see Houze *et al.*, 1985, for a map of the flight tracks). The mass and number concentrations were determined for finite increments of the flight path. The mesoscale variations of concentration appeared to be well represented by 5 km resolution data. Hence, a horizontal cartesian coordinate system centered on the storm was divided into a grid of 5-km square bins. Then each 5-km resolution data sample along the flight track was assigned to the cartesian bin in which it was centered. Mesoscale fields were then obtained by averaging all of the samples in each cartesian bin, and drawing contours to represent the gridded and averaged data. These fields are overlaid, for reference, on a pattern of radar reflectivity observed with the lower-fuselage radar of the lower-level aircraft.

3. Results

A measure of the characteristic particle size within

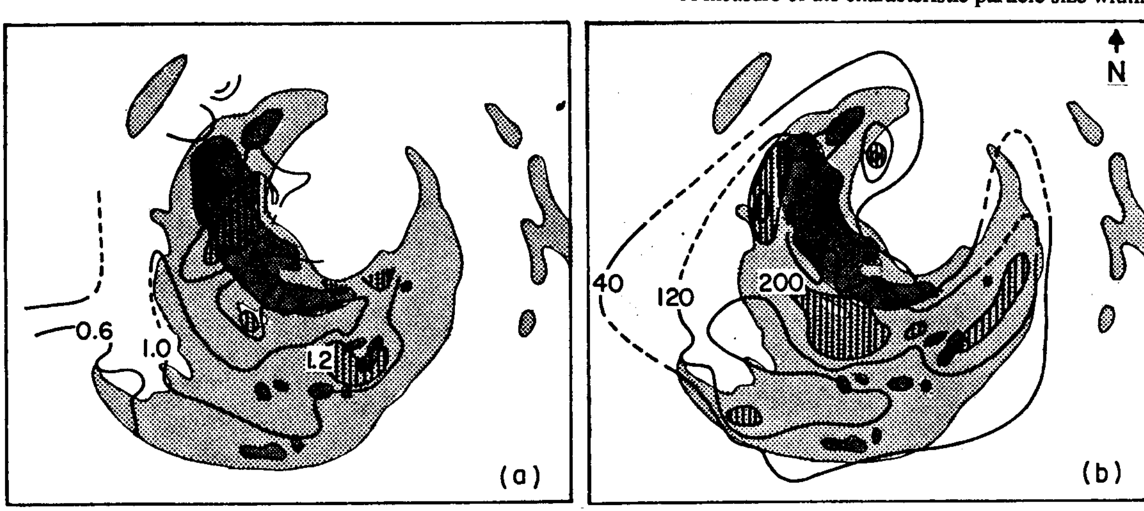

Figure 1. (a) Contours of median diameter of particles observed with the 2DC aboard the NOAA P3 aircraft in Hurricane Norbert shown by solid lines for values of 0.6, 1.0 and 1.2 (interior of 1.0 and 1.2 are hatched) mm. (b) Contours of 2DC particle concentration at the 6 km level shown by solid lines for 40, 120 200 and 280 (interior hatched) per liter. Particle images were obtained at the 6 km level between 0020 and 0420 GMT 25 September 1984. The contours are overlaid on a composite radar reflectivity pattern based on lower-fuselage radar data obtained from 00128-0215 GMT.

an observed population of particles is the *median volume diameter*, defined as the particle diameter that divides the number distribution in half. Isolines of median volume diameters of the size distributions measured by the 2DC probe is shown in Fig. 1a. A similar pattern was seen in the 2DP data, except that the median volume diameters were generally larger for the 2DP. The median volume diameter was highly correlated with radar echo intensity, more so than any of the other fields we derived from the PMS data. Separate elongated maxima of median volume diameter coincided with the eyewall eyewall radar echo surrounding the eye from northwest-southwest-southeast and the stratiform echo band located generally southwest of the eye. Thus, the both the eyewall echo band and the stratiform band were the loci of generally larger ice particles than elsewhere in the storm at the 6 km level.

The total number of particles, per unit volume of air, sampled by the 2DC are indicated in Fig. 1b. Since number concentrations are dominated by the smallest particles present, the 2DC concentrations were always larger than the 2DP, ranging between about 40 and 350 per liter, with typical values of 100 per liter, while the 2DP concentrations (not shown) were 10-70 per liter. The peak values of number concentration (on both the 2DC and 2DP) occurred in a ring surrounding but displaced 10-20 km radially outward from the eyewall radar echo band. A secondary azimuthally elongated maximum of particle concentration was located 60-70 km southwest of the storm center within the stratiform echo band. Individual peaks in number concentration were very strongly anticorrelated with peaks in the patterns of median volume diameter (cf. Fig. 1a). The ring of high particle concentrations surrounding the eyewall echo band indicates that large concentrations of small particles (which dominated the number concentration) characterized the annular strip lying between the eyewall heavy rain zone and the outer stratiform echo region.

4. Conclusions

The results in Figs. 1a and b indicate that at the 6 km level larger particles occurred within the eyewall radar echo region and within the stratiform rainband, while the highest concentrations of particles, nearly all in the small size category, were found in an annular region displaced 10-20 km radially outward from the eyewall rainband. Evidently, small particles in both the convective and stratiform rainbands were swept out by larger particles in the areas of heavier precipitation. This pattern is consistent with the pattern of precipitation fallout suggested by Marks and Houze (1987) for the inner-core region of Hurricane Alicia (see their Fig. 9). According to this pattern, ice particles generated in the eyewall updraft are advected radially outward, with the initially larger particles falling out in the eyewall rainband while the initially smaller particles are carried up and advected outward to fall out eventually in the stratiform rainband region. In the annular region lying between the fallout zones of these two characteristic types of particles, evidently the smaller particles are not as effectively swept out, leaving the zone of higher concentration in between.

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