P3.15 EXTRA LARGE PARTICLE IMAGES AT 40,000 FT. IN A HURRICANE EYEWALL: EVIDENCE OF PARTIALLY FROZEN RAINDROPS?

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1. Introduction.

Classical cloud physics (e.g. Pruppacher and Klett, 1978) indicates that supercooled water freezes homogeneously at a rapidly increasing rate as the temperature of the drops approaches -40°C. The homogeneous nucleation rate is also faster for (large) raindrops than cloud drops. The growth rate of the ice embryos at these temperatures is also expected to be so fast that the drops that are nucleated freeze instantly. These results are so compelling that most researchers assume all liquid water freezes at -40°C, indicating the need for caution in interpreting data that seem to indicate the existence of supercooled cloud in the absence of in-situ observations.

Nevertheless, deeply supercooled cloud liquid water has occasionally been reported. Lidar measurements in cirrus clouds at temperatures colder than -20°C (Sassen and Benson, 2001) and aircraft penetrations at temperatures as cold as -37.5°C in midlatitude convection (Rosenfeld and Woodley, 2000) both indicated that supercooled cloud existed. In the case of Rosenfeld and Woodley, the accumulation of rime ice on the windscreen of their aircraft proved that supercooled cloud was present. Neither of these researchers mentioned observing precipitation

Tropical oceanic convection is not known for the strength of its updraft, but exceptions occasionally occur in hurricanes. Hurricane Emily on 22 September 1987 was one such storm (Black et al, 1994). This hurricane was observed to contain updrafts with peak vertical velocities > 20 m s^{-1} near the melting level continuously for several hours while it was finishing a rapid deepening cycle. Updrafts of this magnitude are required to loft substantial quantities of supercooled cloud drops, raindrops and dense graupel to high altitude. However, we never obtained any direct measurements of particles to confirm that this actually occurs in a hurricane. This situation changed in 1998, when the NASA DC-8 aircraft made several eyewall penetrations in Hurricane Bonnie at about 12,000 m MSL on 23 August 1998. On this day, Bonnie was located east of the Bahamas at about 24.7 N, 71.7 W and was drifting slowly NW at about 2 m s^{-1}.

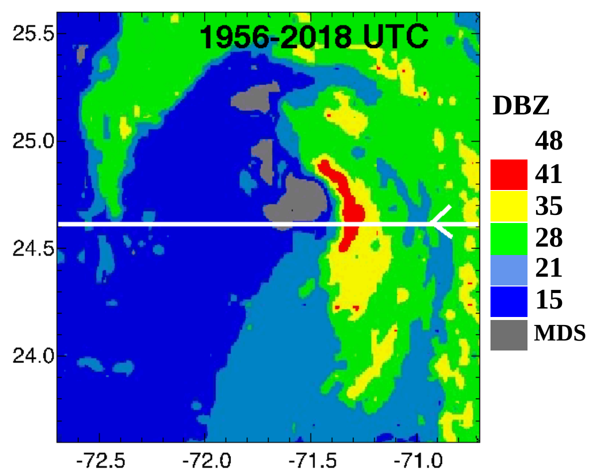

Figure 1: CAPPI at the 12 km altitude made from the NOAA WP-3D aircraft near the time of the ER-2 and DC-8 passes. The ER-2 flight track is shown. Adapted from Heymsfield et al, 2001.

2. Data.

The horizontal PPI radar data were obtained by the NOAA WP-3D aircraft. Doppler radar data presented here were obtained from the NASA ER-2 aircraft, and flight level pressure, temperature, relative humidity and winds were from the DC-8. The discussion about how these data

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were analyzed, as well as a good description of the strong convection in Bonnie's eyewall is found in Heymsfield et al, 2001. High altitude particle image data were obtained from the NASA DC-8 aircraft consisted of Particle Measuring Systems, Inc. 2-D OAP 2D-P (0.2 ¯6.4 mm) and 2D-C (0.025 ¯0.8 mm) image data. The OAP image data were processed using the methods of Black and Hallett (1986), and the imagery were saved as image files for easy perusal. Quicktime™ format movie loops of the images presented here are available from AOML's anonymous FTP site ftp.aoml.noaa.gov in directory pub/hrd/rblack/CAMEX3.

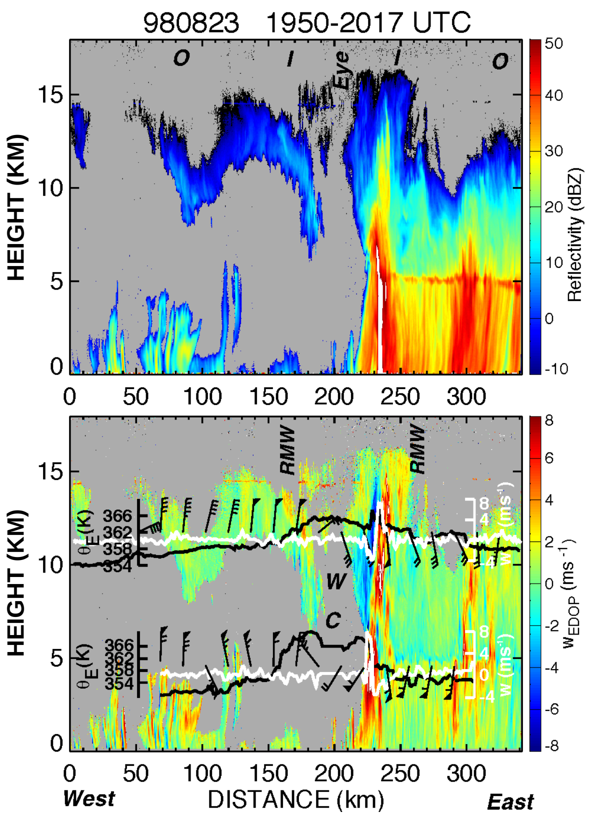

Figure 2. NASA ER-2 Doppler radar (EDOP) cross-secion. The DC-8 and NOAA WP-3D vertical velocity and θ_e are superimposed on the Doppler plot. Radar from Heymsfield et al, 2001.

The DC-8 pass we are interested in occurred on an E-W run (Fig. 1) at an altitude of 11,760 M and a temperature of ¯40°C. The NASA ER-2 made an overflight of the storm coordinated with the DC-8. The DC-8 penetrated the upwind edge of the high altitude reflectivity core in the east eyewall. On the ER-2 radar (Fig. 2), this part of the eyewall exhibited an elevated reflectivity maximum that extended well above the 12 km flight level. Rainfall was continuous down to the surface at this location. Substantial vertical velocity on the order of 8 m s^{-1} was observed in the high reflectivity zone, a necessary condition for supporting large particles at this altitude.

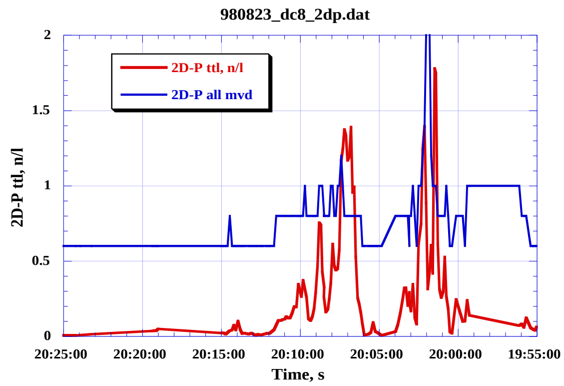

Figure 3. 2D-P Number concentration and Median Volume Diameter (MVD) from the NASA DC-8 2D-P. Data correspond to the radar data in Fig. 2

Prior to and after encountering the large particles, the 2D-P and 2D-C both observed the usual assortment of small (< ~1 mm) irregular ice particles (Fig. 3) expected in a convective anvil. Notice the sharp peak in the median volume diameter (MVD) and number concentration in the east eyewall near 2001:00 which corresponds to the middle of the East eyewall.

The larger particle sizes in the East eyewall is apparent from the spike in the 2D-P MVD. Representative images are shown in Fig. 4. The larger images are 2 - 3 mm in diameter, but the most surprising is the (rejected) splash images in the third row under the label. Such images are unusual in hurricane ice data at -5°C obtained at lower levels by the NOAA WP-3D aircraft, except in narrow mixed-phase regions in the eyewall. In fact, they are reminiscent of the splash images obtained in mixed-phase convection and/or rain, an example of which are presented in Figure 5.

The next question to be considered is if these particles are indeed only partially frozen at these temperatures, what phenomenon can account for this behavior? Figure 5 shows some 2D-P images observed with the same 2D-P just below the melting level in a Oklahoma Mesoscale Convective System (MCS). Note the large partially melted particle in the first strip, and the other large images in the fourth and sixth strips. Note the shapes of these images. While this is not definitive evidence, is is certainly suggestive. Some

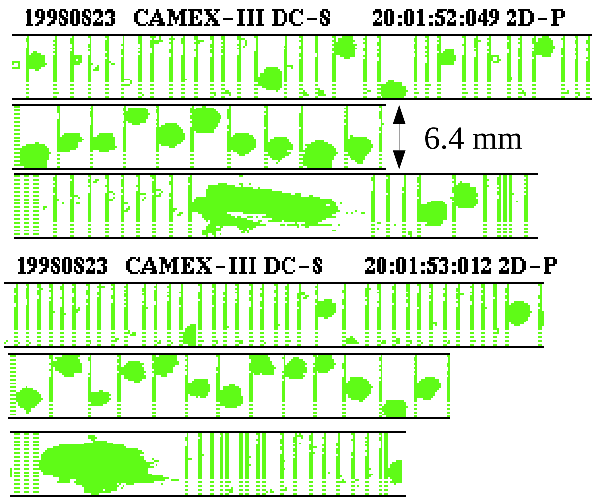

Figure 4: Large particle images observed with the NASA DC-8. The rejected images are in the third row following the strip label.

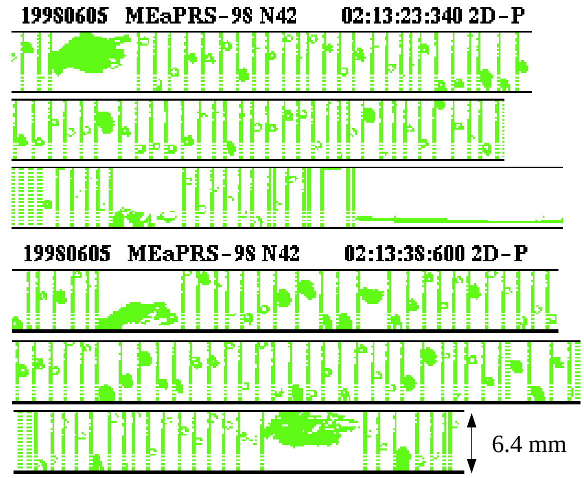

Figure 5: 2D-P images from a descent through a melting layer in a Midwestern MCS. Note the splash images in the first and sixth strips. These images were obtained at a temperature of +1°C.

additional points to consider: First, the images in Figure 4 were observed at ~12 Km MSL at a temperature of -40°C in a hurricane, whereas those of Figure 5 were at ~4 Km AGL at a temperature of ~0°C.

3. **Discussion**.

If we are to believe that the images of Fig. 4 are only partially frozen at best, then either the particles were advected to these levels with extreme rapidity, or the basic assumptions about the vapor pressure difference (a proxy for the entropy difference) between ice and deeply supercooled water must be considered. Assuming the particles were advected vertically from the melting level (~5 km) at 10 m s^{-1} (a large underestimate of the true advection time), at least 700 seconds are required for them to reach the DC-8 flight level. This is clearly more than enough time for all supercooled drops to be nucleated and frozen. Just such an effect was reported at the 13'th ICCP in Reno, Nevada by Prof. N. Fukuta. Fukuta attempted to directly measure the equilibrium vapor pressure of deeply supercooled water. Fukuta's results indicated that at temperatures colder than -20°C, the difference between the saturation vapor pressure over ice and that over supercooled water rapidly decreases, becoming nearly zero at temperatures below -40°C.

Such results, if they can be confirmed, would seem to indicate that if water can be supercooled to ~-40°C without freezing, it may become nearly stable, and persist for substantial time. This in turn would complicate attempts to model radiative transfer though such mixed-phase clouds. In the hurricane context, the existence of large partially frozen particles to the upper reaches of the eyewall will interfere with efforts to remotely retrieve the eyewall precipitation structure, particularly its vertical distribution.

4. **References**.

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