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Observations of Florida Convective Storms Using Dual Wavelength Airborne Radar

G. M. Heymsfield[1], A. J. Heymsfield[2], L. Belcher[3]
[1]NASA/ Goddard Space Flight Center, Greenbelt, MD
[2]National Center for Atmospheric Research, Boulder, CO
[3]Science Systems and Applications, Inc., Lanham, MD

1. INTRODUCTION

NASA conducted the Cirrus Regional Study of Tropical Anvils and Cirrus Layers (CRYSTAL) Florida Area Cirrus Experiment (FACE) during July 2002 for improved understanding of tropical cirrus. One of the goals was to improve the understanding of cirrus generation by convective updrafts. The reasons why some convective storms produce extensive cirrus anvils is only partially related to convective instability and the vertical transport ice mass by updrafts. Convective microphysics must also have an important role on cirrus generation, for example, there are hypotheses that homogeneous nucleation in convective updrafts is a major source of anvil ice particles. In this paper, we report on one intense CRYSTAL- FACE convective case on 16 July 2002 that produced extensive anvil.

During CRYSTAL-FACE, up to 5 aircraft flying from low- to high-altitudes, were coordinated for the study of thunderstorm-generated cirrus. The NASA high-altitude (20 km) ER-2 aircraft with remote sensing objectives flew above the convection, and other aircraft such as the WB-57 performing in situ measurements flew below the ER-2. The ER-2 remote sensing instruments included two nadir viewing airborne radars. The CRS 94 GHz radar (Li et al 2004) and the EDOP 9.6 GHz radar (Heymsfield et al. 1996) were flown together for the first time during CRYSTAL-FACE and they provided a unique opportunity to examine the structure of 16 July case from a dual-wavelength perspective. EDOP and CRS are complementary for studying convection and cirrus since CRS is more sensitive than EDOP for cirrus, and EDOP is considerably less attenuating in convective regions. In addition to the aircraft, coordinated ground-based radar measurements were taken with the NPOL S-Band (3 GHz) multiparameter radar. One of the initial goals was to determine whether dual-wavelength airborne measurements could identify supercooled water regions.

Corresponding author address: Gerald M. Heymsfield, Goddard Space Flight Center, Lab. For Atmospheres, Code 912, Greenbelt, MD 20771; e-mail: gerald.heymsfield@nasa.gov

2. CONVECTIVE EVENT ON 16 JULY 2002

The forecast for 16 July 2002 called for mid-afternoon convection along a synoptic-scale band of low-level moisture convergence extending from an off-shore (Florida east coast) disturbance across the Florida peninsula. The KAMX (Miami) 1200 UTC sounding indicated a moist lower layer (up to 1.5 km) and a strong instability (CAPE of 2598 J kg^{-1}), while the 0000 UTC sounding showed a CAPE of 2119 J kg^{-1} with moderate directional wind shear (300° shear vector). Sea-breeze convection began shortly after 1600 UTC on the east coast of Florida producing a strong thunderstorm north of the KAMX radar. A region of inland convection began at 1845 UTC along an outflow boundary generated by the above mentioned storm. The convective system had many embedded cells, with some strong cells typical of those observed during the CRYSTAL-FACE flights on other days. Figure 1 shows the 3 km and 8 km CAPPIs from NPOL during one of the ER-2 passes. A particularly intense cell (Cell 2) is noted with reflectivities exceeding 60 dBZ at 3 km altitude, and 55 dBZ at 8 km altitude.

Figure 2 shows a height-time history of Cell 2's maximum reflectivity constructed from NPOL CAPPI data. The cell underwent rapid development prior to 1940 UTC and maximum radar-derived storm top height was at 1950 UTC. The peak reflectivity for this cell also occurred at 1950 UTC with 62 dBZ at 4 km altitude; this was about 5 min after the ER-2 pass over the cell. The cell evolution presented in Fig. 2 is typical of convection evolution where an intense growth period is followed by a weakening of the updraft followed by descent of precipitation from higher altitudes.

Figure 3 provides an NPOL-derived vertical reflectivity cross-section through the high reflectivity core of Cell 2 at 1950 UTC. The differential reflectivity (Z_{DR}) contours up to about 3 dB below the freezing level (5 km) are typical for rain drops, and the near-zero (Z_{DR}) values combined with >55 dBZ reflectivities above the freezing level are commonly observed in hail storms (e.g., Bringi et al. 1996). The NPOL volume scan 10 min earlier at 1940 UTC was very different in that the enhanced Z_{DR} region indicating the presence of liquid or mixed phase region, extended up to about 6-6.5 km altitude and the maximum refelctivities were ~55 dBZ (not shown). If hail were present, strong updrafts would be required to loft particles to high altitudes.

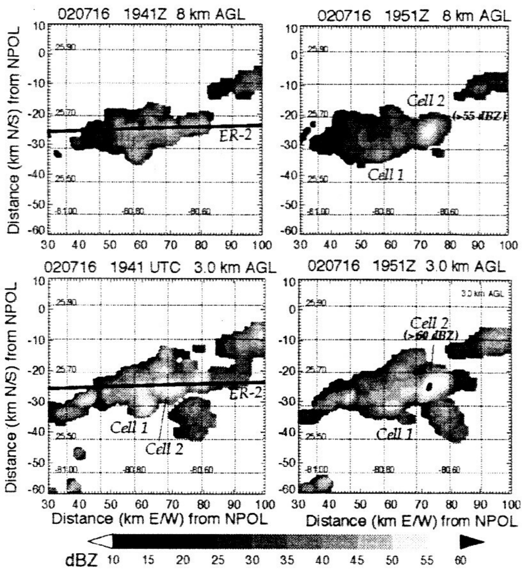

Figure 1. NPOL CAPPIs at 3 km and 8 km altitudes at 1941 UTC and 1951 UTC. Two larger cells are indicated. The ER-2 flight track on 1941 UTC CAPPI passes over Cell 2 at 1946 UTC.

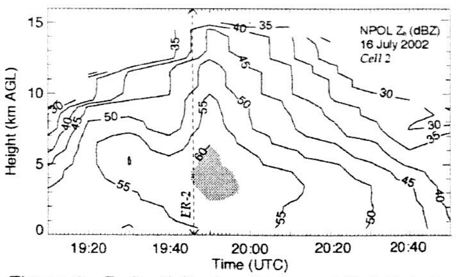

Figure 2. Reflectivity time history of Cell 2 derived from NPOL data

3. DUAL WAVELENGTH OBSERVATIONS

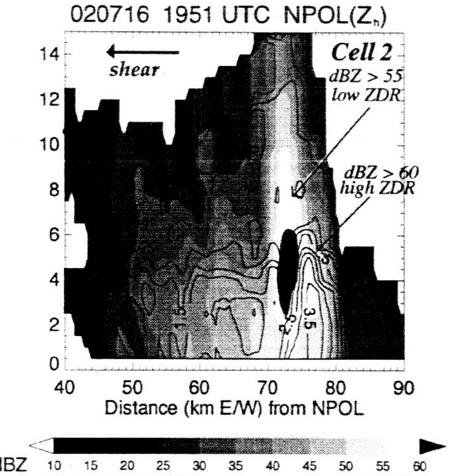

Figure 3. Vertical reflectivity cross section at 1951 UTC. Contours of Z_{DR} are superimposed.

EDOP and CRS images covering Cell 2 at about 1946 UTC is shown in Fig. 4. The EDOP reflectivity (middle panel) has a downshear tilted (toward west) reflectivity core that extends up to ~12 km altitude. Because of strong attenuation and Mie scattering at 94 GHz, CRS reflectivity (top panel) is completely attenuated within 2-3 km penetration of the high reflectivity core. The Doppler velocities bottom panel) show a strongly downshear tilted updraft with Doppler velocities exceeding 15 ms^{-1}. The westward tilted updraft embedded in moderate environmental shear is ~2 km in width. Because of Nyquist considerations and unfolding issues, CRS velocities (not shown) exceeded the acceptable range of +/-15 ms^{-1}.

4. Discussion: Observations of Large Graupel/Hail

The ground-based NPOL measurements clearly point to the presence of hail or large ice in Cell 2. What is of particular interest is the extent of supercooled water and ice in the updrafts and what can be inferred from the dual-wavelength measurements. Individual radar profiles are examined in this preliminary study but will involve further analysis and modeling in future work.

Figure 5 shows vertical profiles of EDOP/CRS dual wavelength measurements and derived properties at three locations in Cell 2's updraft region (Fig. 4). In addition, we have superimposed the 3 GHz reflectivity measurements from the NPOL radar even though the sampling volume is considerably different than

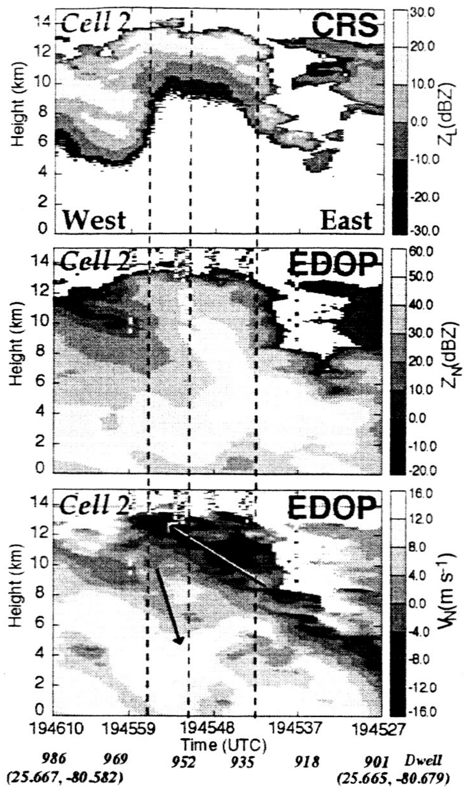

Figure 4. EDOP, CRS reflectivity and EDOP Doppler velocity for Cell 2 at ~1946 UTC on 16 July 2002. Doppler convection: positive (downward) and negative (upward). Vertical dashed lines show locations of profiles in Fig. 5; arrows depict hydrometeor motions. The shear vector is oriented from right to left in the figure. Total cross section width is 8.5 km.

the downlooking measurements from EDOP and CRS. The westernmost profile (left side) in Fig. 5 is on the downshear side of Cell 2's updraft. In constructing the profiles, we have used Florida *in situ* microphysical measurements in graupel regions to derive relations to convert between EDOP 9.6 GHz reflectivity and reflectivity-weighted fallspeed, 94 GHz attenuation, and 94 GHz Mie effects (Fig. 6). These relations have used full Mie calculations.

Cell 2's updraft is indicated by the shaded regions in Fig. 5 (middle row). The vertical air velocities were calculated by adding graupel reflectivity-weighted fall velocity (Fig. 6) to the EDOP Doppler velocities above 6 km altitude, and a rain fall velocity below 4 km altitude; air

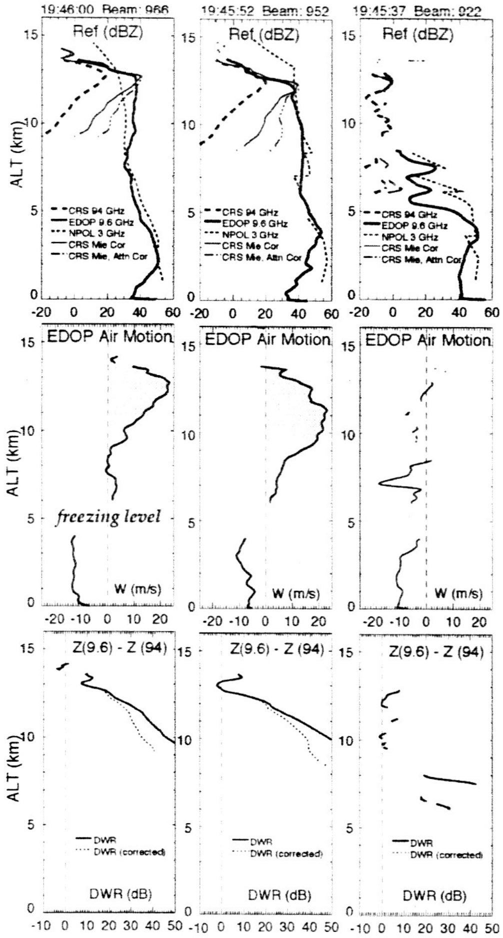

Figure 5. Vertical profiles derived from EDOP and CRS data on 16 July 2002. Top row: EDOP, CRS, NPOL reflectivity, CRS corrected for Mie scattering, CRS corrected for Mie scattering and graupel attenuation. Middle row: Vertical air motion derived from EDOP with assumed rain and graupel fallspeeds. Bottom row: DWR from raw reflectivity data and with CRS corrected for attenuation.

velocities were not calculated near the freezing level. The tilted updraft in Cell 2 exceeds 20 ms^{-1}, as shown by peak values at 11 km and 12.5 km altitudes in the left two profiles. The EDOP and NPOL reflectivity profiles indicate ~40 dBZ extending up to 12.5 km altitude, which is rather high and further suggestive of hail. The CRS profiles show an extremely large decrease with altitude near the level of the updraft maximum, at

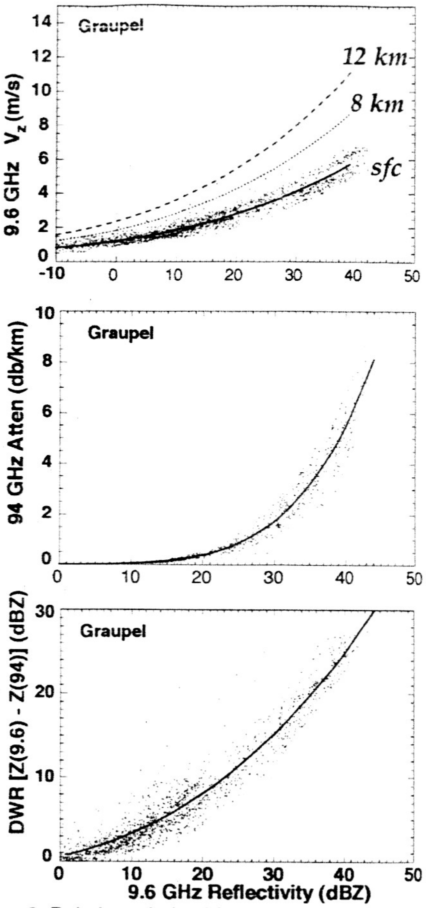

Figure 6. Relations derived for 9.6 and 94 GHz based on Florida in situ measurements of graupel size distributions. Curves are fitted to the in situ observations. The fitted graupel fallspeed curves (top panel) are shown for the altitudes ranging from the surface to 12 km.

the top of the EDOP high reflectivity column. To examine the implications of the 94 GHz reflectivity measurements, we have used the Mie-derived results in Fig. 6 to correct CRS reflectivity for Mie scattering and attenuation by graupel. What is evident from this exercise is that the Mie correction is much larger than the attenuation correction, but the both of these corrections are significant. In addition, it is clear that the graupel relations do not completely correct for Mie scattering and attenuation below the 12 km level.

The lack of agreement between the corrected 94 GHz reflectivity and the EDOP reflectivity that is near Rayleigh, may be due to two factors: a) the presence of cloud water, or, b) the presence of hail that will have larger Mie scattering and attenuation depending on its size distribution and characteristics (density, etc.). The presence of supercooled water would be highly attenuating at 94 GHz if the amounts were greater than 0.5 gm^{-3} for example. In support of the presence of hail, the reflectivity and vertical motion observations suggest that ice hydrometeors are falling from approximately the 12 km level where the updraft magnitude is ~20 ms^{-1}. At the 12 km altitude, fall velocities of 20 ms^{-1} would imply hail dimensions of about 1-1.5 cm depending on the type of hail (Knight and Heymsfield 1983). This would clearly be out the the range of the graupel calculations assumed in constructing Fig. 6. On the other hand, supercooled cloud water must be present in the updraft in order for large graupel or hail to grow. Considering that the –35 C level is in the range of 10-11 km altitude in a rising updraft parcel, this is fully within reason. Future work will focus on providing a consistent picture of the relation between the updrafts, particle growth, and the remote measurements.

Acknowledgements

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