The Relationship between Anvil Clouds and Convective Cells: A Case Study in South Florida during CRYSTAL-FACE

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(Manuscript received 30 October 2007, in final form 27 February 2008)

ABSTRACT

One of the important goals of NASA’s Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida Area Cirrus Experiment (CRYSTAL-FACE) was to further the understanding of the evolution of tropical anvil clouds generated by deep convective systems. An important step toward understanding the radiative properties of convectively generated anvil clouds is to study their life cycle. Observations from ground-based radar, geostationary satellite radiometers, aircraft, and radiosondes during CRYSTAL-FACE provided a comprehensive look at the generation of anvil clouds by convective systems over South Florida during July 2002. This study focused on the relationship between convective rainfall and the evolution of the anvil cloud shield associated with convective systems over South Florida on 23 July 2002, during the CRYSTAL-FACE experiment. Anvil clouds emanating from convective cells grew downwind (to the southwest), reaching their maximum area at all temperature thresholds 1–2 h after the active convective cells collapsed. Radar reflectivity data revealed that precipitation-sized anvil particles extended downwind with the cloud tops. The time lag between maximum rainfall and maximum anvil cloud area increased with system size and rainfall. Observations from airborne radar and analysis of in situ cloud particle size distribution measurements in the anvil region suggested that gravitational size sorting of cloud particles dispersed downshear was a likely mechanism in the evolution of the anvil region. Linear regression analysis suggested a positive trend between this time lag and maximum convective rainfall for this case, as well as between the time lag and maximum system cloud cover. The injection of condensate into the anvil region by large areas of intense cells and dispersal in the upper-level winds was a likely explanation to cause the anvil cloud-top area to grow for 1–2 h after the surface convective rainfall began to weaken. In future work these relationships should be evaluated in differing regimes of shear, stability, or precipitation efficiency, such as over the tropical oceans, in order to generalize the results. The results of this study implied that for these cloud systems, the maximum in latent heating (proportional to rainfall) may precede the peak radiative forcing (related to anvil cloud height and area) by a lead time that was proportional to system size and strength. Mesoscale modeling simulations of convective systems on this day are under way to examine anvil evolution and growth mechanisms.

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# The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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DOI: 10.1175/2008MWR2441.1

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1. Introduction

One of the important goals of the National Aeronautics and Space Administration’s (NASA’s) Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida Area Cirrus Experiment (CRYSTAL-FACE; Jensen et al. 2004) was to improve our understanding of the evolution of tropical anvil clouds generated by deep convective systems. In the tropics, anvil clouds comprised the majority of the cloud area exposed to the earth’s surface and to space (Houze and Betts 1981). Since anvil clouds reflected incoming solar radiation while trapping longwave radiation, they were a key regulator of the global radiation balance, particularly in the tropics (Fu et al. 1995). However, the net effect of anvil clouds on the energy balance was not well known, and in fact represented an important source of uncertainty in simulations of the climate system (Stephens et al. 1990; Wielicki et al. 1995). Improved observations were key to reducing this uncertainty (Stephens et al. 2002). The linkage between the vertical flux of water mass in convective cells and the radiative effects of convectively generated anvil clouds was an important connection that has not been explored fully in cumulus parameterization schemes (Del Genio and Kovari 2002).

An important step toward understanding the radiative and precipitation properties of convectively generated anvil clouds was to study their life cycle and structure in the context of convective organization. Since the smaller anvil clouds associated with isolated convective cells were more common than the larger anvil shields of mesoscale convective systems, both system types have significant radiative impacts (Del Genio and Kovari 2002; Machado et al. 1998). Prior studies of convective system life cycle have emphasized the transfer of water vapor and hydrometeors from active convective cells to the anvil region as an important source of stratiform precipitation under the anvil (Gamache and Houze 1983; Rutledge and Houze 1987). Less attention had been given to the coevolution of the convective cells and the anvil cloud itself, and to the relationship between the cloud structure and the precipitation structure in the anvil region. Rickenbach (1999) observed that cold anvil clouds in the tropical western Pacific often became detached from their convective source in the presence of directional wind shear, and continued to grow following the decay of the parent convection. This growth may have stemmed from a combination of mesoscale ascent in the anvil region associated with midlevel convergence and latent heating (Gamache and Houze 1982), radiational cooling at cloud top (Randall et al. 1991), and gravity wave generation from the convective cells (McAnelly and Cotton 1989). Gravitational sorting, where larger ice particles fall out closer to the convective source, played an important role in the separation of the coldest (highest) portion of the anvil cloud from the convective source (Lilly 1988).

Rainfall retrieval from spaceborne platforms may also benefit from improved understanding of the relationship between convection and anvil clouds. Modern precipitation retrieval algorithms from satellite observations were based on combining geostationary infrared (geo-IR) data, passive microwave measurements from low-orbit platforms, and spaceborne radar observations. Examples include the Tropical Rainfall Measuring Mission’s (TRMM) combined 3B42 product, and the Global Precipitation Climatology Project (GPCP) dataset, which used passive and active microwave measurements to train rainfall estimates from geo-IR data (Kummerow et al. 2000; Huffman et al. 1997). The strength of each instrument complemented the limitations of the others. For example, the TRMM radar sensed near-surface precipitation particles directly but over a small area, while the TRMM microwave radiometer measured scattering and emission from precipitation-sized particles throughout the clouds (not near the surface), but over a larger area. On the other hand, the radar and microwave radiometer suffered from poor temporal sampling (nominally twice per day), whereas the geo-IR data were nearly continuous and global. However, geo-IR data only provided information on the temperature and size of the cloud tops, which was not directly related to rainfall. As a result, biases between these instruments exist, which increased for time and space scales of individual cloud systems. For example, previous studies revealed a time lag in the timing of the diurnal peak in rainfall inferred from geo-IR compared to radar and passive microwave rain retrieval (Negri et al. 2002; Machado et al. 2002; Nesbitt and Zipser 2003).

This paper presented a case study of anvil generation and evolution over South Florida on 23 July 2002, during the CRYSTAL-FACE experiment. The aim of this work was to better understand the connection between the generation of anvil clouds and the evolution of the parent convection. That day was ideal for this purpose because many tropical anvil clouds formed in isolation from well-defined small groups of convective cells and could be tracked throughout their life cycle. Observations from radar, satellite radiometers, aircraft, and radiosondes during CRYSTAL-FACE provided a comprehensive look at the generation of anvil clouds by deep convective cells, and the subsequent coevolution of the anvil clouds, convection, and rainfall. The formation and growth of anvil clouds were well docu-
mented by geostationary infrared satellite imagery. The three-dimensional structure of these convective systems was analyzed with radar reflectivity data from surface and airborne radars. Radar reflectivity maps were combined with infrared cloud top imagery from the Geostationary Operational Environmental Satellite-8 (GOES-8) satellite and radiosonde data to relate the anvil cloud formation to the evolution of convection. Airborne in situ microphysical observations of cloud particles in the anvil region gave insight to mechanisms of anvil region evolution. Radiosonde measurements provided the context for the kinematic and thermodynamic environment in which the convective systems developed.

Results from this study may help to guide the representation of the radiative and latent heating properties of cloud systems in climate models. This observational case study complements a parallel mesoscale modeling analysis, in progress, of the mechanisms for anvil formation and evolution on this day (Lin et al. 2006).

2. Data and analysis

Level-II radar reflectivity data from four National Oceanic and Atmospheric Administration (NOAA) Weather Surveillance Radar-1988 Doppler (WSR-88D) instruments [part of the Next Generation Weather Radar (NEXRAD) network] at Key West, Miami, Tampa, and Melbourne, Florida (Fig. 1) were acquired in near-real time at the NASA Goddard Space Flight Center during CRYSTAL-FACE. This was accomplished by means of a reliable data network established in collaboration with NOAA’s Collaborative Radar Acquisition Field Test Project (Kelleher et al. 2007). The NEXRAD radars provided a detailed view of the three-dimensional structure of convection and precipitating anvil cloud in South Florida, at a temporal resolution of about 5 min. Radar reflectivity data from each of the four NEXRADs were interpolated to a common Cartesian grid (2-km horizontal and vertical spacing) at vertical levels from 2 to 10 km AGL. Radar reflectivity bias between the radars was low (0–2 dB), so no reflectivity corrections were applied to the data.

The rainfall rate was estimated from radar reflectivity at each point at the lowest level (2 km) of the common radar reflectivity grid, using the best available estimate for each radar. For this study, the important results hinged on time variations in rain rate, not on absolute rain rate values. Nevertheless, care was taken to produce an accurate radar-derived rainfall product. The NASA S-band polarimetric radar (NPOL) was deployed near Fort Myers, Florida, for CRYSTAL-FACE, so that there was significant overlap in coverage with the NEXRAD radars at Key West and Miami (cf. Fig. 1). In addition to radar reflectivity and Doppler velocity recorded by the NEXRAD radars, NPOL measured polarimetric variables such as specific differential phase and linear depolarization ratio, which lead to improved rainfall measurement. NPOL polarimetric measurements were used to modify the default NEXRAD reflectivity–rainfall relation for the Miami and Key West radars, minimizing errors associated with radar calibration and beam blockage, following Carey et al. 2000. For the Melbourne WSR-88D, we applied a reflectivity–rainfall (Z–R) relationship based on the TRMM windowed probability matching method (Rosenfeld et al. 1994). Rainfall rate for the Tampa WSR-88D was calculated with the default NEXRAD reflectivity–rainfall relationship (Z = 300R^{1.4}). The resulting instantaneous rain estimates were within about 15% of independent gauges for this day. Each rainy grid point was classified as either belonging to an active convective cell, or associated with weaker homogeneous stratiform (anvil region) rain, using an objective classification scheme based on Steiner et al. (1995), as modified in Rickenbach and Rutledge (1998).

IR cloud-top brightness temperatures, derived from channel 4 irradiance data from the GOES-8 satellite
(nominally 5-km pixel spacing in South Florida), were conavigated with the radar reflectivity maps to earth coordinates. For 23 July, the GOES-8 navigation was fine-tuned by matching coastlines and bays, resulting in an estimated navigation error of 5–10 km (one to two pixels). Cloud-top temperature contours between 250 and 210 K (every 10 K) were conavigated with radar reflectivity maps at two vertical levels: 2 and 8 km above ground level (AGL). The 2-km level was chosen to show the location of active convective cells. Most thick anvil clouds occurred between 6 and 10 km AGL, so 8 km was chosen to illustrate the anvil region’s location and extent. Individual convective cells and small mesoscale cell groups were identified from the radar reflectivity maps. Those cell groups where the associated anvil clouds remained separate from surrounding systems were tracked in time, with each system given a letter designation. Eight such systems were identified, represented by the letters A–H. Time series of rainfall and cloud area (at various temperature thresholds) were calculated for each of the eight systems. In this way the formation and growth of extensive anvil clouds could be studied specifically in the context of the evolution of each parent convective system’s precipitation structure.

The NASA ER-2 Doppler radar (EDOP) system (Heymsfield et al. 1996, 2003) provided time–height cross-section views of the reflectivity structure and wind fields within convective cells and anvil clouds on 23 July during CRYSTAL-FACE. EDOP imagery from the NASA ESPO archive (available online at http://espoarchive.nasa.gov/archive/arc/crystalf/images/edop), and the Doppler analysis presented in Heymsfield et al. (2003), were used to examine vertical motion, wind shear, and reflectivity structure for the two systems designated “G” and “C.” Composite size spectra of anvil cloud particles were available at the NASA ESPO archive (available online at http://espoarchive.nasa.gov/archive/crystalf/data/wb57/MS20020723.WB57). These spectra cover a large range of particle sizes (0.5–1500 μm) by combining measurements from three instruments (i.e., the Cloud Aerosol Precipitation Spectrometer, the Signal Processing Package Model 100, and the Cloud Particle Imager) each sampling in different size ranges. Garrett et al. (2005) used WB-57F microphysical measurements to study cloud particle growth mechanisms in the anvil region of a CRYSTAL-FACE system on a different day. On 23 July the WB-57 sampled the anvil region of system C over an approximately 60-km track along the anvil’s long axis, downwind from the generating convective cells, at 13.1- and 13.7-km altitude. We used these data to examine the change in the particle size spectrum of the anvil cloud as a function of distance from the source convection in system C, which shed light on mechanisms of the anvil cloud’s evolution.

3. 23 July—Synoptic overview

A strong surface cold front extended from the Ohio Valley to Texas on 23 July, with widespread convection across the southeastern United States in the moist southwesterly flow ahead of the front. In Florida, widespread strong convection was restricted to the panhandle region down to central Florida. South Florida experienced weak (less than 5 m s\(^{-1}\)) surface southerly winds associated with the Bermuda high circulation. Southeasterly winds transitioned to southerly then southwesterly from southern to central Florida consistent with the anticyclonic circulation of the high pressure system.

Eta model reanalysis (not shown) of 850–500-hPa relative humidity at 1200 UTC 23 July indicated much drier midlevel air over South Florida relative to central and northern Florida. Soundings from Miami, Key West, and Tampa (Miami sounding shown in Fig. 2) indicated a layer of dry air between 3 and 7 km AGL with a layer-mean dewpoint depression of about 15°C. The dry layer was bounded below by a strong temperature inversion, with a weaker inversion at the top of the layer. At each sounding location, the inversion was strongest in the morning and weakened as the day progressed. The inversion strength and dewpoint depressions were greatest for the Miami (easternmost) soundings. This dry, stable layer over South Florida was likely associated with descending air in the western portion of the Bermuda high. Accordingly, the outlook for widespread convective activity in South Florida was poor for this day.

Wind in the upper troposphere was generally 15–20 m s\(^{-1}\) from the northeast over central and South Florida, accelerating into a weak upper-level low over Cuba. This flow feature led to strong directional shear between the surface southerly winds and the upper-level northeasterly winds. This shear influenced the location and growth of anvil clouds relative to the convective source, by spreading the anvil clouds to the southwest of the active convection.

4. Evolution of clouds and rainfall over South Florida—23 July

The convective systems that formed on this day provided a good opportunity to study the evolution of convectively generated anvil clouds. Many anvil-generating cells, and small groups of these cells, were observed
throughout their entire life cycles. These cell groups were small enough so that developing anvil clouds could be attributed to individual convective cells and small convective systems.

Time series of the average unconditional rainfall rate at 2 km AGL, separated into convective cell versus stratiform type, were constructed from the radar maps for a 2.5° × 4° region of South Florida (24°–28°N, 80°–82.5°W). For the same region, cloud-top area coverage was determined from GOES data for cloud-top temperatures at or less than three thresholds (240, 230, and 220 K). According to the Miami sounding (Fig. 2), these temperatures corresponded to altitudes of approximately 8, 9.5, and 11.5 km, respectively. These thresholds were chosen because on this day, 240 K was a good general indicator of anvil cloud location, while 220 K usually indicated the presence (but not necessarily the precise location) of active convection. These time series are plotted together for 1000 UTC 23 July–0000 UTC 24 July (Fig. 3).

It was evident from Fig. 3 that convective activity on this day matched the typical diurnal pattern of cloudiness and rain during summer in South Florida (i.e., Schwartz and Bosart 1979), with mid-to-late afternoon maxima associated with the local formation of convection. Rain generally increased between 1000 and 1700 UTC (local time = UTC – 4 h) during the increase of solar heating in the morning hours. During this time, local peaks in rainfall corresponded to the formation and decay of small groups of convective cells generally

![Fig. 3. Area (km²) of cloud cover from GOES data at several brightness temperature thresholds, and of unconditional rainfall rate (mm h⁻¹, 2 km AGL) from the NPOL–NEXRAD 10-min rain maps on 23 Jul 2002, within the 2.5° × 4° subregion (24°–28°N, 80°–82.5°W) shown in Fig. 4. Rain is separated into contributions from convective cells (black solid) and stratiform region (black dashed). The IR cloud-top area is shown (15-min interval) for temperature thresholds of 240 (green), 230 (light blue), and 220 (red) K.](http://weather.uwyo.edu/upperair/sounding.html)
along the southeast Florida coast. For the first 3 h of this period (1000–1300 UTC), only a few weak cells occurred near Miami, with little rain and no cold cloud area. However, there was an extensive swath of midlevel cloudiness (240–235-K cloud-top temperature; 8–9-km height) evident from Fig. 3, extending from Melbourne southwest over Lake Okeechobee to the Florida Keys. This cloud swath formed in situ, not associated with current or prior active convection. The 1200 UTC Miami sounding (Fig. 2) showed a moist layer corresponding to the level of this cloud deck. Below this layer, the troposphere was very dry, consistent with the occurrence of only scattered shallow convection along the coast near Miami.

Between 1300 and 1400 UTC, rainfall increased sharply, followed 1 h later by an increase in cloudiness at all temperature thresholds. This increase resulted from the further development of isolated deep convection near Miami, and subsequent anvil cloud growth. Rainfall then increased dramatically between 1700 and 1800 UTC as scattered convection broke out across South Florida, with a maximum at 1830 UTC. As before, the cold cloud area increased rapidly around this time of the rainfall maximum. At this later time, cold cloud area reached a maximum 2 h later, near 2030 UTC. In summary, Fig. 3 suggested a time lag between peak rainfall and peak cold cloud area, with a greater time lag for larger rain maxima.

To explain this observation, we analyzed eight small convective systems that occurred between 1300 and 2300 UTC. These were either individual cells or small groups of cells (the largest group was 80 km in horizontal scale). Two criteria guided the choice of systems to be tracked: that the entire system life cycle was observed inside the radar network, and that the associated anvil cloud did not overlap significantly with surrounding systems. Systems (designated A–H) were tracked using the radar reflectivity maps at 2 km and 8 km AGL, overlaid with cloud top temperature contours. From these data, time series of rain rate, rain area (2
km AGL), and cloud area were constructed for each system, as well as time series of radar echo area at 8 km AGL.

We present maps each hour beginning at 1900 UTC, near the time that Fig. 3 showed maximum rainfall and increasing cloud area for all of South Florida. Figures 4a,b indicated six systems (labeled C–G) at this time (systems A and B had already decayed), each at different stages of evolution. Systems E and F were each a small group of decayed convective cells, with almost no precipitation at 2 km and “orphaned” anvil clouds (250–230 K) elongated to the southwest in the upper-level winds. The radar echo pattern at 8-km height showed the decaying anvil region also extending to the southwest, but not as far or as extensive as the cloud tops. At this late stage of the life cycle, the coldest cloud tops (smaller ice particles) were in each case downwind from the 8-km reflectivity region (larger ice particles), suggestive of gravitational particle sorting downwind from the convective source as described in Lilly (1988).

System C was also in the decaying stage (no rain at 2-km height), but with a larger anvil region (radar echo at 8-km height) and cold cloud area. System D, a larger group of cells 40 km in length, still retained active convection, with colder cloud (<220 K) and an expanding anvil region extending 50 km downwind from the active convection. Systems G and H were in the formative stage: H a small cell group and G a 50-km-long line of cells north of Lake Okeechobee. Neither G nor H had any cold cloud signature at 1900 UTC.

By 2000 UTC (Figs. 5a,b), the small cells E and F were at the end of their life cycle, reduced to small, narrow, and warmer cloud-top remnants with only weak reflectivity at 8 km upwind of the cloud top. The cell groups in systems C and D were in the decaying stage, and had collapsed to a small region of weak echo, leaving extensive expanding anvil cloud tops to the southwest. The reflectivity structure of the new systems G and H suggested intensifying deep convection, with maximum reflectivity values >50
dBZ at 2 km AGL and near 40 dBZ at 8 km AGL. System G had formed into an 80-km-long stationary line of convection parallel to the coast between Melbourne and Lake Okeechobee (likely forced by the sea-breeze front), with a growing region of cold cloud ≤220 K expanding to the southwest. System H, along the southwest coast near Everglades City, Florida, was a smaller group of three convective cells but with similar reflectivity intensity as system G. The expanding cloud shield of system H was correspondingly smaller and warmer.

a. **Aircraft observations of anvil evolution in system C near 2000 UTC**

Around 2000 UTC, aircraft radar and microphysical observations were made in the anvil regions of systems C and G. In this section we discuss these data that, taken together with the previous analysis of surface radar and infrared satellite data, suggested that strong updrafts were ejecting condensate into upper-level sheared flow that fed the growth of anvil clouds over the next few hours. Heymsfield et al. (2003) analyzed cross sections of convective cells at the leading edge of systems G and C, derived from the EDOP radar aboard the ER-2 aircraft, which flew over the systems at this time (the ER-2 flight path was shown by the gray dotted line in Fig. 5). Images of the EDOP reflectivity and velocity cross sections may be seen online at the NASA ESPO archive (see online at http://espoarchive.nasa.gov/archive/arcs/crystalf/images/edop/ED20020723_1939.GIF and http://espoarchive.nasa.gov/archive/arcs/crystalf/images/edop/ED20020723_2004.GIF). They measured updraft speeds in the cells exceeding 10 m s\(^{-1}\) up to 12 km AGL, which they concluded lofted precipitation-sized particles to near the cloud top. EDOP data presented in Heymsfield et al. (2003) revealed that vertical wind shear was present within the anvil cloud of systems G and C, with northeasterly winds above 11 km AGL increasing to a maximum of 18 m s\(^{-1}\) at 13 km AGL. This strong upper-level shear led to advection of hydrometeors to the southwest in the upper portion of the anvil region. A sequence of cloud radar system (CRS) and cloud physics lidar (CPL) time–height cross sections was presented in McGill et al. (2004) over most of the life cycle of systems G and C (see their Fig. 2). The incorporation of lofted condensate by the convective cells into the anvil region was clearly shown. Convection was observed to tilt downslope (to the southwest), consistent with transportation of ice particles into the anvil cloud. CRS reflectivity in the anvil increased downward with height, to a maximum at the 6-km anvil base, which they suggested was associated with the growth of descending by aggregation. Reflectivity values near anvil base decreased with distance away from the convective source. The McGill et al. (2004) observations were consistent with particle size sorting of convective debris ejected into the anvil region.

Composite cloud particle size distributions in the anvil region associated with system C were available from the NASA WB-57F aircraft measurements around this time. The aircraft’s flight tracks (thick black solid and thick black dotted lines in Fig. 5) sampled the anvil cloud downwind of the decaying convective cells along about 60 km of the anvil’s long axis. Between 1952 and 1955 UTC, spectra were compiled every 10 s as the WB-57 flew to the southwest about 13.1-km altitude (dotted black line). The aircraft then turned back to the northeast and made a second series of measurements along the anvil cloud closer to the decaying convection at the slightly higher altitude of 13.7 km, between 2026 and 2028 UTC (solid black line). Shown in Fig. 6 is the variation of median volume diameter of the cloud particle distribution along both flight tracks, arranged in order from closest to the convective cells rearward into the anvil cloud (about 60-km distance northeast to southwest). At 13.7-km altitude the median volume diameter decreased rapidly from over 400 μm closest to the decaying cells to about 80 μm (about 20 km downwind) where the anvil cloud tops are lower. The median diameter decreased to 40 μm at 13.1-km altitude (about
FIG. 7. Composite cloud particle size spectra in the anvil region of system C, with the indicated times and median volume diameters corresponding to Fig. 6. (a)–(f) Spectra are arranged in order along the anvil region long axis indicated in Fig. 5, from distance rearward from the convective region. Spectra in (a)–(c) are at 13.7-km altitude; spectra in (d)–(f) are at 13.1-km altitude.
60 km downwind from the first measurement) toward the rear edge of the anvil region. These observations were consistent with the hypothesis of gravitational size sorting rearward of the source convection.

Examples of six individual spectra along the flight track are presented in Figs. 7a–f, arranged in order from closest to the convective cells to the rearward portion of the anvil region. The distributions closer to the source convection were clearly skewed toward larger particles, with concentrations of precipitation-sized particles (500–1000 μm) of 0.1–0.001 l⁻¹. The low concentration of precipitation-sized particles was consistent with observed radar echo top near 14 km in that region. Concentrations of larger particles decreased steadily with distance rearward, with an absence of particles >60 μm at the rear edge of the anvil region. Again, these spectra supported the idea developed in the previous section that the anvil region evolved in part from the rearward transport of particles and subsequent gravitational size sorting in upper-level northeasterly flow.

b. Decay of anvil clouds

Approximately 1 h later (2110 UTC; Fig. 8) the changes in each system were dramatic. Systems D, E, and F had completely dissipated and were no longer present in either the reflectivity or cloud-top imagery. The cloud-top area of system C was reduced to half its size and continued to warm with only a few pixels reaching 230 K, while the reflectivity pattern suggested that active convection from that system had ceased. The convection in systems G and H had weakened substantially (2 km AGL reflectivity map), while at the same time the 8 km AGL reflectivity and the cloud-top area had expanded by about a factor of 2. As the stationary line of convective cells in system G collapsed, the anvil echo at 8 km AGL expanded as precipitation particles from the previously strong cells were spread southwestward by the upper-level wind. The coldest cloud tops (<220 K) were now displaced 50–80 km downwind (to the southwest) from the previously active convective cells. The general evolution of the cloud top and reflec-
tivity pattern for system H was very similar to system G, except that system H was of a smaller scale. Note also a new active convective cell on the western edge of the collapsed convection in system H, which later contributed to the anvil cloud.

The reflectivity and cloud-top maps at 2200 UTC are shown in Fig. 9. Over the past hour all active convection associated with system G had ceased, while the cloud-top area <250 K had continued to expand to the southwest. The echo pattern at 8 km AGL became narrower and more elongated along the upper-level winds, and weaker as precipitation-sized particles continued to sublimate and evaporate. As before, the cloud-top temperature contours extended 50–70 km downwind of the upper-level echo, and warmed about 10 K over the past hour, consistent with continued particle size sorting and evaporation or sublimation as suggested earlier. System H evolved similarly, although a parallel cold cloud feature emanated from the active convection from 1 h earlier (now collapsed). By 2300 UTC (Fig. 10), most all reflectivity features at 2 and 8 km AGL had dissipated for both systems. The cold cloud area continued to shrink and warm; only cloud tops ≥240 K remained by this time.

5. Connection between anvil cloud area and convection

We summarize the relationship between the evolving cloud top and precipitation for this day by presenting time series of these parameters for system G (the largest system) and scatterplots for all systems illustrating the relation between cloud area and rainfall. The general evolution of system G was similar to the other systems on this day. A companion study, in preparation, presents a mesoscale modeling study of anvil generation that focused on this case.

The time series of rain rate, rain area (2 km AGL), and cloud-top area (Fig. 11a) illustrated the 1–2-h lag between maximum convective rain followed by maximum cloud-top area. The lag between peak convective rain and the coldest cloud-top threshold maximum area (≥220 K) was 1 h. The time lag increased with warmer thresholds, consistent with the growing and warming
cloud tops following the maximum in active convection as described in section 4. The convective radar echo area (area of convective rain) at 2 km AGL most closely matched the 220-K cloud-top area in phase, but the peak convective rain area was about half of the 220-K cloud-top area. Stratiform radar echo area maximum was about 0.5 h later than the convective peak, as expected since stratiform rain is derived in part from the delayed fallout of convective debris. The stratiform radar area maximum was more consistent with the 230 K (i.e., warmer) cloud-top area threshold, but again with a much smaller area than the cloud-top area. Figure 11b showed that the maximum 30 dBZ area at 8-km height (a proxy for the updraft strength of active convection, to be discussed later) at 2015 UTC was followed 0.5 h later by the peak area of 220-K cloud top, illustrating the time delay of upward flux of condensate from the convective region into the anvil cloud. The reflectivity area at 8 km expanded to maximum size an hour later (2110 UTC), most closely matching the 230-K cloud-top area time series in time and space. However, with reference to Fig. 8b (8 km AGL reflectivity and the cloud-top map at 2110 UTC), the 230-K cloud top (approximately 10-km height) was 2 km higher than, and displaced downwind from, the 8 km AGL reflectivity surface. In fact, the 8 km AGL reflectivity surface was contained completely within the cloud-top threshold of the same height (240 K; cf. Fig. 8b), showing that the reflectivity and cloud-top fields were physically consistent.

Based on the previous results, we define the anvil cloud system area using the 240-K cloud-top threshold, which encompassed the lower- and upper-level radar reflectivity features of each system (the subsequent conclusions do not change using colder thresholds). A linear correlation analysis of all eight systems suggested that the greater the peak convective rainfall or the larger the peak cloud-top area, the larger the time lag between peak rain and peak anvil cloud-top area (Fig. 12). The relationship between maximum cloud cover and the peak cloud cover minus convective rain time lag appeared to show a linear trend, with an $r^2$ value of 0.73 (6 degrees of freedom). The maximum convective rainfall of each system also suggested a linear relation-
ship with the time lag (Fig. 12b), though with less variance explained by a linear fit ($r^2 = 0.34$). Note that the relatively small number of points limited the robustness of this trend.

The discussion in section 1 suggested that a key linkage between convective rainfall and cloud-top size was in the updraft strength of the convection. The hypothesis was that the stronger the convective updrafts, the more condensate was injected by the convective cells into the anvil region, contributing to the growth of the anvil cloud. Since measurements of vertical motion were not available for most of the systems in this study, proxy indices of convective intensity were examined.

Figure 13 presented the correlation between two indices of convective strength and the peak cloud cover minus peak convective rain time lag. In the upper troposphere (8 km), the area of convective cells greater than 30 dBZ of convective cells implied the presence of updraft speeds sufficiently high to have ejected larger ice particles there (Zipser and Lutz 1994; Petersen et al. 1996). Figure 13a suggested a positive trend ($r^2 = 0.65$) between the 30-dBZ area at 8 km AGL (thus, larger area of strong updrafts) and the anvil area–convective rain time lag. To separate the effects of updraft strength...
from the area of strong updrafts, we constructed a convective intensity ratio, defined as the ratio between 30-dBZ area at 8 km (strongest convection) and convective cell area at 2 km (all convection). High convective intensity implied greater updraft strength, regardless of the area of convective cells. Convective intensity also increased with increasing time lag (Fig. 13b) though the trend was not as evident ($r^2 = 0.32$) as with the area of intense cells.

In summary, this analysis supported the idea that, for this case, the injection of condensate into the anvil region by large areas of strong cells and dispersal in the upper-level winds caused anvil cloud-top area to grow for 1–2 h after the surface convective rainfall began to weaken. These results offered an explanation for the observation in previous studies (Negri et al. 2002; Machado et al. 2002) of a systematic shift in time between the diurnal maximum of near-surface rainfall and of the cloud-top area (or of rainfall based on infrared cloudiness). Moreover, the present result predicts that the time shift would increase for larger, stronger, and rainier systems, which may be tested in model simulations. This also has implications for model parameterization of latent heat (related to rainfall) and radiative forcing (related to the cloud-top area) of tropical cloud systems.

6. Conclusions

The 23 July 2002 case study of a series of small convective systems during CRYSTAL-FACE illustrated the growth and evolution of anvil clouds and over South Florida, and the relationship of those clouds to deep convective activity. This paper examined the relationship between the life cycle of individual small convective systems observed by radar, and the growth of anvil cloud tops viewed from geostationary satellite. Observations from aircraft radar and microphysical data from airborne probes within the anvil region shed light on mechanisms of anvil region formation and evolution. Since convection was generally suppressed in South Florida that day, individual anvil clouds could be more easily traced to their source from small groups of convective cells and were thus more amenable to study.

Rainfall and cloudiness on 23 July for all of South Florida displayed a typical diurnal pattern, with a general mid-to-late afternoon maximum. However, the maximum in cold cloud area occurred up to 2 h following the rainfall maximum. To understand this relationship, we tracked the life cycles of eight small convective systems using radar reflectivity maps at 2 and 8 km AGL in conjunction with cloud-top temperature maps. Typically, strong convection extended into the upper troposphere soon after the formation of a given system. Anvil clouds emanating from the convection grew downwind (to the southwest), reaching their maximum area at all temperature thresholds after the active convective cells collapsed. The 8-km AGL reflectivity pattern of each system revealed that precipitation-sized anvil particles extended downwind with the cloud tops. The coldest cloud tops moved downwind of the 8-km reflectivity pattern with time. Observations from airborne Doppler radar, combined with cloud particle size spectra data within the anvil region, supported the hypothesis that gravitational size sorting of the small cloud particles and the larger anvil precipitation particles in positive vertical wind shear played a role in the
evolution of the anvil region following the growth and decay of the source convection.

Time series of rainfall, reflectivity at 8-km height, and cloud-top area at various temperature thresholds for a large, isolated system north of Lake Okeechobee showed a lag of 1–2 h between the peak cloud-top area and peak convective rainfall (cloud area following rainfall), with the lag shortest at colder cloud-top thresholds. Linear regression analysis of all systems suggested a positive trend between this time lag and maximum convective rainfall, as well as between the time lag and maximum system cloud cover, on this day. We conclude that, for this case, the larger the cloud area, or the greater the convective rainfall, the larger the time lag between maximum rainfall and maximum cloud area. The injection of condensate into the anvil region by large areas of intense cells and dispersal in the upper-level winds was shown to be a likely explanation to cause the anvil cloud-top area to grow for 1–2 h after the surface convective rainfall began to weaken. Variation in anvil evolution mechanisms can be expected in regimes of differing shear, stability, and precipitation efficiency, for example, in tropical oceanic environments, widespread convection with strong synoptic forcing, or large squall-line systems. More case studies on different days during CRYSTAL-FACE, and in other tropical regions, will be analyzed in future work as a step toward generalizing these results.

One implication of this study was that for this case study of South Florida convection, the maximum in latent heating (proportional to rainfall) may precede the peak radiative forcing (related to anvil cloud height and area) by a lead time that was proportional to system size and strength. A companion modeling study (in progress) will examine mechanisms of anvil evolution, in the context of size, growth rate, and rainfall, with mesoscale modeling simulations of several systems on 23 July. The simulations will focus on the ice mass budget and vertical condensate fluxes of the source convection and the expanding anvil region.

Acknowledgments. The authors gratefully acknowledge the support of the NASA Radiation Sciences program. The comments of two anonymous reviewers greatly improved the manuscript.

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