First Radar Echoes and the Early $Z_{\text{DR}}$ History of Florida Cumulus

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ABSTRACT

The early histories of radar echo and polarization differential reflectivity ($Z_{\text{DR}}$) from growing cumulus clouds observed in Florida with a 10-cm-wavelength radar are reported in detail. Raindrops 1 to several millimeters in diameter are present at about cloud-base level in most cases as soon as any identifiable precipitation echo is seen within cloud (distinct from Bragg scattering and echo from cloud droplets). This is in most cases by the time of the first 10-dB $Z$ radar echo aloft. The very early occurrence of large drops is consistent with origination directly from coalescence on ultragiant aerosol. However, they appear to exist so early and so low in the clouds as to be unexpected if the cumulus were single, vigorous thermals. The explanation may lie in the presence of a more gradual, very early cloud stage that is generally not observed in any detail. Simultaneous $Z$ and $Z_{\text{DR}}$ measurements in the early stages of developing, warm cumulus will provide a powerful test of understanding the onset of drop growth by coalescence.

1. Introduction

The initiation of warm rain is still widely considered one of the classical unsolved problems of cloud physics. However, although a time interval of about 20 min is often quoted for the initiation of warm rainfall, in fact neither the starting nor the ending times have been defined well. Cumulus have rarely if ever been examined from the time of first visible cloud, and it is difficult to define (let alone observe) a distinct starting time that is meaningful for the cloud-physical mechanism in a real cloud. For the ending time, the onset of precipitation defined by the first occurrence of a certain value of radar echo (say 20 dBZ with a 10-cm-wavelength radar, to be quite certain of avoiding Bragg scattering) may be rather easy to determine within a minute or two. However, it is physically ambiguous because the concentrations and sizes of the drizzle or raindrops responsible for it are generally unknown. Aircraft penetrating the clouds can provide some detailed information on microphysical conditions, but not usefully for this problem.

Good radar coverage over the entire life cycle of small cumulus through the precipitating stage is not always easy to obtain. One needs clouds between about 5 and 20 km from the radar to get reasonably good spatial resolution—say 100 to 150 m. Since the scan rate was limited to $5^\circ$ s$^{-1}$ in this work, at most a $30^\circ$ sector could be covered using vertical scans $1.2^\circ$ to $1.5^\circ$ azimuth apart with about a 2-min volume-scan repetition time. Since one cannot zero in very early on a specific cumulus because so few of them grow to larger size, well-covered cases require good luck as well as experience. Truly complete cases in the sense of following a cloud from the very first visible condensation have not been obtainable.

Multiparameter radar measurements have the potential for providing extra information about the initiation of precipitation, which, with the exception noted below, has so far been largely untapped. This paper is an exploration of that potential for studying the initiation of warm rain.

Differential reflectivity ($Z_{\text{DR}}$) is the ratio of the horizontal to the vertical copolar radar signals: in concept, simply the ratio of a horizontally to a vertically polarized radar echo from the same target—the same pulse volume. The two are equal and the ratio is unity (0 dB) if the drops are spheres (drops less than about 500-μm diameter), but $Z_{\text{DR}}$ increases as the drops get larger, becoming more flattened by aerodynamic forces.

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Thus $Z_{DR}$ is a reflectivity-weighted measure of the drop axis ratio and indirectly drop size once precipitation formation is under way. It is expressed in logarithms (dB), as

$$Z_{DR} = 10 \log_{10}(Z_{VH}/Z_{VV}) = dBZ_{HH} - dBZ_{VV}, \quad (1)$$

where $Z_{HH}$ is the equivalent reflectivity factor from a horizontally polarized beam, sensed as the horizontally polarized component of the backscattered radiation, and $Z_{VV}$ is the vertical analogue of that. The far-right-hand side of Eq. (1) means subtraction of the numerical logarithmic values, not of the actual reflectivity factors. The linear depolarization ratio (LDR), given by

$$LDR = 10 \log_{10}(Z_{VH}/Z_{HH}), \quad (2)$$

uses the vertically polarized return from the horizontally transmitted beam ($Z_{VH}$), and is sensitive to nonspherical scatterers that are not aligned symmetrically with respect to the horizontal or the vertical. It is difficult to use in early echo studies because it is a much weaker signal than $Z_{DR}$ (since $Z_{VH}$ is usually two or three orders less than $Z_{VV}$), but it might be useful for small cumulus very close to a sensitive radar.

This paper presents and discusses data from early-echo cases obtained on 7 days in 2-week period in late July and early August of 1998, early in PRECIP 98 (Zhang et al. 2000), with the 10-cm-wavelength, 1º-beam, S-Pol radar (Lutz et al. 1997) in central Florida, on growing cumulus clouds over land. The main objectives of PRECIP 98 left the radar free for this early-echo study until quite heavy precipitation started within the scan area.

Cumulus clouds start appearing typically in mid-morning, and some usually have developed to first-detectable-precipitation echoes with tops at 3 to 4 km above mean sea level (MSL) within 1 to 2 h on the days on which precipitation formation occurs at all. Bases are generally below 1 km, warmer than 20°C. Initiation of vigorous growth is often related to a sea-breeze front visible on the radar.

2. The scientific issues, background

The basic outlines of hydrometeor growth by condensation and coalescence are very well understood (e.g., Rogers and Yau 1989). Small particles (cloud condensation nuclei or CCN) activate cloud droplet formation at liquid water supersaturations of roughly 1% within updrafts, and the rising droplets grow by condensation as the air rises and cools further. Depending upon the size and activity distribution of the CCN (as well as effects of turbulence and inhomogeneities), a distribution of cloud droplet sizes forms and evolves with the ascent. Rainfall forms by a coalescence process within this size distribution, the larger droplets falling faster relative to the air than the smaller ones and colliding and coalescing with them. This coalescence process is very fast for large drops falling through a cloud of small ones because the fall speed difference is large and the collection efficiencies can be greater than 0.5. At an early stage, however, when all the drops are small, fall at about the same low speed, and have low collection efficiencies, it can be very slow. Many papers and texts treat this in a quantitative detail not necessary here. The problem is that cloud physicists have found it difficult to explain how rain forms in small, warm cumulus as rapidly as it has appeared to do.

There are two issues regarding the first rainfall itself. Because the method of detecting it necessarily involves radar, one issue is to understand the first radar echo that rain produces. However, this may differ from the more important, underlying issue, which is to identify and understand the processes that are important in producing rainfall that carries significant amounts of water to the ground. One can easily imagine that the first radar echo from precipitation may be dominated by a very small population of large drops that form on ultragiant aerosol particles (e.g., Johnson 1982) and fall out without having any influence on the processes that form significant precipitation amounts. To the extent that this is the case, the earliest radar echo from hydrometeors is irrelevant to the more important problem, and might even interfere with using radar to study it. That would be an important finding itself, so in either case it is important both to understand the early radar echo development and to appreciate that while it does signify coalescence, it may not signify significant coalescence.

The purpose here is to report data on the simultaneous evolution of radar echo and $Z_{DR}$ from Florida cumulus, discuss the results in terms of these issues, and comment on the use of multiparameter radar in this problem area. Previous work of direct relevance includes the studies of small, developing cumulus using $Z_{DR}$ by Illingworth and others in 1987–89 and work in the Small Cumulus Microphysics Study (SCMS) in 1995. The earlier work (Caylor and Illingworth 1987; Illingworth et al. 1987; Illingworth and Caylor 1988; and Illingworth 1988) used $Z_{DR}$ to show that early, weak radar echoes from cumulus sometimes are from low concentrations of large raindrops, as would result from the action of sparse, ultragiant aerosol. The present study confirms this and extends the results using more detailed data. SCMS was a coordinated radar–aircraft study of small growing cumulus, using dual-wavelength radar (3 and 10 cm; Knight and Miller 1998). This revealed the prevalence of Bragg scattering in the 10-cm-wavelength radar data, from inhomogeneities within cloud due to mixing with the environment: scattering from index of refraction gradients at half-wavelength scale. The Bragg scattering limits the sensitivity at which $Z_{DR}$ can be used at particular locations, at low values of the equivalent reflectivity factor, $Z_{e}$, with a radar of such a long wavelength. Bragg scattering interferes less with the scattering from hydrometeors at shorter wavelengths.
3. Procedures, interferences, and artifacts

Scanning was entirely in RHI mode (vertical scan at constant azimuth), obtaining sequences of vertical sections through the clouds about every 2 min. In most cases, initially a sector about 30° wide containing very small cumulus was scanned until one cloud gave signs of impending, vigorous growth, at which time the sector could be narrowed. Since there was usually little cloud motion, this system worked well. The data were obtained at a scan rate of 5° per second, a pulse length of 1 μs, range gate spacing of 150 m, and averaging 128 pulses. The standard deviation of $Z_{\text{DR}}$ in these conditions is less than 0.1 dB. A clutter filter was used nearly all the time. Vertically pointing polarization data collected in light to moderate precipitation were used to calibrate the zero of $Z_{\text{DR}}$, quantifying the system bias. The calibration was stable during the project.

Previous studies have revealed that small, growing cumulus clouds characteristically have “mantel echoes” on radar from Bragg scattering (Knight and Miller 1993, 1998). They are most intense when the environmental air is driest, and in Florida they not uncommonly reach 10 dBZ at a wavelength of 10 cm. The Bragg echoes have zero $Z_{\text{DR}}$; their $Z_{\text{HH}}$ is always approximately equal to their $Z_{\text{VV}}$, as would be expected from isotropic, turbulent mixing. Their importance here, however, is that they may mask significant $Z_{\text{DR}}$ returns from sparse, large water drops when the reflectivity factor from the drops alone is less than or comparable to that from the Bragg scattering. Thus if in one range gate the radar return consists of 10 dBZ from Bragg scattering (both $Z_{\text{HH}}$ and $Z_{\text{VV}}$ are 10 dBZ) and 0 dBZ from drops that would produce a $Z_{\text{DR}}$ of say 2 dB ($Z_{\text{HH}}$ is 0 dBZ and $Z_{\text{VV}}$ is −2 dBZ), the observed $Z_{\text{DR}}$ would be less than 0.2 dB. Thus the mantel echoes have a potential for completely masking otherwise significant $Z_{\text{DR}}$ at low levels of the reflectivity factor. This will be pointed out later in reference to figures.

It was also found in SCMS that the cloud droplets themselves can produce a Rayleigh echo up to about 0 dBZ in the warm-based, Florida cumuli. Since cloud droplets are spherical they also have zero $Z_{\text{DR}}$. There is a potential for masking weak $Z_{\text{DR}}$ signals from large drops here too, but this would occur within adiabatic cores of the small cumulus, not near cloud edges where the Bragg scattering is strongest.

In this study, the lowest positive, nonzero value of $Z_{\text{DR}}$ displayed is 0.5 dB, and that is only considered to be a real indication of hydrometeor asymmetry when it occurs in reasonable continuity with similar values in adjacent range gates, beams and scans and when it appears very unlikely for it to be an artifact.

Nonzero $Z_{\text{DR}}$ values are produced by beam pattern mismatches in regions of strong reflectivity gradient, and these are common in the data at cloud edges. All the scanning in this work was in RHI mode, and when the RHI plane includes the right- or left-side edge of a cloud, some quite realistic-looking $Z_{\text{DR}}$ artifacts can be produced. Slices through cloud centers often display $Z_{\text{DR}}$ rims at the near and far cloud edges and at cloud top that are more easily identified as artifacts. One learns to recognize and discount these cloud edge effects because of their consistent locations.1 There is more potential here for discounting signals that are “real” than for including as real ones that are not, but very little, we think, in either case. As will be seen, the $Z_{\text{DR}}$ values that are interpreted as indications of hydrometeor flattening are never near the cloud tops or sides where the strongest echo gradients (which are from Bragg scattering) reside in this study. Echo gradients do occur within cloud, of course, but they are not as steep and are very probably not serious in the context of the semi-quantitative use of $Z_{\text{DR}}$ in this study.

Insects also produce strong $Z_{\text{DR}}$ signals in the boundary layer (Wilson et al. 1994) and there is a high probability that significant numbers of them are sometimes elevated into cumulus clouds, perhaps acting as a form of ultragiant aerosol and initiating big drops. On one of the days the radar data showed several small cumulus that became nearly filled with insects and, judging from the Doppler return, birds as well. (Values of LDR > −15 dB were found filling as much as half the volume of weak clouds, tops about 4 km, along with scattered, single pulse volumes of anomalous $Z_{\text{DR}}$ > 15 dBZ, very anomalous Doppler velocities, and highly variable $Z_{\text{DR}}$, with large negative as well as positive values.) Apart from these few Spectacular cases there was no evidence of unusual concentrations of insects in the boundary layer being drawn up into the clouds. Nevertheless the possibility of insects influencing the early echoes is intriguing.

4. Studying $Z_{\text{DR}}$, drop size, and drop concentration

Multiparameter radar studies of rain explore the data in terms of drop size distributions. Since their aim usually has been better remote estimation of rainfall content and rainfall rates, the derivation of more realistic, quantitative, drop size distributions has been their sole purpose. Here, however, the amounts of water involved are often insignificant, the purpose of the work is entirely different, and the drop size distributions might in part be unlike those encountered in heavier rainfall. Since large hydrometeors with fall velocities of several meters per second appear very early in cumulus clouds (e.g., Carbone and Nelson 1978; Illingworth 1988), size sorting is a major factor influencing early size distributions (as was emphasized especially by Carbone and

1 One reviewer of this paper was concerned about high values of $Z_{\text{DR}}$ from mismatched sidelobes from ground targets contaminating the $Z_{\text{HH}}$ data. This particular difficulty is a minor one because of the clutter removal (removing all data with nearly zero Doppler velocity), but above that, the possibility of this never arose in the data analysis because the features being interpreted are unique to the clouds. They move with the clouds, so this problem is not present.
FIG. 1. Parameter $Z_{dr}$ as a function of equivalent spherical diameter for single drop sizes, at several standard deviations of Gaussian distributions of the canting angle, keyed at the upper left. Canting angle effects are negligible for the purposes of this paper.

Nelson 1978). Combined with large-scale irregularities in the airflow, this undoubtedly sometimes gives rise to complex size distributions that are poorly represented by any simple, assumed distribution.

There are two ways of presenting and thinking about the data. The simplest is to present $Z_e$ and $Z_{dr}$ and discuss the results directly in terms of these values, which implies thinking physically in terms of a monodispersed size distribution that satisfies both measurements. Thus $Z_{dr}$ would give a drop size and then $Z_e$ a concentration. This is often a poor approximation of reality, but is good enough for most if not all of the purposes of the present paper. The other is to assume a particular form of drop size distribution, which can enable a numerical estimation of all aspects of the precipitation content of the cloud. The single-size assumption is surely less realistic in general, but it is much simpler, while information based upon a size distribution assumption can be unrealistic at times and is more complicated, but is probably more revealing in most cases.

For most of this paper we choose the former and simply present the data as measured. This has the extra value of providing a feeling for the resolution and local scatter of the actual measurements. One case is presented both ways, showing both smoothing and the extra information an assumed drop size distribution assumption can supply.

Figure 1 and Table 1 combine to show what $Z_{dr}$ and $Z_e$ mean, under the assumption that both are “dominated” by about the same size of drop. Table 1 was constructed using the ratio between backscattering cross sections at horizontal and vertical linear polarizations for spheroidal raindrops (Green 1975), using the T-matrix method (Barber and Yeh 1975). For these early echoes this gives an index of size for the drops that have grown by coalescence as distinct from the cloud droplet population, which contributes very little to either $Z_{dr}$ or $Z_e$ except sometimes at the very lowest reflectivity factors. For instance, 0 dBZ with 2 dB of $Z_{dr}$ would correspond roughly to a single 3.5-mm-diameter drop in 2000 m$^3$ of air while 10 dBZ with 1 dB of $Z_{dr}$ would correspond similarly to one 2.5-mm-diameter drop in 150 m$^3$. Drop concentration and median volume di-

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2 A referee recommended use of a smoothing routine to remove the subjectivity, but we disagree. The amount of smoothing would be a subjective judgment, and the decision of what is meteorologically significant would still be subjective. The $Z_{dr}$ data are noisy looking, but how much of this represents real variations in the clouds is not known. It would be valuable to use a formal smoothing for preparing numerical data of the kind presented in Table 3 and Fig. 10 below, if one were making a wide-ranging comparison of this kind of data, but that is not the purpose of this paper. In the figures, $Z_e$ and $Z_{dr}$ are only displayed for received signal strength $> -115$ dBm, the estimated minimum detectable signal strength for the S-Pol radar.
ameter will be displayed for one case, using an assumed gamma drop size distribution.

5. The first echoes: Three cases

Data were obtained from 31 separate cloud cases, about half of which could be termed fairly complete in the sense of having coverage from the first echo that is clearly due to precipitation, lasting at least to the time of maximum cloud-top height. Table 2 characterizes the clouds in terms of the top rise rate and maximum top height, which are the major dynamic variables determinable directly from single radar data, and the fall rate of the initial echo at 10–20 dBZ. These data were taken only when values were fairly well defined by the data, and they are presented as a rough characterization of the cloud population studied. There is no direct information on cloud base heights, but experience from Florida suggests bases nearly always between about 0.5 and 1 km above ground level (AGL), which is close to sea level (SL), at temperatures between 20° and 25°C (Sax and Keller 1980; systematic estimates from aircraft data in SCMS), the freezing level varies between 4 and 5 km, and cloud droplet populations range from a few hundred to about 1000 cm⁻³. The remainder of this section presents three cases in some detail, starting with a weak, small cloud and ending with the tallest and strongest of the group. Clouds that produced no apparent precipitation echo (either from \( Z_{\text{DR}} \) or from echo behavior) were not included in the sample.

a. A weak case

Figure 2 gives a time–height plot of dBZ and \( Z_{\text{DR}} \) for one of the weakest first-echo cases. Plotted for each volume scan (the times of which are marked with circles below the abscissa) are the maximum and minimum heights of each 5-dB contour of reflectivity factor starting at 5 dBZ, and each 0.5-dB contour of \( Z_{\text{DR}} \). Examples

![Diagram](image_url)
of the RHI scans that contribute to it are given in Fig. 3 and serve as examples of many of the general features of the data for all the cases.

The cloud in the case illustrated in Figs. 2 and 3 was about 10 km from the radar and was scanned well over its entire lifetime. Individual squares of color represent independent data points. Radial resolution is defined by the 150-m pulse length and range gates, and tangential resolution by a combination of scan rate and averaging time in all the figures showing radar data, but is broadened by the 1° beamwidth. In this as in all other cases the RHI scans were spaced 1.2° to 1.5° azimuth apart. At 10-km range, this is 210 to 260 m apart and the 1° beam has a diameter of about 175 m. This cloud is 2 to 3 km wide over most of its lifetime, so there are 6 or more RHI scans within the cloud in each volume scan, and those in Fig. 3 are selected especially to show the $Z_{DR}$ development. Figure 2 shows that $Z_e$ reaches a maximum of less than 20 dBZ and $Z_{DR}$ exceeds 1 dB, a drop diameter of about 2.3 mm. Figure 3f in particular illustrates the local variability of both $Z_{DR}$ and $Z_e$. It also is a good example of the subjective smoothing applied in constructing the time–height diagrams. While Fig. 3f has individual data points with $Z_{DR}$ up to 2.5 dB, the data from Fig. 3f alone would be recorded as 1 dB up to about 2.3 km and 0.5 dB up to about 3.3-km height. One or even several scattered data points are not sufficient to justify a contour, and the attempt has been made to apply this kind of judgment evenhandedly across all the $Z_{DR}$ data.

White in Fig. 3 represents $Z_{DR}$ of zero dB ($\sim 0.25$ to +0.25 dB), and gray is off scale. The largely gray area close to the ground is nearly all $Z_{DR} > +4$ dB, and represents insects (Wilson et al. 1994). This makes the $Z_{DR}$ especially hard to interpret within about 1 km of the ground, in Florida, at low values of $Z_e$. The lowest 1 km is truncated in the time–height diagrams, though the contours can be extended down to the ground with confidence for reflectivity factors above about 15 dBZ.

Figure 3c represents the kind of $Z_{DR}$ signal (two patches of positive $Z_{DR}$, up to about 2 km AGL, at about 9- and 10-km range) that is tempting to interpret as rain but would not be in the present study from that RHI alone. They are ascribed to rain in this particular case because of continuity in space and time with the stronger and larger patch of $Z_{DR}$ in Fig. 3d, which is considered definitely to be rain.

Note the mantel echoes in Fig. 3, consistently to above 5 dBZ but less than 10. The few spots of 10 dBZ in Figs. 3e and 3f are determined to be rain, because of their location and their correspondence to $Z_{DR} \approx 0.5$ dB. The freezing level on 3 August 1998 was recorded at 4.5 and 4.6 km (the 0000 and 1500 UTC soundings from Cape Canaveral, FL), so this cloud was very likely completely ice free at all times.

The two “bursts” of $Z_{DR}$ in Fig. 2 are separated because of the evidence represented in Figs. 3d–f. The cloud evidently has two, somewhat separate updrafts that produce the two, somewhat separate “rain showers,” but the time resolution of the data is such that this analysis is not certain.

The first $Z_{DR}$ return in Fig. 2 appears without any echo signature that one would otherwise associate with scattering from water drops (in both Figs. 3c and 3d). In individual range gates of Fig. 3d there are coexisting $Z_{DR}$ of >1 dB and reflectivity factor < 0 dBZ. Zero dBZ for 2-mm-diameter drops (see Table 1) corresponds to a concentration of about one in 60 m³, below the sampling capability of present aircraft instruments for cloud penetrations 2 or 3 km long.

b. An intermediate case

Figures 4 and 5 show the same kind of data for a nearby cloud, on the same day at about the same time, that ascended faster and farther than the one in Figs. 2 and 3 and attained higher values of both $Z_{DR}$ and $Z_e$. This cloud had a more confused beginning (as the second turret from the left in the larger cloud mass in Fig. 5a), but it was a distinct, single cell with a width less than 2 km. Size sorting is evident in Fig. 4, with the highest values of $Z_{DR}$ always lower in elevation than the highest values of $Z_e$ in each volume scan until very near the end. The relation between the vertical profiles of reflectivity factor and $Z_{DR}$ in the single RHI in Fig. 5c is a good example by itself of size-sorting during growth. The smaller drops remaining higher in the cloud attain higher $Z_e$ in aggregate than the larger drops falling at lower elevation, that are very likely below the strong updraft and high cloud water contents at this time.

It is important to keep in mind here that while these data certainly do show size sorting, the vertical profile of $Z_{DR}$ in cases like Fig. 5c (and Figs. 7e and 7f, below) can be deceptive. While $Z_{DR}$ decreases upward, the concentration of big drops does not necessarily decrease upward at the same time. They could be masked by the stronger echo from much higher concentrations of smaller drops, but they would constitute a much smaller fraction of the total water content in the population of water drops above cloud droplet size.

The initial values of 0.5, 1.0, and 1.5 $Z_{DR}$ are confined to midcloud levels when first detected (Fig. 4), the data from the volume scan at about 1531 UTC), but each has descended into the boundary layer in the next volume scan. As will be seen below, it is common in the PRECIP 98 dataset for the initial values of all $Z_{DR}$ contours to be bounded only at the top: that is, in the first volume scan in which they appear they already extend down to about cloud base or even to the surface. The 0.5dB values of $Z_{DR}$ do extend down to or beyond 1 km AGL at the time of the volume scan from which Fig. 5b was selected, but that is only evident in an adjacent RHI scan, not shown.

The cloud top passes the freezing level between 1531 and 1532 UTC (Fig. 4) with a rise rate about 6 m s⁻¹,
Fig. 3. Examples of RHI scans from the case shown in Fig. 2, $Z_e$ at left and $Z_{DR}$ at right. The first $Z_{DR}$ interpreted as rain appears in (c), at 10-km range. Note the Bragg mantel echo.

and the top height reached its maximum at about $-5^\circ C$ at 1535 UTC. It therefore appears unlikely that ice processes played any significant role in the development of the radar echo history of this cell, though the top several hundred meters of the echo in Fig. 5c is below freezing and may contain some ice.

Lines are provided in Figs. 2 and 4 (and 6) that show rise and fall rates of 10 m s$^{-1}$. Cloud-top rise rates for the present cloud sample vary between about 3 and 9 m s$^{-1}$ and average about 5 m s$^{-1}$ (Table 2). A fall velocity of 10 m s$^{-1}$ is about that of 4.5-mm-diameter drops ($Z_{DR}$ of 2.5 to 3 dB) at 2 km AGL in Florida. Echo descent rates, meaning the descent of the bottom contours of radar echo, average about 10 m s$^{-1}$ (Table 2), as in Figs. 2 and 4. The $Z_{DR}$ contours in the growing stages of clouds cut across the descending echo bottoms at steep angles, as is illustrated in Figs. 2 and 4.

c. A strong case, viewed also with a fitted drop size distribution

The third and last case to be shown in detail was the strongest of those for which fairly complete data were collected, and the data are presented in Figs. 6–8. On 5 Aug, a small area of quite active convection developed between about 5- and 25-km range, the range for best radar coverage. Cells started on the near side of this patch and moved through to the far side as they grew...
and died. These cells tended to form in pairs, and Fig. 6 shows the time–height diagrams for one pair. Figure 7 contains selected RHIs showing especially the development of the strongest case, cell 1, the evolution of which is given in Fig. 6a. The volume scans are marked and numbered along the abscissas in Fig. 6 for easy reference in the text. The two cells are distinct above roughly 2 km, but below that their radar echoes merge and are not distinguishable. Both cells were first distinguishable in the radar data at times when $Z_{DR}$ values in the low cloud levels suggested that large raindrops were probably already present. In particular, there appears to be a reasonable possibility that drops from cell 2 (that in Fig. 6b), which developed radar echo from precipitation several minutes earlier than did cell 1, were present in some of the air that constituted the updraft impulse that initiated cell 1.

Figure 7a (scan 4) shows a growing phase of cell 2 at 14-km range and a very early view of cell 1 showing the mantel echo but no precipitation echo aloft, centered at about 12-km range. Figure 7b, from volume scan 5 at about 1616 UTC, does not intersect the maximum echo strength of either cell, but was selected to illustrate the low-level mingling of the $Z_{DR}$ signatures and the radar echoes of the two cells. Figures 7c–h then give the development of cell 1, but also include a small amount of large-drop precipitation from cell 2 extending up to about 1 km AGL at 16-km range in Fig. 7d and only a trace of it showing in the others. As seen in Fig. 6a, the 10 dBZ first-echo height in cell 1 appears at 2–
4 km AGL, but the first appearance of higher values of reflectivity factor ascends until 45 and 50 dBZ start at about 5.5 km. Meanwhile the maximum $Z_{DR}$ values remain lower, though the 2-dB contour does top 5 km in one volume scan.

The freezing level on this day varied from 4.1 to 4.3 km on the three soundings from Cape Canaveral, but freezing levels were only occasionally identifiable in the RHIs. With the maximum cloud top 3 km above the freezing level, formation of ice at some point is very likely. However, the time between the cloud top passing the freezing level and the first appearance of 50 dBZ (at about 5.5 km and with $Z_{DR}$ approximately 1.5 dB) is only about 8 min for cell 1. A value of $Z_{DR}$ of 1.5 dB would correspond to raindrops 3 mm in diameter, and at 50 dBZ the value of $Z_{DR}$ for the standard Marshall–Palmer distribution (see below) is not far from that, about 2.5 dB. Explaining this as oriented ice crystals or wet snow in these turrets is most unlikely, so we strongly suspect that this is from supercooled or partially frozen raindrops (Smith et al. 1999). Furthermore, the results of Hallett et al. (1978) and especially of Sax and Keller (1980) confirm that ice is often undetectable by aircraft in fresh cumulus turrets at temperatures around −10°C in Florida, while at the same time water drops larger than a few hundred microns in diameter are fairly common. Given this experience and the short time after cloud top passing the freezing level, it seems possible (or likely) that the echo development through volume scan 6 at 1623, the last one during which the top is ascending rapidly, is quite independent of ice processes. The $Z_{DR}$ in scans 7 and 8 (Figs. 7g and 7h) decreases rather abruptly above the freezing level (as does the reflectivity factor in Fig. 7h), suggesting significant glaciation at these times, with descending cloud top. LDR data are available on this and the other cases, but are rather noisy. When smoothed, there is a suggestion of an increase in LDR above the freezing level only in Fig. 7h, suggesting that at that time the portion of the cloud above the freezing level did contain some ice.

Figure 8 shows an interpretation of the development for cell 1 of Figs. 6 and 7, using a gamma drop size distribution fitted as described in the appendix. Top to bottom, the first three rows represent reflectivity factor (dBZ), drop concentration (m⁻³ on a log scale), and rain rate (in mm h⁻¹), calculated using sea level air pressure and zero vertical air motion. (The actual rain rate aloft can be negative, but it is more meaningful intuitively to present the data this way rather than in g m⁻³ of rain content.) The last three rows are $Z_{DR}$, median volume diameter and $\mu$, an exponent in the gamma distribution (see appendix) that indicates the width of the size distribution. When $\mu = 0$ the distribution is exponential, and larger values indicate narrowing at the expense of the smaller sizes. The three columns in Fig. 8 are different times, corresponding to Figs. 7e, 7f, and 7h, following cell 1. The assumptions are the following: 1) the size distribution fits a gamma distribution; 2) it is adequately described using the correlation between $\mu$ and $\Lambda$ noted in the appendix; and 3) glaciation effects are insignificant. This last assumption is probably not true above 4 km at 1628:18 UTC, the right-hand row in Fig. 8, but we are fairly comfortable with the assumption otherwise. Since the $\mu$ versus $\Lambda$ correlation was derived from video disdrometer measurements at the ground (Zhang et al. 2001; in Florida, during PRECIP 98) there is some extra uncertainty attached when applied to the special circumstance of the very early radar echoes and especially near cloud top.

The degree of reliance in these deductions is ultimately a matter of judgment since there is no way of assigning uncertainties, but we think the overall trends shown here are very likely correct. The obvious correlations here among the first three rows and the last three rows are especially striking. The drop concentration, the reflectivity factor and the rain rate correlate very well with each other, and all three correlate very poorly with $Z_{SR}$, median volume diameter and the width of the drop spectrum. Note that the maximum drop concentration increases from a few per cubic meter at 1616:02 UTC (Fig. 7c, not shown in Fig. 8) to several per liter at 1622:48 UTC, the middle column of Fig. 8, with the maximum located at cloud top until the updraft ceases and the cloud top descends. Meanwhile, $D_v$, $Z_{DR}$, and $\mu$ remain rather unchanged, with the largest values near cloud base. The size distribution at the times shown is nearly exponential ($\mu \to 0$) low in the cloud but becomes less so toward cloud top. This and the other cases on 5 August did produce significant amounts of rain, with rates that would be calculated as up to 50 mm h⁻¹ at the ground, though only in small cloud volumes.

d. General observations

In discussing the radar data and their interpretations, we have emphasized the problems, and the subjectivity required for interpretation. However, the $Z_{DR}$ signal in the first echoes is in reality very robust. The examples
shown in Figs. 3, 5, and 7 were selected as good examples, but they are not exceptional in any respect other than coverage. It is difficult to obtain cases as complete as these. The $Z_{DR}$ data combined with the $Z$ histories reveal the time- and height-dependent aspects of the evolution of the drop size distributions as precipitation forms. This appears very solid: both quantitatively meaningful and highly revealing of the early stage of precipitation formation within the clouds. The systematic evolution of the size distributions with height in the precipitation shafts in Figs. 5, 7, and 8 is especially striking. The weak case in Fig. 3 is less so, as might be expected of the case that has a marginally significant $Z_{DR}$ signal. However, its interpretation also appears solid, especially in view of its continuity with the two stronger cases. Thus a major conclusion to be drawn at this point is that the combination of $Z_r$ and $Z_{DR}$ constitutes a powerful tool for testing numerical models of the early formation of warm rain in cumulus. The models must reproduce the simultaneous evolution of $Z_r$ and $Z_{DR}$ if they are to be acknowledged as realistic simulations, and that is probably quite a strict test for the microphysical treatment.

As was noted by Knight and Miller (1998) using $Z_r$ alone, the $Z_{DR}$ information confirms that the earliest precipitation formation detected with the radar is in the form of a central shaft. There is no evidence of precipitation originating at or near cloud edges, as might occur according to ideas of early coalescence being prompted by turbulent mixing.
A striking feature of some small cumulus in Florida that has been seen several times before is three downward protrusions of weak radar echo, one on each side of the cloud and one in the middle. With Z_{DR}, the middle protrusion can now be identified as precipitation and the ones on each side as Bragg scattering. Figure 9 is an example of this.

6. Collated early-echo and early-Z_{DR} results

Figure 10 contains data of first-echo heights at 10-, 25-, and 40-dBZ thresholds, and first-Z_{DR} heights at 0.5, 1.5, and 3.0 dB using data from all 31 cases from PRECIP 98. (All of the maximum-value data were derived using the same subjective smoothing used in constructing the time–height diagrams. The number of cases never totals 31 in one panel because some did not reach the higher thresholds and some were not being recorded early enough for the lower thresholds.) The variability in both Z_e and Z_{DR} heights is striking, as is the often-wide altitude range of first appearance. The width of the altitude range is certainly influenced by the approximately 2-min resolution of the data, but it seems very wide nonetheless. Being from only 7 days, the data cannot be considered truly representative of the climate. The Z_{DR} data are truncated somewhat arbitrarily at 1 km AGL. This removes the boundary layer insect contamination, but the uncertainties from the possibility of insects within the clouds remain.

One obvious trend is the rising first-echo height with increasing reflectivity threshold. Note that all 8 of the 40-dBZ cases come from one day (5 August 1998; see Fig. 6 for 2 of these cases in detail, where it can be seen that the same trend exists in the individual clouds). The other major trend is the lower altitudes of the 3.0 dB first Z_{DR} values, though there is no clear difference between those at 0.5 and 1.5 dB. There is a strong tendency for all first Z_{DR} signals to extend to cloud base, or even to the ground, as already seen in the time–height diagrams. When they do start aloft they virtually always extend to 1 km AGL or below in the very next volume scan, about 2 min later. This Z_{DR} behavior was not expected, since big drops at cloud base must have grown above, and a reason for it is suggested below.

Data relating Z_e with Z_{DR} are shown in Table 3, in which the numbers within the table represent numbers of cases. The maximum Z_{DR} values anywhere in the volume scan are displayed at the time of appearance of the first 10-, 25-, and 40-dBZ echoes, and those further restricted to the height range of the first echoes are also given. For instance, there were 4 cases in which 3.0 to 3.5 dB Z_{DR} were present in the volume scan that first exhibited 10 dBZ, and only one at the same height as the 10-dBZ echo. Below, the maximum echo heights are given at the times as well as time and height ranges of the first 0.5-, 1.5-, and 3.0-dB Z_{DR} values. It is noteworthy that all of the recorded first Z_{DR}s at 0.5 dB occur when the maximum Z_e in that volume scan is below 20 dBZ, and that large drops always accompany 25 dBZ but not necessarily at the same height in the volume scan (always lower). The maximum Z_e data include levels at 0, 5, and 10 dBZ even though 0 and 5 dBZ are nearly always, and 10 dBZ sometimes, from Bragg scattering. The data in these categories would have been more meaningful with a shorter-wavelength radar. It is surprising that the maximum Z_e values at the time of first 3 dB Z_{DR} are so evenly distributed.

The standard Marshall–Palmer raindrop size distribution with an n_0 of 8000 m^{-3} mm^{-1} implies a particular dependence of Z_{DR} upon Z_e, and those values are indicated in Table 3. The Z_{DR} values of the actual data are nearly always higher than those from the Marshall–
Fig. 7. Selected RHIs from the case in Fig. 6. (a) and (b) Portions of both cells: (a) a very early stage of cell 1 at about 12-km range and the upper part of 2 at 14 km, and (b) off-center slices of cells 1 and 2 at about 13- and 15-km range, showing the area of large-drop precipitation from cell 2 undercutting cell 1. (c)–(h) Then center on cell 1, with the RHI scans selected to illustrate the evolution of the maximum $Z_e$ and $Z_{DR}$ values. The freezing level (4.1–4.3 km in soundings) may start to show in the dying stage of this cloud, in (g) and especially (h).

Palmer distribution, as expected: often much higher, and never much lower. These data provide some generality to the early formation and fallout of large raindrops, following the results of Illingworth (1988), and are also consistent with the drop size distributions in Carbone and Nelson (1978), which were very flat in the early stages, implying high $Z_{DR}$.

Perhaps the most surprising result in comparing $Z_{DR}$ and $Z_e$ histories of the early echoes is how little the time–height diagrams resemble each other. This is seen in Figs. 2, 4, and 6 and especially in Fig. 10. The regular descent of the contours that represent the lower bounds of echo developing aloft has been familiar for many years, and it is not surprising that the descent of $Z_{DR}$ contours should be steeper, because of size sorting. However, it was not anticipated that their descent would be so much faster that they would usually not be resolvable with the 2-min time resolution. It would be worth verifying that these very early $Z_{DR}$ signals derive from large raindrops, perhaps with a small airplane at cloud base using the windscreen as the detector to achieve an adequate sample volume.
In contrast to the difference in the $Z_{\text{DR}}$ and $Z_e$ histories of the observed early radar echoes, a numerical modeling study of the growth of ultragiant aerosol in a short-lived, single-cell cumulus shows quite a different result. Lasher-Trapp et al. (2001) examined radar echo formation and precipitation development from high concentrations of ultragiant aerosol based on the observations of Noll and Pilat (1971). The ultragiant aerosol were initialized at cloud base and grew by coalescence with cloud droplets along trajectories derived from a three-dimensional simulation of a Florida cumulus. At 1-min intervals, the radar reflectivity factor was computed in $(200 \text{ m})^3$ volumes in order to construct a time–height diagram, and this was compared with the early radar echo development. It was found that the modeled radar echo history could match the observations well enough to support the possibility of the first precipitation echo arising from ultragiant aerosol. There were no $Z_{\text{DR}}$ data on that cloud, but the $Z_e$ and $Z_{\text{DR}}$ histories from the model results are presented in Fig. 11. The $Z_{\text{DR}}$ contours descend at the same time as those of $Z_e$, only slightly steeper. The $Z_{\text{DR}}$ and $Z_e$ time–height diagrams are as strikingly similar for the model as they are dissimilar for the observations.

This discrepancy is interesting, and our hypothesis is that its resolution may involve two factors: a masking of the upper part of the early $Z_{\text{DR}}$ signal in the observations, and a lack of realism of the numerical modeling of the very earliest stages of the cloud. The very early values of observed, significantly high $Z_{\text{DR}}$ low in the
cloud are accompanied by weak radar echo. In Figs. 2 and 3, for instance, \( Z_{DR} \) values above 1 dB accompany radar echo weaker than \(-5\ \text{dBZ} \) below 2 km. Above them the equivalent reflectivity factor in the cloud, presumably largely from Bragg scattering, exceeds 5 dBZ, so the drop population that causes the weak \( Z_{DR} \) signal may extend up into this region but be completely masked by the cloud echo. This masking may commonly hide the early \( Z_{DR} \) signature of drops descending from higher altitudes.

Assuming that this masking of early \( Z_{DR} \) values exists, there is still a large discrepancy with the model results. The big drops in the observations appear low in the cloud well before the significant echo intensification descends to that level, whereas in the model the descent of significant values of \( Z_e \) accompanies that of \( Z_{DR} \). A possible explanation is that the cloud start-up in the model may be unrealistic. The model initiates the cloud with a Gaussian heat source in the boundary layer (maximum heating in the center of the model domain: a common technique in modeling cumulus initiation), and the cloud grows as a single, vigorous thermal from before the very first appearance of condensation. Figure 12 shows the velocity field in a vertical, central cut through the model cloud, 5 min after first condensation. The cloud top is already above 2.5 km and the maximum updraft exceeds 10 m s\(^{-1}\) and is quite smooth throughout the cloud.

In Fig. 11, the \(-20\ \text{dBZ} \) contour is from the cloud droplet population, not growing precipitation, and shows the strong and very uniform ascent of the early cloud top. The strong initial updraft and very simple cloud circulation in the early stages prevents any drops from descending through the cloud, and when they do descend, all the drops that reach cloud base early are big and the radar echo rises quickly to its maximum value. Perhaps in reality the very early cloud stages are generally more complicated and long-lasting, allowing a little formation and descent of big drops to occur earlier. Perhaps the main thermal gathers itself (so to speak) as embryonic big drops are already forming in the layer of shallow cumulus that is observed usually to precede the more vigorous thermals that produce clouds several km deep. If this is so, the fact that the modeled cloud’s size, top rise rate, and maximum top height are all quite realistic (Lasher-Trapp et al. 2001) does not adequately demonstrate the model’s dynamical similarity to the observed cloud in terms of its use for simulating the microphysics.

The first part of this two-part hypothesis for reconciling the modeled and observed first-\( Z_{DR} \) behavior is testable simply by using a shorter-wavelength radar. To avoid most of the Bragg scattering, X band (3-cm wavelength) would probably be best. At shorter wavelengths the interpretations would be complicated by Mie scattering from the drops. If the second part of
Fig. 8. Data from the RHIs of cell 1 shown in Figs. 7e, 7f, and 7h (scans 7, 8, and 10 in Fig. 6a) are fit to a gamma distribution (Zhang et al. 2001; see appendix) and characteristics of the drops are displayed here as labeled at the left at the three times for the three rows. The last row, \( m \), is an exponent in the gamma distribution. When \( m = 0 \) the distribution is exponential, and as \( m \) increases it narrows. The rainfall rate is calculated as if at the ground with zero vertical air velocity.
the hypothesis is correct, the remedy is not easy. Modeling the very earliest stages of cumulus more realistically probably requires more realistic forcing and considerably better representation of smaller scales of motion. Adequate observations of this stage of cumulus cloud formation and the cloud forcing also would be needed.

7. Use of $Z_{DR}$ in studying the development of significant rainfall

The data herein are consistent with those of Illingworth (1988), and probably also with his conclusion affirming the plausibility of ultragiant aerosol (Johnson 1982) or deliquesced sea-salt nuclei (Woodcock 1952) being progenitors of the early, sparse concentrations of large drops in cumulus. It remains to be shown either by direct evidence that this is actually true, or, by convincing demonstration that other mechanisms are not
FIG. 11. Time–height diagram of first $Z_e$ and first $Z_{DR}$, from a three-dimensional simulation of a single turret, with precipitation only forming from ultragiant aerosol introduced at cloud base. In this example, the model was run with coalescence efficiencies of unity so as to produce fairly high values of $Z_{DR}$ and $Z_e$. A run using the laboratory values of coalescence efficiency produced the same correspondence between the two, but maxima in $Z_{DR}$ and $Z_e$ of only 1.0 dB and 30 dB. The labeled times are minutes after first condensation. The $-20$ dBZ contour is from cloud droplets, providing a contour close to cloud top, but the first condensation was at time zero on the abscissa.

feasible, that it is necessarily true. In any case, as was noted above, these early, large drops may or may not be important meteorologically, except for understanding the radar data.

The present study does extend to the first formation of significant rainfall rates within cloud, in the discussion of the strong case accompanying Figs. 6–8 above. Here, one sees the first formation of significant quantities of rain high in the cloud and its subsequent descent to the ground. This is shown by the rainrate interpretations in Fig. 8, well correlated with $Z_e$ but not with $Z_{DR}$. If one is seeking a meaningful end point for defining a time required for initiating significant coalescence, this is an excellent basis for defining it. While the case in Figs. 6–8 is muddled by the possible influence of ice, it would be quite feasible to coordinate aircraft penetrations with this kind of radar coverage on clouds like this, using standard microphysics instruments, to test the interpretations.

An example of what $Z_{DR}$ might reveal for bigger, more complicated clouds is presented in Fig. 13, which shows $Z_e$, $Z_{DR}$, and radial velocity data from a single RHI. Note the radial velocity structure, suggesting horizontal convergence from about 2 to 6 km AGL and divergence in the upper 2–3 km of the cloud. There is an apparent axis of convergence at about 20-km range, below the freezing level at 2–4-km height, with a maximum at 4 km. This feature and the echo structure suggest that an updraft impulse is ascending along the near (left) edge of preexisting echo. At the near (left) side of this convergence, toward the radar from the preexisting echo, there is a slender shaft of large drops with $Z_{DR}$ values of 2.5–3.5 dB that corresponds with a shaft of $Z_e$ values ranging from about 0 dBZ at the bottom to 20 dBZ at the top. At the far (right) side of the convergence but close to it, at the edge of the major, preexisting echo, $Z_{DR}$ values of 0.5 to 1.0 dB correspond with 20 to 50 dBZ. A possible interpretation here is that a part of the updraft impulse inherits precipitation from the storm, and consequently grows a broad spectrum of drops as it ascends (low $Z_{DR}$, high $Z_e$), while the part of the impulse away from the precipitation shaft inherits little precipitation, and develops larger drops with a narrower distribution (high $Z_{DR}$, low $Z_e$). This recycling of precipitation into portions of updrafts, with consequent development of extreme, local differences of hydrometeor sizes and size distributions might be quite common in storms. The interpretation is of course a speculation, especially risky relying upon radial velocity alone, but the point is that there is a lot of information contained in the $Z_{DR}$ signal that is potentially important for interpreting the microphysical processes within storms, not just the first echoes, especially if obtained within a more complete data context.

8. Conclusions

The present observations are in agreement with those of Illingworth (1988), that the earliest radar echoes from warm-based cumulus often consist of very sparse quan-
Fig. 13. Measurements of $Z_e$, $Z_{DR}$, and radial velocity in one RHI through a small rainstorm. There is an apparent updraft impulse rising along the near (left) side of a precipitating cloud, which produces a shaft with high $Z_{DR}$ with low $Z_e$ at the left and one with low $Z_{DR}$ and high $Z_e$ at the right, within the preexisting precipitation.

Quantities of raindrops 1 or more mm in diameter. This adds plausibility to the ultragiant aerosol hypothesis of first raindrop formation (e.g., Woodcock 1952; Johnson 1982).

However, large drops appear in the cloud base region well before any appreciable quantity of rain (in terms of g m$^{-3}$, or mm h$^{-1}$) arrives at that level. This differs from a model of precipitation growth in a single thermal, in which the first big drops at the ground occur only slightly in advance of the main burst of precipitation. One possible explanation is that the very early, large drops may form in a weak early stage of the cloud that precedes the vigorous thermal that is normally associated with the “first echo.” If so, both observation and modeling of the earliest stage of cloud growth need to be improved.

The use of $Z_{DR}$ as well as $Z_e$ in observational studies of the early stages of precipitation formation in warm cumulus is highly revealing of the evolution of the droplet size spectra in time and space. As such, it constitutes by itself a quantitative definition of the onset of precipitation that has been lacking and that is not available from $Z_e$ alone. In attempting to simulate the evolution from aerosols to significant amounts of precipitation in cloud models, this kind of data will provide a strong and realistic test.

Some of the ambiguities inherent in interpreting the $Z_e$ and $Z_{DR}$ data at 10-cm wavelength can be alleviated with data from aircraft, but only at limited locations and times. The remote-sensing addition that would be most valuable for studies of precipitation formation would be the addition of a shorter wavelength polarization radar, probably $K_a$ band. Data at the 8-mm wavelength would be essentially free of Bragg scattering, and its $Z_{DR}$ would be weighted differently from that at 10-cm wavelength because of Mie scattering from the aspherical drops. This would provide an extra constraint on the drop size distribution. Operated as a dual-wavelength radar, the $S$ and $K_a$ combination would also provide estimates of liquid water content independent of the polarimetric radar observations.

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APPENDIX

Fitting the Gamma Distribution

In situ observations indicate that raindrop size distributions (DSDs) contain fewer of both large and small drops than exponential distributions. Ulbrich (1983) suggested the use of the gamma distribution for raindrop spectra. This distribution is given by

$$N(D) = N_0 D^\mu \exp(-\Lambda D),$$

where $N$ and $D$ are drop concentration (m$^{-3}$) and diameter (mm). The gamma DSD with three parameters $N_0$, $\mu$, and $\Lambda$ is capable of describing a broader variation...
in DSD than an exponential distribution, which is a special case of the gamma distribution with $\mu = 0$.

In a recent analysis of video disdrometer observations in Florida (Zhang et al. 2001), it was shown that two of the gamma DSD parameters, $\mu$ and $\Lambda$, are highly correlated. The values were obtained from the moment of the measured DSDs, and the relation between them, from polynomial curve fitting, is

$$\mu = 0.016\Lambda^2 + 1.213\Lambda - 1.957.$$  

This relation combined with $Z_{HH}$ (the copolar horizontal reflectivity factor) and $Z_{DR}$ constitute the three equations for retrieving the three gamma distribution parameters.

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