A Radar Study of Convective Cells in Mesoscale Systems in GATE.  
Part II: Life Cycles of Convective Cells

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ABSTRACT

This is Part II of a two-part paper describing the vertical profile of radar reflectivity in GATE convective cells. Time-height radar life histories for 42 cells over three GATE days are examined, using data from the Quadra radar with 5-minute resolution. Mean profiles and plots of cell characteristics are generated, and confirm that the mean profiles in Part I are representative of the active portion of the cell lifetime. There are marked differences between the cell life histories of isolated cells and the longer-lived cells associated with mesoscale systems. In contrast to cells sampled in organized systems, the isolated cells are often of very limited vertical extent and must be dominated by the warm rain process. When forcing features exist, such as gust fronts and intersecting lines of convection, they appear to dominate the generation of new convection, and isolated strong echoes are not observed.

Composite life histories for typical GATE cells are constructed. The typical radar echo forms first at an altitude of 2.5 km and reaches the surface about 5 minutes later, strongly suggesting early domination by the warm rain process. At the same time the echo top rises and the mid-to-late stages of cell lifetime involve both warm rain and ice processes. The reflectivity profiles of the longer-lived echoes change relatively little in the middle 50% of the life cycle.

1. Introduction

In Part I (Szoke et al., 1986) we compiled statistics for almost 300 GATE convective cells from several mesoscale systems. We arrived at a mean vertical radar reflectivity profile for the GATE (GARP Atlantic Tropical Experiment) convective cell along with statistics for a number of cell characteristics. The most distinctive result was the weakness of the reflectivity structure, with fairly modest low-level reflectivities decreasing rapidly with height above the freezing level. We hypothesized that the reflectivity structure is a result of the weak updrafts present in GATE cells. In Part II we examine the complete radar life history, by constructing time-height radar histories of 42 representative cells for three of the days studied in Part I.

One of the important questions raised in Part I is: Are the mean GATE profiles representative of the active stage (both updrafts and downdrafts occurring) of the convective cell? In terms of reflectivity, we would expect the active portion of the echo lifetime to occur from the time of the first 40 dBZ surface echo (by our Part I cutoff for a cell) through the time of the overall strongest profile. If we are to make valid inferences about the strength of the updraft from the shape of the vertical reflectivity profiles, the profiles from Part I cannot be biased toward the decaying stage of the echo. Examination of the time-height radar histories will determine whether this is so, and also how the reflectivity profile changes during the life of the echo.

Our analysis scheme involves choosing the profile of maximum reflectivity as in Part I by examining all the PPI scans through the vertical extent of each cell, using the same cell definition set forth in Part I, section 2. Since we need the best possible time resolution, we are restricted to the Quadra radar, the only digitized radar with 5-minute resolution. Characteristics of the Quadra radar are listed in Part I, Table 2. In this study only days 245 (2 September), 255 (12 September), and 257 (14 September) are used. The majority of the cells for each day are from organized mesoscale convective systems, as in Part I. For comparison, a few isolated cases not associated with any such mesoscale cloud systems are included.

It is important, as noted in Part I, to distinguish between what we are calling a cell and a cell in the sense of a single-updraft lifetime (Byers and Braham definition, 1949). Our definition of a cell in terms of reflectivity was given in Part I and is followed here. The spatial resolution of the GATE radars used is sufficient to consider that most of the echoes (and profiles) identified in Part I are, in fact, from a cell as originally defined. However, in Part II we track these echoes and in adding the dimension of time with a resolution of 5 minutes, combined with our spatial resolution, it is safe to assume that in most cases we are tracking radar
echoes composed of more than one updraft lifetime (individual "cells"). Thus many of the echoes which we track (which we will call cells in Part II) should be thought of as being composed of several cells (by the original definition) evolving within a given storm. With the Quadra radar resolution they appear as a continuous (in time) maxima of reflectivity, thus meeting our reflectivity definition of a cell given in Part I. An exception would be for the very short-lived, isolated cells tracked which are more likely to directly correspond to a single-cell lifetime.

We are aware of no other studies using time–height cell history diagrams for tropical convective cells. Such diagrams have been used elsewhere, such as in the analysis of data from the National Hail Research Experiment (NHRE) (see Knight and Squires, 1982, for example), which took place in northeast Colorado in the 1970s. One example from that experiment will be contrasted with our results in section 3.

2. Examples of cell life histories in GATE

In this section we present several examples of radar cell life histories for 3 GATE research days, 255, 257 and 245. A list of all 43 cells studied, along with various cell characteristics, is found in the Appendix. Only cells which could be tracked with reasonable certainty are included. Data gaps during tape changes at the radar site, usually of 10–15 minute duration, were a particular problem during the decay stage and limited the trackable lifetime of the echo.

Generally, cells are followed until they can no longer be clearly identified as echo maxima. In many cases the cells simply become so weak that they blend into the general echo area some distance behind the leading convective line edge. For some cells it is clear that the cell joins one or more other (usually dying) cells to begin or continue an identifiable echo mass. For these cases the echo mass profile, taken as the maximum profile in the echo area which is clearly distinguishable from the general surrounding area, is followed as long as the echo mass remains a clearly defined entity.

a. Day 255, 12 September 1974

Figure 1 is a Quadra radar PPI from a low elevation angle at a representative time during the cell tracking period, 0900 to 1330 GMT, showing the three lines discussed in Part I. (Descriptions of this system are found in Zipser, 1977; Gamache and Houze, 1982; Johnson and Nicholls, 1983; Mansfield, 1977; Zipser et al., 1983). The squall line (SL) moves southwest at 14 m s⁻¹ during the cell tracking period. It intersects a convective line which we have called the moderately fast line (ML, so named for its southwest motion of 8 m s⁻¹), and an intertropical convergence zone band (ITCZ) drifting northwest at only about 3 m s⁻¹. The intersection area, where low-level convergence would be expected to be the greatest, will be referred to as the triple point (TP), and is the location of the most intense convection. Trailing off towards the northeast behind the TP is the anvil region, composed of areas of enhanced rain embedded in a large, mostly stratiform rain area as noted in Part I. Cells in the SL are most intense near the TP, but strong cells are found all along the wide ITCZ band and in portions of the ML band. The SL echoes diminish rapidly north of the TP, but on visible satellite imagery (not shown) a well-defined thin cloud line extends from the weak echoes north of the TP north and then northeastward for over 500 km all the way back to the African west coast.

Most of the tracks of the 17 cells studied on day 255 are shown in Fig. 2, with two leading-edge isochrones bracketing the time of interest. The time periods of the tracks in Fig. 2 are given with some other cell characteristics in the Appendix. Although the three lines move with different velocities, all the individual cells move toward the southwest at moderate speed, regardless of the line to which they belong.

The only environmental air which is relatively undisturbed by convective events is found to the northwest of the ITCZ band and to the southwest of the squall line; i.e., in the western quadrant of Figs. 1 and 2. A representative sounding for this air has a convective available potential energy (CAPE) of about 1500 J kg⁻¹, spread over a deep layer from about 960 mb to above 200 mb (Zipser et al., 1981). The wind hodograph in that region (not reproduced) shows light northerly winds in the lowest kilometer, a marked
the plots is extrapolated, as the lowest recorded radar return is 22 dBZ. We recognize that this cutoff in the data precludes description of the early portion of the echo (and cloud) lifetime and part of its vertical extent; the importance of this will be discussed later.

Among some of the features common to all the cells in Fig. 3, and many of the cells from this area on Day 255, is the first echo height, ranging from 2.5 to 3.5 km. While this is the level where the 20 dBZ echo is first seen, it is consistent with the nose of the contours of the other reflectivity levels, and we believe that it would also well represent the first echo heights at lower reflectivity thresholds. Since the freezing level is near 4.2 km, the inference is that precipitation formation and early growth of echo is due to warm rain processes. This point will be further addressed in a following section.

In the cases in Fig. 3, the time from initial echo aloft to echo reaching the surface (20 dBZ contour) is fairly short, generally 5–10 minutes. There is considerable variability in the time interval between 20 dBZ echo at the surface and the most intense rain of 40 or 45 dBZ. For cells 1 through 4, this interval is longer, with cell 5 (Fig. 3b) having the longest interval of almost 20 minutes. Even for this case, though, the time for the 20 dBZ echo to reach the surface is only 5 minutes.

As most of the cells in Fig. 3 form ahead of the SL early in their lifetime they are usually isolated from other echoes before being overtaken by the main SL echo edge. They often continue to grow as the SL edge discretely propagates ahead, so that by the time the cell decays it can be a considerable distance behind the new leading edge. The cells of this group in their later stages often become hard to identify in the surrounding echo area as they weaken. However, cells 6, 9 and 10 (Fig. 3) join with other weakening cells to form trackable echo masses with surface reflectivities generally between 40 and 44 dBZ. Echo masses 6 and 10 end up 60 km behind the new leading SL edge in their late stages. The concentration of these weakening cells form part of a much larger area of moderate to light stratiform rain, which is important in producing mesoscale divergence and outflow at low levels (Zipser, 1977; Houze, 1977; Leary and Houze, 1979), thus helping to maintain the overall system.

There is some resemblance between the time–height histories of the longer-lived cases on this day and the other days yet to be discussed and distance–height cross sections through convective lines presented by others (Leary and Houze, 1979; Zipser et al., 1981). This resemblance is in agreement with the progression of the echoes tracked from ahead of the line initially to well behind the line and the fact that these lines are long-lived features. Thus the distance–height cross sections show younger cells at the leading edge of the line and a progression toward decaying cells and stratiform rain toward the rear. The same progression occurs with time on our life history diagrams, with some actually show-
ing a bright-band structure, though the bright band is more pronounced in the distance–height cross sections presented in Leary and Houze (1979). We are following echo maxima which in time become merged in the stratiform region, where a general bright-band structure would be expected in accordance with the very weak (if any) updrafts in that region. The lack of a bright band for some of our echo masses could reflect the presence of an updraft, albeit weak, in these echo features. In some cases this updraft may have persisted (though weakening in time) since the cell formation; in other cases of trackable cells into echo masses the updraft may reform in the stratiform region, resulting in an increase in reflectivity and the presence of distinct echo maxima in the stratiform region. The dynamics of the formation of such systems awaits further study.

The spreading of the combined anvils of older cumulonimbi in the ITCZ and TP areas results in an echo overhang which extends downwind as much as 60 km ahead of the surface SL edge. The anvil overhang is likely composed of ice crystals and is generally 5 km thick, from 5 to 10 km in height, and has peak reflectivities as high as 30–33 dBZ. It is thickest and most intense just downwind of the TP area. Radar and time-lapse cloud photography demonstrate that convective cells develop independently below this overhang. However, the growing cells quickly penetrate the overhang, usually within 15 minutes of first echo formation. Most of the cells penetrate well above the anvil radar tops, with the extreme case a 5 km penetration to reach a 15 km echo height for cell 5 (Fig. 3b). However, for the longer-lived cells, such as cell 6 in Fig. 3, the echo top remains nearly constant during the echo mass stage (more stratiform period). The time of the highest echo top is well into the cell life cycle, usually at least 30 minutes after first echo. The surface reflectivities tend to peak much earlier, so that at the time of the highest echo top the surface reflectivity is on the decline.

We can contrast cells 1–10 with cells 11–14, which are cells that are parts of one of the organized lines but remain separate (are never joined by 22 dBZ-or-greater echoes) from other cells in the line. Cells 12 and 13, pictured in Fig. 4, are typical of the cells in this group. Cell 12 (Fig. 4a) forms close to cell 11, approximately 10–15 km north of the TP area along the SL, where the SL diminishes rapidly in intensity. While cell 12 forms near other cells, it does not merge with any other
cells in the SL during its lifetime. The overhang ahead of the SL in this area is considerably weaker than that near the TP. The echo formation height and rate of growth are similar to those cases in Fig. 3, but after reaching reflectivities of greater than 45 dBZ the cell quickly diminishes. The maximum echo height reached is only 5 km, occurring coincident with the peak surface echo, unlike cells 1–10.

Cell 13 (Fig. 4b) forms 13 km north of the north edge of the ITCZ line, southwest of the SL leading edge, but never joins the ITCZ line through its short history. The anvil overhang is quite thick in this area but this cell never penetrates even the lower 5 km anvil base, and has a top echo height of only 3.5 km, below the freezing level. The reflectivity growth rate is comparable to that of the other cells, but very little upward growth occurs from the height of the initial echo. Despite its short lifetime it still attains a brief period of surface reflectivity over 40 dBZ.

Separate cells in the organized lines have characteristically short lifetimes of 30–60 minutes, low maximum echo heights and very modest surface reflectivities. Still weaker are the separate cell cases not associated with any organized line; cell 15 in Fig. 5 is a typical example. Cells of this type are difficult to find on day 255 during the cell tracking period because most of the areas between the lines and within radar range are free of echo. We believe that this is a significant observation and speculate that the strong low-level convergence and forced ascent along the leading edge is of crucial importance in generating strong convective clouds.

The isolated cell 15 is weaker still than cells 12 and 13 discussed previously. Its echo is well below the freezing level, reaching only 3 km in height within 5 minutes of echo formation. The cell begins to diminish only 10 minutes after its initial echo aloft, which forms at only 2 km height, and as low as 1 km for cell 16. Separate cells not associated with any line, like cells 15, 16 and 17, are comparative to maritime cells randomly selected in previous studies, and are similar to those presented by Byers and Hall (1955) for the Puerto Rico area and Saunders (1962) for the Caribbean.

We believe that association with an organized line results in an enhanced echo, other things being equal. The enhanced low-level convergence along the protruding gust front ahead of these lines provides increased updraft and a stronger reflectivity profile, by the reasoning outlined in Part I. Strongest cells occur near the TP where such forcing would be expected to be the greatest. Why some cells growing in the lines are much longer-lived than others is perhaps related both to the amount of low-level convergence and the time spent in the favorable convergence region. From Fig. 2 it is seen that all the echoes move toward the southwest at about the same speed, but the line motions are different so that a cell along the SL should be in a region of favorable forcing longer than one along the ITCZ band. Another factor could be related to the growth of nearby echoes, as it appears on this day that when more separation exists between echoes they have shorter lifetimes. In his study, Lopez (1978) also notes...
that cells growing separately have shorter lifetimes, and speculates that convective cloud elements in composite echoes are protected from the entrainment of dry air which would otherwise diminish the cells. The question still remains whether those echoes which grow strongly in organized systems do so because they happen to be surrounded by other echoes, or whether they are surrounded by and merge with other echoes because the conditions in that particular area are favorable for rapid growth for all echoes.

b. Day 257, 14 September 1974

On this day we focus on the eastward-moving line studied by Zipser et al. (1981), denoted by CL [for convective line, due to its slower motion of 2.6 m s\(^{-1}\) (see Part I)] in the low-level PPI scan at 1438 GMT from the Quadra radar in Fig. 6. In Fig. 7 we depict the cell tracks and some selected isochrones of the CL leading edge. The convective line in Fig. 7 was one of five slow-moving lines identified in the GATE array on this day between 0600 and 2300 GMT.

The line grows mostly by discrete propagation as new cells form approximately 5–10 km ahead of the main echo area along a north-south gust front extending to the east. Because of the slower motion of the CL, some of the new cells spend a longer time than on day 255 growing separately from other echoes. As noted in Zipser et al. (1981), the synoptic scale environment is characterized by deep southerly flow in the low troposphere, decreasing to nearly calm winds in the mid-troposphere, then increasing to 15–20 m s\(^{-1}\) by 250 mb. This wind structure results in the lack of an anvil overhang ahead of the line leading edge, unlike that of day 255. Representative soundings give a value of CAPE of only about 600 J kg\(^{-1}\), lowest of the three days studied in this paper.

Four representative cases from the nine cells tracked on day 257 are presented in Fig. 8. A striking difference between the cells in Fig. 8 (day 257) and those in Fig. 3 (day 235) is the much lower maximum 20 dBZ echo tops, and the lower values of surface reflectivity. (No surface echo as high as 50 dBZ strength was found.) In addition, the vertical dropoff from 40 to 20 dBZ echo is much sharper than on day 255, when the 25 dBZ echo often extends as high as 10–14 km. While the 20 dBZ echo tops are only 7–8 km, Zipser et al. (1981) found that the tops of many cumulonimbus clouds extend to 13 km. This indicates a large cloud area about 5 km deep of weak echo of less than 20 dBZ strength. Zipser et al. speculate that the weaker updrafts on day 257 led to the lower reflectivities aloft, by the reasoning set forth in Part I. The weaker updrafts are in agreement with the lower value of CAPE and the slower line movement on this day, with reduced low-level forcing. Additionally, with the cell movement perpendicular to the line movement (Fig. 7), one would expect the period of most intense low-level forcing to be reduced (from the SL cases of day 255).

Cell 2 (Fig. 8a) is typical of the longer-lived cells on day 257. Its initial echo formation (at 1418 GMT) and growth are similar to the cells on day 255. This area of the CL is developing so quickly that, although cell
Fig. 8. Cell life histories, as in Fig. 3, for four representative cases on day 257. See text for discussion.
2 forms about 5 km ahead of the main CL echo edge, it is connected to the main echo area by 1428 GMT, and by 1439 a new line of echoes has already developed east of cell 2. After one hour the cell joins with other cells in the main echo area to form an echo mass, which has a well-marked bright band of 40 dBZ around 4 km in its decay stage. When tracking ends at 1630, cell 2 is over 40 km behind the new leading edge (see Fig. 7).

Cell 6 (Fig. 8b) also forms along the gust front but farther from the main echo area. While other cells soon after form a line near cell 6, this cell decays before joining with the main echo area. Its life cycle is comparable to the day 255 cases of cells separate from other cells but parts of organized lines.

Cells 7 through 9 are from the area of the CL northeast of the Quadra. In this area cells form farther ahead of the main echo area, and cells are often farther apart and thus more easily followed. Some of the cells in this area are similar to cell 6 but somewhat less intense, while others resemble cell 9 (Fig. 8d), which is a very short-lived and much weaker case. In the area of cell 9, the gust front is moving faster and outruns this set of cells associated with cell 9 and forms the line of cells containing cells 7 and 8 farther to the east, causing cell 9 to be weaker than the other cells discussed above.

While the initial echo height and growth on day 257 are similar to the cases from day 255, there is a lower echo height, lower maximum surface reflectivities, and more rapid reflectivity dropoff. These differences would be anticipated from the generally weaker updrafts measured on this day (LeMone and Zipser, 1980). The observation of cloud tops with less than 20 dBZ reflectivity extending quite high indicates that the updrafts, while weaker than on day 255, extended through as deep a layer, a reflection of the spread of the CAPE over a great depth.

c. Day 245, 2 September 1974

Day 245 is characterized by two long, generally east–west oriented lines of convection moving southward near the Quadra radar. The details of each line and their synoptic environment are discussed in Mower et al. (1979). From the classification scheme in Part I, both lines are intermediate types, moving at 4.5–5.5 m s⁻¹ during their active lifetime. We have tracked cells from the northernmost line (NL), which formed at 1130 GMT as an east–west oriented line about 100 km northwest of the Quadra. The CAPE on this day is about 800 J kg⁻¹, or an instability with magnitude between that of days 255 and 257.

A low-level PPI scan from the Quadra radar on this day is shown in Fig. 9. A feature of significance to the NL is the area of more intense echo directly east of the Quadra. Apparently a westward-moving outflow boundary from this echo area results in an arc of new echoes northeast of the Quadra. As the cells on the arc line grow and precipitate, enhanced westward-moving outflow air results in a new arc line of clouds. This scenario is repeated several times, each time with a clearly identifiable arc line of new echoes, causing this system to propagate westward, while the NL moves southward. Several cells are tracked from these arc lines, the last of which begins intersecting the NL around 1500 GMT, forming an area of enhanced cell development.

Most of the cell tracks and selected isochrones of the NL and the different arc lines are depicted in Fig. 10. As with days 255 and 257 cells form ahead of the existing lines of echoes, presumably along a gust front. The NL is initially east–west but becomes more southwest–northeast by 1530 GMT, and by 1800 GMT is oriented nearly north–south as it approaches the Quadra. The gust front and NL echo edge never actually pass the Quadra, and as the line decays from 1800 to 2400 GMT it drifts slowly westward. The cell tracks all indicate westward cell motion, both in the westward moving arc lines and the southward moving NL.

Cells 1–3 form around 1300 GMT along the developing AL northeast of the Quadra. Some of the cells forming in this area become long lived, like cell 3 in Fig. 11b, presumably producing a new outflow boundary and continuing the development of westward propagating arc lines of echoes. By the time cell 3 is in its dying stages (1444 GMT), it is over 20 km behind the new AL outflow leading edge. Cell 1 (Fig. 11a) and cell 2 are typical of the shorter-lived cases, although stronger than cells of similar lifetimes on other days. These arc lines are a good example of new lines of
echoes apparently developing along an outflow boundary, with the older cells supplying the cold outflow air.

Cells 4 and 5 are part of an isolated echo area which forms ahead of the NL leading edge northwest of the Quadra at 1314 GMT. As this separate echo area moves west-southwest, the southward-moving NL begins overtaking it by 1400 GMT, with intense development occurring as the echo-free area between the NL and the separate echo area decreases. Cell 6 in Fig. 11c is the strongest cell which develops in this area, forming about 4 km ahead of the leading NL echo edge and about 5 km from the northern edge of the separate echo area to the south. Cell 6 develops very rapidly in this area of assumed enhanced convergence, and within 15 minutes has a surface echo of 50 dbZ, as echo closes the gap between the separate area and the NL.

Cells 8, 9, and 10 form within 10 km of each other, as part of the last well-defined AL which develops around 1420 GMT. This AL continues to grow, and by about 1600 GMT merges with the NL. At the time these cells are forming this is an area of enhanced development of fairly strong cells. Cell 8 in Fig. 11d is an example of a long-lived case, which evolves into an echo mass. Strengthening of the echo mass occurs around 1530 GMT coincident with the intersection of the AL and the main NL. During its decay a bright band of just over 40 dBZ appears.

An interesting “jump” in the NL occurs around 1529 GMT as a few cells form ahead of the NL then develop into a solid line of echo by 1540 GMT. The result is a 20-km jump of the NL leading echo edge, while prior to this, new echo formed 5–10 km ahead of the NL main echo edge. The remaining cases, cells 11 to 16, originate in this line, with cell 12 (Fig. 11e) among the strongest echoes followed on this day. At the time of first echo aloft, cell 12 is about 7 km west of the AL echo edge. The initial echo development is slow, but the rapid development at about 15 minutes is coincident with the approach of the AL, with 50 dBZ echo extending up to 3 km and 20 dBZ echo to 15 km. From our hypothesis outlined earlier we would expect such an increase in reflectivity aloft to be associated with a greater updraft. Although we have no direct measurements for this echo, it is growing in an area of merging echoes where low-level forcing should be increased. By 1600 GMT, cell 12 is in its decay stage about 20 km behind the new NL leading edge.

Cells 14 (Fig. 11f) and 15 form along the new developing NL edge but farther from the intersection with the AL. This should be an area of less low-level forcing, and in fact they are weaker than cells 12, 13 and 16, which were nearer the intersection of the AL and NL.

Day 245, then, is a rather complex day, involving the interaction of systems, as on day 255. Noteworthy is the lack of echoes away from the lines and not associated with any forcing feature during the cell tracking period. The pattern of new cells is consistent with the presumption that active or dying echo lines or areas produce gust fronts where development is concentrated. Enhanced development at intersecting points...
of two lines, as noted on the TP area on day 255, is also well-documented on this day. As on day 257 (and cases studied by Houze, 1977), new echoes usually form 5 to as much as 20 km ahead of the old line echo edge, resulting in apparent jumping or discontinuous propagation of the line. Finally, as on the other days, longer-
Fig. 11. (Continued)
lived echoes frequently form ahead of the line, reach maximum intensity near the leading edge, and die behind the line.

3. Discussion

a. GATE results

Our cell tracking sample is compared with the sample used in Part I in the following series of statistical plots. Figure 12 shows 20 dBZ echo height plotted against maximum surface reflectivity. This figure is similar to Fig. 4 of Part I, except that we have considered the entire cell lifetime in constructing Fig. 12 and consequently the maximum echo heights and surface reflectivities are the extreme values. The cells have been divided into five categories based on cell lifetime, as shown in Table 1. It should be noted that 16 of the cells plotted in Fig. 12 are also included as individual profiles in the means of Part I, though most are at different times. If a line were fitted to the points in Fig. 12 it would have a steeper slope than in Fig. 4, Part I, indicating a stronger relationship between cell height and maximum reflectivity at the surface. There is still a large spread in the echo top height with increasing reflectivity above the low 40s dBZ. This is in excellent agreement with Saunders' (1965, his Fig. 11) results for tropical convection in the Caribbean, which showed a sharp increase, beginning at about 42 dBZ, in the spread of echo heights associated with a given peak reflectivity. He concluded from this that the warm rain process of coalescence must be very effective, so that shallow as well as very deep clouds can produce rainfall of similar intensity.

Figure 13 relates the parameters in Fig. 12 by the time of occurrence in the cell lifetime. In general, the time of maximum surface echo intensity is about 20 minutes after the first echo aloft regardless of cell lifetime, while the time to reach maximum echo height is directly related to cell lifetime. There are exceptions: some of the longer-lived echoes produce stronger surface echoes much later in their life cycle. For cases where a maxima occurs early and also during the echo mass stage, we have plotted both values.

One of the most consistent characteristics of the 43 cells is the height of the first 20 dBZ echo aloft, shown in Fig. 14. All cells begin between 2 and 4 km, with the mean of 2.4 km having a standard deviation of only 0.8 km. It is not known whether other first echo thresholds would have given similar heights, but we suspect so. Other studies (from the NHRE, for example; see Knight and Squires, 1982) with radar reflectivity thresholds as low as −5 dBZ have found similar first echo heights for the 0–20 dBZ to even 30 or 35 dBZ levels. Where photographic measurements accompanied the radar time-history it appears that the nose of the weaker reflectivities is about 1 km higher than the middle of the visible cloud (Breed, 1983). For the GATE cells studied, the first echo heights at 25, 30

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<th>Description</th>
<th>Lifetime (hours)</th>
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<td>Long-lived with echo mass</td>
<td>≥2</td>
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<td>2</td>
<td>Shorter-lived with echo mass</td>
<td>1–2</td>
<td>6</td>
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<td>3</td>
<td>Long-lived, no echo mass</td>
<td>≥1</td>
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<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Isolated, short-lived (may or may not be associated with an organized line)</td>
<td>~1/2</td>
<td>9</td>
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and 35 dBZ are all nearly identical to the 20 dBZ height, while the 40 dBZ first echo height is just slightly lower.

Since the freezing level is generally near 4.2 km, the low first echo height strongly suggests that the warm rain process dominates the initiation and early growth of the GATE convective cell. Since we do not have simultaneous visual observations of the same cells for which we have reflectivity plots, or any supporting microphysical aircraft data, we cannot be certain that ice has no role in the initiation of precipitation. We can, however, speculate as to the possibility of any involvement of the ice process in rain initiation, or which clouds, if any, are more likely to involve ice. It has been shown through several studies that in the tropics rain is produced from clouds whose tops do not penetrate the 0°C level (Byers and Hall, 1955, or those noted in Mason, 1957, for example). The types of echoes studied, however, were small shower-producing clouds resembling our category 5 isolated cells.

The more difficult question is whether the cells which become cumulonimbus are also initiated totally by the warm rain process. Ludlam (1965) has calculated the minimum depth of cloud needed before precipitation-sized drops (1 mm) fall out and finds this distance to be as small as 1 km, requiring about 10 minutes in time to grow, for the tropics. He points out that the broad droplet spectra and high liquid water content result in a very effective coalescence process. Mason (1957) also makes these points, noting further that with weak updrafts the required time for precipitation-sized drops to grow from condensation and coalescence can be accomplished in a smaller cloud depth. It is apparent, however, that as updraft speeds increase the cloud will reach higher levels in the time required to produce rain by coalescence. Thus, in the case of the cells which develop in the regions of enhanced low-level forcing, such as near the TP on day 255, it is likely that the cloud extends above the freezing level by the time a first echo of 20 dBZ is observed. This would leave open the possibility that the ice process may actually occur as early as the time of first echo, especially for the more vigorous cells.

Other possibilities of involving the ice process fairly early in the cell lifetime could occur for those cells growing beneath the thick anvil overhang of ice particles. While the 20 dBZ echo is not connected to the anvil until after or at the time of the first 20 dBZ echo reaching the ground, it is possible that ice crystals descending from this anvil could seed the growing cumulus without reaching 20 dBZ reflectivity. Another possibility would be ice particles advecting into a growing cumulus from a nearby glaciated cumulonimbus, producing earlier glaciation than would occur in an isolated cloud (Ludlam, 1965).

A feature consistent with the results of Part I is the low height of the highest reflectivity value aloft, also plotted in Fig. 14. The value plotted is the height of the highest reflectivity above 0.5 km during the lifetime of the echo, beginning when 20 dBZ reflectivity reaches the ground, similar to Part I for an individual profile. The result is consistent with the results from the individual profiles in Part I; in both cases (see Fig. 7, Part I), over 90% of the cells have the height of the maximum reflectivity below 3 km. This is also consistent with the weak vertical velocities in these cells not being able to suspend large particles aloft.

Also shown in Fig. 14 is the maximum height of the 20 and 40 dBZ echo. The 20 dBZ echo height can be compared directly to Fig. 5, Part I. The low height of the 40 dBZ echo is consistent with the weak vertical velocities in GATE cells, by the reasoning in Part I. The height of the various reflectivity levels (20, 40 and 45 dBZ, for example) for the cell-tracking cases varies with the days considered (plots not shown). Thus on day 255 there are more cells with higher echo heights (for the various reflectivities), while day 257 is distinctly lower, with day 245 having a large spread (including the highest values). This is consistent with the types of systems from which these echoes are taken (various low-level forcing) as well as the variations in CAPE values noted earlier.

Figure 15 gives cumulative frequency of the time from first 20 dBZ echo aloft to first 20 dBZ surface echo, which ranges from 3 to 11 minutes. The analogous time for the 40 dBZ echo is systematically shorter.

Figure 16 shows the cumulative frequency of the cell lifetime, defined here as the time from the first echo aloft until the end of the 40 dBZ surface echo or the end of cell tracking, whichever comes first. As noted earlier, this should be thought of as echo lifetime composed of possibly several cell updraft lifetimes. Category 5 cells would represent most closely the cell as defined in Byers and Brahnam (1949), and has an echo lifetime of about 30 minutes. While the mean lifetime for all echoes in this study is about 45 minutes, the range is considerable. The duration of 40 dBZ surface echo also
extends over a rather large range. For the shorter-lived cells the stronger echo decreases rapidly after it peaks, while in the longer-lived cases the duration of stronger reflectivity can be quite long.

The composite life-history profiles from our study are shown in Fig. 17. They are formed by taking profiles during each life history case at specific time intervals and events. Time of the first 20 and 40 dBZ surface echo, maximum echo height and maximum surface reflectivity are used as events. A problem that is apparent is the wide variation in cell lifetime, so we have compiled the cell life histories into the five different categories outlined earlier in Table 1.

One feature common to categories 1–3 (Fig. 17) is the similarity of the life histories through their early stages. General differences include a decrease in the time required to obtain the maximum height and surface reflectivity, and the duration of stronger surface echo as we move toward shorter lifetimes (higher category number). The actual maximum echo heights and maximum surface reflectivities are very similar, though, for categories 1–3. There is, however, a drastic height decrease for cells which have trackable lifetimes under one hour (category 4) and for the shorter-lived, isolated category 5 cases. For the category 5 cases we are able to estimate (dashed lines) the death of the cell, while most of the cells in the other categories merge with surrounding echo in their dissipating stage.

The highest reflectivities below the melting level occur while the echo top is still growing. As noted earlier we cannot be certain that the coalescence (warm rain) process is entirely contributing to the early growth of all echoes, regardless of their eventual vertical size, although we have presented strong circumstantial evidence that it is dominant in the formation of the early precipitation. Those cells with stronger forcing usually reach greater heights, and it is expected that the ice process contributes significantly to the precipitation once cloud tops reach sufficiently cold temperatures. As noted in the discussions of the echoes on each individual day, the wide range of low-level (and other) forcing contributes to a range of echo heights for our sample. The fact that even the highest of the echoes produces reflectivities of no more than the low 50s (dBZ) indicates that updraft velocities, even for the stronger cells, are not very strong, by our hypothesis in Part I. The lack of sustained forcing for the category 4 and 5 cases is presumed to be the explanation for their short lifetimes. When some echoes remain in a
region of apparent forcing near the line leading edge, such as near the TP on day 255, we infer sustained updrafts and longer-lived echoes. As mentioned earlier, another reason for sustained echo lifetime during the echo mass stage could involve dynamic forcing at mid-levels when the echoes are within the stratiform region, in a manner not well understood (Leary and Houze, 1979; Zipser et al., 1983).

Various researchers have devised means of estimating mean vertical velocity from reflectivity measurements. Although they all involve various assumptions, especially as related to the drop size distribution, it is instructive to apply them to the mean vertical GATE profiles (Fig. 3, Part I, or Fig. 18) to arrive at rough estimates of updraft velocity. Using methods discussed in Kessler (1969), in particular with reference to his Fig. 3.1 on p. 5, one arrives at estimates of about 4–6 m s\(^{-1}\) for the 40 dBZ profile strength, and about 5–8 m s\(^{-1}\) for 50 dBZ. For 35 dBZ (about 5 km on mean GATE profile) one estimates about 2 m s\(^{-1}\) (assuming ice; about 4 m s\(^{-1}\) for rain), and only about 1 m s\(^{-1}\) for 30 dBZ. These values are consistent with measured updrafts in GATE from Zipser and LeMone (1980) and LeMone and Zipser (1980). Other work relates reflectivity to vertical velocity directly, mostly by Doppler-derived techniques or raindrop-size distribution methods (Battan, 1973). Aoyagi (1969) derived a theoretical relationship from the Doppler method, and if we apply our GATE Z-R relationship, we calculate updrafts of 6.3 m s\(^{-1}\) for 30 dBZ, 7.5 m s\(^{-1}\) for 40 dBZ, and 8.7 m s\(^{-1}\) for 50 dBZ. It is important to note that the above estimates are applicable mainly for rain or small ice particles with small terminal fall velocities. Were precipitation aloft to include appreciable numbers of large ice particles (not observed), it would be consistent with far larger vertical velocities (not observed). By inference, both sets of observations are consistent with GATE clouds having little if any hail aloft.

One way to address the question of whether the profiles of Part I are representative of the active part of the cell lifetime (updraft coexisting with downdraft) is to construct mean profiles from the sample of cells tracked and compare the results to the overall GATE means in Fig. 3, Part I. This is done in Fig. 18, where we use the maximum strength profiles for the cell tracking cases, which represent a subjective selection of a profile usually between the time of maximum surface reflectivity and maximum echo height. In order to ensure uniformity with Part I, only the raw five-minute data are used, and the profile must have a surface reflectivity of at least 40 dBZ. The differences between the profiles in Fig. 18 are not considered great enough to lead to conclusions different from those reached using Fig. 3, Part I.

b. Comparison with a continental cell

As noted earlier, life history profiles were used in the analysis of data from the NHRE, which was cen-

![Fig. 18. Comparison of the mean, median, and top and bottom 20% (by the strength of the surface echo) profiles compiled from the maximum strength profiles for the category 1–4 cell tracking cases, with similar profiles for the 296 cells studied in Part I.](image-url)
tered in northeast Colorado during the summers of 1972–76. A summary of some of the research results from that project appears in two volumes edited by Knight and Squires (1982). The example we present in Fig. 19 is from the 25 July 1976 “Butler” storm and is not a particularly strong case, but rather representative of a more populous class of High Plains thunderstorms. It is a small storm by comparison with some of the larger supercell storms studied in the NHRE, being, at most, 15 km across and 200 km² in echo area, and produces little if any hail but fairly heavy rain. The storm is of the multicell type, and the letters at the top of Fig. 19 identify the different cells, cores and turrets (reflectivity maxima of varying scale). Figure 19, then, is composed of the maximum reflectivity profile at each radar volume scan for the entire storm. Since the GATE radar data is of coarser resolution than the NHRE data, our GATE cell definition refers to a larger scale than the NHRE cell definition, so that what we call a single cell may be several cell lifetimes in the NHRE nomenclature. Thus the life history in Fig. 19 makes a better comparison with our GATE results than would the life history profiles for each individual cell or core indicated by the letters in Fig. 19.

The early growth displayed in Fig. 19 is rather weak, with aircraft-measured and Doppler radar-derived updrafts of only a few meters per second, comparable to GATE values. As new turrets continue to form on the southwest side of the storm they grow stronger and more persistent. Turrets F and H at 1925 MDT are part of an identifiable core with an early growth pattern more typical of most of the NHRE examples and comparable in form to our GATE cells. That individual life history, like Fig. 19 and most NHRE examples, indicates the initial echo forms at approximately 6–8 km MSL (note: subtract about 1.6 km if height above the surface is desired), usually at −15 to −20°C. As confirmed by aircraft measurements, this initial echo growth is totally by the ice process. Despite the higher formation level for the NHRE cell, the 20 and 40 dBZ echo contours spread vertically to the surface about twice as fast as for GATE cells.

If we compare the life history after 1915 MDT in Fig. 19 to the GATE cases we find the NHRE cell is considerably stronger. Note the heights to which the 40 and 50 dBZ echo extend, and the appearance of more than 60 dBZ echo below cloud base. (Cloud base is much higher than for GATE.) While some GATE cells had 40 dBZ echo as high as 7.5 km, the highest vertical extent of 50 dBZ echo is only to about 3 km, and our maximum echo strength found was 54 dBZ. Other cases from the NHRE are much stronger than that shown in Fig. 19, with 50 dBZ echo above 11 km MSL and 60 dBZ echo above 7 km MSL on 22 July 1976, for example, and maximum echo strength as high as 71 dBZ on 22 June 1976 (Knight and Squires, 1982).

In terms of the echo top (20 dBZ level for comparison with GATE), the GATE cells are closely comparable to Fig. 19 and other stronger NHRE examples, so the GATE clouds are thicker than this continental example. Examination of maximum strength updraft profiles compiled for some of the NHRE life histories indicates maximum updraft speeds of 20–30 m s⁻¹ and more (20 m s⁻¹ at 7 km in this case), much stronger than GATE. In many cases of comparisons with strong continental thunderstorms, the positive area on the

![Fig. 19. Time–height radar life-history of a thunderstorm on 25 July 1976 from the NHRE, from Knight and Squires (1982). Contour intervals are every 5 dBZ, beginning at 5 dBZ.](image)
sounding (CAPE) will be substantially greater than in the GATE soundings, but that is only part of the reason for the stronger updrafts. In fact, for the 25 July 1976 example the CAPE was about equal to that of the GATE days studied here. This occurrence may not be unusual at all, as composite soundings for different types of systems for GATE (Barnes and Sieckman, 1984) and NHRE (Fankhauser and Mohr, 1977) show similar values for CAPE.

Why then are the GATE updrafts weaker than those in the continental cells? One obvious difference between the NHRE case and the GATE cells is the much lower cloud base in GATE, about 0.5 km compared to 2.5 km, due to the much higher moisture in GATE, 17 g kg⁻¹ on average compared to 8.5 g kg⁻¹ (mean value of lowest 50 mb). Additionally, the broad droplet spectra of the marine environment favors rapid growth by coalescence (Braham, 1968). The end result is heavy liquid water loading rather quickly above cloud base in the GATE clouds. Since a 1°C reduction in effective buoyancy occurs for about each 3.5 g kg⁻¹ of condensate, there can be a large percentage reduction on buoyancy for the GATE clouds.

It is for the above reasons that the shape of the maximum strength updraft profiles associated with some of the NHRE examples exhibits a marked peak at about 7 km MSL, often followed by a rather sharp decline. The GATE updrafts, although weaker, seem to decrease more gradually with height above their peak at about 3–4 km (LeMone and Zipser, 1980). Thus the shape of the updraft profile may explain why the GATE clouds are able to extend as high as the NHRE clouds, while the magnitude of the updrafts help explain the differences in echo intensity.

4. Summary and conclusions

In Part II we have compiled cell life histories for 43 cells over three GATE research days in order to expand on the insights into the GATE convective cell gained from Part I, and in particular to verify that the mean profiles from Part I were not biased toward the decaying stage of the cell life cycle. The discussion in the previous sections has presented evidence which shows that, indeed, the mean profiles from Part I represent an active portion of the cell lifetime and are not weighted toward a decaying cell profile. Thus our overall conclusion remains: the vertical profile of radar reflectivity in the GATE cell is in general weak and characterized by a rapid dropoff with height above the freezing level.

Our final figure summarizes some of what we have learned about GATE convective cells and follows from some of the discussion in Section 3a. Using the composite cell life histories from Fig. 17 for categories 1 to 4 [thus considering only cases where a 40 dBZ surface echo persisted for at least 10 minutes (33 cases)], we have arrived at composite vertical profiles for five different growth stages of the GATE cell. To form Fig.

![Graph showing composite vertical radar reflectivity profiles for the category 1–4 cell tracking cases over the cell lifetime from the early to late (period 4) stage. The mean time for each profile is indicated.](image-url)
20, we first divided each composite life history in Fig. 17 into five parts; an early stage, from the first 20 dBZ echo aloft to the first 40 dBZ surface echo; and four equal time periods of growth over the period from the first 40 dBZ surface echo to the last 40 dBZ surface echo. A modification was made for the echo mass cases (categories 1 and 2), where the end point is the time when the surface echo decreases to about 42.5 dBZ, since it is likely that the weaker stages of an echo mass tracking period would not resemble a cell as chosen from Part I. A profile was extracted at the midpoint of each of the five time periods, then similar growth stages were averaged from all four categories to yield the profiles in Fig. 20. The average length of each time period was about 12 minutes.

The early stage profile in Fig. 20 shows an elevated maximum reflectivity below the freezing level at about 2.5 km, equal to the mean height of the first (20 dBZ) echo for all 43 cell tracking cases. Profile 1, about 12 minutes after the early profile, indicates fairly rapid growth in strength and height, to well above the freezing level, with an elevated maximum near 1 km. Period 2 has the highest surface reflectivity, but the highest echo top is reached during Period 3. Surface and lower level reflectivities show a decrease by Period 4, although the top of the echo remains nearly constant. The mean time of this last profile in the beginning of the decay stage is 55 minutes after initial echo aloft.

If the mean GATE profile from Fig. 2, Part I, is overlaid on Fig. 20, it falls generally over the active profiles, again indicating representativeness towards an active portion of the cell. All the stage 1–4 profiles in Fig. 20 show a definite change in slope occurring at or near the freezing level.

We began by noting that the GATE convective cell is dominated by weak vertical velocities, and therefore the vertical profile of radar reflectivity in the GATE cell should be fairly modest and show a rapid dropoff with height above the freezing level. Using this as a framework, our conclusions regarding the nature of the GATE convective cell (from Parts I and II) are summarized below:

1) Vertical profiles of radar reflectivity in GATE cells exhibit generally modest reflectivity at low levels, decreasing rapidly with height above the freezing level.

2) Mean GATE vertical profiles of radar reflectivity are similar to those in hurricanes, consistent with their similar updraft speeds in convective cores.

3) The vertical profiles of radar reflectivity in continental thunderstorms are significantly stronger than those for GATE convective cells, consistent with their much stronger updraft speeds.

4) GATE convective cells of all sizes have an initial echo well below the freezing level, with a first echo height near 2.5 km, and an early rainout period likely dominated by the warm rain process. While it has long been known that the warm rain process dominates trade cumuli and other small oceanic clouds, to our knowledge this is the first study which presents evidence that large cumulonimbi may also develop their first echo at temperatures above freezing.

5) During the mature and dissipating stages of the cells, all but the shortest-lived (and usually isolated) cells penetrate well above the freezing level and therefore likely involve ice processes. However, the weak reflectivity and weak vertical velocities permit the inference that hail aloft is rare or absent in GATE convective cells.

6) There are two different stages of growth: 1) early rapid growth resulting in the strongest reflectivities at the surface while the echo top is still growing; 2) an extended period of at least 40 dBZ surface echo, often with a secondary (later) surface maximum of reflectivity; it is usually not as strong as the early maximum and may be associated with growth within the otherwise trailing stratiform region.

7) For convective cells which are parts of mesoscale lines and have at least a 40 dBZ surface echo, the mean height of the echo top (20 dBZ) is 8.2 km, with a mean surface reflectivity of 45 dBZ. Surface reflectivities above 50 dBZ are not common, but do occur in the stronger cells, as do 20 dBZ echo tops as high as 15 km. No reflectivity above 54 dBZ was found for any cell at any level.

8) While all profiles showed a marked decrease in radar reflectivity above the freezing level, the gradient of echo decrease varies even for similar cloud tops (days 255 and 257, for example), probably a result of different intensity and shape of the updraft profile.

9) Very few cells were found not associated with any organized line feature during the cell tracking periods, and those that existed were usually very weak, shallow, short-lived, and dominated by the warm rain process. Forcing features, such as gust fronts, were found to be important triggers for convective lines, and intersecting lines important areas for enhanced cell development.

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### APPENDIX

#### Summary of Cell Characteristics

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#### Day 257

#### Day 245

#### Legend

- **No.**—Cell number
- **Cat.**—Category (see Table 1) (* for cell 7 Day 255 indicates beginning time not available)
- **Line**—See text for abbreviations: Sep. = Separate (does not belong to any line)
- **Begin**—Beginning and end times
- **End**—End of cell tracking
- **\(D_i\)**—Distance (km) tracked
- **\(OH\)**—Anvil overhang present? (yes or no)
- **\(D\)**—Distance cell forms ahead of line (km)
- **\(H_{FE}\)**—Height of first echo (km)
- **\(T_{FE}\)**—Time from first echo aloft to first surface echo (minutes)
- **\(R_A\)**—Maximum echo aloft (dBZ)
- **\(H_i\)**—Height of R \(R_s\) (km)
- **\(R_s\)**—Maximum surface echo (dBZ)
- **\(T_2\)**—Time of first occurrence of \(R_s\) (min)
- **\(T_{40}\)**—Duration of >40 dBZ surface echo (min)
REFERENCES


