# Merging of Convective Clouds: Cloud Initiation, Bridging, and Subsequent Growth

NANCY E. WESTCOTT

*Illinois State Water Survey, Champaign, Illinois*

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## ABSTRACT

This study examines the growth of radar echoes from the time of their initiation to several minutes after they have merged to ascertain what factors are important in determining the frequency of merging events, the manner in which echo cores join together, and the effect of merging on subsequent echo core growth. Three-dimensional radar reflectivity data were examined for two convective periods, 25 July 1986 and 26 August 1986. It was found that echoes that merged were initially taller and slightly larger than those that dissipated without merging, suggesting they were more vigorous and thus more likely to grow and join with another echo. While meteorological conditions on the two days were quite different, 25% of the mergers occurred between young echoes, 65% occurred between a young echo and a parent storm, and 10% occurred between echo cores from two different systems. Previous case studies have indicated that merging is accomplished through differential storm motion or through the growth of a new echo core between adjacent cores. Echo cores in this study appeared to merge primarily through horizontal expansion. Two mechanisms were proposed to account for this expansion: moisture-laden outflow air may have resulted in the presence of precipitation-sized drops at low altitudes in areas bridging the cores, and an intercell flow mechanism may have been at work at middle and upper levels. About 45%–70% of the cores were growing just after merger. Generally, the cores that grew were young, were growing prior to or at the time of merger, and thus were likely to continue growing.

## 1. Introduction

An important element of the growth of convective cloud systems is that clouds combine to form larger systems. A number of statistical studies of populations of merging clouds were made in the 1970s and early 1980s: Houze and Cheng (1977), Lopez (1976, 1978), Simpson et al. (1980), and Wiggert et al. (1981). Merged systems in tropical and subtropical regions were found to be larger and to produce more rain than isolated systems. In a similar study carried out in the Midwest, Changnon (1976) found that merged systems generally grew taller and lasted longer than nonmerging systems. It has been thought that merging in and of itself would cause a system to grow larger and produce more rain through a dynamic invigoration of the storm (see review, Westcott 1984).

A limited number of case studies employing numerical models investigated factors that might influence whether individual cells will merge. Orville et al. (1980) and Turpeinen (1982) found that a favorable pressure gradient must be present for merging to occur, and such a gradient could occur between cores of different ages or sizes. Tao and Simpson (1989) found that favorable pressure gradients often were associated with low-level convergence resulting from cold outflows. Additionally, the storm orientation with respect to the cloud-layer winds was found to impact the minimum separation distance required for merging (Tao and Simpson 1989). A limited number of observational case studies have shown that low-level convergence can be important in increasing the likelihood of merger (Petersen 1984; Cunning and DeMaria 1986; Westcott and Kennedy 1989) and that merging can be initiated by new cell growth bridging existing echoes or by differential cell motion (Cunning et al. 1982; Ackerman and Westcott 1984; Westcott and Kennedy 1989). However, the conditions most favorable for merging to occur, the size and age characteristics common to a merging pair of cores, and the way in which individual entities merge have not been examined for a large population of storms, nor has the possibility of the dynamic invigoration of the merging entities been investigated.

Thus, the objectives of this study are to examine several different populations of echo cores observed under differing environmental conditions to identify factors that might be important in determining whether merging occurs, how merging commonly occurs, and whether the merging entities grow.

## 2. Data source and analysis procedures

Three-dimensional reflectivity data were obtained by the CHILL 10-cm radar, which has a beamwidth of 1°. The radar was located in east-central Illinois near

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*Corresponding author address:* Nancy E. Westcott, Clouds and Precipitation Research Office, Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820.

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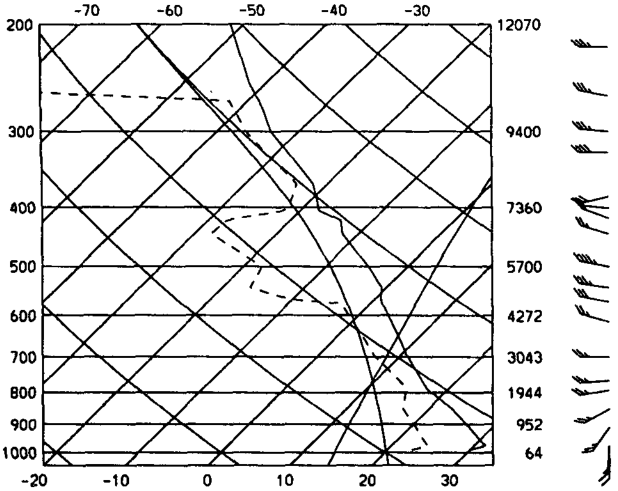

FIG. 1. Skew $T$–log$p$ plot of the 1900 LT Salem, Illinois, (SLO) sounding for 25 July 1986. Only a single moist adiabat and a single saturation mixing ratio line are shown. Wind speeds are in meters per second, with a long barb representing 5 m $s^{-1}$. Height is indicated in meters above mean sea level.

Champaign (CMI). Only reflectivity data were available during the summer of 1986. The minimum observable reflectivity recorded on the first day (25 July 1986) was 20 dBZ, and was 14 dBZ on the second day (26 August 1986). For comparison purposes, a 20-dBZ threshold was imposed on the data presented herein. The radar was operated in a 360° scan mode, with the intent of topping all echoes in 10–16 elevation sweeps in 2–5 min.

The radar data were processed by computer software that compressed three-dimensional volumetric data into six two-dimensional Cartesian grids. At each grid location the following parameters were determined: echo-top height, echo-base height, the height at which reflectivity is at a maximum, the reflectivity at echo top and at the echo base, and the maximum reflectivity within each vertical column. The radar was located at the center of a 121 × 121 grid roughly encompassing a 150-km × 150-km area, with a horizontal grid resolution of 1.25 km. Only echoes within 75 km of the radar were examined to minimize inaccuracies in height estimation. The sample included echoes that clearly were topped by the radar beam and ones that formed within the analysis grid.

For the early echo characterization study, a sample of 152 isolated cores echoes were identified and tracked over time by computer and then checked by a radar analyst. These cores were tracked until they dissipated or until they merged with an adjacent echo. Each echo core in the sample had to contain at least two 20-dBZ grid points ($\sim$3 km$^2$) and had to exist for at least two consecutive radar volumes.

Merging occurred when two reflectivity cores from two separate echoes combined at the minimum reflectivity level. It was assumed that once two clouds containing precipitation-sized drops become joined that some interaction was occurring between the two units. The merging cores considered could either be isolated or already part of a multicelled system. An echo core was defined as a maximum in reflectivity, with boundaries delineated by a minimum trough of reflectivity, and thus was an identifiable entity for at least 5–10 min after merging. For an echo to be considered merged with its neighbor, it had to be linked by at least two grid points and the bridge merging the two cores had to be present for at least two consecutive radar volumes. During the two convective periods on 25 July and 26 August 1986, 90 such mergers occurred.

Only cores initially separate from neighboring cores were considered in this study, so that premerger growth characteristics could be determined. This, however, is only one way in which storms expand in horizontal area or merge. There were many cases where reflectivity cores when first observed were already joined to a parent storm at the 20-dBZ contour level. If a lower minimum reflectivity threshold had been used, there would have been many fewer isolated first echoes in the sample. Even at the threshold of 20 dBZ, the total number of merging cores would have more than doubled on 25 July 1986, if the 42 reflectivity cores that were already joined when first observed were included in the first echo sample. On 26 August, 33 echo cores were already joined when first observed, in addition to the 79 merging first echoes. Because distinct cores were observed in an area previously having no echo, it is thought that the growth of both the isolated cores studied here and those already joined with a parent echo when first observed grew by strong evolution—that is, that an updraft separate from the parent storm was associated with each new core during its growth stage (Foote and Frank 1986). On 25 July, echo growth by weak evolution also was believed to occur when an echo expanded horizontally before the appearance of a distinct core within the existing echo mass. In this case a new updraft is assumed to surge upward within the bounds of an existing updraft and commonly occurs in severe storms (Foote and Frank 1986).

Various characteristics were recorded for each of the merging echo cores at the radar volume just before (2–5 min), during, and just after (2–5 min) merger. The cores were qualitatively tracked for two to four volumes following merger to confirm the trends in area and height growth and changes in the reflectivity of the cores.

## 3. Storm descriptions

### *a. 1533–1901 LT 25 July 1986*

During the afternoon of 25 July 1986, convection in central Illinois formed in association with a cold front that moved through the area at about 1700 LT (central

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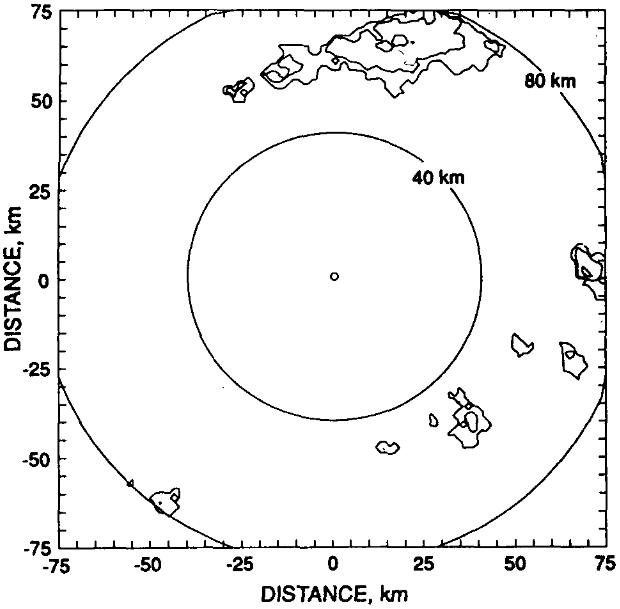

FIG. 2. Echo field on 25 July 1986 for the radar volume with a midtime of 1648 LT, as depicted by maximum reflectivity values. Reflectivity is contoured from 20 to 65 *dBZ* at 15-*dBZ* intervals. The location of the CHILL 10-cm radar and the 40- and 80-km range rings are indicated. Tick marks are spaced at 5-km intervals from 75 km west and south of the radar to 75 km east and north of the radar.

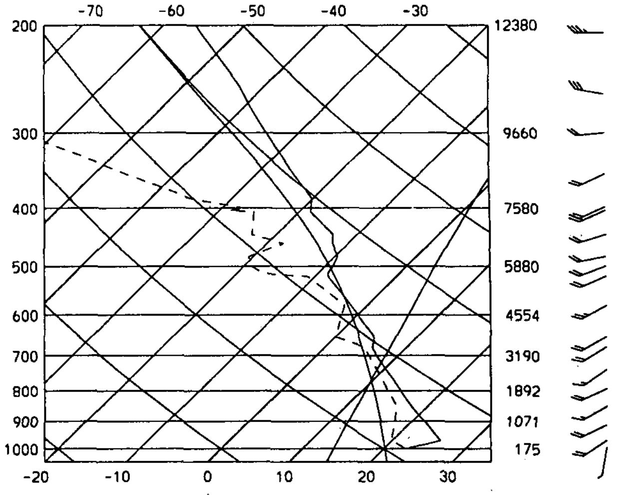

FIG. 3. Skew *T*–log*p* plot as in Fig. 1 but from the 0700 LT SLO sounding on 26 August 1986.

daylight time). The 1900 LT sounding taken at Salem, Illinois, (SLO, 160 km to the south-southwest of CMI) indicated a conditionally unstable atmosphere to about 400 mb (Fig. 1). Two major cloud lines developed, one about 60 km to the north of CMI and another about 50 km to the south (Fig. 2). The echoes composing the northern line joined into a solid line within about 30 min. The southern line was broken and included at least six storms separated by 10–15 km. The echoes in the southern line remained as separate systems for much of their history, with some only joining after two hours. Along both lines, echo growth appeared to be by both weak and strong evolution. While the two convective lines missed most first-order and cooperative National Weather Service (NWS) observing stations, the NWS storm data indicated that a portion of the southern storm that passed over Effingham, Illinois, produced strong winds, 2.5 cm of rain within a half-hour period, and 2.5-cm-diameter hail.

### *b. 0800–1230 LT 26 August 1986*

On this morning, thunderstorms were forming in a warm air mass about 300 km ahead of a strong, slow-moving cold front. The SLO 0700 LT sounding showed a conditionally unstable atmosphere to 500 mb, above a shallow surface inversion, and substantial moisture to 450 mb (Fig. 3). Satellite images indicated the presence of a cirrus overcast that likely inhibited surface heating, and an analysis of NWS surface station winds indicated only weak convergence in the area. The area of storms consisted of a field of many small convective lines and several large lines (Fig. 4). The echoes appeared to grow by strong evolution. No severe weather was reported. By 1145 LT, the storms were rapidly diminishing in intensity and areal extent.

## 4. First-echo properties

Both modeling studies (Ochs and Semonin 1979; Johnson 1979; Miller and Smith 1986) and observational data (Ochs and Johnson 1980; Miller and Smith 1986) have shown that first echoes provide information

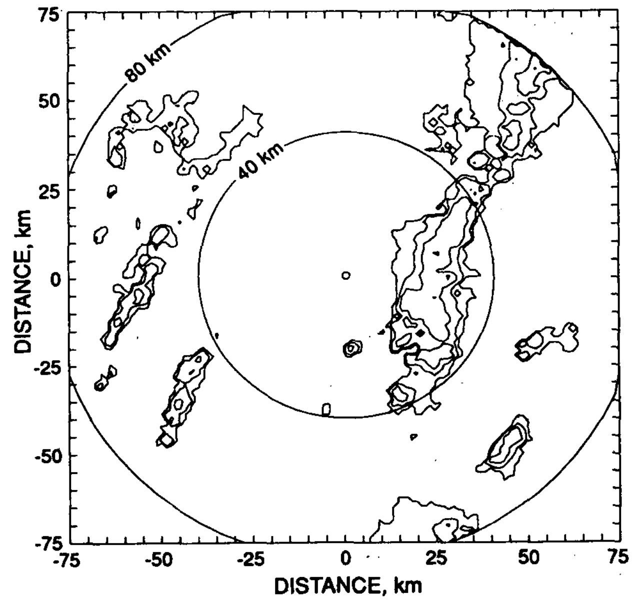

FIG. 4. Echo field as in Fig. 2 but for 1031 LT 26 August 1986.

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regarding updraft strength. These studies indicated that for clouds with stronger updrafts, first echo tops were observed at a higher altitude, because the collectors had less time to collect supercooled water, and first echo bases were raised due to the reduction in the sedimentation of larger drops. Additionally, the results of several studies indicate that more organized cloud systems (Changnon 1978) and hail storms (Towery and Changnon 1970) have taller first echoes. Thus, the first echo characteristics of the cores that eventually dissipated without merging and the merging cores have been compared to determine if these clouds differ in nature at the time they are first observed by radar.

Forty first echoes were examined during the afternoon of 25 July 1986, and 112 during the morning of 26 August 1986. Many of these first echo formed within 5 km of another echo (Fig. 5a) and then merged within 10 min (Fig. 5b). The median height of the tops and bases of first echoes that would merge were typically 1 km greater than for those not merging (Figs. 6a,b). The distribution of values of the base, top, and maximum reflectivity heights for merging and dissipating populations were significantly different at the 5% level on 26 August, and the top and maximum reflectivity heights were significantly different on 25 July 1986. Significance levels were computed using a one-sided Wilcoxon rank sum test (Bickel and Doksum 1977). While differences in the initial core heights were more pronounced, the median area of the merging first echoes also was greater than for the dissipating cores (Fig. 5c), although the difference was only significant to the 10% level.

If higher first echoes are due to stronger updrafts as others have suggested, it appears that the merging echo cores were more vigorous than dissipating cores at the time they formed. Thus, one might propose that factors resulting in more vigorous clouds also might predispose the same echoes to merge.

### *a. Differences between the two convective periods*

The first echo characteristics of the merging cores were different on 25 July and 26 August 1986. As seen in Fig. 6a, the first echo bases and tops were distinctly higher on 25 July 1986. The first echo areas also were larger than on 26 August (Fig. 5c). With similar updraft speeds, the larger subcloud mixing ratio on 25 July (19 as opposed to 13 g kg$^{-1}$ on 26 August) probably would have resulted in lower first echoes on 25 July. However, the height of the maximum reflectivity within the echo cores and the top of the cores first appeared higher in altitude. It is likely that stronger updrafts provided less time for droplets to grow. This is a reasonable assumption considering the closer proximity to a cold front, the occurrence of afternoon surface heating, the larger value of convective available potential energy (3772 m$^2$ s$^{-2}$ on 25 July, and 1394 m$^2$ s$^{-2}$ on 26 August), the suggestion of weakly evolv-

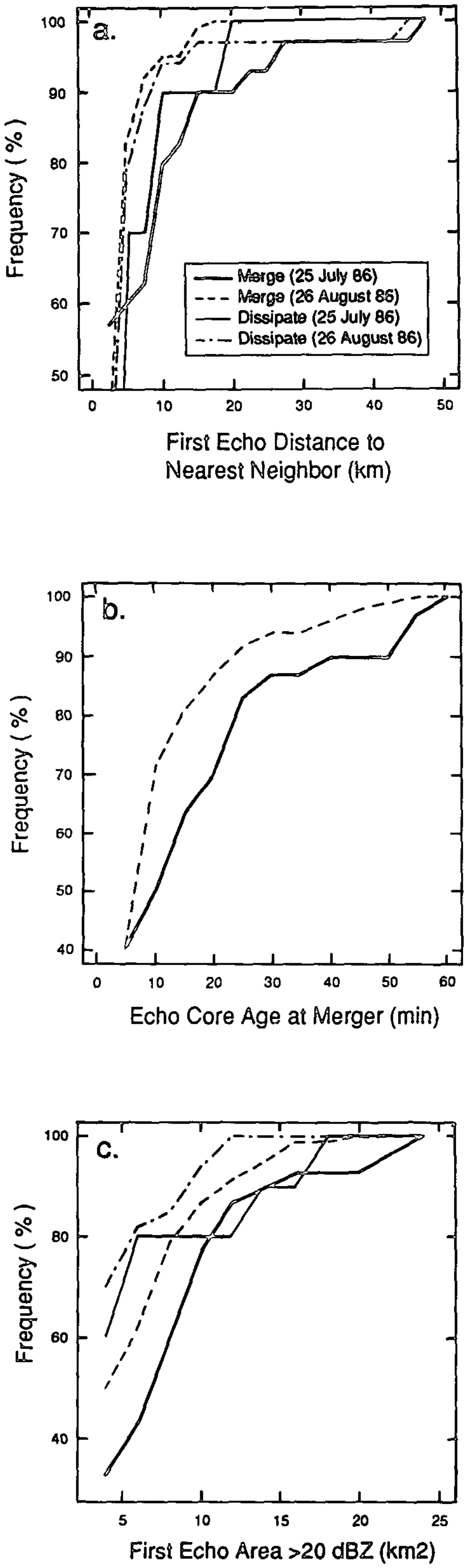

Fig. 5. Cumulative frequency curves for early echo properties on 25 July and 26 August 1986: (a) first-echo distance to nearest neighbor; (b) age of echo core at merger, and (c) first-echo area (>20 dBZ).

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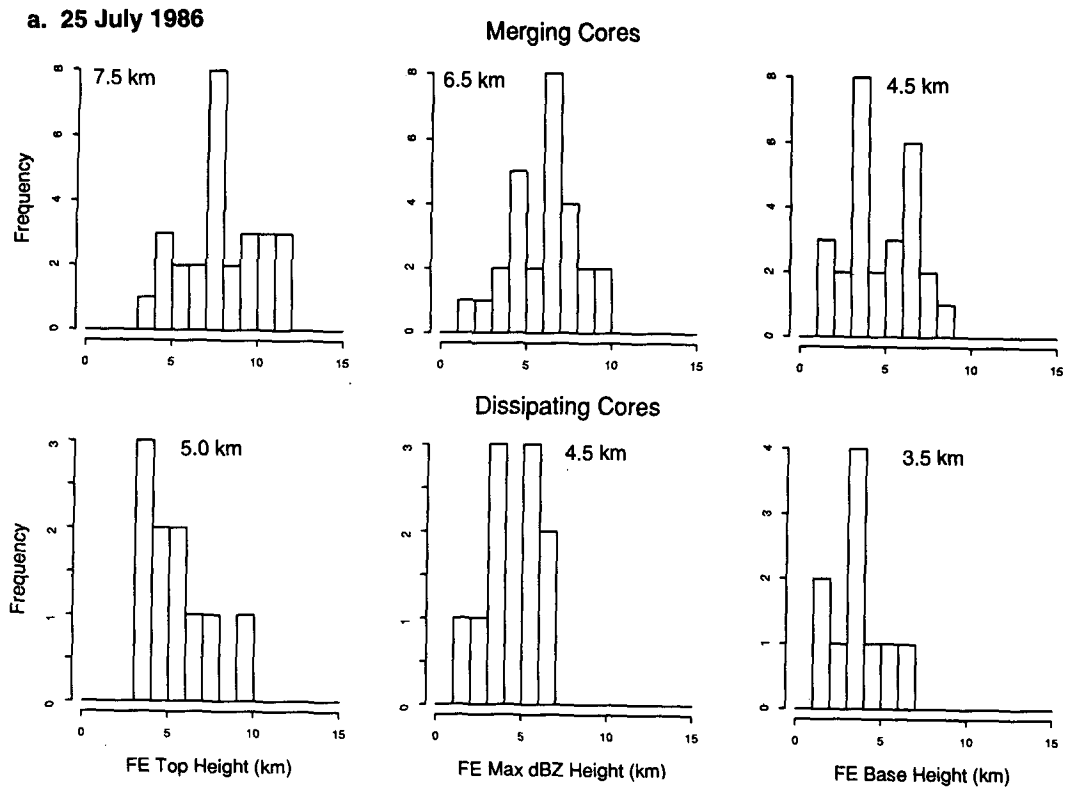

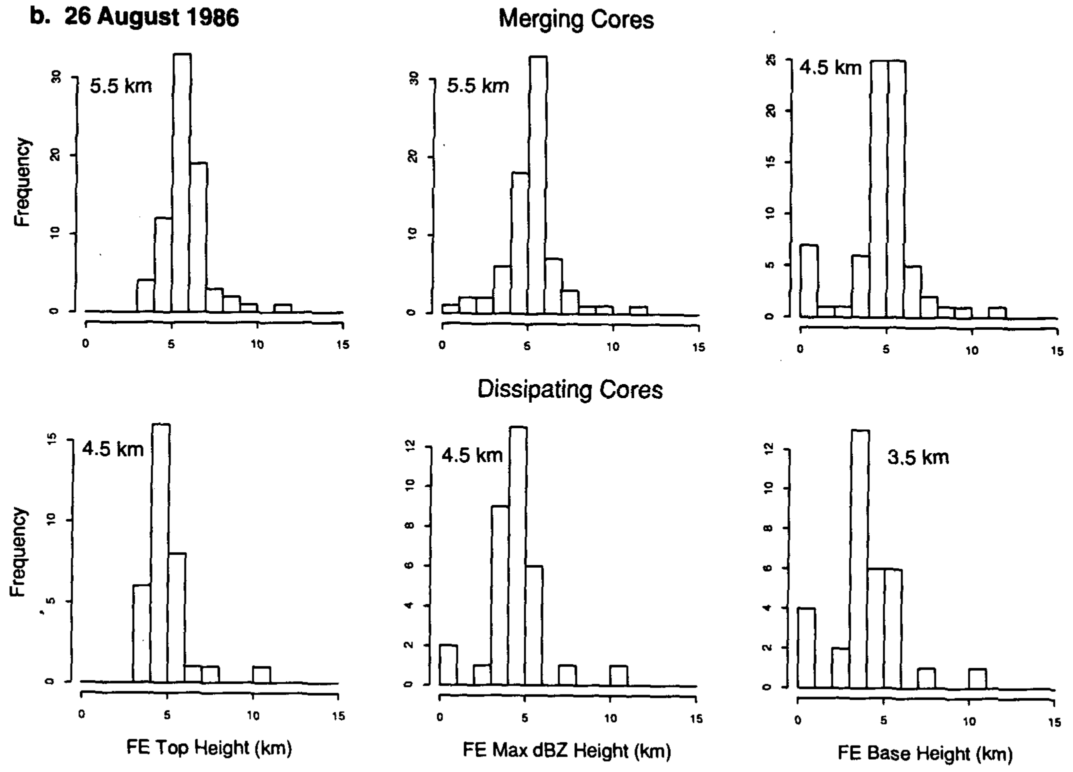

FIG. 6. Distribution of first-echo (FE) base and top heights, and height of the maximum reflectivity within the core for dissipating and merging echo cores for (a) 25 July 1986 and (b) 26 August 1986. Median values are indicated.

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ing storms, and the presence of severe weather on 25 July.

On 25 July, the first echoes that eventually merged tended to form farther from other echoes (83% within 12.5 km) than on 26 August (83% within 5 km, Fig. 5a). Merging often occurred very rapidly on both days (Fig. 5b) but more slowly on 25 July as might be expected from the wider echo spacing. On 25 July, 50% of the first echoes that merged did so within the first 10 min of their history, and on 26 August, 71% merged within 10 min. These observations suggest that the way in which clouds become organized and merge may differ for these two convective periods.

### *b. Location of new core growth and merger*

The first echoes on 25 July and 26 August 1986 were examined further to see if there was a preferred location for the formation of echoes that would merge and, if so, to determine any significant differences between those echoes forming in preferred locations and elsewhere. In particular, the echo cores were stratified by distance and quadrant relative to their nearest neighbor at the time of their first detection.

On 26 August, 28% of the first echoes formed in an ''overlap area,'' between and within 5 km of two echoes. On 25 July, when the edge-to-edge spacing between new echoes was greater, only 12% formed in this area. On 26 August, about the same proportion (70%) of first echoes within the 5-km range merged whether forming in the overlap area or in other quadrants relative to the closest echo. The cores in the 5-km range also were of a similar size and height, although the ones forming between neighbors did merge more rapidly.

Other investigators have observed clouds to form on the right flank of an existing cloud system (Browning and Ludlum 1962; Dennis et al. 1970; Marwitz 1972). Typically those storms developed under conditions of moderate to strong shear and were severe in nature. Low-level shear (surface to 3 km) was weak ($1.2 \times 10^{-3}$ s$^{-1}$) on 26 August 1986 and moderate ($4.55 \times 10^{-3}$ s$^{-1}$) on 25 July 1986. Even under these conditions, the right rear flank of the parent storm was the preferred direction of formation. About 30% of the first echoes formed to the southwest on 25 July, and about 19% formed to the south on 26 August. However, as observed by Byers and Braham (1949), while some cores may form in a preferred location, echoes form in all quadrants from their closest neighbor.

On 25 July, a large difference in echo height was found between cores forming to the southwest and those forming elsewhere but the cores were similar in area and reflectivity. The southwest cores had a median height of 10.5 km and those forming in other quadrants had a median height of only 7.5 km. The southwest cores were more likely to merge than cores in other quadrants on 25 July (90% versus 75%). However, of the nine cores forming to the southwest of their merging partner, six formed 10 km or more from that partner. Also, the median time to merge was 21 min for the southwest cores and 5 min for the other merging cores. As the southwest merging cores generally were taller and thus likely more vigorous than other cores on 25 July, these cores were able to survive long enough to merge. On 26 August, cores forming to the south were only slightly more likely to merge than those forming in other quadrants (75% versus 70%) and no significant differences were observed in their median properties. Thus, it appears that only on 25 July was the relative orientation of the cores important in increasing the likelihood of merging.

## 5. Description of merging echo cores

One of the earliest studies presenting observational evidence of merging cloud units was obtained in aircraft measurements of updrafts joining to form a towering cumulus (Malkus 1954). Other studies have shown that reflectivity cores are associated with updrafts (e.g., Byers and Braham 1949; Kingsmill and Wakimoto 1991). It was assumed early on that merging of echo cores involved the merger of updrafts. A number of recent case studies using Doppler measurements or numerical simulations have examined this supposed feature of merging. In one study, successive cores within a multicelled unit were observed to merge (Westcott and Kennedy 1989). Several of the merging cells appeared to have a prolonged duration and perhaps reinvigorated after merger but there was no obvious enhanced growth in terms of area or cloud top height. In a second study, small cores of a very young storm merged (Ackerman and Kennedy 1989). In neither case was there evidence of merging updrafts but more simply of one updraft superseding another in time. Updrafts were generally associated with young reflectivity cores. A similar history of successive updrafts also was observed in the modeling work of Tao and Simpson (1989).

On 25 July and 26 August 1986, 24 and 66 mergers were observed, respectively. The merging pairs were stratified into three groups, roughly based on the degree of organization of the cores: type 1, a merger between two echo cores that had not merged previously; type 2, a merger between a core that had never merged with an echo core that had merged (i.e., between a feeder cloud and its parent storm); and type 3, the merger of echo cores from two different echo complexes (i.e., both cores were already merged with another echo). Table 1 presents the median characteristics for the type 1 and type 2 merging pairs, and the median characteristics of the area of echo that bridged the individual cores. Because of the small number of type 3 mergers and the wide variance in their characteristics, these data were not included. While fewer mergers occurred on 25 July than on 26 August 1986, a similar proportion of merging pairs was found in each merger category on

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TABLE 1. The median values of age, area, height, and reflectivity parameters describing the merging echo cores and the median height and reflectivity values of the area bridging the echo pairs for the total sample of merging echo core pairs stratified by merger type on 25 July and 26 August 1986. Type 1 includes pairs where it is the first merger for both cores, and type 2 includes mergers where core 1 had been previously merged.

| Echo core and bridge properties for type 1 mergers | 25 July 1986: sample = 6 | | | 26 August 1986: sample = 17 | | |
|---|---|---|---|---|---|---|
| | Core 1 (first merging) | Bridge | Core 2 (first merging) | Core 1 (first merging) | Bridge | Core 2 (first merging) |
| Age at merger (min) | 13 | | 5 | 8 | | 4 |
| Area ⩾ 35 dB$Z$ (km$^2$) | 4 | | 0 | 8 | | 2 |
| Max reflectivity (dB$Z$) | 40.0 | 23.8 | 32.5 | 42.5 | 27.5 | 37.5 |
| Top height (km) | 9.5 | 6.0 | 6.0 | 6.0 | 4.5 | 5.5 |
| Max reflectivity height (km) | 5.5 | 3.5 | 4.0 | 3.5 | 4.5 | 3.5 |
| Base height (km) | 1.5 | 2.5 | 1.5 | 1.5 | 1.5 | 1.5 |

| Echo core and bridge properties for type 2 mergers | 25 July 1986: sample = 15 | | | 26 August 1986: sample = 43 | | |
|---|---|---|---|---|---|---|
| | Core 1 (already merged) | Bridge | Core 2 (first merging) | Core 1 (already merged) | Bridge | Core 2 (first merging) |
| Age at merger (min) | 35 | | 12 | 16 | | 8 |
| Area ⩾ 35 dB$Z$ (km$^2$) | 22 | | 8 | 27 | | 12 |
| Max reflectivity (dB$Z$) | 45.0 | 25.0 | 40.0 | 52.5 | 25.0 | 45.0 |
| Top height (km) | 11.5 | 9.5 | 10.5 | 8.5 | 5.5 | 6.5 |
| Max reflectivity height (km) | 6.5 | 6.5 | 6.5 | 3.5 | 4.5 | 4.0 |
| Base height (km) | 1.5 | 3.5 | 1.5 | 1.5 | 1.5 | 1.5 |

the two days. About 25% of the mergers were observed to occur between young echoes, 65% occurred between young echoes and an echo complex, and 10% between echo complexes.

Both cores in the merging pair tended to be younger if they had not merged previously, and the bridge between them was lower. For both merger types, however, there was a distinct difference in the age and thus in the size and reflectivity of the two merging cores. Based on the results of Byers and Braham (1949) and Kingsmill and Wakimoto (1991), it was assumed that the cores were representative of cells growing, maturing, and decaying with a total duration of about 30 min. According to this assumption, the larger core 1 was likely in its growth or mature stage for type 1 mergers or in the mature or dissipation stage for type 2 mergers. The smaller core 2 generally was in its growth stage. The modeling results of Orville et al. (1989), suggesting that mergers are more common between cores of differing sizes and ages, are borne out by these data.

## 6. Bridge formation

The enhancement of low-level convergence by storm outflows has been found to be significant in initiating the growth of new echo cores and in increasing the likelihood of merger (e.g., Simpson 1980; Simpson et al. 1980; Cunning and DeMaria 1986; Fankhauser 1982; Tao and Simpson 1989; Westcott and Kennedy 1989). No evidence of preexisting outflow boundaries was observed on either day, even using a 14-dBZ threshold on 26 August. Without surface winds or Doppler data, it is difficult to properly assess the importance of interacting outflows in initiating convection for the two days. However, perhaps some inferences can be made regarding the origin of the echo bridging the two merging cores, based on its height in comparison to the heights of the first echoes and the merging cores.

It might be expected that if enhanced low-level convergence was the primary factor involved in the bridge development, the bridge base or at least the height of the maximum reflectivity core might be higher in altitude than for the first echoes, assuming that updrafts were significantly invigorated. However, the bridges clearly had lower bases than the first echoes on both days, and the height of the maximum reflectivity core was about the same for the bridge and the first echo (Table 2). Additionally, if the bridge were the result of vigorous new cloud growth, one might expect that a distinct new echo core would form in the bridging area. However, a new core bridging existing cores occurred only in two cases on 25 July and in six cases on 26 August.

The lower bridge bases might have resulted from a number of factors. If updrafts in the bridge area ingested air with raised environmental moisture contents from prerain outflows or from the spreading of outflow air from mature or dissipating clouds (Byers and Braham 1949; Goff 1976), precipitation drops or an echo could form at a lower altitude. About 50% of the bridge bases were observed at heights of 1–2 km on 25 July, and about 50% of the bases on 26 August were observed at or below cloud base. Thus, moisture-laden

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TABLE 2. Median characteristics of the first echoes that later merge and for the bridge area between two merging echo cores on 25 July and 26 August 1986.

| | 25 July 1986 | | 26 August 1986 | |
|---|---|---|---|---|
| First echo and bridge properties | First echo | Bridge | First echo | Bridge |
| Sample size | 30 | 24 | 79 | 66 |
| Max reflectivity (dBZ) | 26.9 | 25.0 | 28.7 | 27.5 |
| Echo-top height (km) | 7.5 | 8.5 | 5.5 | 5.5 |
| Max reflectivity height (km) | 6.5 | 6.5 | 5.5 | 4.5 |
| Echo-base height (km) | 4.5 | 3.0 | 4.5 | 1.5 |
| Freezing level (km) | 4.5 | | 4.3 | |
| Cloud-base height (km) | 1.5 | | 1.1 | |
| Cloud-base temperature (°C) | 21.0 | | 19.0 | |

outflow air from adjacent cores may have contributed to the bridge formation on both days. Also, rain-out from a mature or dissipating cloud might cause the bridge base to be lower than that of a first echo. This may have been a factor on 26 August, when about 20% of the bases extended to the surface.

The presence of precipitation-sized drops lower in the bridge also might occur if a cloud were seeded laterally or from above. As the merging pair was generally the same height or taller than the bridge, it may be that precipitation embryos were being transported into the bridge area. Overhanging shelves often observed from convective clouds and evaporating droplets at midlevels may have induced cloud mergers by seeding lower clouds (Simpson 1980) or by destabilizing the air through evaporative cooling (Ackerman and Westcott 1984). On 25 July, when severe weather was observed, the lowered bridge base also may have resulted from the recirculation of precipitation particles by downdrafts into the low-level inflow area (e.g., Miller et al. 1982). Usually when the bridge bases were at low altitudes, however, the bridge itself extended upward to at least the midlevels of the adjacent clouds, and thus, the origin of this cloudy air cannot be identified.

A limited number of observational case studies have shown that merging can be initiated by differential cell motion (Cunning et al. 1982; Ackerman and Westcott 1984; Westcott and Kennedy 1989). For the two study days, in only a few instances of merger did differential motion play a role. On 25 July, the storm motion and core motion were generally in the same direction (252°) and at about the same speed, 13 and 12 m $s^{-1}$, respectively. The similarity in core motion with respect to the storm and the wider spacing likely contributed to the longer time required for merger of the southwest cores on 25 July and to the paucity of merger events. On 26 August, the storms moved from 270° at 19 m $s^{-1}$ and the cores also moved at 19 m $s^{-1}$ but from 248°. The median time to merge for all cores during this period was 7 min and the median initial edge-to-edge separation at first echo was about 4 km, suggesting that a differential speed of about 10 m $s^{-1}$ would be required for merger. In only two instances on 25 July and in one instance on 26 August did differential speed play a role in merging. However, on 26 August, the difference in the direction of motion likely played an important part. Intuitively, one might speculate that many closely spaced clouds moving in differing directions would be more likely to merge, such as on 26 August, than a few more widely spaced clouds moving in the same direction as on 25 July.

In this study, the horizontal expansion of echo cores appeared to be the primary mechanism leading to merger. In all cases on both days the area of one or both echo cores was increasing during merger. Horizontal expansion of echo cores has been observed to be a factor in the merging of clouds by previous studies as well (Ackerman and Kennedy 1989; Simpson 1980). This expansion simply may be a result of closely spaced clouds growing together or of outflow from the mature updrafts of vigorous systems. The intercell transport of cloudy material at middle and upper levels resulting from the radial outflow above the maximum updraft level of an actively growing cloud has been found to be significant in intensifying the bridge between merging cores (Westcott and Kennedy 1989). If particle transfer were the primary cause of bridge formation, the bridge might first be observed at higher altitudes where outflow from mature updrafts would be expected. On 25 July, about 30% of the bridges had bases at heights of at least 5 km (Fig. 7). In these cases, the bridge base was at least 4 km above the base height of each of the merging pairs, implying that detrained air emanating at upper levels from the mature cells was present in the bridge area. On 26 August, the echo cores formed at a lower altitude and did not grow as tall. Only about 20% of the bridges formed at or above 4 km (Fig. 7), and only two-thirds of these higher bridges formed more than 2 km above the bases of the merging core pair. Thus, on the day with stronger environmental winds and stronger vertical shear, it appears that the horizontal expansions resulting from particle transfer aloft may have been more common.

## 7. Growth of the merging cores

It is commonly believed that larger systems will last longer and produce more rain than smaller, more isolated systems. In part this may be due to feedback mechanisms where new cores are initiated by established convection and where the older storms provide an environment that limits the negative effects of entrainment, so that individual cloud units thrive. The following discussion addresses whether the merging process affects the merging components, such that they are dynamically invigorated or that they are likely to grow after merger.

The frequency of cores that grew just after merging is presented in Table 3. On both days, between 45%

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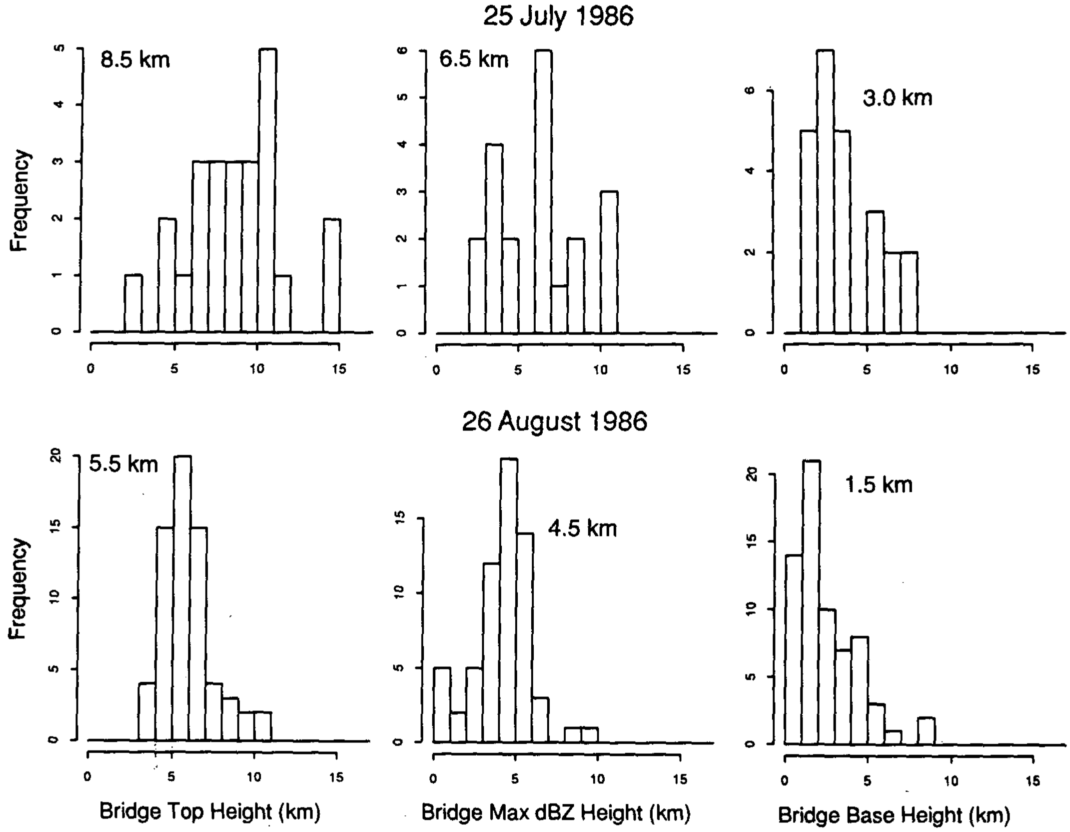

FIG. 7. Distribution of bridge base, maximum reflectivity, and top heights for (a) 25 July 1986 and (b) 26 August 1986. Median values are indicated.

and 70% of the total sample of merging cores increased in area of at least 20 dBZ, or area of at least 35 dBZ (Table 3a). Only a minority of the cores grew in height in the 2–5 min following merger, and the frequency was especially small for the older and larger core 1 cases. The median age at merger for core 1 for all mergers was 26 min on 25 July, and 15 min on 26 August, which suggests that they were typically in the mature or dissipation stage when an increase in height might not be expected. This agrees with the findings of Simpson (1980) and Westcott (1990) that echoes often continue to expand in area following vertical growth.

A larger proportion of the population of cores that were growing before merger (Table 3b) grew after merger than for the population of cores as a whole (Table 3a). Few of the young core 2 cases that were growing before merger did not continue to increase in either reflectivity, height, or area, about 11% on 25 July, and about 18% on 26 August. However, when considering only this group of cores that might be expected to grow after merger, still only about half grew in height after merger (Table 3b).

Differences in the properties of the merged pairs in which the younger core 2 was growing, or in which it remained steady or diminished after merger, were examined to determine what factors might lead to continued growth after merger. The growing cores were found to form near parent cores that were younger (median age of 15 and 10 min for core 1 on 25 July and 26 August, respectively), whereas cores that were not growing tended to merge with older cores, with a median age of 30 and 18 min for core 1, respectively, for the two days. One might speculate that the outflow boundary from a younger core 1 in the growing cases may be in a location to impact the low-level convergence field to enhance the growth of the young core 2 and possibly the bridge between them. This was observed in the Westcott and Kennedy (1989) case study. For cases where core 2 was steady or diminishing, core 1 was likely in the later part of its mature stage, and the outflow associated with it may have been spreading out at some distance away from the merger site and was no longer able to enhance low-level convergence.

A large fraction of the cores that grew after merger were increasing in area, reflectivity, or height before merger (Table 3c). As illustrated by Fig. 8, the core 2 cases that were growing after merger were younger and the height of their maximum reflectivity was higher than for those that did not grow. This suggests that the cores that grew were earlier in their growth stage at the

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TABLE 3. Percent of growing echo cores on 25 July and 26 August 1986.

| Increasing echo core properties | 25 July 1986 |  | 26 August 1986 |  |
|---|---|---|---|---|
|  | Core 1 | Core 2 | Core 1 | Core 2 |
| (a) Of the total population of merging echo cores, the percent that grew just after merger. |  |  |  |  |
| Max reflectivity (dBZ) | 22 | 58 | 48 | 62 |
| Area ≥ 20 dBZ (km$^2$) | 48 | 48 | 67 | 65 |
| Area ≥ 35 dBZ (km$^2$) | 62 | 52 | 71 | 59 |
| Top height (km) | 33 | 46 | 29 | 34 |
| (b) Of the population of echo cores growing just before merger, the percent that continued to grow after merger. |  |  |  |  |
| Max reflectivity (dBZ) | 27 | 71 | 56 | 69 |
| Area ≥ 15 dBZ (km$^2$) | 60 | 62 | 79 | 66 |
| Area ≥ 35 dBZ (km$^2$) | 82 | 69 | 84 | 67 |
| Top height (km) | 17 | 50 | 30 | 46 |
| (c) Of the population of echo cores that grew after merger, the percent that were growing just before merger. |  |  |  |  |
| Max reflectivity (dBZ) | 60 | 86 | 72 | 81 |
| Area ≥ 15 dBZ (km$^2$) | 67 | 91 | 88 | 86 |
| Area ≥ 35 dBZ (km$^2$) | 69 | 92 | 91 | 85 |
| Top height (km) | 13 | 73 | 33 | 48 |

time of merger and thus more likely to grow after merger. In addition, when the median growth rates in terms of area, reflectivity, and height were examined, no significant difference was found between growth rates for the time periods just before merger and just after merger. Thus, at least for the time period just following merger, no compelling evidence was found for enhanced growth following merger.

While merging results from the interaction of two clouds, it appears that merging in general is a passive process—that is, a process that is largely the result of the horizontal expansion of adjacent clouds and one that generally does not appear to significantly invigorate the merging echo pair. The echo cores that grew after merger typically were ones that were young and also growing before merger, and thus likely to continue growing. While merging itself may be considered a passive process, it often signals or is the result of the presence of organized, active convection.

## 8. Conclusions

Past studies established that the aggregation of cloud elements is an important element in the growth of large convective cloud systems and that these merged systems are larger, longer-lived, and produce more rain than more isolated systems. The intent of this study was to closely examine the behavior of the individual convective elements that merge. Merging was defined here as the joining of two echo cores previously separated at 20 dBZ.

First-echo characteristics for two echo populations occurring under very different environment conditions indicated that the cores that eventually merged were taller than those that never merged, suggesting that they had stronger updrafts and thus a priori were more vigorous and thus more likely to grow and merge. Of the echo cores that were observed to grow after merger, most were growing before merger. The most prominent factor in determining whether an echo core grew following merger was the age of the two cores. Younger echo cores tended to grow more, as well as ones adjacent to cores early in their mature stage. Evidence of a synergistic interaction between the merging cores was not obvious.

The echo cores appeared to merge largely by horizontal expansion; that is, the cores may have simply grown together. In only 15% of the cases did differential motion or the growth of a new core play an ob-

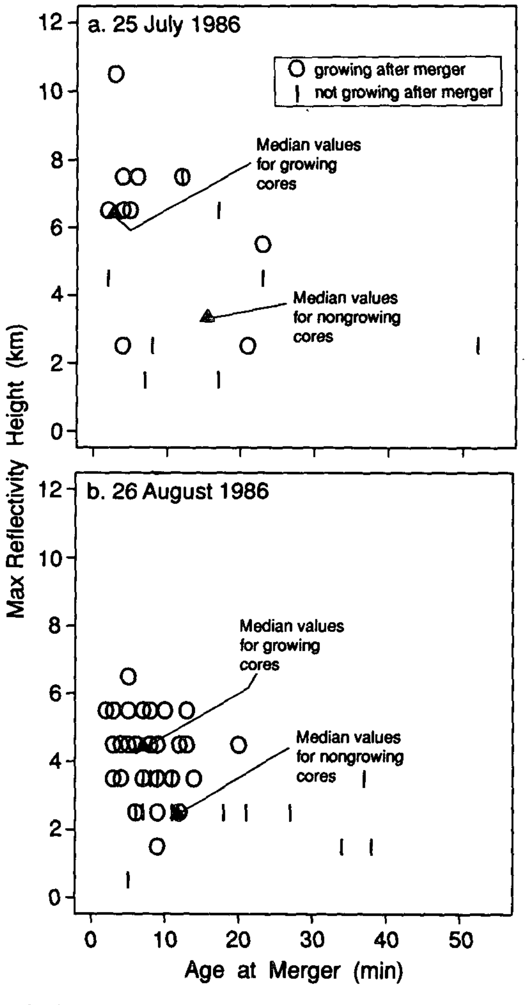

FIG. 8. Echo core 2 age and maximum reflectivity height at the time of merger for growing and nongrowing cores for (a) 25 July 1986 and (b) 26 August 1986.

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vious role in causing echo cores to join. The manner of horizontal expansion was inferred from the height of the bridge between the merging pair. On 25 July, when more vigorous convection occurred, it was more apparent that the transport of material from actively growing updrafts played a large role. On both days, it appeared that moisture-laden downdraft air was important in the presence of precipitation at lower altitudes within the area bridging the echo cores.

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