Radar and Other Observations of Two Vaulted Storms in Northeastern Colorado

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ABSTRACT

Detailed radar echo structures and histories of two storms are presented. Both advanced into cloudless skies and had prominent, bounded weak echo regions. The storms had comparable size and intensity, and their environments provided similar amounts of shear and potential instability. One was an organized, multicellular storm, and had detailed photographic coverage from an aircraft. The combination of visual and radar data suggests the possibility of seeding of vortices in the “flanking line” by ice particles falling from the anvil. The other storm was a supercell. It had a rather steady echo configuration with a radar echo vault for about 40 min, and produced an exceptionally heavy hail swath, with hail up to 10 cm deep. However, the heavy hailfall at the ground started before vault formation and ended well before vault dissipation. The hailfall relates best to the onset of the strong updraft that (presumably) produced the vault, but does not relate to the mere fact of the existence of the bounded weak echo region.

The radar reflectivity structure and evolution of these two storms provide an interesting contrast. They are discussed in terms of the distinction between multicellular and supercell storms, and the concepts of storm and cell motion.

1. Introduction

Two small but fairly severe hailstorms were observed near Grover, Colorado, on 8 June 1976 and 19 July 1978. Both storms were scanned in detail by the S-band radar at Grover and both were observed with aircraft to some extent. The data combinations that make the two storms worth describing are the radar reflectivity structure and evolution, along with detailed time-lapse photography on 19 July, and with observations of a very severe hailfall and the hailstones that comprised it on 8 June. Neither, however, had adequate Doppler radar coverage even for deducing horizontal wind fields, though some single-Doppler data were taken, and neither had good surface mesonet coverage in the inflow sector.

The two storms are described together herein because they also provide an interesting contrast of storm types. As such, they may stimulate further thought about the significant differences between supercells and organized, multicellular storms. These storms will be described and discussed separately followed by a brief discussion of their contrasting organization.

2. 19 July 1978

The storm of interest on this day was the smaller of a pair of similar, vaulted storms that moved on an east-southeasterly course from Wyoming into Colorado. The storms were aligned east–west, about 40 km apart, and the westernmost one, described here, was observed in the most detail. There are few data on the origin of the storms.

The coverage from the 10 cm wavelength radar at Grover consisted of sector scans about two minutes apart, but with awkwardly large elevation steps. Figs. 1 and 2 are two complete PPI scan series through the storm without the lowest level scan, which was contaminated with ground clutter. In the low and middle cloud levels an echo maximum lies to the north of a prominent notch in the southern echo boundary of the storm, that leads upward into a bounded weak echo region, or vault. In the later of the two scan sequences shown (Fig. 2), the vault leads upward to an echo maximum aloft that appears to be distinct from the maximum to the north.

While this general character was present for most of the hour of storm observation (from about 1600 MDT when the scanning of the storm started until about 1700, when the storm was too close to the radar to be scanned effectively), detailed tracking of the identified features reveals that the storm’s progression was not steady. Fig. 3 shows a map of the three distinctive features (notch in the echo, N; bounded vault, V; and local reflectivity maximum, M) identified in each scan within about 1 km of the 8 km MSL level. (Ground

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

2 With cloud base at 4 km MSL, low, middle and upper levels are used to refer to 4–6, 7–9 and above 10 km.
Fig. 1. Radar echo PPIs, at times and elevation angles shown, with three fiducial lines to help in tracing the vertical continuity of the features. Contours are at 10 dBZ intervals, and echo stronger than 55 dBZ is shaded. Altitude axes on the PPI surfaces are given, as is the maximum echo value for each scan. The echo maxima of Cell B and the vault of Cell C (Fig. 3) are indicated on the 8.7° PPI, and the characteristic notch in the south side of the echo is shown at 5.8°. Closed contours surrounding echo minima are indicated by short bars normal to the contour lines, in analogy with the system used on topographic maps. This is radar scan 5 in the system of Fig. 3. The points labeled P are for reference in Fig. 6b.

level is about 1.6 km MSL.) The overall storm motion (solid line) is from 295° at 13.5 m s⁻¹ on the average, yet the vault positions tended to track across the storm from the west, from between 240° and 270° at speeds between about 12 and 22 m s⁻¹. Furthermore, the usual progression of features from left to right along these crossing tracks are first a deep notch in the southern extremity of the radar echo, then a bounded echo vault, and finally an echo maximum. Toward the end of the observation period, this regular behavior is less well defined than in the earlier part, either because the storm changed its character somewhat or because the steeper scans made the structure less evident.

As has also been observed by Foote and Wade (1982) in a different storm, the cellular evolution at the cloud base level is not as well-defined in the radar echo history as it is in the middle and upper cloud levels. The notch (see the 3.0° scans in Figs. 1 and 2) moves towards the southeast with no distinct, periodic fluctuations. The echo maximum at cloud base does, however, reflect the pattern of Fig. 3. The data on this storm are not adequate to determine whether or how much the cloud base updraft fluctuates in strength or location, as a cause for new cell formation.

This kind of periodic, cellular behavior, with vaults evolving to echo maxima within each cell, is described by Chisholm and Renick (given in Browning, 1977), drawing on their own observations and those of others, as their prototype, organized multicellular storm pattern. The only major difference between this case and their prototype is the very prominent notch in the echo at low levels in the 19 July storm, and the much greater size and bounded character of the echo vault. Note also that in the present storm the new cell is not always completely distinct from the old one. In Fig. 3, V7 and V8, and M12–M16 seem to bridge the gap, in some sense, between cells C and D.

The behavior of the vaults in this storm also fits closely with the description of a supercell by Nelson and Braham (1975), a storm that did possess a similar reflectivity notch. They viewed the vault as a single continuous feature, with a superimposed evolution that produced individual, successive, peaks in the weak echo region, tracking across the storm path much as Fig. 3 shows.

It appears that interpretation of the 19 July storm either as a multicellular storm with discrete, temporary echo vaults or as a very unsteady supercell could be argued to be valid. However, the usually discrete transformation of each vault into a separate echo maximum strongly favors the multicell interpretation. In Nelson and Braham’s study, radar limitations prevented delineation of echo maxima, but otherwise their storm is very similar to this one.

Figures 4 and 5 are the atmospheric sounding and the hodograph judged to be most representative for this storm, with storm and cell motions (the variability of cell motion is noted above) included.

The 19 July storm advanced into completely cloudless skies, and was photographed roughly from the south at about 1600–1610 and from the west thereafter, using a quantitative, airborne time-lapse system described by Biter et al. (1983). The vicinity of the echo maximum was always obscured by the anvil cloud, but there was a “flanking line” of cumulus development, a ramp of turrets, that extended upward into the storm from the south. The location of this line corresponded with the location of the notches and vaults. Fig. 6a is a view from the south-southwest at 1608:09, corresponding closely with the radar PPIs in Fig. 1, and Fig. 6b shows some of the radar features superimposed upon a tracing of the photograph.

From the west (Fig. 7a), the flanking line is seen extending up under the anvil, with turrets poking up
Fig. 2. As in Fig. 1, but about 10 min later. Cell C is now an echo maximum through much of the cloud layer, whereas it was a vault in Fig. 1. The areas inside the strongest echo contours are shaded. This is scan 10 in the system of Fig. 3.

Fig. 3. Radar scan sequences from about 1600 to 1700 MDT are marked 1 to 33, and the echo notches (N), vaults (V), and maxima (M), examples of which can be seen in Figs. 1 and 2, are plotted using data from the middle cloud level. Storm motion is shown by the solid line NW to SE, and cell motion by the dashed lines, SW to NE. The scan sequences are about 2 min apart, but are not completely regular: sequence 1 is centered at about 1603; 6, 1611; 11, 1621; 16, 1629; 21, 1640; 26, 1649 and 31, 1701.
the region, according to a study by Knight et al. (1983), and that is the timing shown in the case of the one turret that was distinct enough on radar and visible enough from the air to provide good data. Fig. 8 shows this turret’s top height history (the cell is F in Fig. 3), along with the early echo history of the cell. The first radar echo of this cell was just separate enough from the main echo to be distinguished in three or four scans. In general, the visual turrets were about twice as frequent as the radar “cells” labeled with letters in Fig. 3, but the radar features being tracked were usually invisible within the cloud mass, as illustrated in Fig. 7.

While they do not provide strong evidence either for or against seeding from the anvil, three penetrations were made by the South Dakota School of Mines and Technology, armored T-28 aircraft, through the flanking line just at the southernmost extent of the [5 dB(Z)] radar echo at about 6.5 km MSL. The largest particles observed were a very few graupel up to 5 mm in diameter, using the particle camera, at the edges of the region containing updraft and cloud water.

An argument for seeding from above is the fact that bounded weak echo regions are rarely, if ever, seen developed in isolated cells to anywhere near the extent found here. The precipitation forming within isolated cells (and, indeed, most cells that are not isolated) quickly fills the cell but rarely if ever forms a marked sheath around the outside. Furthermore, the notch in the radar echo open to the south would be a natural result of seeding from above, with the seeding accounting for the extent of the two arms of echo extending down the sides of the flanking line and the updraft preventing the precipitation from entering into the notch itself.

Though the evidence is far from unequivocal, it does appear that seeding from above may be an important process in this storm, with the particles cascading down the sides of the updraft of a turret and gradually mixing around and into it while growing, producing first the echo notch, then the vaults and

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2 It is common experience on the High Plains for radar echo as strong as 40 to 50 dB(Z) to be associated with clear air to the naked eye, evidently because the thunderstorm precipitation can be composed of sparse, relatively large graupel.

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FIG. 5. Hodograph for the combined sounding of Fig. 4, with storm motion and approximate cell motion. The cell motions were not very uniform.
finally the echo maxima as the mixing and growth proceed and the updraft (the cell) dies. This recycling is, in principle, very much like that suggested by Browning (1963) for the Wokingham storm. Since

\footnote{Note, however, that Browning (1963) and later Browning and Foote (1976) propose their recycling model (or models) for a strict supercell, so that both the embryo and the final hail growth stages occur within the same updraft. While the 19 July storm is multi-cellular, the mechanics of the possible trajectories can be very similar, and the cellularity seems to make little difference in principle. Nonetheless, here the recycling, if it happens at all, is from the main updraft into daughter cells. In the storm analyzed by Heymsfield et al. (1980), the proposed recycling was from feeder cells into the main updraft: a rather different organization in principle from that suggested herein for 19 July 1978.}

Fig. 6. (a) Photograph (frame from the time-lapse movie) of the storm at 1608:09.0 MDT, taken from the south-southwest, approximately (−53, −21) km in “Grover” coordinates. (b) Cloud outline from Fig. 6(a), with 5 dB(Z) radar silhouette (points identified in Fig. 1) superimposed. The elevation angles of the scans from which the points were taken are indicated, as is the approximate scale and beam diameter at the range of the vault. Ranges from both radar and aircraft are somewhat larger for points P6–P8 at the left side, so both scales are a little larger there. The dashed lines represent very schematic profiles of the echo through the notch and the vault, and at the western extremity of the echo (see Fig. 1).
Fig. 7. (a) Photograph from the aircraft at 1619:30 MDT, from the west, about (−68, +29) km from Grover, looking east at the "flanking line" and the southern edge of the anvil. (b) Tracing of the photograph, with radar data. Note that the "tops" of the cumulus development under the anvil in the outline of Fig. 7b, are not really cloud tops but positions of the shadow from the edge of the anvil. The height scale at the left gives the approximate altitude at the range of the turrets and the vaults. The two vaults shown in the 11.6° scan of Fig. 2 are shown in outline with Xs marking the data points: the northern one is defined by a 25 dB(Z) "contour," the southern one at 5 dB(Z). The southernmost extremity of the 5 dB(Z) echo in the anvil is also shown, and suggests seeding of the turrets by fallout from the anvil aloft. The radar beam diameter at the range of the main vault from the radar is about 0.6 km.
Fig. 8. The "first echo" of Cell F (Fig. 3) was just barely separated from the main echo for a short time, and is shown here in a plot of maximum echo in the cell at the time of each constant-elevation sweep, in each volume scan, against its height. Data from the anvil directly above, from the 17" scan, are also shown, and echo contours are extended to that height with dashed lines to indicate the uncertainty of this interpolation. Circles are the locations of the echo values used to define the contours and Xs are the surrounding noise-level values. The visual top of this torrent is shown by the dots. It rose very steadily at about 6 m s\(^{-1}\) and was visible for several seconds above the anvil before becoming obscured.

Foote et al. (1975) and Foote and Mohr (1979) discussed in some detail the sensitivity of the shape, and even the existence, of radar echo vaults to the fall speeds of the precipitation particles that define them. This is a theme to which one must always return, in discussing the significance of radar reflectivity features such as weak echo vaults. Their interpretation is usually a somewhat ambiguous mixture of cloud dynamics and particle growth.

3. 8 June 1976

In its early phase this storm was a rather disorganized, multicellular complex that formed near Cheyenne, Wyoming, and moved south toward Briggsdale, Colorado. The observations of this phase are documented by Breed (1979). Near Briggsdale the southern end of the complex became organized into a vaulted storm that appeared to have a steady configuration for more than 30 min and deposited the heaviest swath of hail observed in the years of National Hail Research Experiment (NHRE) studies: hail as deep as 10 cm on the ground, though the biggest individual stones found were only 3 cm in diameter.

Figure 9 contains all the radar scans above the 0.5° one, for a time toward the end of the vaulted period. This is close to the "classical" supercell configuration (e.g., Browning, 1977), though in this case the echo maximum does not extend above the weak echo vault. Note that the size and general dimensions of this storm, such as vault size and distance between the vault and the echo maximum, are similar to the 19 July storm described above. The radar echo values are slightly stronger in the 8 June storm. Fig. 10 contains hand-contoured vertical sections from the same scan sequence, through the center of the vault, along and normal to 112°, the storm motion.

The vault was present from about 1641 to 1720, and it was of interest to examine the steadiness of the echo configuration in as much detail as possible, to compare with the 19 July case described above. For this purpose, a trace of the vault at 10 dBZ(Z) was made for each 11.7° radar scan, shifting to the 8.9° scan as the storm moved away from the radar. A map of some of these outlines is shown in Fig. 11a, and all are given in Fig. 11b after adding an artificial storm velocity of 1.5 km min\(^{-1}\) to the east to reduce the overlap. The altitude varies from about 6.5 to 8 km. The steady motion and size of this vault contrast markedly with the case of 19 July, shown in Fig. 3. The motion is along a straight line, toward approximately 112°, at about 7 m s\(^{-1}\). The echo maximum is not plotted because its progression is along the very same line about 5 km behind the vault (see also Figs. 9 and 10; the 112° line is plotted on the 11.7° PPI in Fig. 9). Its track also has no tendency to deviate from the track of the storm as a whole. Fig. 11c shows positions of

![Map of radar scans for 8 June 1976 storm](image-url)
the most remarkable attribute of the 8 June storm was its hailfall. The hail at the ground accumulated to 10 cm in depth over a localized swath, which was mapped by surface hail chase teams along the available roads. While the hailstones were not giant-sized, much of the 10 cm depth was 2 to 3 cm stones, which is fairly large by the standard of NE Colorado hail (Knight and Knight, 1979). Note also that the available buoyancy for the updraft was notably small for a storm of this character (Fig. 12).

Figure 14a shows the hailswath and the observation lines and points, with times of observation of the actual hailfall, where available. The storm was producing hail both before and after this swath: the usual, relatively light, small hail mixed with a lot of rain that is common from thunderstorms in northeast Colorado (e.g., Knight and Knight, 1979). The swath that is mapped in Fig. 14a represents an exceptional depth of hail, the ground being completely covered. Sufficient hail even to leave a visible, white swath after a storm passes is fairly rare. To check the surface hail timing, Fig. 14b gives the swath of 60 dB(Z) radar echo from the 11.7° scans, for which the swath center is at 6 to 6.5 km MSL.\footnote{We use a level well within cloud rather than closer to the surface because the main purpose is to compare the timing of the hail production with the time of existence of the vault; not to compare echo strength with hailfall per se.}

The 60 dB(Z) echo swath and the heavy hailswath correspond nicely to each other, and both exist during the early period of existence of the vault, starting even before the vault formed (see Fig. 11), and ending at about 1710, before the vault collapse, which is at 1727. The same time history is seen in a plot of the maximum radar echo history on a time–height diagram, in Fig. 15. Here the 65 dB(Z) contour shows a steep-sided maximum from about 1640 to 1710.

If the circulation responsible for the echo vault were responsible for the exceptional hail production in the sense of the Browning and Foote (1976) model, in which the hail defines the radar vaults, one would have expected the onset of heavy hail at the ground at least five minutes after the vault first appeared, and its cessation a corresponding period after the vault ceased to exist. Actually, the reverse was the case, as is summarized in Fig. 15.

Figure 11 shows that the vault formed within pre-existing radar echo, in that the vault at 1643 is almost entirely within an area that had contained, at 1638, an echo of at least 10 dB(Z).\footnote{It is interesting to contrast the formation of this bounded weak echo region with that of the several BWER’s of the other storm. The rule, on 19 July 1978, was for the vaults to form by radar echo moving and/or forming out and around the vaults. The one distinct exception to this rule was V(10), shown at 11.6° in Fig. 2, which did form to an appreciable degree by the decrease of radar reflectivity factor at a location within preexisting echo.}

The 8 June storm during its vaulted phase fits very well the supercell concept as summarized by Browning (1977), the most basic aspect of which is steadiness in time. In fact, the marked contrast with the 19 July storm described above reinforces our opinion that the former should be called multicellular, in spite of the fact that it possessed a bounded weak echo region or regions. But apart from its steady radar configuration,
Fig. 11. (a) Traces of the location of the bounded weak echo vault, at 10 dB(Z), mostly from every other scan sequence during its existence. The numbers represent approximate scan times (minutes only) from 1628 to 1727 MDT. Before the first bounded vault appeared at 1641 (not shown), the position of the echo front is shown at 1628 and 1638. Note that the first vault was formed within a preexisting echo. The 1648 vault position is omitted for the sake of clarity. The 11.7° scan was used for most of the data, but the 8.9° scan was used from 1719 to 1727 to maintain a more nearly constant elevation. The 7.5 km height is shown at the two elevation angles, as well as the location of the mesonet station 1276. (b) Giving the storm an artificial, extra eastward velocity of 1.5 km min⁻¹, all vault locations are shown with the scan times. Solid contours are from 11.7°, dashed from 8.9°. The time and space resolution are comparable to the 19 July case (Figs. 1–3) but no trace of deviation of vault motion from storm motion is seen. (c) The location of the upper level (10 km MSL) echo maximum is given for each scan, from the 22.8° scan except for 1717 and later, which are from the 17.4° scan. Constant elevation arcs are given. Note the distinctly non-uniform motion of the maximum.

to illustrate the echo evolution and vault configuration throughout the vaulted phase of the storm, a series of vertical sections along the direction of storm motion (112°) and approximately through the vault center and echo maximum, are given in Fig. 16. The overhanging echo greater than 50 dB(Z) at altitudes approaching 10 km develops as the vault develops, but then decreases as the height of the top of the vault increases. At the same time, the total area of 50 and 60 dB(Z) echo decreases.

As can be seen in Fig. 16, the resolution of the altitude of the top of the vault is rather poor because of the 3 km spacing between the 11.8 and 17.4° scans of the radar. The only good data on the height of the top of the vault come simply from noting the times at which the vault is present in the 17.4° scan, and some measure of its size in that scan. This is done in Fig. 15, where large Vs represent vaults with minimum reflectivity less than 10 dB(Z), and small v's vaults with minimum greater than 10 dB(Z). Vaults in the 11.8° scan were shown in Fig. 11, and where there are no Vs or v's in Fig. 15, there was no closed-contour
Fig. 12. "Representative" sounding for the 8 June 1976 storm, from Grover, Colorado, using the 1530 MDT sounding up to 700 mb and the 1410 one thereafter. The steeper temperature lapse rate just above 700 mb was present on both. Cloud base was deduced from aircraft data in the inflow and data from one surface mesonet station, located in Fig. 11.

The echo minimum in the 17.4° scan. The rise of the vault top correlates well with the decrease of the echo maximum and with the end of the swath of hail.

The word "collapse" describes the final end of the bounded weak echo region rather well. The height of the top of the vault first descends below the 17.4° scan and then a new echo maximum forms at the level of that scan (10 km) where the vault had been. This then "collapses" through the old position of the vault, whose last vestige is a small indentation at low cloud levels in the southern boundary of the echo. All the while the storm’s maximum radar echo decreases (Fig. 15).

The description has shown that while the bounded weak echo vault existed as a single entity for some 40 min, and the storm had a supercell configuration for most of that period, the details of the configuration—the amount of overhang of the strong echo and the vault height—did evolve during that period. It is not possible to decide how much of the detailed evolution was due to the storm’s dynamics and how much to the microphysical processes that produced the radar echo itself. Data from a Queenaair in the storm inflow below cloud base (shown in Knight et al., 1981) suggest a gradual, slight decrease of water vapor mixing ratio and equivalent potential temperature, but the updraft measurements themselves did not have an obvious trend with time. The decreasing overall echo top (Fig. 15) also suggests gradually weakening updraft, but this could be either an artifact due to poor radar coverage at the upper levels or it also could be a result more of microphysical than of dynamical evolution. The increase in vault size, on the other hand, would normally lead one to expect increasing updraft strength with

Fig. 13. Hodograph for the 8 June storm. The storm motion is equivalent to the cell motion for this storm at the time of interest. Aircraft wind data below cloud base in the actual storm inflow showed southeasterly winds up to cloud base. These are not used here because they were obviously influenced by the storm itself. This hodograph represents an estimate of the actual environmental winds—meaning not influenced by the storm itself—from the available data.

Fig. 14. (a) The heavy hail swath (defined as the region over which the ground was white with hail after the storm had passed) was mapped by ground teams along the accessible roads, shown as solid lines. The one point to the NW was a collection site, and hail was collected during fall also along the N–S road 10 km W of Grover. Times of fall, where available, are noted. The hail was especially heavy for the indicated 1 km in the swath 10 km W of Grover. (b) The 60 dBZ "swath" from the 11.7° scan, centered at about 6–6.5 km MSL, corresponds well with the surface hail swath.
time. However one views this storm, the data do not fit with “normal expectations” from a supercell, and herein lies much of the interest of the case. The 19 June case shows furthermore that echo vaults can be poor indicators of storm type, so one theme of this article must be the fallibility of echo vaults as indicators of either hail potential or storm type.

Using the echo configurations shown in Figs. 10 and 9, one can easily rationalize the lack of prolific hail formation later in the vault’s lifetime. The front (ESE) wall of the vault is nearly vertical, such that any embryos that do travel around the south side of the storm to enter the ESE side of the updraft are very unlikely to be carried over the vault. Most of them must be carried nearly straight upward to the -40°C level (past which they cannot grow), or, in fact, be carried out to the ENE in the anvil. This is not the configuration in the earliest vault stages shown in Fig. 16. The steepening of the east side of the vault may correlate with the decrease of echo intensity over the vault, though one cannot be certain because of the large interval between the 11.8 and 17.4° scans (see Fig. 16, the panel at 1659). In this interpretation, the major factor in the vault evolution could be the updraft becoming more vertical, not necessarily more intense.

It is also easy to rationalize the early onset of the heavy hailfall, using Fig. 16. The major updraft impulse penetrated into and through some quite high radar echo, which probably provided the small hail that could grow quickly into the 2 to 3 cm sizes observed at the ground.

Hailstones were collected in several places, both from the ground and in collectors, and were found to have remarkably uniform structures. Of the more than 300 sectioned, all had graupel embryos and almost all were predominantly dry growth with very small crystals. Three of the larger stones are shown in Knight et al. (1981), and their growth altitudes according to deuterium analyses of their growth shells are given there. Both the crystal sizes and the deuterium analyses indicate simple up-and-down trajectories, with growth confined to the temperature interval between about -10 and -30°C. Without quantitative wind field measurements in the storm, not much can be done with this information. However, it is interesting to note that the structural uniformity and simplicity of the hailstones is a unique feature among the several dozen hailstone collections from the region that have been analyzed. Usually there is much less uniformity among the stones of a collection. This correlates in a satisfying way with the organizational simplicity of the 8 June storm, which also is unusual for northeastern Colorado.\(^7\)

One cannot help asking oneself why this storm produced so much hail—so much more than any other storm observed in NHRE, in terms of a local amount. The storm did move slowly—about 7 m s\(^{-1}\)—and that contributed to the hail depth, but the hailfall would have been exceptional even with much faster movement, and the hailstones were exceptionally large for NE Colorado. Without information on the flow fields of this and the more typical storms of the region, any attempt at explanations must be very speculative. However, it seems very probable that the echo vault in this case does represent the approximate size and location of the main updraft of this storm, that this storm possessed an exceptionally broad and steady updraft, though probably not exceptionally strong, and that in general terms this provided the environment conducive to the exceptional hail formation. While hail growth trajectories of the type suggested by Browning and Foote could well have dominated much of the heavy hail production, the evidence shows that the echo vault itself was neither a sufficient nor a necessary feature for the hail production.

4. Comparing the storms

While students of convective storms would probably be unanimous in calling the 8 June storm a supercell,\(^7\) A reviewer asked about the possibility of calculating the hailstone number concentration in this exceptional hailfall. Unfortunately the time-resolving collector got clogged with hail, but a rough calculation is possible, using the three minute heavy hailfall duration, 5 cm as a somewhat conservative hail depth estimate, and 2 cm as an estimated stone diameter. One gets several hailstones per cubic meter and about 10–20 g m\(^{-3}\) ice content; both large, but not astonishingly so.
the 19 July storm might well be called a supercell by some and multicellular by others. Since discrete cells are identifiable in the 19 July storm, each following a progression similar to the three stages defined in the Thunderstorm Project (Byers and Braham, 1949), it seems correct to call it multicellular. However, if the...
radar data had been less detailed, with five- instead of two-minute time resolution, say, and somewhat poorer spatial resolution as well, the discrete cellular nature of this storm could have been much less clear, and a designation as a supercell might have been more likely.

Regardless of how one classifies them, the behavior of the two storms described here was strikingly different, and it is worthwhile to discuss the difference briefly. Foote and Wade (1982) and Foote and Frank (1983) have recently described the radar reflectivity evolution and airflow of a NE Colorado hailstorm that had attributes of both supercells and multicells and they characterized it as being about midway between the two conceptual extremes. They distinguished three storm behaviors: quasi-steady, weak evolution, and strong evolution. Their storm, a case of weak evolution, seemed steady at lower levels, but broke down to discrete cells higher in the cloud. Nelson and Braham (1975) noted the same behavior in the storm they described, and the 19 July storm described herein also has the same general character. The vaulted stage of the 8 June storm described above has almost no multicellular character at all.

It is easy to visualize a transition between supercell and multicell that is just a matter of steadiness (discrete propagation grading into continuous propagation), but it is clear that the distinction between the two storms described here is more than just that. In a steady version of the 19 July storm, according to Fig. 3, the echo maximum and the vault would travel along parallel tracks a few km apart. (In Figs. 1 and 2, it can be seen that coexisting vaults and echo maxima tend to be aligned north–south, while the storm track is 115°.) In the 8 June storm however, the vault and the echo maximum travelled the same track (Figs. 9 and 11 and discussion). Since the evolution of a thunderstorm cell is a progression from updraft to echo maximum, a cellular version of the 8 June storm (assuming nothing changes but the steadiness) would have to have a cell motion parallel to the storm motion, but not necessarily at the same speed. In fact, what trace of cellular character there is, at 10 km MSL, does behave this way as shown in Fig. 11c.

Thus another conceivable path of gradation between the extreme multicell and supercell storm types is one in which the cell motion becomes more and more nearly parallel to the storm motion, and any cellular character becomes harder and harder to distinguish for that reason. It may be that distinctly multicellular storms usually have cell motions at a substantial angle to the storm motion, while more nearly steady storms have cell motions more nearly parallel to the storm motion. In the storm described by Foote and Frank (1983) as an example of weak evolution, cell motion was nearly parallel to storm motion but at only about half the speed (Wade and Foote, 1978). Also, in the typical supercell shown schematically by Chisholm and Renick (see Browning, 1977), the echo maximum and the bounded weak echo region are lined up along the storm track, as in the 8 June case described here. In storms normally called multicellular (Marwit, 1972, tabulates several), the storm and cell motion are in distinctly different directions.

In general, storm motion is determined low in the boundary layer: it follows the track of a surface convergence center, which can be influenced by a number of factors, some strongly related to the storm itself. This is necessarily the case when negative buoyancy exists at cloud base, as is the case for both of these storms and as is usually true for thunderstorms (see Fankhauser et al., 1982, for a review of the northeastern Colorado data). On the other hand, cell motion is usually thought to be determined largely by the winds at the low cloud levels. The cell motion in the 19 June storm described here agrees nicely with the winds at the low to mid-cloud level, according to the sounding in Fig. 5. Lacking surface data, one can only speculate about the causes of the storm motion, but it is certainly plausible that the storm is following a region of surface convergence that moves relatively independently of the cloud level winds: perhaps related to the storm's own surface outflow boundary (e.g., Weaver and Nelson, 1982). The storm (cell) on 8 June moved with the winds at cloud base (Fig. 13) and in general there was much weaker wind relative to the storm up to the mid-cloud levels on 8 June than on 19 July. (Note, however, that this is not typical of supercell wind hodographs, as given by Browning, 1977.) To the extent that one can think of storm motion as independent of cell motion, then perhaps the more cellular character of the 19 June storm relates to the fact that there seems to be a much stronger reason for cell motion to differ from storm motion in that case. (G. B. Foote pointed out a suggestive difference between the 8 June and 19 July soundings. The dryer midlevel air on 19 July could have stimulated stronger downdrafts and therefore more substantial surface outflow on 19 July, a possible cause for the storm motion to deviate from the cell motion.)

A somewhat different approach has been taken by Weisman and Klemp (1982) who related a bulk Richardson number to the "cellularity" of storms. The Richardson number, R, is the ratio of the buoyancy to the energy available from the horizontal motion of the inflow relative to the storm. Weisman and Klemp found that higher values of R correlated with multicellular storms while lower values correlated with supercells, both in a storm model and in natural cases. A number of simplifications were made in computing R, including using the average wind over the lowest 6 km instead of actual storm motion, but for the two storms described here, R = 34 for 8 June and 21 for 19 July. This would in fact predict more multicellular character for 19 July, the multicellular storm. It is interesting that using the real storm or cell motion would increase the shear for the 19 July storm by
nearly a factor of 2, decreasing R to about one quarter of the calculated value and accentuating further the predicted supercellular character for that storm.

5. Conclusions

The radar echo history of two storms with very prominent, bounded weak echo regions has been described in some detail using data with two-minute time resolution, and spatial resolution of one kilometer or better for both storms. One storm is a supercell and the other an organized, multicellular storm. Analysis of time-lapse photography gives evidence for the seeding of the flanking line by precipitation falling from the anvil, in the multicellular storm. The exceptionally heavy hailfall from the supercell comes from the period when the vault is forming, and may relate more importantly to the unsteadiness of the airflow during the vault-forming period than to the relatively steady circulation around the vault itself.

The two storms form in similar conditions and in similar settings, and it is not easy to account for their different organization, but one important factor may be the tendency for cell motion to be different from storm motion. Treating storm motion as given, the multicellular storm had much stronger storm-relative winds in the low cloud levels than the supercell.

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