Visual Cloud Histories Related to First Radar Echo Formation in Northeast Colorado Cumulus

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ABSTRACT

Using quantitative analysis of time-lapse motion pictures from aircraft and a sensitive meteorological radar, the cloud top history is related to the early radar echo development in 12 vigorous, summer, convective cloud turrets in northeastern Colorado. At a threshold of about 5 dB(Z), the first echoes appear typically 5-10 min after the cloud top passes the ~20°C level. The first echo either appears at cloud top or reaches the top very quickly. It sometimes appears at a well-defined height, but sometimes nearly simultaneously over an altitude range of 3 km or more. Radar echo at 5 dB(Z) typically fills the visual cloud 5-10 min after first echo. In terms of overall cloud lifetime there is plenty of time for the particles responsible for the first echo to form by the ice process. A detailed model of the rates of ice particle formation by vapor growth followed by riming gives a 5 dB(Z) radar echo within 7-10 min at concentrations as low as 1 m⁻³, at most temperatures between ~10 and ~20°C and in cloud conditions realistic for northeast Colorado. The natural echo development may often result from the transport of embryonic ice particles into regions with vigorous updraft and high liquid water content where growth by accretion is rapid, rather than from growth entirely within the vigorous updrafts, for which the time may often be insufficient.

1. Introduction

The formation of precipitation in convective clouds is governed both by microphysical processes such as the rates of ice nucleation and growth, accretion and coalescence, and by the organization of the air currents, which determines the length of time individual precipitation elements may remain aloft within environments conducive to growth. Undoubtedly all researchers concerned with these processes appreciate the difficulty of dealing with this problem in realistic detail. While hailstone growth trajectories are now being calculated using wind fields deduced from Doppler radar data and growth models that use assumptions about the growth conditions [Paluch (1978) evidently was the first to do this], there is generally not a strong enough radar return during the first formation of precipitation in a cloud to provide Doppler velocity data. Reasoning about first precipitation formation has been based upon idealized models.

The models range from autoconversion schemes that by-pass the mechanisms of the formation of the first precipitation entirely, to quantitative, one-dimensional parcel treatments, and to more complex ideas like the ring-vortex, or "thermal" model (Scorer and Ludlam, 1953). The more complex models are less tractable for detailed, numerical calculations, but can be the basis for qualitative or semi-qualitative reasoning (Ludlam, 1952). Unfortunately, in order to test any model critically against the reality of first precipitation formation in a convective turret, one still needs to know a good deal more about the airflow as it varies in time and space than can be obtained from a few aircraft penetrations.

Models of precipitation growth within air parcels in specified flow fields have been favored for studies of early precipitation formation because the particle fall velocities probably can be neglected without overly serious consequences. Air parcel "lifetimes" are very difficult to arrive at from field data, however. A much simpler piece of information to obtain is the cloud lifetime, starting from some known size or cloud top height, because, in principle at least, the visual cloud history can provide that. The purpose of the measurements reported below was to obtain the lifetimes of individual convective turrets and try to relate precipitation development (the early radar echo) to the stage of visual evolution. This type of information seems fundamental, especially in a climate in which the ice process dominates. Cloud top height is a measure of the minimum cloud temperature, which in turn is likely to be a measure of the maximum expected ice crystal concentration. Yet virtually no data of this type were found to exist.

Five time-lapse photography sites in northeast Colorado were manned in 1976, but few useful data were obtained because of obscuring clouds. A one-month

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field study was carried out in July 1978 to try to obtain detailed radar coverage of first echo formation coordinated with visual data from an experimental, airborne, quantitative, time-lapse photography system. The results of these coordinated visual and radar studies are reported in this paper.

2. Historical

a. Radar first echo heights

During the early days of radar meteorology several systematic regional observations of first echo heights were made, primarily for the purpose of deducing general information about the mechanism of precipitation formation. Mean first echo temperatures were reported, of −10°C in New Mexico (Workman and Reynolds, 1949), +5°C in Ohio (Battan, 1953), about −2°C in Arizona (Braham, 1958), −1°C in Texas (Clark, 1960), and >0°C in Missouri (Braham et al., 1963). With the possible exception of New Mexico, these first echo temperatures are generally consistent with the warm rain process acting to initiate precipitation. The average first echo temperature in northeastern Colorado is between −15 and −20°C (Dye et al., 1974; more data confirming this result appears in Knight et al., 1982), and it is known that the ice process dominates there (op. cit.) Battan (1963) found first echo height to be correlated better with height above cloud base than with temperature in convective clouds in Arizona, and argued that the first precipitation in the clouds of that area therefore formed by the warm rain process.

b. Scientific cloud photography

While visual cloud observations have played a large role in cloud research, systematic scientific application of cloud photography is rather rare. Both Ludlam and Scorer based arguments about convective cloud circulation on careful visual observations, work that culminated in a quantitative study of turret growth rates by Saunders (1961). They and others (Anderson, 1960; Warner et al., 1973) deduced a ring vortex-like structure in rising convective turrets. The McGill University group has used quantitative time-lapse stereo photography in systematic studies of storms (Balshaw, 1967; Shaw and Marshall, 1972; Warner, 1973).

c. Coordinated visual and first radar echo studies

Workman and Reynolds (1949) studied the relation between visual and radar histories of 12 storm cells in New Mexico, and their composite shows the first radar echo (see footnote 2) at −10°C at which time the visual top is about 2.5 km higher, at about −25°C. At the visual top rise rate shown, the cloud top had passed the −10°C level more than 10 min before first echo. Vonnegut et al. (1958) observed inverted cup-shaped first radar echoes “several thousand feet” below the visual cloud top, in cumulus over a mountain in New Mexico. Saunders (1965) observed near Barbados, first radar echoes 300–1200 m below the visual tops of cumulus congestus that had started to grow from fructocumulus 25–35 min before. The echo values at first ranged from about 15 to 25 dB(Z), but the radar scanning procedure apparently did not assure that the first observed echo was the “first echo,” since the same region may not have been scanned a short time previously without finding echo. Jones and Marwitz (1966) found that visual tops were sometimes several kilometers above the radar tops in developing cumulonimbus in northeastern Colorado, at reflectivity factor values in the 20–30 dB(Z) range. Renick (1971) reports cloud top and 20 dB(Z) echo top data on several cells of a hailstorm in Alberta, and found the heights to agree quite well with each other, but the visual top data did not typically extend back to or before the first echo. Shaw and Marshall (1972) observed three convective showers in Quebec with radar and stereo photography. At the reflectivity threshold of 23 dB(Z) one first echo was observed to form very near cloud top at a low altitude (∼4 km MSL, 0 to −5°C). In several instances the visual top exceeded the echo top by several kilometers.

Other workers have compared echo tops to radar tops without studying the first echoes (Saunders and Ronne, 1962; Changnon and Bigler, 1957). The difficulty of obtaining coordinated radar and visual data from the ground has been remarked by a number of authors. It is remarkable how few data of this kind have been obtained, especially at low reflectivity factors, and this was one motivation for attempting the airborne photography.

3. Equipment and techniques

The radar used was the CP-2, 10 cm radar at Grover, Colorado, with a 1° beam and digital recording. At the ranges used in the present study the threshold sensitivity was often 5 dB(Z), or better. Time and space resolution were somewhat variable, as the data in the figures will show, but nominal val-

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2 A first radar echo is, of course, the first detectable radar return from the meteorological target. What this means in terms of the nature of the target itself is usually rather obscure in the early radar work, because of calibration uncertainties and beam filling considerations combined with the variable range to the clouds. In this work (see below) it is usually at about 5 dB(Zr), using a 1° pencil beam, and the radar beam size at the target is shown on the figures (range gates were 100–200 m apart).

3 All radar reflectivity factor values used herein are equivalent values, calculated using the dielectric constant of liquid water.
ues were about 2 min and 1 km. Decreasing one would have meant increasing the other.

The photography system consisted of two 16 mm time-lapse cameras viewing out port and starboard windows of NCAR Queen Air 304D. The cameras were ordinarily operated at one frame per two seconds, and time was recorded on each frame to 0.1 s and in the recorded aircraft data to 0.05 s using event marks. The aircraft attitude angles were determined with an Inertial Navigation System (INS) and recorded also to 0.05 s time resolution, and the camera pointing angles were derived from the attitude angle data. The analysis procedure and the error analysis are reported by Biter et al. (1983). The accuracy of deducing cloud tops with this system at the usual ranges used is a few hundred meters. Range to a cloud was calculated from the aircraft position and the radar location of the cloud. Internal validation comes from comparing the calculated cloud base heights in cases when cloud base was visible in the photos and the aircraft was not far from cloud base height (so that accurate range was not needed), with cloud base height directly measured with other aircraft, and from the very close match between the visual tops and the echo tops at low reflectivity factor values.

The experimental procedure was to have the aircraft take off early on the basis of a forecast so as to identify pre-echo turrets. The radar was directed to scan any promising developments in some detail well before any detectable echo appeared. This was successful twice during the month, but most of the successful photography was of new turrets that developed near pre-existing ones, with a recognizable pattern of development.

4. Results

a. 12 July 1978

The ancillary data on this case (primarily sailplane data) and a preliminary photographic analysis of the first of the two echoes have been presented in detail by Hunter and Knight (1980). The photography aircraft and the sailplane took off well before there was any radar precipitation echo, and the time-lapse photography of the cumulus congestus that produced the first radar echo in the entire region began nearly 10 min before the first, 5 dB(Z) echo. Fig. 1 shows a map of the track of the photography aircraft during its mission along with a very coarse representation of the history of the first and second discrete radar echoes which, incidentally, were the only two of the day in the entire region. Fig. 2 shows three views of the clouds, and Fig. 3 shows diagrams of maximum reflectivity factor versus height and time, along with the visual cloud top history, for both radar echoes.

![Diagram of aircraft track and radar echoes](image-url)

Fig. 1. The track of the photography aircraft plotted along with the 4 dB(Z) contour from the Grover CP-2 radar, from a series of scans at 8.8° elevation. The 7.5 and 10 km MSL altitudes on this PPI surface are shown. At the first three times only echo 1 appears, and the areas are cross-hatched or stippled, as indicated. Only echo 2 appears at this elevation angle at the last two times shown.
Fig. 3a typifies the kind of data that were the major objective of the present field study: turret top height and temperature before and during the first echo formation. Detailed study of the photographs of the cloud tops in this and all the other cases revealed subunits, presumably the bubbles, or thermals, of Scorer and Ludlam (1953), that were first visible at the western, upwind sides and moved through and over the overall turrets, disappearing at the eastern sides. (Note in Fig. 1 that the overall echoes also tended to move from west to east, but not as fast.) The scatter in the cloud top points in Fig. 3 results both from system errors and the succession of these subunits. These visual subunits usually could not be correlated with radar features, and are smaller in scale than what radar meteorologists call cells. The increase in the radar resolution in the vertical soon after first echo is common in much of the data and is caused by the fact that the early radar scan must cover a wider area to insure observing the first echo at all.

Fig. 2. Photos of the 12 July 1978 cloud from the NCAR Queen Air 304D, from the south at a range of ~35 km: (a) was taken at 1536:48, (b) at 1551:16, and (c) at 1559:31. (a) shows the turret (arrow) that led to first echo 1, 5 min after the photo; (c) shows the echo 2 turret (arrow) with pilaeus upstream; and (b) shows the general cloud mass.
While a general discussion will follow the data presentation, a few features are worth pointing out here. In all cases excepting 30 July (see below), the visual top and the radar top at about 5 dB(Z) agree quite well, which lends credence to the quantitative, visual top data. In both of the 12 July cases the top of the first echo itself also matched the visual top rather well. It is interesting to contrast the 12 July cases with each other. Echo 1 appeared while the visual top was descending, and spanned some 3 km in the vertical at its first appearance; echo 2, covered with greater radar resolution at its onset, had less vertical extent, and appeared while the visual top was ascending. The time from the visual top passing through the \(-20^\circ C\) level (deduced temperature within cloud, assuming adiabatic ascent\(^4\)) to the first 5 dB(Z) radar echo was about 9 min for echo 1 and at least 4 min for echo 2.

\(\text{b. 10 July 1978}\)

The storm of interest on this day grew out of a relatively thin cloud deck, containing no detectable radar echo, about 30 km north and 20 km west of Grover. There was a large storm some 30 km away to the northeast and a small one more than 20 km to the east, but the observed storm developed as a completely isolated radar feature and from the photographs taken from the southwest, the storm appeared to be visually isolated. Fig. 4 shows a rather long segment of the aircraft track with a representation of the early echo history. The storm later grew severe, attaining 70 dB(Z) and a visual top height of 14 km MSL about 40 min after first echo. On 10 July, using cloud base data for the storm of interest and the 1523 MDT Grover sounding, the adiabatic, cloud temperature excess over the environment at 500 mb, the stability index, was 6°C. A visual turrettop during the most vigorous phase of this storm was observed to rise at 10 m s\(^{-1}\).

Fig. 5 gives the visual top history and the first echo history. At 5 dB(Z) the first echo appeared at about \(-25^\circ C\), some 6 min after the visual top passed the \(-20^\circ C\) level. Again the first echo height corresponded well to that of the visual cloud top. The cloud was exceptionally unobstructed on this day, and was therefore chosen as one of the cases for presentation of a sequence of radar echo silhouettes overlain on the cloud outline. Fig. 6 gives three such views, at first echo and about 5 and 10 min later. This and the 30 July case presented later illustrate the rapidity with which the echo typically fills the entire horizontal as well as the vertical extent of the convective turrets.

\(\text{c. 11 July 1978}\)

On this day vigorous convection began shortly after noon, with scattered storms to the north and west of
Grover. The convection organized into a broad, northwest–southeast line after about 1400, and one new turret was photographed during its first echo stage at about 1500. The first echo was on the southwest side of the line, isolated from the nearest echo in the line by about 7 km. The photography was from the southwest (Fig. 7), and intervening low clouds obscured the lower parts and earlier history of the turret top, previous to the data given in Fig. 8. Again the first echo was at about 8 km and extended to the visual top at the time of formation. The first echo appeared at a time when the visual top started to rise, after remaining at a nearly constant height for several minutes.

d. 13 July 1978

A mature, multicell storm on this day was characterized by the formation of vigorous new turrets on its western, upwind side. The turrets drifted eastward with the mid-level winds, sometimes merging with previous turrets to the east and sometimes developing to be the major storm activity which at times had radar echo stronger than 70 dB(Z). The location where new turrets and first echoes first developed remained stationary at first, but later drifted slowly westward. There were at least eight distinct, isolated first echoes during the storm which would have provided more good data for the present study except for the existence of occasional intervening clouds. As it was, four cases were obtained. The cloud base temperature was +3 to +4°C, similar to the other cases, and the 500 mb temperature excess of an adiabatic parcel, the stability index, was about 3.5°C.

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5 A technical note describing the measurements on this day, which involved four research aircraft as well as the photography aircraft, by D. Breed, is being prepared.
are in Fig. 10. Echo 1(a) first appeared about 2 km below cloud top. Two minutes later, at the time of the next radar scan, Echo 1(a) had expanded to the visual cloud top. Its onset was about 11 min after the cloud top passed the $-20^\circ$C level. Echoes 1(b) and 2(c) were close to their neighbors and quickly merged with them.

e. 30 July 1978

On this day a small, isolated patch of rather vigorous cumulus congestus formed to the southeast of Grover within an extensive field of fair weather cumulus that never itself developed any detectable radar echo. The photography aircraft flew a long arc at a range of more than 100 km (Fig. 11), above the cumulus layer at about 4.6 km. (One of the operational constraints of photography with side-looking cameras is that range to the photographed object cannot be changed quickly while maintaining coverage. Addition of a nose camera would remedy this problem.) Four good first echo cases were obtained (Fig. 12). Echo motion was from northwest to southeast. Echoes 1 and 2 were relatively isolated, but 3 and 4 formed closely upwind (to the northwest and west) of echo 2 and soon merged with it. It is interesting to contrast the histories of 1 and 2 with those of 3 and 4, in light of the differing amount of isolation. Echo 1 started [at 5 dB($Z$)] more than 5 min after the visual top passed $-20^\circ$C. Unfortunately, it was poorly resolved on the radar. Echo 2 was very similar, taking about 6 min, but it appeared at a time when the visual top was not rising. Echoes 3 and 4 appeared much earlier, with echo 3 forming at the same time that the top reached $-20^\circ$C, and echo 4 appearing only about 2 min after the top passed $-20^\circ$C. Of all of the first echoes studied, only number 4 on this day started well below cloud top.

The two sailplane ascents on this day yielded two cloud base temperatures, $+5$ and $+8^\circ$C. The stability index at 500 mb was about $3^\circ$C.

Fig. 13 shows the development of echo 3 along with portions of the other echoes on this day, in silhouette with the visual outline. The starboard camera calibration for this day was clearly incorrect, for reasons that remain unresolved, and the top height data from that camera have been increased by 750 m in Fig. 12, an amount shown by the arrow in Fig. 13. (Fig. 13 shows the uncorrected data.) This is an error of camera pitch angle of about $0.4^\circ$. The very long range to the cloud on this day makes the error serious and the data of Fig. 12 and Table 1 have been cor-

![Fig. 8. First echo and visual top history for the 11 July 1978 case.](image-url)
Fig. 9. (a) The early histories of the 0 dB(Z) contours of echoes 1a and 1b on 13 July 1978 are shown, with lines of constant height from the PPI from which they were taken, along with the tracks of the photography aircraft. The echoes are merged at 1626:07. (b) Similar to (a), for echoes 2a and 2c. Echo 2b was in between, and only appears merged with 2c at 1640:13.

We have collected the data from these 12 cases into a summary table (Table 1), in spite of the fact that several of the fundamental parameters listed are quite imprecise. The present data are exceptionally complete and detailed in comparison with the data from corrected by this amount. (The camera yaw angle is incorrect also by about 1°, but that does not influence the data used here.) Fig. 13 shows rapid filling of the visual cloud by radar echo, horizontally and vertically, similar to Fig. 6.
FIG. 10. The early echo and visual top history of echoes 1a(a), 1b(b), 2a(c) and 2c(d) on 13 July 1978.
which other first echo statistics have been derived, yet it is interesting to note how approximate (or even almost arbitrary) the selection of a first echo height or temperature can be in some cases (e.g., Figs. 3a, 10c, 12c). Most former studies use a higher echo threshold, at which first echo parameters may be more definite, though our data do not indicate this. The rise rate of the visual top is also not well-defined, and the numbers in the table are averages over periods of roughly 15 min during and before the first echoes. As the data presentations show, one of the better-defined aspects of these data in many cases is the descent rate of the bottom of the first echo. Time of first echo formation is usually meaningful to between \pm 1 and \pm 2 min.

5. The rate of radar echo formation through the ice process according to a microphysical model

The purpose here is to assess the major variables that influence the time scale of radar echo formation by modelling ice particle growth in uniform, un-
FIG. 12. First echo and visual top histories of the four first echoes examined on 30 July 1978. Note the increased vertical resolution at about 1242 in (a) and (b).
changing supercooled clouds. Temperature, liquid water content, and aspects of the droplet size spectrum are the variables, and the results are to be used, to the extent possible, in discussing the time to first echo as determined by the field data. The model is kept to this extreme simplicity because of the generalized nature of the observations. Depletion of liquid water by the growing ice is very probably not important in first echo formation, but particle trajectories and growth environments certainly are. Since neither of these factors are well understood, the point of view here is to look only at the coarser time scale provided by the cloud itself. Likewise, the microscopic processes are simplified by disregarding factors that might possibly speed echo formation, such as the possible presence of small concentrations of precipitation-sized water droplets, the influence of ice particle aggregation, and the vapor growth of ice crystals in the more complex shapes such as capped columns.

The question being asked is whether, in the framework of this simplistic view, the clouds produce radar echo within times that are reasonably consistent with the time scales of particle growth at concentrations of the magnitude expected from conventional ice nucleus measurements. The answer will be “yes.”

In the model, ice crystals start (time \( t = 0 \)) as ellipsoids of revolution with diameter 10 \( \mu \text{m} \) and thickness 5.7 \( \mu \text{m} \). The first growth “regime” is pure diffusional growth at saturation with respect to supercooled water. In this regime (as in the others), the exchange of heat and mass with the environment uses the formulation of Hall and Pruppacher (1976). In diffusional growth, ice crystal habit is simulated by requiring the crystals to be ellipsoids of revolution with axial ratios as a function of size taken from Auer and Veal’s (1970) Fig. 1 for plates, Fig. 6 for thick plates, and Fig. 7 for columns. These habits are apportioned at the different temperatures as follows, using Magono and Lee’s (1966) summary of the habit-temperature relation:

<table>
<thead>
<tr>
<th>( T ) (^{\circ}\text{C} )</th>
<th>Habit</th>
<th>( T ) (^{\circ}\text{C} )</th>
<th>Habit</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>Plates and thick plates</td>
<td>-15</td>
<td>Plates</td>
</tr>
<tr>
<td>-6</td>
<td>Columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-9</td>
<td>Columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-12</td>
<td>Plates and thick plates</td>
<td>-24</td>
<td>Columns</td>
</tr>
</tbody>
</table>

The openness of real crystal shapes—the branching for “plates,” the hollowness of columns—is simulated by varying the densities of the vapor-grown crystals according to temperature using Fukuta’s (1969) Fig. 12, and density does not vary with crystal size in the model. This “classical” approach to calculating the vapor growth of ice crystals was also used by Miller and Young (1979). They compare the results with the experimental and observational evidence, and find that the model is quite successful.

Calculation of the riming rates of the crystals uses terminal velocities taken from Jayaweera and Cottis (1969) and for the droplets, from Beard (1976). The equation for mass growth rate is

\[
\frac{dm}{dt} \bigg|_{\text{rime}} = 0.25\pi D^2 \int_{0}^{\infty} \rho_w 4\pi r^3 f(r) V(D, r) \times |V(D) - V(r)|dr,
\]

FIG. 13. The development of 30 July echo 3. Note how rapidly it fills the visual cloud and how close it is to echo 2, with which it merges. The first time is from the starboard camera, the height data from which have been moved upward 750 m (see arrow) for Fig. 12, though not changed in this figure, because of the obvious faulty calibration (see text). The other two frames are from the port camera.
### Table 1. Early echo and visual top data.

<table>
<thead>
<tr>
<th></th>
<th>Cloud base height (km MSL)</th>
<th>500 mb stability index (°C)</th>
<th>First echo height, temperature (km MSL, °C)</th>
<th>Time, visual top at −20°C to first echo (min)</th>
<th>Visual top rise rate (m s⁻¹)</th>
<th>Echo top rise rate (m s⁻¹)</th>
<th>Echo bottom descent rate (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-12-78</td>
<td>4.4, +3</td>
<td>−2</td>
<td>8.0, −20 (broad)</td>
<td>8</td>
<td>2.5</td>
<td>−0</td>
<td>10</td>
</tr>
<tr>
<td>7-10-78</td>
<td>4.4, +3</td>
<td>−6</td>
<td>9.0, −27</td>
<td>6</td>
<td>4</td>
<td>−0</td>
<td>10</td>
</tr>
<tr>
<td>7-11-78</td>
<td>4.3, +2</td>
<td>−2</td>
<td>8.1, −20</td>
<td>4</td>
<td>0</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>7-13-78</td>
<td>4.2, +3</td>
<td>−3.5</td>
<td>7.7, −16</td>
<td>11</td>
<td>3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>7-30-78</td>
<td>3.8, +6.5 (±5 to +8)</td>
<td>−3</td>
<td>7.0, −12</td>
<td>5</td>
<td>6.5</td>
<td>−</td>
<td>10</td>
</tr>
<tr>
<td>3.8, +6.5 (±5 to +8)</td>
<td>−3</td>
<td>6.8, −10</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>3.8, +6.5 (±5 to +8)</td>
<td>−3</td>
<td>5.7, −5 (broad)</td>
<td>7.0, −12</td>
<td>0</td>
<td>5</td>
<td>14</td>
<td>−</td>
</tr>
<tr>
<td>3.8, +6.5 (±5 to +8)</td>
<td>−3</td>
<td>6.5, −10 (broad)</td>
<td>8.0, −19</td>
<td>2</td>
<td>5.5</td>
<td>15</td>
<td>−</td>
</tr>
</tbody>
</table>

where $V$ is fall velocity, $D$ the plate diameter, $r$ the droplet radius, $f(r)$ the droplet concentration, $E$ the collection efficiency and $\rho_w$ the density of water. The collection efficiencies for plates follow Hall’s (1980) formulation when the axis ratio is less than 0.2, and use Beard and Grover’s (1974) results otherwise. Ice particle temperature is influenced by both diffusional growth and riming. Collection efficiencies of columns for droplets were taken from Schlamp and Pruppacher (1977).

Rime density is taken directly from the experimental results of Pflaum and Pruppacher (1979) and is apportioned as follows. For the plates the volume of accumulated rime is accommodated by increasing the thickness until the axis ratio reaches unity. After that time, the shape is constrained to be spherical. For the columns the riming increases the column diameter until the axis ratio reaches unity.

The model was run at the temperatures and habits listed above, using both of the listed habits at −3, −12 and −21°C. Needles were not included, since their occurrence is confined to a very narrow temperature range. The model uses altitudes appropriate to the temperatures (the effect of the air density is small) and uses clouds with the following range of fixed properties: liquid water contents of 1 and 1.5 g m⁻³, cloud droplet concentrations of 500, 1000 and 1500 cm⁻³, and cloud droplet logarithmic dispersions of 0.05, 0.10, 0.15 and 0.20. The total range of mean radius $\bar{r}$ is from about 6 to 8 μm. The cloud droplet size spectrum is assumed to be log-normal, i.e.,

$$f(r) = \frac{N}{\sqrt{2\pi} \sigma r} \exp\left\{-\frac{(\ln r - \mu)^2}{2\sigma^2}\right\},$$

where $\sigma$ is the dispersion, $N$ the total concentration and $\mu$ the logarithmic mean radius. The range of cloud conditions used represents the summer conditions in northeastern Colorado (Knight et al., 1982), where the clouds are typically continental and have relatively cold cloud bases. The model was run for 1200 s (20 min), and its outputs included the melted diameter $D_m$ and the equivalent radar reflectivity factor $Z_e$ for a particle concentration of 1 m⁻³.
For nearly all sets of conditions of temperature, liquid water content, droplet concentration and dispersion, growth by riming either entirely dominates vapor growth by the time 200–400 s have elapsed, or it does not become the dominant mechanism in the entire 1200 s. In the cases where riming does dominate, the temperature difference between the graupel and the air rapidly increases to 2 to 3°C and the radar reflectivity factor also grows rapidly, reaching 0 dB(Z) within 400–700 s.

At the modelled conditions, graupel formation is a strong function of crystal habit. Thick plates always form graupel at −12 and −21°C, but never at −3°C in the time allowed, since the growth from the vapor is too slow. Columns never form graupel because they do not get thick enough in the 1200 s to attain appreciable collection efficiencies for the cloud droplets. Plates at −12 and −18°C do form graupel in some clouds but not in others, depending mainly upon the dispersion of the droplet size spectrum and the mean droplet size. Plates at −15°C never formed graupel, since the habits here are thin discs with a density of 0.1 g cm⁻³. This gives zero, or nearly zero, collection efficiencies for the small cloud droplets in the model cloud. In actuality, of course, these crystals are branched, and they might rime somewhat more readily than the model indicates. The applicability of the model at this one temperature is thus uncertain, but since the very fast a-axis growth occurs only over a narrow temperature interval, the problem is not very important in the present context.

The results for one set of conditions are given in Fig. 14, in which radar reflectivity factor [dB(Z)] is contoured as a function of time and temperature for a concentration \( N = 1 \text{ m}^{-3} \). The growth conditions are 1.5 g m⁻³ liquid water, 1000 droplets cm⁻³ and the dispersion \( \sigma = 0.15 \). This figure is for the habits in the first column of the list given above: plates at −3 and −12°C and thick plates at −21°C. Changing \( \sigma \) while keeping everything else constant, at \( \sigma = 0.10 \) graupel forms only at −12 and −21°C, and at \( \sigma = 0.05 \), only at −21°C. There is little difference between \( \sigma = 0.15 \) and 0.20. Looking at all the results, if \( \sigma \approx 0.20 \) and if the lack of graupel formation at −15°C is a result of the model assumptions and not a reality, graupel forms at about the same rate throughout the plate–thick plate temperature range from about −10 to −20°C and, at one per cubic meter, produces 0 dB(Z) in about 7–10 min starting from ice nucleation.

It is interesting that this fairly rapid development of graupel from plates and thick plates involves the onset of rapid rime at diameters < 150 µm. The onset of riming of ice particles has been shown by numerous authors to be a function of the shape and size of the collecting particles and of the cloud droplet size. Ono (1969) observed that columnar crystals begin to rime when their width is between 50 and 90 µm, and that simple plates begin to rime at a diameter between 300 and 400 µm. Harimaya (1975) reported similar observations for columns, and for more plate-like crystals he found the onset of observed riming to vary with the detailed habit, ranging from diameters of 300 to 900 µm. He argued that the observed “threshold” was due more to the time spent in cloud than to a real threshold of collection efficiency.

Hall's (1980) analysis of the theoretical data of Pitter and Pruppacher (1974) and Pitter (1977) on the collision efficiencies of thin, plate-like, oblate spheroids concluded that the collision efficiency depends upon two parameters: the Reynolds number \( (N_{Re}) \) of the collecting ice particle and the mixed Froude number \( (K_{Fr}) \) or the Stokes impaction parameter of the interacting ice particle-cloud droplet pair:

\[
N_{Re} = \frac{D V(D)}{v},
\]

\[
K_{Fr} = \frac{[V(D) - V(r)] V(r)}{0.5 D g}.
\]

Here \( V \) is the terminal velocity of the collector particle (diameter \( D \)) and droplet \( (r) \), \( v \) is the kinematic viscosity and \( g \) the gravitational constant. The collision efficiency data were then fitted to the available plate data yielding

\[
E_c = \{1 - 0.20[\log_{10}(K_{Fr}) - \log_{10}(K_{crit}) + \sqrt{5}]^2\}^{1/2},
\]
where

$$K_{\text{crit}} = \begin{cases} \frac{5.52(N_{\text{Re}})^{-1.12}}{1.53(N_{\text{Re}})^{-0.325}}, & N_{\text{Re}} < 5.0 \\ 0, & N_{\text{Re}} > 5.0. \end{cases}$$

When the mixed Froude number is below $K_{\text{crit}}$, the value of $E_z$ becomes zero.

The extrapolation procedure allows one to estimate the collision efficiency at other atmospheric conditions. The empirical fit was based upon data for thin plates that showed a riming threshold for thin plates at a diameter near 300 $\mu$m at $T = -10^\circ$C and $P = 700$ mb, and it predicted accurately Pitter's (1978) riming threshold at a diameter near 240 $\mu$m, again for thin plates, at $T = -18^\circ$C and $P = 400$ mb. The same fit yields yet smaller riming thresholds when applied to thicker plates because of the increase in their terminal velocity for the same diameter, and this contributes to the results in Fig. 14.

Realistic liquid water contents in most of the clouds studied herein are less than about 3 g m$^{-3}$. Increasing the water content speeds the riming proportionately, but, of course, leaves the vapor growth rate unchanged. Increasing the liquid water content for the conditions of Fig. 14 from 1.5 to 3.0 g m$^{-3}$ only speeds the formation of 0 dB(Z) by 100–200 s.

The effect of the concentration of the growing ice particles on the echo growth times is straightforward, since every factor of 10 increase in concentration adds ten to the dB(Z) value. For instance, the time to 0 dB(Z) at a concentration of 1 m$^{-3}$ is the same as that to +30 dB(Z) at 1 L$^{-1}$. At $-18^\circ$C in Fig. 14, it takes about 7 min to develop 0 dB(Z) at 1 m$^{-3}$ and about 4 min at 1 L$^{-1}$.

In the cases in which graupel does develop, Fig. 14 shows the increase with time of the rate of dB(Z) increase as diffusion gives way to riming growth at 100–300 s, and the decrease with time of the rate of dB(Z) increase thereafter, as particle size increases.

In general, the model results show time scales from ice nucleation to radar echo development [at 5 dB(Z), to compare with the field data] of 500–800 s (8–13 min) for concentrations of 1 m$^{-3}$ and 300–600 s (5–10 min) for concentrations of 1 L$^{-1}$ (10$^5$ m$^{-3}$), in the $-10$ to $-20^\circ$C temperature range, and these times are not drastically influenced by temperature or liquid water content except, of course, at very low liquid water contents. This time scale depends to some extent on assuming a cloud droplet dispersion of at least 0.15 to 0.20, which may be realistic though the data are not unequivocal (Knight et al., 1982). The influence of the droplet size spectrum on the onset of riming growth appears to be quite important. It may significantly retard growth in undiluted updraft cores, where the droplet spectrum may be very narrow.

Direct comparison of this time scale for graupel formation with that in other models described in the literature is difficult because of differing model conditions. However, the time scale found here is comparable to those deduced by Hindman and Johnson (1972), Scott and Hobbs (1977) and Harimaya (1981) except for the fact that in the present calculations graupel does not form from columns within 20 min.

In applying these time scales to real data, one needs to keep in mind the difference between available growth time and cloud lifetime, and that the calculations are for single sizes. Nevertheless, cloud lifetime is an upper limit for the available growth time, and radar tends only to “see” the upper end of the particle size spectrum because of the $D_m^{-5}$ dependence of $Z_e$.

For interpreting real data some ice nucleus concentration values are also needed, and we use

$$N = 0.2 \left(\frac{SS_1}{16}\right)^{3.5},$$

where $N$ is the concentration of ice nuclei active per liter of air at supersaturation with respect to ice ($SS_1$) in percent (Vali et al., 1982). The values 0.2 and 3.5 are characteristic of the northeastern Colorado area, determined by aerosol collections on filters, developed in thermal diffusion chambers. The resulting ice populations as a function of temperature, using saturation with respect to supercooled water, are plotted in Fig. 15. Variability from the line might realistically be expected to be from 0.2 to 5 times the value given. Results with the Langer counter are within a factor of 5 of these values. Furthermore, the ice contents of unmixed updraft cores in the region have been found to be roughly consistent with the magnitudes of these nucleus measurements (Heymsfield et al., 1979).

6. Discussion

a. Background

The field measurements reported here were made in part because combined radar and visual data on young convective clouds were not available, and it was felt that such data were fundamental (necessary but perhaps not sufficient) to an understanding of first

![Fig. 15. The typical summertime ice nucleus spectrum in northeastern Colorado, according to Vali et al. (1982).](image-url)
echo formation. In spite of the difficulty of interpreting data of this kind in terms of specific processes, the data should be valuable in the future as a touchstone for numerical models attempting to combine realistic cloud dynamics and microphysics for these types of clouds.

The main specific goal for the data was to compare the time scale of existence of the active cloud or cell—that is, the time that is apparently available for first echo formation in terms of overall, active cloud lifetime—with the time scale that the microphysical mechanisms impose upon the growth of the precipitation particles. Recent attempts to study the possibilities of increasing precipitation from small convective clouds by seeding with ice nuclei or ice crystals have encountered the limit that cloud lifetime places on particle growth (Isaac et al., 1982; W. A. Cooper and A. B. Super, personal communications concerning HIPLEX I results—report in preparation). In principle, when visibility permits, photography can be the best way to record a cloud’s lifetime, and help to discover whether a time “window” for effective seeding may exist or not. Houghton (1968) noted that, according to Project Whitetop data, cell lifetimes were comparable to the times required for precipitation particle growth. It seemed important to attempt to compare these two time scales with more precision.

b. Interpretation of the results

There is some rather solid knowledge about the clouds involved in this study that can serve as a basis for discussion. Much of this comes from previous studies of similar clouds of the same region at the same time of year, summarized and extended recently by Frankhauser et al. (1982) and Knight et al. (1982). The process of precipitation formation in the clouds of the present study is very likely to be the ice process, with liquid coalescence contributing little, according to the overwhelming bulk of the field evidence. The clouds tend to be dynamically both vigorous and complicated, even before the first radar echo formation. Updrafts to 20 m s⁻¹, downdrafts stronger than 10 m s⁻¹, and adiabatic portions as much as several kilometers above cloud base are common. Measurements from aircraft passes through clouds of this type typically show more than one updraft, one or more downdrafts, and cloudy regions without very strong drafts, and a strong correlation of the higher liquid water contents with the stronger updrafts.

In the few cases when aircraft observations of the precipitation particles have been made in the very early radar echoes, graupel of several millimeters diameter were responsible for the radar echo (e.g., Dye and Martner, 1982; Breed, 1979; Hunter and Knight, 1980). The radar data on the early echoes support this as being true in general, because the echo increase rates are typically several dB per minute (see the figures), much too fast to be easily accounted for other than by accretional growth.

The time from the visual cloud top passing the −20°C level (in cloud) to the first 5 dB(Z) radar echo varies from 0 to at least 11 min, averaging at least 5 min. While visual data much earlier in the cloud lifetime are usually lacking, it appears that an average time interval of at least 15 min from the top passing the −10°C level to the first echo occurrence is a conservative estimate. According to the model it takes less than 10 min for a concentration of 1 m⁻³ of 10 μm ice particles to grow enough to produce a 5 dB(Z) radar echo, at temperatures between about −12 and −21°C. Thus, the observed clouds usually do have lifetimes that are more than adequate for precipitation production in this way, according to the echo growth rates calculated for Fig. 14 and the ice nucleus population of Fig. 15. Indeed, in a number of the cases the amount of time seems superabundant. We will return to a discussion of the variability of the measured time interval later.

The first echo temperature and distance above cloud base in this study (−16°C, 3.5 km) are consistent with more extensive climatological averages (−15.8°C, 2.8 km) given in Knight et al. (1982). Taking as given that the ice process is the growth mechanism and that the first echo particles are graupel growing by accretion, it is easy to rationalize the common occurrence of first echoes at or near cloud top. The strong updrafts are generally the best environments for accretion, since they have the highest liquid water content, and are generally strong enough to elevate graupel particles several millimeters in diameter quite rapidly. Growing graupel would naturally be expected to be largest near the cloud top, although this expectation could fail in some special circumstances, depending upon the details of how and where the graupel enter the strong updraft and their size when they do so.

The depths of some of the first echoes are not so easy to rationalize (Figs. 3a, 10c, 12a–d). It is difficult to see how the ice process or any other process, operating in a one-dimensional conceptualization, could give this kind of result: precipitation appearing almost simultaneously over a depth of 3 km (15°C) or more. Dye et al. (1982) reported a similar broad height of first echo development in the storm they studied in great detail, and Miller et al. (1982) interpret it as evidence of complicated, three-dimensional growth trajectories. We also interpret this as evidence of extensive mixing of embryonic ice particles within these clouds, providing accretors to grow in the region with higher liquid water content wherever they are able to mix or fall into regions of strong updraft. Rapid mixing of precipitation throughout these clouds, once precipitation first forms, is consistent with the rapid spread of echo horizontally as well as vertically.
thoughout the visual cloud, and is plausible in view of the vigorous and complicated up- and downdraft structure often encountered in clouds of this type.

According to the modelled ice particle growth rates, it is within the realm of possibility that the first echoes that form within narrower altitude intervals might be the result of primary nucleation and particle growth within fairly vigorous updrafts. In the conditions assumed for Fig. 14, and at most temperatures from about −12 to −21°C, riming growth completely dominates vapor growth by 5 min after nucleation. At an updraft speed of 10 m s$^{-1}$, 5 min corresponds to a vertical extent of 3 km, which is not too much thicker than the layer in which the diffusional growth is conducive to this rapid onset of riming. The concentrations of ice particles needed to produce the 5 dB(Z) first echo in 300–400 s is 10–100 m$^{-3}$, consistent with a nucleation temperature of −8 to −10°C (Fig. 15), the lower (warm) side of the layer. Taking the 10 July case, for example, a first echo of 5 dB(Z) at −25°C is reasonably consistent with nucleation at about −10°C and growth in a single updraft averaging some 10 m s$^{-1}$.

It may not be worthwhile to carry the interpretive discussion much further, except to say a little about the rather great variability of the time of first echo as measured from the attainment of a certain cloud top temperature (−20°C has been used here for convenience). The quickest first echoes in these terms were the last two on 30 July, which started very close to previous echoes. It is tempting to speculate that this may have been due to early seeding from the nearby radar echoes, an effect that has been a common part of field lore for years. Observations of this phenomenon in eastern Montana were recorded recently by Hobbs et al. (1980). It is also interesting to note that the sounding on that day was exceptionally dry, with dew points below −30°C above about 550 mb (−10°C) so that penetrative downdrafts could also have been unusually vigorous. Furthermore, the cloud base temperature on 30 July was also unusually warm, compared to the other clouds in the present study, which is yet another potentially important difference. Correlations of this kind would be interesting, but cannot be pursued usefully with the limited data at hand.

Throughout this discussion we have assumed that the ice process, vapor growth of snow crystals followed by accretion of supercooled cloud droplets, is the way precipitation forms in the clouds of interest. The possibility that giant aerosols may contribute to or even dominate first echo formation has been ignored, though Johnson (1982) showed that it is a possibility. The existing field data cannot rule it out, because the instruments are not capable of detecting several-hundred-micrometer drops within cloud at concentrations of only a few per cubic meter or less. Vali et al. (1982) and Knight et al. (1982) summarize and discuss the NHRE data concerning giant aerosol particles and their potential role.

While the possibility of an important influence of giant aerosol particles on the first echoes cannot be ruled out, it does not greatly influence the discussion given above. The estimates of the times that the clouds allow for first echo formation have been the times from the tops attaining a certain temperature level to the first radar echoes themselves, and these times appear to be ample. If the actual first echoes represent some other, faster process like accretion on giant aerosols, then a better estimate of the time available for the simple ice process as modelled here to operate would be even longer. Giant aerosols at concentrations of a few per cubic meter are unlikely to be important in the formation of important amounts of precipitation unless they start a “Langmuir chain process,” which the field data show to be very unlikely (Knight et al., 1982). Likewise, the speculations about mixing do not seem to be seriously altered if this mechanism is important for some of the first echoes, though it does confuse the issue some.

7. Conclusions

Detailed comparisons of visual and early radar echo histories of vigorous convective turrets in northeast Colorado reveal that:

1) In the sample of 12 cases, the time from cloud top reaching −20°C to first radar echo at 5 dB(Z) varied from about 0 to 1 min.
2) The first 5 dB(Z) echo typically appears near or at visual cloud top, and spreads to fill the visible cloud in 5–10 min.
3) In accord with previous data in that region, the temperature at the center of the first echo is typically between −15 and −20°C.

There is a lot of variability in the vertical extent of the first echo and in the time of first echo formation measured with respect to the time at which the visual cloud top passes a given temperature level. This variability itself, as well as some of the data of specific cases, suggests that complicated processes are often involved in determining first echo height and vertical extent.

The data show that there is usually plenty of time for precipitation to form by the ice process, in terms of the length of time that cloud exists below any given temperature. In at least some cases, the data suggest rapid mixing of particles throughout the visual clouds, and that this mixing contributes to the first echo formation. The lateness of most of the natural first echo occurrences in these clouds should tend to make one optimistic rather than pessimistic about the possibility of modest enhancement of precipitation by very early seeding with ice nuclei or ice crystals. However, these data alone do not demonstrate such a possibility.
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