Case Studies on Convective Storms
Case Study 5

12 July 1978: First Echo Case

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This is one of a series of Technical Notes reporting data on aircraft penetrations in convective clouds, ranging from cumulus congestus to thunderstorms, in northeastern Colorado and adjacent portions of Wyoming and Nebraska. The June and July 1976 field season of the National Hail Research Experiment has been the setting of the first several of these Notes. This note concerns a case from the 1978 CSD field season. All of the cases involve aircraft data, including vertical velocity, state parameters and usually cloud physical data, obtained in coordination with detailed S-band radar scans, normally taken with about two-minute time resolution.

Some of these cases will be the subject matter of formal publications, in which case the Tech Note will supplement the publication by providing a more extensive presentation of data. Other cases will be presented only in the Tech Notes, but usually some portions of the data will be included in publications on general properties of convective clouds over the high plains.

These Tech Notes will always have the following components: a brief synoptic setting, a representative sounding, a brief, general radar reflectivity history, a more detailed radar history of the cloud or storm investigated with the aircraft tracks superimposed, a presentation of the aircraft data, and a discussion. The presentation will not be truly complete either as regards radar data or cloud droplet or precipitation particle size spectra, because these data are too voluminous. However, the general data, such as particle concentrations and liquid water content, will be presented along with some examples of the more complete data and remarks on typical aspects.

The data quality is in some cases difficult to assess. There is no absolute standard for many in-cloud measurements, even of temperature. Trust in the listed values for liquid water content and droplet sizes and concentrations must always be qualified to some degree. These Technical Notes will include remarks on data quality that record
the opinions of those closest to taking the data, and the reasons for
the opinions. Work on the data reliability will be continuing, however,
and because of this, some of these opinions may change. Any such
changes will be recorded in the Tech Note series, along with reference
to previous notes in which changes should be made.

This series of Tech Notes is intended to provide a lasting record
of cloud data in the high plains area that may be of use in unforesee-
able ways in future atmospheric studies. The data in the present Note
were gathered in a cooperative field program managed by the Convective
Storms Division of the National Center for Atmospheric Research, which
is funded by the National Science Foundation.

Charles A. Knight
December 1979
We thank the CSD operations staff at Grover (A. Heymsfield was operations director on July 12) and the NCAR Field Observing and Research Aviation Facilities for their support of the field operations. T. Cannon and C. Cullian are responsible for the aircraft time-lapse system. J. Fankhauser helped with the meteorological synopsis.
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ABSTRACT

A small, isolated, short-lived cumulus congestus was studied using primarily a 10 cm radar, a cloud penetration with an instrumented sailplane, and time-lapse photography from an aircraft some 40 km distant. The radar data reveal a conventional reflectivity history for the northeast Colorado region. The sailplane penetration shows updraft until the reflectivity maximum was reached, then downdraft, and that the precipitation formation was through the ice process primarily. The photography indicates that the cloud top attained -20°C nearly fifteen minutes before the first 5 dBZ echo, which occurred nearly simultaneously throughout a vertical zone from -10 to -30°C.
I. METEOROLOGICAL SYNOPSIS

Figure 1 shows the surface synoptic conditions at 1300 MDT, near the time of initial convection in the NHRE region. A Canadian high pressure system centered in northern Wyoming was pushing slightly cooler air toward the study area on weak north-northwesterly flow. The advance was led by a diffuse cold front that passed Grover at 1000. Lower pressure and maritime tropical air lay to the east and northeast, with moisture gradients indicated by the 10 and 15°C isodrosotherms. The streamlines show west-northwesterly surface winds bringing dry air in southern Wyoming across the NHRE area: the dew point temperature at Cheyenne dropped from 7°C at 1000 to -4°C at 1300. However, east-southeast winds prevailed over the mesonet near Grover until 1400, giving some low-level moisture inflow. This perturbation of the synoptic-scale flow was probably associated with the lee trough and may have caused convergence in the vicinity of the front. These mechanisms probably combined with strong and early surface heating (the temperature at Grover was 27°C at 1000) to initiate convection in the Grover area by 1300.

The 500 mb analysis at 0600 on the morning of 12 July (Fig. 2) shows a large-amplitude trough extending from central Canada to eastern Montana, bringing positive vorticity advection to the northern Great Plains (North Platte had a height fall of 40 gpm during the preceding 12 hours). The NHRE area experienced moderate cold air advection due to westerly winds throughout the day.

1 All times are MDT.
Fig. 1. Regional surface map for 1300 MDT on 12 July 1978 showing the synoptic conditions shortly before the initiation of convection in northeastern Colorado. The area of investigation is shaded. Temperature, dew points, and winds are plotted at each station. The dashed lines are isotherms of 10°C and 15°C, and the position of the dryline is indicated by the dot-dashed line. The general streamline pattern is shown by arrows.
Fig. 2. 500 mb map of the western U.S. for 0600 MDT on 12 July 1978 showing the early morning midlevel synoptic conditions. Solid lines are geopotential height contours (x 10 m) every 40 m; dashed lines are isotherms (°C) every 2°C and wind vectors are plotted around the NHRE airspace (shaded area).
The closest sounding in time and space to the first echo development was the 1252 release from Grover, which is plotted in Fig. 3 along with the $\theta_e$ profile in the upper left insert. A nearly dry adiabatic lapse rate exists up to the 4.4 km cloud base, with positive buoyancy extending to 11.8 km. Cloud base height was determined by the sailplane and by lidar measurements. These in turn determine the adiabatic $\theta_e$, within cloud, and the $\theta_e$ profile has been altered to give a $\theta_e$ of 343 K in the mixed layer. The dew point discontinuity on the sounding near the surface has not been altered, though it is a common occurrence of (presumably) instrumental origin. The very dry layer between 5.5 and 7 km was also evident in the Denver 0612 and the Grover 1700 soundings. This layer may have been an important factor in cloud development, since only the small "storm" described herein extended above it. Entrainment of this very dry air could help suppress convection, as could the thin layer with nearly neutral lapse rate at its top. Two mesonet stations near Grover indicate surface $\theta_e$ values of 344-345 K, though there is a possible error of ±5 K because of uncertainty in relative humidity. The highest $\theta_e$ measured from the sailplane, in the updrafts, was a comparatively low 340 K, suggesting substantial entrainment or that the data near Grover were not appropriate, since the storm was about 30 km east and 20 km north of Grover.

The cloud base height and 8 g km$^{-1}$ mixing ratio imply a considerable drying and deepening of the mixed layer between the time of the sounding and the development of the cloud some 2.5 hours later. However, photographs of the cloud (see below) show that the cloud base just beneath the active turrets was lower by 200-300 m (up to 500 at
Fig. 3. Thermodynamic diagram showing the vertical distribution of temperature and dew point from Grover 1252 sounding. Selected dry and moist adiabats and mixing ratio have been plotted as dashed lines and labeled. Winds are plotted every kilometer; full barb is 10 m s\(^{-1}\). Insert in the upper left shows \(\theta_e\) vs. pressure for this sounding, with the cloud base to surface \(\theta_e\) altered to correspond to a well-mixed boundary layer. Sailplane altitude range during cloud penetration is indicated by vertical arrow.
the maximum) than the general cloud base. The most active core presumably drew in part upon somewhat moister air, closer to the surface.
II. RADAR HISTORY

The cloud mass investigated on this day was unusual in that it pro-
duced the only significant reflectivities within the range of the radar. Not only was the echo isolated, but it was composed of just two distinct first echoes, which developed in close proximity to each other and eventually merged at low levels. The echoes contained several individual reflectivity maxima that were not discrete but could be identified and tracked from one scan to the next. These maxima will be called "cells", referring to reflectivity characteristics only, as distinct from the two discrete first echoes, which are called "Echo 1" and "Echo 2."

Figure 4 shows the overall radar reflectivity history of the storm, in RHI format. First Echo 1 first appears just after 1541, some 35 km northeast of the Grover radar at a height of about 7 km. Echo 1 expanded rapidly in the horizontal and vertical direction, became elongated in a northeast-southwest orientation, and attained a maximum at about 1552. Shortly after 1554 Echo 2 first appeared at about the 7.7 km level to the west of Echo 1. By 1558, Echo 1 had collapsed somewhat, forming a long southwest to northeast line at middle and lower levels, and the intensifying Echo 2 merged with its western end at those levels. The overall movement of the entire cloud mass (both echoes) between roughly the 6 and 8 km levels was about 6 m s$^{-1}$ to the east-northeast. After 1600 Echo 1 continued collapsing while Echo 2 intensified further (Fig. 4). After 1611 Echo 2 began to collapse and to spread horizontally.

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2 All radar data plots have the Grover radar at the origin of the coordinate system, except when otherwise noted, as in this case.
Fig. 4. Vertical sections and one CAPPI through the storm at 5 minute intervals, using 10 centimeter data from the Grover CP-2 radar, show the development of Echo 1 and Echo 2. The coordinate system is oriented approximately along the elongation of the storm, as shown in the one CAPPI at 8 km MSL, about 1800, and indicated in Fig 6d and e; dBZ<sub>e</sub> contours are at 4 dB intervals. 4 dBZ<sub>e</sub> is approximately the noise level at the range of the first echoes. The first three vertical sections are oriented through the maximum reflectivity of Echo 1, the last four through that of Echo 2. (Figure continued on next page.)
CAPPI $Z = 8$ km

ORIGIN RELATIVE TO GROVER

(37.0, 12.0)

155939-160053 SCAN

Km 325° FROM ORIGIN

155939-160053 SCAN

Km MSL

160440-160552 SCAN

(33.3, 16.2)

Km MSL

160936-161044 SCAN

(36.0, 16.5)

Km MSL

KILMETERS 55° (AZ) FROM ORIGIN

Figure 4 (continued)
Finally, both echoes collapsed to form a line at lower levels that was nearly 40 km long in the east-west direction. This line was still detectable with radar as late as 1720, but no further active convection occurred after Echo 2.

The reflectivity histories of Echoes 1 and 2 are given in Figs. 5a and 5b. Echo 1, which was penetrated by the sailplane, was first detected at about 1541. The echo grew rapidly in the vertical during its early stages, reaching peak reflectivities above 45 dBZ$_e$ between 1550 and 1551, at a height of about 6.3 km. It began a steady decay shortly afterwards, around 1556. Echo 2 was more vigorous, especially at higher levels, and longer-lived than Echo 1. It appeared about 1553 and developed reflectivity greater than 45 dBZ$_e$ just before 1608.

Echo 1, which had the greatest horizontal extent, contained several cells, each with a largest diameter of one to three kilometers. The cellular structure is best seen in the PPI's of Fig. 6. During the early growth stages of Echo 1, the major cells were in its northern half; but as it elongated in the east-west direction, existing cells moved toward its central axis while new cells made their appearance at the echo's west end. Echo 2 had an approximately circular reflectivity core (Fig. 4) and was primarily a single cell.

Cell motion was less systematic than that of the parent echo. However, the cells within Echo 1 generally moved from its west to east ends at about 12 m s$^{-1}$, about twice as fast as the echo itself. The propagation of the storm was thus westward (actually west-southwest) at

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3 All altitudes refer to mean sea level (MSL) unless otherwise stated.
Fig. 5. a) Time-height profile of maximum reflectivity for First Echo 1, which was penetrated by the sailplane. The contour intervals are 5 dB. The sailplane altitude within the echo is shown by the solid line; and its altitude within cloud, but not in the radar echo, is shown by x's. b) Time-height profile of maximum reflectivity factor for First Echo 2, with contour intervals the same as 4a.
about 6 m s\(^{-1}\). The cells finally became indistinguishable at the echo's eastern end.
III. SAILPLANE PENETRATION

The sailplane was towed to a height of 6 km and released into the side of what appeared to be an actively growing cumulus congestus at 1540. The sailplane searched for updraft within cloud, finding 5-10 m s\(^{-1}\) just after 1543 and spiralling upward 600 meters by 1551. Meanwhile the penetrated cloud produced the first radar echo of the day (First Echo 1) at 1541, at about 7 km. The echo spread rapidly, and the sailplane entered the reflectivity core of the echo shortly after 1551, finding slight downdrafts and moderate ice particle concentrations. The descent continued to 5.1 km, and the craft left the cloud just prior to 1558.

Figures 6a-f show segments of the sailplane track superimposed on pertinent PPI radar echo plots. These PPI's were selected so as to represent the reflectivity structure at the time and altitude of penetration: indeed, all but two of these scans show the radar "skin paint" of the sailplane. Seven different verifications of skin paint during the penetration period enabled a mean correction of FAA positions (0.75 km to the east-southeast) to be applied. The track was also corrected for an average cell motion of 12 m s\(^{-1}\) to the northeast. The resulting tracks plotted in Fig. 6 are accurate to within 1 km of actual position, with respect to the cells.

The sailplane began its upward spiral at about 1543, on the northwest side of Echo 1 (Figs. 6b,c). Eventually it traversed the region of strongest reflectivity gradients, reaching some of the most intense (35-40 dBZ\(_e\)) cells near the top of its spiral, after 1551 (Fig. 6d).
Fig. 6a-f. Segments of sailplane tracks are plotted on the most appropriate radar PPI, showing the history of the sailplane penetration with respect to the radar echo. Times (minutes after 1500 MDT) are shown either on the magnified tracks in the insets or on the figures. Constant altitude arcs on the PPI surfaces are labeled in kilometers. The altitude range of each track segment is indicated. The sailplane first entered cloud at 1540, two kilometers due south of its 1541 position. These tracks are taken directly from data recorded by the FAA, using a system not suitable for very tight maneuvers. The most erratic of the wiggles are certainly not real, and the spirals are much smoother than shown. All echo shown in this figure is part of Echo 1. (Figure continued on next two pages.)
Figure 6 (continued)
Figure 6 (continued)
This is also shown by Fig. 5a, in which the sailplane's altitude with
time is superimposed on the cloud's time-height profile of maximum reflectivity. The sailplane continued its flight through the echo's cellular area (Fig. 6e), in weak but steady downdraft, until 1554:30; it then recrossed the tight echo gradient to exit the echo just before 1555. It finally descended on a path paralleling the echo's northwest edge until it came out of cloud at about 1557:30 (Fig. 6f).

Two cells were traversed by the sailplane. These are identified in Figs. 6c and 6d as A and B. Cell A was traversed from about 1551:30 to 1552:30 and B from about 1553:30 to 1554:30. The cells and the sailplane's descent through them are also displayed in vertical cross-sectional format in Fig. 7. The location of these cross sections are drawn on the PPI's of Figs. 6d and 6e. From these PPI's one can see that the sailplane deviates 1 to 2 km to either side of the plane of the vertical section. Each echo maximum is entirely aloft at the times of the sailplane penetration and of the cross section.

The time-height profiles of Cells A and B are given in Fig. 8. Each profile includes a plot of the sailplane's descent within the cell. All contours of Cell A began a gradual descent at 1551, signaling the onset of the steady downdrafts experienced by the sailplane as it traveled through the cell core at greater than 40 dBZ_e. The FSSP droplet counts and both LWC traces fell to near-zero levels upon entering cell A, about 1551:40. This coincided with a downdraft maximum of about 10 m s\(^{-1}\). Ice particle concentration (Fig. 9) increased from 8 \(Z^{-1}\) to 66 \(Z^{-1}\) across A, with rimed crystals (a few were identifiable as dendrites) the dominant particle form. Aggregates and graupel were
Fig. 7. The radar echo structure of Cells A and B are shown in vertical sections with the sailplane track segments at the times of the PPI's also shown. Cells A and B are labeled, and the contours are at 4 dBZ intervals from 4 dBZ₀.
Fig. 8. Time-height profile of maximum reflectivity from Cells A and B on 12 July 1978. Contours are at 5 dB intervals from 5 dBZ, and dashed lines indicate locations where reflectivity was below the 4 dBZ threshold of the radar. The heavy solid line is the sailplane's altitude as it traveled through each cell.
Fig. 9. Sailplane data from 1540 to 1600 showing (from top to bottom) altitude, temperature, vertical airspeed, liquid water content, and droplet concentration and mean diameter. The solid altitude line is from the Hamilton Standard device and the dashed one is derived from the variometer. The solid temperature line is from the reverse flow probe, and the dashed one is from an exposed "window" probe. The solid liquid water content (LWC) line is from the J-W probe, and the dashed one is from integrated cloud droplet spectra from the FSSP probe. On the lowest plot the solid line is total droplet concentration with scale on the left axis, and the dashed one is the mean diameter with the scale on the right axis. The prominent spikes in this trace from 1552-1554 are characteristic artifacts always found when high concentrations of ice crystals are present. Times of ice particle image detection are shown above the LWC plot by dots (single events) and lines (continuous events). Line thickness indicates particle concentrations according to the legend beneath the 1550-1600 plot, and the letters indicating particle character are also explained in the legend. Each large black dot just above the droplet plot represents one liquid water drop detected on the particle camera film. (Figure continued on next page.)
Figure 9 (continued)
also numerous. The reflectivity history of Cell B was similar to that of A except that it was less intense (35-40 dBZ, 10-30 ice crystals \( k^{-1} \), 5 m s\(^{-1} \) downdraft maximum). Particle forms were again rimed crystals, aggregates, and graupel. FSSP liquid water contents, however, were somewhat higher than those in A, reaching peak levels of 0.4 g m\(^{-3} \). By 1554:30 the sailplane had exited Cell B. It descended out of echo by 1555, and out of cloud by 1558.

The data gathered by the sailplane within cloud are presented in Fig. 9. The parameters are altitude, temperature, vertical speed, J-W liquid water content (LWC), LWC determined by integrating the droplet spectrum, the droplet concentration and mean droplet diameter, plus indications of particle images from the cloud particle camera (CPC). General characteristics of note are the low LWC (values were generally less than 1 g m\(^{-3} \) throughout the penetration) and the maxima of ice particle concentration within the major cells (compare with Fig. 6e). Also interesting are several supercooled water drops of precipitation size detected by the cloud particle camera. Most of these were found in the mild downdrafts, within cloud but outside the radar echo, and all but one had a 0.2 mm diameter, the lower size detection limit.

The variations in the J-W and FSSP liquid water content traces agree favorably with each other, and they correspond with vertical speed and \( \theta_e \) fluctuations (the latter not shown) as well. However, the J-W hot-wire device evidently was experiencing reduced sensitivity on this day and measured absolute values of LWC that appear to be too low. The LWC derived by integrating the cloud droplet data from the FSSP probe was also low when compared to adiabatic LWC values for flight
levels. The peak FSSP LWC was 1.4 g m$^{-3}$ (in steady updraft around 1554) while adiabatic values remained about 2.2 g m$^{-3}$ for most of the updraft region. However, as noted before, $\theta_e$ values within the cloud were also less than adiabatic; evaporation due to entrainment could have depleted liquid water to the levels derived by the FSSP. The $\theta_e$ values from 1543:30 to 1545:30 varied mostly between 338 and 340°K, but were more often between 335 and 337, or lower, during the rest of the penetration. Both LWC curves were highest in the updraft of 1543-1550. At the same time, ice particle concentrations were at their lowest (0-1 ℓ$^{-1}$). This situation was reversed in the cell downdrafts (around 1552), when ice particles reached a maximum concentration of 66 ℓ$^{-1}$ and the LWC hovered near zero.
IV. TIME-LAPSE PHOTOGRAPHY

The main purpose of the 1978 field season was to obtain detailed visual records of convective clouds, particularly in their first echo stages and before, in coordination with radar and direct aircraft measurements of the cloud microphysical properties. For this purpose, two 16 mm cameras were mounted in NCAR Queen Air 304D, facing to opposite sides at approximately the location of the rear door. The aircraft was flown for the sole purpose of obtaining the quantitative visual record; seeking a location from which the area of convective activity would be visible and flying a zigzag course in that area so that alternate cameras recorded the clouds with about one minute gaps in coverage during the turns. Time was recorded on each frame to 0.1 second with an LED display and the ultimate purpose is to use the pitch, yaw and roll angles from the inertial navigation system (INS) to derive quantitative data of cloud top heights from the photos.

Detailed evaluation of this method and of the accuracies attainable thereby is underway, and both the method and the results obtained from the 1978 data with it will be reported separately. For the purpose of this Tech Note, however, we report here the results from a cruder analysis of the photos, because the conclusions are important. More precise subsequent analysis will very probably supplant the present study only in detail.

The "storm" of July 12, 1978 was visible from the south, and the aircraft flew at about 3.5 km MSL at a range of 30 to 40 km from the storm while the photographs were taken. Figure 10 is a schematic of
Fig. 10. The track of the photography aircraft is plotted along with the 4 dBZe contour of radar echo from a series of scans with 8.8° elevation angle. The 7.5 and 10 km MSL altitudes on this PPI are shown. The first three times reveal Echo 1 only, and are cross-hatched. The last two reveal Echo 2 and left empty; the first of these is the dashed contour, the last a solid line, as indicated.
the flight path, to show its relation to the echo. As examples of the appearance of the storm, Fig. 11 gives three views, the first showing the Echo 1 turret about five minutes before first echo, and the last showing the Echo 2 turret about five minutes after first echo. Note the lowered cloud base beneath the Echo 1 turret, also mentioned in Section I. We use as height reference the general cloud base level (not the lowered part) which is usually quite well-defined because the aircraft is approximately at that altitude, and take it to be 4.4 km MSL as determined by the sailplane and lidar measurements. Range is given by the aircraft location and the echo location, and cloud top heights are then simply determined using the focal length of the lens, 10.4 mm. For Echo 1, the cloud location before the echo appeared was extrapolated from the first echo location and motion.

The pre-echo visual history of Echo 2 is obscure in the present analysis because a distinctive turret is not apparent in the photos (see Fig. 11b). Later detailed analysis may reveal some useful data. Echo 1, however, is visible for nearly fifteen minutes before first echo, and Fig. 12 gives the top height results for that period. It seem remarkable that the cloud top reached -20°C nearly 15 minutes before the first 5 dBZ radar echo, and that that echo then appeared nearly simultaneously over the range of -10 to -30°C.

Considering the range error to be at most ±2 km and the error in measuring the cloud base to cloud top distance to be ±5%, the error in cloud top height is at most approximately ±0.5 km. Since the maximum visual heights measured in this way are about 0.5 km lower than the maximum radar tops for both Echoes 1 and 2, it seems that the visual tops are
Fig. 11. Photos of the storm from NCAR 304D, from the south at a range of approximately 35 km. a) was taken at 1536:48, b) at 1551:16, and c) at 1559:31. a) shows the turret that led to First Echo 1 (arrow), five minutes after the photo; c) shows the Echo 2 turret (arrow) with pilaeus upstream; and b) shows the general cloud mass. (Figure continued on next page.)
Figure 11 (continued)
Fig. 12. The visual cloud top height previous to First Echo 1 is shown with the 5 dBZ contour of the echo from Fig. 4 and a temperature scale along with the height scale.
probably correct within better than ±0.5 km, since a 1° radar beam at the range of this storm will overestimate top heights by almost 0.5 km by detecting echo only in the lower portion of the beam. It appears therefore that the visual tops deduced by this crude technique are either "about right" or low by a "few hundred" meters.
V. OTHER MEASUREMENTS

Lidar depolarization measurements were made in the general vicinity of this cloud, and may reveal some general features of the glaciation. These measurements will be published elsewhere if they prove interesting, as will a more comprehensive and detailed time-lapse analysis and comparison with radar data.
VI. SUMMARY AND CONCLUSIONS

The relatively weak potential instability of the atmosphere on July 12, 1978, in the vicinity of Grover, Colorado, led to significant convective activity at only one location, for a period of only about thirty minutes. Presumably this was due to surface convergence at that location, though surface data were not adequate to describe it.

Two discrete first radar echo occurrences, with a threshold of 5 dBZ$_e$, were documented in detail with the 10 cm radar. The first one, which was the first detectable radar reflectivity of the whole region that day, was also the object of a penetration by the NCAR/NOAA sail-plane and of time-lapse photography from an NCAR Queen Air. While a few small supercooled water drops about 200 µm in diameter were detected about 1 km away from the first echo at the time of its formation, the cloud particle photographs taken within the radar echo later on as it grew to 45 dBZ$_e$ show the usual total dominance of rimed snow crystals, aggregates and graupel.

The time-lapse photography shows that the top of the convective turret that produced the first echo had attained $-20^\circ$C, at which temperature the ice nucleus content is ordinarily of the order of one per liter, nearly 15 minutes before first echo formation. Since the first echo occurred nearly simultaneously throughout the layer from $-10$ to $-30^\circ$C, a plausible concept of the precipitation formation is that ice crystals, mostly formed near cloud top five to ten and more minutes before first echo formation, mixed throughout the cloud and grew by accretion to produce the echo throughout the 4 km layer nearly
simultaneously. This concept, if verified by further studies, would have implications for weather modification.

The two first echoes and their subsequent history described correspond well to the cell evolution concept first given in *The Thunderstorm* (Byers and Braham, 1949). Evidently the radar reflectivity increased until the updraft ceased, as indicated both by the sailplane measurements and the reflectivity history. It seems that precipitation growth was therefore in all probability limited by the duration of the updraft. The surprisingly long time before echo appearance with the top temperature below \(-20^\circ\mathrm{C}\) and with active updrafts as judged from its visual appearance makes this sort of cloud an interesting prospect for precipitation enhancement by seeding with ice nuclei very early in its life.

The 27 July 1976 case study (Breed, 1979) is quite similar to this one in some ways.
APPENDIX A

GROVER RADAR SPECIFICATIONS

The radar reflectivity data presented in the text were obtained by the Grover S-band radar (CP-2) during the 1978 field season. The specifications of the radar set are given in the table below.

<table>
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<td>Vertical beamwidth (deg.) ........ 0.94</td>
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<td>Gain (dB) ................................ 44.2</td>
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<td>PRF (s⁻¹) ................................. 900.9</td>
</tr>
<tr>
<td>Pulse duration (μs) ....................... 1.0</td>
</tr>
<tr>
<td><strong>Receiver (logarithmic)</strong></td>
</tr>
<tr>
<td>Minimum detectable signal (dBm) .. -107.4</td>
</tr>
</tbody>
</table>

In calculating $Z_e$ (effective reflectivity) from the radar equation for meteorological targets, $|K|^2$ was set equal to 0.93, which is the value for water targets. ($|K|^2$ is related to the complex index of refraction of the target.) The CP-2 radar has an unambiguous range of 166 km.

Methods used for calibration of the radar and more detailed information about the radar are described in Foote *et al.* (1976) and Eccles (1975).
APPENDIX B

SAILPLANE INSTRUMENTATION

The meteorological parameters of interest measured or calculated from measurements by the NCAR/NOAA sailplane are pressure altitude, vertical airspeed, temperature, liquid water content, cloud droplet spectrum and precipitation particle concentration and type. Data are sampled every second and recorded on magnetic tape at a ground station via FM telemetry from the sailplane. True airspeed is generally about 40 m s\(^{-1}\) and bank angle in the spiral flight mode is roughly 15 to 30°.

Pressure Altitude

A Hamilton Standard pressure transducer is used to measure pressure, which is then reduced to altitude using a nearby sounding. Accuracy is about ±10 m. The resolution, which is important in the calculation of vertical airspeed, is 0.5 m. Electronic noise occasionally interrupts a timing circuit directly involved in the measure of pressure. When this happens, the altitude always deviates to lower values, and these temporary drops are quite apparent on the altitude plot of the sailplane data.

A variometer is also used to determine pressure altitude by summing rates of change with time and adding the resultant height to the initial altitude of the sailplane. Although the response time of this instrument is slower than that of the Hamilton Standard device, agreement between the two is usually very good. Errors, brought about by sharp gradients of updrafts or downdrafts or other flight phenomena
that are not adequately measured by the variometer, are cumulative, with the result that the altitude measured in this way can drift to 500 m in 10 min.

Vertical Airspeed

The equation for calculating vertical airspeed (see Dye and Toutenhoofd, 1973) is:

\[ w = \frac{dz}{dt} + \frac{|\vec{v}| D}{mg} + \frac{1}{2g} \frac{d}{dt} \left( |\vec{v}|^2 \right) \]

where \( w \) is the vertical airspeed, \( t \) the time, \( \vec{v} \) the sailplane velocity, \( D \) the drag force on the sailplane, \( m \) the mass of the sailplane and \( g \) the acceleration due to gravity. Assumptions include hydrostatic equilibrium of the atmosphere, no side slip of the sailplane and no abrupt flight maneuvers. Also, vertical speed induced by horizontal wind changes is ignored. In other words, it is assumed that the horizontal wind is steady, or that over a few seconds, small-scale fluctuations average out to zero. Uncertainty from this calculation when the sailplane is spiralling in clouds is about 2 m s\(^{-1}\). The most important variables are rate of change of altitude and true airspeed. Minor variables are temperature, pressure, bank angle, angle of attack, and indicated airspeed which are used to derive the true airspeed and the sailplane's drag force. Significant errors in vertical airspeed are caused by errors in the major input parameters. True airspeed can be lost altogether due to icing of the pitot tube, or false altitude changes can be caused by the deviations in the Hamilton Standard-derived altitude mentioned above. Vertical airspeed can be calculated
using the Hamilton Standard-derived $dz/dt$ or using the $dz/dt$ determined directly by the variometer. Usually the vertical airspeed plots derived by the two methods are nearly identical.

Temperature

Air temperature is measured by a reverse flow temperature probe, designed for the slow flight speeds of the sailplane. Discussion of the calibration and intercomparison of this probe with other sources is presented in Heymsfield et al. (1978). Wetting of the sensing diode when in cloud does not appear to occur with the sailplane probe, and the stated accuracy of ±0.5°C appears to be correct. Another source of air temperature data is collected by a "window" probe, and is usually plotted with the reverse flow temperature. The "window" probe is an identical sensing diode exposed to the airstream in a vent located in the nose of the sailplane. The accuracy of the diode is also ±0.5°C but it inherently becomes wetted or iced during cloud penetrations.

There is one significant problem with the temperature data. When the communications radio is transmitting, RF noise influences the voltage drop across the diode, thereby causing increased temperature readings. This noise is evident in other (minor) data channels as well as in the sharp changes in the temperature plot, and is easily identified. It has not been edited out of the data plots presented in the text.

Liquid Water Content

A Johnson-Williams hot-wire device is used for measuring liquid water content (LWC). Calibration and comparison discussions are presented in Heymsfield et al. (1978). Best estimates suggest an accuracy
within ±20%. However, when the sailplane encounters high liquid water contents in supercooled conditions for extended periods, the probe's strut accumulates enough ice apparently to interfere with the flow to the sensor. This is usually identifiable by the "spikey" appearance of the J-W LWC trace, which has also become uncorrelated with the vertical airspeed trace. This condition occurs only when the high liquid water conditions have existed for roughly 10-15 minutes.

The FSSP (described below) integrated cloud droplet spectrum also provides a measure of LWC, and is plotted with the J-W output.

Cloud Droplet Spectrum

A Particle Measuring Systems (PMS) Forward Scattering Spectrometer Probe (FSSP), mounted on the sailplane, measures cloud droplet spectra. This probe, reported in various articles (for example see Knollenberg, 1976), sizes particles 2-30 μm in diameter with a suggested error of ±10% or ±2 μm, whichever is greater. Concentration accuracy had not been determined, and comparison with the J-W LWC, vertical airspeed, and different flight conditions suggested that the FSSP on the sailplane was measuring concentrations lower than would be expected.

Investigation of the probe's electronic design by personnel at the University of Wyoming revealed that coincidence errors, coupled with a retriggerable electronic delay (which allows time for the electronics to size and count pulses), results in a greatly reduced measured droplet concentration in comparison to the true concentration. Assuming that the time between individual droplets can be described by a Poisson distribution, Dr. W. A. Cooper of the University of Wyoming has shown
that the equation

\[ N_m = N_0 \exp \left( -uA\tau N_0 \right) \]

can be used to determine the measured concentration \( N_m \) from the true concentration \( N_0 \), where \( u \) is the true airspeed, \( A \) the total sampling area, and \( \tau \) the delay time. For the sailplane FSSP and the range of droplet concentrations found in northeastern Colorado, \( N_m \) is a monotonic function of \( N_0 \). Therefore the FSSP concentration data presented in the text have not been corrected for this error, and are lower limits.

Ice particles passing through the sample area apparently give multiple, specular reflections which are measured by the FSSP as individual particles. In regions where considerable ice particles are present, this artifact is most noticeable as a spectrum tail in the larger channels and invalidates any measurements in the largest 7 or 8 channels as well as the calculated droplet dispersion. The counts in these regions should not be used as a measure of the ice particle concentration, since one ice particle apparently gives rise to more than one apparent droplet count.

An added problem with the FSSP data arises due to icing of the probe. After only a few minutes of in-cloud sampling, icing of the FSSP causes noticeable degradation of the data. Wind tunnel tests suggest that icing primarily causes a shift of the spectrum to smaller sizes, but examination of field data also shows a definite decrease of concentration with time. Apparently, the erroneous measurements are caused
by wetting or icing of the prism and mirror, and also by the accumulation of ice on the front of the sampling tube. No attempt has been made to correct the data for these problems, due to the variable results found in the wind tunnel tests. Therefore, even when the concentrations have been corrected for coincidence errors, the FSSP data are definitely not trustworthy beyond a few minutes into a cloud penetration, and the reliability might be questionable even in the first few minutes.

Cloud Particle Camera (CPC)

Cloud particle concentrations, sizes and types are measured by the Cannon cloud particle camera which photographs atmospheric particles in situ (Cannon, 1974). The size range measured by the sailplane CPC is 16 μm to 48 mm diameter, and the sampling volume increases with the particle size. For photographic images ≥ 170 μm diameter, water droplets can be distinguished from ice particles by the two-dot method (i.e. refracted images from the two flashlamps by the water drop). The camera has a film capacity of 3200 frames, which is equal to 27 minutes of exposure time at the maximum rate of 2 frames per second.

About the only flight-related difficulty encountered with the CPC occurs when the airspeed is incorrect. This affects the synchronization of the rotating mirror with the speed of the sailplane, which is necessary to allow stop-action photography of the particles passing through the sampling volume. An incorrect airspeed will blur the images on the film, while the loss of airspeed, as may be caused by icing of the pitot tube, will cause blank frames on the film since the rotating mirror and the flashlamps will have ceased to operate. This problem is easily detected in examination of the film along with the true airspeed data trace.
REFERENCES


