The Mechanism of Precipitation Formation in Northeastern Colorado Cumulus III. Coordinated Microphysical and Radar Observations and Summary

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ABSTRACT

Much of the previous work which has led to the conclusion that coalescence is the dominant precipitation forming mechanism in cumulus clouds is reviewed. Observations in northeastern Colorado from several independent methods of investigation are summarized to show that in northeastern Colorado the ice (Bergeron-Findeisen) process is in all probability the dominant mechanism in spring and summer cumuli in their early and intermediate stages of development.

Results of microphysical observations coordinated with simultaneous radar observations are presented. The microphysical observations in clouds with observed effective reflectivities of up to 40 dBZ show that the observed reflectivities can be accounted for by measured ice particle sizes and concentrations. Liquid precipitation elements are not necessary and have been observed only rarely in these clouds except below the melting level.

Possible explanations of the differences between clouds in northeastern Colorado and those in other areas are discussed. The rarity of liquid precipitation particles coupled with the general inefficiency of the ice process at temperatures warmer than −10C suggests that there is potential for rainfall enhancement in the clouds in northeastern Colorado.

1. Introduction

The origin of precipitation in clouds has been a topic of scientific concern for a long time. As early as 1904 Bentley suggested that most precipitation originated from melting ice particles. The first satisfactory quantitative explanation for precipitation formation in clouds was put forward by Bergeron (1933). After examining several possible mechanisms he concluded that the only one that could occur in a reasonable amount of time was that postulated by Wegener (1911). Ice crystals form in the cloud, grow by diffusion at the expense of the supercooled droplets, and melt as they fall to the ground. Strong support for this conclusion was provided by Findeisen (1938) from his observations in clouds over Germany. For more than a decade thereafter most cloud physicists considered the ice phase process to be the only process acting even in the tropics.

Gradually, scattered observations in the tropics showed that rain did fall from clouds totally warmer than freezing, so that another process must be acting. The work of Langmuir (1948), Houghton (1950), Bowen (1950) and Ludlam (1951) brought to light the importance of the coalescence mechanism. Bowen and Ludlam showed that a few unusually large droplets at cloud base could grow to precipitation size drops by colliding and coalescing with other droplets.

The observations in Ohio in 1947 in Project Thunderstorm were some of the first to show that coalescence was acting in mid-latitudes (Byers and Braham, 1949). Using radar data from Project Thunderstorm, Battan (1953) showed that 60% of radar first echoes in Ohio were totally below the melting level. Thus, the coalescence mechanism was clearly dominant in these clouds. Additional radar as well as observational evidence from aircraft flying through convective clouds in the central United States gave support to this conclusion (Battan and Braham, 1956). If there were any doubts concerning the dominant precipitation mechanism in the central United States, they were firmly eliminated by the observations during Project Whitetop in Missouri. Microphysical observations from aircraft showed that near-millimeter-sized drops formed in the clouds before any ice was detected. Then when ice did form in the clouds, the larger drops that had formed by coalescence were the first to freeze (Koenig, 1963; Braham, 1964). The radar observations showed that 50% of all first echoes (2700 cases) were wholly warmer than 0C, 40% straddled the melting level, and only 10% were colder than 0C (Braham *et al.*, 1964). Similarly, Mossop *et al.* (1970, 1972) concluded from studies in

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Australia that the formation of precipitation in cumulus clouds there was proceeding in the same way as in Missouri.

In the arid southwestern United States where cloud bases are high, early studies in New Mexico indicated that the ice phase could not be ruled out (Workman and Reynolds, 1949; Braham *et al.*, 1951). In later observations near Tucson, Ariz., by Braham (1958) and Ackerman (1960), first echoes were observed to form over a wide range of temperatures with no sharp dependence on temperature. However, on some days high, cold first echoes were observed. They concluded that the mechanism for producing precipitation was not closely tied to temperature, but did not speculate on the details of the mechanism. Battan (1963) inferred that coalescence was the dominant mechanism even in Arizona. When he examined the average of at least ten echoes on 35 different days he found a weak but statistically significant correlation between cloud base and the altitude of the first echo. Also, as the altitude of the cloud base increased, the separation between cloud base and the midpoint of the first echo increased. This was argued to imply a coalescence process and not the ice process. Additional evidence that the coalescence mechanism was acting in Arizona was reported by MacCready and Takeuchi (1968). At or slightly below cloud base they observed large droplets (25–50 μm diameter) which grew to drizzle size drops in cumulus clouds 3–4 km deep.

These studies along with several others seem to have persuaded most cloud physicists that coalescence is the dominant process in the formation of precipitation in cumuliform clouds in mid-latitudes. When the ice phase does act, it starts from drops that already have grown to precipitation or drizzle size through coalescence. Braham (1964) reports impressive circumstantial evidence that the freezing of these drops does enhance precipitation, probably by affecting collection efficiencies. It is the purpose of this series of papers to report observations which show that the ice phase is the dominant mechanism of precipitation development in cumulus clouds in their early and intermediate stages of development over northeastern Colorado. There is probably a stage of diffusional growth of ice from the vapor in the development of precipitation. Although some of the individual observations are not conclusive in themselves, several different and independent kinds of observations all point to the same conclusion. The total strength of the combined argument is stronger than the individual parts would be by themselves. In many of the previous studies, direct microphysical measurements were not made and the arguments were based primarily on radar data. In the present study detailed measurements from a sailplane as well as radar observations have been used and in several cases in close coordination.

This work has been done partly in cooperation with, and partly as an integral part of, the National Hail Research Experiment. The observations made from *The Explorer* sailplane including *in situ* cloud particle photographs of both water and ice, and measurements of droplet concentration from the electrostatic disdrometer are reported by Cannon *et al.* in Part II. The observations of the ice particles collected on board the sailplane and brought back to the ground for analysis and of hail collected on the ground are reported by Knight *et al.* in Part I. This paper reports the results of coordinated sailplane flights with radar tracking and surveillance and a preliminary study of first echoes from summer convective clouds in northeastern Colorado.

2. Radar observations

During the summer of 1973 an X-band transponder was added to the instruments already used on the sailplane (Sartor, 1972) so that the sailplane position could be determined. Tracking of the sailplane was performed by personnel working with the tracking portion of the M-33 radar operated by the Desert Research Institute, University of Nevada. Comparison of the tracking data with positions determined by fixed landmarks observed from the sailplane indicated that the accuracy of the horizontal positions obtained from the radar was approximately ±500 m.

In order to determine the origin of first echoes in northeastern Colorado, as well as for reasons of safety, the Grover radar often was used to scan the clouds in which the sailplane was flying. The radar[2] is a 10-cm unit operated jointly by personnel from the NHRE staff and NCAR's Field Observing Facility. The minimum reflectivity that could be observed was about 27.5 dBZ independent of range because of the use of a sensitivity time control (STC) circuit.

a. Sailplane-radar coordination

On eight days during the 1973 field season real-time viewing of the radar indicated that the sailplane was flown in clouds which had an echo at the time the sailplane was in the cloud or nearby in time and space. For these cases there were simultaneous reports from the sailplane of precipitation particles. Observations from only the five best days will be reported here. Recorded pilot and observer comments, photographs from the particle camera, and collected ice particle samples were used to document the type of precipitation and, where possible, to determine the size and concentration. Examples of camera photographs and photographs of collected particles are shown in Parts II and I, respectively. On these five days there were six clouds for

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[2] Radar characteristics: wavelength 10.7 cm, peak power output 500 kW, pulse duration 1.2 μsec, pulse repetition frequency 937.5 and 1071.4 pps, 1° pencil beam, and maximum unambiguous range 120 km.

TABLE 1. Summary of observations from sailplane in a radar echo.

Date	Approximate time in echo >27.5 dBZ (MDT)	Altitude (km)	Reflectivity at S/P (dBZ)	Particle camera Operating	Particle camera Comments	Ice collections Time (MDT)	Ice collections Comments	Remarks
9 July	1354–1355:30	6	27–28		reloading	1355:04–1355:55 (out of cloud)	lots of 1–1.5 and 2–2.5 mm graupel	Echo above and to the south of the sailplane lowers as the sailplane spirals in the updraft; enters the 27.5 dBZ echo leaving the cloud; pilot reports graupel periodically while spiralling and increases beginning 1353.
9 July	1404–1405	4.8	<27.5	1403:15–1405	57 ice photos	1403:05–(enter cloud) 1404:50	lots of 1–2 mm graupel	Re-enters part of above cloud; cloud looks glaciated; finds weak downdraft.
12 July	1637:30 on edge of echo		$\sim$30	1637–1641	no ice photos		four samples taken but all melted	Pilot reports gradual increase in graupel intensity.
12 July	1729:30–1731:30	5.7–6.0	27.5–30		reloading		bottles all used previously	Pilot reports overhang on east side of cloud before entry; reports ice particles from 1721, graupel 1726, bigger graupel 172850, and gradual increase in intensity during the climb.
23 July	1928	4.3	<28		reloading 1927–1931	1920–1924 1925–1926 1926–1929 1929–1931	messy rime messy rime 1–1.5 mm dense graupel dense graupel	Pilot reports small drizzle drops that change to graupel as go through 0C; intensity of precipitation increases from base $\sim$3.5 km to 5 km; weak updraft; reports graupel almost continuously after 1925.
	1941–1942	4.8	28–35	1941–1942	56 ice photos		bottles all used	
	1945–1946	4.6	28–32	1945–1946	43 ice photos			
28 July	1531–1532	5.8–6.3	27.5–30	1527–1531:50	no ice photos	1530:30–1533	nothing	As sailplane climbs echo lowers; track shows sailplane in and out of echo for two spirals; pilot reports light graupel corresponding to times when sailplane in echo; cloud top looks glaciated after exit.
29 July	1741–1742:30	4.6–4.5	30–42		malfunction	1741–1742	4–5 mm graupel	Sailplane climbs from 3.2 to 4.6 km in updraft, encounters large graupel falling from the anvil while and after leaving the cloud.

which precipitation particles were encountered in conjunction with a radar echo. The clouds on 9, 12, 23 and 28 July can be classed as small cumulonimbus or very large cumulus congestus. The cloud on 29 July was investigated by the sailplane in the cumulus congestus and early cumulonimbus stages as it developed into a mature storm which produced hail on the ground. The observations for these six clouds are summarized in Table 1. On some of the days, camera or collector data are missing because of the operational difficulty of doing both simultaneously. But in each case there is sufficient information to be certain about the type of precipitation particle present.

For the cases of 9, 23 and 29 July it was possible to calculate the expected effective radar reflectivity from the particle camera photographs and/or ice particle collector information. The effective reflectivity Z_{ew} of spherical water drops is given by

$$Z_{ew}=\sum_i n_i D_i^6,$$

where n_i is the concentration per cubic meter of particles in size interval i, and D_i is the diameter (mm) of the particle. For ice particles the backscattering coefficient $|K^2|$ is $\sim$4.7 times less than for water. Also, the backscattering is proportional to the mass of the particle so that the measured diameter must be corrected by the density of the particle. Incorporating these changes the effective reflectivity for ice particles of diameter D_i

and density ρ_i is approximately given by

$$Z_{ei} \approx \frac{1}{4.7} \sum_i n_i D_i^6 \rho_i^2.$$

The calculated values using this equation and observed concentrations and sizes are compared to the observed reflectivities in Table 2. The range (in parentheses) for the camera is due to the statistical uncertainty in concentration arising from the limited number of particles photographed by the camera. The upper and lower limits of reflectivity were calculated using concentrations at the 95% confidence level in each class interval of 0.2 mm diameter (Cornford, 1967).

For the ice particle collections the size and number of particles determined from the photographs were used to calculate the reflectivity. Since we did not anticipate using the collections in this manner photographs were not taken of all of the collected particles. The calculated value is shown in Table 2 as the minimum. Other errors, such as the decrease of the aperture of the collection tube due to riming, and the uncertainty in the actual amount of time ice particles are being collected while the bottle is on, all lead to values of reflectivity that are too low. Reasonable assumptions for these uncertainties showed that the value could be as much as 10 dBZ too low. These values, indicated in the upper limits shown in Table 2, should be considered very approximate. For the sample on 29 July the particles were large enough and the number of photographs was sufficient to calculate a reasonable value along with confidence levels as was done with the camera data.

The most complete case was on 23 July. A plot of sailplane altitude, altitude of the top and bottom of the echo, times of particle collections, and cloud particle camera photographs and pilot-observer comments are shown in Fig. 1. The track of the sailplane from 1934 to 1947 (all times MDT) is superimposed on reflectivity contours at the altitude of the sailplane in Fig. 2. Although a comparison of the sailplane position with the reflectivity contour is valid only for 1942:14, the sailplane was in this echo most of the time from about 1935 to about 1943. The echo started above the sailplane and as the echo fell the sailplane climbed up into the echo. This pattern was also true for 9 and 28 July. In these three cases, the sailplane was investigating the echo within about 6 min of their formation. For 12 July the echo first appeared about 20 min before the sailplane penetration. The sailplane was investigating an adjacent cloud in which graupel was encountered. On 29 July the echo appeared at least 45 min before the sailplane penetration. However, the sailplane had been flying in and exploring this same cloud system even prior to the formation of the first echo and had encountered graupel sporadically during a previous penetration from 1702 to 1718. It is interesting to note that most of the echo which was penetrated from about 1740:45 to 1742:30 on 29 July resulted from fallout of graupel from the developing anvil and was not in cloud at all. The flight path of the sailplane and the echo contours are shown in Fig. 3. There was no evidence of liquid precipitation particles above the freezing level at any time during the investigation of this cloud. This cloud produced 1.5 cm hail which was collected on the ground several hours after the sailplane flight.

The results in Table 2 show that the observed ice particles are of sufficient size and concentration to account for the observed echoes. In comparing the calculated values with the observed, it should be noted that the portion of the cloud which the sailplane investigates is only a small fraction of the volume viewed by the radar—at 50 km range this is about 10^8 m^3. Observations from the sailplane show inhomogeneities in ice particle concentrations over regions as small as a few hundred meters. Some of these regions are smaller than the radar can resolve at the range involved in these cases. Therefore, the calculated values should not be expected to reproduce exactly the observed values of reflectivity. In spite of expected differences, the agreement is good. Liquid precipitation particles are not needed to account for the observed reflectivities above the freezing level, and, in fact, as shown in Parts I and II, are not found.

b. First echoes

The above information on sailplane measurements in observed echoes gives information on specific cases. In

Table 2. Observed and Calculated reflectivities.

		Calculated reflectivity (dBZ)						
Date	Time (MDT)	Particle camera	Maximum size (mm)	Average concentration (m^{-3})	Ice collections	Maximum size (mm)	Average concentration (m^{-3})	Range of observed reflectivity (dBZ)
9 July	1355	—	—	—	17–≈27	2.8	—	27–28
	1405	21(20–38)*	3.1	1.1×10^3	15–≈25	1.9	—	<27.5
23 July	1928	—	—	—	12–≈22	2.1	—	<27.5
	1941	27(11–34)	2.1	3.6×10^3	—	—	—	28–35
	1945	27(14–35)	1.9	2.9×10^3	—	—	—	28–32
29 July	1742	—	—	—	33(21–43)	5.1	17**	30–42

* Value in parentheses are reflectivities calculated from concentrations determined at the 95% confidence level.
** Concentrations of particles >2 mm equivalent diameter.

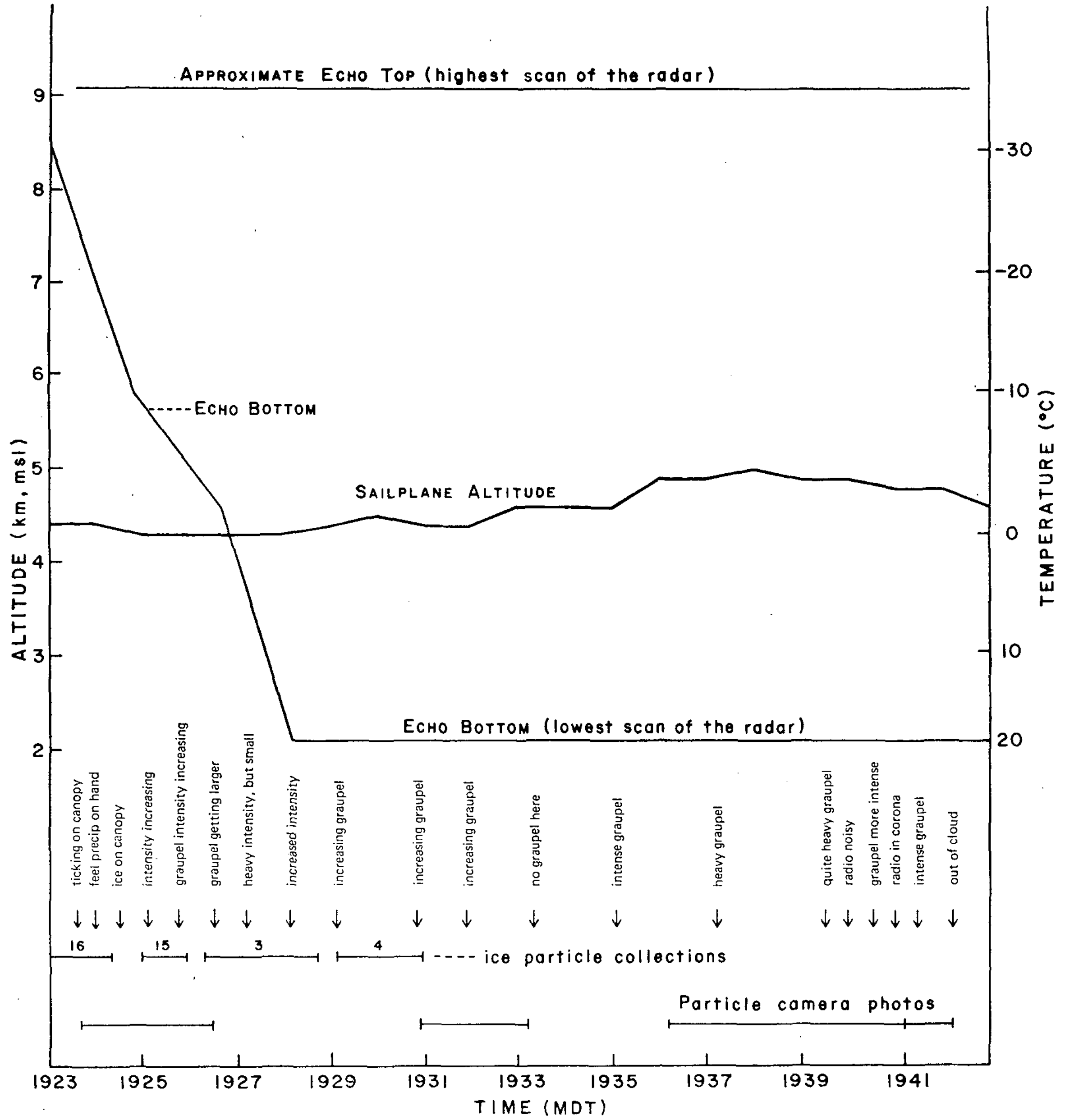

FIG. 1. Altitude of the sailplane and the top and bottom of the 30-dBZ effective reflectivity contour for 23 July 1974. Summarized comments of the pilot or observer and times of particle collections and particle camera photographs are shown along the bottom of the figure.

order to draw a more general picture, a study of first echoes was undertaken using PPI data from the Grover radar for the summers of 1972 and 1973. The details of this study will be presented elsewhere. For the purposes of this paper it is sufficient to say that when the number of first echoes was plotted versus the temperature of the midpoint of the echo for isolated cells a bimodal distribution was obtained. There is a primary maximum at approximately −15C with a secondary maximum around 0C. The occurrence of a maximum in first echoes near −15C, the temperature of fastest vapor growth of ice in supercooled clouds, and a secondary maximum around the melting level, although not conclusive in itself, is certainly suggestive of the ice process.

3. Climatological and microphysical differences

The conclusions from coordinated microphysical and radar observations presented in this paper, as well as the observations of the ice particles reported by Knight *et al.* in Part I and the microphysical measurements presented in Cannon *et al.* in Part II, lead to the conclusion that precipitation originates from the ice phase in northeastern Colorado convective clouds in their early and intermediate stages of development. This contrasts with the opinion of many who, from studies in different regions, feel that the coalescence mechanism is dominant. Might there be climatological and/or microphysical differences that can explain the contrast?

One obvious difference between the clouds in northeastern Colorado and those in the central United States is the difference in cloud base. In Colorado the average convective cloud base for June of 1972 and 1973 was about 3400 m compared to 1200–1500 m in the central United States. In Arizona the average cloud base, reported by Battan (1963), was 3000 m which is slightly lower than those reported here. Also, the freezing level in Arizona tends to be higher than Colorado, 4900 m compared to 4600 m. Certainly the larger the separation between cloud base and the freezing level, the higher the liquid water content, and therefore the more likely coalescence is to occur for a given vertical development. Although differences in cloud base may be responsible for the observed differences in precipitation mechanisms between the central United States and northeastern Colorado, it seems insufficient to explain the differences between Arizona and Colorado.

Another factor might be the differences in concentrations of giant nuclei in different geographical locations. Arizona and especially the Tucson area is close to the Gulf of California, a potential source of giant nuclei. Observations by MacCready and Takeuchi (1968) and Takeuchi (1970) have shown that large particles were present below cloud base in the Flagstaff, Ariz., area. Squires and Twomey (1960) found giant sea-salt nuclei 200–600 m inland in southeastern Australia. They found that the concentration of these nuclei had a strong, positive correlation with total cloud drop concentration, and concluded that during very dry weather the sea salt nuclei survived quite large transportation distances inland. During dry weather the land surface was also a good source of CCN, and hence the positive correlation. The southwestern United States should be an almost ideal site for this same effect to occur, because of the fairly short distance from the Gulf of California and the Pacific Ocean and because of the prevailing dry climate. In Colorado the air must travel a much greater distance over land and therefore its content has more chance to be modified with possible depletion of the giant nuclei. This possible deficiency of giant nuclei will be investigated in future studies.

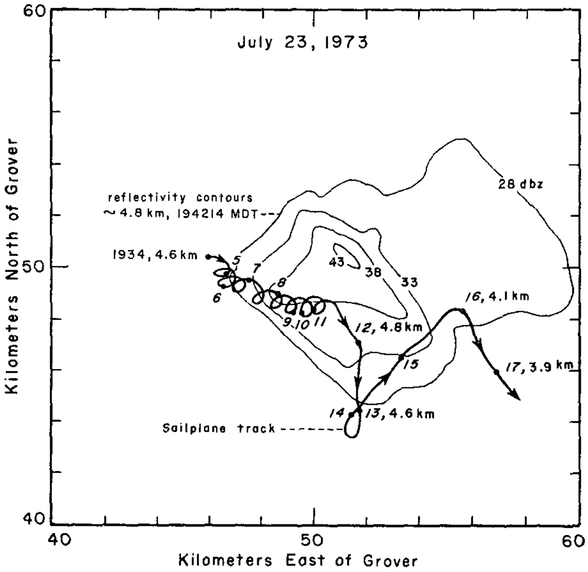

FIG. 2. Flight of the sailplane in a cloud producing a radar echo on 23 July 1973. The numbered spots along the sailplane track indicate time after 1930 MDT. Altitude of the sailplane is shown after some of these times.

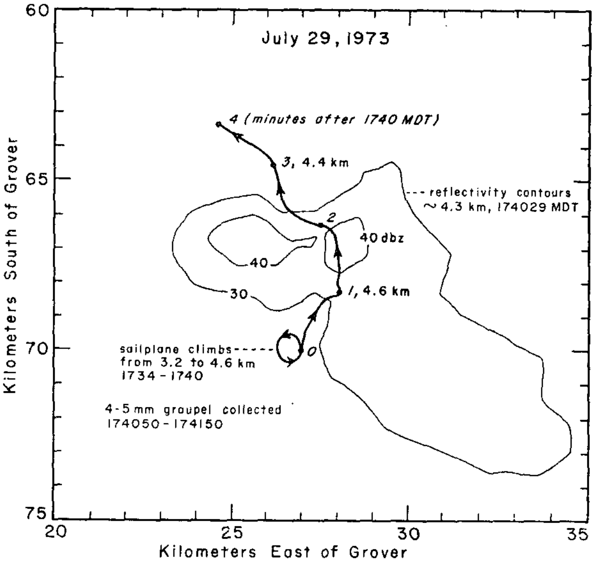

FIG. 3. As in Fig. 2 except for 29 July 1973.

It is worth pointing out that the observations reported here agree very well with those of Gagin (1971). In winter convective clouds over Israel he found an absence of droplets $>100\,\mu\text{m}$ diameter and showed that the largest observed droplets could be accounted for by condensation. In spite of the proximity to the Mediterranean, Gagin showed that the air masses in which the clouds grow are largely of continental origin. The continental nature of clouds in both Israel and Colorado, typified by droplet concentrations of 500–1000 cm^{-3} and sometimes as high as 2000 cm^{-3} (see Part II) may give the clouds colloidal stability. In addition, we suspect that there is a deficiency of giant nuclei in both cases.

4. Summary and conclusions

The results of investigations from several different sources lead to the conclusion that the dominant mechanism for precipitation formation in convective clouds in their early and intermediate stages of development in northeastern Colorado is growth through the ice phase. Diffusional growth of ice crystals at the expense of supercooled water is probably a necessary step. Direct observations reported in Parts I and II of precipitation particles in the cumulus congestus and small cumulonimbus stage with vertical developments of up to about 8 km show the presence of ice particles but the absence of larger liquid droplets. With very few exceptions (see Part I) the largest droplets appear to be considerably less than 50 μm radius, as shown by *in situ* photographs of cloud particles reported in Part II and by the examination of the collected precipitation particles themselves reported in Part I.

Microphysical measurements have been made in several clouds which had a radar return. Ice particles of sufficient size and concentration to account for the observed reflectivity were found in the region of the cloud containing the echo. The structural details of the samples of ice collected in the above four clouds were reported in Part I. Graupel which did not originate from large frozen drops was observed in most of these cases. The observations in about 40 cumulus clouds ranging from cumulus mediocris to small cumulonimbus during the summers of 1971, 1972 and 1973 show that precipitation development in northeastern Colorado in clouds of this size is almost exclusively through the ice phase. Previous measurements of the droplet spectrum in the bases of cumulus clouds in northeastern Colorado led Auer (1967) to argue that the coalescence mechanism was not acting in this area. The largest droplets he found from impaction slides, which have a relatively small sample volume, were 8 μm radius. This is consistent with our findings at cloud base.

A radar study of isolated first echoes shows a frequency maximum at about -15C with a secondary maximum near the melting level. This is suggestive of the ice process and in the seven cases shown in Table 1, the backscatter was definitely caused by ice particles. With a 27.5 dBZ minimum detectable reflectivity those clouds had to be large enough to produce millimeter-sized particles in concentrations of a few tens or more per cubic meter, over a cloud volume of at least 10^8 m^3. It is very likely that precipitation reached the ground from these clouds.

Even in mature convective clouds over northeastern Colorado there is evidence suggesting that the ice phase is the dominant mechanism. Eighty percent of all hailstones collected on the ground had graupel embryos (see Part I). Only 14% originate from precipitation size water drops. However, observations of what appear to be large water drops have been made in large, mature storms in northeastern Colorado with a foil impactor mounted on the South Dakota School of Mines and Technology T-28 armored, penetrating aircraft. The concentrations which they are finding are on the order of 10–100 m^{-3} (May, private communication). There is some doubt about how well one can distinguish water drops from mixed phase particles containing only a small fraction of ice from the impressions on the foil. Additional observations in the large storms are needed before we will be able to tell to what degree coalescence is occurring in the more mature stages.

Even if the results of the present study contrast sharply with those of some previous studies, they do not imply disagreement with the previous results. As pointed out above, geographical differences may account for the differences in cloud processes in one or both of two ways: 1) differences in cloud base temperature, and 2) different condensation nucleus population and size.

Knowledge of natural precipitation mechanisms is a first step in intelligent modification of the precipitation. While a part of the present results (Part I) is in direct contradiction with the concept of the accumulation zone in hail formation, too many pieces of the puzzle are still missing to enable one to say how this information should affect hail suppression procedures.

However, the potential for rain enhancement seems promising. Rain stimulation in these continental cumulus clouds could proceed either by changing the ice nucleus population or by adding hygroscopic nuclei below cloud base. Since nature is using ice nuclei, it is not at all unlikely that there are often fewer than the optimum number of such nuclei and that ice nucleus seeding could stimulate rainfall. Our observations frequently show the absence of ice in these clouds at -10C. The apparently successful rain stimulation by ice nucleus seeding in Israel (Wurtele, 1971; Gagin and Neumann, 1974) may apply directly to these high plains clouds, which seem so similar to those in Israel (Gagin, 1971). On the other hand, since few if any precipitation-size liquid drops are found in these clouds, the addition of hygroscopic nuclei to form larger droplets also appears to be a promising approach.

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