# CUMULUS CLOUD PRECIPITATION AS REVEALED BY RADAR—ARIZONA 1955

*By Roscoe R. Braham, Jr.*

The University of Chicago[1,2]

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ABSTRACT

An AN/TPS-10 radar, located at the Institute of Atmospheric Physics, University of Arizona, has been used to make extensive measurements of radar returns from cumulus clouds in the vicinity of Tucson. Data from ten days in the summer of 1955 have been analyzed with a view toward establishing the level of first formation of precipitation, day-to-day variation, average dimensions of first echo, average duration, and fraction reaching ground. Strong day-to-day variations and mountain effects are revealed. Although echoes form much more frequently over mountains than over nearby valleys, these echoes individually are less likely to produce rain at the ground.

## 1. Introduction

Shortage of good water is a very serious problem facing vast areas of the world today. An acute awareness of this shortage was one of the motivating factors which led to the formation of the Institute of Atmospheric Physics at the University of Arizona. Among the various research projects currently being carried out at the Institute is one involving the meteorological physics of arid region clouds. An important part of this research concerns the development of natural precipitation. This study has been going on for several years in direct cooperation with the Cloud Physics Laboratory of the Department of Meteorology, the University of Chicago.

The mechanisms of *natural* precipitation are considered important because of a firm belief that with increased knowledge of the natural rain processes will come an increased capacity to do something toward increasing the rain, thus helping to alleviate the water shortage.

This paper concerns the development of precipitation in summer convective clouds in Arizona, as that development is revealed by radar. The radar used for this study was an AN/TPS-10, a three-cm wavelength, height-finding radar capable of giving, as a function of time, both vertical and horizontal measurements of rain cores in clouds within a radius of 50 mi of the radar site at the University of Arizona.

Radar is useful in this study because it accurately determines, through the presence of a radar echo, the space and time characteristics of precipitation regions inside the clouds. There is no other way, short of flying through the clouds, for obtaining such information.

Cumuli are the dominant clouds of the summer months in the Southwest, and rain from them forms a substantial fraction of the water resources of the region. In Arizona and New Mexico, summer cumuli form in broad currents of moist maritime air which make their way from the Gulf of Mexico, across northern Mexico and into the United States from the south and southeast. The moisture streams then usually recurve to the northeast and spread out over the Great Plains area. In Arizona and New Mexico, the summer cumulus clouds are closely associated with the mountains (fig. 1), although the actual role that the mountains exert in the formation and subsequent development of the clouds is rather poorly understood.

The goal of the present study is to determine, if possible, the mechanisms of precipitation formation in the summer cumuli of Arizona and to learn more about the role the mountains play in the cloud development.

## 2. Basic measurements

During the summer of 1955 the AN/TPS-10 radar was operated throughout the hours of convective cloud activity within a radius of 50 mi of Tucson, Arizona. Also operated were stereocameras and other cloud measuring systems, the data from which are the subjects of other research papers.

During most of this observational period the radar was operated on a 360 deg azimuth scan which provided echo height and distance data in all directions from the radar at time intervals ranging up to several minutes. An O-15 radar camera was used continuously and automatically to photograph the radarscope. One of these photographs, which illustrates the type of data obtained, is shown in fig. 2.

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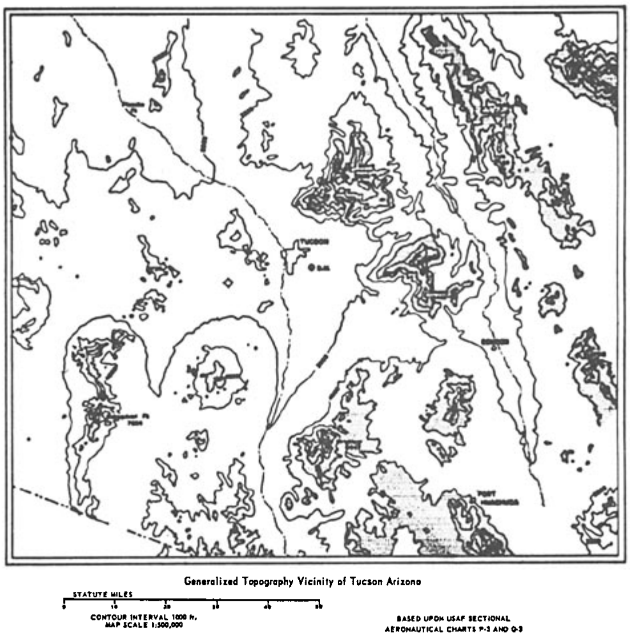

FIG. 1. Map of area around Tucson, Arizona.

The time resolution of the data taken in this manner is primarily a function of the azimuth sweep-speed of the radar. Ideally one would like the time intervals between successive azimuth scans as short as possible. Unfortuately three minutes was about the shortest time which would permit a full 360 deg scan in azimuth. In order to shorten the time interval between successive measurements on a few clouds the radar was occasionally operated on a sector-scan basis. In this operation the antenna was caused to sweep between two fixed limits of azimuth three times during every full azimuth sweep. This compromised some of the data however, since it meant obtaining better time resolution on some of the echoes at the expense of poorer resolution on others. This difficulty is most important in the study of newly formed precipitation cores (called "first echoes"), and is relatively unimportant for other types of analyses.

In the present study, data for first echoes are divided into two categories depending upon the radar azimuth sweep speeds. One category includes all new echoes for which less than three minutes had elapsed between the time the new echo was first seen and the last time the radar had looked at the same point in space previous to the echo appearance. Obviously the zero to three minutes data are most suited for deductions concerning conditions attending the initial formation of the precipitation echo. Data for cases in which three to six minutes had elapsed between successive azimuth sweeps in areas of new echo formation were separately tabulated and analyzed. Echoes involving sweep intervals of more than 6 min were not used for first echo studies. All the data are combined for certain studies such as geographical location of first formation, movement, maximum growth, *etc.*

Echo data were extracted from the films in the following manner. Using a microfilm reader, the radar film was examined frame at a time for an extended period during convective activity. Starting with a particular frame each echo was given a number and the time, azimuth, range and height of top and base were recorded on a small card. This procedure was continued for every echo between ranges of 10 and 50 mi. After the radar had completed one azimuth sweep (360 deg) and started around a second time, the numbered echoes were identified, from previous azimuth and range data, and new measurements were entered on the same cards. In other words the identity of each echo was maintained insofar as it was possible to do so. Whenever a new echo was detected appropriate information was entered on a new card and the film was turned backward to the *last* previous time the radar had scanned the same area in space, in order to determine that the echo was actually "new" and had not been overlooked or misidentified on the previous azimuth sweep. As echoes dissipated the cards were taken from the deck.

This procedure of identifying *every* echo detected by the radar regardless of echo size, made it possible to study echo characteristics without cloud selection

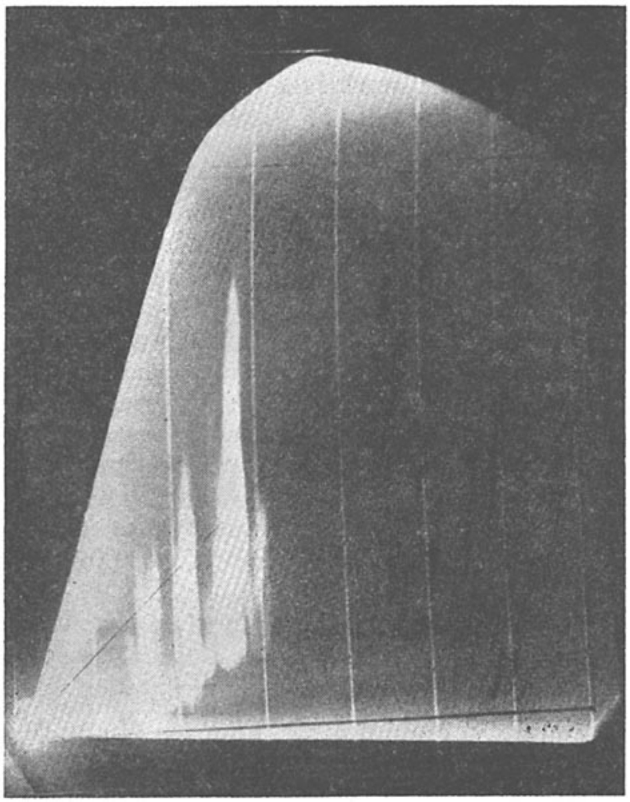

FIG. 2. Photograph of AN/TPS-10 radarscope. Range from radar set is displayed from left to right along abscissa. Height is displayed vertically. White areas represent rain cores within clouds.

bias. In this regard this study is fundamentally different from previous studies which have been based upon echoes selected in one way or another from the whole echo population. Some of the more revealing consequences of this study result from this unbiased manner of obtaining the basic data. Since all echoes within 50 mi of the radar were included in the sample, a question arose concerning a possible bias due to the differing ranges to the echoes. This point was investigated by considering the daily-mean first-echo top-temperature as a function of range. This study showed differences of less than 0.1 deg between the various 10-mi range-interval classes. From this it is concluded that the precipitation process, once initiated, proceeds sufficiently fast that the reflectivity of a precipitation echo quickly increases to a value capable of giving an echo at the greatest range. As a corollary the range effect is unimportant in this study.

Periods ranging from 31 min to more than three hours on each of ten days in the middle of the 1955 convective season were selected for analysis in the manner oulined above. The exact periods for analysis were selected after consideration of the availability of radar data and with a view of obtaining as large an echo sample as possible, consistent with the great amount of effort required in data reduction. Table 1 lists all the periods selected for study, the number of echoes studied, number of first echoes observed, and the number of echoes followed for their entire life cycle. The numbers of echoes in the various columns are not the same for any given day for the reason that some the echoes studied were present at the time of *first* sweep of the radar and thus could not contribute to "first echo" data, whereas others were present at the end of the period of study and as a result could not be used for any study requiring knowledge of the entire life cycle of the echo.

The procedure adopted for reducing the data was designed to obtain a sample of the entire population of precipitation echoes as detected by the TPS-10. The present sample of 633 echoes is considered large enough for analysis involving the whole sample. However, there are too few echoes to adequately study certain day-to-day differences.

Table 1. Basic data used in Arizona echo study.

| Date (1955) | Time of day MST | Number echoes studied | Usable first echoes (0–6 min) | Number echoes followed through life cycle |
|---|---|---|---|---|
| July 11 | 1344–1515 | 138 | 71 | 39 |
| July 13 | 1157–1304 | 25 | 18 | 0 |
| July 14 | 1256–1520 | 45 | 26 | 18 |
| July 15 | 1305–1618 | 97 | 28 | 28 |
| July 19 | 1345–1502 | 42 | 14 | 14 |
| July 20 | 1040–1205 | 55 | 44 | 39 |
| July 21 | 1130–1337 | 96 | 76 | 29 |
| July 26 | 1110–1141 | 47 | 19 | 5 |
| August 25 | 1311–1426 | 40 | 30 | 21 |
| August 26 | 1159–1312 | 48 | 31 | 16 |
| Totals | | 633 | 357 | 209 |

It is a fundamental property of cumulus echoes that they tend to develop near existing ones. This is because cumulus clouds have a marked tendency to develop adjacent to existing clouds. On many occasions, echoes which were separate and distinct at the time of formation grew into or merged with adjacent echoes so that it was not possible to follow them through a complete life cycle. When this happened in the sample, the echo card was marked to indicate that the echo had merged with another. Such an echo was considered valid for all studies of first echoes. For studies involving the life history of the echo (*e.g.*, growth, duration) only the echo with which the new echo merged was considered. This procedure tends to increase the average duration and average maximum height of echoes since it is likely that the clouds were under a continual state of change with new cloud material forming as other evaporated.

In a few instances the echo clusters were too complex to be resolved with the sweep-time and beam resolution of the TPS-10. In such cases it was necessary to lump the several echoes and to treat them as one, thus reducing the total number of echoes considered. Fortunately, there were relatively few cases of this kind. Most of these complex echo groups were located over mountainous terrain. The effect of so treating these data is to reduce the relative frequency of echo formation over mountains. It is considered unlikely that this error will amount to more than a few per cent in the present sample. A serious consequence of this difficulty, however, is that these data are not usable for detailed studies of the dynamics of mountain clouds. Such a study will require better space and time resolution in the radar data. Steps to correct this deficiency have already been taken at the Institute.

## 3. Analysis

From the basic data it was possible to study the following characteristics of precipitation echoes: a. effect of mountain terrain upon the frequency of echo formation, the character of initial echoes, and the nature of echo development; b. height and temperature of the tops of first radar echoes, both as a function of day and terrain height; c. height and temperature of the bases of the first radar echoes as a function of day and terrain height; d. range of heights and temperatures involved in initial precipitation development; e. size of initial echo volumes; f. amount of growth of echoes after first detection; g. duration of echoes; h. fraction of echoes producing rain at the ground; i. rate of growth and decline of the tops of

TABLE 2. Distribution of height of terrain within a radius of 50 mi of Tucson, Arizona and a comparison with the relative frequency of echoes which form over terrain of different heights.

| Terrain height intervals (ft-MSL) | Distribution of terrain height (per cent) | Distribution of first echoes (per cent) | Relative frequency | |
|---|---|---|---|---|
| 1000–1999 | 6.1 | 0 | 1 | Low valley land<br>35.5 per cent of land<br>6.4 per cent of new echoes |
| 2000–2999 | 29.4 | 6.4 | | |
| 3000–3999 | 31.0 | 25.8 | 6.1 | 50.3 per cent of land<br>54.7 per cent of new echoes |
| 4000–4999 | 19.3 | 28.9 | 8.2 | |
| 5000–5999 | 10.4 | 19.6 | 10.4* | Mountain terrain<br>14.2 per cent of land<br>38.9 per cent of new echoes |
| 6000–6999 | 2.5 | 12.6 | 27.8 | |
| 7000 and over | 1.3 | 6.7 | 28.5 | |

* Average for terrain over 5000 ft is 15.1.

echoes, from which something of the cloud motions can be inferred; j. movement of echoes after formation.

*Terrain effect on relative numbers of first echoes.*—One of the most obvious characteristics of the visual clouds which form in Arizona is their association with the mountains. The effect of the mountains on the formation of precipitation echoes in such clouds is one of the most interesting and most important parts of this study.

The frequency of formation of radar echoes over land of various heights above sea level is shown in table 2. About 35 per cent of the land within 50 mi of Tucson lies at an altitude of less than 3000 ft MSL. Less than seven per cent of the observed first echoes formed over this low valley land. About one-half of the land about Tucson lies between 3000 ft and 5000 ft MSL, and about one-half of the first echoes formed over this terrain. The mountains can be considered to consist of all the terrain above 5000 ft. About 40 per cent of the first echoes formed over the mountains, even though only about 14 per cent of the land can be so classified.

The frequency of echo formation over various terrain height classes, *relative* to that over low valley land, increases with terrain height to a value in excess of 25 for echoes over the higher terrain. The average relative frequency of new echo formation over the mountains is about 15 times that over the low valley terrain.

It is well known that the amount of rain received at the ground in Arizona is strongly dependent upon terrain height. However, the ratio of precipitation in the valleys to that on the mountains is nowhere near the 1 to 15 ratio found for the formation of precipitation echoes (1 to 28 for the highest terrain). The rain at Florence and Casa Grande (terrain less than 2000 ft) is less than 9 in per year; Tucson receives between 11 and 12 in. The tops of the Santa Catalina Mts. and Mica Mt. receive a little over 30 in of rain and other mountain areas record similar annual rainfall amounts. Thus the mountain/valley rain ratio is about three compared with 15 to 25 for the development of new precipitation echoes. This obviously means that precipitation regions in clouds over the mountains are individually less effective in producing rain than are similar regions in clouds over the valleys, just the reverse of what one might have expected *a priori*. This terrain difference in the echoes is also found in other cloud characteristics.

*Heights and dimensions of first echoes.*—The level of initial formation of precipitation in convective clouds has frequently been used as an index of the mechanisms of precipitation formation. It was from such data that Battan (1953) was able to show that non-ice processes were very important in mid-latitude clouds. Subsequently other investigators have used first echo data as a means of drawing inferences about precipitation processes. Frequency distributions of the individual top and base heights of the first echoes are shown in fig. 3. It can be seen that the top heights form a broad distribution which centers approximately at the 20,000 ft level. The distribution of base heights is similarly broad, although slightly skewed, with a modal height of about 14,000 ft.

Although interesting in a general way, these distributions of the lumped data conceal some of the most important information to be derived from the first echo measurements. The daily mean heights of the

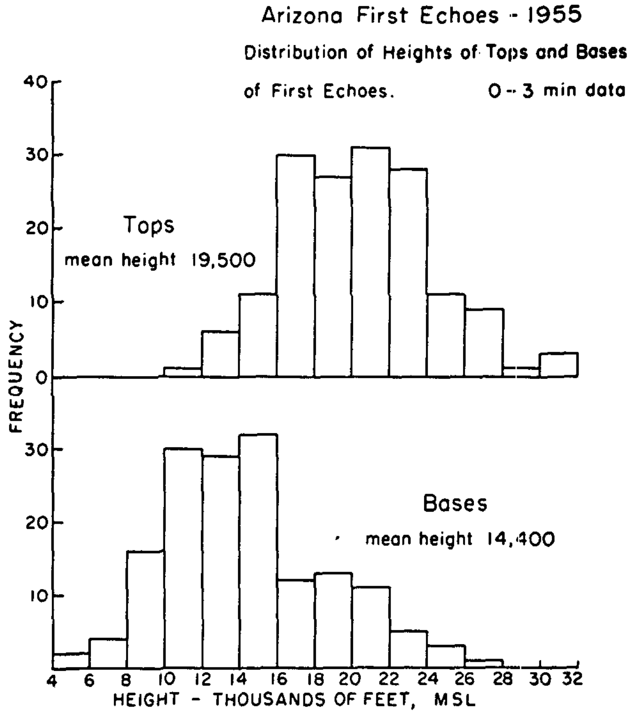

FIG. 3. Distribution of heights of tops and bases of zero to three min first echoes—Arizona 1955.

bases and tops of the first echoes, the mean thickness of the echo when first seen, and the fraction of the bases and tops which were colder than 0C are shown in tables 3 and 4. It is immediately noted that the daily mean height of first echo formation underwent marked change from day to day. These day-to-day variations are large enough, compared to instrumental-drift effects, as to seem real and not an effect of day-to-day height calibration shifts. The first echoes were high and cold during the first days included in the study. In the data, ranked by calendar date, one notes a progressive lowering and warming of the first echo from the first day of data 11 July 1955 through 25 August 1955. On 26 August 1955, the echoes were again forming at heights and temperatures characteristic of early July. These large differences in the first echo heights from one day to another are hardly ascribable to accidental variations in the physics of precipitation, rather they suggest day-to-day differences in initial conditions from which the clouds and precipitation subsequently developed. As a corollary, they suggest day-to-day variations in the large-scale meteorological conditions present in the research area. It is not known whether the apparent *progressive* change in first echo heights through the first nine days of data is a real phenomenon. Such a trend is certainly suggested and merits a considerable amount of additional study.

The range of mean temperatures at the bases and tops of the first echoes in this study is somewhat greater than was found by Battan for a 12-dy period of convective echoes over Ohio in August and September 1947. The data obtained on the days of lowest and warmest first echoes in the present study are virtually identical with the data presented by Battan. The Ohio data did not show, however, the days with high, cold first echoes.

In an effort to reduce the effect of marked day-to-day variations in the height of the first echo, the top height data were plotted as a function of the deviation from the daily mean, fig. 4. It is found that these data form a broad smooth distribution extending from roughly 5000 ft above to 5000 ft below the mean height. Such a 10,000-ft height range would correspond roughly to a temperature range of about 20C. This suggests that whatever the dominant precipitation mechanism, it is not very temperature dependent, or alternatively, if both the ice and non-ice mechanisms are important, they must both shift in phase from day to day in the height at which they are effective (since

TABLE 3. Daily mean values of first-echo top and base heights and temperatures—0–3 min data.

| | Tops | | Bases | | | Per cent colder than 0C | | |
|---|---|---|---|---|---|---|---|---|
| Date | Height (ft-MSL) | Temperature (C) | Height (ft-MSL) | Temperature (C) | Top height minus base height | Tops | Bases | Sample size |
| July 11 | 24,500 | −16.1 | 19,100 | −5.8 | 5,400 | 100 | 82 | 22 |
| July 14 | (21,000) | (− 7.0) | (19,000) | (−5.0) | (2,000) | Single case | | 1 |
| July 15 | 21,600 | − 8.2 | 16,600 | +1.8 | 5,000 | 80 | 60 | 5 |
| July 19 | 20,300 | − 9.8 | 16,300 | +2.7 | 4,000 | 100 | 70 | 10 |
| July 20 | 19,300 | − 6.4 | 11,200 | +9.1 | 8,200 | 88 | 16 | 32 |
| July 21 | 18,900 | − 5.3 | 13,300 | +5.9 | 5,600 | 85 | 16 | 68 |
| July 26 | 17,900 | − 4.5 | 11,300 | +7.8 | 6,600 | 77 | 0 | 13 |
| Aug. 25 | 17,200 | − 1.3 | 12,300 | +7.7 | 6,700 | 67 | 0 | 6 |
| Average | 19,500 | − 7.2 | 14,400 | +4.4 | 6,100 | 88 | 29 | Total 157 |
| Ohio 1947 (Battan) | | + 0.4 | | +10.0 | | 42 | 11 | |

TABLE 4. Daily mean values of first-echo top and base heights and temperatures—3–6 min data.

| | Tops | | Bases | | | Per cent colder than 0C | | |
|---|---|---|---|---|---|---|---|---|
| Date | Height (ft-MSL) | Temperature (C) | Height (ft-MSL) | Temperature (C) | Top height minus base height | Tops | Bases | Sample size |
| July 11 | 22,500 | −12.2 | 13,100 | + 4.2 | 8,100 | 94 | 31 | 49 |
| July 13 | 24,600 | −15.1 | 16,300 | + 0.4 | 8,300 | 89 | 39 | 18 |
| July 14 | 20,600 | − 7.4 | 12,900 | + 7.3 | 7,700 | 87 | 13 | 25 |
| July 15 | 19,900 | − 4.5 | 14,300 | + 5.8 | 5,600 | 82 | 23 | 23 |
| July 19 | 19,700 | − 8.9 | 15,500 | + 1.0 | 4,200 | 100 | 50 | 4 |
| July 20 | 18,800 | − 5.7 | 12,200 | + 6.8 | 6,600 | 92 | 25 | 12 |
| July 21 | 17,800 | − 3.5 | 11,600 | + 8.9 | 6,100 | 75 | 12 | 8 |
| July 26 | 17,800 | − 4.5 | 9,300 | +10.7 | 8,500 | 83 | 0 | 6 |
| Aug. 25 | 17,900 | − 2.8 | 12,500 | + 6.7 | 5,400 | 54 | 4 | 24 |
| Aug. 26 | 24,500 | −17.5 | 17,800 | − 5.0 | 6,700 | 100 | 77 | 31 |
| Average | 21,300 | − 9.6 | 13,900 | + 3.8 | 7,000 | 85 | 30 | Total 200 |

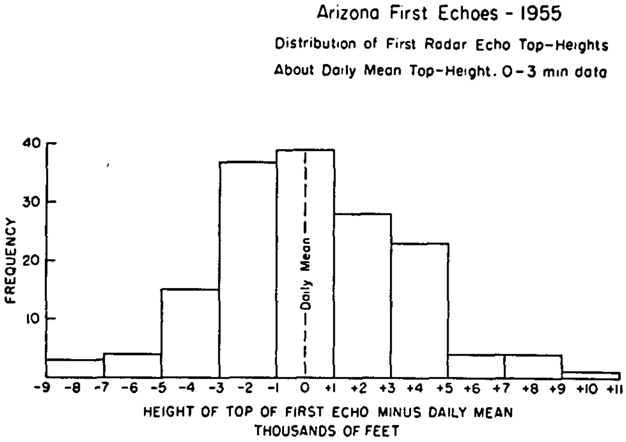

FIG. 4. Distribution of heights of first echo tops about the daily mean top height—zero to three min data.

there were strong day-to-day differences in mean heights of first echo formation). If the ice mechanism were dominant on some days and the non-ice mechanism dominant on others, it would be expected that the distribution about the daily mean would be markedly more narrow than the distribution of the original data. Actually these two distributions are remarkably similar.

*Terrain effect on height of first echo.*—The effect of the mountainous terrain upon the height in the atmosphere where echoes first formed was studied by stratifying the 0–6 min first echo data according to the height of the terrain under the point of formation. The results are shown in table 5. It is to be noted that there is a suggestion that the height of the tops of the first echoes which formed over the valleys was lower than those which formed over the mountains. The magnitude of this mountain effect is about 2000 ft in the mean. It is suspected that the actual difference due to the mountains is somewhat larger than this value. In analysis of the data it was very evident that echoes would tend to cluster *around* but not necessarily on *top* of the mountains. This effect could not be allowed for in the present study, and results in many echoes, which were undoubtedly influenced by the mountains, being classified as forming over the valleys.

TABLE 5. Effect of terrain height on height of tops of first echoes—0–6 min data.

| Terrain height intervals (ft-MSL) | Mean height of top first echo (ft-MSL) | Sample size number echoes |
|---|---|---|
| 2000–2999 | 18,000 | 23 |
| 3000–3999 | 20,500 | 92 |
| 4000–4999 | 21,300 | 103 |
| 5000–5999 | 20,700 | 70 |
| 6000–6999 | 20,900 | 45 |
| 7000 and over | 20,400 | 24 |
| | Total | 357 |

TABLE 6. Day-to-day variation in the fraction of echoes which grew and which rained to the ground.

| Date | Mean height of top of first echo (0–3 min data) ft-MSL | Per cent of echoes which grew | Per cent of echoes raining to ground | | Sample size |
|---|---|---|---|---|---|
| July 11 | 24,500 | 46 | 54 | | 39 |
| July 14 | 20,600* | 70 | 64 | | 18 |
| July 15 | 21,600 | 61 | 20 | | 28 |
| July 19 | 20,300 | 43 | 29 | | 14 |
| July 20 | 19,300 | 31 | 39 | | 39 |
| July 21 | 18,900 | 41 | 55 | | 29 |
| July 26 | 17,900 | — | — | | 5 |
| Aug. 25 | 17,200 | 29 | 62 | | 21 |
| Aug. 26 | 24,500* | 56 | 75 | | 16 |
| Average | 19,500 | 44 | 47 | Total | 209 |

* Denotes data for 3–6 min first echoes. Used in cases where the 0–3 min data are very few.

*Maximum growth of echoes.*—Out of the sample of 633 echoes studied, it was possible to follow 209 of them through the entire life cycle, *i.e.*, the echo was observed to form and dissipate during the period of observation. These echoes were examined for maximum growth. By maximum growth is meant the algebraic difference in the maximum height reached by the echo and the height of the top at first detection. The results of this part of the study are shown in fig. 5 and tables 6 and 7. It may be surprising to some to find that most of the echoes in the sample clouds were at their maximum height at the time of formation. In other words, well over half of the echoes studied *did not* grow after formation. Only a very small fraction of the data, 10 per cent, grew as much as 6000 ft after formation and about 5 per cent grew as much as 10,000 ft. Thus we infer that, on the average, for summer cumuli in Arizona, the time required for natural precipitation to develop is almost exactly equal to the mean growth time for the individual cloud elements.

The day-to-day variation in the fraction of the clouds which show growth after formation was found to be very large. For example on July 14 and 15, over 60 per cent of the clouds grew, whereas on July 20 and August 25, the corresponding figure is about 30 per cent. This also illustrates the importance of synoptic

TABLE 7. Variation in the fraction of echoes which grew after first development and the fraction of echoes which rained to the ground as a function of terrain height.

| Terrain height (ft-MSL) | Per cent of echoes which grew | Per cent of echoes raining to ground | Sample size |
|---|---|---|---|
| 2000–2999 | 69 | 53 | 23 |
| 3000–3999 | 49 | 51 | 92 |
| 4000–4999 | 44 | 53 | 103 |
| 5000–5999 | 33 | 41 | 70 |
| 6000–6999 | 40 | 54 | 45 |
| 7000 and over | 40 | 39 | 23 |

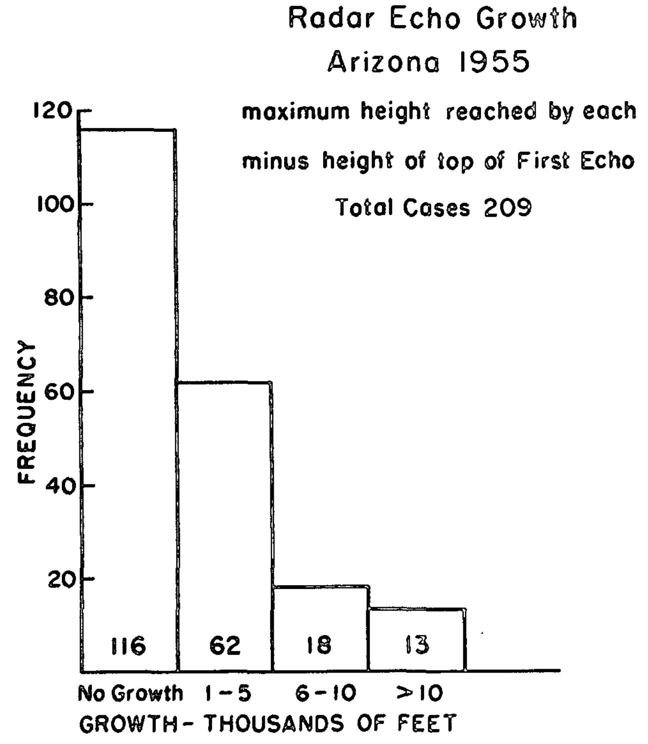

FIG. 5. Frequency distribution of amount of echo growth following first formation.

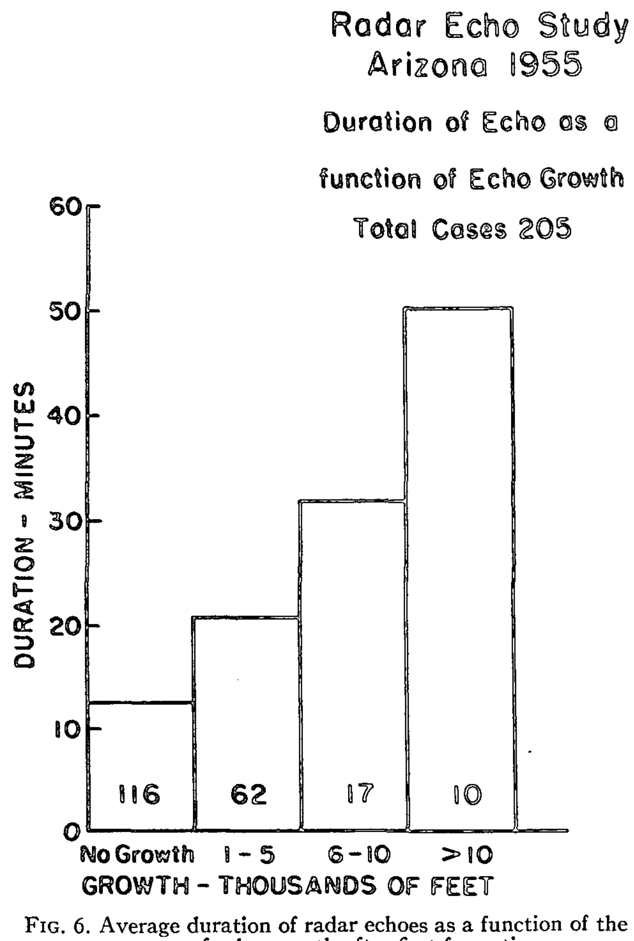

FIG. 6. Average duration of radar echoes as a function of the amount of echo growth after first formation.

variability in controlling the development of individual clouds.

The effect of the mountains on the fraction of the echoes which grew is striking. It was found that about 70 per cent of the echoes over the valleys show growth, but only about 40 per cent of the mountain echoes grew after first formation. This tendency for mountain echoes not to grow must represent part of the explanation for the differences in the mountain/valley rain ratio and echo ratio, but the physical causes of this are not clear.

*Durations of radar echoes.*—The lengths of life of the individual radar echoes range over wide limits. As one would suspect the duration of an echo is strongly correlated with the amount of growth of the echo. The duration data are shown in fig. 6. The 116 echoes which did not grow had an average life of less than 15 min. This value is a little uncertain because of time resolution limitations of the radar scanning cycle. The relatively few echoes which grew after formation had lives lasting upwards of an hour.

*Rain to the ground from radar echoes.*—The ultimate goal of the present study is to attain an understanding of natural rain processes with a view toward making better use of this natural resource. It is important, therefore, to relate the various echo parameters to the amount of rain which reaches the ground. The AN/TPS-10 radar is particularly useful in this regard since the radar echo is a fairly reliable indicator of regions of rain. Radar echoes which extend to the ground indicate with fair certainty the presence of measurable rain at the ground surface. Similarly, if a radar echo fails to reach the ground, we can infer that very little, if any, rain from the cloud reached to ground.

The present data are readily amenable to a study of the relationship between rain aloft and rain at the ground. The minimum height reached by the radar echo was read directly from the radarscope photographs. The height of the terrain under the echo at the time the echo base reached its minimum height was determined by locating the echo in azimuth and range on a suitable contour chart. A difficulty arose in the cases of echoes which were located beyond the first radar horizon. In such cases, the mountain would cast a radar shadow and the radar would not be able to see that portion of any echo which extended to a level lower than the height of this radar shadow. At first it was planned that the analysis would consider only those echoes which were inside of the first radar horizon and thus eliminate this difficulty. Unfortunately, however, there are too few such cases in the sample and it was necessary to extend the analysis to the entire sample. Thus, in this study, it is assumed that an echo reached the ground if (1) the echo was located inside the first radar horizon and the echo extended to the height of the terrain at the echo location, (2) the echo was located beyond the first radar horizon and the echo extended down to the height of the radar shadow at the location of the echo. Thus this analysis overestimated the fraction of the radar echoes reaching the ground.[3]

The fraction of the echoes extending to the ground and the effect of the terrain on this echo parameter are shown in tables 6 and 7. As was found for other echo statistics, there is a strong day-to-day variation in the fraction of the echoes reaching the ground. Again we find evidence that the large-scale meteorological factors dominate the microphysics of the clouds. The effect of the terrain height on the fraction of echoes which rain to the ground is not obvious. There is a slight suggestion that fewer of the mountain echoes rain to the ground, in spite of the greater height of the terrain, than in the case of valley echoes. The data do show, however, that the increased height of the mountains is not an important factor in accounting for the greater amounts of rain which fall on them. Other things being equal, an echo over the valley is just as likely to rain to the ground as is one over the mountains. There are, of course, many more echoes which form over the mountains than over the valleys.

*Role of existing echoes in the formation of rain.*—One of the new developments of cloud physics in the past few years is the realization of the importance of incipient precipitation particles falling into and growing at the expense of cloud droplets in the lowest levels of the atmosphere. Cunningham (1952) has pointed out that a substantial fraction of the water that falls from cyclonic systems in the humid eastern areas has its source in the lowest levels of the atmosphere. This effect is potentially important in two ways when one considers the cumuli of the Southwest. It is likely that the lack of moist lower levels in the clouds upon the mountains as contrasted with valley clouds, contributes substantially to the fact that there is less rain per echo from the mountain clouds than from the valley clouds.

The possibility that an existing echo might affect the development of new echoes was also investigated. It might be reasoned that raindrops or snowflakes, too sparse to be seen by the radar, could initiate a new echo in low level clouds into which they might fall. To investigate this point it was decided to stratify the data on new echo formation according to the distance separating the new formation from existing echoes, or from the point where an echo had been within the past 15 min. This involved plotting in polar coordinates each new echo, in the order of formation, and scaling the distances to the nearest neighbor. Because of the tedious nature of this analysis this was done only for the data of 11 July 1955. This study showed that there was no difference in the mean height of the tops of first echo in the various distance classes. Thus we conclude that any tendency for new echoes to form at low levels because of incipient precipitation falling into clouds from above, is completely masked in this sample by the great natural variation in the first echo heights.

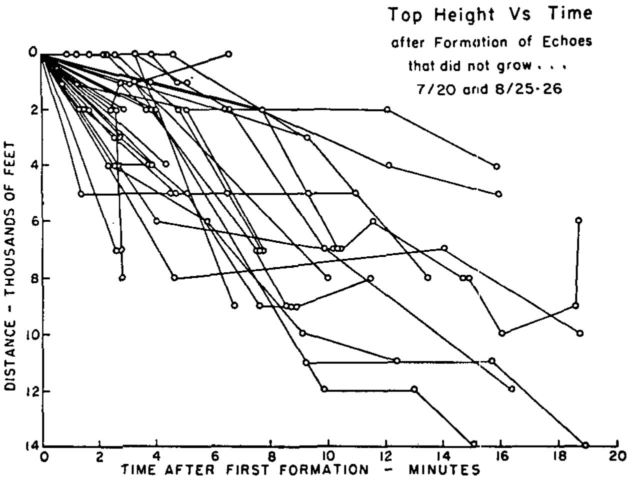

FIG. 7. Decline of the echo tops as a function of elapsed time after first formation for echoes which did not grow.

*Rate of subsidence of echo tops.*—From the rates of fall of the tops of the echoes which did not grow, it is possible to make certain inferences about the motions of the air parcels within such clouds. On fig. 7 has been plotted the amount of decline of the echo top as a function of elapsed time after first detection of the the echo. The data for 20 July, 25 August, and 26 August, have been combined into this figure. The data are similar for the other days and have been omitted for fig. 7 for reasons of clarity. It can be seen that the tops of the echoes characteristically remain at a fixed height for a short period, differing with different echoes, after which it falls at a rate of about 1000 ft per min. Since time, $t = 0$, represents the time of initial formation of the echo, we can estimate that the precipitation particles, if liquid drops, would be about 0.2 mm in diameter at that time.[4] The falling speed of a drop of this size is about 140 ft per min. If the particles are snow pellets the size would be somewhat larger but the falling speed would be even less. From this we conclude that the air within these clouds was sinking at speeds between 700 and 850 ft per min.

This is tied in with the earlier conclusion that the air in the "average Arizona cumulus" has reached its maximum height and started back down before precipitation has had a chance to develop to detectable size.

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[3] Since the radar shadow, thusly used, arises from geometrical considerations it does not allow for radar-beam diffraction around the mountain edges. This further tends to overestimate the number of echoes reaching the ground. This is "conservative" in the sense used in this paper.

[4] This threshold size is computed from radar theory, making use of known values for the radar constants and typical values of liquid water content in cumulus clouds.

*Movement of cloud echoes.*—The 209 echoes for which complete life histories were obtained can be used to obtain information concerning the movement of precipitating clouds in the Tucson area. It has been shown by other investigators that convective clouds usually move with the integrated mean wind between the cloud base and cloud top. In view of the circumstance that summer conditions in Arizona are characterized by a complete reversal of winds with height (from southeasterly at the surface to northwesterly with height) one would forecast that cumulus clouds in Arizona move very little during a normal cloud lifetime. This prediction is borne out by the data which are shown in fig. 8. In this study, movement is defined as the maximum displacement of the echo from the point of first detection, during the life of the echo. In accordance with expectations it is found that these echoes move very little. It must follow that the clouds likewise show very little movement.

This leads to the important conclusion that the rain showers which occur over the lowland near the mountains *did not* form and drift off of the mountains as is frequently assumed. While it is undoubtedly true that the mountains exert strong influences on the rain over the valley areas, this influence must be an indirect one. It seems likely that those storms which appear to have drifted from off the mountains, actually result from progressive development of new cells at successively greater distances from the mountains.

An attempt was made to find a possible steering effect exerted by the mountains upon the echoes nearby. Unfortunately the total movement of echoes was much too small to permit detection of such an effect.

## 4. Conclusion

Based upon a radar study of 633 echoes, 357 first echoes and 209 life histories of echoes in Arizona summer cumuli, it has been found that the frequency of formation of precipitation echoes over the mountains is greater than would be suggested by the difference in rainfall between mountains and valleys. In every respect, however, the echoes which form over the mountains were found to be individually less capable of producing rain to the ground. Mountain cloud echoes form higher in the atmosphere, usually grow less after formation, and, on the average, fewer of them rain to the ground than in the case of their valley counterparts.

The wide range of heights and temperatures at which the initial precipitation echoes first appear suggests that the dominant precipitation mechanism is *not* closely tied to temperature. This study did not show whether the sublimation-coalescence *or* the condensation-coalescence mechanism of precipitation formation is most active in the summer clouds of Arizona. This important point awaits further study.

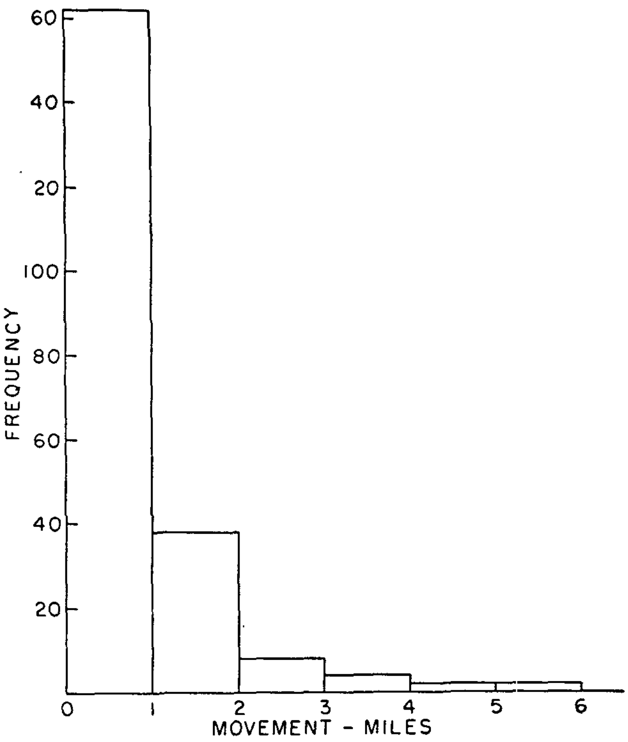

FIG. 8. Frequency distribution of echo total movement during lifetime of echoes.

One of the most striking points revealed by this study was the marked day-to-day variations in *every one* of the cloud parameters studied (with the exception of echo movement). This is interpreted to mean that the microphysics of convective clouds is strongly controlled by the macroscopic meteorological variables which characterize the atmosphere in which the clouds form. This point, long maintained by synoptic meteorologists, has largely been forgotten by scientists working in cloud physics. Research in this "middle ground" between synoptic meteorology and conventional cloud physics is sorely needed.

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