Relationship Between Cloud Base and Initial Radar Echo[1]

LOUIS J. BATTAN

The University of Arizona

(Manuscript received 11 October 1962, in revised form 4 February 1963)

ABSTRACT

The altitudes of the average initial precipitation echoes in convective clouds in Arizona for particular days have been compared with the altitudes of the calculated cloud base. They are found to be positively correlated. The implication of this result is that the dominant precipitation initiation mechanism in convective clouds in southern Arizona is the coalescence process.

Various authors have presented observations of the altitudes and temperatures of the initial radar echoes in convective clouds and interpreted the results in terms of the precipitation processes (Reynolds and Braham, 1952; Battan, 1953; and others). On the basis of observations of this kind it has been inferred that the condensation-coalescence process often can account for the formation of the precipitation particles.

In a recent paper, Braham (1958) presented an analysis of initial radar echoes observed in convective clouds in southeastern Arizona by means of an AN/TPS-10 radar set. He observed a general decrease of the altitude of the average echoes as the summer progressed. Braham wrote, "It is not known whether the apparent *progressive* change in first echo heights through the first nine days of data is a real phenomenon." In an attempt to explain Braham's data and possibly learn something about natural rain processes in convective clouds, the change of altitude of the initial echoes has been compared with corresponding changes in the cloud base altitude.

Braham presented two sets of data. In the first set, only those echoes were included where the time interval between radar observations was less than 3 min (Braham's Table 3). In the second set, observations taken when the interval was 3 to 6 min were tabulated (Braham's Table 4). The decrease of echo altitudes as the summer progressed was most clearly shown by the observations in the first set. Only these observations are considered in this study.

Since measurements of the heights of cumulus cloud bases were not available, they were determined from a thermodynamic diagram by means of the parcel method. Radiosonde data taken in the afternoon (1700 MST) were employed. Average conditions in the lowest 2500 ft were considered and the air was lifted dry adiabatically until the convective condensation level was reached. Admittedly, this procedure has some shortcomings, but it is generally regarded as giving satisfactory estimates of the heights of cumulus bases.

Fig. 1 presents the altitudes of the mean echo tabulated by Braham for each day against the calculated cloud base. The solid lines represent days with 10 or more observations. The dashed lines represent days with 5 and 6 observations. Braham also listed a day with only one echo; this one has not been included. It should be recognized that on any day the heights of initial echoes vary over a fairly large range. Clearly, in such a circumstance, the greater the number included in the average, the more meaningful is the average.

As can be seen from Fig. 1, there appears to be a definite relationship between the height of the cloud base and the height of the initial echo.

Observations of the altitude of initial radar echoes in southeastern Arizona in 1956 have also been studied by Ackerman (1960). The author accumulated data for the years 1957, 1958 and 1959. All measurements were made with an AN/TPS-10. On all days when at least 10 initial echoes were observed, the data were averaged and form the basis for Fig. 2. In this diagram, the altitude of the midpoint of the average initial echo for each day was plotted against the calculated cloud base altitude. The midpoint was chosen because it should be more representative of the position of the initial echo than either its top or bottom.

Immediately after the initial echo is detected, its bottom almost always descends at speeds ranging from a few hundred to a few thousand feet per minute (see Battan, 1953). At the same time, the top of the echo may either ascend or descend (Ackerman, 1960; Battan, 1953; Braham, 1958; Clark, 1960). It is evident that the size and duration of the initial echo depends, to a certain extent, on the intervals between radar observations. As

---

[1] This research was supported by the National Science Foundation under Grants G 4175, G 5607, G 8216 and G 19639.

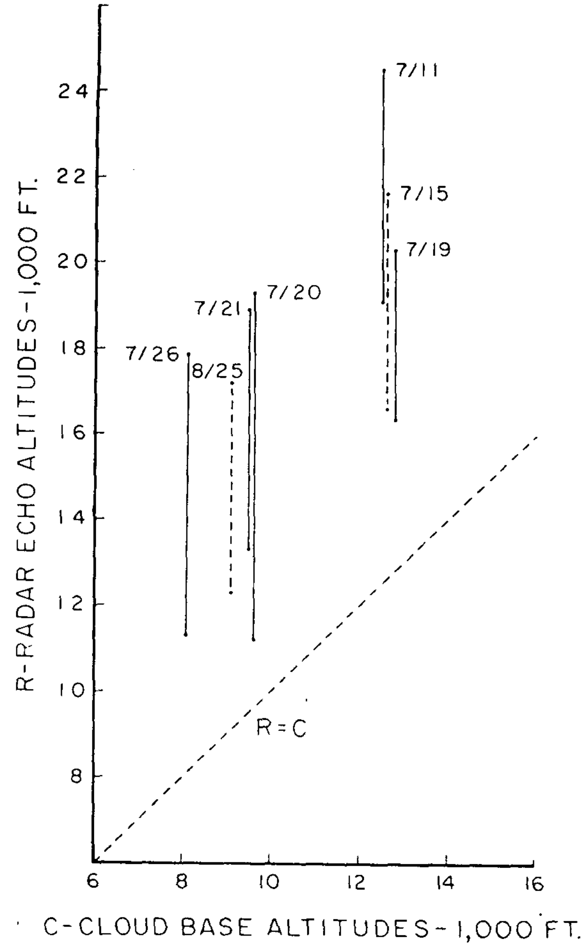

FIG. 1. Mean altitudes and sizes of initial echoes on seven days in 1955. From Braham (1958).

already noted, the Braham (1958) data shown in Fig. 1 were taken at intervals of less than 3 min. The average thickness of the initial echo was 6100 ft. If the interval between observations was reduced to say one minute, one would expect the average thickness to be somewhat less. Battan (1953) found this to be true, but even when observations were 15 sec apart, the initial echoes still were 2000 to 4000 ft thick.

If the top of the echo is rising and the bottom is descending, the center of the echo is a better measure of the altitude at which the first large particles appear than either the top or bottom of the echo.

The data plotted in Fig. 2 include only those observations collected when the interval of observation was equal to, or less than, 4 min. It is felt that the scatter of the points on this diagram is partly a result of changes in echo altitude caused between the time the first large drops appeared and the time the radar beam scanned through the cloud and detected the first echo. Part of the scatter must also be caused by uncertainties in the computed cloud base altitude as well as other factors to be cited later.

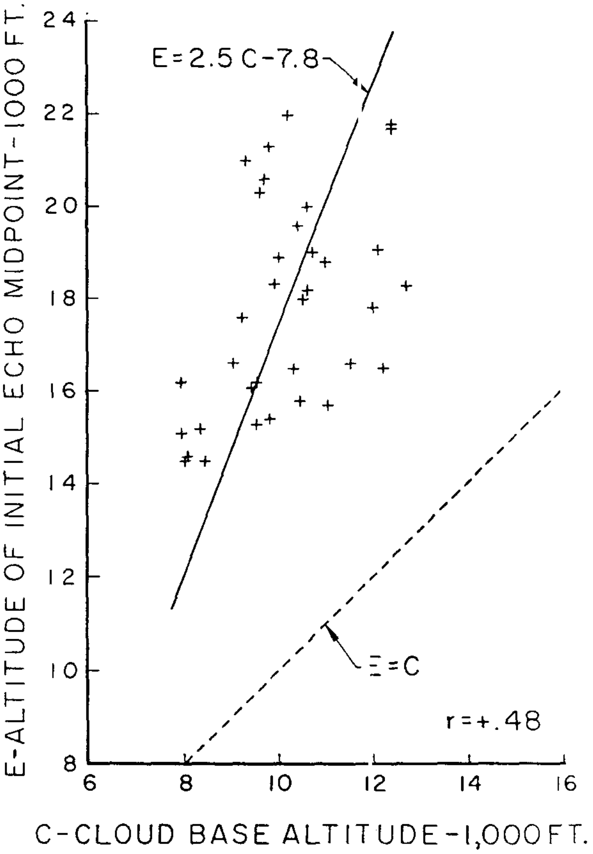

FIG. 2. Average altitude of the midpoint of initial echoes plotted against altitude of visual cloud base.

The correlation coefficient between the variables plotted in Fig. 2 is 0.48. The value certainly is not large numerically but still is significant statistically at a level below 0.01.

Clark (1960) reported that observed heights of the tops of initial echoes in Texas were not correlated with the heights of the convective condensation level. He observed clouds at intervals of 5 min. The extra minute or two in the observations could cause a deterioration of the correlation to the point where it would no longer be detected. Ackerman (1960) also indicated that variations in initial echo heights were not related to heights of the condensation level, but she had observations on only seven days.

Surely there are other factors besides the height of the cloud base which determine whether or not precipitation develops and, if it does, at what altitudes. On any one day the heights of cumulus bases may be at about the same altitude. Some clouds fail to rain, while in others the initial echoes may vary in altitude over a distance of many thousands of feet. One important factor is the

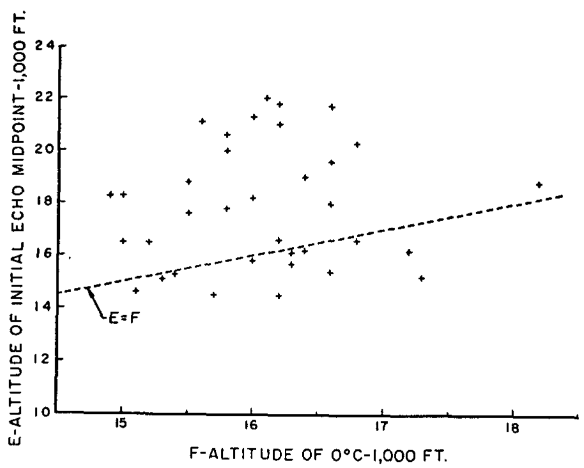

Fig. 3. Average altitude of the midpoint of the initial echo plotted against the altitude of the 0C isotherm.

horiztontal extent of the cloud. In a narrow cloud, entrainment and mixing may lead to a reduction of the liquid water content to a value less than the one which would be present in a wide cloud having the same cloud base altitude. The strength of the updraft and the cloud-droplet spectra at the cloud bases also are important in determining the growth of precipitation. Measurements of these factors do not exist for the clouds involved. But cloud-droplet measurements in growing convective clouds in maritime air masses show the presence of water droplets with diameters exceeding 100 microns in concentrations of 100 m^{-3} or greater. [See Ludlam (1958) for a summary of observations.] The observations in Figs. 1 and 2 show that the height of the cloud base is also important.

The solid line drawn through the points on Fig. 2 is the regression line calculated to minimize the square of the deviations from the line. The equation was obtained by following the procedure proposed by Morgan (1960) and was checked by employing a technique discussed by Sellers.[2] The altitude of the initial echo increases with increasing cloud base altitude. It can be inferred from a comparison of the solid and dashed lines that, in general, the centers of the regions of initial precipitation particles are located about 5000 to 10,000 ft above the cloud base. The regression curve suggests that the higher the cloud base, the greater is the distance above the base at which the initial precipitation particles are formed.

Ackerman (1960) found no relation between the altitude of the initial echo and that of the 0C. The same negative result is found when more data are employed (Fig. 3). Although there are more points above the 0C line, there is no indication that the higher the freezing level, the higher the echo. The diagram shows, as was already demonstrated by Braham (1958), that in convective clouds in southeastern Arizona the high cloud bases lead to initial echoes which are often at temperatures below 0C.

On the basis of the information already presented, the schematic drawing in Fig. 4 was constructed. It presents average altitudes and temperatures. The terrain over which the echoes were observed ranged from 2000 to almost 9000 ft. It is of some interest to know the altitude of the cloud base above the terrain. Braham (1958) gives a topographic map of the area and presents some figures of the percentages of the area surrounding the radar set which fall between particular altitude intervals. These data were used to compute an average terrain altitude and yielded a value of 3600 ft. This figure does not give a representative average altitude because on 18 of the total of 35 days included in this analysis, the radar observations were restricted to the region between 0 and 90 degrees of azimuth around Tucson and within a range of 10 to 35 miles. We have not attempted to make quantitative analysis of this factor, but rather have estimated that 4000 ft is an appropriate average terrain altitude.

The observations discussed in this paper show that the altitude of the region where precipitation particles first appear depends, among other factors, on the altitude of the cloud base. According to the calculated re-

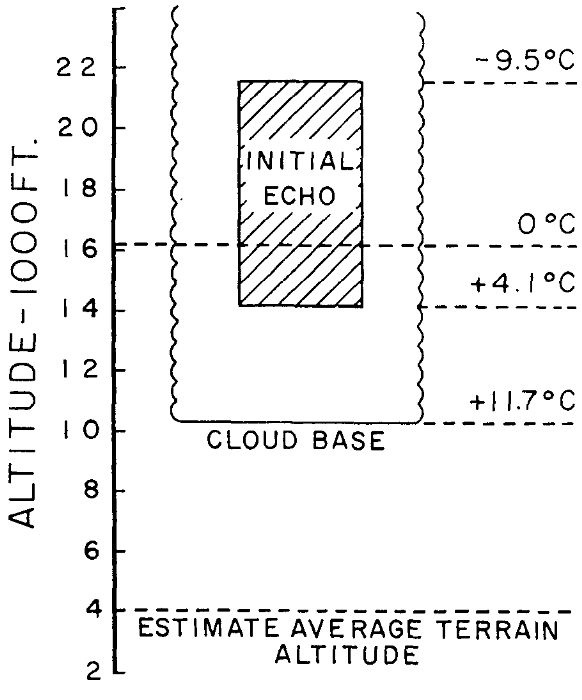

Fig. 4. Schematic representation of the average altitudes and temperatures of the cloud base and the top and bottom of the initial echo.

---

[2] Sellers, W. D., 1957: A statistical-dynamic approach to numerical weather prediction. Sci. Rep. No. 2, Stat. First Proj., M.I.T., 151 pp.

gression line, as the latter increases from 8000 to 12,000 ft, the midpoint of the average initial echo rises from about 14,000 to 22,000 ft, but there is considerable scatter around the regression line. For the most part, the initial echo straddles the 0C isotherm.

The data shed some light on the mechanism of precipitation initiation in convective clouds. Once the largest particles, be they water or ice, have reached equivalent water diameters of about 100 microns, further growth will be by coalescence either with overcooled or supercooled droplets. A vital problem is to explain if these particles are caused by sublimation growth on minute ice crystals or if they grow because of the collision and growth of unusually large cloud droplets. We call the former the "ice crystal process" and the latter the "coalescence process."

Ludlam (1951) calculated that the minimum cloud depth for shower production by the coalescence process was between about 5000 and 6000 ft, provided droplets of 20 microns radii are present near the cloud base. He further predicted that if the cloud base temperatures exceeded 8C, showers could form even if the clouds did not grow to the 0C level. The data used in this study show that cumulus clouds in southeastern Arizona usually have base temperatures exceeding +8C. On the basis of Ludlam's arguments, it would have been predicted that if cloud droplets of 20 microns radii or greater formed near the cloud base, precipitation drops would develop by the coalescence process.

The temperatures of the midpoints of the mean initial echoes ranged from about −12C to +3C. Note that on almost all the days involved the 0C was within the 2500 ft interval from 14,800 to 17,300 ft. It is reasonable to expect that few ice crystals formed at temperatures warmer than −10C to −15C. Therefore, if the echoes had been initiated by ice crystals, the particles detected by the radar set must have been falling and growing by *coalescence*. They would not be observed until they grew to sizes where their *equivalent* water volumes were equal to a droplet of 200 to 300 microns in diameter. Since the growth by coalescence is proportional to the liquid water content, if the particles were initiated above the region of detection and grew as they fell, one would expect that the greater the liquid water content, the higher the region of the initial echo. As already noted, the liquid water content at a given level in a cloud increases as the cloud base temperature increases (and its altitude decreases). Thus, it would be expected that if the initial echoes were caused by ice crystals which were falling and growing by coalescence, *the altitude of the initial echo would increase as the altitude of the cloud base decreased.* This is contrary to the observations which show that just the reverse is true.

On the other hand, if large cloud droplets near the cloud base grow by coalescence as they ascend, the higher the liquid water content associated with lower and warmer cloud bases, the lower would be the region of the initial precipitation particles. Also, the lower the cloud base, the smaller the distance between the cloud base and the initial echo. It is concluded that the observations presented in this paper support the view that the initial precipitation particles were usually formed by the coalescence process.

It has been felt that the ice-crystal precipitation process was the dominant one in the convective clouds of the semiarid Southwest and that only in a small number of clouds did the coalescence process initiate precipitation. It now can be affirmed that just the reverse is the case. Furthermore, it is reasonable to expect that in more humid regions where cumulus cloud bases are at warmer temperatures, the same conclusion is valid. However, one must still admit the possibility that in some convective clouds the droplet spectra may be so uniform that precipitation growth is inhibited until ice crystals form in the supercooled part of the cloud.

REFERENCES

Ackerman, B., 1960: Orographic-convective precipitation as revealed by radar. *Geophys. Monogr. No. 5*, Amer. Geophys. Union, 79–85. (Also Sci. Rep. No. 11, Inst. Atmos. Phys., Univ. of Ariz., July 1959, 66 pp.).

Battan, L. J., 1953: Observations on the formation and spread of precipitation in convective clouds. *J. Meteor.*, **10**, 311–324.

Braham, R. R., Jr., 1958: Cumulus cloud precipitation as revealed by radar, Arizona, 1955. *J. Meteor.*, **15**, 75–83.

Clark, R. A., 1960: A study of convective precipitation as revealed by radar observations, Texas, 1958–59. *J. Meteor.*, **17**, 415–425.

Ludlam, F. H., 1951: The production of showers by the coalescence of cloud droplets. *Quart. J. R. meteor. Soc.*, **77**, 402–417.

——, 1958: The hail problem. *Nubila*, **1**, No. 1, Verona, 12–96.

Morgan, W. A., 1960: Determination of the straight line of best fit to observational data of two related variates when both sets of values are subject to error. *Quart. J. R. meteor. Soc.*, **86**, 107–113.

Reynolds, S. E., and R. R. Braham, Jr., 1952: Significance of the initial radar echo. *Bull. Amer. meteor. Soc.*, **33**, 123.