SEEDING OF SUMMER CUMULUS CLOUDS

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Introduction

As a result of basic studies of the properties of summer cumuli carried out during the period 1953 to 1957 by the University of Arizona and the University of Chicago, it was established that building cumuli in southeastern Arizona are generally supercooled to levels colder than -10° C. Furthermore, it was found that over the mountain ranges surrounding Tucson, Arizona, there are large convective clouds for 40 to 50 days each summer and that most of these clouds do not rain naturally. It was concluded that the prevalence of supercooled cloud droplets indicated a deficiency of effective ice nuclei, and that as a result, these clouds might be amendable to modification through the introduction of artificial nuclei.

On the basis of present-day theories of clouds and precipitation, a program of observations was devised from which it was possible to obtain these measurements which would permit a study of natural physical processes and an evaluation of the effects of artificial nuclei.

Field experiments were conducted during the summers of 1957, 1958, and 1959. The first year's program consisted of a joint operation by the Universities of Arizona and Chicago. The research was sponsored in part by a National Science foundation grant to the University of Chicago. The investigations conducted in 1958 were conducted by the University of Arizona under Grant Number NSF-G5607 with an equal contribution of State funds. This report summarizes the results of the research conducted through 1959.

Design of Experiment

The design of the seeding experiment has been discussed in some detail in an earlier report (1).[2/] Briefly, the procedure involved an objective prediction, made prior to 0900 MST of each day, as to whether or not cumulus congestus or cumulonimbus clouds would form over the Santa Catalina Mountains. The main criterion for the prediction was whether or not the precipitable water at Tucson, Arizona, exceeded 1.10 inches. When this occurred, the day was considered to be suitable for seeding, and an envelope was opened which specified which of two adjacent suitable days would be seeded. If more than one unsuitable day separated two suitable days, the first day of the pair was rejected and a new pair was started. The scheme of randomized pairs was adopted in order to take into account day-to-day correlations and to assure that there would be an equal number of seeded and not-seeded days.

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The actual seeding was carried out with an Australian-type airborne silver-iodide generator suspended under the wing of a Supercub airplane owned and flown by the Hudgin Air Service. The flight plan involved repeated passes at about the -6° C. level on a track upwind from the mountain range. The pilot normally started the generator at about 1230 MST and continued his flight until all the seeding material was exhausted or the burner went out. Normally the seeding period was of the order of 4 hours. The generator consumed a 20 percent solution of silver iodide in acetone at a rate of 2 to 2-1/2 gallons per hour.

Observations

In order to permit studies of cloud and precipitation processes a variety of observations were made.

Properties of visual clouds.--A pair of carefully calibrated ground-located K-17 aerial cameras was installed at the ends of a 3-mile base leg. Both cameras were triggered simultaneously at 10-minute intervals. When particularly interesting clouds were present photographs were taken at 1-minute intervals. From the pairs of photographs it was possible to make accurate calculations of cloud top heights (4).

Time lapse photographs at 7-second intervals were also taken with a 16-mm. camera.

Precipitation formation as revealed by radar.--An AN/TPS-10A radar set was operated throughout the summer. This set was modified to give a symmetrical one-degree beam. The scanning rate was rigidly controlled so that the vertical scanning rate was exactly one per second and the azimuthally scanning rate was exactly one degree per second. The region over the mountain range was examined once every 3 minutes.

From the film records of the radar scope, it is possible to study the location of the initial precipitation echoes, the rates of spread of precipitation, and the frequency of large convective clouds.

Rainfall.--A network of 29 recording rain gauges was installed to measure the amount and distribution of rainfall.

Lightning.--A lightning counter of commercial design and a Weather Bureau electric field meter were installed on Mount Bigelow, a peak which has an elevation of about 8,500 feet. Various difficulties prevented consistent lightning observation with these two instruments; however, two observers made reliable visual observations of cloud-to-ground lightning strokes.

Results

The number of pairs of days investigated during 1957, 1958, and 1959 were 16, 16 and 20 respectively. On the basis of preliminary statistical and physical analysis one of the 1959 pairs has been tentatively rejected. One of the days of this pair had an extraordinary amount of precipitation. The difference between the rainfalls on the seeded and not-seeded days fell more than six standard deviations away from the mean of the other pairs.

Although the analysis is still in progress, the results to date suggest that the AgI seeding caused some important changes in the natural cloud processes. The results obtained thus far are briefly summarized in subsequent paragraphs.

There have been fairly large differences in the results from year to year. The data accumulated in 1957 and 1958 favored the hypothesis that AgI seeding increased rainfall, caused more large thunderstorms, more lightning and more precipitating clouds (2). In 1959 the results were generally in the opposite direction. There was more rainfall, more lightning, and more large thunderstorms on the not-seeded days. Could this have been a result of the seeding or was this an accidental result which came about because the clouds on the seeded days were smaller and less vigorous than on the not-seeded days? In order to minimize the effects of differences of clouds on seeded and not-seeded days randomization has been employed. It should be recognized, however, that randomization will assure similar samples of seeded and not-seeded clouds only if the samples are large. Twenty pairs do not represent large samples. From observations of the clouds during the summer of 1959, it seemed evident to the authors that, on the whole, the convective clouds on the not-seeded days were more numerous and more vigorous than on the seeded days. In order to arrive at valid conclusions it is necessary to group the data together. The experiments are designed so that this can be done. Final evaluations must await the completion of the planned five years of experiments. In the discussion of the results, statistical evaluations are given, but the reader is urged to treat them with reservations.

Rainfall.--When the data for three years were combined it was found that the mean rainfall per gage was 7 per cent higher on the seeded days. However, the probability that the observed differences in the mean rainfall occurred by chance was very high, 0.30. This value was obtained from a sign-rank test (see reference 4, page 596) which made use of a ranking of the differences of the mean rainfall on pairs of days.

A comparison of the extreme rainfalls on seeded and not-seeded days was made by taking the differences of the maximum rainfalls at any station on days of each pair. During 1957 and 1958, heaviest rains fell most frequently on the seeded days. In 1959 the reverse was true. A sign-rank test showed that the probability of obtaining the observed differences by chance was 0.33.

It is evident that the rainfall data have failed to show that seeding causes increases in precipitation. However, it is also clear that rain gages spaced 4 to 5 miles apart have serious shortcomings when one wants to measure precipitation from convective showers having diameters of 2 to 3 miles. Evaluation procedures which make use of observations of large regions of the cloud should more readily detect changes if any are produced by cloud seeding.

Heights of thunderstorms.--An objective way to measure the relative frequencies of large thunderstorms is to take radar observations every 30 minutes and note whether there is at least one echo extending above any particular altitude. The results for the first three years of operations are given in table 1. It can be seen that the data for 1957 and 1958 are more numerous than that presented in an earlier report (1). This has come about because the evaluation was changed in order to include more observations. During 1957 and 1958, the radar film was changed on the hour. As a result there were many missing photographs exactly on the hour. In the new evaluation, the film was examined during the period five minutes before and five minutes after the hour and the film closest to the 30 minute marks was analyzed. As was the case with the original film analysis, it was done by someone who was not apprised of which days were seeded.

Table 1. Frequency of observations with thunderstorms exceeding the indicated altitudes (in thousands of feet)

	Altitudes			
	≥30	≥35	≥40	≥45
Seeded	135	75	48	11
Not-Seeded	104	55	36	8
Ratio s/NS	1.30	1.35	1.33	1.38
P	0.21	0.21	0.16	---

It is evident that on the seeded days there were 30 to 40 percent more large thunderstorms than on the not-seeded days. By taking the differences by pairs of days one can make use of a sign test (see reference 4, p. 598) to calculate the probabilities of obtaining the observed differences by chance. The results of such an analysis are given in the last row. The indicated probability (P) values of the order of 0.18 are encouraging but certainly not conclusive.

Lightning.--Lightning observations were not made in 1957. In 1958 it was found that on the seeded days there was about nine times more lightning. In 1959, the seeded days had only about half as many strokes as on the not-seeded days. See Table 2.

Table 2. Number of observed lightning strokes.

	Seeded	Not-Seeded
1958	1265	138
1959	357	692
Totals	1622	830

When both years are combined, the ratio of strokes is close to two with more having been observed on the seeded days. A sign-rank test revealed that the probability of chance occurrence of the observed ranking of the differences of strokes on pairs of days was about 0.14. This is considerably higher than the value of 0.015 found from the 1958 data alone.

Initiation of precipitation.--By means of the cloud camera and radar data, it was possible to note the vertical extent of clouds (and thus cloud-top temperatures) and whether or not they contained precipitation. When a sufficient number of clouds have been examined it becomes possible to speak of the "probability of precipitation" of clouds whose summit temperatures are between -12° and -18° C., or any other temperature interval. Figure 1 shows a summary of the observations made during 1957, 1958 and 1959.

It should be noted that this evaluation of the results of seeding differs from the others discussed in earlier paragraphs because it does not depend on the total number of clouds on seeded or not-seeded days. Instead, it examines the ratio of clouds with rain. Thus the presence of more clouds on seeded (or not-seeded) days should not materially affect the results provided the number of clouds are sufficiently large.

It is evident from Figure 1 that at all subfreezing intervals between -6° C. and -37° C., the likelihood of precipitation echoes was higher on seeded days. The differences were particularly large in clouds whose summit temperatures were below -18° C. Over the temperature interval -6° C. to -36° C. the fractions of cloud with radar echoes on seeded and not-seeded days were 0.37 and 0.24 respectively. These data strongly suggest that the AgI nuclei induced precipitation in clouds which would not have precipitated naturally.

Altitude of initial echoes.--A study is being made of the altitudes and temperatures at which the initial radar echoes formed. The results of the analyses of all the 1957 and most of the 1958 observations are shown in Fig. 2. Several features of these diagrams are worthy of comment. First of all, it is noted that on the seeded days, there were considerably more initial echoes at all altitudes except in the 10,000 to 12,000 ft. interval. However, the difference may not be immediately assumed to have been a result of seeding. A sign-rank test of the differences of numbers by pairs of days failed to show them to be significant.

The diagrams also show that distribution curves on seeded days were shifted to higher altitudes and lower temperatures. These data suggest that the silver iodide crystals may have caused the cloud particles to reach detectable sizes at higher elevations in the clouds.

Also shown in Fig. 2 are the data on initial echoes obtained by Braham (5) from an analysis of radar observations made at the University of Arizona in 1955. It is seen that the distribution curve is shifted to even lower altitudes than the not-seeded curve. Ackerman (6) analyzed Arizona data collected in 1956 when there was no seeding. She also found a maximum frequency in the 18,000 to 22,000 ft. interval, but the peak was flat, with the next highest interval only slightly less frequent. The mean heights of the tops initial echoes during non-seeded periods were 19,500 ft. in 1955, 21,500 ft. in 1956 and 21,800 ft. for 1957 and 1958. On the other hand, on seeded days during 1957 and 1958 the mean height of the echo tops was 22,600 ft.

The data show that on the seeded days, the initial echoes tops had a mean temperature of -11.3° C. while on the not-seeded days it was -9.4° C.

The shift of the mean echo top to higher altitudes and lower temperatures on seeded days, if it were caused by seeding, may have come about in two ways. First, the introduction of the nuclei may have caused precipitation to form in clouds which would not have formed echoes naturally. If this were to occur, and data presented in Fig. 1 suggest that this did happen, it would be expected that clouds having temperatures substantially below -5° C. would be necessary. The AgI particles may be active at this temperature but the crystal must be in supercooled cloud for perhaps 10 minutes before it can be detected. If the nucleation occurs in a region of ascending air, the initial echo would not be expected to be found until the particles have been carried upwards perhaps 10,000 ft. Figure 1 shows that a large difference between the likelihood of precipitation in seeded and not-seeded clouds was not found until cloud top temperatures of -18° C. were considered. If the reasoning here is valid, one would expect that if precipitation were initiated in clouds which would not have precipitated if they were not seeded, the mean echo height in these clouds would be higher than in naturally precipitating clouds represented by the dashed lines in Fig. 2.

A second way in which seeding may influence the location of the initial echo might be through accelerating the precipitation process in clouds which would have precipitated naturally. Braham (5) and Ackerman (6) have shown that about half the convective echoes they observed had reached their maximum height at the time of initial detection. It could be argued that just before the particles reached detectable size they were either ascending or descending according to whether the echoes ascended or descended immediately after initial detection. If this were true, then acceleration of the growth process may cause the "artificial initial echo" to be either lower or higher than the "natural initial echo" would have been. The observed factor of one-half suggests that statistically this effect of seeding would be difficult to detect.

Summary

The results of experiments conducted during the first three summers of a five-summer research program strongly suggest that the AgI seeding produced some important effects. However, on the basis of the statistical tests, one must still admit the possibility that the results were brought about by chance. The continuation of the program should permit the accumulation of sufficient data to answer, in definite terms, whether or not the results observed were caused naturally or artificially.

References

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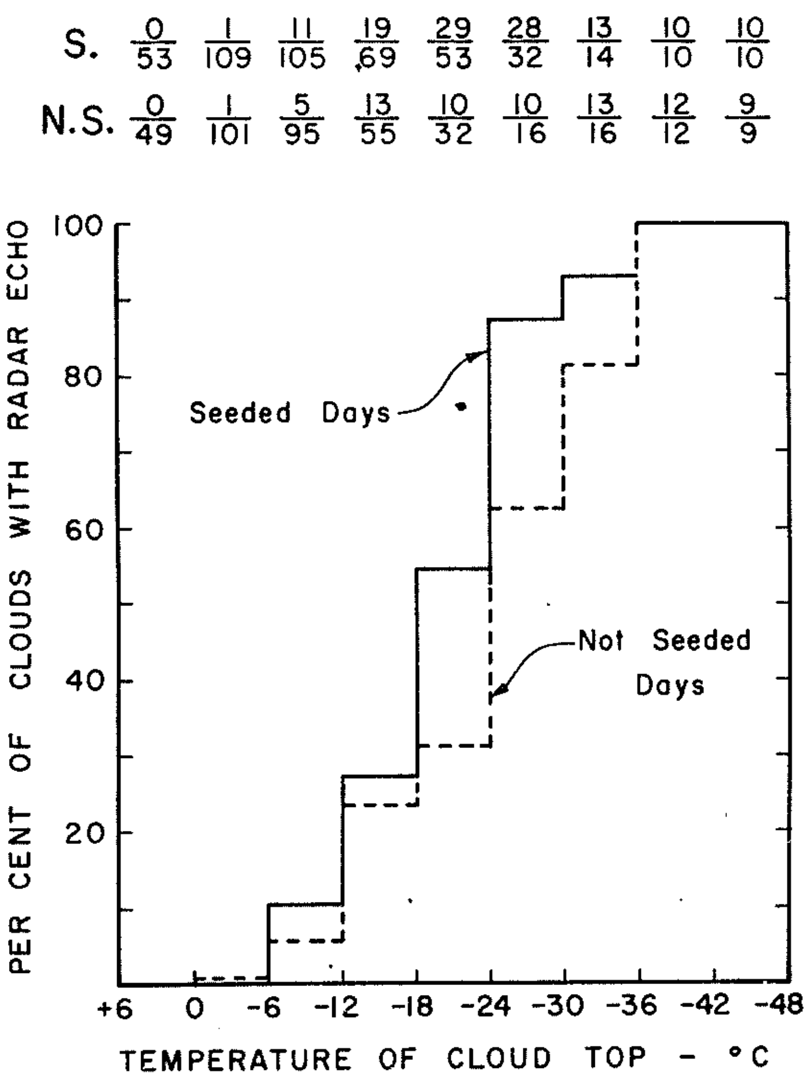

Figure 1

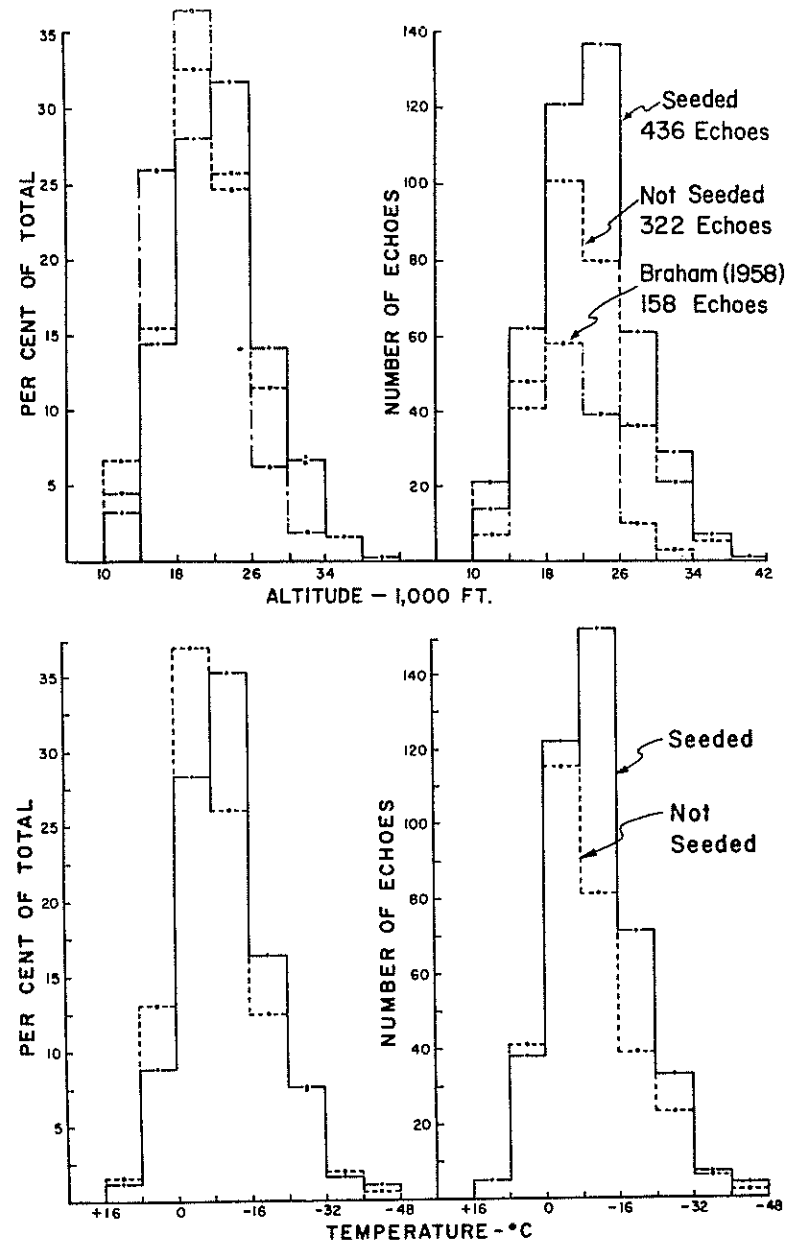

Figure 2

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