Silver-Iodide Seeding and Rainfall from Convective Clouds¹

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ABSTRACT

Summer convective clouds over a fairly isolated mountain range over southeastern Arizona were seeded by means of airborne silver-iodide generators. The selection of days to be seeded was made according to a randomization scheme involving the examination of pairs of days. After a program conducted during the period 1957 to 1960 failed to show that rainfall was increased, the experimental procedures were changed and a second set of tests were performed during 1961, 1962 and 1964.

This report deals with the analysis of rainfall measured by networks of recording rain gages over the mountain target. The data do not support a hypothesis that rainfall was increased as a result of the silver-iodide seeding.

1. Introduction

During the summer, the climate of southeastern Arizona is characterized by high temperatures and convective precipitation. Starting during the first week of July and ending in early September, it is common to observe convective clouds forming over the mountains and growing to the sizes where considerable rainfall and lightning are produced. Some of the characteristics of these clouds have been reported by Morris (1957), Braham (1958) and Battan and Kassander (1960).

As noted in the last reference, it appeared in the middle fifties that the convective clouds could be modified by the introduction of ice nuclei. The reasons for this supposition were the following: 1) Clouds seldom develop precipitation until their summit temperatures are below -10°C and even at temperatures of about -20°C fewer than half the clouds develop precipitation echoes on an AN/TPS-10, a 3-cm radar set; 2) measurements of ice nuclei showed the normal background to be below about 0.1 per liter at -10°C ; 3) it appeared that precipitation in these clouds might depend on the Bergeron-Findeisen process. Principally for these reasons, a program of cloud physical studies and cloud seeding experiments were initiated in 1957 as a cooperative effort of The University of Chicago and The University of Arizona. The latter organization then continued the program from 1958 through 1964. Over the entire period, cloud seeding tests were conducted for a total of seven summers.

All the tests during the summers 1957 to 1960 were carried out according to the same experimental procedure. This phase of the research will be called Program I. In 1961 the experimental design was changed and a new series of tests were conducted during the

summers of 1961, 1962 and 1964. This will be called Program II.

2. Design of the program

Recognizing the fact that there is no satisfactory theory for predicting the quantity of rain which will fall from a convective cloud or even for explaining the amount of rainfall after the fact, it was decided at the outset that it would be necessary to use statistical procedures in order to discriminate between natural rainfall and rainfall which might be caused to fall as a result of the seeding.

Battan and Kassander (1960) have already described in detail the design of Program I. Briefly, the essential factors were the following.

On the basis of earlier studies, an objective forecasting technique was devised, based almost entirely on the precipitable water between the ground and 400 mb as observed by the radiosonde taken at about 0500 MST. When the precipitable water exceeded 1.10 inch, clouds capable of producing rain were predicted and the day was considered to be suitable.

On the first such day an envelope was opened in which were contained instructions for two successive suitable days. The instructions were "seed today—do not seed tomorrow" or *vice versa*. The first of these instructions was determined by a randomization scheme; the second day was just the opposite of the first. One suitable day was allowed between members of a pair. This included Sundays which were all non-working days, and days when the precipitable water fell below 1.10 inch. If more than one day interrupted the pair, it was discarded and a new envelope was opened.

The target area was the Santa Catalina Mountains, a region about 15 by 20 mi (Fig. 1). The highest peak extends to an elevation of 9200 ft MSL.

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FIG. 1. The network of 29 recording rain gages over the Santa Catalina Mountains in southeastern Arizona used as a target area during the period 1957 to 1960.

On seeded days a Supercub airplane, equipped with a silver-iodide generator of Australian design, was flown at the -6°C level (18,000–20,000 ft) during the period between about 1230 and 1630 MST. The actual duration of seeding ranged between 2 and 4 hr depending mostly on the functioning of the generator. The airplane was flown back and forth along a line 15–20 mi long perpendicular to the wind at flight level and about 30 min upwind from the foothills of the mountains. Silver-iodide consumption was at a rate to produce a calculated average concentration of about 80 nuclei per liter at -10°C . This calculation, made to obtain some idea of the concentrations of ice nuclei, assumed that the particles were uniformly distributed through a depth

of 1 km over the “target area.” It is not likely that the concentration of nuclei was uniform, but the degree of nonuniformity is hard to specify. The aim of the seeding procedure was to produce a blanket of nuclei through which cumuli would penetrate as they grew to higher altitudes.

Nuclei should have been entrained into the cloud through the cap and sides of the growing clouds. The evidence for entrainment is well established both theoretically and experimentally [see, for example, Simpson *et al.* (1965)].

Assume that a mass M of cloud air completely devoid of nuclei passes through the proposed layer of nuclei having a depth of 1 km and a uniform nuclei

concentration of 80 per liter. If the entrainment rate is 10^{-6} cm^{-1} (Squires, 1962), the mass of rising air at the top of the layer will have increased to 1.1 M and have an average nuclei concentration of 7 per liter effective at -10°C . Over the estimated range of actual entrainment rates of 4×10^{-7} to 10^{-5} cm^{-1} , the computed average nuclei concentration in the rising mass of air would range from 3 to 40 per liter.

It is recognized that in some clouds the concentrations of nuclei would be much smaller and in others much larger, than the calculated averages found to be of order 10 per liter.

Observations of the following physical variables were made during the period 1300 to 1800 MST on all seeded and nonseeded days.

a) Rainfall was measured by recording gages distributed as shown in Fig. 1. All the records for the entire summers were reduced by student assistants who did not know which days were seeded. They tabulated hourly amounts.

b) The occurrence and spread of precipitation was observed by means of a vertically scanning 3-cm, AN/TPS-10 radar set located about 18 mi southwest of the highest peak in the Santa Catalina Mountains.

c) The visual properties of clouds over the target area were observed by means of a pair of ground-based aerial cameras at the ends of a 3-mi base leg directed along parallel horizontal lines. One of the cameras was located at the same place as the radar set. These cameras normally took photographs simultaneously at intervals of 10 min. In addition, a 16-mm camera took time-lapse pictures at 5-sec intervals.

d) Visual observers located at a mountain observatory recorded cloud-to-ground lightning over the target area.

Analyses of the observations collected by these means have been and continue to be made. While the final report of this research project will not be complete until all the results have been published, some have already appeared (Battan 1963, 1964). In this article only the analysis of the rainfall data will be discussed. Other analyses will be reported in future papers.

3. Rainfall at the ground, 1957–1960

The decision to randomize by pairs of days over a single “target” area was made after consultations with Drs. A. K. Brownlee and W. A. Kruskal, statisticians at The University of Chicago. It was based on various considerations. At the start of the research there were no data which would allow the correlation of rainfall over various mountain areas in this region. In fact, visual observations of the clouds indicated that even over nearby mountain ranges the correlation was low. This situation dictated against a target-control-area procedure. Subsequent to the start of this program, rainfall over the Santa Catalina Mountains was com-

pared with that over a watershed in the vicinity of Tombstone some 60 mi to the southeast. There was virtually no correlation. The same is true when the mean rainfall over the mountain area during the period 1300–1800 MST, was compared with the mean daily rainfall of 4 gages located in the valley in which Tucson is located. These results are presumably a consequence of the fact that almost all the summer rain is from convective clouds whose initiation and growth depend on mesoscale properties of the atmosphere and the topography.

The decision to use pairs of essentially consecutive suitable days was based on various considerations. At the outset there appeared to be some day-to-day correlation of rainfall. After the rainfall data were collected, calculations were made of day-to-day correlations among the pairs of days used in the seeding tests. It was found that in both Programs I and II, the correlation coefficients were 0.10 or less.

The use of a seeding procedure based on pairs of days has the advantage of producing the same number of seeded and not-seeded days during each summer. For reasons still not understood, some summers are wet, others are dry. During a typical summer, one can expect about 30 suitable test days. If each day were either seeded or not seeded on a random basis, it would be reasonable to expect unequal number of seeded and not-seeded days during each summer. If the randomization scheme led to a higher percentage of seeded days during dry summers, a “negative” bias might be introduced into the experiment. The pair scheme guarantees an equal number of seeded and not-seeded days during all summers and acts to eliminate this particular source of bias.

At the start of the program it was decided that the difference of rainfall on seeded and not-seeded days would be measured as the difference between the average rainfall on seeded and not-seeded days of each pair. One can regard this average as a measure of the total rainfall standardized in such a manner as to take into account the effects of inoperative rain gages.

Table 1 presents rainfall data for Program I. At the outset, the Wilcoxon signed rank test [see Wallis and Roberts (1956, p. 596)] was selected as a suitable one for calculating the probability of chance occurrence of the observed results. This test is most powerful when the two elements of a pair are perfectly matched. It is also valid when they are not well matched, but the sensitivity of the test diminishes as the correlation diminishes. The finding of the extremely low correlation between days in the pairs leads to the conclusion that the individual days can be treated as being independent. Thus, tests of inference have also been made by means of the Mann-Whitney U test, one of the most powerful of the non-parametric tests (Siegel, 1956).

Average rainfall on seeded and not-seeded days is given in Table 2. This includes all the data including

TABLE 1. Tabulation of precipitable water in inches, total and mean rainfall per gage between 1300 to 1800 MST in inches and the number of stations with rainfall on seeded and not-seeded days during summers 1957 to 1960.

Date	Seeded				Not seeded				Difference of means
	Precipitable water	Total rain	No. gages with rain	Mean rain	Precipitable water	Total rain	No. gages with rain	Mean rain	
July 1957									
8	1.54	0	0	0	1.26	4.01	22	0.154	-0.154
10	1.15	4.16	14	0.154	1.19	0	0	0	+0.154
13	1.31	0.07	2	0.003	1.24	0.22	5	0.008	-0.005
16	1.42	2.26	7	0.084	1.25	0.83	5	0.033	+0.051
19	1.38	0.04	1	0.002	1.60	0.87	7	0.035	-0.033
29	1.34	4.09	10	0.157	1.40	0.19	2	0.007	+0.150
30	1.22	0.28	2	0.010	1.37	3.50	18	0.140	-0.130
August 1957									
1	1.54	0	0	0	1.65	0.60	2	0.022	-0.022
9	1.36	0.04	1	0.002	1.37	0	0	0	+0.002
12	1.64	2.12	8	0.078	1.50	1.99	10	0.074	+0.004
15	1.65	2.63	11	0.101	1.42	0.06	1	0.002	+0.099
16	1.57	4.56	9	0.169	1.45	8.26	18	0.318	-0.149
20	1.62	3.61	9	0.139	1.62	2.41	10	0.096	+0.043
22	1.37	4.46	24	0.172	1.49	0	0	0	+0.172
24	1.30	0	0	0	1.33	0	0	0	0
26	1.31	0	0	0	1.18	1.30	8	0.050	-0.050
Totals (1957)	22.72	28.32	98	1.071	22.32	24.24	108	0.939	+0.132
July 1958									
17	1.54	3.94	12	0.152	1.36	0.37	11	0.013	+0.139
18	1.68	0	0	0	1.43	0	0	0	0
24	1.11	0	0	0	1.25	12.47	19	0.445	-0.445
31	1.28	0.05	2	0.002	1.59	0	0	0	+0.002
August 1958									
2	1.29	0.19	1	0.007	1.40	2.30	6	0.079	-0.072
4	1.54	0.36	5	0.013	1.83	0.15	1	0.006	+0.007
6	1.40	4.52	15	0.161	1.22	0.21	1	0.008	+0.153
12	1.34	0	0	0	1.47	0.03	1	0.001	-0.001
14	1.51	7.40	16	0.274	1.52	0.02	1	0.001	+0.273
16	1.44	0.02	1	0.001	1.44	0.69	4	0.025	-0.024
19	1.46	3.53	14	0.122	1.65	1.33	6	0.046	+0.076
21	1.29	2.83	11	0.101	1.46	0.20	1	0.007	+0.094
August 1958									
25	1.53	0.31	4	0.012	1.63	0.52	2	0.019	-0.007
28	1.23	0.05	2	0.002	1.11	0	0	0	+0.002
29	1.51	1.66	10	0.066	1.45	0	0	0	+0.066

TABLE 1 (Continued).

Date	Seeded			Not seeded			Difference of means
	Precipitable water	Total rain	No. gages with rain	Precipitable water	Total rain	No. gages with rain	
September 1958							
4	1.45	1.07	13	1.12	0.31	4	+0.028
Totals (1958)	22.60	25.93	106	22.93	18.60	57	+0.291
July 1959							
7	1.35	0.39	4	1.23	0	0	+0.015
10	1.13	0	0	1.12	0	0	0
14	1.11	0	0	1.25	2.14	13	-0.086
16	1.38	0.53	4	1.49	0.16	2	+0.015
18	1.24	0	0	1.40	2.76	13	-0.115
20	1.38	0.09	1	1.57	2.24	7	-0.086
23	1.40	0.28	2	1.32	0	0	+0.010
28	1.55	0	0	1.57	0	0	0
30	1.42	1.42	12	1.19	0	0	+0.055
August 1959							
4	1.58	0.10	3	1.50	1.97	3	-0.072
6	1.46	1.38	5	1.57	2.24	8	-0.037
7	1.36	0	0	1.33	0	0	0
11	1.75	0	0	1.49	2.18	8	-0.078
12	1.55	2.51	13	1.72	3.27	10	-0.031
18*	1.66	0.79	6	1.69	28.80	28	-0.999
20	1.15	0	0	1.55	3.03	10	-0.104
22	1.53	0.84	4	1.30	0.68	3	+0.009
24	1.53	3.73	16	1.57	2.07	15	+0.061
27	1.49	2.25	10	1.35	0.07	2	+0.081
29	1.52	0	0	1.44	0	0	0
Totals (1959)	28.54	14.31	80	28.65	51.61	122	-1.362
July 1960							
7	1.15	0	0	1.25	0.27	3	-0.010
8	1.12	0	0	1.22	0	0	0
25	1.68	1.04	14	1.19	1.37	10	-0.015
27	1.42	0	0	1.37	0.99	14	-0.040
				1.14	0	0	+0.042
August 1960							
1	1.18	0.97	7	1.50	0	0	0
2	1.30	0	0	1.56	1.96	8	-0.093
8	1.52	0	0	1.54	3.85	9	-0.031
10	1.72	3.20	13	1.69	0	0	0
12	1.35	0	0	1.13	0	0	0
17	1.30	0	0	1.34	0	0	0
22	1.47	0	0	1.17	0	0	0
25	1.13	0	0	1.16	0	0	0
27	1.52	0	0	1.11	0	0	0
31	1.47	0.20	7				+0.008

TABLE 1 (Continued).

Date	Seeded				Not seeded				Difference of means
	Precipitable water	Total rain	No. gages with rain	Mean rain	Precipitable water	Total rain	No. gages with rain	Mean rain	
September 1960									
2	1.38	1.07	10	0.040	1.37	1.62	16	0.060	-0.020
6	1.51	0.08	3	0.003	1.48	2.76	11	0.102	-0.099
8	1.14	0.30	3	0.011	1.54	1.15	8	0.041	-0.030
Totals (1960)	23.36	6.86	57	0.298	22.76	13.97	79	0.586	-0.288
Grand totals	97.22	75.42	341	2.850	96.66	108.42	366	4.077	-1.227
Mean 69 pairs	1.41	1.09	4.9	0.041	1.40	1.57	5.3	0.059	-0.018
Totals minus 17-18 Aug. 1959	95.56	74.63	335	2.822	94.97	79.62	338	3.050	-0.228
Mean 68 pairs	1.40	1.08	4.9	0.042	1.40	1.17	5.0	0.045	-0.003

* See text for discussion of these days.

the pair of days on 17-18 August 1959. The last line shows the over-all averages when this pair is not included. In an earlier mimeographed report² the authors questioned whether or not this pair should be included in the analysis because of the large quantity of precipitation on 17 August 1959. As far as the statistical tests of significance are concerned, the extreme magnitude has little influence but it obviously has a great effect on rainfall averages. We proposed that this pair might be rejected on the grounds that the likelihood of its being from the same meteorological population as the other days was extremely small. Subsequent experiments show that this might not be the case. One statistician has made the point that since 17 August 1959 cannot be shown to belong in another population, the pair should be retained.

The question arises whether these data support the hypothesis that silver-iodide seeding decreased precipitation. By means of the Wilcoxon signed-rank test, a calculation was made of the probability that the results

TABLE 2. Summary of average of mean rainfall 1300-1800 MST (in inches) on seeded and not-seeded days for the years 1957-1960.

Year	Number of pairs	Seeded days	Not-seeded days	$\frac{S}{NS}$
1957	16	0.067	0.059	1.14
1958	16	0.059	0.041	1.44
1959	20	0.026	0.094	0.28
1960	17	0.018	0.034	0.51
All years	69	0.041	0.059	0.70
With 17-18 August 1959 not included	68	0.042	0.045	0.93

of the program could have occurred by chance. This analysis yields a one-tailed probability of 0.30 when all data are included and a value of 0.38 when the pair on 17-18 August 1959 is excluded. The Mann-Whitney U test made with all the data gave a one-tailed probability of 0.45. Clearly the results might have occurred by chance, and do not allow rejection of the hypothesis that silver-iodide seeding, carried out in the manner used in these tests, had no effect on precipitation.

One might reasonably ask if the seeding influenced the lateral extent of the rainfall. The number of gages with rain is a measure of this effect. Note that Table 1 lists this information. In order to take into account the fact that on some days one or more gages were inoperative, the number of gages with rain was standardized to 29 gages by multiplying by the factor 29 divided by the number of operating gages. It can be seen from the standardized data in Table 3 that the total number of gage-days with rain was 375 on seeded

² Battan, L. J., and A. R. Kassander, Jr., 1962. Evaluation of effects of airborne seeding of convective clouds. Sci. Rep. No. 18, Inst. Atmos. Phys., The University of Arizona, March 1962, 69 pp.

days and 403 on not-seeded days. This represents a difference of about 7 per cent. The signed-rank and the Mann-Whitney U tests yielded one-tailed probabilities of 0.41 and 0.48, respectively. These data do not allow the rejection of the hypothesis that seeding had no effect on the lateral distribution of rainfall over the rain-gage network.

A question will surely arise as to whether it is valid to group the data for all four years. It would be tempting to say that during the first two years the meteorological conditions were suitable for seeding and, therefore, there was an increase in the rainfall on the seeded days, while during 1959 and 1960 the reverse was true. As was noted earlier, the pairing scheme was adopted so that data from succeeding years could be grouped.

Another point of interest is whether or not there was, over the entire period of experimentation, a difference in the likelihood of rain on the seeded or not-seeded days. We pointed out in our earlier paper that at least statistically, the higher the precipitable water, the

was discontinued and a new set of experiments was initiated.

Major features of new seeding project. One of the difficulties with the original experimental design was that it was not sensitive enough. The major reason for this is the high rainfall variability. In order to reduce the number of days with zero rainfall, the criterion for selecting suitable working days was made more restrictive. As noted earlier, the primary criterion for predicting suitable days in Program I was that the precipitable water, as indicated by the 0500 MST radiosonde data, be greater than 1.10 inch. In the new program, a day was considered to be suitable only if the precipitable water was equal to or greater than 1.15 inch at both 0500 and 1700 MST. If it was assumed that the rainfall data collected during the period 1957 to 1960 was truly representative, this criterion would have led to the rejection of many days with zero rainfall.

It was calculated, from data collected during 1957 to 1960, that under this criterion for selection of suitable days, it would have been possible to establish, if it existed, a 20 per cent rainfall increase (at the 0.05 significance level) after about 5 years of experimentation.

A second step taken to attempt to reduce the sampling variability was to increase the concentration of rain gages. During the period 1957 to 1960 there were 29 gages dispersed over the target area. The concentration of gages amounted to about one gage every 13 mi². From a comparison of radar and rain gage data, it was clear that some showers had fallen between the gages.

In the new tests the number of gages was increased to 35 and the area was reduced to such an extent that the average density of gages was about one every 7 mi² as shown in Fig. 2.

A third major change in the experimental design was that the silver-iodide particles were dispersed at altitudes which usually were 1000–2000 ft below the cloud bases.

Two Project Skyfire generators designed by the U. S. Forest Service (Fuquay, 1960) were mounted on a Cessna 172 airplane. The generators burned a 10 per cent solution of silver iodide in acetone at a rate of about 4 gal hr⁻¹. Except for the altitude at which seeding was done, the flight procedures were the same as those used in Program I. It is estimated that the rate of production of nuclei was of the same order of magnitude as with the Australian burner, but possibly higher by a factor of two to five. The new generator vaporized AgI at about the same rate but is regarded to be somewhat more efficient than the Australian burner.

In Program I, the airplane was flown only on the seeded days. In the revised program, it flew the same type of pattern on not-seeded days, that is across the wind at flight level at a distance corresponding to roughly 30 min of wind movement upwind from the

TABLE 3. Summary of the number of stations with rain for all pairs 1957–1960.

Year	Seeded days			Not-seeded days	
	Number of pairs	Actual number	Standardized to 29 gages	Actual number	Standardized to 29 gages
1957	16	98	108	108	121
1958	16	106	113	57	59
1959	20	80	86	122	131
1960	17	57	68	79	92
Total	69	341	375	366	403

greater the probability of rainfall occurrence. Data gathered since the start of these seeding experiments bear out the earlier findings, but unfortunately, the correlation between the precipitable water on any day and the *quantity* of rainfall during the 1300 to 1800 MST period is low, the correlation coefficients being less than 0.27. It is of interest, however, to note that over the four summer periods the average precipitable water was about 1.4 inch on both seeded and not-seeded days. The difference was less than one-half of 1 per cent. The fact that these numbers are almost identical indicates that the randomization procedure did produce two samples, which as far as precipitable water was concerned, were statistically quite similar.

4. Rainfall at the ground, 1961, 1962, 1964

Following extensive analysis of the data collected during the years 1957–1960, it was clear that a continuation of the same program for any reasonable number of years would not succeed in showing that seeding could increase rainfall. For this reason, the program

FIG. 2. The network of 35 recording rain gages over the Santa Catalina Mountains used as a target area during the years 1961, 1962 and 1964.

nearest mountain slope. This step was taken to equalize the probability of exclusion of either a seeded or not-seeded day on the grounds the airplane was not able to fly because of meteorological or mechanical difficulties.

Except for the factors mentioned, all other aspects of randomization and data collection were identical in Programs I and II.

Rainfall observation. Table 4 presents the data for all suitable pairs of days in the same format as Table 1. The tabulated values of precipitable water represent averages of the quantities calculated on the 0500 and 1700 MST soundings. Note that the over-all mean is about the same as was found in Program I, about 1.40 inch.

Table 5 gives a summary of mean rainfall amounts for each summer.

It can be seen that in terms of mean rainfall there was 30 per cent less on the seeded days. The vital

question is whether this difference occurred because of the silver-iodide seeding or was strictly a matter of chance. The Wilcoxon signed-rank and the Mann-Whitney U tests yield probabilities of 0.16 and 0.30 on the basis of a one-tailed test where the alternative hypothesis is that seeding decreases rainfall. The calculated probabilities are so high that one cannot reject the hypothesis that the observed results could have occurred by chance.³

³ At the Fifth Berkeley Symposium on Mathematical Statistics and Probability in December 1965, R. Gabriel suggested that since the Mann-Whitney U test was appropriate, the sample of days could be increased by including individual valid days of pairs which had to be discarded (see Section 2). In Program I there were only 8 such days and the addition of these data to the 69 pairs already employed had an inconsequential effect on the significance level. In Program II there were 13 additional days. When these were included in the analysis, the results were as follows: The mean rainfall on seeded days was 78 per cent of that on not-seeded days; the Mann-Whitney U Test yielded a one-tailed probability of 0.44.

TABLE 4. Tabulation of precipitable water in inches (mean of morning and afternoon soundings), total and mean rainfall per gage between 1300 and 1800 MST in inches and the number of stations with rainfall on seeded and not-seeded days during 1961, 1962 and 1964.

Seeded					Not-seeded				
Date	Mean precipitable water	Total rain	No. gages with rain	Mean rain	Date	Mean precipitable water	Total rain	No. gages with rain	Mean rain
July 1961					July 1961				
17	1.30	0	0	0	18	1.26	0	0	0
22	1.39	6.69	28	0.203	21	1.34	0.63	10	0.019
24	1.30	0.90	5	0.029	26	1.28	3.29	11	0.122
29	1.48	0.69	3	0.025	27	1.48	2.53	17	0.097
31	1.48	0.74	13	0.025					
August 1961					August 1961				
2	1.42	2.72	18	0.094	1	1.32	8.00	22	0.285
8	1.30	0	0	0	3	1.26	1.35	15	0.044
10	1.40	0	0	0	9	1.23	0	0	0
12	1.28	3.37	16	0.105	11	1.30	0	0	0
15	1.46	0	0	0	14	1.34	0.07	2	0.002
18	1.38	1.22	10	0.038	16	1.34	0.52	7	0.017
21	1.41	0	0	0	17	1.46	2.72	14	0.091
23	1.33	0	0	0	19	1.50	0.17	3	0.005
24	1.44	1.05	9	0.031	22	1.70	5.18	26	0.167
28	1.30	1.34	15	0.039	25	1.28	0.36	3	0.010
					29	1.51	5.09	22	0.154
September 1961					September 1961				
9	1.33	0.17	1	0.005	8	1.38	8.00	29	0.235
12	1.37	0	0	0	11	1.42	18.49	32	0.560
Totals (1961)	23.37	18.89	118	0.594		23.40	56.40	213	1.808
July 1962					July 1962				
20	1.40	1.41	21	0.042	19	1.31	0.02	1	0.001
23	1.47	1.23	8	0.037	21	1.60	0	0	0
24	1.45	0.53	7	0.016	25	1.26	5.95	15	0.186
27	1.58	0	0	0	26	1.38	0.08	3	0.002
					31	1.26	0.38	5	0.012
August 1962					August 1962				
1	1.26	0	0	0	21	1.39	0	0	0
20	1.32	3.37	12	0.109					
September 1962					September 1962				
5	1.38	0.05	2	0.002	4	1.50	2.18	12	0.070
Totals (1962)	9.86	6.59	50	0.206		9.70	8.61	36	0.271
									-0.068
									-0.065

TABLE 4 (Continued).

Seeded				Not-seeded						
Date	Mean precipitable water	Total rain	No. gages with rain	Mean rain	Date	Mean precipitable table water	Total water	No. gages with rain	Mean rain	Difference of means
July 1964										
8	1.35	3.88	14	0.117	9	1.26	3.47	10	0.102	+0.015
13	1.49	4.13	11	0.129	11	1.18	1.40	6	0.042	+0.087
15	1.71	16.56	27	0.552	14	1.30	0.48	5	0.015	+0.537
17	1.23	0	0	0	16	1.20	1.34	7	0.039	-0.039
20	1.29	0.23	5	0.007	18	1.42	3.06	16	0.090	-0.083
21	1.36	0.61	5	0.018	22	1.49	2.37	8	0.072	-0.054
24	1.51	7.30	27	0.208	25	1.44	7.72	22	0.220	-0.012
30	1.50	1.35	10	0.053	29	1.42	12.25	24	0.360	-0.307
August 1964										
4	1.54	0	0	0	3	1.50	0	0	0	0
7	1.16	0.02	1	0.001	5	1.22	0	0	0	+0.001
10	1.45	4.15	15	0.126	8	1.36	0.04	1	0.001	+0.125
14	1.33	0.12	4	0.004	13	1.28	0	0	0	+0.004
17	1.50	3.26	16	0.102	19	1.18	0	0	0	+0.102
Totals (1964)				135	1.317	17.25 32.13 99 0.941				+0.376
Grand totals				303	2.117	50.35 97.14 348 3.020				-0.903
Mean per day				8.2	0.057	1.36 2.63 9.4 0.082				-0.024

TABLE 5. Summary of mean rainfall 1300–1800 MST (in inches) on seeded and not-seeded days for the years 1961, 1962, 1964.

Year	Number of pairs	Seeded days	Not-seeded days	S	
				NS	
1961	17	0.035	0.106	0.33	
1962	7	0.029	0.039	0.74	
1964	13	0.101	0.072	1.40	
Three years	37	0.057	0.082	0.70	

Table 6 shows the number of stations with rain on seeded and not-seeded days.

For the three summers of the experiment, there were about 15 per cent fewer gages with rain on the seeded days. This difference is in the direction of more widespread rainfall on the days which were not seeded. The Wilcoxon signed-rank test yields a one-tailed probability of 0.29. This figure is so high that it must be concluded that the differences in number of gages with rain came about as a result of chance rather than because of the seeding.

An examination of Tables 5 and 6 and the corresponding ones for Program I indicate that the mean (or total) rainfall is related to the number of gages with rainfall. In other words, the more widespread the rainfall the greater the amounts. This is clearly illustrated in Fig. 3 where the average rainfall during the

TABLE 6. Summary of the number of stations with rain.

Year	Number of pairs	Seeded days		Not-seeded days	
		Actual number	Standardized to 35 gages	Actual number	Standardized to 35 gages
1961	17	118	130	213	242
1962	7	50	53	36	40
1964	13	135	144	99	102
Total	37	303	328	348	384

period 1300–1800 is plotted against the number of gages with rain. Similar results were found with the data of Program II. This diagram demonstrates that the two tests of the effects of seeding already discussed, namely, the ones dealing with quantity and lateral distribution of rainfall, are not independent.

The relationship illustrated in Fig. 3 indicates that at least over the area employed in this study and probably other areas where convective precipitation is involved, the more widespread the convective clouds the greater the likelihood of large thunderstorms producing high rates of rainfall.

5. Rainfall and the height of the cloud base

After Mr. Robert D. Elliott⁴ learned the results of Program I, he suggested that positive and negative effects of seeding might be sorted out if the days involved in the study were classified according to the height of the cloud base.

On any particular day the cloud-base height is fairly constant so long as there are not extensive showers and thunderstorms. Once they occur, the cloud base is lowered as the relative humidity of the subcloud air is increased by evaporating rain.

By means of the cloud photographs, measurements were made of the cloud-base heights of specific clouds. Unfortunately, the number of measurements varied from one day to the next and on some days none were obtained. In order to make it possible to utilize all of the rainfall data, it is desirable to have a convenient index of the height of the cloud base. One might expect that the greater the relative humidity in the subcloud air, the lower the cloud base. This is confirmed by Fig. 4 where the measured height of the cloud base is plotted against the dew-point temperature spread at the 850-mb level at 1700. The scatter of the points can be attributed, in part, to the fact that each point represents the average of only a limited number of cloud-base measurements, that on some occasions there are uncertainties in the measurements, and that the clouds were observed from 4 hr before to 1 hr after the sounding was made. Nevertheless, the two variables are clearly correlated.

⁴ Private communication.

FIG. 3. Scatter diagram of mean rainfall per gage during the period 1300 to 1800 MST vs. the number of gages with measurable rainfall for the period 1957 to 1960. The dashed line was sketched in by eye.

FIG. 4. Scatter diagram of measured cloud-base altitude vs. the 850-mb dew-point spread at 1700 MST.

It is concluded that when the dew-point spread at 850 mb is small, the cloud-base height is relatively low and the relative humidity is relatively high. All the days included in the seeding experiment in the period 1957 to 1960 were classified according to the 850-mb dew-point spread at 1700 MST.

Following a suggestion by Mr. Elliott, the days were divided into three nearly equal groups. The group with low-cloud bases correspond to a dew-point spread of 3–12.0°C, the next group included dew-point spreads of 12.1–16.0°C, while the group with high cloud bases included all days with dew-point spreads greater than 16.0°C. A summary of the data is given in Table 7.

The differences between the seeded and not-seeded days represented by line 1 were examined by means of the Mann-Whitney U test and found to be significant at the 0.21 level (one-tailed test). If the data for 17 and 18 August are excluded, the Mann-Whitney U test yield significance levels of 0.11. The greatest difference was found in the sample of days represented by the last line of Table 7. The Mann-Whitney U test yielded a significance level of 0.02.

These results indicated that this type of analysis was worth pursuing further even though no conclusions regarding the effects of seeding could yet be drawn.

The new data collected during Program II were subjected to the same analysis as the one just described. Table 8 summarizes the results.

It is clear that for every category the mean rainfall was less during the seeded period. Calculations by means of the Mann-Whitney U test yielded one-tailed probabilities of chance occurrence greater than 0.10. Thus, one is led to conclude that the results probably occurred by chance.

From Tables 7 and 8, it is evident that on the average, the quantity of rain is related to the 850-mb dew-point spread and to the height of the cloud base. If all the data are combined, it is found that the rainfall averages for the three classes of dew-point spread, 3–12.0°C, 12.1–16.0°C, 16.1–32.0°C are 0.086, 0.051, 0.026 inches. From Fig. 4 one can associate these quantities with mean cloud-base altitudes of about 8500, 10,500 and 12,500 ft. It is not surprising that there is a large range of rainfall amounts for any cloud base height because other factors may greatly influence the quantity of rainfall.

6. Hourly rainfall and cloud seeding

Elliott (1962) proposed that the effects of silver-iodide seeding might become more evident if precipitation rates measured over short periods of time were

TABLE 7. Summary of mean rainfall (1300–1800 MST) for three categories of 850-mb dew-point spread at 1700. Date collected: 1957 to 1960.

Dew-point spread (°C)	Seeded days			Not-seeded days		
	Number of days	Mean rainfall	Days with zero rain	Number of days	Mean rainfall	Days with zero rain
3–12.0	25	0.071	5	28	0.078	6
(3–12.0) *	24	0.073	5	27	0.043	6
12.1–16.0	20	0.036	6	18	0.062	5
16.1–32.0	23	0.013	14	22	0.034	12

* This line excludes the pair of days, 17 and 18 August 1959, listed in Table 1.

TABLE 8. Summary of mean rainfall (1300–1800) MST for three categories of 850-mb dew-point spread at 1700. Date collected: 1961, 1962 and 1964.

Dew-point spread (°C)	Seeded days			Not-seeded days		
	Number of days	Mean rainfall	Days with zero rain	Number of days	Mean rainfall	Days with zero rain
3–12.0	17	0.086	4	10	0.144	2
12.1–16.0	14	0.035	5	19	0.067	5
16.1–32.0	6	0.028	2	8	0.041	2

considered. This view was based on analysis of hourly rainfalls observed in the course of the Santa Barbara Weather Modification Project, a program concerned with the seeding of winter storms. Specifically, he noted that over the mountains, the maximum *hourly* rainfall amounts during seeded periods, at the peak of the 12-hr unit of observation, was 87 per cent higher than during the not-seeded periods. In the light of this result, the data collected in Arizona were examined to see if there was a difference in hourly rainfall amounts.

Elliott (1962) commented that his analysis was made after the data had been analyzed from other points of view. This fact precludes conclusions of statistical significance. The same may be true in our case. Nevertheless, as pointed out by Elliott, these types of exploratory analyses may shed light on the physical mechanism involved and may serve as foundations on which future cloud-seeding programs may be designed.

The rainfall data recorded during the period 1300–1800 were examined by an analyst who did not know which days were seeded and a tabulation was made of the maximum hourly precipitation. The results are

tabulated in Table 9. Columns (4) and (7) represent the sum of the maxima for each day divided by the total number of experimental days, e.g., 16 days in 1957. Columns (5) and (8) represent the sum of the maxima divided by the number of days on which some rainfall was actually observed. The last column is the result obtained by dividing the quantity in column (4) by the one in column (7). It is a measure of the difference between the seeded and not-seeded rainfalls.

It can be seen that when all the data are considered, the mean maximum-hourly rainfall [Column (9)] on seeded days was 15 per cent less than the corresponding value on the not-seeded days. Of the seven summers, the result was in the direction of less rainfall on the seeded days in four of them, a result not unexpected if seeding had no effect.

The maximum-hourly rainfalls for all test days were tabulated and the Mann-Whitney U test was used to test if the observed results could have occurred by chance. The calculations yielded one-tailed probabilities of 0.18 and 0.28 for the Program I and Program II data, respectively.

TABLE 9. Summary of data on maximum hourly rainfall in inches during the period 1300–1800 MST on seeded and not-seeded days.

(1) Year	Seeded days				Not-seeded days			
	(2) No. of pairs	(3) No. of zeros	(4) Mean (all days)	(5) Mean (zeros excl.)	(6) No. of zeros	(7) Mean (all days)	(8) Mean (zeros excl.)	(9) (4)/(7)
1957	16	4	0.56	0.75	4	0.35	0.46	1.60
1958	16	3	0.39	0.48	4	0.25	0.34	1.56
1959	20	8	0.23	0.38	7	0.53	0.82	0.43
1960	17	10	0.12	0.28	9	0.32	0.68	0.38
1961	17	7	0.29	0.50	3	0.50	0.60	0.58
1962	7	2	0.22	0.30	2	0.23	0.32	0.96
1964	13	2	0.60	0.71	4	0.50	0.73	1.20
Total and means	106	36	0.34	0.51	32	0.40	0.57	0.85

These results do not lead to the same conclusion as the one drawn by Elliott (1962). They do not support the position that airborne silver-iodide seeding caused an increase of the maximum hourly rainfall amounts. However, it should be noted that the Arizona experiments were carried out on summer convective clouds over a small but high mountain range and involved airborne seeding. Elliott's analyses were based on winter orographic storms seeded from the ground. The precipitation mechanisms in these storms may be significantly different from those taking place in fairly isolated summer cumulonimbus clouds.

7. Summary and conclusions

None of the analyses discussed in this paper support the hypothesis that airborne silver-iodide seeding of convective clouds increased rainfall or influenced its areal extent over the mountain range where the convective clouds formed. As a matter of fact, the observed differences are such as to suggest that if there were any seeding effect at all, it was to cause a reduction of rainfall. However, the statistical tests indicate that the observed results could have occurred readily by chance.

Howell (1960) has listed 28 seeding projects in the tropics where rainfall measurements were made. Virtually all were carried out by commercial operators. In these projects the excess of rainfall on seeded occasions ranged from 9 to 61 per cent. The duration of the programs ranged from 2 to 80 months but 25 were less than 9 months. Howell argued on the basis of these data, that "a hypothesis that silver-iodide seeding is incapable of increasing the rainfall in tropical clouds over land is open to serious doubt."

Subsequent articles by Howell (1965) and Lopez and Howell (1965), Siliceo *et al.* (1963, 1964) and others also have concluded that convective precipitation can be increased by means of silver-iodide seeding carried out at the ground. The recently released report of the National Academy of Sciences (1966) discusses a number of cumulus seeding programs and notes that though the evidence is confusing, the analyses indicated rainfall increases of 10 to 20 per cent might have been produced by ground-based seeding. The results of the experiments discussed in this paper obviously do not support these conclusions. The reasons for the differences are not clear.

Certainly the convective clouds in Arizona differ in many respects from those normally observed over more humid regions of the world. But the differences in cloud properties are such that one might expect the Arizona clouds to be more amenable to rainfall stimulation by means of silver-iodide seeding than would clouds in more humid areas. In Arizona the cloud bases are generally higher and more importantly, the tops generally reach greater altitudes and lower temperatures before precipitation is produced naturally.

Perhaps the Arizona results differ from those cited

above because of differences in seeding techniques. Perhaps silver iodide released from aircraft in the manner described earlier fails to supply the appropriate numbers of ice nuclei at the correct time and place in the clouds. In the light of recent reports of the work at the Commonwealth Scientific and Research Organization in Australia, it is conceivable that rainfall from some clouds was increased while rainfall from others was decreased with the resultant being an undetectable net change.

On the other hand, one must also admit the possibility that the ice nuclei, in this and the other experiments as well, did, in fact, enter the cloud, but that they did not play an important role in governing how much precipitation reached the ground.

The view that seeding might not have an important effect on rainfall from certain clouds is supported by analyses which concluded that the dominant precipitation mechanism in the convective clouds in Arizona is the coalescence mechanism (Battan, 1963). This view has also been expressed by Braham (1964) who based his conclusions on the investigation of convective clouds in the Middle West. Battan's (1964) analyses of convective clouds in Arizona also led to the assertion that the microphysical properties were not the controlling factors governing the quantity of rainfall.

It appears safe to conclude that additional research is needed to resolve the conflicting views on the physics of convective precipitation and on the efficacy of various cloud seeding techniques.

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