Silver-Iodide Seeding and Precipitation Initiation in Convective Clouds[1]

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ABSTRACT

Convective clouds on seeded and not-seeded days were observed by means of radar and a pair of high quality, ground-based cameras. Stereographic analysis allowed calculation of cloud-top heights, bearing, and distance from the radar set. Radiosonde data were used to convert cloud-top altitudes to summit temperatures. During the periods 1957 to 1960 (Program I) and 1961 to 1964 (Program II) the total number of clouds observed were 1249 and 522, respectively. The analyses indicate that on days when silver-iodide seeding was carried out from an airplane, a higher fraction of clouds developed precipitation echoes. When all the clouds in Program I with temperatures between −18 and −42C are considered, the effects of seeding were found to be significant at the 0.07 level according to the Mann-Whitney U test. When the data for both programs are combined, the same test yields a significance level of about 0.03 for clouds with summit temperatures between −18 and −42C. The results lead to the conclusion that airborne silver-iodide seeding may influence the precipitation-initiation process in convective clouds.

1. Introduction

Since the experimental and theoretical work in the forties by I. Langmuir, V. J. Schaefer, and B. Vonnegut, there has been little doubt that ice nuclei can influence a cloud of supercooled droplets. Subsequent experimental work by many others has confirmed the early results.

Under a seeded stratus cloud, some 10 min or so after seeding, ice crystals and snowflakes are seen to fall in those cases where the seeding produces visually observable effects. These effects of seeding are most obvious when the clouds are relatively uniform in structure, shallow in depth, and producing no precipitation naturally. In such experiments the quantities of precipitation reaching the ground have been small. It is not possible to state how small because measurements are lacking. One reason for expecting small quantities is that the experiments with unequivocal results have involved mostly clouds with thicknesses of the order of a few hundred meters.

It has been argued that with thick clouds, those several kilometers deep, the initiation of precipitation by means of ice-nuclei seeding would cause measurable precipitation increases. By the word *measurable* we refer to quantities greater than about 5%. In view of the variable nature of precipitation, the determination of smaller increases presents great experimental difficulties.

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A large number of investigations of precipitation *initiation* by means of ice nuclei have involved stratiform clouds (for example, Schaefer, 1953; aufm Kampe *et al.*, 1957; Vickers and Church, 1966). Some experiments have also involved convective clouds (Kraus and Squires, 1947; Langmuir, 1950; Braham *et al.*, 1957; Bethwaite *et al.*, 1966; and others). For the most part, these experiments have dealt with individual convective clouds.

During the summers of a 7-yr period between 1957 and 1964, convective clouds over the Santa Catalina Mountains in southeastern Arizona were seeded with silver iodide. Earlier articles by Battan (1966, 1967) discuss the analyses of rainfall measurements and lightning observations, respectively. This paper concerns itself with the effects of silver-iodide seeding on precipitation initiation.

2. Experimental design

Details on the experimental design have been given by Battan and Kassander (1960) and Battan (1966). Some of the essential points are the following. The experimental area was a mountain range having dimensions of about 15 by 20 mi. When convective showers were predicted to occur by an objective scheme, the day was accepted as suitable for study. Pairs of days were taken together and one or the other was seeded on a random basis. When seeding was required, an airplane carrying a silver-iodide burner took off about 1230 MST and seeded for periods of from 2–4 hr. It flew back and forth along a line perpendicular to the wind at flight altitude and about 30 min of "wind time" upwind from the nearest edge of the experimental area.

During the period 1957 to 1960 (Program I) the airplane was equipped with an Australian-designed generator consuming a 20% solution of silver iodide in acetone. It was flown at about the level of the −6C isotherm, normally between 18,000 and 21,000 ft MSL.

During the summers of 1961, 1962, and 1964 (Program II) the airplane carried Forest Service designed generators burning a 10% solution of silver iodide in acetone. The flight level was generally 1000–2000 ft below the cloud bases, but still upwind of the experimental area as in the earlier set of tests. During the summer rainy season, the cloud bases were most often in the vicinity of 10,000 ft.

At the outset of the program in 1957 the period 1300 to 1800 MST was selected as the one where the effects of seeding, if they occurred, were likely to be detected.

3. Measurements

As noted in earlier articles dealing with this project, measurements on all days were made by means of raingages, radar, and cloud cameras. Quantitative data on cloud properties were obtained by employing a pair of aerial cameras mounted at the ground at the end of a 3-mi base leg. The cameras expose 9-inch strip film and take high quality photographs with precise registry marks. They were normally activated automatically at 10-min intervals. The technique of analysis has been described by Orville and Kassander (1961).

Effects of the silver-iodide nuclei were investigated by means of the *cloud-census technique*, an approach first employed by Braham *et al.* (1951) to study the so-called *seedability* of clouds. On every experimental day, at intervals of 30 min, appropriate pairs of stereographic photographs were examined and clouds having sharply defined tops were noted and numbered. The first photographs examined were those for 1310 MST and the last for the time 1740 MST. The 30-min interval was selected at the outset because it was desirable that any cloud not be examined more than once in this particular study. Very small clouds were not included and the restrictions on sharply defined tops eliminated clouds with a fuzzy character or topped with an anvil.

The actual selection of many of the clouds was done by the author some months after the summer. The procedure involved starting at the beginning of the film and going through every day, marking every cloud top. The actual measurements of cloud-top heights, bearing, and distance were done by research assistants who did not know which days were seeded. It might be suggested that since the author had earlier knowledge of which days were seeded, he might have introduced some bias in cloud selection. This is not considered likely because of the fact that an attempt was made to examine each cloud with a distinctive top on each day. Furthermore the random nature of the seeded days makes it difficult some months after the summer to remember which days were seeded.

Radiosonde observations taken by the U. S. Weather Bureau at Tucson International Airport were used to convert cloud-top altitudes to cloud-top temperatures.

After the measurements were made from the photographs, all clouds closer than 10 mi or further than 35 mi were discarded on the grounds that they were located outside the *target area.*

Having tabulated the bearing and range to the clouds, radar data were examined by research assistants to establish whether or not the clouds contained radar echoes. An AN/TPS-10A radar set was employed for noting the presence of precipitation echoes. Its antenna scanned the vertical plane once per second as it rotated in azimuth at a rate of one degree per second. Scope photographs were taken of each sweep. The quadrant between 0° and 90° including the target area was scanned once every 3 min.

During the summers 1957 to 1960 (Program I), a total of 1249 clouds were examined of which 664 were on seeded days. Fig. 1 shows the per cent of clouds containing precipitation echoes as a function of temperature of the cloud top. Not shown here are 14 clouds with temperatures above 6C, none of which produced an echo, and 47 with temperatures below −42C, 46 of which produced echoes.

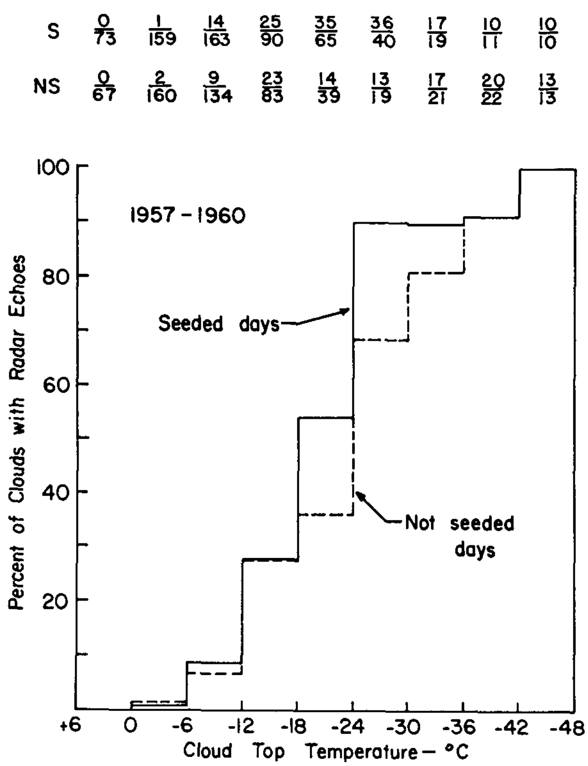

FIG. 1. Per cent of clouds which contained precipitation echoes on AN/TPS-10 radar set as a function of cloud-top temperature. Data on which the diagram is based are shown at the top of the drawing. These clouds occurred during the summers of 1957 to 1960.

It is evident that at temperatures above −18C and below −36C, there were no differences on seeded and not-seeded days. However, at intermediate temperatures, there was a higher percentage of clouds with echoes on seeded days.

Fig. 2 shows the data for the summers of 1961, 1962, and 1964 (Program II). There was a total of 522 clouds of which 307 were observed on seeded days. There were 18 clouds with temperatures below −48C and all of them produced radar echoes. It can be seen that in the temperature range −18 to −42C there was a greater per cent of clouds with echoes on seeded days.

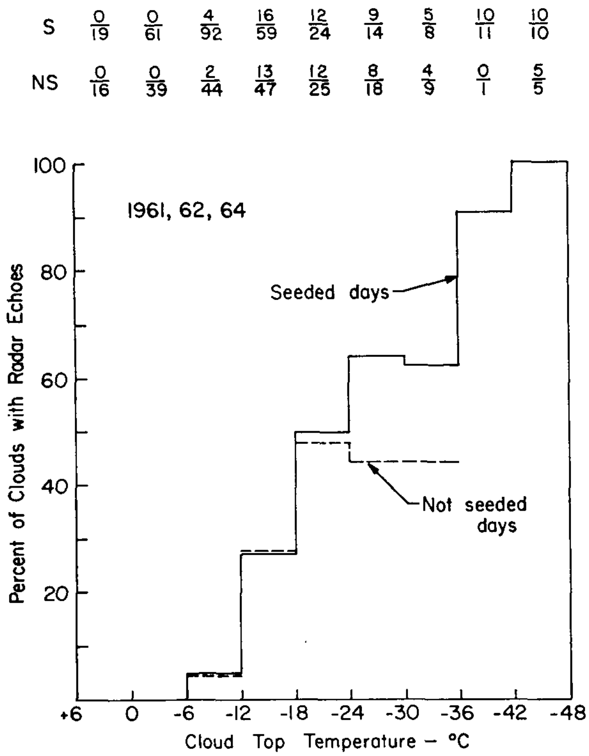

Fig. 2. Same as Fig. 1 for clouds which occurred during the summers of 1961, 1962, and 1964.

In Fig. 3 the data for all years are combined. On the basis of these results, it would seem reasonable to conclude that the silver-iodide seeding initiated precipitation in some convective clouds.

4. Statistical tests

In an earlier report presenting the data for Program I (Battan and Kassander, 1962),[2] statistical tests were described which employed the signed-rank test. Attempts were made to take into account the pairing scheme built into the experimental design. Since the

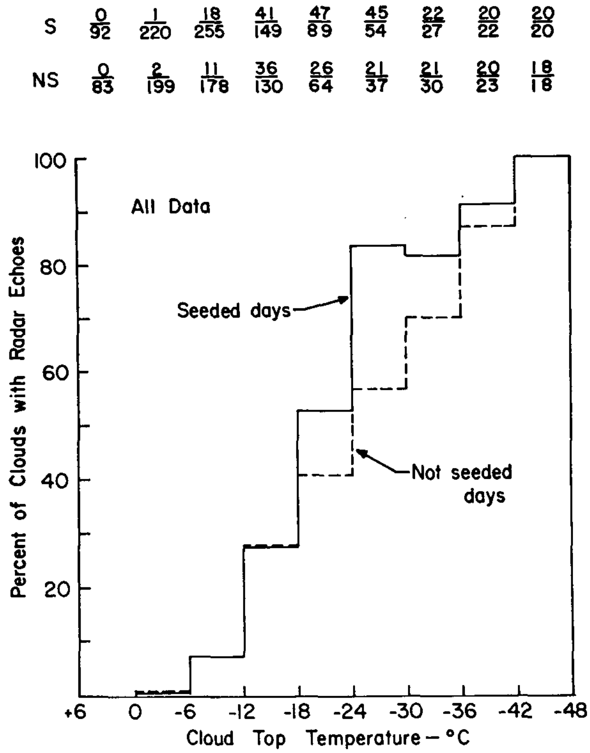

Fig. 3. Same as Fig. 1 for clouds during 7 yr of experimentation.

number of clouds on individual days varied from zero to an observed maximum of 23, it was not feasible to compare days within single pairs. In order to obtain more meaningful data, observations on successive days were combined. All the data on seeded days were tabulated chronologically by days. The same was done with not-seeded clouds. Starting with the first pair of days, the total number of clouds on successive days were added together until there were at least 10 clouds in each group (except for the last group).

By considering only the clouds with summit temperatures between −12 and −42C, 11 subsets resulted and the signed-rank test gave a one-tailed significance level of 0.08. When only the clouds between −18 and −42C were included, this yielded 7 subsets and the signed-rank test gave a significance level of 0.14.

A similar procedure was employed with the data collected during Program II. Of the 6 subsets appropriate to the temperature interval −12 to −42C, half gave higher per cents on the seeded days and half gave the opposite results. However, the grouping of days was such as to place 55 of the 116 seeded days in one subset. In a sense this result defeated the aim of the procedure.

It was felt that another statistical approach would be more meaningful. In the analysis of the rainfall data, Battan (1966) pointed out that the day-to-day correlation of rainfall amounts was quite low, about 0.1. The

[2] Battan, L. J., and A. R. Kassander, Jr., 1962: Evaluation of effects of airborne seeding of convective clouds. Sci. Rept. No. 18, Inst. Atmos. Phys., University of Arizona, Tucson, Ariz., 69 pp. Note that the data in Fig. 1 differ slightly from those presented in this earlier report. Errors in addition have been corrected.

TABLE 1. Fraction and per cent of clouds with radar echoes on seeded and not-seeded days. Data collected 1957 to 1960.

$T=-12$ to -42C				$T=-18$ to -42C			
Seeded		Not-seeded		Seeded		Not-seeded	
12/19	0.632	3/11	0.272	10/14	0.714	12/22	0.545
7/11	0.636	11/23	0.478	11/17	0.647	6/10	0.600
2/11	0.182	8/15	0.533	5/11	0.454	7/12	0.583
4/14	0.286	7/22	0.318	10/13	0.770	7/16	0.437
5/18	0.278	7/26	0.269	9/11	0.818	9/12	0.750
10/16	0.625	6/11	0.545	9/12	0.750	6/10	0.600
11/12	0.919	12/13	0.924	13/14	0.929	17/19	0.894
7/11	0.636	4/10	0.400	14/18	0.779		
7/11	0.636	10/20	0.500	9/13	0.691		
3/12	0.250	1/12	0.082	8/12	0.667		
8/10	0.800	18/21	0.857				
9/12	0.750						
14/21	0.667						
10/23	0.435						
5/10	0.500						
9/14	0.643						
Totals							
123/225	0.547	87/184	0.472	98/135	0.726	64/101	0.633

TABLE 2. Same as Table 1 for years 1961, 1962, and 1964.

$T=-12$ to -42C				$T=-18$ to -42C			
Seeded		Not-seeded		Seeded		Not-seeded	
6/10	0.600	2/12	0.166	8/10	0.800	5/13	0.384
4/10	0.400	4/11	0.364	7/11	0.636	5/11	0.454
2/10	0.200	4/11	0.364	16/22	0.727	8/10	0.800
13/16	0.814	2/11	0.182	5/15	0.333	5/11	0.454
8/15	0.533	10/10	1.000			1/8	0.125
14/24	0.584	5/10	0.500				
1/13	0.077	4/11	0.364				
4/18	0.222	4/10	0.400				
		2/14	0.143				
Totals							
52/116	0.448	37/100	0.370	36/58	0.621	24/53	0.453

virtual absence of correlation among the pairs of days indicated that the Mann–Whitney U test (Siegel, 1956) would be appropriate. It was decided to employ the same test in the analysis of the cloud-census observations.

Again the data were tabulated chronologically, but this time the seeded data were taken alone and successive days were grouped until the sample reached at least 10. The same procedure was followed for the clouds on not-seeded days. This process lead to the quantities shown in Table 1. The Mann–Whitney test yields one-tailed probabilities of about 0.11[3] and 0.07 for the temperature intervals -12 to -42C and -18 to -42C, respectively.

The grouping of days in Program II yielded the quantities shown in Table 2. The sample is small and gave one-tailed probabilities of about 0.15[3] and 0.28 for the temperature ranges of -12 to -42C and -18 to -42C, respectively,

Statistically the cloud types in Programs I and II were the same. Identical evaluation techniques were employed. Although different silver-iodide generators were used, the outputs differed by a factor of no more than about 5 according to the designers of the devices. The chief difference in the seeding operations was in the altitude of seeding. The degree of importance of this difference is difficult to evaluate. The similarity of Figs. 1 and 2 suggests it was small. For this reason the data of Program I and II were combined and tests of inference were made by means of the Mann-Whitney test.

When the data in Tables 1 and 2 are taken together, the resulting probabilities are 0.07 and 0.03 for the temperature intervals of -12 to -42C and -18 to -42C, respectively. If all the data are grouped and only the clouds with temperatures between -18 and -36C are included, one obtains a significance level of about 0.08. These one-tailed probabilities are at such levels, that if the tests are valid, one can, with reasonable confidence, reject the null hypothesis that seeding had no effect. It leads to the conclusion that the observed differences came about as a result of the seeding.

[3] Estimated by extrapolating from tables published by Siegel (1956).

5. Discussion

Some aspects of the results shown in Fig. 3 appear easily explainable. It is not surprising that there is little difference between seeded and not-seeded clouds with summit temperature below -36C. Even if the appearance of precipitation depended only on the presence of the nuclei, the probability of natural nucleation at these temperatures is so high that artificial nuclei would contribute little.

The similar probabilities of echoes at temperatures above -18C may seem surprising. It is well known from laboratory experiments that silver-iodide nuclei introduced into a supercooled cloud begin the nucleation process at about -5C. If, in fact, the excess of clouds with echoes observed at colder temperatures was caused by seeding, why not in the interval -6 to 18C?

If most of the clouds were ascending at the time of the seeding, it is possible that the nucleation process did begin at temperatures of about -5C but that the particles did not reach detectable sizes until carried up to about the -18C level. In Arizona, on a typically rainy day in the summer, the -5C level is at about 5.7 km, with the -18C level at 7.8 km. If the time needed for the growth of detectable ice particles (estimated to be the water equivalent of drops about 300 μ in diameter) is 10 min, an updraft of about 3.5 m sec^{-1} would carry a particle from -5 to -18C before detection. Updrafts of this magnitude and greater are not unexpected. Hence, it appears reasonable to infer that the absence of a difference in the echoes from seeded and non-seeded clouds at temperatures above -18C can be explained.

If the effectiveness of the nuclei depended on the temperature at which the nuclei were injected into the cloud, one might expect the evidence of effectiveness to vary from the Program I to Program II. Since such differences did not appear, this explanation is not supported by the data on hand.

The results already presented here lead to the inference that airborne silver-iodide nuclei affected precipitation initiation in convective clouds. These results cannot be said to be unexpected. Data such as those represented by the dashed line in Fig. 3 were available before the program began [see Table 1 in Battan and Kassander (1960)]. As a matter of fact, the observations that many supercooled clouds fail to produce precipitation echoes was one of the chief reasons why the seeding program was begun. It was believed that the addition of artificial nuclei would initiate precipitation in clouds incapable of doing so naturally or at an earlier time in the clouds growth. In either case this would lead to a shift of the line in Fig. 3 in the direction of higher temperature. It was *assumed* that such a shift would lead to more rainfall at the ground.

A number of cloud-seeding investigations have led to the conclusion that silver-iodide caused a rainfall increase. See, for example, Howell (1960). Recently Bethwaite *et al.* (1966) have reported some very interesting work in Australia. They seeded individual convective clouds by means of an airborne silver-iodide generator. Known quantities were dispensed under individual cumulus. They reported that clouds with tops −10C or colder which were treated with 20 gm of silver iodide yielded significantly more rain than similar untreated clouds.

The results in our illustrations, as already noted, also show a *threshold* temperature. It differs by being somewhat below −10C at the time the precipitation was detected, but by making suitable assumptions about air motions and other cloud properties the differences might be resolved.

One difference between the results of this experiment and those of Bethwaite *et al.* and others is that our rainfall analyses do not indicate that an increase of rainfall at the ground accompanied the increase of the relative number of clouds with echoes (Battan, 1966). It is true that the rainfall measurements were not restricted to the clouds represented in this study. But still, the clouds represented samples on seeded and not-seeded days. Both the cloud observations and the raingage observations might have been expected to give representative samples from which meaningful averages could be computed.

If one considers all the clouds in the temperature range −18 to −42C, the per cent of clouds with precipitation echoes was 69.8 and 57.1 on seeded and not-seeded days, respectively. The former is 22% higher than the latter. On the other hand the average rainfall on seeded days was found to be about 30% less (but not statistically significant) on seeded days.

The question naturally arises as to whether or not the quantity of rainfall reaching the ground from the Arizona cumulus depends on the details of precipitation initiation. More specifically the question could be phrased, "Does a shift in the precipitation initiation curve as in Fig. 3 necessarily lead to an increase of rainfall?" This question was examined from another point of view in an earlier paper (Battan, 1965). Days were grouped according to precipitation amounts and it was asked, "Is there a difference in the precipitation initiation curve on days with light and heavy rain?" The answer obtained was negative. This result led to the tentative conclusion that the precipitation initiation mechanism does not have an important influence on the quantity of rainfall. This conclusion also follows from the analysis in this article.

In an earlier article, Battan (1963) was led to the conclusion that the coalescence process is the dominant precipitation initiation mechanism in convective clouds of the type observed in the summer in southern Arizona. The results of this investigation do not necessarily contradict that conclusion. They do indicate, however, that there are many clouds in which precipitation initiation can be influenced by ice-nuclei seeding. Included among these clouds one would expect some which would not have developed precipitation particles by the coalescence process alone. In other clouds, the seeding may have caused precipitation to develop earlier in the life of the cloud. The failure of the raingage data to reveal an increase of rainfall indicates that other factors besides those affecting precipitation initiation are chiefly responsible for the quantity of rainfall reaching the ground. These results do not preclude the possibility that the seeding may have produced an augmentation of precipitation which was too small to be detected in the background of the natural variability.

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