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Evidence of Widespread Effects of Cloud Seeding at Two Arizona Experiments

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ABSTRACT The average effect of two cloud seeding experiments (1957–1960; 1961, 1962, and 1964) over the Santa Catalina Mountains, Arizona, on the 24-hr precipitation at Walnut Gulch, 65 miles away, was an apparent 40% loss of rainfall ($P = 0.025$) on seeded, as opposed to not-seeded, experimental days. Larger apparent losses, some highly significant, were found for experimental days on which Walnut Gulch was downwind from the seeding site (but not on upwind days), and also on "second days" of the randomized pairs (but not on "first days"). The timing of significant apparent effects indicated that the afternoon maximum of precipitation, which is very pronounced on days without seeding, is either absent or weakened on days with seeding. This phenomenon was observed earlier in a study of the Whitetop Project.

In his many writings (1) in the late 1940s and early 1950s, Irving Langmuir suggested that cloud seeding in a given locality might have strong effects on precipitation at very large distances and during considerable periods of time. More recently, attempts to stimulate rain were limited to relatively small areas. The first experimental evidence of widespread effects of seeding came to light from the analysis (2) of the 7-yr long Grossversuch III experiment, to prevent hail, in Switzerland. On days when Zürich was downwind (wind at the 1500-m level) from the site of the experiment (Ticino, some 80 miles to the south), the average 24-hr rainfall near Zürich on seeded days with inversions was double that without seeding ($P = .004$). Similar, but somewhat less pronounced, effects were found also for the vicinity of Neuchâtel, some 120 miles from the seeding site. However, no significant effects were found in any area upwind. More recently (3, 4), widespread apparent effects of cloud seeding on 24-hr rainfall were found for the Whitetop Project in the Missouri–Arkansas area. Specifically, on air-mass days (but not on frontal days) significant and highly-significant apparent losses of rain were found in vast areas up to 180 miles from the target center. Most unexpectedly, the large significant apparent losses of rain from seeding, equal to 75% of the average without seeding, were found not only downwind, but upwind from the source of seeding material. These surprising findings raised the question of the possible generality of the phenomena noted. Specifically, the following questions suggest themselves: (*i*) did the silver iodide seeding in any of the other completed experiments show significant effects, positive or negative, on precipitation in areas far removed from the intended target? Also, in case of an affirmative answer, (*ii*) are such effects limited to periods of time when the particular areas were downwind from the source of seeding material, as in the case with Grossversuch III, or are they also noticeable upwind, as in the Whitetop Project?

The present study was undertaken to obtain at least partial answers to these questions with regard to two consecutive experiments in Arizona. Factual findings, based on a large number of raingages at Walnut Gulch, are given (see *Results*). The term "apparent effect of seeding," as used here, means the quotient 100 {[(average seeded rainfall) − (average not seeded)]/(average not seeded)}. The two-tail significance probabilities, P, were calculated using the methodology published earlier (5). Some hypothetical explanations of the factual findings are also presented (see *Some Explanatory Hypotheses*).

When the results are appraised, it is well to remember that the three experiments, Grossversuch III, Whitetop, and the Arizona trials, were conducted in very different geographical and climatic conditions. Also, methods of seeding were different. In Switzerland, seeding was from ground-based silver iodide smoke generators. In the other two experiments, it was done from aircraft flying at assigned altitudes. In general, the Whitetop and the Arizona trials were more comparable with one another than with Grossversuch III. In particular, almost all the precipitation during the experimental period (summers) in Arizona appears to be of air-mass type; this allows for a meaningful comparison with results for the air-mass days of the Whitetop Project.

The two Arizona experiments (6, 7) were performed during the summer months of 1957–60 and in 1961, 1962, and 1964. The target area was an isolated body of mountains known as the Santa Catalina Mountains, with dimensions of roughly 15 by 20 miles. Seeding was performed over a period of 2–4 hr, and began at 12:30 p.m. The experimental unit was a "suitable" day. Determination of the suitability of a given day was made in the morning; the essential criterion was a high level of precipitable water. The experimental design was in randomized pairs of suitable days, subject to the restriction that the 2 days of a pair be separated by not more than 1 day diagnosed as not suitable. For the first day of each pair, the decision whether to seed or not was purely random. Whatever this decision was, it required a contrary decision for the second day. The second experiment differed from the first in the following respects: more gages scattered over a somewhat smaller area, level of seeding, and more stringent selection of suitable days.

The original evaluation of possible effects of seeding was based (6, 7) on the average rainfall over the 5-hr period from 1300 to 1800, MST, as measured by a substantial number of recording gages scattered in the target. In both experiments the results of the evaluation were about the same—a not significant 30% apparent loss of rain ascribable to seeding. On days when cloud bases were high, these apparent losses were heavier than on days when the cloud bases were low.

WALNUT GULCH EXPERIMENTAL WATERSHED

The Walnut Gulch Experimental Watershed was established in 1953 by the Soil and Water Conservation Research Division

TABLE 1. *Apparent effects of cloud seeding over Santa Catalina Mountains on 24-hr precipitation in Walnut Gulch, Arizona*

	Days with and without rain					Rainfall per rainy day			Rainfall per experimental day (wet or dry)		
Category	No. dry	No. wet	% wet	% E	*P*	Inches	% E	*P*	Inches	% E	*P*
All experimental days											
S	29	77	73	−7	.425	.1278	−35	.042	.0929	−40	.025
NS	23	83	78			.1978			.1549		
Downwind days											
S	13	16	55	−31	.047	.0706	−60	.068	.0390	−73	.010
NS	8	33	80			.1764			.1420		
Upwind days											
S	15	61	80	+3	.919	.1428	−33	.124	.1146	−31	.174
NS	14	50	78			.2119			.1656		
First days											
S	10	37	79	+3	.948	.1460	−17	.536	.1150	−14	.631
NS	14	45	76			.1754			.1338		
Second days											
S	19	40	68	−16	.199	.1110	−51	.024	.0753	−58	.008
NS	9	38	81			.2243			.1813		

of the Agricultural Research Service. Its purpose is to study water yield and sediment production from thunderstorm rainfall on semiarid rangelands in the Southwestern United States. The Walnut Gulch Watershed is about 13 miles long and, at its widest point, about 5 miles wide. It is approximately 65 miles from the Santa Catalina Mountains (Fig. 1). The elevations of the watershed vary from about 4000 to

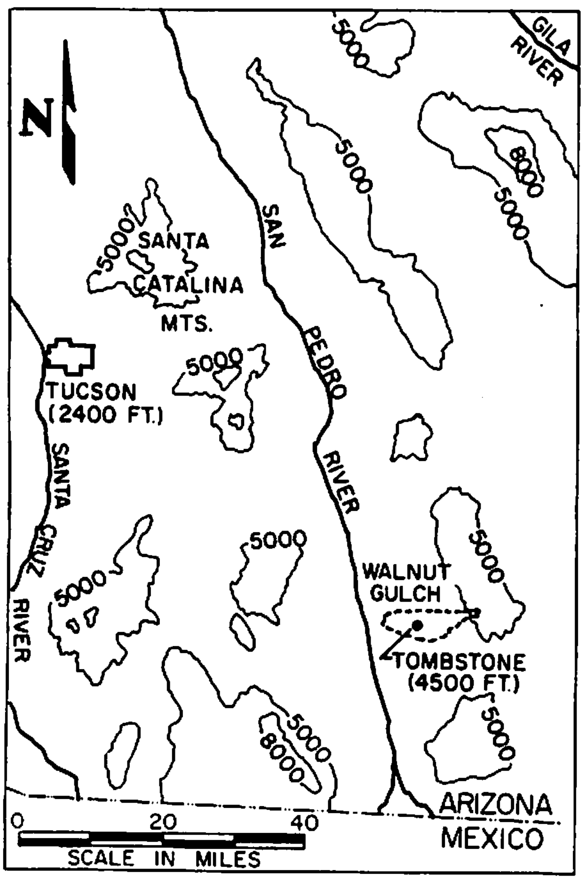

FIG. 1. Approximate map of the experimental region in Arizona.

6000 ft (MSL). The topography of the region is rather complex, combining flat plateaus with steep ridges of mountains. The San Pedro River Valley leading from the Santa Catalina Mountains to Walnut Gulch is something like a corridor among these ridges.

Out of the gradually developing dense network of recording gages at Walnut Gulch, a total of 26 had good continuous records during all 7 years of the Arizona experiments. These records are used for the analyses in this paper.

RESULTS

The study is concerned with two aspects of observational data. One is the 24-hr precipitation from noon of the given experimental day to noon of the next, averaged over all 26 gages in Walnut Gulch (Table 1). The other aspect is the diurnal variation in the seeded and not-seeded average hourly precipitation as recorded by the same gages (see Fig. 3).

Table 1 is composed of five pairs of horizontal lines, each pair corresponding to a category of experimental days specified in the left margin. These are the 212 experimental days of the two experiments combined, days when Walnut Gulch was downwind from the source of seeding material ("downwind days", etc.). The two lines of each pair give the data for seeded and for not-seeded days, respectively. Vertically, Table 1 is divided into three multiple columns. The first is concerned with the question of whether seeding affects the initiation of measurable rainfall at the ground. The successive entries are numbers of zero-rain days and of rainy days, percentages of rainy days, apparent effect of seeding, and the significance probability, *P*. The second multiple column is concerned with the apparent effect of seeding on precipitation averaged per rainy day. The first column of the second multiple column gives 24-hr precipitation amounts in inches averaged per rainy day. Next is the apparent effect, and the corresponding *P*. The third multiple column of figures is similar to the second, but is concerned with, so to speak, final effects of seeding; it combines the possible effect on initiation of rainfall with the possible effect on the amount recorded.

The findings, relating to the principal objectives of this

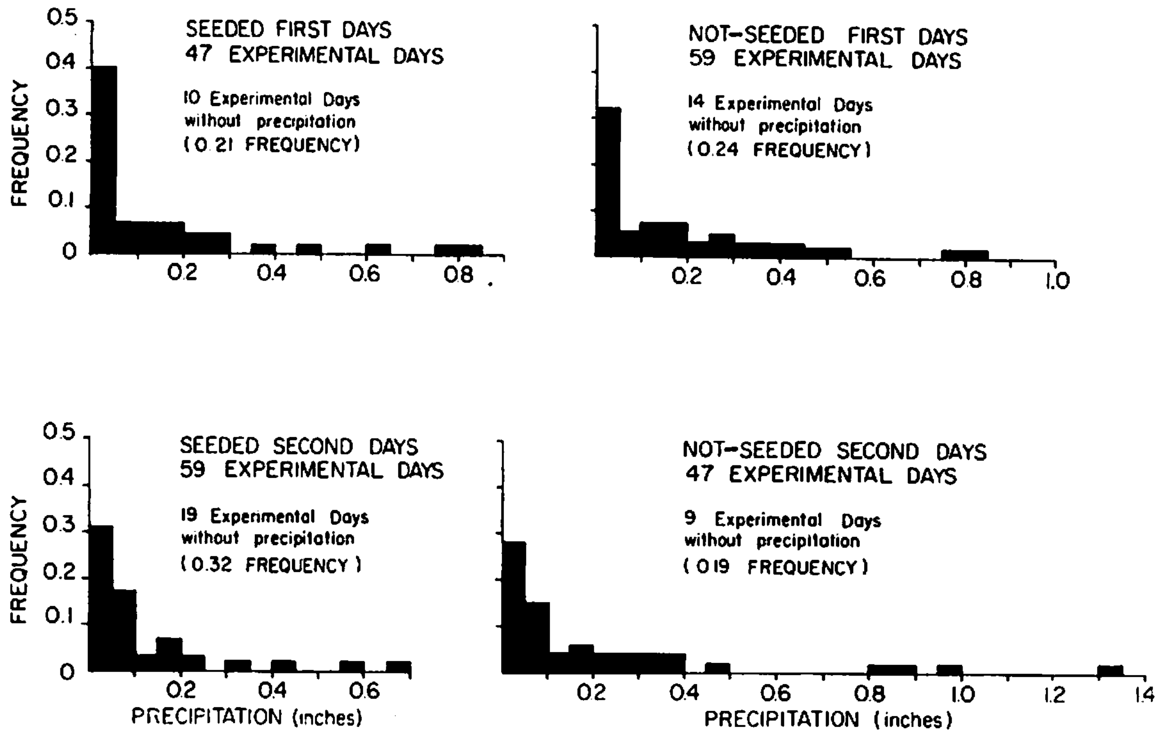

FIG. 2. Histograms of 24-hr precipitation amounts on first and second days of randomized pairs.

paper, (*i*) and (*ii*) above, are given in the first three double lines of Table 1. The first shows that the seeding over Santa Catalina Mountains was actually accompanied by a significant apparent 40% loss in 24-hr rainfall at a distance of 65 miles from the intended target, $P = 0.025$. This, then, constitutes an affirmative answer to question (*i*). The next two double lines in Table 1, meant to answer question (*ii*), are the result of stratification of the experimental days into two categories—"downwind" and "upwind" days. If, on a particular day, the noon-seeding-level wind had a velocity component toward Walnut Gulch, then this day was labeled a "downwind day". The definition of "upwind days" was analogous. Two zero-rain days, one of them seeded, could not be classified because of the lack of wind data. The analysis of Grossversuch III was based on a similar stratification (2). In the upwind-downwind study of the Whitetop Project, the availability of a dense network of gages permitted the establishment of a much sharper relationship between the apparent effects of seeding and wind directions (4).

Table 1 shows that the significant apparent effects of seeding over the Santa Catalina Mountains on rainfall in Walnut Gulch were limited to days when this locality was downwind from the site of seeding; none were found when it was upwind. Although the sign of the apparent effect of seeding was positive for Grossversuch III and negative for Arizona, there is a degree of parallel sm between these two experiments. The apparent 73% loss of rain on the downwind days at Walnut Gulch, significant at 1%, is comparable to the downwind apparent losses at the Whitetop trials. However, the striking upwind losses found for the Whitetop experiment have no parallel in the Walnut Gulch data.

The above comparison of the three experiments, Grossversuch III, Whitetop, and the Arizona trials, can be summarized in three points. (*A*) For all three experiments, large significant apparent effects of seeding were found at substantial distances from sites of seeding. (*B*) In Grossversuch III, these apparent effects are gains in rain, while in the other two projects they are losses. (*C*) For Walnut Gulch and for several areas in Switzerland, the significant apparent effects of seeding are limited to downwind days; the Whitetop Project is the only one showing significant apparent effects of seeding in the upwind areas.

The stratification reflected in the last two double lines of Table 1, stimulated by the thoughts of Horace Byers (1, pp. 551–2), was performed because the design is randomized pairs: only the first day of each pair was selected for the experiment, without prior knowledge whether it would be seeded or not. Table 1 shows that the difference between the category of "first days" and the category of "second days" is quite sharp, but its sign is opposite to that visualized by Byers. There is a highly significant 58% apparent loss of rainfall on seeded second-days and a far from significant 14% apparent loss on seeded first-days. A crossclassification (upwind–downwind) × (first day–second day) was performed. There were only a few days in each of the four strata, and only one of them gave a significant apparent effect of seeding. This was an 86% apparent loss, $P = 0.008$, on second days when Walnut Gulch was downwind.

As was the case with the Whitetop data, the mechanism of all significant apparent losses of rain at Walnut Gulch consisted of concurrent operation of two factors. First, in the seeded category, there were relatively more days with no rain at all than in the category without seeding. (See Table 1, 29 vs. 23, 13/29 vs. 8/41, and 19/47). Second, the precipitation averaged per rainy day was smaller for the seeded stratum than that for the not-seeded. Fig. 2 illustrates the differences in rainfall on first and second days, seeded and not-seeded.

Fig. 3 was constructed to supplement the results exhibited in Table 1. The four panels give two graphs, each showing

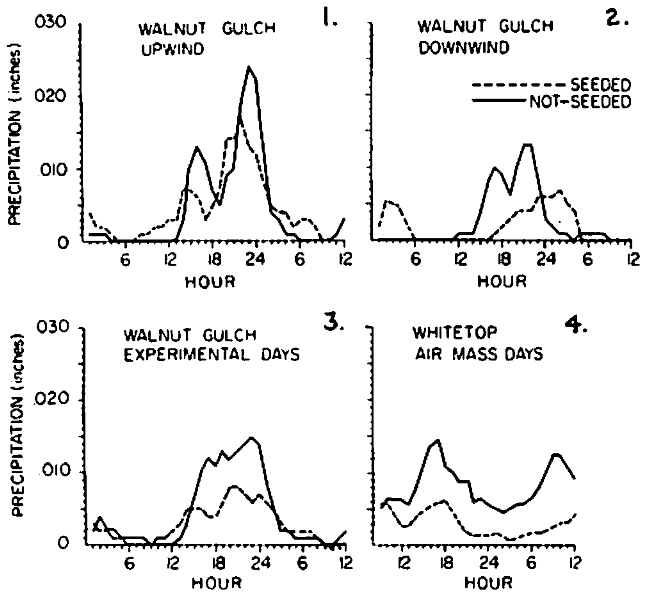

FIG. 3. Diurnal changes in the hourly precipitation amounts: 3-hr moving averages.

the diurnal change in the hourly seeded and not-seeded precipitation amounts. The first three panels refer to Walnut Gulch and to three categories of days of particular interest in this study—upwind days, downwind days, and all (212) experimental days. The fourth panel, added for comparison with the third, refers to the 88 air-mass days of the Whitetop trial. It is based on 24 recording gages, all within 80 miles of the target center. The feature common to all four panels is that, on days without seeding, the hourly precipitation amounts have a pronounced maximum occurring within 12 hr after the start of seeding. On days with seeding, this maximum is decreased, moderately in panel 1 and considerably in other panels. The following difference between the Walnut Gulch and the Whitetop data attracts our attention: the hour of maximum not-seeded precipitation at Walnut Gulch is not in the afternoon, as occurred in Whitetop, but at night. In particular, in panel 3, referring to all 212 experimental days, the period of large excess of not-seeded over seeded precipitation extends roughly from 5 p.m. to midnight.

The lateness of the apparent effect of seeding on precipitation at Walnut Gulch suggests that the lack of significant apparent effects in the original evaluations of the Arizona experiments (6, 7) may be due to the brief time over which the rainfall used for evaluation was measured, from 1300 to 1800 MST. While this presumption seems plausible, our attempts to verify it on data from some gages near the Santa Catalina Mountains were not successful.

SOME EXPLANATORY HYPOTHESES

The sharp difference between apparent effects on first and on second days of randomized pairs is startling and justifies speculations about possible mechanisms. On second days, the average seeded precipitation was 0.0753 in, substantially less than 0.1150 on first days. We have no hypothesis to explain this difference. The average not-seeded precipitation amounts on second and on first days were 0.1813 and 0.1338 in, respectively. For the difference between these two numbers, the following tentative explanation was evolved in conversations that included John M. Hammersley of Trinity College, Oxford. The mechanism visualized, which might be labeled the delayed-rainfall model, involves four hypotheses.

(*A*) It is assumed that seeding over the Santa Catalina Mountains did inhibit precipitation, not only over the intended target, but also over some areas surrounding it. (*B*) It is assumed that this inhibition was limited to the day of seeding. (*C*) It is visualized that inhibiting rainfall by seeding reduced evaporative cooling on the following day and thus, indirectly, increased the potential for convective heating on that day. (*D*) The day after seeding, there may have been more moisture retained in the air than if rainfall on the first day had not been inhibited by seeding. Obviously,the operation of factors (*C*) (H.B.O.) and/or (*D*) (J.M.H.) with (*A*) (*B*) would produce relatively higher average precipitation on not-seeded second days than on not-seeded first days. Whether the factors described did, in fact, operate we are not sure, but the model is specific enough to be tested empirically. Interestingly, simple calculations, based on mean precipitation amounts in Table 1, show that, if this mechanism of delayed rainfall did in fact operate, then the actual net loss in rainfall on Walnut Gulch during the 212 experimental days must have been of the order of 7%, really very little. What would have happened if the seeding was operational (that is, without not-seeded days) is not clear.

CONCLUDING REMARKS

A. Evidence of significant apparent effects of local seeding on precipitation at distant areas, found for Grossversuch III, for Whitetop Project, and now for the Arizona experiments, is a strong argument against the cross-over design. The all-important question, whether seeding increased or decreased the rainfall, cannot be answered by cross-over experiments. Equally unreliable are conclusions based on comparison areas. However, comparison areas can be used to study widespread effects. This is how the apparent effects near Zürich came to light.

B. The first day–second day results raise a number of questions. One example is (*a*): are these results really due to seeding, through the mechanism hypothesized, or otherwise? A reliable answer might come from a factorial experiment with pairs of days (N,N), (N,S), (S,N), (S,S), properly randomized as insisted on by Byers, so that the selection of the second day of a pair is made without information whether it will be seeded or not. Also (*b*): once it is admitted that seeding on one day may affect the rainfall on the next, we have the uncomfortable question about the third day, and so forth.

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1. Langmuir, I., Collected Works (Pergamon Press, New York, Oxford, London, Paris, 1962), vol. II.
2. Neyman, J., E. L. Scott, and M. A. Wells, *Review of Int. Stat. Inst.*, 37, 119 (1969).
3. Lovasich, J. L., J. Neyman, E. L. Scott, and J. A. Smith, *Proc. Nat. Acad. Sci. USA*, 64, 810 (1969).
4. Lovasich, J. L., J. Neyman, E. L. Scott, and M. A. Wells, *Proc. Nat. Acad. Sci. USA*, 68, 147 (1971).
5. Neyman, J., and E. L. Scott, in *Proc. Fifth Berkeley Symp. Math. Stat. and Prob.* (Univ. of Calif. Press, Berkeley and Los Angeles, 1967), Vol. 5, pp. 371–384.
6. Battan, L. J., *J. Appl. Meteorol.*, 5, 669 (1966).
7. Battan, L. J., and A. R. Kassander, Jr., in *Proc. Fifth Berkeley Symp. Math. Stat. and Prob.* (Univ. of Calif. Press, Berkeley and Los Angeles, 1967), Vol. 5, pp. 29–33.