

Re-Evaluation of the Arizona Cloud-Seeding Experiment

(randomization/timing of apparent effects)

JERZY NEYMAN*, HERBERT B. OSBORN†, ELIZABETH L. SCOTT*, AND MARCELLA A. WELLS*

* Statistical Laboratory, University of California, Berkeley, Calif. 94720; and † USDA-ARS Southwest Watershed Research Center, Tucson, Arizona 85705

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ABSTRACT The apparent effect of cloud seeding on the average 24-hr precipitation in the Santa Catalina Mountains during the two programs of the 7-year-long Arizona experiment was found to be a 30% loss of rain ($P = 0.06$). Considering rainy days only, the apparent effect is a 34% loss of rain ($P = 0.03$). On South-East days the apparent loss was 40% ($P = 0.03$). The analysis of the diurnal variation in the amounts of hourly precipitation brought out two suggestions: (i) more active silver iodide enters the clouds through seeding at their bases than at the -6°C level; (ii) the population of experimental days includes two categories with opposite responses to seeding: augmentations of rain in one case and losses in the other. These suggestions require independent confirmation.

This is a sequel to the earlier paper (1) primarily concerned with the broad question whether "local" cloud seeding with silver iodide, intended to augment the rainfall over a limited area, can in fact affect the precipitation at relatively large distances. The specific object of study was the possible effect of cloud seeding over the Santa Catalina Mountains in Arizona (2-4) on the 24-hr precipitation at Walnut Gulch, some 65 miles to the SE. It was found that the effect averaged over all the 212 experimental days of two experimental programs, 1957-60 and 1961, 1962, and 1964, is represented by the apparent 40% loss of rain at Walnut Gulch ($P = 0.025$). Larger apparent losses of rain, 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 study of the diurnal variation in the hourly precipitation amounts on several categories of days showed two pronounced maxima of rain on not-seeded days, one at about 1800 Mountain Standard Time (MST) and the other, more pronounced, at about midnight. On seeded days, these maxima were hardly detectable.

While confirming the possibility of widespread effects of local cloud seeding, the above results stimulated our interest in the apparent effects of the same seeding of the 24-hr precipitation that fell in the Santa Catalina Mountains, the intended target of the seeding operations.

The Santa Catalina experiments were performed by Battan and Kassander. Their evaluations of the results (3, 4), limited to 5-hr precipitation, from 1300 to 1800 MST, were about the same for both programs: an insignificant 30% apparent loss of rain. The seeding commenced at about 1230 MST and continued over 2 to occasionally more than 4 hr. The rationale behind the choice of the period 1300 to 1800 MST is not clear but seems to have been motivated (2) by the belief that the

effects of seeding must be limited to clouds injected with silver iodide smoke that is not deactivated. The findings for Walnut Gulch tend to contradict this belief. So does the earlier analysis (5) of the Swiss experiment Grossversuch III conducted on the southern slopes of the Alps. Here, on days with stability layers and low southerly winds (but not with northerly winds), the seeding appears to have doubled the 24-hr precipitation near Zürich ($P = 0.004$), about 80 miles to the north. Similar, but somewhat less pronounced significant apparent increases of rain were found in the vicinity of Neuchâtel, about 120 miles northwest of the seeding site. The amount of silver iodide smoke over Walnut Gulch, over Zürich, and over Neuchâtel could have been only minute, if any at all. [Earlier, in similar discussions, we used to quote (6) apparent widespread effects of seeding found for yet another experiment, the Whitetop (7). However, a more recent study (8) showed that the noted significant differences in precipitation on seeded and not-seeded days occurred *not only after* the commencement of seeding *but also during several hours before seeding*. Until a satisfactory explanation is found, this circumstance discourages us from quoting the Whitetop results in support of any hypothesis regarding the effects of seeding.]

The above considerations, coupled with the later occurrence of daily maxima of hourly not-seeded rainfall found at Walnut Gulch, suggested the possibility that the absence of significant apparent effects in the evaluations of Battan and Kassander may be due to the shortness of the period of rainfall studied. Real effects of seeding may have been there, but could have occurred mostly after 1800 MST. This is the motivation for the present study. It is limited to factual findings regarding the rainfall in the Santa Catalina Mountains compared with those for Walnut Gulch and, very briefly, with some findings for two other localities. It is emphasized that phrases like "apparent gain", "apparent loss" of rain, and the inclusive "apparent effect" are brief references to the relationships between observed averages of seeded and not-seeded precipitation amounts, and are not intended to suggest causality. Suggestions of causality may be gained from P , the two-tail significance probabilities. Attempts at interpretation are relegated to a subsequent paper.

MATERIALS AND METHODS

During the first program, 1957-60, the rainfall in the Santa Catalina Mountains was measured by 29 recording gauges. During the second program there were 35 recording gauges

scattered over a somewhat smaller area. The charts of all the gauges and their readings were in the possession of Prof. L. J. Battan, but the readings had been verified only for the 5-hr period investigated. We are indebted to Prof. Battan for delivery to one of us (H. B. O.), at our request, of all the charts of the recording gauges. The understanding was that Prof. Battan would have about 1 year priority for studying the readings. The charts were read using the facilities of the USDA-ARS Southwest Watershed Research Center in Tucson. In December 1970, the deck of IBM cards, bearing hourly precipitation amounts for all the available gauges for all the 212 experimental days, was delivered to Prof. Battan for his prior study. The present paper is based on these new data, which are now public property and are available at the cost of duplication and shipment.

We are indebted to Prof. Battan for two more sets of his observations: the radar data and the photographs of the clouds over the Santa Catalina Mountains.

The findings for the Santa Catalina Mountains are compared with those for three other localities at various distances from these mountains: Walnut Gulch (1), Safford, and "North 4." The sources of the data are available upon request.

The general pattern of the present study parallels that of the earlier paper (1) concerned with the rainfall over Walnut Gulch. The statistical methodology used is that explained in ref. 9.

RESULTS

Table 1 summarizes the evaluation of the apparent effects of seeding on the 24-hr precipitation in the Santa Catalina Mountains and shows a comparison with the earlier findings for Walnut Gulch. The first four multiple columns refer to Santa Catalina Mountains. The first multiple column attempts

to answer the question whether seeding influenced the frequency of days with some rain ("wet days"). The second column is concerned with the question whether seeding affected the rainfall averaged per wet day. The third column evaluates the combined effect of both elements of the mechanism, the frequency of some rainfall and the amount fallen. Here the averaging of the amounts of rain is done per experimental day, wet or dry. The last triple column in Table 1 reproduces the results for Walnut Gulch averaged per experimental day, as published earlier (1).

The five double rows in Table 1 refer to different categories of 212 experimental days in the two programs of the experiment. First, the totality of all the 212 days is studied. Next come the two categories that were particularly interesting in the study of the rainfall at Walnut Gulch: days on which Walnut Gulch was "downwind," that is, days on which the noon seeding level wind was between limits 225-359° and 0-44°. These days are labeled "NW days." All other days are labeled "SE days." This subdivision is quite crude, but it had to be adopted to avoid the consideration of very small numbers of observations.

The remaining two double lines in Table 1 refer to the fact that the experimental design used was in not completely randomized pairs of experimental days. The first day of each pair was chosen to be an experimental day without the knowledge whether it would be seeded or not, and the decision regarding seeding was purely random. On the other hand, the choice of the second day of the pair was made with precise knowledge as to whether it would be a day with seeding or without, and this knowledge could introduce a bias. The separate evaluation of the results for Walnut Gulch showed a sharp difference between first and second days of particular pairs, and there is a degree of ambiguity in the interpretation.

The symbol %E in Table 1 stands for "apparent effect,"

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

Category	Rainfall over Santa Catalina Mountains									Rainfall over Walnut Gulch			
	Days with and without rain				Rainfall per					Experimental day			
	No. dry	No. wet	% wet	P	Rainy day			Experimental day			Experimental day		
					Inches	%E	P	Inches	%E	P	Inches	%E	P
All days													
S	10	96	91	0.39	0.138	-34	0.03	0.125	-30	0.06	0.093	-40	0.02
NS	15	91	86		0.208			0.179			0.155		
NW wind													
S	5	24	83	0.68	0.146	-17	0.57	0.120	-9	0.78	0.039	-73	0.01
NS	10	31	76		0.176			0.133			0.142		
SE wind													
S	5	71	93	1.00	0.136	-40	0.02	0.127	-40	0.03	0.115	-31	0.17
NS	5	59	92		0.228			0.211			0.166		
1st days													
S	3	44	94	0.18	0.134	-41	0.04	0.126	-34	0.13	0.115	-14	0.63
NS	10	49	83		0.228			0.189			0.134		
2nd days													
S	7	52	88	1.00	0.142	-24	0.32	0.125	-25	0.31	0.075	-58	0.01
NS	5	42	89		0.185			0.166			0.181		

* Both programs are presented.

defined as the quotient (seeded-not seeded)/(not seeded) multiplied by 100.

The apparent effects of seeding on the initiation of rain-

fall are predominantly positive, but none is significant. Contrary to this, the apparent effects of seeding on the rainfall averaged per rainy day are negative throughout, and three of them are significant by customary standards ($P \leq 0.05$). The apparent effects of seeding on rainfall averaged per experimental day are all negative, but only one is significant. This is the apparent 40% loss of rain on SE days ($P = 0.03$). The effect averaged over all the 212 experimental days is an apparent 30% loss of rain ($P = 0.06$).

The comparison of the results in the last two triple columns in Table 1 poses a number of questions. Both triple columns give evaluations per experimental day, wet or dry, one for the seeding site at the Santa Catalina Mountains and the other for Walnut Gulch, about 65 miles to the SE. *A priori* one might expect the effects of seeding, if any, to be more pronounced near the site of seeding than at a distant locality. Table 1 suggests the contrary. In particular, at Walnut Gulch the seeded second days of the randomized pairs had 58% less rain than days without seeding ($P = 0.008$), while at the Santa Catalinas, the difference was only 25% ($P = 0.31$). The presence of a highly significant 73% apparent loss of rain at Walnut Gulch on the NW days, when it was downwind, coupled with the absence of significant effects on the SE days, is intuitive. At the Santa Catalina Mountains, the significant 40% apparent loss on SE days is also consistent with intuition, even though one might have expected this effect to be stronger. On the other hand, the absence of significant effects on NW days is a surprise.

Fig. 1 was constructed to illustrate the diurnal variation in the average hourly precipitation on experimental days, with and without seeding. The first two rows summarize the findings averaged over all the 212 experimental days, but refer to four different localities. The remaining panels all refer to the rainfall in the Santa Catalina Mountains on experimental days variously stratified.

A comforting circumstance deserves notice. This is that, whatever differences between the diurnal variation of hourly rainfall on days with and without seeding are indicated by Fig. 1, these differences occur at hours of the day *after* the scheduled commencement of seeding, and *not before*.

Panel I refers to the Santa Catalina Mountains, the site of seeding, and panel II to Walnut Gulch, with a kind of "corridor" between rather tall mountains connecting them. Panel III gives the results for eight recording gauges, labeled "Safford." These gages are 60-90 miles east of the seeding site and are separated from it by two chains of high mountains. Finally, panel IV summarizes the findings for the four gauges, labeled "North 4," between 90 and 120 miles to the NNE from the Santa Catalina Mountains, with four chains of substantial mountains between.

Unexpectedly, at Walnut Gulch the differences between hourly precipitation amounts on days with and without seeding appear substantially stronger than at the site of seeding. On the other hand, the situation near Safford and at the North 4 gauges is more consistent with intuition: the greater the separation from the source of silver iodide smoke, the smaller are the apparent effects of seeding. At Safford, the apparent effect of seeding is in the late afternoon. At the North 4 gauges the apparent effect in the afternoon is minute, but is noticeable about midnight. This may reflect the time necessary for the propagation from the distant site of seeding.

The remaining panels of Fig. 1 refer to rainfall in the Santa

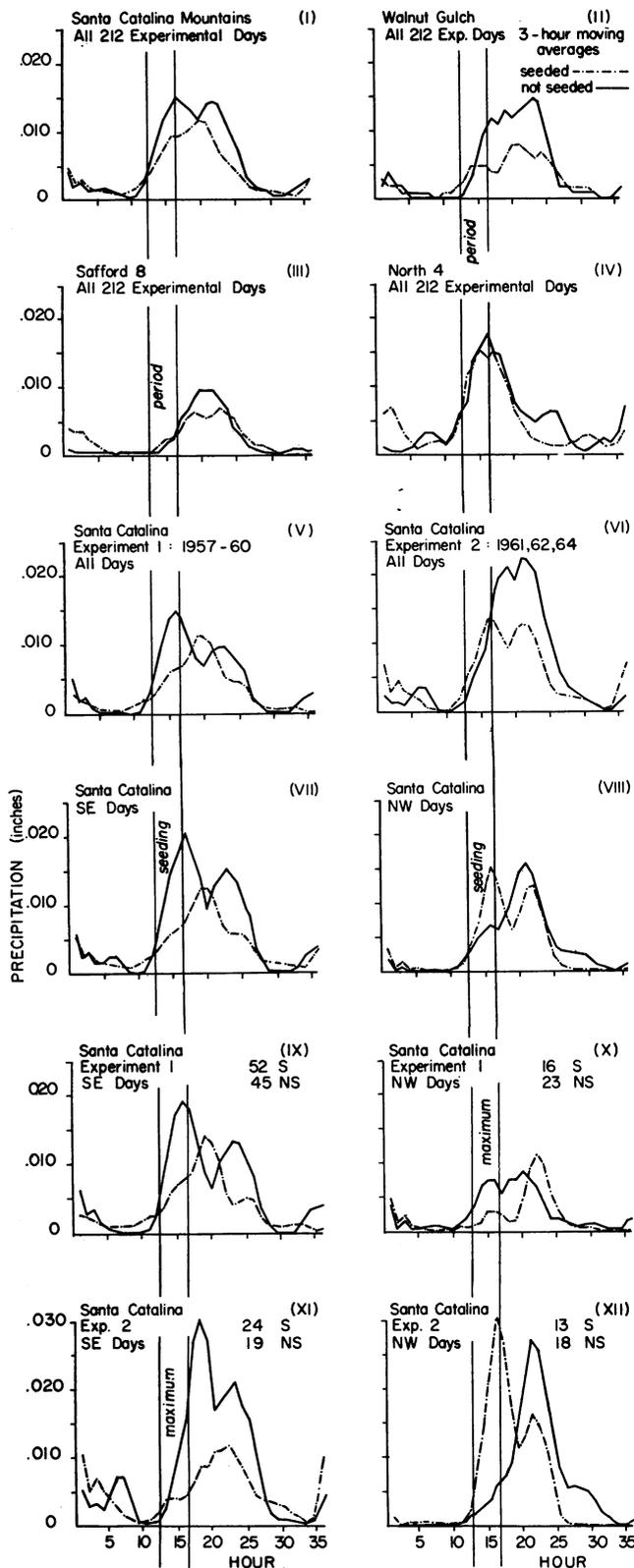


FIG. 1. 3-hr moving averages of hourly rainfall.

Catalinas and represent the search for clues regarding the complex phenomenon of precipitation. The reader will realize that the validation of these clues, and even the support of their plausibility, must depend upon data from some independent experiments. The stratifications used reflect our interest in two questions: (a) what was the difference in the apparent effects of seeding between the two programs, 1957-60 and 1961-62, 1964, (panels V, VI) and (b) what are the details of the noted difference between SE and NW days (panels VII and VIII). The differences in the diurnal patterns suggested the cross stratifications shown in the remaining four panels of Fig. 1.

The negative apparent effects of seeding on SE days are dramatically stronger for the second program than for the first. Even a more dramatic difference between the two programs occurred on afternoons of NW days: an apparent loss of rain in the first program changed to a large apparent gain in the second. Despite the meager number of observations (shown), a search for possible causes seems indicated. These include: changes in weather types, in local air pollution, and in the experimental procedure. In the second program there was more moisture in the air (higher precipitable water), different equipment, and a much lower level of upwind seeding, at the cloud base rather than at -6° temperature. The original level was chosen (2) for shortness of linear distance from the supercooled region of the growing cumulus. However, because of the complexity of downdrafts and updrafts (10), the actual path followed by the seeding material may have been shortened by seeding at the cloud base.

The panels of Fig. 1 referring to NW days attract special attention. Contrary to all other partial evaluations of the Arizona experiment, these panels suggest the possibility that, by an appropriate choice of days for seeding, the 24-hr precipitation over the Santa Catalina Mountains could be increased, rather than decreased, by seeding. This presumption is based on the fact that panel VIII and, to a greater extent, panel XII exhibit a large apparent gain in precipitation over the period approximately up to 1800 MST. Subsequently, the relationship is reversed. The hope for the possibility of augmenting rain depends on whether the reversal is typical for all the NW days or reflects the existence of some two categories of these days with opposite patterns of rainfall.

The perusal of Fig. 1 indicates that, quite frequently, the diurnal variation of rainfall on not-seeded days has two maxima, one in the late afternoon and the other near midnight. It is possible that this is a pattern typical for all the experimental days, including the NW days: some rain in the afternoon, then a respite, and then some rain at night. However, it is also possible that the stratum of NW days contains two special categories of "early" and "late" days, with the early category characterized by substantial rain in the afternoon and practically none at night, and with the late category having the opposite pattern. If this is the case, then panel XII suggests that by seeding from the cloud base on early NW days, one could increase the afternoon rainfall without affecting the rain at night, which is zero.

Tenuous as the experimental evidence is, the interest in the above possibility dictated the construction of Fig. 2. In the four scatter diagrams the "late" precipitation (from 1800 to 2400 MST) is plotted against the "early" (noon to 1800 MST). All four panels of Fig. 2 show a degree of clustering near the two axes of coordinates. On seeded

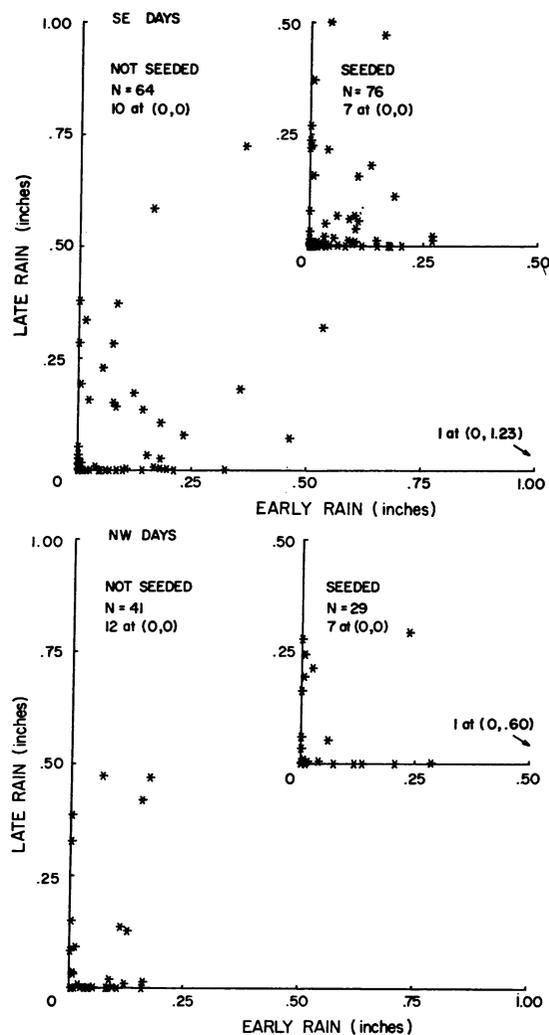


FIG. 2. "Late" 6-hr rainfall plotted against "early" rainfall.

NW days this clustering is quite pronounced: with just one exception, all the observational points fall either exactly on the axes of coordinates or very close to them. Thus, such data as are available do confirm the presumption that the two categories of NW days, early and late, may be a reality.

However, even if such separate categories exist, there is the problem of their identification. To be useful, this identification must be in terms of observations available before the scheduled time of seeding. Efforts were made to use the rainfall before noon, the radar data, and the photographs of the clouds, but, thus far, without success. Presumably, if the category of early NW days is a reality, its identification will have something to do with the presence and nature of freezing nuclei, possibly dependent on the path of the moisture followed before it reaches the Santa Catalina Mountains. The location of sources of air pollution, such as Tucson and the various copper smelters, might be pertinent here. The possible identification of the subcategory of NW days with positive effects of cloud seeding would contribute considerably to the understanding of the rainfall phenomena, particularly if it clarifies the contrast with the apparent effects at Walnut Gulch. Here, the average effect of seeding on the same NW days was a highly significant apparent 73% loss of rain.

CORRECTION

The first two panels of Fig. 3 in the earlier paper (1) are mislabeled. The correct labels are "Walnut Gulch, Upwind—1st Days" and "Walnut Gulch, Downwind—1st Days," respectively.

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