Downwind and Upwind Effects in the Arizona Cloud-Seeding Experiment

(moving grid method/randomization)

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ABSTRACT The principal subject of this report is a comparison of precipitation on days with seeding with that without seeding, averaged over those rain gauges that on each particular day were "downwind," "upwind," or to the sides. Two estimates of relevant wind directions are used, based on successive radiosondes at Tucson that bracketed the scheduled time of seeding. By use of these radiosondes, the apparent effects of seeding on rain in downwind localities 90-180 miles (145-290 km) away from target were found to be an apparent 45% loss of rain ($P = 0.002$) and an apparent 34% loss of rain ($P = 0.028$), respectively. Other results indicate considerable geographic heterogeneity.

An earlier study (1) showed that the "local" cloud seeding in the two "programs" of the Arizona experiment, intended to affect the precipitation in a relatively small target, was accompanied by large and statistically significant changes in the rainfall in a locality far from the site of seeding. The present paper is concerned with the generality and extent of this phenomenon. Specifically, our purpose is to investigate the possible effects of seeding in the Arizona experiment on the 24-hr rainfall measured by all the Weather Bureau rain gauges (and a few others) located within 180 miles (290 km) of the intended target.

The two programs of the experiment, 1957-60 and 1961, 1962, 1964, were conducted by Battan (2). The target was the chain of the Santa Catalina Mountains, some 25 miles (40 km) long. The silver iodide seeding was performed from a plane flying upwind from the target in the directions perpendicular to that of the wind. The design was in not-completely-randomized pairs of "suitable" days, with 1 day seeded and the other not. The 2 days of the pair could be separated by no more than one "unsuitable" day. The decision whether to seed or not on the first day of a pair was random, and determined the opposite decision for the second day of the same pair. Thus, the "suitability" of the second day was determined with knowledge whether it will be seeded or not. This distinction between first and second days of the pairs dictates the necessity of three separate evaluations—for all the 212 experimental days, for 106 first days, and for the equal number of second days.

The earlier study (1) was concerned with apparent effects of seeding on the 24-hr rainfall measured by the 26 recording gauges in Walnut Gulch, some 65 miles (105 km) SE from the Santa Catalina Mountains. Five separate evaluations were performed: for all experimental days, for first and for second days of pairs, and for days when Walnut Gulch was downwind and when it was upwind from the seeding site.

All apparent effects were negative, three of them significant:

All 212 days:	apparent loss of rain 40%, $P = 0.025$
Second days:	apparent loss of rain 58%, $P = 0.008$
Downwind days:	apparent loss of rain 74%, $P = 0.010$

Battan's own evaluation of his experiment (2) was limited to rainfall during 5 hr, from 1 p.m. (13.00) to 6 p.m. (18.00), local time, and showed a not-significant apparent 30% average loss of rain. Our reevaluations (3), concerned with 24-hr rainfall and performed separately for the five categories of experimental days mentioned above, all indicated losses of rain, of which two had small significance probabilities.

All 212 experimental days:	apparent loss of rain 30%, $P = 0.06$
141 days with SE winds:	apparent loss of rain 39%, $P = 0.03$

Closer study suggested the existence of a thus-far unidentified category of days on which the seeding may have increased the rainfall, perhaps through an interaction of silver iodide with some form of local air pollution.

The present study is concerned with the apparent effects of the Arizona cloud seeding on 24-hr rainfall in the broad area around the target, as measured by all the available rain gauges up to the distance of 180 miles (290 km) from the target center. The analyses reported below fall under three headings: (i) apparent effects on rainfall at Atterbury Watershed, some 25 miles (40 km) to the SE from Santa Catalinas; (ii) "moving grid study" of apparent effects of seeding in various localities that on each particular day were at preassigned distances from the seeding site and at preassigned angles from the prevailing winds, and (iii) average seeded and not-seeded precipitation within two broad zones, one up to 90 miles (145 km) from the target center and the other from 90 to 180 miles (145-290 km).

MATERIALS AND METHODS

Fig. 1 represents a schematic map of the area studied, within 180 miles (290 km) from the target center. Dots indicate the locations of rain gauges used. In addition to the 29-35 gauges in the Santa Catalinas and 26 in Walnut Gulch, there were 71 gauges used. Regrettably, no complete data were obtained from Mexico. The list of all the gauges used is available upon request. Obviously, because of the small number of gauges in the area, an evaluation based on all of them, including all the gauges in the Santa Catalinas and in

FIG. 1. Schematic map of the area of the Arizona experiment.

Walnut Gulch, would have been dominated by the happenings in these two small areas for which separate evaluations are published (1, 3). In order to counteract this dominance somewhat, the two tight groups of gauges were reduced. In the Santa Catalinas 10 gauges were found that were not moved during all the 7 years of experimentation. These 10 gauges were used in the present study. At Walnut Gulch, the 26 real gauges were replaced by four imaginary gauges dispersed over the area. For each experimental day an imaginary gauge was assigned the rainfall measurement equal to the mean rainfall in the surrounding real gauges that this imaginary gauge replaced.

We are indebted to Prof. Martin M. Fogel for providing us with data from a network of gauges at Atterbury Watershed, about 25 miles (40 km) from Tucson, maintained by the University of Arizona. Two of these gauges are recording. Their data, representing 24-hr rainfall measured from noon to noon, were used in the present study.

The general statistical method of evaluation used here is the same as that in the earlier studies (1, 3). The theory of the method is given in ref. 4.

All the above applies to the evaluation for well-defined groups of gauges. Separate comments are needed to explain the "moving grid method" of defining groups of gauges used in evaluating the effects upwind, downwind, and to the sides. The method used is a modification (5) of that invented by Braham (6). Applied through the use of a digital computer, this method is equivalent to the following manual operation. On a piece of transparent plastic two perpendicular lines are drawn, intersecting at a point labeled the center of the grid.

Next, two circles are drawn about the center, with radii corresponding to distances of 90 and 180 miles (145 and 290 km). There result eight cells of the grid, four of them labeled "near" and the others "far." A third line is drawn through the center, bisecting a pair of the right angles between the two original lines. This third line, labeled wind line, is meant to indicate the "day's wind direction" as defined below. Now, the eight cells are labeled indicating both their distance and their orientation: "near-downwind cell," "far-downwind cell," etc.

For each particular experimental day, the plastic sheet with the grid is placed on the map of the area, with the center coinciding with the estimated center of the seeding line, and so that the wind line has the day's wind direction. Next, for each of the eight cells the rain gauges falling in them are identified and their rainfall measurements are recorded. On a particular day, the day's wind direction may be from the southeast. For this day, then, the far-downwind cell will contain Phoenix and several localities around it. On another day, that same far-downwind cell will contain only two gauges, AJOO and AJOW (see Fig. 1). The evaluations were performed separately for the eight cells of the grid, each cell with groups of gauges that varied from day to day depending upon the day's wind direction.

A difficulty due to the scarcity of rain stations in the area must be mentioned. On a sizeable number of experimental days, one or the other of the "far" cells did not contain a single gauge. These days, then, had to be ignored. This difficulty did not apply to "near" cells, and the evaluations for these cells were based on all the 212 experimental days.

Two different definitions of the "day's wind direction" were used. These were seeding-level (or closest available) wind directions, as determined by the successive Tucson radiosondes, at 5 a.m. (5:00) and 5 p.m. (17:00) local time. The scheduled time for seeding was 2-4 hr, beginning at 12:30 p.m.

RESULTS

The three evaluations for the two recording gauges at Atterbury Watershed gave just one significant result. This is a 173% apparent gain in rain on second days of experimental pairs. As hypothesized earlier (3), such gains might result from AgI interacting with air pollution from nearby Tucson and copper smelters. On these same second days, the apparent effect on rain in Walnut Gulch was a highly significant 58% loss, a remarkable case of geographic heterogeneity.

The purpose of the moving grid studies was to obtain information as to possible effects of cloud seeding over the Santa Catalina Mountains on rainfall in far-away localities to which the prevailing winds could carry the silver iodide

smoke released over the target or, at least, the masses of air into which this smoke was introduced while they were over the target. Two complete sets of calculations were performed. One of them refers to localities that were "downwind," "upwind," or to the sides at 5 a.m. (5:00), and the other to localities at the same orientations with respect to winds at 5 p.m. (17:00).

Separate studies were performed to answer questions about: (i) the frequency of days with some rain, (ii) the rainfall averaged per wet day, and (iii) the rainfall averaged for experimental day, whether wet or dry. Also, there were stratifications: all the 212 experimental days, first days, and second days of the randomized pairs. Also, separate evaluations were made for the first of the two "programs" (1957-60) and for the second (1961, 1962, 1964). Finally, all the above evaluations were performed twice, with two different definitions of day's rainfall per cell. Consider two experimental days with different wind directions. Suppose that on the first of these days a particular cell of the grid, say the far-downwind cell, contains some 20 gauges, and that on the second day this

FIG. 2. Moving grid study of the Arizona experiment. Upper line entries in each cell: mean seeded and mean not-seeded rain, inches. Lower line entries: apparent effect in % of not-seeded rain, positive or negative, and significance probability. Cases of statistical significance are marked by underlining the *P* value.

same cell contains just one gauge. One set of evaluations was performed using the *average* rain recorded by the 20 gauges that were in the cell on the first of the 2 days, and treating this average on par with the record of the single gauge in the same cell on the second day. Here then, the localities relatively rich in rain stations are, in a sense, dominated by those with only a few such stations. The other set of calculations is based not on *average* precipitation amounts, but on the *totals* recorded by all the gauges that on each day were present in any given cell. As a result, one might say that the localities with many rain gauges dominated those with only a few. The two sets of evaluations answer two different questions, and it is important to distinguish them.

The above variety of evaluations posed the problem of a fair summary. We believe such a fair summary is provided in Fig. 2, giving the results for *average* precipitation per cell (not for *totals*), averaged per experimental day, wet or dry. The two columns are based on the morning and the afternoon radiosondes, respectively. Only the results for the three categories of days are reported: all days, first days, and second days.

The reader will notice that, with a single exception (all days, p.m. winds), the statistically significant results refer to far cells. Again with a single exception (first days, p.m. winds), these significant apparent effects are losses of rain, predominantly in the far-downwind cell. The following items of information are important.

(i) The many different evaluations mentioned above are more consistent with each other when based on the afternoon winds than on the early winds. In particular, the general pattern of results for *total precipitation amounts* obtained with afternoon winds is very similar to that in the right column of Fig. 2.

(ii) The second program of the experiment shows sharper effects than the first.

(iii) On no experimental day was Walnut Gulch in a "far" cell of the grid. Hence, the significant apparent losses of rain in the far-downwind cell reflect happenings in localities other than Walnut Gulch.

(iv) Considerations of relative dominance of particular localities raise a question about the total amounts of rain water in all the available gauges on all the experimental days with and without seeding. For the two broad areas, up to 90 miles (145 km) and from 90 to 180 miles (145–290 km) from the target center, the calculations gave a 19% and a 15% apparent loss of rain, respectively.

PRINCIPAL CONCLUSIONS AND SPECULATIONS

If the randomization was faultless at least for the first days of the experimental pair, the conclusion seems inescapable that cloud seeding in the Arizona experiment must have decreased the rainfall in those areas that were far downwind. This result, then, answers the question as to the generality and extent of the phenomenon noticed for Walnut Gulch. Curiously, the apparent losses of rain in the near-downwind cell are weaker than in the far-downwind cell.

The practical consequence of the above findings is the conclusion that the frequently used cross-over design of the experiment is unreliable. Because the amount of silver iodide smoke at a distance of some 100 miles (161 km) from its source, even downwind, must be minute, the other important conclusion is that the mechanism governing the effects of AgI seeding cannot be limited to nucleation of supercooled droplets.

Recent discussion (7) of the lack of success in seeding convective clouds suggests the following possibility: frequently, as the Arizona experiment was performed, the seeding may have initiated rain high above the ground; when falling through dry air, this rain evaporated and decreased the temperature; while carried downwind the parcel of cool air eventually reached the ground and inhibited convection.

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