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Further Studies of the Whitetop Cloud-Seeding Experiment

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ABSTRACT **By means of two stratifications of experimental days of the Whitetop Project—into categories E and W and into categories air mass and frontal—the effects of cloud seeding on precipitation downwind, upwind, and to the sides, up to 180 miles from the seeding line, were investigated. No significant effects were found for W and frontal days. On the other hand, for E and air-mass days, significant and highly significant apparent effects of seeding were found in all directions and in areas at distances up to 180 miles. All these significant apparent effects are negative, the largest of them indicating that seeding reduced precipitation to one quarter of its unseeded value.**

The Whitetop cloud-seeding experiment was performed by Braham (1) over five summers (1960–64). The target center was near West Plains, Mo. The original evaluation (2) showed that within the so-called "Missouri Plume" the average seeded precipitation "per fair hour" was about half that without seeding. Several [illegible]sequent studies (3, 4) were concerned with amounts preci[illegible]ted per 24 hr in a fixed area ("area studied") up to 180 mi[illegible]rom the target center and, separately, in 6 parts of that a[illegible]designated A to F. Region A extends up to 30 miles from[illegible]e target center. Regions B to F are concentric circular ri[illegible]each 30 miles wide. It was found (3) that in all six regions [illegible]average 24-hr precipitation on the 102 days with seeding [illegible] less than those on the 96 days without seeding. For the e[illegible]re area, the apparent loss of rain was 21%, with $P = 0.13$. [illegible]ough none of the apparent effects was found significant b[illegible]stomary standards, further studies appeared justified by th[illegible]t that if the 20% apparent loss of rain was actually cause[illegible] seeding, this would mean operational (contrasted with [illegible]erimental) cloud seeding under similar conditions wou[illegible]sult in a loss of about 8 million acre-feet of rainwater p[illegible]summer or, possibly, about $80 million loss of revenue to th[illegible]al economy.

In the next study (4), the [illegible] experimental days were stratified into two categories a[illegible]ding to patterns of winds aloft, by three different metho[illegible]One category was supposed to "conform," and the other n[illegible]o conform, with Braham's rule of determining experime[illegible] days. F[illegible]r "conforming" days, no significant effects of see[illegible]g were fo[illegible]d. On the other hand, the apparent effects of s[illegible]g on no[illegible]onforming days were negative in all the regio[illegible]A–F, and [illegible]ere frequently significant or highly significant [illegible]r the entire area studied, the effects were −39% (with [illegible]0.03), −36% ($P = 0.04$), and −46% ($P = 0.005$) for the [illegible]e systems of stratification, respectively. Thus, there is litt[illegible]oubt that, among the 198 experimental days of the Whitet[illegible] Project, there is a category within which the seeded rainfa[illegible]as roughly 40% less than that without seeding and that t[illegible] difference could hardly be explained by chance variation. If we assume that randomization was faultless, the differences must have been caused by seeding. However, specialists in meteorology appear divided on this point.

With reference to our earlier paper (3) Battan questioned (5) the possibility that the differences between seeded and not-seeded amounts of precipitation could have been caused by seeding. Contrary to this attitude, Tribus hypothesized (6) that the apparent losses of rain, from 9% in ring E (120–150 miles from target center) to 30% in region A, may have been caused by overseeding. This same hypothesis of overseeding is also mentioned in a recent preprint by Braham and Flueck (7) who performed an independent study. However, their hypothesis that overseeding caused a real decrease in rain refers only to the central part of the area studied, up to 60 miles from the target center. The question whether there was a real effect of seeding beyond this limit is left open by these authors.

The purpose of the present paper is to bring out additional verifiable facts about the apparent effects of the Whitetop Project. The "apparent effect" is defined as [100 (average seeded rainfall − average not seeded) / (average not seeded rainfall)]. When the two-tail significance probability, P, corresponding to an apparent effect is small, it is safe to assume that the relevant apparent effect could not have resulted from chance variation. The construction of hypotheses on the actual causes of significant apparent effects must be left to specialists in meteorology.

sceptical that they are saying anything here except believe me.

Text

SPECIFIC QUESTIONS AND OBSERVATIONAL DATA

The specific questions studied are those suggested by the comments of Battan (5): (*a*) How are the apparent effects of seeding at the Whitetop Project distributed with respect to wind directions and at various distances from the source of seeding material? (*b*) Did the significance of particular apparent effects result from only a few days with exceptional rainfall?

Text

The study is based on 253 raingauges scattered over the area studied and concerns the 24-hr-precipitation amounts measured from morning to morning. Two independent stratifications of experimental days are used. One is the stratification into categories E and W described earlier (4) (the early evaluation contains a small error, now corrected—see Table 1). The other stratification used was performed for us by Dr. H. C. Chin under the supervision of Prof. M. Neiburger; it is a pleasure to record our indebtedness.

Text

The evaluations reported below involve only two strata: 88 *air-mass* days and 106 *frontal* days. The stratum of air-mass

253 rain[illegible]ges scattered over the area stu[illegible]s —24hr-precipitation m[illegible]ured from morning to morning

E and W stratifications

who are the specialists in meteorology

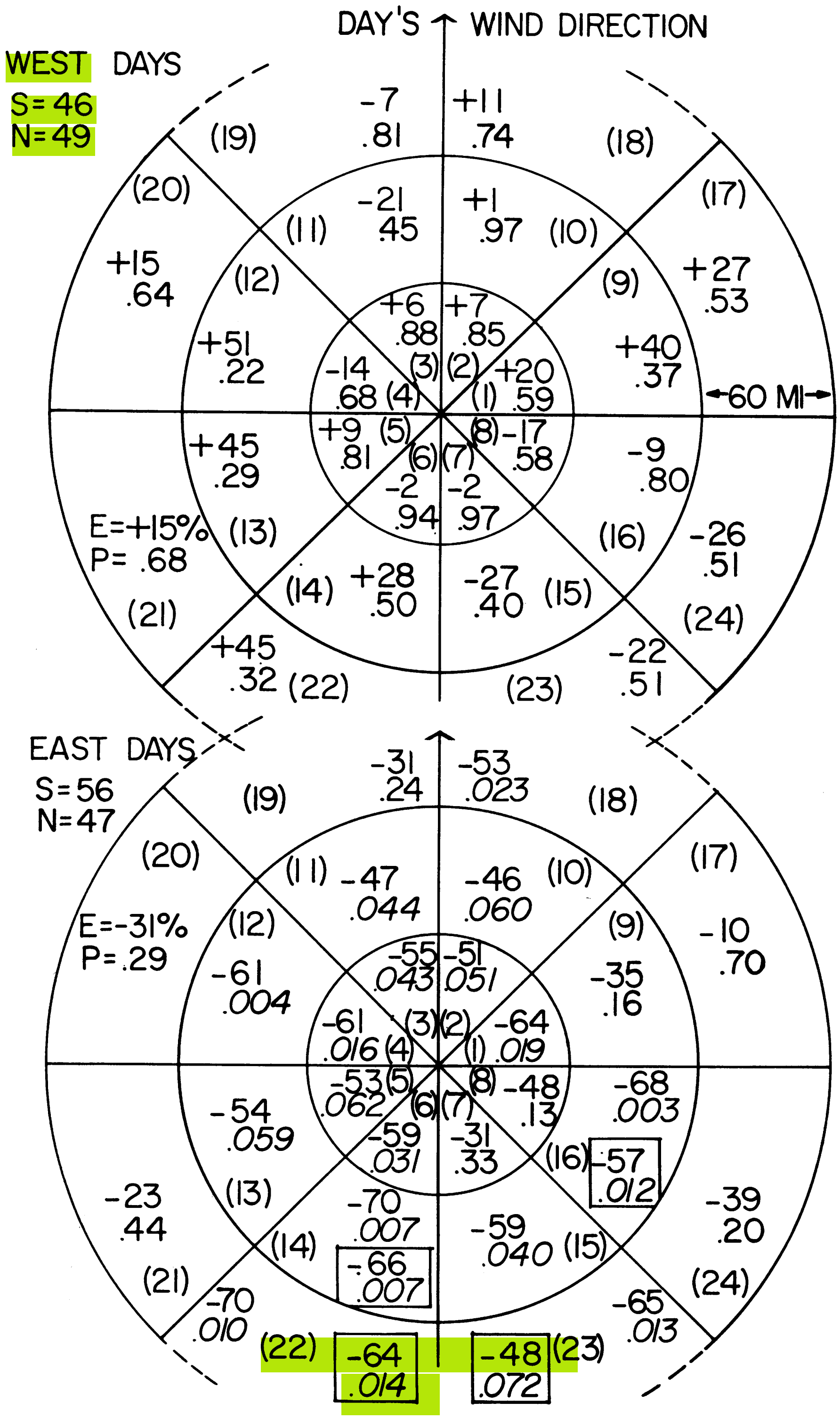

FIG. 1. Upwind–downwind apparent effects of cloud seeding on W (*upper*) and on E days (*lower*). Day's wind direction: from middle fix towards target center. Entries: percentage apparent effect and two-tail *P*.

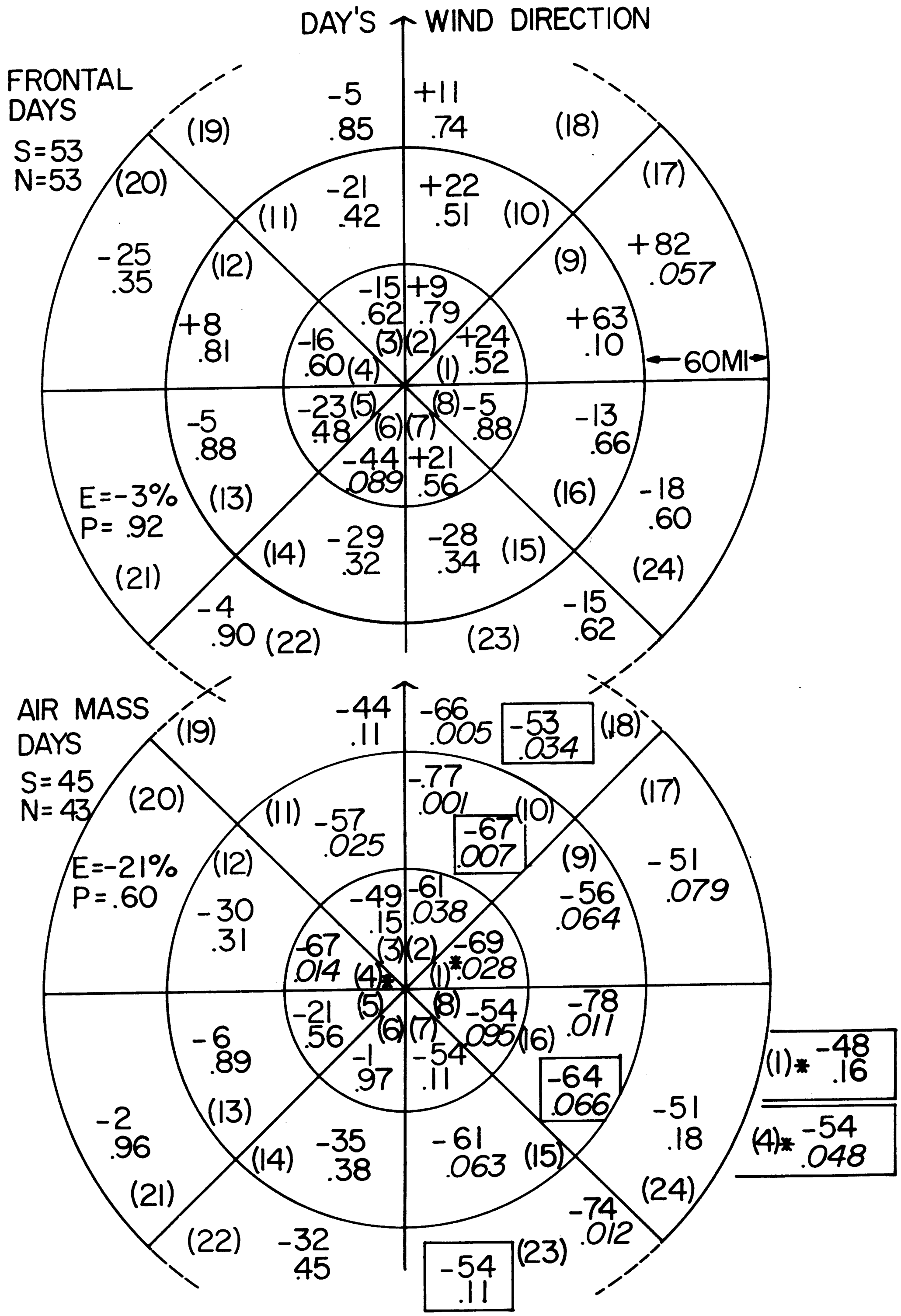

FIG. 2. Upwind–downwind apparent effects of cloud seeding on frontal (*upper*) and on air-mass days (*lower*). Day's wind direction: from middle fix towards target center. Entries: percentage apparent effect and two-tail *P*.

TABLE 1. *Apparent effects of seeding on 24-hr-precipitation amounts in fixed regions A to F, by stratifications (E, W) and (air mass, frontal)**

	E days		W days		Air mass		Frontal	
Region	% effect	*P*	% effect	*P*	% effect	*P*	% effect	*P*
A	−63	0.006	+7	0.85	−59	0.042	−10	0.74
B	−46	0.033	−8	0.78	−61	0.015	−2	0.93
C	−46	0.019	+5	0.86	−43	0.080	−4	0.87
D	−45	0.020	−1	0.96	−51	0.016	−1	0.97
E	−43	0.025	+23	0.32	−28	0.24	+2	0.93
F	−48	0.005	+4	0.84	−43	0.039	−6	0.76
Entire	−46	0.005	+7	0.75	−43	0.029	−3	0.89

* The evaluations for E, W are corrected from those published earlier (4).

days is of particular interest because, according to Braham (1), the efforts at the Whitetop experiment were primarily directed toward the afternoon air-mass convective clouds. Also, the category of air-mass storms was given special attention by Changnon and Huff (8). Dr. Chin's stratification and other details are available upon request.

Of the 88 air-mass days, 50 are E and 38 W days. Of the 106 frontal days, 50 are E and 56 W days. Thus, there is some tendency toward associations, but this tendency is very weak. Table 1 compares the apparent effects, averaged per experimental day (whether wet or dry), computed for fixed regions *A* to *F*, separately for the two stratifications E or W and air-mass or frontal. It is seen that, in spite of only slight association, the two stratifications show a remarkable degree of resemblance between categories air-mass and E and between frontal and W: an abundance of significant strongly negative effects in one case and an absence of effects nearing significance in the other. The cross-stratification (E, W) × (air-mass, frontal) resulted in four evaluations. The stratum (E air mass) indicated strong apparent negative effects, significant or highly significant, for all regions. No significant effects were found for the three other strata. However, it is interesting that the apparent effects for (W frontal) were all positive and for the other two all negative, with a single exception. The exceptional result is for ring E, which attracted our attention earlier. A substantial part of this ring is occupied by the Mississippi and Missouri Rivers, which may have created special conditions. In particular, for frontal days, four stations near Memphis showed an almost significant 103% apparent increase in rain. For air-mass days, the apparent effect was strongly negative but not significant.

METHOD OF MOVING GRIDS

The method used for the study of apparent seeding effects in areas at various distances and at specified orientations with regard to the wind direction (the "upwind–downwind" study, for short) is an extension of that used by Braham in his preliminary study (9) of radar data. The following details of the experimental procedure are relevant. The seeding was done by three planes flying at the cloud-base level, each backwards and forwards over a 10-mile path. The three 10-mile paths formed a 30-mile seeding line, the location of which was determined for each experimental day in accordance with prevailing weather conditions. Specifically, a group of 24 clearly identifiable ground objects (termed "fixes") were selected to serve as centers for the 10-mile paths of individual seeding planes. Thus, the middle fix of any particular day represents the center of this day's source of silver iodide smoke. silver iodide smoke?

While the actual upwind–downwind analysis was performed on a digital computer, the method is equivalent to the following manual procedure. upwind-downwind analysis performed on a digital compute T On a sheet of transparent plastic, four lines are drawn forming 45° angles, all passing through the same point (called the vertex). The vertical line is assigned a positive direction upwards, meant to symbolize the "day's wind direction." Two definitions of the day's wind direction were used, labeled W_1 and W_2. Definition W_1 (after Braham, ref. 9) means the direction from the day's middle fix toward target center. W_2 means the wind direction at 4,000 feet at 8 a.m. In addition to the four lines, three circles are drawn on the plastic (see Fig. 1 and 2) with radii of 60, 120, and 180 miles. The four lines and the three circles form a grid of 24 cells.

The first step in the upwind–downwind study consists of determining, separately for each experimental day, the identity of those gauges (out of the 253 available) that on this particular day are in one or another of the 24 cells of the grid. middle f For this purpose, the transparent sheet of plastic is placed on the map of the region so that the vertex coincides with this day's middle fix and so that the vertical line on the sheet has the direction of the day's wind. Next, for each of the 24 cells the gauges covered by each cell are identified and listed. The second step consists in calculating, separately for each cell, the day's average precipitation. This is the arithmetic mean of the particular day's 24-hr-precipitation amounts measured by the gauges that on the given day were within the cell considered. Finally, these average day's precipitation amounts are subjected to the usual analysis (10) comparing seeded and not-seeded days.

Apart from the two definitions of the day's wind direction, the present study differs from Braham's (9) in two respects: (*a*) measurement of 24-hr precipitation at the ground instead of radar echoes, and (*b*) the area covered by the investigation. Braham was interested in the area accessible to his radar located at the target center, up to about 60 miles in all directions. Because the seeding lines were, frequently, some 45 miles away from the center of the target, Braham's investigation was practically limited to points downwind. Our own effort refers to the complete circle of 180-mile radius, divided into 24 cells.

RESULTS

The upwind–downwind study was performed, separately, using the two definitions of the day's wind direction, W_1 and

W_2, combined with the two stratification systems (E, W) and (air mass, frontal). The general patterns of the four sets of results are about the same, but there are differences in detail. Fig. 1 summarizes the results for (E, W) and Fig. 2 those for (air mass, frontal); both were used with wind direction W_1.

Each cell of the grids contains three entries: the identification number of the cell, 1–24, in parentheses; the per cent apparent effect of seeding averaged per experimental day, whether wet or dry (preceded by plus or minus); and the significance probabiliby, P. These entries will be referred to as "wet- and dry-day results." In addition, several cells contain two more entries in rectangles. These are "wet-day results," the per cent apparent effect of seeding averaged per wet day, and the corresponding P.

Three features of Fig. 1 and Fig. 2 deserve particular attention.

(*i*) There is a striking contrast between the upper and the lower parts: a practical absence of significant apparent effects of seeding on W and on frontal days and a multiplicity of significant and highly significant apparent effects, all negative, on E and on air-mass days. (The exceptional, an impressive 82% apparent augmentation of rain on frontal days in cell 17, with $P = 0.057$, may possibly be connected with the findings for the Memphis area, mentioned earlier.)

(*ii*) The magnitude of some of the apparent losses of rain on E and on air-mass days is striking: in several cells the average seeded 24-hr precipitation is found to be about one-fourth that without seeding. For short periods of time, apparent losses of rain of that order of magnitude were noted before, for example, by Braham and Flueck (7), who studied two periods, the 6-hr period of seeding and the 4- to 5-hr period immediately after seeding. For a period of 24 hr, the apparent losses of rain in Fig. 1 and 2 appear unprecedented.

(*iii*) Even more impressive than the magnitude of the apparent losses of rain is the location of some of these significant losses: not only downwind, but frequently upwind, and to the sides, and in cells 120–180 miles from the seeding line. As noted by Battan (5), we offered no hypothesis as to what may have been the cause of the apparent losses of rain in the Whitetop Project; none is advanced now. The reported results reflect facts that happened; plausible explanations may be expected from specialists in cloud physics and meteorology. We do wonder whether the hypothesis (6) of an overseeding mechanism is plausible.

Mechanism behind the significance of upwind–downwind apparent effects

The unexpected results above justify closer examination of the particular features of the data determining the distinction between E and W and between air-mass and frontal days, and those determining the significance of the noted unprecedented apparent losses of rain. Such analysis was performed and indicated the following general pattern.

The mechanism of significant negative apparent effects depends on two factors. First, precipitation per seeded wet day of the E or air-mass category was regularly less than that not seeded, occasionally significantly so. Second, generally, E and air mass had more zero rain days than W and frontal strata, particularly in the upwind cells. Also, in the E and air-mass categories, zero rain occurs more frequently with than without seeding. For example, with W_2 winds, the three upwind cells—23, 15, and 16—had the following numbers of dry air-mass days with and without seeding: (28 vs. 20), (27 vs. 22), and (30 vs. 19), in each case totalling more than half of all air-mass days. In the downwind cell 18, those numbers were lower (15 vs. 9).

TABLE 2. *Apparent effects of seeding evaluated per wet day and per experimental day, wet or dry. Air-mass category*

	Wet days only		Wet and dry days	
Cell	% effect	P	% effect	P
23	−49	0.168	−64	0.056
15	−69	0.026	−75	0.018
16	−62	0.078	−77	0.010
18	−56	0.013	−63	0.005

The concurrent operation of these two factors resulted in the following apparent effects and P values computed for cells 23, 15, 16, and 18 as mentioned above, first with reference to wet, and second to all experimental air-mass days (Table 2).

With only wet days taken into account, the negative apparent effect may be not significant or only mildly significant; the inclusion of dry days increases this effect and makes it more significant. (See also wet-day entries in Figs. 1 and 2.) The regularities described refer to E and to air-mass days only. They are not present in the strata of W and of frontal days.

As expected by Battan (5), days with widespread rain did occur. Rainy or dry weather, when widespread, contributes to the interdependence of results obtained for different areas. However, with the valid tests used, the results for any given area are not vitiated.

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