THE EVALUATION OF RAINFALL RECORDS FROM A FIVE YEAR CLOUD SEEDING EXPERIMENT IN MISSOURI

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1. Introduction

During the five year period from 1960 through 1964 a weather modification experiment was conducted in south central Missouri and north central Arkansas. The experiment involved the use of silver iodide which was placed in the atmosphere from aircraft. This project was designed and operated by the Cloud Physics Laboratory of the University of Chicago under the name "Project Whitetop." The participation by the University of Missouri in the investigation consisted only in the basic reduction of the rainfall records obtained from the recording raingages and performance of the analyses from these rainfall records. The entire program was sponsored by the National Science Foundation.

A detailed description of Project Whitetop has been presented by Braham [1] and will not be repeated in detail here. The basic responsibility of the University of Missouri was to evaluate the hypothesis that the average rainfall was influenced by placement of silver iodide into the atmosphere. Data collected, through radar and by an instrumented aircraft, concerning the development and testing of other hypotheses, either have been or will be reported by Braham [2], [3] and his co-workers at the University of Chicago.

2. The experimental design

The experiment was designed to study the influence of seeding clouds which were formed by convective processes during summer. For this reason, the seeding operation was confined to a six hour period beginning at midday and extending to approximately 1800 CST. This, of course, excluded all nocturnal rain beginning late in the night and the rain occurring during the daylight hours prior to noon.

Only days during which instability showers were expected in the afternoon were included in the experiment. These operational days were defined on the basis of the amount of precipitable water at Little Rock, Arkansas and Columbia, Missouri for the 0600 CST sounding of each day. Precipitable water of 1.05 inches

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or more at Columbia and 1.30 inches or more at Little Rock was required. Further, the wind, as computed from a pilot balloon sounding had to be from 170° to 340° at 4000 ft msl before the day was designated operational.

If the 0600 precipitable water and wind criteria were satisfied, a random selection of the seeded and nonseeded days was accomplished. This provided two groups of days during which afternoon convective activity was expected, with one of the groups containing days selected at random for seeding. Prior to the randomization of the days, the personnel operating the project selected a seeding line that was 30 miles long and located upwind from the center of the research area. The seeding aircraft was deployed along this line on days which were seeded. In addition, this line formed the initial boundary of the plume areas for both seeded and nonseeded days.

The plume positions for each hour were computed by use of the most divergent winds between the seeding level (the base of the cumulus clouds) and 14,000 feet. Thus defined, the plume area would extend itself downwind from the seeding line by the mean wind in this layer and the plume would expand laterally according to the divergent winds in the layer. Using this technique, the plume area was the maximum region over which the seeding agent could have spread. By arbitrary definition, the plume was not permitted to extend beyond 60 miles from the center of the research area. This boundary was imposed by the limitation of the radar located near the center of the research area. The extent of these plumes were defined for both seeded and nonseeded days by the Cloud Physics Laboratory of the University of Chicago, and the plumes thus derived are called "Chicago" plumes.

Later, a redefinition of the plumes was made at the University of Missouri. The assumption was made that the silver iodide was spread from the seeding line according to the winds occurring at the flight altitude of the seeding aircraft. These plumes, which are called the "Missouri" plumes, are not spread laterally over the research area by divergent winds. They are smaller in extent than the Chicago plumes, but one can be reasonably sure that the seeding agent is found within all of the area contained in the Missouri plumes.

It should be noted that the exact extent of the treated area is unknown. The areas defined as the Chicago and Missouri plumes are only estimates of the extent of seeding over the research area.

When the seeding was discontinued at 1800 CST, the plume was allowed to drift across the research area according to the existing wind patterns. In any case, the evaluation was discontinued at midnight even for those cases where a portion of the plume still remained in the research area.

Rainfall measurements were obtained from the regular Weather Bureau network of raingages, and from an auxiliary rainfall network which has been installed for this five year experiment. The number of rainfall stations varied from year to year, ranging from 36 to 49 during the five year experiment. Since the research area was nearly 12,000 square miles in size, there was about one raingage for each 300 square miles. Although it is conceded that this rainfall network is

inadequate, it represented the only information available so far as rainfall reaching the ground is concerned.

The hourly total rain from each precipitation station was plotted on maps on which the plume areas for the respective hour had been superimposed. Using the Thiessen Polygon technique, the rain at each station was weighted to form the average in-plume and out-plume rain for every hour. All stations located within the plume were assigned the closest in-plume areas, while each of the out-plume stations were assigned the nearest area outside the plume. An example of the polygons are shown for the hour ending at 1200 CST on August 19, 1963 in

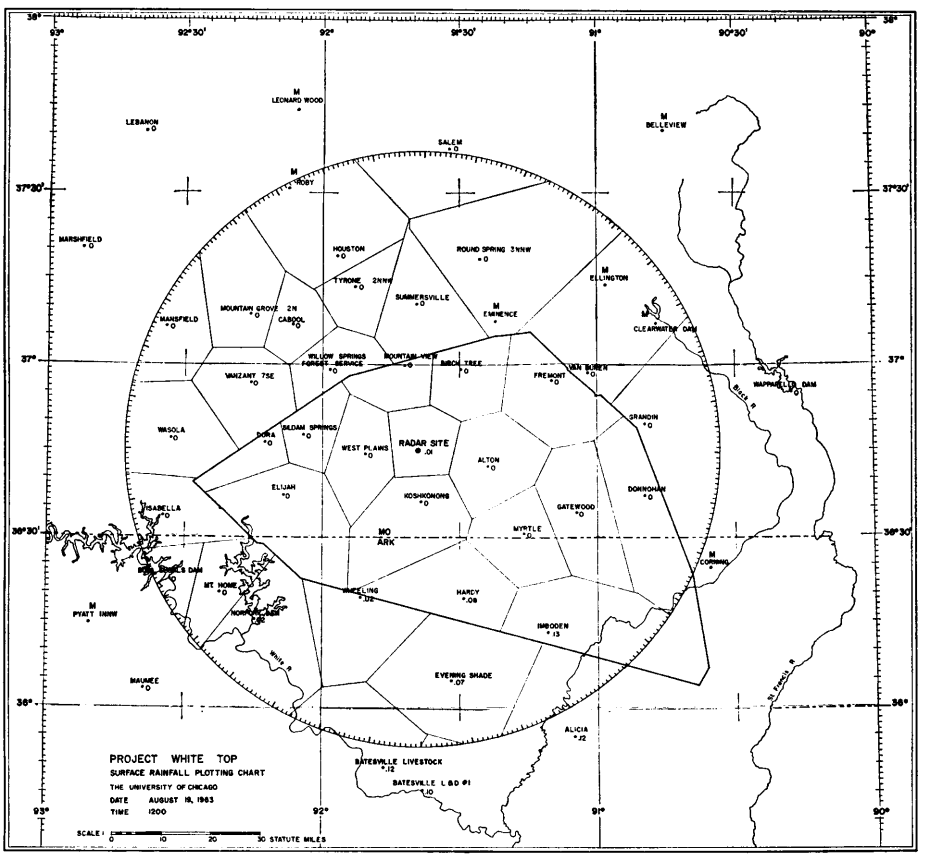

FIGURE 1

The extent of the Chicago plume (outlined in heavier lines) for 1200 CST August 19, 1963 with polygons and hourly rainfall.

figure 1, and the computations of the average in-plume and out-plume rainfall for the hour are shown in table I.

Because of the small density of the raingages, for some of the hours none of the

TABLE I

COMPUTATION OF IN-PLUME AND OUT-PLUME AVERAGE PRECIPITATION FOR THE HOUR ENDING AT 1200 ON AUGUST 19, 1963, USING THE CHICAGO PLUME

In-Plume				Out-Plume			
Station	Area (sq mi)	Rainfall	Weighted Rainfall	Station	Area (sq mi)	Rainfall	Weighted Rainfall
Radar Site	172	.01	1.72	Batesville Live.	201	.12	24.12
Hardy	306	.08	24.48	Batesville L. D.	9	.10	.90
Imboden	376	.13	48.88	Evening Shade	578	.07	40.46
Doniphan	391	0	0	Norfork Dam	450	.02	9.00
Gatewood	334	0	0	Wheeling	323	.02	6.46
Fremont	329	0	0	Alicia	190	.12	22.80
Myrtle	251	0	0	Grandin	566	0	0
Alton	284	0	0	Van Buren	616	0	0
Birch Tree	218	0	0	Round Springs	717	0	0
Mt. View	138	0	0	Salem	336	0	0
Koshkonong	371	0	0	Summersville	356	0	0
West Plains	237	0	0	Tyrone	184	0	0
Siloam Springs	133	0	0	Houston	455	0	0
Dora	110	0	0	Willow Springs	180	0	0
Elijah	455	0	0	Cabool	167	0	0
				Mt. Grove	326	0	0
				Vanzant	325	0	0
				Mansfield	233	0	0
				Wasola	373	0	0
				Isabella	281	0	0
				Bull Shoals	121	0	0
				Mt. Home	218	0	0
Totals	4105		75.08		7205		103.74
Average Rain			.0183				.0144

stations were located within the plume and for other hours the plume was extended over the entire research area with no rainfall stations in the out-plume region. Each of these cases was labeled as an unfair hour and was not included in the computation of average daily rainfall. The average in-plume and average out-plume rainfall for every operational day were derived from the average of all fair hours. An example of the computations for August 19, 1963 is shown in table II. Both the hourly and daily averages are included in a report by Decker and Schickedanz [4] to the National Science Foundation which may be obtained upon request.

3. Results of the analysis

Shown in table III are the averages of the rainfall for the various seeded and nonseeded areas. Although these figures were derived on the basis of the 13 hour period from 1100 to midnight, they are expressed in inches per hour. The average

TABLE II

SUMMARY OF HOURLY DATA USING THE CHICAGO IN-PLUME AND OUT-PLUME PORTIONS OF THE RESEARCH AREA FOR AUGUST 19, 1963

* Unfair hour, that is, either no rainfall stations within the in-plume or out-plume areas.

		In-Plume			Out-Plume		
Date	Time	Area (sq mi)	Number of Stations with Rain	Average Rain (in/hr)	Area (sq mi)	Number of Stations with Rain	Average Rain (in/hr)
8/19/63	1100	1306	2	.0148	10,004	10	.0096
	1200	4104	3	.0183	7206	6	.0144
	1300	5542	2	.0093	5768	1	.0003
	1400	5093	0	0	6217	1	.0012
	1500	4420	0	0	6890	1	.0073
	1600	3881	0	0	7429	0	0
	1700	3086	0	0	8224	1	.0051
	1800	2557	0	0	8753	0	0
	1900	1838	0	0	9472	1	.0044
	2000	987	0	0	10,323	0	0
	2100	642	0	0	10,668	1	.0065
	2200	233	0	0	11,077	0	0
	2300*	0	0	0	11,310	0	0
	2400*	0	0	0	11,310	0	0
Total				.0424			.0488
Average				.0035			.0041

TABLE III

AVERAGE RAINFALL (INCHES/HOUR) FOR THE IN-PLUME AND OUT-PLUME AREAS FOR SEEDED AND NONSEEDED DAYS

	Seeded Days			Nonseeded Days		
	Chicago Plume		Missouri Plume	Chicago Plume		Missouri Plume
Year	Within	Outside	Within	Within	Outside	Within
1960	.0065	.0084	.0048	.0078	.0104	.0057
1961	.0093	.0072	.0050	.0137	.0126	0160
1962	.0021	.0040	.0008	.0147	.0088	.0140
1963	.0066	.0058	.0100	.0065	.0057	.0096
1964	.0066	.0065	.0033	.0075	.0045	.0059
All years	.0063	.0065	.0051	.0104	.0085	.0106

of the in-plume and out-plume rainfall for both seeded and nonseeded days are presented for each year for both the Chicago and Missouri plume areas.

The largest of the average rainfall was for the in-plume areas on the nonseeded

days. In the case of the Chicago plume, in four out of five years the nonseeded days produced a higher average rainfall within the plume area than the average of the in-plume rainfall on the seeded days. This appears to suggest an adverse effect from cloud seeding. However, in four out of the five years the average rain within the plume areas on the nonseeded days was greater than the average for the out-plume areas on the same days. In the latter comparison, of course, no treatment effect is expected since the seeding operation was not being done on these days. In addition, it will be noted that the average rainfall within the Chicago plumes on seeded days was nearly identical with the average rainfall outside of the plumes on these same days.

When the Missouri plumes are employed on every year, the seeded days received less rain in the plume than was received in the plumes on the nonseeded days. Indeed, in four out of five years the average rain experienced within the Missouri plume on seeded days was less than that obtained in the area outside of the Chicago plume.

An array of differences for paired values may also be produced. For example, the difference between the in-plume and out-plume rain on the same day may be obtained. For the Chicago plume the average difference between the in-plume and out-plume rain on seeded days was very nearly equal to zero. However, on nonseeded days the average difference between the in-plume and out-plume rain favored the in-plume area.

4. Tests of significance

One of the objectives of Project Whitetop was to provide data from a randomized experiment which could be used to test hypotheses concerning the effect of seeding on the amount of rain reaching the ground. The participation of the University of Missouri in the analysis involved performing these basic tests in addition to the data reduction. The design of the experiment suggests the testing of the basic null hypothesis concerning the equality of the mean rainfall from an area treated with the seeding agent with an area without seeding.

Because the frequency distribution of rainfall is skewed toward the right (the mean exceeds the modal value), tests should not be directly employed which involve the assumption of normality in the original population. Either a transformation of the rainfall data to a normal distribution should be made, or a test employed which does not involve the assumption of normality.

The daily rainfall for the treated and nontreated areas were transformed by a logarithmic transformation. The arrays of daily rainfall for the in-plume and out-plume areas on seeded days and the in-plume and out-plume areas on nonseeded days were each transformed. The use of this technique presents at least two difficulties. First, it is impossible to utilize daily rainfall statistics when the daily rain is zero. In the case of this experiment, on 43 of the 102 seeded days there was no rain measured within the in-plume area, while no rain fell on 44 of the 96 nonseeded days within the in-plume area. Second, it is possible for

the sign of the difference between the means of treated and nontreated areas to be reversed by the transformation. If $\overline{IP}$ is the mean rainfall for the in-plume area and $\overline{OP}$ the mean for the out-plume area for all seeded days, the sign of $\overline{IP} - \overline{OP}$, may be opposite to the sign of the $(\overline{\log IP} - \overline{\log OP})$. This offers great difficulty since the test is for the difference between the average of logarithms, while it is actually the differences in the depth of rainfall which have meaning.

Nevertheless, the daily rainfall for the Chicago plumes were transformed and tests were made concerning the differences between the treated and nontreated means. These tests were: (1) the Chicago in-plume on seeded days versus the Chicago in-plume on nonseeded days; and (2) the Chicago in-plume on seeded days versus the Chicago out-plume on the same days. Using the t test it was not possible to reject the null hypothesis of equality for a two tailed test at the five per cent level of significance for either of these comparisons. As a uniformity trial the mean of the Chicago in-plume on the nonseeded days was compared with the mean of the Chicago out-plume on the same days. The resulting t value obtained was not significant, as expected.

Other t tests were performed, using the paired differences between daily rainfall of the in-plume and the daily rainfall for the out-plume areas on seeded days and on nonseeded days. For each seeded day the difference was obtained by subtracting the rainfall for the out-plume area from the rainfall for the in-plume area. A similar array of differences was obtained for the nonseeded days. In these tests the zero values for the daily rainfall were not removed from the data, since no transformations were made. The null hypothesis that the mean difference between the in-plume and out-plume average rainfall was equal to zero was tested. For both the seeded and nonseeded days this hypothesis could not be rejected at the five per cent level using a two tailed test.

In order to overcome the difficulty arising from the nonnormality of the original rainfall data, the Mann-Whitney U test was employed. This test could provide evidence for the rejection of the null hypothesis that the distribution of the rainfall from the seeded area was the same as the distribution from the nonseeded area. The computations for the Mann-Whitney test involved ranking the observations. The resulting statistic U must be corrected for ties in the ranks. Due to the large number of ties resulting from the numerous zero rain days, the correction term tends to dominate the computed statistic. For this reason, the days with zero in-plume or out-plume rain were excluded from the test.

A comparison was made of daily rainfall from the Chicago in-plume with the Chicago out-plume on seeded and on nonseeded days. Also, a comparison was made using the daily rainfall from the Chicago in-plume on seeded days with the Chicago in-plume on nonseeded days. The null hypothesis was accepted in all cases.

Using the Chicago plumes, none of the tests produced significant differences. The approximate probability levels for larger values of t and for larger values of Z in the Mann-Whitney test are shown in table IV.

TABLE IV

SUMMARY OF APPROXIMATE PROBABILITY LEVELS FOR t AND Z STATISTICS FOR THE t TEST AND MANN-WHITNEY U TEST

Comparison	Probability of a Larger Statistic		
	Using t from Transformed Data	Using t for Paired Differences	Using Z for Mann-Whitney
Chicago in-plume seeded vs. in-plume nonseeded	.14	—	.15
Chicago out-plume seeded vs. out-plume nonseeded	.06	—	.06
Chicago in-plume seeded vs. out-plume seeded	.89	.85	.82
Chicago in-plume nonseeded vs. out-plume nonseeded	.85	.28	.84
Missouri in-plume seeded vs. in-plume nonseeded	<.01	—	<.01
Missouri in-plume seeded vs. Chicago out-plume seeded	.90	.28	.88
Missouri in-plume nonseeded vs. Chicago out-plume nonseeded	.08	.34	.11

Tests were also made, using the daily rainfall from the Missouri plumes. The only comparison made was between the in-plume rain on seeded days and the in-plume rain on nonseeded days. When these data were transformed the t test indicated that the differences between the means were highly significant. When plume areas were restricted in size according to the assumptions of the Missouri plume, the seeded days had significantly less rainfall within the in-plume area than on the nonseeded days. The null hypothesis of no differences in the distributions of rainfall for the in-plume seeded and in-plume nonseeded areas defined by the Missouri plumes were subjected to the Mann-Whitney test. A highly significant difference was also obtained and the null hypothesis rejected. As before, this indicated that the seeded days had less rainfall within the plume than the nonseeded days.

Tests were also made between the rainfall for the in-plume areas of the Missouri plume and the out-plume area from the Chicago plume analyses. Using these comparisons three separate tests of significance were made for the seeded days. These include (1) a t test using the logarithmic transformation, (2) a t test based on the paired differences of the in-plume and out-plume rain on each seeded day, and (3) the Mann-Whitney U test based on the ranks of the daily rainfall from the Missouri in-plume and Chicago out-plume areas. All three tests failed to achieve significance at the five per cent level using the two tailed test, and the null hypothesis was accepted.

The acceptance of the null hypothesis that the in-plume rain for the Missouri plume was equal to the out-plume rain for the Chicago plume leads to the conclusion of no differences due to seeding with silver iodide. The fact that the

Missouri plume on seeded days had less rain than occurred on nonseeded days must be attributed to meteorological events.

In table IV are shown the approximate probability levels for the t and Z values. Remarkable uniformity is noted between the probability level of these tests.

5. Summary

Since the mean rainfall on the nonseeded days was greater than the rainfall for the seeded days, there is, by this experiment, no evidence of increases in precipitation due to cloud seeding. Using the smaller Missouri plumes, the no treatment days produced significantly greater rainfall than the seeded days. However, another comparison of the seeded versus no treatment effects was provided from a comparison of the rainfall for the Missouri in-plume and Chicago out-plume on the seeded days. This second estimate of the treatment effect produced no difference of significance. Further, a comparison of the out-plume (no treatment) areas on seeded and nonseeded days shows greater rainfall on the days without treatment with the difference approaching significance (0.06). This appears to indicate that in spite of randomization, the no treatment days were meteorologically favored with rain. This meteorological difference is confounded with any treatment effects.

When interpreting the results of this experiment, one should remember that the cloud seeding activity was conducted under rather specific meteorological conditions. These were summer days during which convective activity was occurring in the central United States, and during which the cumulus clouds were developing in a scattered, and, perhaps, random fashion. It is possible that under these meteorological conditions the ice crystal process may not be the controlling mechanism in the release of the precipitation. A different result might have occurred if the thunderstorm and shower activities of the hours from midnight until noon had been included.

At present, other analyses are under investigation at both the University of Missouri and the University of Chicago concerning these data. This includes an analysis which terminates the experiment at the 2100 hour and one which ends the experiment when the seeding aircraft ceases to operate. Also, to be reported by the University of Chicago are the results of the radar analyses and a covariance analysis between the rainfall and radar.

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