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Statistical Evaluation of the Santa Barbara Randomized Cloud-Seeding Experiment [1]

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ABSTRACT

The experimental conditions of the Santa Barbara Project over the three years 1957 through 1959 were not uniform. In 1957, there was no seeding in the adjoining areas. In 1958, seeding went on in Ventura County at every opportunity. In 1959, the seeding operations in the two counties were factorially randomized. These changes created partial confounding of possible effects of seeding with possible effects of changes in weather pattern. Whatever the cause, some of the apparent effects were very large. In particular, the average apparent increase in the rain in Santa Barbara, obtained in the absence of seeding in Ventura, amounted to about 100 per cent. The last section of the paper is concerned with recommended changes in the design intended to increase the accuracy of the experiment.

1. Introduction

The organization outline of the Santa Barbara Project was published in the Bulletin of the American Meteorological Society, Vol. 39, 1958, pp. 162–164. Briefly, the North American Weather Consultants, Inc. (NAWC, for short), with Robert D. Elliott as President, conducts the seeding operations, using ground generators; the California State Department of Water Resources is responsible for maintenance of raingages, obtained on loan from the United States Weather Bureau, and for the collection of data; the Statistical Laboratory of the University of California at Berkeley is responsible for the randomization of the experiment and for its statistical evaluation. Concurrently, Meteorological Research, Inc. performs certain physical measurements and observations. However, this is done independently from the other work, and the results obtained by Meteorological Research, Inc. are not evaluated by the Statistical Laboratory.

The purpose of the present paper is to present the results of the statistical study of the data collected during the first three years of operations, 1957 through 1959. The main text is written from the point of view of evidence of the effects

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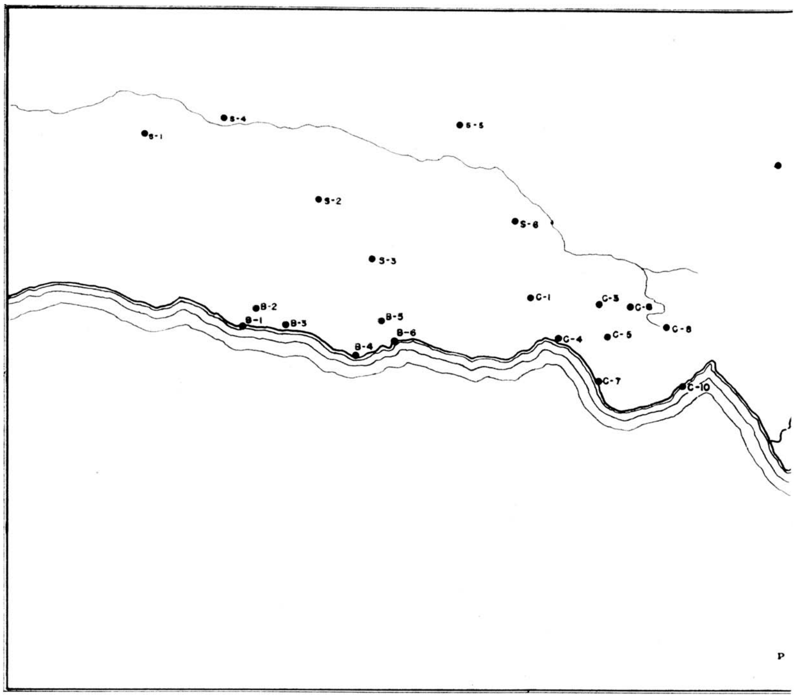


FIG. 1. Location of recording raingages in Santa Barbara

of seeding. In addition, by using the experience gained during the first three years of the experiment, a study was made of the dependence of the precision of the experiment on several experimental factors, of the number of years of experimentation needed to have a reasonable chance of detecting the effect of a given magnitude, and of a few modifications of the present design. A summary of the conclusions of this study is given in the last section of the paper.

Although in the course of study several different methods of evaluation were used, the results presented here are based on the method adopted by the Board of Directors at the outset of the Project. Also, the study is limited to the evidence of the effects of seeding without subdivision for night and daytime operations, which was not contemplated at the outset. Other results are briefly alluded to whenever they are relevant to the problem of the design of the experiment.

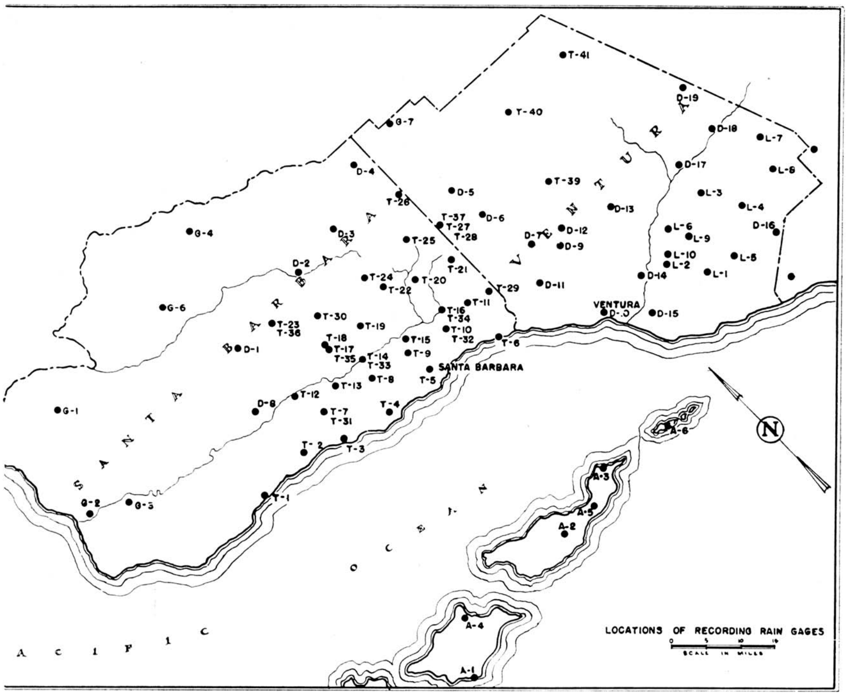
In the next section, we outline the experimental procedure, give the definitions of certain terms necessary for the understanding of the paper, and explain the method of evaluation. Further details may be found in the joint report on the Project [1].

2. Experimental procedure and method of evaluation

Fig. 1 is a map showing the two main targets of the seeding operations and the three control areas. The main targets are the County of Santa Barbara and the adjoining County of Ventura. The three control areas are A, the Channel Islands; B, the San Simeon-Cape San Martin area; and C, the San Luis Obispo-Morro Bay area. In the course of study, it was found expedient to combine the originally designated area B with an extension to the east, including a part of the Salinas Valley. This extended control is symbolized by BS.

Circles, with various symbols attached to them, mark the location of raingages. For purposes of evaluation, each of the main targets is subdivided into three subtargets. These subtargets are defined in terms of the raingages used in evaluation as follows.

Santa Barbara: Target Coast, raingages T1, T2, T5, T6.
Target Valley, raingages T7, T12, T17, T23.
Northwest, raingages F1, G1, G2.
Entire, raingages T1, T2, T5, T6, T7, T12, T17, T23, D1, D8, G1, G2.



and Ventura Counties and in the three control areas.

Ventura: North, raingages D5, D6.
Santa Clara, raingages D7, D9, D10, D11, D12, D13, D14, D15, D17, D18, D19.
Calleguas, raingages D16, L1, L2, L3, L4, L5, L6, L7, L8, L9, L10.

It will be seen from the map that the subtargets of Santa Barbara contain a substantial number of raingages not mentioned in the above definitions. For reasons explained below, these raingages could not be used in the present evaluation.

The basic experimental procedure is as follows. The seeding season, January through April of each year, is divided into 12-hr periods, each from 10 o'clock to 10 o'clock termed "units of observation." Some time before the beginning of each unit of observation, the NAWC decides whether this unit is suitable for seeding. If the decision is in the affirmative, then this unit of observation is labeled a "seeding opportunity." Between 8 and 9 o'clock, morning and evening, the NAWC contacts the Statistical Laboratory by teletype and communicates its decision as to whether the forthcoming unit of observation is or is not a seeding opportunity. Also, in the positive case, the NAWC indicates which of the three control areas are "appropriate" for the given seeding opportunity. These are the control areas which the NAWC expects not to be contaminated by seeding over the targets. Upon receiving these messages, the Statistical Laboratory communicates to the NAWC its randomized decision: "Seed" or "Do not seed."

The evaluation of the experiment, agreed upon at the outset of the project, is based on the precipitation in the targets recorded for all diagnosed "seeding opportunities" and no others. These amounts of precipitation are compared with the amounts falling simultaneously in the "appropriate" control areas.

Basically, two kinds of statistical evaluations were performed, one using the so-called normal theory and the other using nonparametric methods.

In order to stabilize the conditional (residual) variance of the measure of target precipitation given the precipitation in the appropriate controls, the amounts of rain in each subtarget, observed for the particular seeding opportunities and averaged over the corresponding raingages, were replaced by their square roots. These square-root measures were then used for the regression analysis. Specifically, in order to decide whether there was any effect at all from seeding, the familiar F-test was used to test the hypothesis that the target-control linear regressions corresponding to seeded seeding opportunities coincided with corresponding regressions for those seeding opportunities which were left unseeded. Subsequently, the regression equations computed using the square-root precipitation measures for non-seeded seeding opportunities were used in order to estimate the square-root target precipitation to be expected for seeded seeding opportunities if there were no seeding. These estimates were recalculated in terms of inches of rainfall and, after an appropriate correction for bias due to the transformation of variables [2], were compared with the actual target precipitation for each seeded seeding opportunity. The differences between these two quantities, averaged over all seeded seeding opportunities, represent estimates of the average effect of seeding.

The above procedure was used because of its familiarity and relative ease. However, because of the various well-known uncertainties regarding the applicability of normal theory to precipitation data, even if they are expressed in square roots, a parallel but much more laborious evaluation was performed leading to a randomization test of the hypothesis that the seeding had no effect. This test was based on the familiar λ-criterion. However, the distribution of this criterion was obtained not from normal theory but empirically, by using a high-speed electronic computer to perform repeatedly the randomization procedure on the totality of data for both seeded and non-seeded seeding opportunities. The significance probabilities obtained in this manner are given in table 3 under the heading "permutation test."

3. Historical sketch of three years of operations

The history of the Santa Barbara Project illustrates the difficulties that an experiment of considerable scope, planned for several years, is likely to encounter, particularly if it is to be conducted not by a large single institution with centralized decisions but by a cooperative arrangement of several organizational units with heterogeneous interests.

Some of the difficulties would have been experienced at the start of a large project, independently of the organizational setup. The terrain of the interior Santa Barbara target is very rugged, and installation and servicing of raingages there presented considerable difficulties. Eventually, particularly in bad weather, they were serviced by helicopter. There were similar difficulties in installing and servicing the gages located in the Channel Islands which are practically uninhabited. As a result, instead of starting on 1 January 1957, the official beginning of the experiment was set on 10 January 1957. However, even after that date, some gages were not yet in operation and many of the gages had incomplete data. In a few instances, the raingages were damaged by bullets. In order to include the maximum number of seeding opportunities in the evaluation, we could utilize in the County of Santa Barbara only 13 gages out of the 31 installed in 1957, for which there are continuous usable records over all three seasons. Here the word "usable" means not only clear-cut record on the chart but also those cases where, because of late servicing, the gages recorded accumulations over longer periods of time which could be "distributed" convincingly among the several adjoining units of observation. Finally, in the continuity of records of even these 13 gages, there is a most unfortunate gap: in April of 1958, there was a long period of substantial rain, with eight diagnosed seeding opportunities, during which all the inland gages in the Santa Barbara target could not be reached even by helicopter. The precipitation accumulated during this period exceeded the capacity of some of the raingages and they overflowed while others had accumulations. In other words, while the evaluation of Target Coast and of Santa Barbara NW could be made by using all of the 34 seeding opportunities of 1958, in evaluating Target Valley it was necessary to omit the eight opportunities of April 1958. Because the nonavailability of these data is due to the high values of the dependent variable (rain in the target), their omission in the evaluation subjects its results to the danger of bias.

Not only was the number of "missing" records heavy but also, in some cases, the geographical distribution of gaps was unfortunate. A glance at the map in fig. 1 will convince the reader of the importance of control area A, with six raingages located more or less on a straight line East-West and covering a distance of 48 mi. This line of gages frequently cuts across the path of storms reaching Santa Barbara and thus promises a good predicting value for the rain in the target. In 1957, there were only three gages installed in the Channel Islands, but, unfortunately, usable data are available for only one gage A2. In 1958, there were five gages in the islands of which three, A1, A2 and A5, had usable records. This improvement continued and was general so that, for 1959, usable data are available for almost all the gages available to the Project, including the six gages in the control area A.

From the point of view of continuation of the Project on a new basis, by using more gages as of 1959, this circumstance is very encouraging. However, in the present evaluation it was possible to use the records of just one gage in area A—namely, gage A2.

As already mentioned, the above difficulties are intrinsically connected with the setting up of a meticulously efficient machinery for servicing gages in a mountainous region and could hardly be avoided in the working of any young organization. However, the Santa Barbara Project was affected by certain other difficulties which might have been avoided if the experiment were conducted by a single powerful scientific organization.

At the outset, in 1957, the experiment was concerned with just one target, the County of Santa Barbara, and there was no seeding going on in the adjoining areas. The seeding opportunities were randomized in two categories only, seeded and not seeded. In 1958, there was a significant change in this situation brought about by the sudden decision of the Board of Supervisors of Ventura County, just east of Santa Barbara, to conduct seeding operations in their area. The contract for seeding went to the NAWC who were promised some sort of cooperative arrangement with the Santa Barbara Project.

The inclusion of Ventura County into a single cloud-seeding project, combined with that in Santa Barbara, opened very interesting possibilities. The question as to whether seeding operations conducted in one area affect the precipitation in an adjoining area and in what sense is important for practical purposes and is interesting theoretically. By an appropriate adjustment of the seeding schedules in Santa Barbara and in Ventura, and granting a reasonable duration of the experiment, these questions could receive at least a partial answer. For this reason, the Statistical Laboratory was enthusiastic about the forthcoming seeding operations in Ventura County and suggested that these operations be subjected to factorial randomization. Under this design, all the seeding opportunities would have been randomly divided into four categories:

(i) no seeding in either county,
(ii) seeding in Santa Barbara but no seeding in Ventura,
(iii) no seeding in Santa Barbara but seeding in Ventura,
(iv) seeding in both counties.

The comparison symbolized by (ii)–(i) would then indicate the effect of seeding in Santa Barbara in the *absence* of seeding in Ventura. This effect could have been estimated separately for both targets. Again, the comparison symbolized by (iv)–(iii) would provide estimates of the effect of Santa Barbara generators experienced *in the presence* of seeding in Ventura. The comparisons of the type (iii)–(i) and (iv)–(ii) would give the effects of the Ventura generators, separately in the absence and in the presence of seeding in Santa Barbara.

Unfortunately, in part because of the extended drought afflicting Ventura Country, the advice of the Statistical Laboratory was not followed, and, in 1958, seeding operations were conducted in Ventura County at every opportunity.

One might perhaps think that this decision did not affect adversely the conduct of the experiment. In fact, one might argue that, while the seeding operations of 1957 provided observations of the categories (i) and (ii), those of 1958 contributed to categories (iii) and (iv) which could be combined into an organized whole. Unfortunately, presumptions of this kind are mistaken. The point is that, as established earlier [3], the target-control regressions of precipitation depend upon the type of storms. The frequency of the various types of storms, determining what might be vaguely called the weather pattern, changes considerably from one year to the next. As a result, the observations of 1957 provide information on categories (i) and (ii) with reference to the weather pattern of that year, and the observations of 1958 give data of categories (iii) and (iv) with reference to the weather pattern of 1958 which, as evidenced by the data given in the sequel, was very different from that in 1957.

If both years had been subjected to the indicated factorial randomization, the data for these two years would have been indicative of the various seeding effects averaged over the two different weather patterns. As things are, the possible effects of seeding are partially "confounded" with the effect of weather pattern.

In 1959, there was a salutory change in the design: seeding operations in Ventura were combined with those in Santa Barbara into a single factorially randomized experiment. Unfortunately, 1959 proved to be an exceptionally dry year, with only nine seeding opportunities. The data for about one-half of these opportunities can be combined with the data of 1957 providing estimates of the effects of seeding averaged over the weather patterns of 1957 and 1959. The other half combines with the data of 1958 providing estimates of the different effects of seeding averaged over 1958 and 1959. There are obvious difficulties of interpretation. Because of these difficulties, the substantive aspect of the Santa Barbara Experiment (namely, its contribution to the question as to whether seeding with ground generators affects the rain in the target) is a disappointment. On the other hand, the encounter with the various difficulties enumerated, none of them anticipated at the outset, provides experience which is likely to be valuable in the organization of future experiments with cloud seeding. A summary of conclusions suggested by this experience will be found in the last section of the present paper.

4. Selection of seeding opportunities

Because of the frequently made claims of the validity of historical evaluation of commercial seeding operations, it is interesting to establish the relationship between the duration of actual seeding and the amount of time of significant precipitation in the target. Table 1 gives two classifications. One refers to days covered by the contracts for seeding in all the commercial operations in California in 1951–52 (for which we have easily accessible data). The other refers to the 12-hr "units of observation" over the three years of the Santa Barbara Project. In both cases, there is a two-way classification: according to the amount of rain in the target, averaged over the relevant raingages, and according to whether or not there was any seeding. The data for the first part of the table were taken partly from the hourly precipitation records published by the United States Weather Bureau and partly from the official seeding logs published by the State of California [4].

It will be seen that in both cases a substantial proportion of units of observation, close to one-half, is left not seeded. Incidentally, the comparison of the two parts of the table indicates an aspect of conformity of the seeding policy in the Santa Barbara Experiment with usual practice of commercial cloud seeding.

In addition to the numbers of units of observation with some rain in the target, it is interesting to examine the corresponding joint distribution of precipitation in the target and in the control area. Figs. 2 and 3 give such distributions separately for the units of observation in the Santa Barbara Project diagnosed as seeding opportunities and for those not so diagnosed. It will be seen that the two distributions differ considerably in their general character. On the other hand, the difference between the seeded and not-seeded seeding opportunities, indicated in fig. 2 by different symbols, is much less pronounced. The conclusion is that the population of seeding opportunities does not coincide with the population of all corresponding periods of time with some rain in the target. As a result, even if the year-to-year changes in the weather pattern did not affect the target-control regressions, the validity of storm-by-storm evaluations of seeding operations, based on comparisons between the population of seeded

TABLE 1. Classification of units of observation according to average rain in the target and suitability for seeding.

	Nine commercial operations in California 1951–1952			Santa Barbara Project 1957–1959		
Average precipitation in inches	Total no. of days under contract	No. days seeded	% seeded	Total no. 12 hour units of obs.	No. units seeded	% seeded
Exactly zero	640	52	8	563	7	1
0.00–0.03	93	21	23	36	10	28
over 0.03	303	167	55	102	51	50
over 0.10	220	130	59	75	38	51

Legend: (i) The commercial seeding operations are identified in [4] as follows:

Southern Sierra Corp.; Kern County; Southern California Edison; San Diego County Weather Corp. and Santa Ana River Weather Corp.; Santa Barbara County Water Agency; Antelope Valley Water Development Corp.; Santa Clara County Weather Corp.; Carrisa Corp.; Ventura County Cloud Seeding Corp.

(ii) The precipitation amounts for the Santa Barbara Project were those for the four coast stations T1, T2, T5, T6, for which there is a continuous record over the three years of operations.

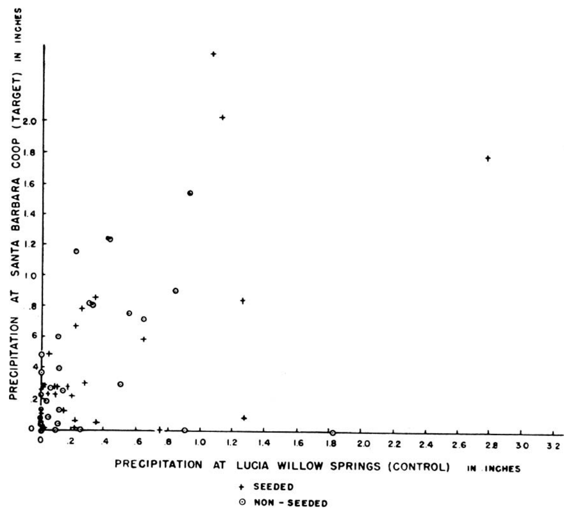


FIG. 2. Precipitation at Lucia Willow Springs and at Santa Barbara Coop for seeding opportunities only in 1957, 1958 and 1959.

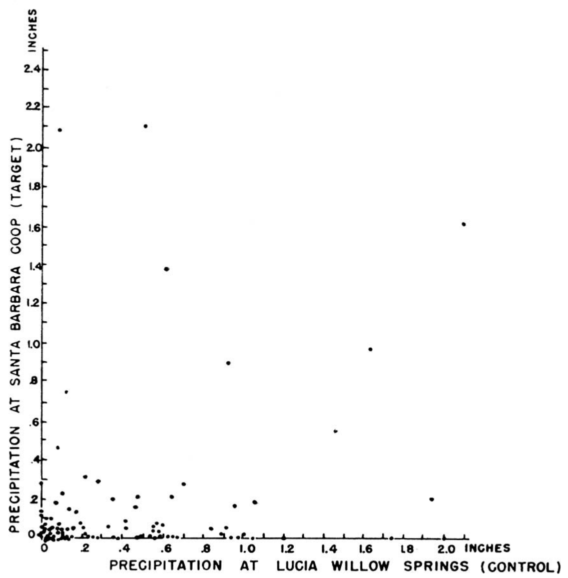


Fig. 3. Precipitation at Lucia Willow Springs and at Santa Barbara Coop for not-seedable opportunities only in 1957, 1958 and 1959.

storms in one period and the population of all storms in another period, is open to question.

5. Data used for evaluation

Data used for the present evaluation are exhibited in table 2. Each entry represents the amount of rain in inches recorded over a separate seeding opportunity, averaged over all the raingages in the given subtarget or in the given control area. The table is divided into four parts. The two parts on the left refer to seeding opportunities which were seeded in Santa Barbara. The two parts on the right correspond to no seeding in Santa Barbara. The two upper parts of the table refer to no seeding and the two lower parts to seeding in Ventura. Separate lines in each part of the table correspond to particular seeding opportunities identified on the left by their dates and the symbols "ev" and "m" indicating "evening" or "morning" (that is, the twelve-hour periods from 10 p.m. to 10 a.m. and from 10 a.m. to 10 p.m., respectively). The second column indicates the control areas which for the given seeding opportunity were diagnosed as "appropriate." It will be seen that control area C was appropriate in only a very few cases. For this reason, the evaluations given below are based on control areas A and BS only. Subsequent columns of the table refer to separate subtargets, as defined by the raingages identified at the bottom.

The confounding of the effects of seeding and the weather patterns in the years 1957 and 1958 is clearly seen in table 2. Notice that the two upper parts of the table are dominated by data of 1957 and the two lower parts by those of 1958. Notice also that, while the corresponding figures in the left and in the right parts of the table show but mild differences, ascribable to seeding in Santa Barbara, the differences between the corresponding entries in the upper and in the lower parts of the table are very pronounced. This applies not only to entries corresponding to the various targets but also to data referring to control areas. This latter circumstance indicates that at least some of the differences between the upper and the lower parts of the table are connected with the change in the weather pattern between 1957 and 1958 and not with seeding in Ventura.

Unfortunately, the same confounding of the two different effects causes difficulties in the regression analysis given in the next section.

6. Estimation of effects of seeding on precipitation in the two targets

The results of the regression analysis, performed by methods briefly outlined in the second section are given in table 3. Because of the already emphasized confounding and of the loss of data for the eight seeding opportunities in April 1958, most of the effects indicated in table 3 are questionable. Nevertheless, for the sake of illustration, the table is compiled as if there were no losses in data and as if the operations over the three years were factorially randomized. In the course of the discussion of the table, we indicate those conclusions which are valid subject only to the condition that the data on which the table is based are reliable.

Table 3 is divided into four parts indicated by vertical lines. The first two evaluate the effect of "Santa Barbara generators"—that is, of the generators meant to increase rain in the County of Santa Barbara. Similarly, the last two parts evaluate the effect of "Ventura generators."

Over certain periods of the experiment (namely, in 1957 and partly in 1959), the Santa Barbara generators were alternating between seeding and no seeding, while there was no seeding in Ventura. The effect of the Santa Barbara generators on the rain in the different subtargets, produced in the absence of seeding in Ventura, is estimated in the first part of table 3. Similarly, the effect of the same generators in the presence of seeding in Ventura (years 1958 and 1959) is estimated in the second part of the table.

TABLE 2. Simultaneous precipitation in target and comparison areas seeded in Santa Barbara opportunities. (Average precipitation in inches.)

Seeding opport. Not seeded in Ventura	Approp. comp. area	T-coast	T-valley	SB-NW	SB entire	A	BS	V-north	V-S.C.	V-Calleguas
1957										
1–12 ev	A, B	0.460	1.035	0.223	0.640	0.500	0.454	0.905	1.095	0.749
1–22 ev	A, B	0.005	0.000	0.000	0.002	0.000	0.008	0.000	0.031	0.061
1–23 m	A, B	0.145	0.198	0.137	0.164	0.190	0.000	0.155	0.142	0.164
1–25 ev	A, B	0.255	0.235	0.077	0.185	0.470	0.028	0.100	0.345	0.307
1–27 m	B, C	0.020	0.005	0.000	0.008	0.000	0.000	0.130	0.146	0.095
2–7 ev	A, B	0.278	0.445	0.577	0.414	0.140	0.088	0.180	0.146	0.057
2–8 m	B, C	0.270	0.312	0.287	0.302	0.100	0.052	0.120	0.090	0.037
2–23 m	A, B	0.000	0.070	0.007	0.027	0.000	0.160	0.025	0.027	0.010
3–8 ev	A, B	0.095	0.148	0.160	0.134	0.060	0.178	0.010	0.045	0.043
3–17 m	A, B	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.010	0.000
3–18 ev	B	0.070	0.062	0.070	0.067	0.430	0.000	0.060	0.085	0.061
4–17 m	A, B	1.228	1.728	0.867	1.315	0.440	0.872	0.915	1.158	0.610
4–18 m	B	0.015	0.008	0.003	0.008	0.000	0.000	0.010	0.009	0.000
1959										
1–5 ev	A, B	0.805	1.960	0.213	1.074	0.520	0.316	1.725	1.567	1.064
2–7 m	A, B	0.022	0.200	0.000	0.086	0.000	0.066	0.060	0.024	0.026
	Mean	0.245	0.427	0.175	0.295	0.190	0.148	0.295	0.328	0.219
Seeded in Ventura										
1958										
1–24 m	A, B	0.308	0.775	0.823	0.518	0.730	0.326	0.095	0.333	0.265
1–25 ev	A, B	0.648	1.232	0.660	0.814	0.250	0.760	0.535	0.578	0.740
2–1 m	A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2–3 ev	B, C	0.835	1.428	0.430	1.019	0.090	1.196	2.110	1.135	0.882
2–12 m	A, B	0.318	0.558	0.513	0.472	0.240	0.070	0.095	0.099	0.085
2–18 ev	A, B	2.510	2.740	1.257	2.405	2.990	1.226	3.195	2.445	2.086
2–19 m	A, B	0.022	0.010	0.080	0.017	0.000	0.000	0.075	0.007	0.009
3–6 m	B, C	0.000	0.055	0.017	0.018	0.030	0.000	0.220	0.033	0.055
3–14 m	A, B	0.370	0.948	0.290	0.567	0.010	0.946	0.210	0.361	0.171
3–21 ev	A, B	0.085	0.358	0.017	0.162	0.020	0.042	0.270	0.437	0.431
3–30 m	A, B	0.208	0.320	0.057	0.205	0.150	0.046	0.220	0.430	0.379
3–31 m	A, B	0.048	0.142	0.013	0.066	0.060	0.232	0.010	0.031	0.002
4–2 ev	A, B	0.788	—	0.853	—	0.490	0.614	1.725	1.756	0.994
4–3 m	B, C	0.065	—	0.160	—	0.010	0.074	0.000	0.024	0.013
4–5 m	A, B	0.000	—	0.000	—	0.000	0.576	0.000	0.000	0.000
4–6 m	A, B	0.628	—	0.463	—	0.430	0.476	0.465	0.387	0.378
4–6 ev	A, B	0.525	—	0.250	—	0.790	0.052	1.025	0.743	0.655
4–7 m	B	0.022	—	0.010	—	0.000	0.000	0.005	0.000	0.000
1959										
1–5 m	A, B	1.652	2.046	1.553	1.862	0.740	1.764	1.995	1.113	0.730
2–15 ev	A, B	1.170	1.421	0.597	1.060	3.360	1.382	2.040	1.040	0.568
2–21 m	A, B	0.112	0.234	0.193	0.176	0.220	0.102	0.120	0.180	0.236
	Mean	0.491	0.818	0.392	0.624	0.505	0.471	0.686	0.530	0.413

Seeding opport. Not seeded in Ventura	Approp. comp. area	T-coast	T-valley	SB-NW	SB entire	A	BS	V-north	V-S.C.	V-Calleguas
1957										
1–11 ev	A, B	0.158	0.212	0.030	0.148	0.120	0.546	0.330	0.203	0.035
1–20 m	A, B	0.315	0.265	0.047	0.227	0.220	0.034	0.275	0.270	0.305
1–23 ev	A, B	0.055	0.100	0.043	0.086	0.110	0.000	0.090	0.188	0.152
1–28 ev	A	0.102	0.152	0.017	0.105	0.090	0.030	0.050	0.040	0.086
2–7 m	A, B	0.055	0.180	0.123	0.102	0.100	0.054	0.125	0.102	0.091
2–8 ev	A, B	0.008	0.015	0.000	0.008	0.000	0.000	0.000	0.004	0.002
2–22 ev	B, C	1.102	1.682	0.580	1.150	1.500	0.870	1.850	1.720	1.114
2–24 m	B, C	0.000	0.002	0.000	0.001	0.000	1.094	0.000	0.000	0.000
2–28 m	A	0.585	0.688	0.060	0.485	0.560	0.134	0.585	0.955	1.881
3–15 ev	A, B	0.008	0.072	0.127	0.058	0.000	0.000	0.070	0.329	0.595
4–20 m	A, B	0.188	0.302	0.100	0.192	0.440	0.180	0.065	0.252	0.379
4–20 ev	B, C	0.000	0.008	0.000	0.007	0.060	0.000	0.000	0.002	0.000
1959										
2–16 m	A, B	0.118	0.276	0.103	0.161	0.000	0.012	0.230	0.498	0.311
4–25 m	A, B	0.542	0.588	0.120	0.432	0.900	0.044	1.170	0.807	0.408
	Mean	0.231	0.324	0.096	0.226	0.293	0.214	0.346	0.384	0.383
Seeded in Ventura										
1958										
1–26 m	A, B	0.042	0.325	0.133	0.175	0.060	0.058	0.025	0.047	0.099
2–2 m	A, B	0.778	1.635	0.113	0.943	1.400	0.736	1.120	0.685	0.431
2–2 ev	A, B	0.478	1.128	0.883	0.795	0.690	0.340	2.195	0.803	0.629
2–3 m	A, B	0.415	0.335	0.030	0.275	0.140	0.104	0.470	0.280	0.359
2–4 m	A, B	0.382	0.785	0.223	0.467	0.030	0.154	0.460	0.545	0.185
2–7 m	A, B	0.118	0.482	0.023	0.268	0.000	0.052	0.110	0.070	0.004
3–10 ev	A	0.225	0.258	0.117	0.229	0.040	0.010	0.440	0.314	0.168
3–14 ev	A, B	0.915	0.972	0.667	0.818	2.510	0.406	0.880	1.112	0.716
3–15 m	A, B	0.882	0.785	0.100	0.607	2.210	0.890	0.720	1.088	0.846
3–15 ev	A, B	0.080	0.162	0.230	0.142	0.040	0.100	0.065	0.345	0.272
3–20 m	A, B	0.710	0.772	0.380	0.600	0.860	0.624	0.570	0.749	0.595
3–23 m	A, B	0.002	0.022	0.060	0.013	0.000	0.346	0.000	0.051	0.019
3–31 ev	A, B	1.338	2.655	1.410	1.888	0.430	1.234	2.270	1.626	1.129
4–1 m	A, B	0.302	0.358	0.263	0.311	0.290	0.078	0.565	0.424	0.417
4–4 m	B, C	0.005	—	0.000	—	0.120	0.006	0.020	0.013	0.000
4–5 ev	A, B	1.398	—	1.020	—	0.950	0.328	1.015	1.052	0.795
1959										
2–10 m	A, B	0.895	2.751	0.833	1.665	0.540	0.970	1.735	0.783	0.212
2–10 ev	A, B	0.538	0.921	0.613	0.723	0.300	0.262	0.940	0.892	0.815
	Mean	0.528	0.897	0.394	0.620	0.589	0.372	0.756	0.604	0.427

T-coast: T1, T2, T5, T6.
T-valley: T7, T12, T17, T23.
SB-NW: F1, G1, G2.
SB-entire: T1, T2, T5, T6, T7, T12, T17, T23, D1, D8, G1, G2.
Comparison A: A2.

Comparison BS: B1, S1, S2, S3, S4.
V-north: D5, D6.
V-Santa Clara: D7, D9, D10, D11, D12, D13, D14, D15, D17, D18, D19.
V-Calleguas: D16, L1, L2, L3, L4, L5, L6, L7, L8, L9, L10.

TABLE 3. Indicated effects of Santa Barbara generators.

Target	Comp.	When there is *no* seeding in Ventura: Average seeded in target	Expected seeded in target	Percent increase ascribable to seeding	Significance probability: F-test	Permutation test	When there is seeding in Ventura: Average seeded in target	Expected seeded in target	Percent increase ascribable to seeding	Significance probability: F-test	Permutation test
		inch	inch				inch	inch			
T-Valley*	A, BS	0.547	0.238	+130	0.03		0.899	1.115	−19	0.74	
	A	0.547	0.246	+122	0.05	0.05	0.830	0.898	− 8	0.61	0.57
	BS	0.427	0.291	+ 47	0.03	0.08	0.876	1.120	−22	0.55	0.95
T-Coast*	A, BS						0.621	0.609	+ 2	0.96	
		(Does not apply)					0.573	0.516	+11	0.55	0.43
							0.592	0.634	− 7	0.78	0.61
T-Coast	A, BS	0.299	0.170	+ 76	0.11		0.587	0.611	− 4	0.82	
	A	0.299	0.181	+ 65	0.12	0.10	0.552	0.541	+ 2	0.54	
	BS	0.245	0.200	+ 22	0.21	0.12	0.516	0.625	−17	0.62	
SB-NW*	A, BS						0.504	0.449	+12	0.83	
		(Does not apply)					0.466	0.378	+23	0.48	0.41
							0.464	0.449	+ 3	0.98	0.69
SB-NW	A, BS	0.206	0.072	+186	0.18		0.476	0.468	+ 2	0.76	
	A	0.206	0.069	+199	0.04	0.04	0.448	0.406	+10	0.47	
	BS	0.175	0.103	+ 70	0.10	0.10	0.412	0.454	− 9	0.95	
SB-entire*	A, BS	0.367	0.163	+125	0.02		0.694	0.758	− 8	0.84	
	A	0.367	0.172	+113	0.04	0.05	0.640	0.622	+ 3	0.51	0.51
	BS	0.295	0.203	+ 45	0.04	0.07	0.669	0.768	−13	0.73	0.86
V-North	A, BS	0.373	0.267	+ 40	0.58		0.755	0.898	−16	0.45	
	A	0.373	0.256	+ 46	0.48	0.15	0.710	0.774	− 8	0.29	0.50
	BS	0.295	0.332	− 11	0.43	0.23	0.720	0.888	−19	0.61	0.75
V-Santa Clara	A, BS	0.417	0.274	+ 52	0.05		0.621	0.696	−11	0.66	
	A	0.417	0.318	+ 31	0.11	0.07	0.585	0.624	− 6	0.40	0.61
	BS	0.328	0.356	− 8	0.19	0.17	0.557	0.701	−21	0.43	0.87
V-Calleguas	A, BS	0.281	0.208	+ 35	0.06		0.483	0.469	+ 3	0.96	
	A	0.281	0.371	− 24	0.39	0.50	0.455	0.438	+ 4	0.72	0.51
	BS	0.219	0.284	− 23	0.29	0.20	0.434	0.487	−11	0.78	0.69
	Period	1957: Jan. 10–Apr. 30; 1958: none; 1959: Jan. 1–Apr. 30					1957: none; 1958: Jan. 1–Apr. 30 (*Apr. 1); 1959: Jan. 1–Apr. 30				

Simultaneous precipitation. Regression analysis by square root inches, assuming normality, *etc.*, and ignoring lack of randomization in Ventura in 1957 and 1958. All seeding opportunities for which comparisons are "appropriate." All stations with continuous data, Jan. 10–Apr. 30, 1957; Jan. 1–Apr. 30 (*Apr. 1), 1958; Jan. 1–Apr. 30, 1959.

In exactly the same manner, the third and the fourth parts of table 3 characterize the effect of the Ventura generators, first in the absence and then in the presence of seeding in Santa Barbara.

Table 3 is composed of nine triplets of lines. Each triplet refers to a separate target or subtarget identified on the left. First, there are three subtargets in Santa Barbara, with Target-Coast and Target NW evaluated twice; then there is a triplet corresponding to the entire Santa Barbara County and, finally, there are three triplets of lines for the subtargets in Ventura.

The first line in each triplet gives the results of evaluation based on those seeding opportunities for which both the control area A and the control areas BS were "appropriate." Here, then, the amounts of rain in both these areas were used as predictors of the rain in the target. Because of the general paucity of data and because there were quite a few seeding opportunities in which only one of the control areas A or BS was appropriate, separate evaluations were performed by using just one control as predictor. The results are given in the second and in the third line of each triplet.

The two evaluations of data for the Santa Barbara Target Coast and Target NW were made for those parts of table 3 which refer to seeding opportunities seeded in Ventura. The reader will remember that this category of data is dominated

TABLE 3. (*con't.*). Indicated effects of Ventura generators.

		When there is *no* seeding in Santa Barbara				When there is seeding in Santa Barbara			
Target	Comp.	Average seeded in target	Expected seeded in target	Percent increase ascrib-able to seeding	Significance probability F-test	Average seeded in target	Expected seeded in target	Percent increase ascrib-able to seeding	Significance probability F-test
		inch	inch			inch	inch		
T-Valley*	A, BS	0.939	0.413	+127	0.28	0.899	1.704	−47	0.05
	A	0.897	0.427	+110	0.08	0.830	1.337	−38	0.25
	BS	0.939	0.384	+145	0.03	0.876	1.289	−32	0.27
T-Coast*	A, BS	0.525	0.362	+ 45	0.48	0.621	1.001	−38	0.19
		0.506	0.381	+ 33	0.14	0.573	0.830	−31	0.31
		0.525	0.266	+ 97	0.09	0.592	0.656	−10	0.88
T-Coast	A, BS	0.580	0.372	+ 56	0.58	0.587	0.895	−34	0.38
	A	0.559	0.393	+ 42	0.13	0.552	0.767	−28	0.33
	BS	0.546	0.259	+111	0.07	0.516	0.581	−11	0.87
SB-NW*	A, BS	0.397	0.081	+390	0.41	0.504	0.566	−11	0.68
		0.380	0.081	+369	0.05	0.466	0.461	+ 1	0.51
		0.397	0.124	+220	0.06	0.464	0.436	+ 6	0.85
SB-NW	A, BS	0.436	0.082	+432	0.41	0.476	0.514	− 7	0.84
	A	0.418	0.082	+410	0.04	0.448	0.433	+ 3	0.56
	BS	0.411	0.122	+237	0.04	0.412	0.389	+ 6	0.84
SB-entire*	A, BS	0.646	0.288	+124	0.25	0.694	1.147	−39	0.18
	A	0.620	0.308	+101	0.06	0.640	0.910	−30	0.37
	BS	0.646	0.264	+145	0.03	0.669	0.852	−21	0.65
V-North	A, BS	0.821	0.520	+ 58	0.69	0.755	1.028	−27	0.69
	A	0.799	0.508	+ 57	0.27	0.710	0.876	−19	0.74
	BS	0.774	0.424	+ 83	0.19	0.720	0.671	+ 7	0.99
V-Santa Clara	A, BS	0.660	0.368	+ 79	0.51	0.621	1.217	−49	0.20
	A	0.639	0.503	+ 27	0.50	0.585	1.047	−44	0.18
	BS	0.621	0.410	+ 51	0.14	0.557	0.761	−27	0.60
V-Calleguas	A, BS	0.470	0.198	+137	0.52	0.483	0.785	−38	0.38
	A	0.452	0.561	− 19	0.92	0.455	0.703	−35	0.26
	BS	0.443	0.294	+ 51	0.21	0.434	0.474	−8	0.84
	Period	1957: Jan. 10–Apr. 30; 1958: Jan. 1–Apr. 30 (*Apr. 1); 1959: Jan. 1–Apr. 30.				1957: Jan. 10–Apr. 30; 1958: Jan. 1–Apr. 30 (*Apr. 1); 1959: Jan. 1–Apr. 30.			

T-Valley: T7, T12, T17, T23; T-Coast: T1, 2, 5, 6; SB-NW: F1, G1, G2; SB-entire: T1, 2, 5, 6, 7, 12, 17, 23, D1, 8, G1, 2; Comparison A: A2; Comparison BS: B1, S1, 2, 3, 4; V-North: D5, 6;
V-Santa Clara: D7, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19; V-Calleguas: D16, L1, 2, 3, 4, 5, 6, 7, 8, 9, 10.

by the year 1958 when, in April, there were eight seeding opportunities with no usable records of rain in Santa Barbara other than in Target Coast and Target NW. Asterisks mark those lines in table 3 which give the evaluations, possibly affected by a bias, which are based on curtailed data of 1958, with the omission of April. For Target-Coast and for Target NW, two evaluations are given, one based on complete data of 1958 and the other on curtailed data, in order to see whether the omission of April data of 1958 makes a substantial difference. It will be seen that the difference between the two evaluations is negligible.

Significance probabilities obtained from the F-test are given for all categories of observations and for all subtargets. In the first two parts of the table, there are also given significance probabilities based on the permutation test. As already mentioned, these probabilities are obtained by a lengthy process on the IBM 701 high-speed computer, and this work is not yet completed. It will be seen that there is a considerable correlation between the F-test and the permutation significance probabilities. This circumstance suggests that the general picture of the results of the experiment will not be changed by the availability of all significance probabilities based on the permutation test. If the contrary should happen, a brief note will be published by the authors.

The reader is warned not to become hypnotized by the prevalence of large positive indicated effects in some columns and the prevalence of considerable negative effects in some others. In fact, an inspection of these columns might suggest that, no matter what the statistical tests show, the multiplicity of similar estimates represents indisputable evidence of a real effect. This conclusion would have been justified, and also it would have been reflected in the statistical tests, if the results in the particular lines of table 3 referred to different experiments and were independent. In actual fact, of course, any two triplets of lines in table 3 are not independent because they are based on *the same* seeding opportunities and refer to subtargets located at relatively very small distances. Thus, an attempt to summarize the general picture, either by counting indicated positive effects of seeding in a given column or by averaging the effects, is somewhat comparable to tossing a penny just once, looking at it a dozen times from different angles, and then arguing that the penny is biased!

A summary picture of the indicated effects in Santa Barbara is shown by the middle triplet of lines marked "Santa Barbara entire." For this triplet, there was a summary test of the hypothesis that no real difference exists among the target-control regressions corresponding to the four categories of observations (i) to (iv) defined earlier: no seeding in either county, seeding in one but not in the other, and seeding in both. With reference to the control area BS, this test yielded the significance probability of 0.06. As a result, the authors are prepared to adopt the attitude that the joint distributions of precipitation data in the target and in the control, underlying these four groups of observations, were not the same. The same test, applied to Ventura-Calleguas, which is the most important part of the Ventura target, failed to show significance.

In the light of these results, the details of table 3 may be examined. They indicate that, when there was no seeding in Ventura (that is, predominantly in 1957), the actual rain in the target recorded for seeding opportunities seeded in Santa Barbara exceeded expectations by about 100 per cent of the latter. As indicated in the earlier lines of table 3, this effect is not evenly distributed over the whole of the target. In the northwest part of the county, it is strongest, reaching 200 per cent.[2] It is weakest on the coast; the effect in the Target Valley is intermediate.

It will be noted that the above results are based on a random subdivision of seeding opportunities (all those of 1957 and a few of 1959) with one random sample subject to seeding and the other random sample left unseeded. Therefore, the conclusions enumerated are not affected either by confounding or by loss of data and re-

[2] The first evaluation of the results of 1957 was included in the progress report of the Statistical Laboratory, presented to the Board of Directors on 4 September 1957. The estimates of the increase in rain ascribable to seeding were given in table 4. Although these estimates were based on preliminary data then available, the general picture they presented was very similar to that now given in the first part of table 3: increases in precipitation by factors 2 and more.

Several months later, there appeared in print an article [5] signed by Robin R. Reynolds, Chairman of the Board of Directors of the Santa Barbara Project. In this article, it is stated that the data of 1957 indicate an increase in the target precipitation due to seeding of about 23 per cent. Also, the same estimate of 23 per cent increase appears in a paper-bound mimeographed booklet issued by the North American Weather Consultants, dated December 1957.

Both publications describe the cooperative character of the Santa Barbara Project, with the Statistical Laboratory as one of the participants, but fail to indicate the authorship of the estimate of 23 per cent. In fact, the relevant sentences collected from page 4 of the booklet of the North American Weather Consultants read as follows: ". . . the statistical design and analysis is being conducted by the Statistical Laboratory of the University of California at Berkeley. . . . The data for the first year have been analyzed. . . . The average increase for the first season was 23 per cent, although this figure must be considered tentative until several more years of data are accumulated."

The subsequent paragraph in the same booklet has an explanatory value and we quote it in full: "Thus, although the evaluation of any one cloud seeding project is difficult, even when they have been conducted for several years in succession, the fact that the Advisory Committee's findings and the preliminary results of the Santa Barbara project agree so closely with our findings for the Upper San Joaquin Valley project lends considerable additional confidence to these results."

It is seen that the estimate of 23 per cent increase at Santa Barbara is used to reinforce the confidence in the NAWC evaluation of its success in the Upper San Joaquin Valley project.

The present authors wish to make clear that this estimate was reached and published without their knowledge and that it bears no relation to table 3 of the present chapter nor to the preliminary evaluation reported to the Board of Directors of the Santa Barbara Project on 4 September 1957.

The two publications involving the estimate of 23 per cent came to the authors' attention in the Spring of 1959 at which time the present authors registered their regret.

On 24 October 1959, the Statistical Laboratory announced its intention of withdrawing from the Santa Barbara Project at the conclusion of the work on the 1960 cloud-seeding season. At the time of this writing (November 1959), the authors were informed by Mr. Elliott that, following their protest in March, the NAWC circularized the recipients of the report of 1957 requesting that the estimate of 23 per cent be removed.

quire only the unique assumption of reliability of the data.

The second part of table 3 is almost equally straightforward, particularly for Target Coast and Target NW. This part of the table is based on randomized seeding in Santa Barbara of those seeding opportunities which were seeded in Ventura (predominantly in 1958 and a few in 1959). Here, the loss of the April data in 1958 may conceivably affect the evaluation for Target Valley and Santa Barbara Entire. The comparison of the two evaluations performed for Target-Coast and Target NW suggests that the effect of the loss of April data is negligible.

Taken by itself, then, the second part of table 3 indicates that, in the presence of seeding in Ventura (in 1958–59), the seeding by the Santa Barbara generators had no noticeable effect on rain in any of the subtargets. That much is unambiguous. The ambiguity appears when an attempt is made to interpret the difference between the first and the second parts of the table. Here, because of the lack of factorial randomization, the striking difference is ascribable either to the effect of seeding or no seeding in Ventura *or* to a difference in the circumstances of the experiment in 1957 and in 1958 *or* to a combination of these two factors.

A strict interpretation of the third and of the fourth parts of table 3 is more complicated, and here the lack of factorial randomization over the three years is felt more strongly. For both these parts, in order to obtain the amount of target precipitation to be expected without seeding in Ventura (whether in the absence of seeding in Santa Barbara or in its presence) it was necessary to use the data referring to those seeding opportunities during which there was no seeding in Ventura; these were predominantly in 1957. On the other hand, the target data corresponding to seeding in Ventura with which these expectations are compared refer predominantly to 1958. In other words, the two sets of seeding opportunities, one with no seeding in Ventura and the other with seeding in Ventura, were not randomly drawn from the same population but represent two different populations. One of these populations is characterized by the weather pattern of the years 1957 through 1959 and the other by the weather pattern of 1958–1959. As a result, the figures in the third part of table 3 referring to the Santa Barbara targets admit a whole spectrum of possible interpretations including the following extremes.

A. In the absence of seeding in Santa Barbara, the seeding by Ventura generators increases the rain in Santa Barbara County by amounts of the order of 100 per cent, and it reaches 400 per cent in the North-West.

B. The weather in 1957 and in 1958 (ignoring the small admixture of 1959) was dominated by two different types of storms. If one compares the typical storm of 1958 with a storm of 1957, both depositing the same amounts of precipitation in the control areas, then the average Santa Barbara precipitation from the 1958 storm will be about twice as high as that of the 1957 storm. For the North-West part of the Santa Barbara target, the estimate of this ratio is about 5 to 1.

A similar ambiguity applies to the fourth part of table 3. The difference between the third part and the fourth is that in the latter the expectations of the target rainfall of 1958–59 when there was seeding in Ventura are based on the 1957-through-1959 data, with no seeding in Ventura but with seeding going on in Santa Barbara. As described with reference to the first part of the table, the seeding in Santa Barbara in the years 1957 through 1959 was accompanied by the doubling of rain in the target, and this may be the explanation of the apparent negative (but not significant) effect of the Ventura generators indicated in the fourth part of the table.

Of the targets and subtargets for which separate evaluations have been made, the most impressive results correspond to Santa Barbara N.W. Fig. 4 gives graphical representation of the results given in table 3. Also, crosses and dots illustrate the scatter of the target precipitation for particular seeding opportunities. Curves, fitted to dots, represent the estimated non-seeded precipitation.

It will be seen that the unexpectedly high proportional increases in target precipitation ascribable to seeding (see in particular the left upper panel of fig. 4) are due not to exhorbitant amounts of precipitation for seeded seeding opportunities but rather to the extremely low amounts falling without seeding. One explanation for this phenomenon is that (predominantly) in 1957 there was over the target a deficiency of natural nuclei. Hence, there was extremely low precipitation without seeding and a large effect of seeding.

Turning to the other lines of table 3, one might say that no significant effects of either sets of generators are noticeable on the precipitation in Ventura.

7. Summary and conclusions

(i) The three years of operations of the Santa Barbara Project are marked with an unexpectedly

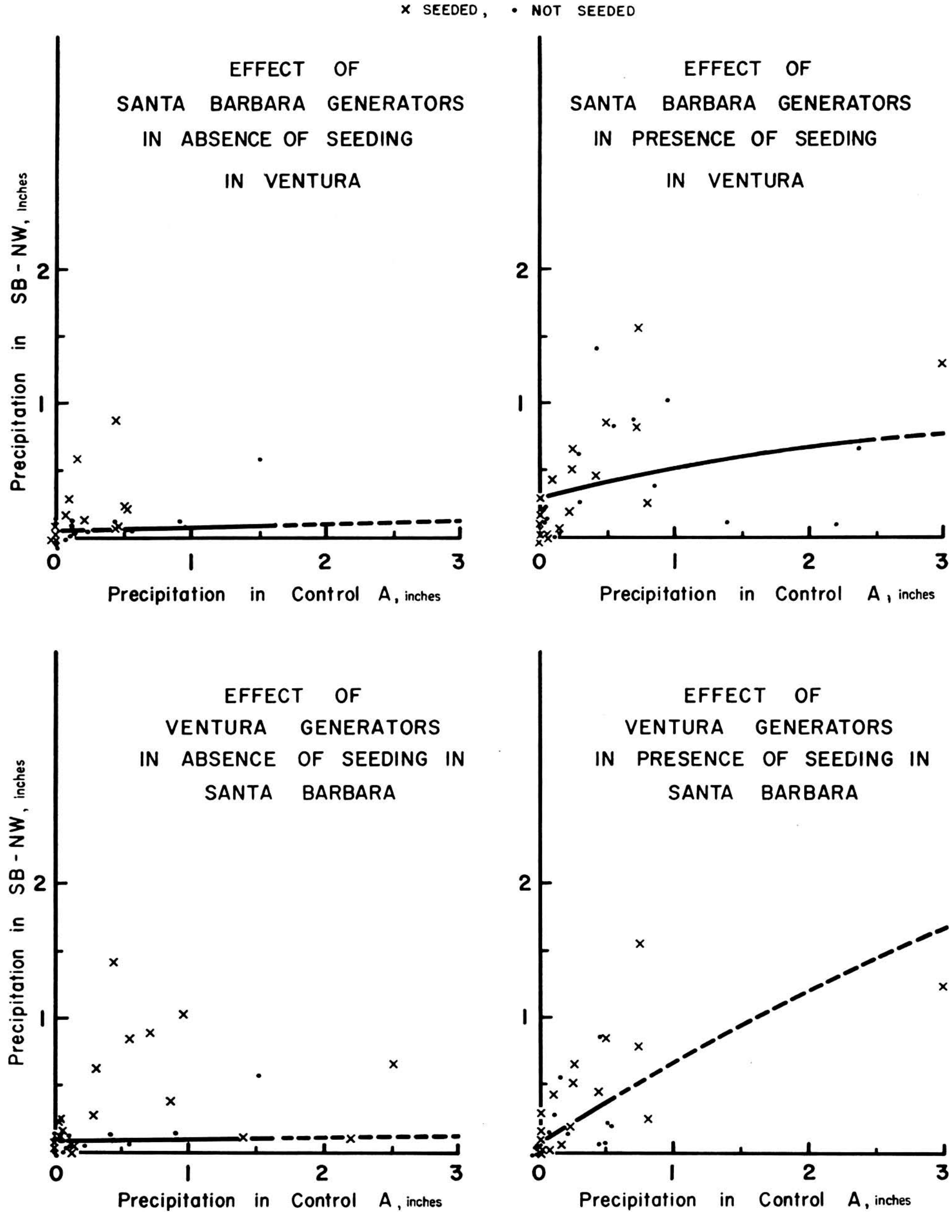


FIG. 4. Results from table 3.

high apparent effect of seeding in Santa Barbara, observed predominantly in 1957 when there was no seeding in Ventura, accompanied by a spectacular change to zero, observed in 1958 when there was seeding in Ventura at every opportunity. This high effect of seeding in Santa Barbara, averaging about 100 per cent for the entire county, must be compared with recent expectations [6] of about 15 per cent. However, it is relevant that this high proportional increase refers to a low base: in the years 1957 through 1959, the average amounts of precipitation in the two control areas A and BS were (see left parts of table 2) 0.190 and 0.148 inches respectively. In 1958 and 1959, these averages were 0.505 and 0.471.

(ii) Experimentation with two distinct target areas, one in Santa Barbara County and the other in the adjoining Ventura County, offers very interesting possibilities of evaluating the effects of seeding in one county on the precipitation in the other. Unfortunately, the lack of factorial randomization in the years 1957 and 1958 creates a confounding of the possible effects of seeding with the possible effects of changes in the weather pattern.

(iii) In the above connection and also because of the lack of data for many gages, particularly in 1957, the authors are inclined to consider the first three years of the Santa Barbara Project as an extensive "uniformity trial," customary in other domains of experimentation, providing valuable experience and indicating useful changes in the design applicable either in the continuation of the same experiment or in the organization of similar experiments.

(iv) From this point of view, the following two points are predominant: (a) utmost care must be exercised to insure the availability and reliability of data, by putting a reasonable number of gages out of danger of interference by target practicing hunters, *etc.*, and, at the same time, so that they can be serviced without undue hardship. Also, it may be appropriate to use raingages which require less frequent servicing. (b) It is imperative to arrange that, for a reasonable number of seasons, there is no fundamental change in the conditions of the experiment comparable to the sudden start of seeding in Ventura County which occurred in 1958.

(v) An effort was made to use the data collected in the years 1957 through 1959 in order to estimate the number of years of experimentation needed to insure a reasonable probability of detecting the effect of seeding if this is of a stated magnitude.

The outcome of such calculations must depend upon the level of significance and upon the magnitude of the effect which one wants to find significant at this particular level. The customary level of significance is 0.05 and the computations we performed all refer to this level. However, our results, combined with the importance of not missing the effects of seeding if such exist, indicate the desirability of adopting a more lenient level—0.10, for instance.

As to the magnitude of the effect of seeding which one should be prepared to detect, the figure frequently mentioned [6] is 15 per cent. This figure requires interpretation. One possibility is that it refers to a single seeding operation. According to this interpretation, if appropriate clouds are seeded over a certain period of time, then, on the average, the amount of precipitation from these clouds will exceed the amount which would have fallen without seeding by 15 per cent of the latter quantity.

Our calculations show that, if this is the appropriate interpretation and if the precision of the Santa Barbara experiment cannot be markedly improved, then the number of years necessary to insure a reasonable probability of detecting a 15 per cent increase is likely to be prohibitive. In fact, it appears that with nine years of experimentation, this probability is still below one-half.

However, we believe that the above interpretation of the expected 15 per cent increase due to seeding is not correct. What is probably meant is that, on the average, the precipitation in the target falling during a year covered by a contract for seeding exceeds by 15 per cent that which would have fallen during that year without seeding. If this is the right interpretation of the 15 per cent increase, then the situation is much more hopeful. The point is that, ordinarily, the rainy season is substantially longer than the period covered by contracts for seeding. For example, in the Santa Barbara region, the rainy season begins in the fall and lasts through April. However, because of certain crops which might be damaged by excessive rain, the seeding season extends only from January to April. Furthermore, as is seen from table 1, normal seeding operations are not conducted over all the days covered by contracts during which there is some rain in the target but only during about one-half of such days. Now, it must be clear that, in order to increase the total seasonal rainfall by 15 per cent by seeding over a fraction of the days when it rains in the target, the increase per seeding opportunity must be much higher than 15 per cent, perhaps amounting to 50 per cent. Naturally, this is much easier to detect than a 15 per cent increase.

Unfortunately, the variability of precipitation is so great that even this much easier problem, of detecting a 50 per cent increase for seeding opportunity, requires quite a few years of experimentation. Our calculations show that, with the precision of the experiment coinciding with that in Santa Barbara in the years 1957 through 1959, with factorial randomization of seeding over two targets over eight years of experimentation, the probability of five per cent significance corresponding to a 50 per cent increase in rain is equal to 0.54. If the experiment is limited to one target of Santa Barbara, requiring a simple randomization, with three years of experimentation, the same probability has the value of 0.68. This is much more hopeful than the probability of 0.54 after eight years of experimentation with two targets.

However, one must realize that cutting the experiment down to one target will preclude the possibility of answering many important questions and will push it away from the desirable status of basic research. In fact, the resumption of the experiment with just one target and simple randomization will preclude the possibility of solving the tantalizing question whether the impressive difference in the effects of seeding in Santa Barbara observed in the years 1957 through 1959 and in the years 1958 and 1959 [see (i) and (ii)] is due to seeding in Ventura or to a change in the weather pattern.

In order to gain an intuitive feeling of the situation behind the above small probabilities of positive results of experimentation with two targets, the reader is referred to table 2 which shows that the relevant standards of comparison are very low. For example, if one experiments with factorial randomization and is concerned with the seeding effects in Santa Barbara, then the standard of comparison is the Santa Barbara precipitation observed without seeding in either target. This happens to be only 0.224 inches on the average, so that 50 per cent of this quantity is only 0.112 inches. When one refers to fig. 2, it is easy to visualize that, in order to have a high probability of detecting a difference of this order of magnitude, it is necessary to experiment for a considerable time or to improve the precision of the experiment.

Our conclusion is that, if the Santa Barbara experiment is to continue, it is imperative to seek methods of improving its precision. The experience gained during the first three years of operations indicates several possibilities as outlined below.

(vi) The data indicate that the correlation between precipitation amounts in a given target and those in a control depends on the location and the shape of this control. In planning an experiment, it is expedient to select the control area so that it cuts across the paths frequently followed by storms contributing rain to the target. Also, the control area should be sufficiently extended in the appropriate direction. Thus, for example, the change from the concentrated control B to the extended control BS resulted in a decrease in the residual variance by a factor of 1.8. Also, the calculations on the data of 1958, not available for 1957, indicated a decrease in the residual variance by a factor of 1.7, due to the use of three raingages in area A as against a single gage A2 used in the actual evaluation given in this paper.

If the Santa Barbara Project is to continue on a new basis, it is very essential to see that the data from all six gages in the control area A have continuous records and be used in the evaluation. Also, it may be found advisable to add some more raingages in the area BS so as to extend it farther east.

(vii) A glance at fig. 2 is sufficient to indicate that the low accuracy of the experiment is due in considerable extent to those cases, quite a few of them, where precipitation in the target is accompanied by no precipitation in the control and vice versa. Thus, the precision of the experiment is likely to be improved if, by a change in the design, the frequency of these cases is diminished. They result from three sources.

First, there is the difficulty in comparing the precipitation in the target with the "simultaneous" precipitation in the control. On occasion, a storm reaching Santa Barbara from the north passes quickly over the control area BS and, by the time there is considerable precipitation in the target, the weather in area BS is all clear. Thus, the precision of the experiment is likely to improve if the precipitation in the target is compared not necessarily with the "simultaneous" precipitation in the control but with the precipitation during an appropriately defined "corresponding" period in the control.

Secondly, there is the difficulty with the rigid "units of observation," each from 10 o'clock to 10 o'clock. In some cases, a seeding opportunity may extend over the whole 12-hr unit of observation. In other cases, it may obtain over a small part of this unit. It is obvious that, even if the effect of seeding is very uniform, in these two cases this effect will be unevenly reflected in the precipitation measured from 10 o'clock to 10 o'clock. Thus, the precision of the experiment will be improved if the rigid "units of observation" are abandoned and replaced by appropriately defined units of varying duration, more nearly corresponding to the duration of actual opportunities for seeding.

Finally, the large scatter of points in fig. 2 and the residual variance are due to the unavoidable errors of forecasting. The NAWC listed a number of them over the three years of operation. Undoubtedly, the frequency of such errors will be decreased if diagnosing of seeding opportunities is not limited to 9 a.m. and to 9 p.m. but is allowed to be made at more frequent intervals, perhaps every 2 hr.

In conclusion, then, we recommend the following three changes in the design of the experiment:

(a) The seeding organization (the NAWC in the case of the Santa Barbara Project) should be allowed to forecast seeding opportunities at frequent intervals rather than just twice a day.

(b) The duration of a "seeding opportunity" should not be fixed but should be adjusted to atmospheric conditions as diagnosed by the seeding organization.

(c) While diagnosing the "appropriate" comparison areas, the seeding organization should be allowed to diagnose the time periods which in each such area "corresponds" to the already forecast duration of a seeding opportunity.

Naturally, in order to insure objectivity, the randomized decision whether to seed or not must be communicated to the seeding organization *after* the above three forecasts are made and recorded.

It is expected that, as the combined effect of the three changes in the design indicated, the precision of the experiment will be improved. Of course, the degree of the improvement will depend upon the skill and good luck in forecasting. However, the forecasts suggested above must be easier than those required under the present system. For example, under the system proposed, the diagnosing of a seeding opportunity may be delayed until the beginning of the rain in the target, which alone will eliminate some of the troublesome variability in the data.

(viii) We believe that the Santa Barbara Project is adversely affected by its detachment from a comprehensive theory of precipitation and from actual physical measurements other than those of precipitation. It is true that theoretical considerations are involved in the process of diagnosing seeding oportunities. However, there are no concurrent measurements capable of statistical evaluation which could either confirm or disprove the underlying hypotheses. For example, one of the hypotheses frequently mentioned is that for seeding to be effective it is necessary that the − 5C temperature level not be too high. In these circumstances, a systematic measurement of this level at the beginning of each seeding opportunity, perhaps through a timely radiosonde, promises very interesting results. A comparison between these measurements with the precipitation might indicate whether the hypothesis is valid or not. Also, the height of the − 5C level may serve as a valuable predictor and improve the precision of the experiment. In a report on the operations in 1957 by the Arizona Institute for Atmospheric Physics, another interesting predictor is mentioned. This is the precipitable water. According to the report, whenever the precipitable water is below 1.0 inch, there is usually no rain in the target. On the other hand, if the precipitable water exceeds 1.1 inches, there is almost always some rain. For this reason, the amount of precipitable water is computed every morning and serves as a criterion as to whether a given day is a seeding opportunity. In the Arizona seeding experiment, the variability of precipitation is about as troublesome as it is in the Santa Barbara Project. In these circumstances, the question as to whether the use of precipitable water evaluated each morning can reduce the residual variance is very interesting.

It should be clearly understood that the two particular parameters, the − 5C level and the precipitable water, are mentioned here merely as illustrations. The nature and timing of physical measurements likely to improve the precision of the experiment and, at the same time, provide important information on the mechanism of rainfall are wholly within the domain of competence of meteorologists. Our own point is that some such measurements should be made as a regular element of a randomized experiment and subjected to a statistical evaluation. A similar suggestion was made by Roscoe R. Braham, Jr. [7].

(ix) As a final point, we wish to express the conviction that a fully successful study of atmospheric physics requires the development of a comprehensive stochastic theory of the atmosphere, somewhat on the lines of the recent attempts [8; 9] at a statistical cosmology. A theory of this kind would include the anatomy of the meteorological unit variously called "storm," "disturbance," "front," *etc.*, by using such elements as the frequently discussed "cells" which are subject to notorious random variability. Also, this theory would include dynamical considerations developed by the Scandinavian School. In their present form, the results of this school, while highly interesting and illuminating, are difficult to apply in practice because they are mostly deterministic (just as are the results of classical cosmological theories) and do not involve explicitly chance mechanisms capable of representing the striking variability of weather phenomena.

The construction of the stochastic theory of atmospheric phenomena is a problem of very considerable difficulty and may be solved only by an organized team effort of competent meteorologists and probabilists-statisticians. Some steps in this direction have been made by LeCam and Morlat in France and are vaguely reflected in some of their papers [10; 11]. Also, similar efforts appear to be in progress in the Institute for Atmospheric Physics of the USSR Academy of Sciences.

REFERENCES

1. Department of Water Resources, State of California, 1959: *Santa Barbara weather modification project.* Interim Rep. of the Board of Directors.
2. Neyman, J., and E. L. Scott, 1960: Correction for bias introduced by a transformation of variables. To be publ. in *Ann. Math. Stat.*
3. Jeeves, T. A., L. LeCam, J. Neyman, and E. L. Scott, 1954: *On the methodology of evaluating cloud seeding operations.* A rep. publ. in Bull. No. 16, California State Water Resources Board, August, pp. D-1 to D-47.
4. Department of Water Resources, State of California, 1954: *Weather modification operations in California.* Bull. 16, California State Water Resources Board, August, pp. 2-9 to 2-14 and plates 1-5.
5. Reynolds, R. R., 1957: *Santa Barbara project.* Final Rep. Advis. Comm. Wea. Control, Vol. 2, 249-252.
6. *Final Report of the Advisory Committee on Weather Control,* Vol. 1, 1957, p. vi.
7. Braham, R. R., 1959: *Physical evaluation of seeding effects II. Physical properties of clouds.* Pap. presented at joint Meet. Amer. Meteor. Soc. and Amer. Soc. Civil Eng., Denver, Colorado, August.
8. Neyman, J., and E. L. Scott, 1959: Stochastic models of population dynamics. *Sci.,* **130**, 303-308.
9. ——, 1958: Statistical approach to problems of cosmology. J. r. Stat. Soc., B, **20**, 1-43.
10. LeCam, L., 1947: Un instrument d'étude des fonctions aléatoires: la fonctionelle caractéristique. *Comptes rendus,* **224**, 710-711.
11. LeCam, L., and G. Morlat, 1949: *Les lois des débits des rivières francaises.* La Houille Blanche, Special Issue B.

ABOUT OUR MEMBERS

John D. Alyea of the Weather Bureau, Des Moines, Iowa, was appointed state climatologist for Wyoming in July.

Prof. *Jacob A. Bjerknes,* University of California, Los Angeles, and Dr. *Walter Orr Roberts* of the High Altitude Observatory, Boulder, Colorado, and Director of National Center for Atmospheric Research were among the 116 new fellows elected by the American Academy of Arts and Sciences in May.

Walter A. Bohan, senior meteorologist at Cook Research Laboratories, Chicago, was one of the chairmen of the underwater-instrumentation sessions at the 15th Annual Instrument-Automation Conference held in late September in New York by the Instrument Society of America. Mr. Bohan has been giving talks to science seminar groups in Chicago during the past year for which the AMS has contributed source material. Mr. Bohan recently assumed command of Naval Research Company 9-1, Chicago, a unit of civilian research specialists under the technical sponsorship of the Office of Naval Research.

E. Brewster Buxton of Pan American World Airways has been appointed superintendent of the Overseas Division, New York International Airport, Jamaica, New York.

John L. Cerutti has joined Tryck, Nyman and Associates as project engineer with assignment in Anchorage, Alaska. He was formerly in the Public Works Department, Mayport, Florida.

M. R. Dasgupta of the Indian Meteorological Department, New Delhi, accepted an assignment as United Nations technical expert to the Government of the Sudan and is posted at Khartoum for one year.

Dr. *Christopher Dean,* formerly of the Physics Department, University of Pittsburgh, recently joined the staff of Allied Research Associates, Inc., Boston.

R. de Chancenotte has left Pan American World Airways and is now associated with the Stormy Weather Research Group, Macdonald Physics Laboratory, McGill University, Montreal.

Roy M. Endlich this summer became affiliated with Stanford Research Institute, Menlo Park, California. He was formerly with the Geophysics Research Directorate, Bedford, Massachusetts.

Edward S. Epstein and *Paul R. Julian* were awarded Ph.D.'s in meteorology by Pennsylvania State University in January 1960. Master's degrees were conferred at the same time on *Hugh M. O'Neil, Melvin H. Rajala,* and *Alonzo Smith, Jr.*

Robert F. Gentzler recently joined the staff of the Sandia Corporation, Albuquerque, New Mexico.

A. Vaughn Havens of Rutgers, The State University, New Jersey, was promoted from associate to full professor of meteorology, effective 1 July 1960.

Dr. *Woodrow C. Jacobs,* director of climatology for Air Weather Service since 1948, has resigned this post to take over an assignment as physical scientist with the Legislative Branch of the Government with offices in the Library of Congress. Dr. Jacobs is chairman of the AMS Board for Certified Consulting Meteorologists.

Joseph Kaplan, professor of physics, University of California, Los Angeles, has received the Exceptional Service Award, highest civilian decoration given by the Air Force. The honor was in recognition of Dr. Kaplan's leadership in geophysics as head of the U. S. Committee for the International Geophysical Year.

Early this year *John M. Mercer,* research meteorologist, transferred from the Meteorology Division of the Army Research and Development Laboratory, Fort Monmouth, New Jersey, to the Navy Weather Facility, Norfolk, Virginia.

James E. McDonell, teacher and research meteorologist in the Department of Oceanography and Meteorology, A. and M. College of Texas, has now joined the staff of the National Weather Analysis Center, Suitland, Maryland.

As head of the speakers bureau of The East Ohio Gas Company, *Richard E. Miller* has given about fifty talks on weather.

Having completed graduate study at Pennsylvania State University, *J. Murray Mitchell, Jr.* has returned to the Office of Climatology, U. S. Weather Bureau, Washington.

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