15 April 1960, Volume 131, Number 3407 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Randomized Cloud Seeding in Santa Barbara

The effectiveness of cloud seeding during a period of three years is statistically evaluated.

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To our knowledge, the Santa Barbara project has unique status in weather control studies in that it is a randomized experiment designed to test the effectiveness of cloud seeding from ground-based silver iodide generators. The experiment was conducted over three seeding seasons, in 1957, 1958, and 1959, and the present article gives a brief summary of the results (*1*). More details are available in a mimeographed report issued by the Statistical Laboratory, University of California, Berkeley.

The organizational outline of the Santa Barbara project was published at the outset of the experiment (*2*). Briefly, North American Weather Consultants, Inc. (NAWC), of which Robert D. Elliott is president, conducts the seeding operations, using ground generators; the California State Department of Water Resources is responsible for maintenance of rain gages, obtained on loan from the U.S. Weather Bureau, and for the collection of data; and the Statistical Laboratory of the University of California, Berkeley, is responsible for the randomization of the experiment and for the statistical evaluation.

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Experimental Procedure and Method of Evaluation

Figure 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 elsewhere in this article by *BS*.) Solid circles, with various symbols attached to them, mark the location of rain gages.

The basic experimental procedure is as follows. The seeding season, January through April of each year, is divided into 12-hour periods, each from 10 o'clock to 10 o'clock, termed "units of observation." Some time before the beginning of each 12-hour period or unit of observation, the NAWC decides whether this unit is suitable for seeding operations. 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 affirmative case, the NAWC indicates which of the three control areas are "appropriate" for use during the given seeding opportunity. These are the control areas which the NAWC expects will not 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, by a method agreed upon at the outset of the project, is based on the precipitation recorded in the target areas for all periods designated "seeding opportunities" and for no others. The amounts of precipitation recorded in the target areas are compared with the amounts falling simultaneously in the "appropriate" control areas.

Basically, two kinds of statistical evaluations were made; for one, the so-called normal theory was used; for the other, nonparametric methods.

In order to stabilize the conditional (residual) variance of the measure of target precipitation, given the precipitation in the appropriate control area, the amounts of rain in each subtarget area, observed for the particular seeding opportunities and averaged over the corresponding rain gages, 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 seeding opportunities in which there was seeding ("seeded seeding opportunity") coincided with corresponding regressions for seeding opportunities in which there was no seeding ("nonseeded seeding opportunity"). Subsequently, the regression

equations computed with the square-roots of precipitation measures for "nonseeded seeding opportunities" were used to estimate the square-roots of 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 had been made for bias due to the transformation of variables, were compared with the actual precipitation in target areas during each seeding opportunity in which seeding was carried out. The differences between these two quantities, averaged over all seeding opportunities in which seeding was carried out, represent estimates of the average effect of seeding.

This procedure was used because it was familiar and relatively easy. However, because of the various well-known uncertainties regarding the applicability of normal theory to precipitation data, even if the data 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.

Three Years of Operations

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

Some of the difficulties would have been experienced at the start of any large project, regardless of the organizational setup. The terrain of the interior of the Santa Barbara target area is very rugged (Fig. 2), the installation and servicing of rain gages presented many difficulties. Eventually, particularly in bad weather, the gages were serviced by helicopter. Similar difficulties were encountered in installing and servicing the gages located in the Channel Islands, which are practically uninhabited. As a result, the official beginning of the experiment was moved from 1 January to 10 January 1957. However, even after that date some gages were not in operation, and data from many of the gages are incomplete. In a few instances the rain gages appeared to have been used as targets for practice shooting and were damaged by bullets. In trying to include the maximum number of seeding opportunities in the evaluation, we found that, out of the 31 gages installed in the county of Santa Barbara in 1957, we could use only the 13 for which there are continuous usable records over all three seasons. By "usable records" is meant not only clear-cut records on the chart but also those records where, because of late servicing, the gages recorded, over longer periods of time, accumulations which could be "distributed" convincingly among the several adjoining units of observation.

As mentioned above, such difficulties are intrinsic parts of setting up 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 met with certain other difficulties which might have been avoided if the experiment had been 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 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, and some sort of cooperative arrangement with the Santa Barbara project was anticipated.

The inclusion of Ventura County in a single cloud seeding project, combined with the project in Santa Barbara, opened very interesting possibilities. The questions of whether seeding operations conducted in one area affect the precipitation in an adjoining area, and if they do, in what sense, are important practically and interesting theoretically. By an appropriate adjustment of the seeding schedules in Santa Barbara and in Ventura, in experiments of reasonably long duration, at least a partial answer to these questions could be obtained. 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; and (iv) seeding in both counties.

The relationship symbolized by [(ii) − (i)] would 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 relationship symbolized by [(iv) − (iii)] would provide estimates of the effect of Santa Barbara generators when seeding was being carried out concurrently in Ventura. The relationships [(iii) − (i)] and [(iv) − (ii)] would give the effects, respectively, of the Ventura generators in the absence of, and concurrently with, seeding in Santa Barbara.

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

In 1959 there was a salutary 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 data for 1957 to provide estimates of the effects of seeding averaged over 1957 and 1959. Combination of the other half with the data of 1958 provides estimates of the different effects of seeding averaged over 1958 and 1959. There are obvious difficulties of interpretation.

Estimates of Average Effects of Seeding

The evaluation was performed separately for six subtarget areas in the counties of Santa Barbara and Ventura. In each case an effort was made to evaluate the effects of the two separate sets of silver-iodide generators, one intended to increase rainfall in Santa Barbara, the other to increase rainfall in Ventura. The effects of seeding on rainfall in Ventura were generally statistically nonsignificant. On the other

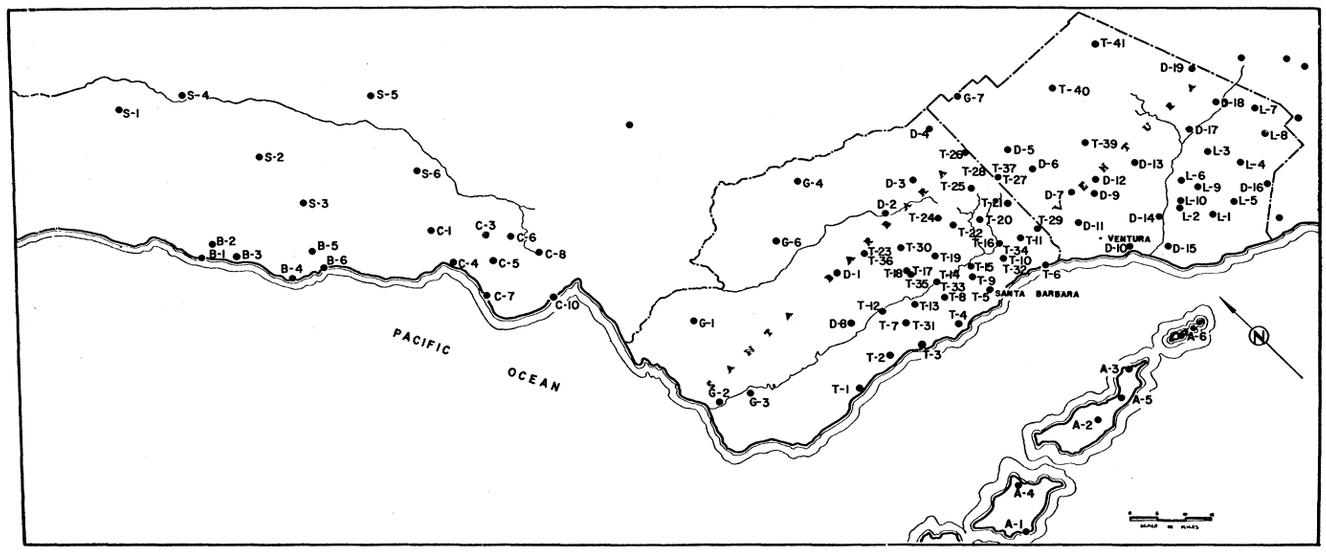

Fig. 1. Locations of recording rain gages.

Fig. 2. Part of Los Padres National Forest in Santa Barbara County, showing the rugged terrain of the target area. [David Muench]

Table 1. Estimates of the average effect of seeding by Santa Barbara generators.

Control area	In the absence of seeding in Ventura (1957, 1959)			In the presence of seeding in Ventura (1958, 1959)		
	Av. seeded precipitation (in.)	Precipitation expected without seeding (in.)	Increase ascribable to seeding (%)	Av. seeded precipitation (in.)	Precipitation expected without seeding (in.)	Increase ascribable to seeding (%)
			Target: Santa Barbara (entire)			
A, BS	0.37	0.16	+125	0.69	0.76	−8
A	0.37	0.17	+113	0.64	0.62	+3
BS	0.30	0.20	+45	0.67	0.77	−13
			Target: Santa Barbara (N.W.)			
A, BS	0.21	0.07	+186	0.48	0.47	+2
A	0.21	0.07	+199	0.45	0.41	+10
BS	0.18	0.10	+70	0.41	0.45	−9

hand, the differences in precipitation from seeded and from nonseeded clouds as observed in Santa Barbara appeared to be significant. In fact, an over-all test indicated that similar or greater differences could be produced by chance alone with probability of 0.06. Samples of the relevant results are given in Tables 1 and 2, and one of these sets of results is illustrated in Fig. 3. One set of results refers to the whole target of Santa Barbara; the other, selected for its high values, refers to the subtarget Santa Barbara North-West area.

As mentioned at the outset, for the evaluation of the experiment, three distinct control areas were contemplated, A, BS and C. However, area C was so rarely appropriate that it could not be used. Because of the general paucity of data, three evaluations were made for each of the target areas: in the first, seeding opportunities for which both control areas A and BS were appropriate were used; in the second, all the seeding opportunities (there were a few more of them) for which area A, but not necessarily BS, was appropriate; and finally, the seeding opportunities for which control area BS, but not necessarily A, was appropriate. Thus, the results for the three rows grouped together in Tables 1 and 2 are not independent.

In interpreting these tables it is necessary to keep in mind the conditions under which the experiment was conducted. In this respect there is an important difference between the two tables, and this difference suggested the desirability of making two tables rather than one. In Table 1, each group of three columns, taken by itself, is unaffected by confounding and, therefore, if the reliability of the records of the rain gages is taken for granted, represents the effects directly ascribable to seeding. In fact, the average precipitation from cloud seeding in the target area given in Table 1 was computed from observations on seeding opportunities *selected at random for seeding operations out of the same seeding-opportunity population which served for estimating the amounts of rain that would have fallen without seeding.* In the evaluation of the effect of the Santa Barbara generators *in the absence* of seeding in Ventura, the seeding-opportunity population consisted mainly of seeding opportunities that occurred in 1957, plus a few that occurred in 1959. In the evaluation of the effect of the Santa Barbara generators when seeding was being carried out concurrently in Ventura, the population consisted of seeding opportunities that occurred in 1958 plus a few that occurred in 1959. As a result, it is the comparison between the two three-column groups in Table 1 that is affected by confounding, not the contents of the two groups taken separately. The difference between the two groups may be due to the occurrence or lack of seeding in Ventura or to a change in the experimental conditions in 1957 and in 1958—perhaps to a change in the pattern of weather.

The situation reflected in Table 2 is much more complex and much less satisfactory. Here the amounts of rain to be expected in the absence of seeding by the Ventura generators were, of necessity, computed mainly from 1957 data. These expectations were then compared with data for precipitation from cloud seeding which occurred mainly in 1958. Hence, the ambiguity of interpretation. In order to avoid this ambiguity, the experiment should have been conducted with a factorial randomization over the whole of its duration, 1957–1959.

In spite of these shortcomings, the results given in the two tables are very interesting. If the reliability of data is granted, Table 1 indicates the possibility that extremely unexpected year-to-year differences in the effects of seeding occur. In 1957–1959, when there was no seeding in Ventura, the Santa Barbara generators appear to have produced increases in rain amounting to as much as 199 percent of what was to have been expected without seeding (*3*). On the other hand, in 1958–1959, when seeding was going on in Ventura, the effect of the Santa Barbara generators appears to have been nil. The cause of this difference has not been determined, and it represents an important subject for further studies.

Table 2 is also interesting, even though its interpretation is ambiguous. One possible interpretation of the first three columns of Table 2 is that, when there is no seeding by the Santa Barbara generators, the seeding by the generators in Ventura is very effective in increasing rain in Santa Barbara, the

Table 2. Estimates of the average effect of seeding by Ventura generators.

Control area	In the absence of seeding in Santa Barbara			In the presence of seeding in Santa Barbara		
	Av. seeded precipitation, 1958, 1959 (in.)	Precipitation expected without seeding 1957, 1959 (in.)	Increase ascribable to seeding* (%)	Av. seeded precipitation, 1958, 1959 (in.)	Precipitation expected without seeding 1957, 1959 (in.)	Increase ascribable to seeding* (%)
			Target: Santa Barbara (entire)			
A, BS	0.65	0.29	+124	0.69	1.15	−39
A	0.62	0.31	+101	0.64	0.91	−30
BS	0.65	0.26	+145	0.67	0.85	−21
			Target: Santa Barbara (N.W.)			
A, BS	0.44	0.08	+432	0.48	0.51	−7
A	0.42	0.08	+410	0.45	0.43	+3
BS	0.41	0.12	+237	0.41	0.39	+6

* Or to a change in the experimental conditions between 1957, 1959 and 1958, 1959.

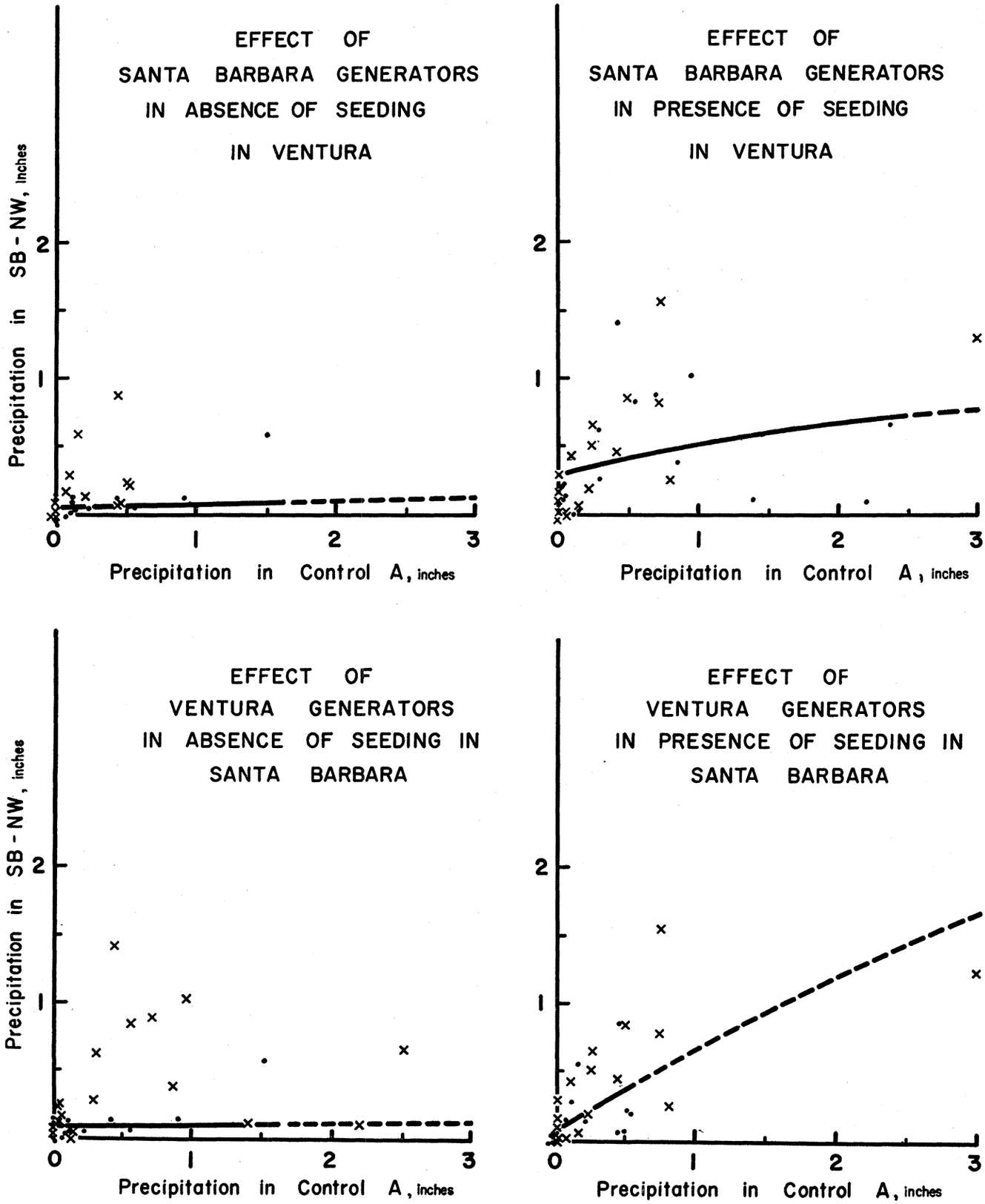

Fig. 3. Effects of seeding in Santa Barbara and Ventura counties. (Crosses) Seeded; (dots) not seeded.

indicated increases amounting to as much as 400 percent of what would have fallen if the Ventura generators had been inactive. The other possible interpretation is that the storms of 1957 were in some way different from those in 1958 and that the target-control relationships of precipitation from these two types of storms were very different. This phenomenon of the dependence of the target-control relationship on the type of storm has been noted elsewhere (*4*).

In order to make the results of Tables 1 and 2 more graphic, Fig. 3 was constructed. It gives the scatter diagrams of precipitation from seeded and from nonseeded clouds in the subtarget Santa Barbara North-West area and in control area A. The curves represent the precipitation to have been expected in the target area in the absence of seeding by the generators indicated.

The striking feature of Fig. 3 is that the unexpectedly high proportional increases in precipitation noted above are due not to very heavy amounts of rain on the target from seeded clouds but to the fact that spectacularly low amounts fell when there was no seeding. One possibility is that in 1957 (not in 1958) the clouds passing over Santa Barbara County had a marked deficiency of natural ice-forming particles, hence there was very little natural rainfall and an unusual increase due to seeding.

Further experimentation is needed in order to answer the many interesting questions raised by the Santa Barbara project. This further experimentation should be factorially randomized and should be broader than the experimentation reported here; it should include several physical measurements (for example, of the density of nuclei) capable of supporting or contradicting the basic hypotheses underlying cloud seeding. Also, it is to be hoped that in these further experiments it will be possible to install the all-important rain gages in locations where they can be serviced without undue hardship and, at the same time, be out of range of hunters engaged in target practice and protected from other possible interference.

References and Notes

1. This work was done in the Statistical Laboratory, University of California, Berkeley, with the partial support of the National Science Foundation, grant G-8211.
2. J. Neyman, *Science* **125**, 61 (1957).
3. 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 Sept. 1957. The estimates of the increase in rain ascribable to seeding were given in Table 4 of that report. Although these estimates were based on preliminary data then available, the general picture they presented was very similar to that given here in the first three columns of Table 1; and showed increases in precipitation by factors of 2 and more. Several months later there appeared in print an article signed by Robin R. Reynolds, chairman of the board of directors of the Santa Barbara project ["Final Report of the Advisory Committee on Weather Control" (1957), vol. 2, p. 249]. In this article it is stated that the data of 1957 indicate an increase in the target precipitation due to seeding of about 23 percent. Also, the estimate of a 23-percent 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 source of the estimate of 23 percent. In fact, the relevant sentences collected from page 4 of the booklet 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 percent. . . ." We wish to make it clear that this estimate was reached and published without our knowledge and that it bears no relation to Table 1 of this article or to the preliminary evaluation reported to the board of directors of the Santa Barbara project on 4 Sept. 1957. The two publications in which the estimate of 23 percent is given came to our attention in the spring of 1959, at which time we registered our regret. At the time of this writing (November 1959) we were informed by R. D. Elliott that, after our protest in March, the NAWC circularized the recipients of the report of 1957 requesting that the estimate of 23 percent be removed.
4. T. A. Jeeves, J. Neyman, E. L. Scott, *Bull. Calif. State Water Resources Board Publ. No. 16* (1954), p. D-1.

CURRENT PROBLEMS IN RESEARCH

Quantum Phenomena in Biology

Natural, ultraviolet, and high-energy radiation processes are compared.

C. Reid

This article is confined to the discussion of phenomena in which the absorption or emission of energy is clearly demonstrable as initiating or terminating a sequence of biochemical events. Doubtless many of the "dark" processes occurring in biological systems without such initiation or termination will one day be examined in terms of the "quantum phenomena" involved, but as yet few data are available about the participation of excited states in such reactions.

Living things have evolved in a world where light is the only widely available source of energy at a high enough potential to excite molecular electrons into new energy levels. Thanks to various absorbing layers in the upper atmosphere, most of the small fraction of solar radiation of high enough energy to cause gross rupture of chemical bonds is conveniently filtered out, leaving appreciable intensity only at wavelengths greater than 300 millimicrons. Since excited molecules often undergo reactions which are energetically unfeasible in the ground state, light is a major factor in the struggle of living organisms to decrease their entropy at the expense of the environment. It is not surprising, therefore, that the great majority of organisms—with the possible exception of a few parasitic forms—make use of light energy in one way or another.

Such processes we will call normal quantum phenomena. They may be characterized by the following features.

1) Absorption of light energy is confined to special molecules, located in special regions of the organism. This is possible because none of the major constituents of the living cell—water, proteins, nucleic acids, and their building blocks—have significant absorption at wavelengths greater than 300 millimicrons.

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